Prototype BLSS Lunar-Mars Habitat Design

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Abstract

Sadler Machine Company, working in collaboration with the University of Arizona Controlled Environment Agriculture Center, UA Aerospace/Mechanical Engineering School, and other NASA Steckler Space Grant partners, proposes a future Bioregenerative Life Support System (BLSS) oriented Mars Habitat. Initial human Mars surface exploration missions will most likely be of limited duration (~60 days) due to the narrow return window resulting from the roughly biennial Earth/Mars alignment. Once longer missions are undertaken, this same Earth/Mars biennial alignment will dictate missions of approximately ~500 days with crews spending over a year living on Martian surface. These initial "picnic missions" (~ 60 days) will rely almost exclusively on meals brought from Earth, utilize very small crew quarters, and be supported by physicochemical life support systems (PCLSS). Once the longer duration missions of ~500 plus days are undertaken, crop production in the habitat becomes feasible, which can augment the crew's diets while recycling their water and revitalizing their atmosphere. BLSS works in concert with Physicochemical Life Support Systems (PCLSS) and adds another level of dissimilar system redundancy for crew life support safety while extending the PCLSS functional longevity. BLSS enables incorporation of ISRU of Mars' carbon dioxide atmosphere, water, and sunlight into the mission to reduce dependency on stowed or resupplied food and water, and could help support a crew for an unintended extended mission duration. The habitats utilized for an extended presence on the lunar surface and the ~500 day Martian missions will most likely be of common design. Utilizing the earlier BLSS based UA/SMC Lunar Habitat design a comparison of the Lunar and Martian habitats challenges are explored.

I. Introduction

Numerous mission architectures and targets exist within the space community for the human exploration of Moon and Mars, common to all is the need for a habitat to support its surface crew if an extended presence is envisioned. Many propose a direct mission to Mars while others propose first establishing a lunar base which could act as a test bed for Mars hardware (Constellation Program). Either way, many of the challenges that will need to be addressed are common to both endeavors, such as radiation shielding, power production, life support systems, material recycling, transportation/deployment of the structure, etc. Sadler Machine Company (SMC), working in collaboration with the University of Arizona Controlled Environment Agriculture Center (UA-CEAC), UA Aerospace/Mechanical Engineering School (UA-AME), and other NASA Steckler Space Grant partners, proposes one possible design for a future Bioregenerative Life Support System (BLSS) oriented Mars Habitat. Impacting future habitat design criteria is mission architecture, delivery vehicle capabilities, crew size, mission research targets, single mission vs. multi-mission use, location, etc. This proposed BLSS Mars Habitat design is based on a mission architecture where first this habitat would be utilized on the lunar surface, possibly the rim of Shackelton's Crater, and later iterations of this common habitat design utilized for a ~500 day Mars Mission.

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The lunar environment consists of no appreciable atmosphere, solar insolation of ~1366W/m2 with lunar daytime temperatures at Shackelton's Crater averaging constant temperature of ~ -13^{0}C (8^{0}F) (Krujiff, M, 2000). The lunar regolith consists of a fine grain abrasive sand generated by continuous bombardment of meteorites and micrometeorites over the millennia, and can extend down beneath the surface many meters. Micro-meteorite bombardment impacts the entire lunar surface with every square meter being struck on average once every two years (Ming, D. Henninger, D., 1989). Constant background Galactic Cosmic Radiation (GCR) and random Solar Energetic Particle (SEP) events associated with Coronal Mass Ejections, or Solar Flares impact the crew's survival, and which both can be lethal. Lunar gravity being 1/6th of Earth's, once a month an event called the Lunar Terminator occurs, which is the transition from the lunar night into the lunar day, and charged regolith dust particles are lifted upwards and settle on all surfaces, including photovoltaic arrays, flat panel heat exchangers, etc. (Taylor, L. et.al, 2005). Researchers have suggested that water may exist in the eternally shaded areas of craters at the lunar poles, but in the form of permafrost which would make extraction difficult (LRO). One NASA suggested site for a future lunar base is on the rim of Shackelton's Crater on a "Peak of Eternal Light" with continuous sunlight ~94% of the time (Busseya, D., 2010). The lunar polar regions are the "relatively" most hospitable sites on the Moon for a human mission with reduced temperature extremes, reduced radiation hazards, and a possible water source. Conversely, Mars' environment is much more hospitable to humans than the Moon's, except that instead of a few day return trip to LEO, it is a matter of 6 months, depending on the Mars Transit Vehicle. It has a carbon dioxide atmosphere with a total pressure of roughly 1% of Earth's, solar insolation is ~50% of Earth's, equatorial temperatures can range from +35^{0}C day to -90^{0}C night (NASA, JPL, 2007), frozen water and carbon dioxide exist at some locations, micro-meteorite hazards are greatly reduced, and it has ~1/3 of Earth's gravity.

II. UA-CEAC/SMC Lunar Habitat Design

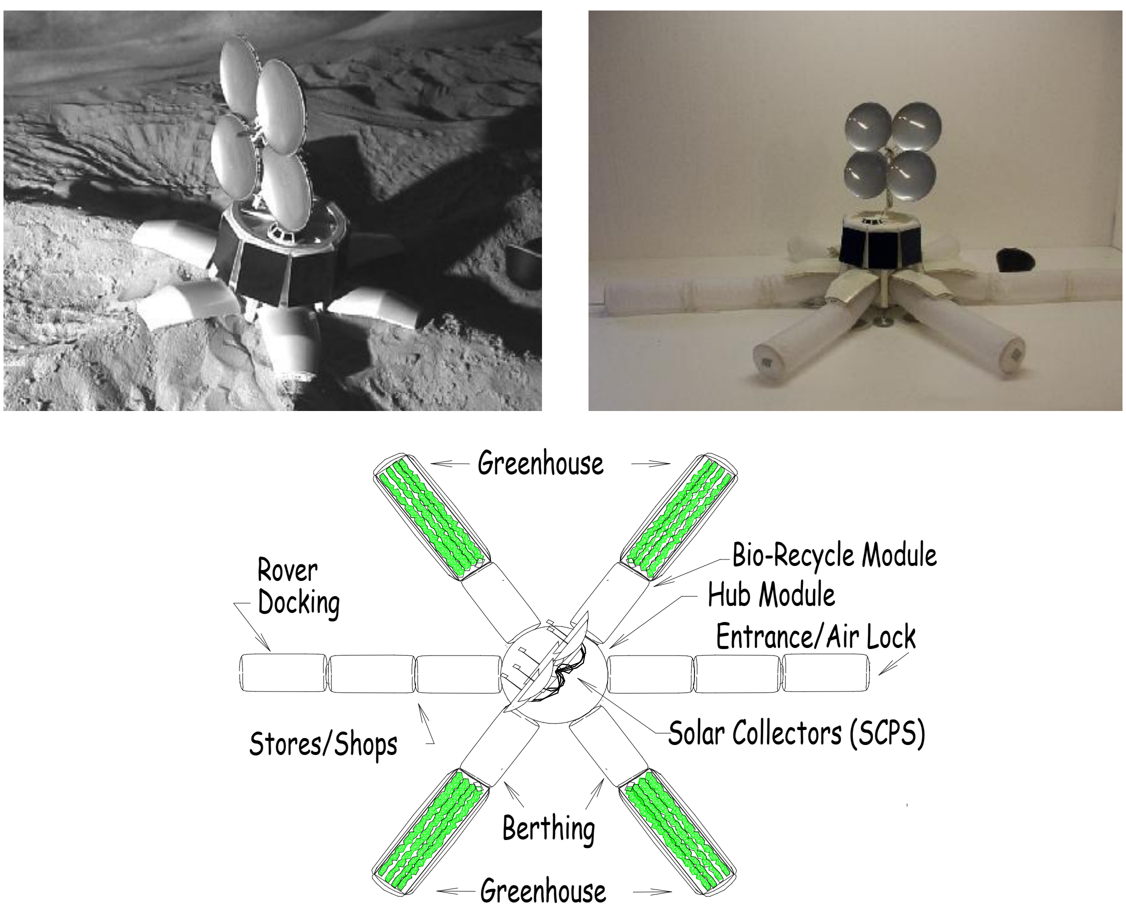

Figure 1. a. Prototype Lunar Habitat buried beneath lunar regolith b. Uncovered c. Overview

Inflatable modules may be part of a Moon/Mars habitat design given their low mass, ease of stowage, and their potential to increase available crew space. Our proposed design utilizes small individual inflatable membrane modules that can be ganged together (Figure 1a.,1b,1c) (Sadler, P. et.al.,2008). The Prototype BLSS Mars Habitat design is common to the proposed Prototype BLSS Lunar Habitat, "Hub and Spoke" design with the surface delivery/landing vehicle containing the stowed membrane modules (See video 1 listed in the appendix.). This provides the six "Spoke" module trains radiating from the "Hub" section. The advantages of this design over a single toroidal shaped structure or other designs that use a single common interior environment are that; a) the individual membrane modules can be detached and moved by crew members b) burying the membrane module provides counter forces to the module's interior stress by interior pressure pushing outward and extends the service life of the membrane c) should a fire or catastrophic decompression occur the entire habitat would not be lost and the damaged module could be removed and/or a new membrane installed d) having a 225cm diameter it could be more easily buried on the Moon and support the 1 meter of lunar regolith or shielding on Mars e) multi-storied habitats can be fatal in the event of a fire/smoke event to crewmembers trapped on the upper level and these also would have greater radiation exposure for the crew on the upper floor f) the aluminum folding structure offers more solid mounting area on the walls than one large annulus or cylinder shaped habitat utilizing a membrane envelope.

The Prototype BLSS Lunar/Mars Habitat employs an internal folding aluminum structure that is tethered to the membrane envelope and as the envelope is inflated it draws out the folding aluminum structure which locks into position (Figure 9)(See video 2 listed in the appendix). The pressure differential between the interior cabin pressure and the vacuum of the lunar surface environment, and the almost non-existent Mars surface atmosphere, would be sufficient to support a meter of lunar regolith on top of the membrane structure without the inner aluminum structure for radiation shielding (Sadler,P.,Giacomelli,G.2007). But if catastrophic envelope failure and decompression does occur, the folding aluminum structure would be able to independently support the one meter of regolith overhead and not have it crush the crew or hardware. Additionally, this folding rigid structure maximizes solid attachment space for rigid interior components such as galley, work stations, berthing, science and exploration gear, etc. and gives the crew a solid surface to walk on with better structural attachment points to the membrane envelope. Many components will require wiring harnesses, plumbing systems, HVAC systems, that too will require solid mounting to this folding aluminum structure. Inherent to a buried membrane structure is that the membrane envelope will consist of numerous dedicated layers for abrasion, insulation, heating, etc. But, being buried dictates that the inner pressure shell must be an inner layer accessible from the inside, probably with removable insulated wall blankets. Once buried, there is little access from the outside to affect repairs or patches to the pressure shell layer without excavation. And given the differential pressures from the inside to the outside, repairs would need to be accomplished from the inside.

III. Radiation Shielding

Radiation countermeasures and shielding will be one of the key drivers in the design and development of a Moon/Mars habitat. While covering a habitat with 1-2 meters of regolith is presently a widely accepted approach to providing GCR radiation shielding for the crew (Howe, S. , Sherwood, B., 2009), other new technologies are being developed that also provide radiation shielding and ultimately a hybrid approach will most likely be incorporated into future habitats. Materials such as LDPE (RXF-1) (Barghouty, A.. Thibeaul.,S., 2006), boron fibers, hydrogen impregnated carbon nano-tube structures, or incorporation of electro magnetic fields into composite materials may all hold promise (Mckay, C., Chen, B., 2012). These new shielding technologies will constantly advance as a Lunar or Mars Mission is pursued. For this proposed habitat design, we will limit the design to an ISRU mass based approach using lunar regolith or Martian water for shielding, and as these other new technologies advance, the ISRU mass based component hopefully will be reduced or eliminated entirely. With an ISRU mass approach, many issues impact the habitat's design such as; targeted location for the mission, what ISRU materials are available, how much shielding is required, what equipment will be available to collect and move this shielding material, what shielding properties can be incorporated into the habitat reducing dependence on a mass based shielding approach. Before any human exploration site is identified, robotic probes will need to explore the location, gathering data on all aspects of its physical environment, and adjusting the mission to that environment.

The habitats will be constantly exposed to GCR which is generated from all directions from the cosmos while the SEPs originate from a single point source, our Sun. The GCR radiation shielding issues become more pronounced as the Moon/Mars surface mission's length increases from a short duration Apollo like mission to a sustained presence on the Moon, and from ~30 days to ~500 days on the Martian surface. SEP events occur both in cycles and randomly, but they can be detected by satellite based solar observatories and the crew provided with an advanced warning for a lunar outpost. Being given this advanced warning will allow the crew to shelter in small survival enclosures with greatly enhanced shielding capabilities for short durations. On the lunar surface, if the habitat is located at the Lunar South Pole and covered with a meter of regolith, depending on how the module was buried and the angle of incidence of the SEP, its path would make the regolith shielding functionally much greater and provide extra SEP shielding (Figure 2a). On the Martian surface the availability of regolith will vary depending on where the habitat is located. During the recent Curiosity Rover landing NASA's Sky Crane engine thrust blew away the loose Martian surface regolith and it could be seen to be only a few centimeters thick at that spot, this becomes a challenge when the vehicle that is suppose to push the shielding material is an extremely light weight machine working in 1/3 gravity. Additionally, most Mars photo show a considerable amount of free surface rocks that would be detrimental to the habitat's covering if they were placed against it. It may be possible to fill in around the habitat with Martian regolith but most likely the regolith would only go partially up the sides and some other shielding like water bladders would extend overtop (Figure 2b).

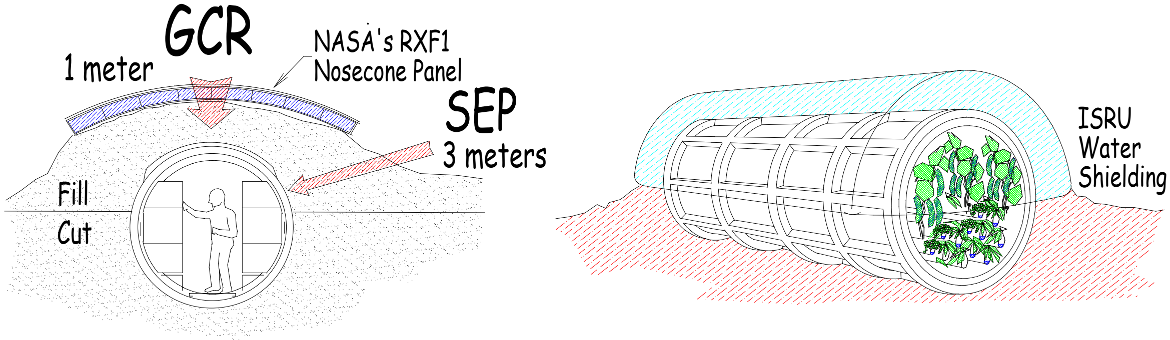

Figure 2. a. Lunar Habitat regolith shielding b. Martian Greenhouse with ISRU water shielding

Snow at the Antarctic South Pole could provide a good analog for Lunar Regolith in that it has a similar weight once the 1/6th lunar gravity is factored in. Based on data from the Apollo Missions the samples 1 meter below the lunar regolith and Antarctica's South Pole surface suggests that the temperatures could be similar (Heiken, G.,1991). One great advantage with lunar regolith in burying a structure is that it is crystalline in nature, similar to snow. This is a huge advantage in burying a lightweight structure in that a normal 1-to-1 fall, (45degree side slope) will lift the module up as the material is backfilled in around the module. Being able to dig a trench with vertical walls allows the operator to get closer and fill in overtop the module with little or no lifting, as well as reducing the amount of material by over 50% that is required to be excavated. It will be difficult for cold rooms to reproduce the -83C temperatures that can occur at the NSF's South Pole Station for hardware testing, such as burying a habitat. This location needs further investigation for use as a lunar/Mars analog environment for future habitat development and deployment.

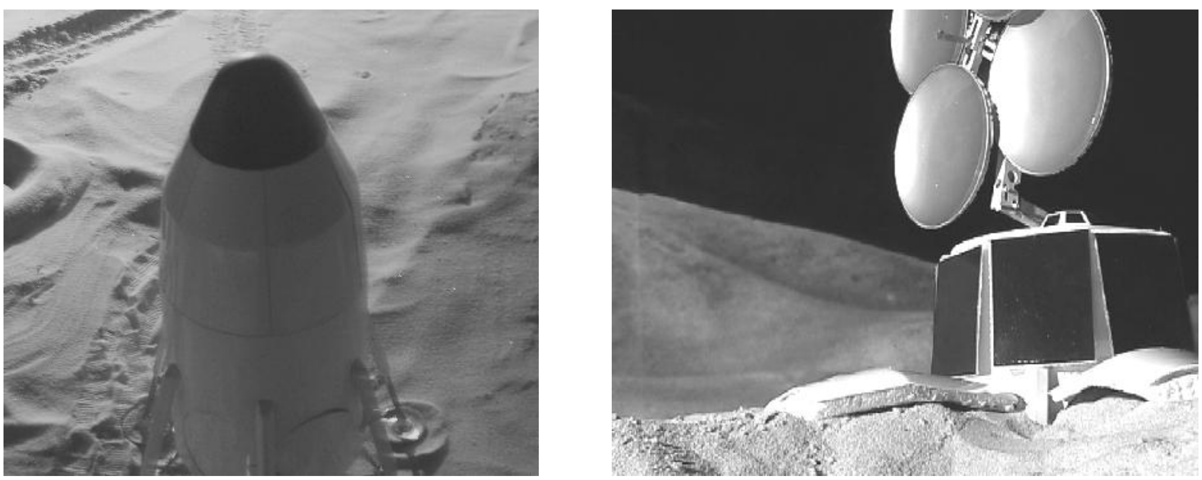

Figure 3. a. Lunar Habitat Vehicle b. Lunar Habitat buried with GCR shielding deployed

Even with burying the Lunar Habitat it may still benefit by incorporating other shielding material like NASA's RXF-1into fairings and nosecone panels from the vehicle landing and placed overtop the buried habitat modules (Figure 3a,3b). The Hub Module is a two story structure with the crew space on the bottom and second story being dedicated to mechanical systems and water storage, and an outside observation cupola. With this design water storage and radiation shielding is located overtop the crew space in the Hub Module to provide protection from GCR and secondary particles while regolith would be pushed up around the bottom story walls. Additionally, if a SP100 like nuclear generator is employed, then a berm of regolith will need to be pushed up to shield the crew from the generator's radiation (Mason, L. et.al.1984). A two story habitat with crews living on the second story would require a taller berm for generator radiation shielding.

IV. Thermal Well for Heat Rejection

Energy production and heat rejection are two critical systems for a human exploration missions of Moon and Mars. Given the vital nature of these two systems a high degree of dissimilar system redundancy will be required. Solar power systems, both Photovoltaic and Solar Concentrating Power Systems, could be the primary systems of both Moon and Mars. Both Moon and Mars have issues with dust, the Moon has the Lunar Terminator and Mars has dust storms that can last for weeks, both could compromise solar power generation using photovoltaic panels and flat panel radiators for heat rejection. A secondary power generation system will probably rely on nuclear power similar to NASA's SP100 type. Even with nuclear power generation the reactor would not be impacted by dust, but heat would still need to be rejected from this process and the habitat. Micro-meteorite bombardment and dust issues on the lunar surface, and dust on Mars could negatively impact a large array of flat panel radiators laying on the surface, so here again dissimilar system redundancy should be included.

It is proposed that ISRU water could be used for radiation shielding for the Martian Habitat which would require considerable amounts being extracted from permafrost. Given the results of the Phoenix Mars Mission, water in the form of ice has been proven to exist on Mars (Smith, P.,2009). James Dohm of the University of Arizona's Hydrology Department as well as a number of other researchers suggest that there may be considerable amounts of frozen deposits of water on Mars that are covered over by a thick frozen mantle of regolith (Murry, J.B. et.al,2005). Finding and extracting this ISRU water on Mars is key to a successful long term human presence. While permafrost in the Earth's polar regions is made up of a percentage of interstitial ice, it is very difficult to extract and separate from the parent regolith. The same will hold true on Moon/Mars with the added problem of sublimation once the ISRU frozen water is exposed. The proposed Thermal Well concept is based on the principals of the Rodriquez Well system used at the NSF's Amundsen-Scott South Pole Station for extraction of fresh water from the miles of ice beneath the station and also Geothermal Home Heating Systems (Elke Bergholz, 2007). The Thermal Well concept (Figure 4b) capitalizes on the

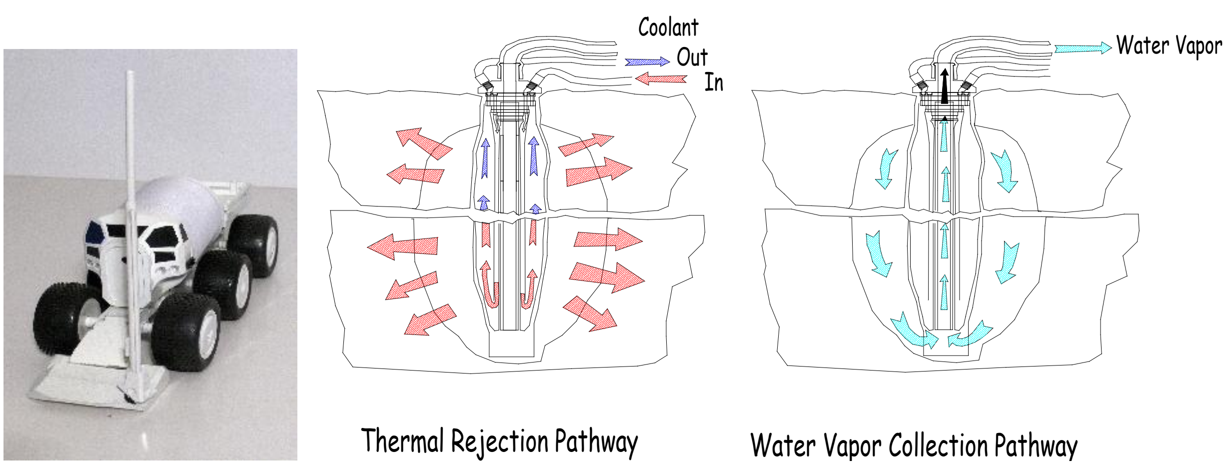

Figure 4. a. Rover with Coring Drill b. Thermal Well Pathways

thermal mass below the habitat and the sublimation process, and operates as a dissimilar redundant system to flat panel radiators for heat rejection. It circulates an antifreeze fluid from the habitat's heat generating processes into bladders that are inserted into core holes drilled into bedrock next to the station using the geologist's coring drill on the Rover (Figure 4a). This fluid rejects its heat into the bedrock's thermal mass as the fluid circulates in the Thermal Well and then returns the cooled fluid back to the habitat to collect more heat. As a "windfall" of this process on Mars, if interstitial ice is present the hot fluid melts the ice and the resulting water immediately sublimates, the vapor is then extracted from the well as a vapor and transferred to the habitat where it is condensed and collected as a liquid.

The Lunar regolith is the result of millions of years of meteorite and micro-meteorite strikes and is a good insulator, and for the Thermal Well to reject heat on the Moon, the lunar regolith will need to be removed to access the bedrock's thermal mass. On Mars, in order to find and harvest ISRU water the habitat would need to be located over or near frozen ice deposits or permafrost. A possible analog testing site for this system might be in the McMurdo, Antarctica area where thick mantels of regolith exist over top sea ice (Black Island).

V. Lunar Greenhouse Modules

Bioregenerative Life Support Systems are based on the concept of including biological systems that occur naturally on Earth and incorporating them into human life support for space exploration. With our UA/SMC BLSS Lunar-Mars Habitat effort we are investigating crop production and composting for atmosphere revitalization, water recycling, and food production in a semi-closed system. Based on NASA estimates it is suggested that if a BLSS system can produce half of a crewmember's food requirements in a space greenhouse, that 100% of their water recycling and atmosphere regeneration can be met successfully (Wheeler,R. 2003). Currently with our NASA supported Steckler Space Grant funding we have operated a single prototype lunar greenhouse module with a goal of targeting biomass production in Phases I and II, and water recycling. We have met our expectations of water recycling with a maximum output of 47L/day, but our oxygen production goal was not met (Giacomelli,G.,2012). For NASA Steckler Space Grant Phase III we are proposing investigation of algae cultivation as a means for additional oxygen generation and further closing the system by incorporation of a composter with the addition of the Bio-Recycle Module. Currently, we have three more Lunar Greenhouse modules under construction to allow us to work in "full size" for a target crew of four persons using space greenhouse modules that conceivably represent lunar-Mars surface like structures.

Figure 5. a. Lunar Greenhouse module end view b. LGH side view

In our quest to reduce overall mass and stowage, the Lunar Greenhouse may not necessarily require the folding aluminum structure, given that the interior cabin air pressure can support the regolith shielding without it. Except for the aluminum door structure and rigid components that would connect to the next module, the remainder of the greenhouse module's growing systems and components could be of membrane construction. These would be constructed so that they could withstand being crushed by the regolith shielding and then be able to be re-inflated and put back into service. The hazard to the crew and habitat from this approach is that even with the lunar $1/6^{th}$

gravity, or Mars' 1/3rd gravity, a meter of regolith or other shielding material still weighs enough to crush a crewmember or hinder their rapid escape from the module if it were to depressurize. Given the frozen nature of the two environments below a meter of lunar regolith and the Martian surface environment, one possible solution is to develop an ice composite structure that would allow the module not to collapse suddenly and provide some opportunity for crewmembers to escape and to repair the leak (Figure 6b). A personal experience at the NSF's Amundsen-Scott South Pole Station (-32C) where I needed to remove a frozen composite of spun fiberglass insulation (Owens-Corning Pink) and ice leads me to suggest that this same composite of ice and spun carbon fiber could be used as a structural element in the frozen environments of space. It was extremely strong at -32C and could be a lightweight alternative to a metal structure if ISRU water is successfully mined. If the module were to collapse and re-pressurized, this carbon fiber/ice composite outer structure could be melted, reformed to its original shape, and re-frozen providing the module with its original level of structural support. In the frozen environments beneath the lunar surface and on Mars surface, ice is an ISRU building material that could complement a membrane structure and should be investigated.

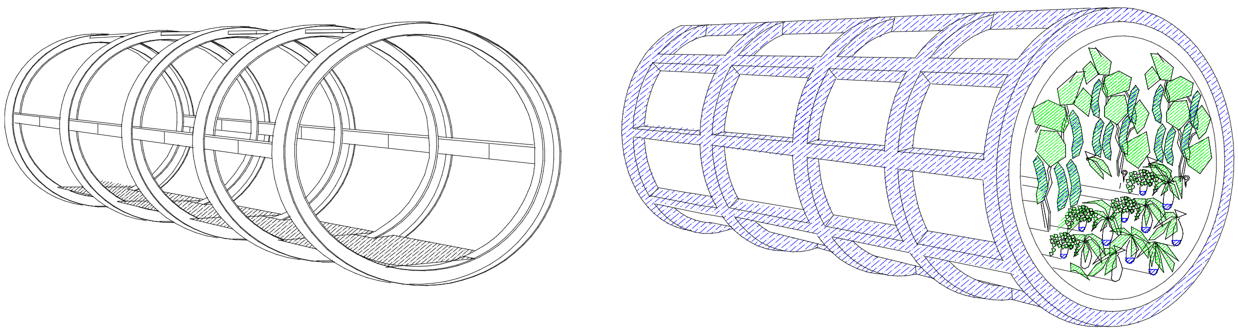

Figure 6. a. Lunar-Mars folding habitat structure b. Ice composite greenhouse membrane structure

Elimination of the aluminum structure in favor of the ice composite structure allows the greenhouse to be stowed in a lighter and much more compact package (Figure 7a). The pressure differential between the outside vacuum and the interior pressure would provide sufficient tension on the two aluminum end structures to keep the cables that support the growing systems taut (Sadler, P., Giacomelli, G. 2007). The reduced gravity would also aid in supporting the growing systems and plants. But, for terrestrial analog applications spreader bars would be required to separate the two rings because of the lack of a pressurized cabin interior.

Figure7. a. Rigid Aluminum Lunar Greenhouse End Structures b. Interior view

VI. Bio-Recycle Module

Our NASA Steckler supported BLSS efforts have mainly focused on the Lunar Greenhouse in Phase I and II, generating biomass, developing models for water recycling, oxygen generation, nutrient usage, plant lighting, mass balances, etc. But, to complete the BLSS closed system we also need to look at post harvest solid waste recycling, (composting), human waste recycling (aqueous bioreactors), crew waste water recycling, etc. and these processes will be undertaken in our new Bio-Recycle Module (Figure 8, 9). The Composting-Wick-Evaporator (CWE) is key to the solid waste/carbon and water recycling, where the organic solid waste stream is mostly converted to carbon dioxide and water while the crew's waste water stream is fed into the CWE at a rate that maintains optimum moisture content for degradation. These grey and black water feeds evaporate or are released as a vapor by microbial respiration and generates elevated humidity levels inside the CWE. This interior humidity is condensed and harvested providing a condensate water, leaving the solids behind in the CWE. This CWE condensate water is supplied to the hydroponic systems for nutrient makeup water for the greenhouse. This CWE condensate water in the plant nutrient water is absorbed by the crops and transpired into the greenhouse's interior atmosphere as humidity, which is then condensed and harvested as crew water, completing the semi-closed water cycle. There will be losses due to EVAs or leakage of atmosphere/humidity from the habitat, and with food and water resupply the system will have gains and losses. To meet NASA's water quality standards for potable water it would require another level of polishing via filters, but for other crew functions such as laundry, cleaning, showers, it might suffice. With this water recycling process, the solid wastes, soaps, other organics, in the water are left in the composter to be consumed by microbes. Composting reduces the waste stream by approximately 90%, the other 10% would need to be carbonized to extract the remaining resources. In addition to the shower and toilet, composters, and water storage systems, the Bio-Recycle Module would also contain the galley and laundry with the dining facility being located in the Hub Module. This would greatly simplify plumbing, food processing, cleaning, etc.

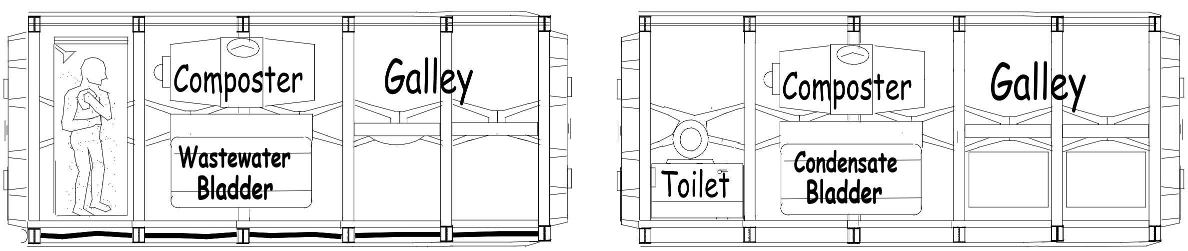

Figure 8. Bio-Recycle Module Interior Layout a. left side view b. right side view

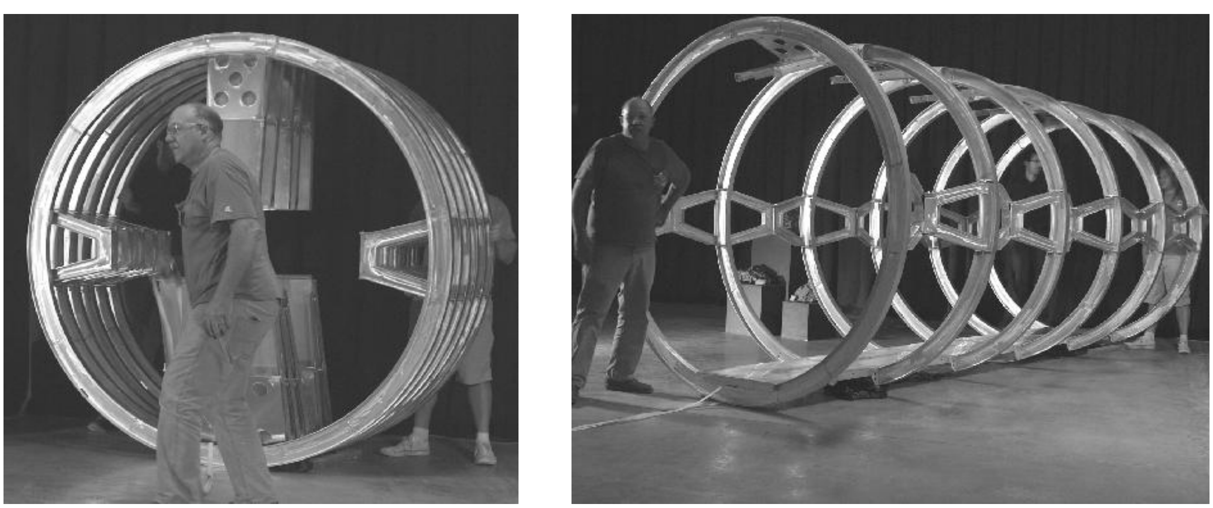

Figure 9. Bio-Recycle Module aluminum folding structure a. stowed b. deployed

VII. Habitat "Forwarding" using the Sky Crane concept

With the recent success of NASA's Curiosity Rover's Sky Crane, this successful design opens up totally new opportunities with regards to the habitat deployment, conservation of mission resources, and aerial vehicle use. While the Lunar polar regions are the relatively most hospitable locations for a lunar exploration mission, they are also possibly the most interesting locations with their potential for ISRU water, oldest crater in our Solar System, they look deeper into an area of space with fewer stars and galaxies, and with the smaller size of the Moon, traverses from a polar base could be successfully conducted. Conversely, Mars is larger and has more geological features of interest located in the equatorial regions. This equatorial environment is relatively more hospitable than the Martian polar regions which have polar ice caps of frozen carbon dioxide and water which extend to lower latitudes during the Martian winter, which encase everything in ice. Mission planners may target the Lunar polar locations for a sustained presence while the human exploration of Mars would most likely be similar in nature to the Apollo Program with new and different exploration sites being targeted with each mission. And similarly to the Apollo missions, all the hardware besides the return vehicle for the crew would be abandoned at the past site and the next mission would need to bring all new hardware to the future exploration site. To sustain a crew of 4-6 persons for the ~500 day mission would require considerable hardware in not only the habitat, but spare parts, emergency rations, nuclear generator, Rover, Sky Crane, photo voltaic power systems and heat rejection hardware, water, and a number of other resources and hardware. These components for each mission could be viable for many successive missions if they can be "forwarded" to the next Martian exploration site, this provides incentive to use BLSS and conserve physicochemical life support systems beyond just the ~500 day mission length. This forwarded hardware and resources, if made available to the next crew, would greatly improve safety, allow for greater human exploration efforts, reduce costs, and accelerate exploration of Mars.

The Curiosity's Sky Crane concept could be employed to land the Mars Habitat on the surface safely and then be repurposed by the crew to operate as a remotely operated vehicle (Figure 10a)((Davoodi, F.,2013)(Thangavelu, M. et.al., 2007). It could be used to place remote scientific equipment packages far away from the base, put in fuel caches for traverses, rescue the Rover should it break down or get stuck, it could have many useful functions assisting the human crew during their initial exploration missions. Once the crew was ready to depart, the membrane modules could be stowed back into the habitat's Hub module and the Sky Crane could lift the modules to the next exploration location (Figure 10b). Once multiple Rovers, habitats, Sky Cranes, etc. are located at the next exploration site it would create a "critical mass" whereby greatly improve safety by having a means to rescue stranded Rovers, other Sky Cranes, establish a "salvage yard" for spare parts, and after many flights, if Sky Crane flight is deemed safe enough for human flight, then maybe a large permanent Mars Base with a greater number of astronauts could be established and field camps included.

This added surface mobility would greatly aid in exploration efforts and increase the safety of the crew. The importance for BLSS efforts is that it greatly lowers the Equivalent Systems Mass (ESM) metric to be able to "forward" greenhouse and recycling modules to the next exploration site, along with its associated hardware and water. What is of importance with the use of this Sky Crane concept is that future mission planners and habitat designers take this "forwarding" option into consideration in their future hardware and architecture development.

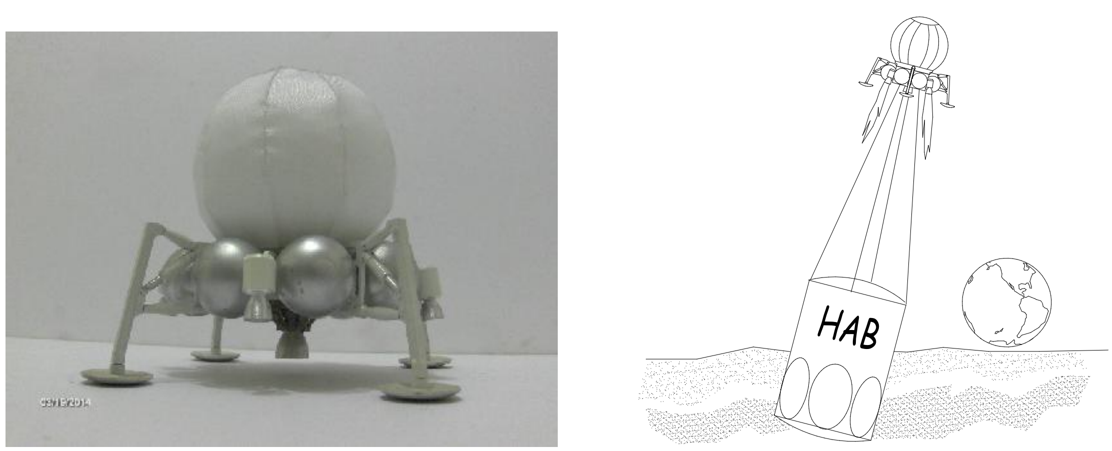

Figure 10 a. Sky Crane UAV b. Sky Crane moving Lunar Habitat

VIII. Conclusion

Providing radiation shielding for a future Moon/Mars Habitat will have a major influence on its design. One or two meters of regolith shielding overtop the crew represents a possible safety hazard if supported solely by inflation pressure and limits utilization of many advanced habitat designs. Hopefully new light weight radiation shielding materials will be developed in the future to eliminate a mass based shielding approach utilizing regolith or ISRU water.

Heat rejection is equally as important as power generation, and the Thermal Well concept is capable of rejecting heat into the frozen bedrock near the habitat on Moon and Mars. For utilizing the Thermal Well concept for ISRU water harvesting as a windfall of heat rejection, it needs to be tested in a vacuum chamber to see if water vapor can be extracted from permafrost and condensed once inside a pressurized environment. The need for dissimilar system redundancy for heat rejection should dictate that this approach be included in addition to flat panel radiators.

Given the exploration of a planet which possesses adequate sunshine, water, and carbon dioxide for crop production inherently lends itself to including a BLSS approach for crew life support, and again providing another level of dissimilar system redundancy. With a biennial alignment issue for transit to Mars, the crew is isolated for over two years on the surface and in transit, and should problems dictate a rescue effort, the mission could be over four years long. Incorporation of BLSS and sustainability into these life support systems could be very desirable. Development of crop production module designs with the lowest possible ESM would enable their inclusion into future missions.

Other components of a BLSS, besides the greenhouse modules, need to be included, such as composters and post harvest processing in their own dedicated module, along with lavatory, laundry, and galley. The Bio-Recycle Module represents this module and hopefully we will incorporate it into our UA-CEAC BLSS effort.

The Sky Crane and the "forwarding" concept in this paper, habitat mobility and using hardware and resources over a number of missions and surface exploration sites elevates crew safety while lowering costs and increasing exploration potential. For including BLSS in future habitat designs, if its components and hardware can be spread over multiple missions, and resources like mined ISRU water can be Forwarded to the next exploration site, possibly where ISRU water might not exist, the BLSS habitat's ESM penalty could be greatly reduced.

Videos

An animated video of a model Lunar Habitat deploying on the lunar surface
video1 http://www.youtube.com/watch?v=Ic7SGj2ivXs&list=PL413299491AED2F9C

A video showing the Lunar Greenhouse module structure unfolding and crops growing in it
vid.2) http://www.youtube.com/watch?v=ETnwPICxrl0

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