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ADVICE FROM ARES: ENHANCING HABITAT AND LIFE SUPPORT SYSTEM DESIGN WITH MARTIAN AND LUNAR ANALOGUE TEST SITE MISSIONS

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Since mid-2011 the German Aerospace Center Institute of Space Systems has been working in the field of habitat design, specializing also in life-support systems within the project EDEN. Having conducted several design studies about off- and on-planet habitats and greenhouse systems, the Department of System Analysis Space Segment had the opportunity to participate in the International Lunar Exploration Working Group's EuroMoonMars B mission (Crew 125) at the Mars Society's Mars Desert Research Station (MDRS) in early 2013. This participation took place mainly under the auspice of relating the analogue test site with the habitat design studies of the department and to prepare future missions with the perspective of greenhouse system tests. One year later in 2014 the department participated in the Reliability and Redundancy of Extreme Environment Habitat Structures and Power Systems mission (RAR Mission) within Crew 135. The main focus of the mission has been structural and power assessments to improve habitat performance, efficiency, reliability and redundancy. In particular a study on illumination and nutrient delivery systems of the GreenHab was performed to make it more efficient in terms of plant production and crew time use. The authors present in this paper an overview about the research conducted off-site, describe the status of MDRS and the missions and elaborate the experiments and lessons learnt during the Crew 125 and Crew 135 participation. It is shown how analogue test site utilization enhances the department's research in the field of habitat and life-support system design and in general the preparation of human missions to Moon and Mars.

I. INTRODUCTION

Analogue missions are an important step for future human space exploration. They enable the testing and maturing of new technologies and procedures in relevant operational environments prior to actual space missions. Furthermore they provide the opportunity to study one critical part of human space exploration in a space-like environment, which is crew interaction. Many analogue test sites, like the Mars Society Mars Desert Research Station (MDRS) provide facilities to conduct scientific experiments in relation to space exploration in a simulated Martian environment. MDRS consists of a main habitat and a greenhouse module, the GreenHab, which gives higher fidelity to the simulations, since a greenhouse module will be necessary for long-duration missions on the Moon or Mars.

In mid-2011 the German Aerospace Center (DLR) Institute of Space Systems began working on research regarding planetary habitats in the Department of System Analysis Space Segment (SARA).

One major step has been a Concurrent Engineering study [1,2,3] with the purpose of designing a habitat prototype designed to allow technology maturation and qualification [4]. This design, labeled "Facility of Laboratories for Sustainable Habitation" (FlaSH), has been further refined in the aftermath of the study [5].

In addition the department began research in the area of controlled-environment agriculture in a laboratory exclusively built for this purpose. This Evolution & Design of Environmentally-closed Nutrition sources

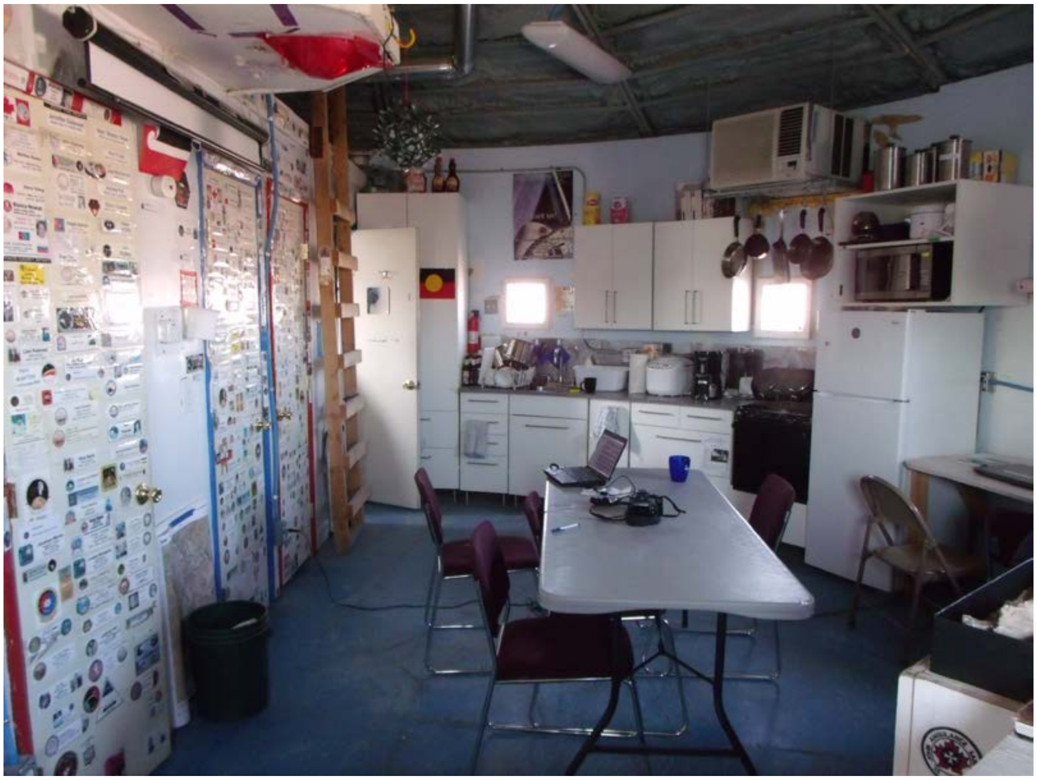

Figure 1: The partial upper floor of MDRS during EuroMoonMars B in 2013. Center background: kitchen area and food storage, center and right: working area and dinner table, left: crew compartments.

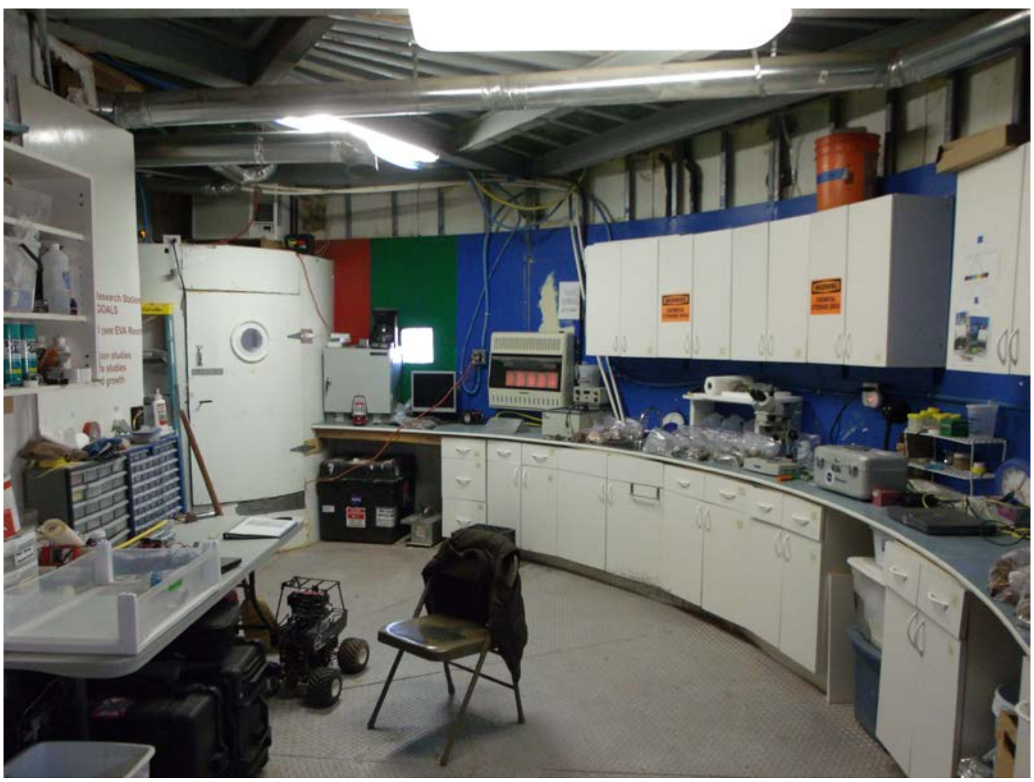

Figure 2: The partial lower floor of MDRS during EuroMoonMars B in 2013. Right and background: laboratory, left background: secondary airlock, left: workshop table.

(EDEN) Lab has facilities to investigate plant growth in various environmental, light and nutrient conditions [6,7,8].

In 2012 SARA began preparing its participation in an analogue mission to bolster design of space habitats and greenhouse modules by hands-on experience within a relevant operational environment. The first participation of SARA occurred in early 2013 within the International Lunar Exploration Working Group's EuroMoonMars B [9] mission at MDRS, in the desert of Utah. The main goal of this participation was to provide reviews on habitat design and assess the installation of new greenhouse technology. The overall purpose was continued during MDRS Crew 135 in early 2014, mainly concentrating on plant illumination technology and greenhouse optimization.

This paper summarizes the results of these studies and points out how analogue missions at MDRS provided direct results for research in a technological area, which would have been less straightforward without access to an analogue test site.

II. HABITAT DESIGN INVESTIGATION DURING CREW 125 PARTICIPATION

MDRS consists of two floors in the main habitat building (the other one being the GreenHab). It is 8m in diameter and height. The upper floor houses the common crew area, i.e. working area and computer stations as well as the kitchen with the table for meals and meetings (Fig. 1). The second half of the upper floor is taken up by the six small crew compartments, which mostly provide a bunk and a small table with room to store personal belongings.

Above the crew's staterooms there is a loft, which houses the internal water tank and pump system to support habitat's piping.

Figure 3: MDRS interior floor beams in 2013, note the slightly rusty spots.

The lower floor is home of the laboratory areas (Fig. 2), equipped with spectroscopy and microscopy utensils, as well as the workshop for repairing hardware and preparing experiments. The station has two entry and exit points on this floor (besides a number of emergency exists), which are used as airlocks to simulate decompression procedures for EVA activities. Adjacent to the main airlock there is an EVA preparation room, also used as storage area for EVA equipment (e.g. suits, mobile radios). Sanitary installations are on the ground floor as well, including a small shower, a sink, and a toilet.

The two main materials used for MDRS construction are wood and steel. The basic frame structure (see example in Fig. 3) of the station consists of steel beams; four support beams are also used for the outside. The wall covers and the remaining interior are made up of wood, including the upper level's floor. The laboratory is equipped with a metal floor. Thermal insulation is achieved by insolation foam on the roof and between the inner and outer walls as well as at critical locations, e.g. the windows.

Figure 4: MDRS interior deck-cover. Upper level wood (left) and lower level metal (right).

II.I Condition of the Mars Desert Research Station

MDRS began its operation in December 2001 [10] and even after that time it is in a good condition, despite the harsh environmental conditions in the semi-desert of Utah. There are regular maintenance crews present at the station to keep it in working order and day to day maintenance is conducted by the research crews as well.

Changes since its operation have been the exchange of a water system partly recycling grey water in the greenhouse vs. a system that is not recycling. Also the power system has been updated to a far more autonomous condition – the daily routine only tracks the amount of diesel left for power generation. Interaction with the generators has become unnecessary and is strictly forbidden by MDRS management.

It shall be noted that the described condition has been present in early 2013.

Wear-Off

The interior and exterior show clear signs of wear off, including e.g. the occasional sign of rust (see Fig. 3) and paint damage. Considering the heavy usage by crews, the harsh environment with significant temperature changes and dryness, this is to be expected however. In no instance does this hinder the operation of the habitat.

The upper deck originally had a carpet floor, which has been removed, unveiling a wooden floor to the outside. This floor has been extremely worn off in colour and surface, see Fig. 4 at the time of EuroMoonMarsB (but has been refurbished for the season of 2013/2014).

This is most likely due to the dusty environment, which – even while cleaning – is scraping off the surface colour.

The integrity and structure is sufficient, however the wood texture and surface cracks complicate the cleaning efforts. The metal floor with bumps in the lower level allows easier cleaning and provides friction. Regarding space application it is also most likely the more advantageous material (e.g. because of material strength vs. material volume and regarding outgassing). Of course the colour and nature of the wooden floor would certainly contribute to the crew's comfort.

A major issue of wear-off during EuronMoonMarsB was the condition of the airlock doors. Both of them are significantly misaligned, which makes closure and opening troublesome, especially for smaller and weaker crewmembers. However this misalignment is also the only way to "lock" the doors in place when closed. The engineering airlock's door is especially difficult to close from outside, only strong and tall crewmembers can do

Figure 5: Left picture: The closed outer engineering airlock door. Note the hinges on its right side and the lack of support on its left side. Right picture: One of the bottom hinges. It is strongly constructed, but decay and probably dynamic forces made it loose a screw.

this by lifting the door up. The hinges are under strong stress, especially because there is no support at the opposite end of the door (see Fig. 5). Also the hinges have decayed to a point where they lose screws (likely due to rust and dynamic loads). Also when the winds are strong the door is pulled on very strongly and can crash into the hinges. Generally the doors are the major wear-off element in the whole habitat.

One major equipment issue is the suits, primarily the helmets. Heavy usage has led to decay on joints and in the overall material, which is mainly plastic. UV radiation, dryness and generally the environmental conditions (likely also simply age) have made the helmets very brittle, even after replacement for the following season after EuroMoonMarsB. However despite the simple design, the suits are potently portraying the illusion of a closed system and strongly support the feeling of being on a different planet, which is especially helpful for studies of the crew's psychological condition.

II.III Repercussions on Habitat and Mission Design

One significant issue in the whole habitat is the dust from outside entering through the airlocks and venting opening at the top of the roof. Without implementing an actual closed cycle (or at least a surplus pressure inside the habitat to "blow out" any potential dust) this problem cannot be addressed. Application of an actual airlock system should already prevent the majority of dust entering the habitat simply due to the increased pressure of the inside. The mitigation solution implemented by Crew 135 to avoid dust contamination in the habitat, was to leave shoes used for EVAs or in the GreenHab in the airlock and only use sleepers inside the hab.

The airlock doors could be likely improved. Their sheer size already creates heavy loads on the mechanical structure. First of all the large area – when subjected to a pressure of approximately one bar vs. the pressure of the outside would create a large amount of load. To mitigate this, an actual habitat's airlock could have the outer door open inwards so that it is pressed into its mounting when under pressure. This way the whole frame can take the load instead of only the hinges. Also while moving the door – especially the outer engineering airlock door – the load is heaviest on the hinges. While the main airlock uses a small wheel to reduce the stress and support the door's weight, the still dislocated alignment of the door points to the fact that this support is not sufficient. It might be helpful to introduce another support, possibly from atop on the outer end of the door, analogously to heavy fire doors in ordinary buildings. Another possibility would be to apply sliding doors (comparable to transport vehicles) and mount rails on the habitat walls. This would have three advantages:

- no dynamic loads on the door itself and its mounting
- no area which can be attacked by wind forces
- the door can be opened independently of the relative pressure from out- and inside

In any case the current construction allows exposure to severe wind forces, which do occur and introduce even more stress into the hinges and door support. An easier alternative might be to construct a porch around the airlock doors, which holds of wind forces and could also help with protection against dust.

Considering the large amount of utensils used in the habitat (especially for various experiments and also supply storage), more storage room could be used. Certain elements could likely be stowed away on the ceilings of the rooms, as there is a strong steel beam structure, which is currently unused. Also an actual protocol for inventory and removing unusable elements from the inventory could help reduce the amount of required storage space.

An excellent utensil is the water-free soap, which can be used for cleaning hands and such. It is used in very small amounts and supports water conservation.

The wooden floor seems to be more impractical than the metal floor, especially regarding potential damage from water leakage and e.g. falling equipment and such. As described above from a pure technical point of view a metal floor in the upper deck might be preferable. Adding aesthetic considerations it might be possible to use a linoleum floor covering. However glue in a space environment might be a problematic component and in the dry and UV-rich environment of MDRS it might cause more problems like dangerous fumes, etc.. A further alternative would be plastic which can withstand the wear-off but with a more natural view than metal cover for an increased crew comfort.

Two points especially regarding the stateroom condition. While there is enough room to have privacy and live relatively comfortably, the air flow within the rooms is minimal. Hot air is introduced via a venting system, creating a warm and dry atmosphere, which especially is disadvantageous for sleeping. As a result, crewmembers tend to sleep with open doors, which is also problematic because of the noise of the overall station venting system and water pump. Therefore effective and noise reduced venting measures need to be implemented in an actual habitat.

Windows in the staterooms would also add crew comfort. These would likely create structural, radiation and heating problems (especially when regarding actual flight-hardware, which would have to resist launcher loads). It could on the other hand reduce the power demand as during daylight no artificial source for illumination is required.

In 2013 the crew felt that adding to the crews' comfort would possibly a plant in the living area, maybe a small tree-like plant near the dining table. Besides the visual comfort it could likely also improve the room climate. This measure was taken in the following season in 2014 (three plants have been present during Crew 135's rotation).

III. GREENHOUSE INVESTIGATIONS DURING CREW 135 PARTICIPATION

The goal of the Reliability and Redundancy (RAR) mission lead by Crew 135 in February 2014 was to assess the reliability of the habitat's mechanical, structural, and power systems. An optimization study was performed on the GreenHab in terms of illumination and automation [11].

The current GreenHab is a basic horizontal cylindrical structure divided into two parts: one for vegetables growth over the season and to perform experiments within the greenhouse facility; and the second one is a Zen garden with flowers for crew well-being.

Figure 6: The GreenHab in February 2014. Credits: Filip Koubek, Proficam.

III.I Illumination Analysis Results

Before Crew 135's mission, there was only natural lighting coming through a transparent plastic roof for plants illumination. Crew 135 installed a red and blue lamp in the GreenHab (see Figure 7, right side). Light levels in the Greenhab were greatly enhanced by this addition of an electrical light source. It also enabled plants to have a longer photoperiod – and thus receive more light over one day - since the LED lamp was still providing light after sunset. The mission was in February so days were short; sunrise was around 7:00 and sunset was around 17:30. The LED lamp ran from 8:00 to 19:00, thus providing supplemental light for 11 hours per day and prolonging the photoperiod by an hour and a half, totalizing a photoperiod of 12 hours every day.

A small experiment with young lettuce sprouts and three-week old lettuce plants was conducted: one treatment staying under natural light and one treatment under natural and supplemental red and blue LED light. Depending on the cultivar, old lettuce plants showed an increase in fresh mass from 11 to 21% with the addition of supplemental light, while young lettuce sprouts showed an increase in fresh mass from 13 to 34%. Additionally the hypocotyl length of the young lettuce sprouts was from 20 to 28% shorter on the treatment with supplemental LED lighting compared to the one with only natural lighting. Hypocotyl length is a sign of plant development: an elongated hypocotyl is a sign of lack of light or poor light quality. The fact that young lettuce sprouts under the treatment with supplemental LED lighting have smaller hypocotyls shows that their development is better with this extra light source.

This experiment suggested that the addition of supplement electrical lighting in the GreenHab could improve vegetable mass produced by almost 25% over the season and this recommendation was given to the MDRS management as a way to make the GreenHab more efficient and profitable for crews coming early in the season.

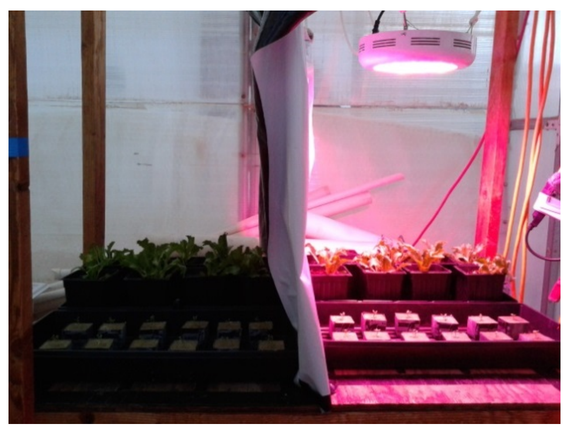

Figure 7: Experiment with lettuces. Left: treatment with natural light. Right: treatment with natural light supplemented with red and blue LED light.

III.II GreenHab State and Space Arrangement

The GreenHab is poorly maintained and space to actually grow vegetables is very limited compared to total available space. This could easily be fixed by having a storage room outside of the GreenHab itself. In February 2014 the necessary equipment and material for plant growth such as bag of soils, nutrients, and pots were stored inside the GreenHab and thus using precious growth space as shown on Figure 8 [11].

Growth shelves are made of naked wood and, with the harsh environmental conditions, are starting to wear out, even becoming a hazard for crew members working in the GreenHab because of the many splinters sticking out of them.

Figure 8: Wooden growing shelves and material storage underneath them in the Greenhab in February 2014.

Recommendations of Crew 135 to mitigate this problem was to change for metallic or plastic shelving – plastic being preferred because metal would rust quickly since water is used on a daily basis in the GreenHab [11]. Otherwise, these wooden shelves could just be varnished and thus provide adequate protection against splinters.

Instead of having one-level shelves, as it is currently the case, it is highly advised to have multiple-level shelving available for plant growth. Three levels would be feasible given the height of the GreenHab. Of course, if this solution is implemented, electrical lighting will become necessary to illuminate plants located on lower shelves.

III.III GreenHab Watering System

Plants growing in the GreenHab are currently manually watered every day by the GreenHab officer. It is not a time-consuming task in itself but it represents a lot of constraints and responsibilities on this specific crew member. Also, it is not realistic of a space mission, which would have an automatic watering system.

Therefore, Crew 135 recommended that the GreenHab transitions to a fully automatic hydroponics system [11]. If this change is too demanding for immediate implementation, a smaller transition could consist in having an automatic watering system on a timer going to each pot, like it is often done in amateur gardening.

The GreenHab officer duties in the GreenHab would still include plant health checks, sowing and harvesting, as well as to supply water to the reservoir tank used to water the plants, but the overall watering constraint would be eliminated.

III.IV GreenHab Temperature and Humidity Control

Diurnal and weekly variations of temperature inside the GreenHab were great in February 2014, from close to 0°C in the morning before sunrise (despite a running heater), to over 35°C on sunny days [11]. These are not optimal temperatures for plant growth, and consequently it was noted that plants grew at slower rates than they would in an optimized environment. This phenomenon was probably accentuated with the low relative humidity values encountered in this region, from 13 to 23% [11].

A remote thermometer/hygrometer display is placed in the hab, enabling the crew to constantly monitor temperature and relative humidity in the GreenHab and take adequate measures when necessary (e.g. move young plants in the hab for the night when temperatures are too low). When temperatures get too high, a fan automatically starts and blows hot air out, allowing colder air to enter.

A first option to reduce heat losses in the GreenHab would be to provide an actual insulation layer to the structure [11]. Currently it is only made of a double hard plastic walls and ceiling. This might interfere with incoming light but would greatly improve temperature conditions in the Greenhab. It would also reduce the energy burden of having a heater run the whole night to countermeasure heat losses.

Second, since great temperature variations are not desired for plant growth, Crew 135 advised to build a small control loop which would regulate the inside temperature. Since a fan already runs when temperatures exceed a certain threshold, the same could be implemented with a heater. The settings could allow for a night and a day optimal temperature and the whole system would stay within a 1°C margin of the set temperature [11].

III.V Lessons learnt and greenhouse module design

The work during Crew 135's mission showed how space utilization is an important factor in the design of future planetary greenhouse modules.

It also emphasized the necessity of developing autonomous facilities, for watering as well as for temperature and humidity control. That is to say future greenhouse modules should mainly be operated by robots for these tasks. However the act of taking care of plants was found very relaxing and different from the rest of the maintenance and routine tasks in the habitat.

Therefore some activities in the future greenhouse modules need to be left to human crews for psychological well-being during long-duration missions.

Last but not least, the illumination analysis shows the importance of adequate lighting systems. Relying solely on solar light is not a solution at MDRS and it would not be one on Mars or on the Moon either, due to solar storms on Mars or extended dark period on the Moon. Having two illumination systems based on two different technologies, acting as back-up when one is not working, appears to be an efficient solution for the design of future greenhouse modules.

IV. CONCLUSION

Especially considering the long operation of MDRS, the condition of the habitat is good. There are no major operational problems and no structural issues. In general the station is very well capable – in combination with its unique location – to create the illusion of an exploratory stay on Mars.

A large impact on station design has been the airlock-design, which needs more structural protection against dynamic loads and possibly wind and dust protection.

The GreenHab is very useful to the hab, for fidelity of the simulation (future crews on Mars will have to take care of plants) as well as for the crew diet. It's overall state and the simulation fidelity could be improved by minor changes. It nevertheless provided a unique opportunity for SARA to link hands-on activities to conceptual projects.

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