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Human Factors for Small Net Habitable Volume: The Case for a Close-Quarter Space Habitat Analog

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Increasing efforts in sending humans to Mars calls for greater consideration of the ways in which vehicle and habitat design can influence crew performance and behavioral health. The isolation, confinement, boredom, and lack of privacy over what may be a multi-year mission to Mars can severely impact personal well-being, and consequently, team dynamics. So far, space stations and most terrestrial analogs have provided some insight on the human factors of a fully-functioning, acceptable "space-home." However, more research is needed on emergency, modified-habitats, for off-nominal scenarios on deep-space missions. In the event that parts of a Mars-mission habitat are compromised or are no longer habitable, the crew may be forced to temporarily live and operate from a significantly reduced volume of space. Some of the analogs operational today are capable of supporting research on reduced net habitable volume by restricting habitation to a smaller area. However, these analogs are often difficult to gain access to, or can be considerably expensive to operate given such a focus on a specific partition. To overcome these obstacles, an interdisciplinary team at Embry-Riddle Aeronautical University has been designing and developing their own space habitat analog: The Mobile Extreme Environment Research Station (MEERS). Designed out of the compact shell of an Airstream trailer, MEERS will be capable of housing 4-6 crewmembers in a net habitable volume of 40 m^3 for up to 2 weeks fully self-sustained. It is unique in its capability of being towed to any particular research location and allowing for mission-specific layout configurations, all while operating at a reduced cost. This paper provides the argument for increased research on emergency habitation modules, and describes how the MEERS facility may contribute to our understanding of this critical topic.

Nomenclature

ERAU	=	Embry-Riddle Aeronautical University
ICE	=	isolated and confined environment
LDSF	=	long-duration space flight
LEO	=	low Earth orbit
MEERS	=	Mobile Extreme Environment Research Station
NHV	=	net habitable volume
SHEE	=	Self-Deployable Habitat for Extreme Environments

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I. Introduction

TO date, no other human has spent more consecutive days in space than Russian cosmonaut Valery Polyakov, who lived onboard the Mir space station for approximately 14 months.[1] Similarly, no one has traveled farther into space than astronauts Jim Lovell, Jack Swigert, and Fred Haise, who swung around the Moon at approximately 400,000 km from Earth during the Apollo 13 mission, which ironically is better remembered for its emergency return to Earth after an unexpected explosion damaged the service module.[2] However, it is in human nature as explorers to continue to push the limitations of physical capability, to break records, and to travel into uncharted territory. Since 1961, human spaceflight has become a branch of science that demands the cross-integration of every major discipline. Now as we begin to consider deep-space travel more than ever before, we must also begin to emphasize the importance and equal-relevance of human factors and psychological well-being among all considerations that go into space vehicle and habitat design. Never before have we had to accommodate human requirements for a system that will exist in an environment relatively independent from Earth's resources and support. Just as human health and safety are stressed and accounted for in the design of cars and buildings, so too should they be enforced in deep-space vehicle and habitat design. Safety protocols on space missions thus far have not had to account for the months that it would take to deliver rescue or help. Crews sent to Mars will have independence and responsibility-for-self that no one in history has ever experienced. In the event of an off-nominal occurrence, they will become their own emergency personnel and will be forced to make due with what they have, even if it means scavenging whatever remaining resources are left and living in a less-than-ideal, makeshift habitat. If the anticipated psychological stressors of deep-space travel (Table 1) were not already enough to deal with, these inconveniences will be further exacerbated by a sudden reduction in habitation and supplies, and the crew will struggle that much more to successfully function as a team. It is paramount that decrements in behavioral health as a result of living in an extremely isolated and confined environment (ICE) for such an extended period of time does not affect the crew's ability to safely recover from their situation. Our work with the MEERS facility will address psychological stressors that factor into habitat design (Table 2), and will study team dynamics and maturation of interactions as they relate to mission success within the context of a highly confined space habitat analog.

Table 1. Major psychological stressors experienced during long-duration ICE habitation related to habitable volume or design as categorized in NASA/TM-2011-217352.[3]

Allocation of Space	• Lack of personal space • Lack of privacy • Feeling of crowdedness	• Confinement • Separation from home (physical) • Involved logistics management and lack of or inefficient storage
Workspace	• Meaningless work • Workload boredom • Faulty design or layout	• Faulty procedures • Faulty equipment
General and Individual Control over Environment	• Lack of individual control over the environment	• Lack of accommodation/customization for cultural differences or personal preferences
Sensory Monotony	• Lack of sensory stimulation • Sensory deprivation • Under-stimulation	• Poor aesthetic design • Lack of food freshness and variety • Physical monotony (muscular, tactile, etc.)
Social Monotony	• Isolation • Social deprivation • Limited communication • Separation from family and friends	• Family problems • Separation from family routine • Emotional connections with mixed gender
Crew Composition	• Composition • Recruitment and selection	• Training
Physiological and Medical	• Hygiene separation • Sleep disruption • Medical procedures	• CO_2 • Nutrition • Radiation
Contingency Readiness	• Event (something external that requires contingency planning)	• Safety • Lack of duplicate vehicles

Table 2. The specific stressors that factor into habitat design as described in NASA/TM-2011-217352.[3]

Category	Psychological Stressor	Description
Allocation of Space (This category deals with the allocation and positioning of certain types of volume to meet psychological needs of the crew.)	Lack of personal space/ Lack of private space	Private and personal space were both identified as highly important to the psychological well-being of crew, providing a retreat from social stressors, separation from work areas, a place to interact with family members, and providing a location for personal items and pastimes.
	Feeling of "crowdedness"	The perceived volume is adversely affected by the increased number of crew "traffic interactions" which can include the displacement of one crewmember to allow for translation of others, or desired simultaneous use of equipment and workstations). Leads to a feeling of inadequacy of the size or layout of the habitat. This stressor can be mitigated by either implanting layout changes or adjusting schedule to reduce forced crew interaction/displacement.
	Lack of privacy of waste & hygiene compartment	Increased privacy of highly personal activities such as crew waste collection and hygiene, contributes to a decrease in intra-crew conflict that could lead to decreased performance.
Workspace (This category addresses the space allocated and workstation designed for meaningful work and activities needed for the psychological health of the crew)	Lack of meaningful work/activity	A lack of meaningful or motivating work/activity during a long-duration mission can lead to work apathy and disinterest, boredom, frustration, personal doubt and loss of focus, resulting in psychological and psychosocial stress and performance decrements.
	Sense of poorly placed stowage	Poorly placed stowage for performance of tasks can contribute to frustration or other forms of psychosocial stress.
General and Individual Control of Environment (Control over lighting, airflow, temperature, etc.)	Lack of individual controls over temperature, ventilation, or lighting	Particularly in crew quarters, anecdotes indicated that insufficient levels of control over personal environment, particularly during sleep, can lead to poor sleep and the associated psychological stressors.
	Lack of reconfigurability for cultural difference / personal space preferences	Customize-ability and reconfiguration to best suit needs of the crew can significantly decrease frustration at inflexible spaces. In addition, the ability to reconfigure and customize the environment and space adds the perception of choice and individual control, important personal concepts that are often lacking in isolation and confinement.
Sensory Deprivation and Monotony (Space and resources should be provided to	Lack of stimulation / sensory variability	Current missions to the ISS provide a window with a close view of Earth, real-time communication with loved ones at home, and crew care packages that bring novel items with high sensory impact (i.e., fresh fruit) to astronauts throughout the duration of their 6-month stay. Future long-duration missions will not have these countermeasures as a way to mitigate sensory deprivation. Evidence shows that

stimulate cognitive, visual, auditory, tactile, gustatory, olfactory, motor, etc.)		cognitive, visual, auditory, tactile, gustatory, olfactory, motor monotony, as experienced in isolated, confined, and extreme environments, can serve as a chronic stressor to the individual. Also, long-term lack of choice and control over work format and leisure can negatively impact mood – this impacts on volume as choice and control necessitate a minimum amount of variety.
Social Monotony (Resources and new technologies should be provided to facilitate communication with family and friends back home, to mitigate the monotony of being with the same small set of people for an extended duration of time, in a confined space.)	Social deprivation / Lack of common areas	Lack of group spaces to encourage group activities can result in decreased crew cohesion.
	Limited communication with home	Communication system with family and friends at home that offers confidence and privacy, providing a mechanism for the dissolution of frustrations, concerns, fear and anger, which in turn is essential for minimizing interpersonal conflicts.
Crew Composition (Number, gender, cultural differences, roles, leadership, relationship, crew selection and training.)	Crew composition may be a cross-cutting / high-level driver / overarching category that impacts several other stressors in other categories, and can be addressed via other habitat requirements. Inputs and suggestions are welcome here.	1) Crew number can impact crew dynamics (e.g., potentially higher risk of marginalization and group dysfunction with 3 crew versus 4 or more). 2) The presence of female crewmembers among predominantly male crews can have a positive influence on group dynamics – mixed crews may impact design and layout (evidence on female vs. male preferences regarding environment and need for hygiene privacy). 3) Crewmembers of differing nationalities and cultures will have different expectations and needs regarding private space, leisure, etc.
Physiological and Medical Issues (Includes waste management.)	Lack of hygiene separation	Separation of dirty-clean areas has a psychological component beyond the functional requirement separating these areas. Other issues largely mitigated through space allocation and other venues.
Contingency Readiness (Planning to resolve emergency situations related to habitability and other equipment/resources.)	Lack of “backup plan” / “rescue scenario”	Long-duration isolation in extreme environments places severe stress on individuals that is magnified by the perception that certain contingencies have been overlooked. This “no escape” perception can be alleviated by providing backup contingencies for every scenario, including loss of a module.

II. Mars Mission

The list of proposed Mars mission architectures seems to grow every day. However, common mission parameters include a total duration of 30 months and a crew of 6 (Table 3).

Table 3. Summary of NASA Mars Design Reference Architecture 5.0 mission parameters as referenced in NASA/TM-2015-218564.[4,5]

Total Mission Duration	30 Months
- In transit to	6 months
- At target	18 months
- In transit from	6 months
Crew Size	N = 6
Crew Composition	Pilot, Physician, Geologist, Biologist, Engineer, Electrical Engineer
Gender Mix	Variable; exact mix undefined
Cultural Mix	Presumably some combination of US, Russia, Europe, Canada, and Japan
Mission Tempo	Long periods of low mission tempo, interspersed with high activity times (for example, launch, jettison tanks, dock, landing)
Communication Delays	Up to 22 minutes one-way with blackout periods
Autonomy from Ground	Increasing en route to Mars, decreasing during return to Earth

For comparison, the longest consecutive stay in space by a human that scientists have been able to study (14 months) does not even match half of the proposed total mission duration for Mars (30 months). This unprecedented period of time in isolation from Earth poses one of the major, unique behavioral health hurdles for crew participating in such a mission. The closer they get to Mars, the greater the time delay for communication between the spacecraft and Earth. Crewmembers' conversations with loved ones back home will go from real-time transmission and reception to up to 20 minute delays each way. With only 5 other living beings to immediately interact and communicate with for the majority of their 2.5 year trip, crewmembers will be at risk for mental health decrements on top of the usual physiological health threats (i.e., solar radiation, cosmic rays, muscle atrophy, reduced bone density, cardiovascular deconditioning, fluid shift, etc.).

Crewmembers will attempt to keep healthy and occupied by exercising, training, carrying out mission tasks, and conducting experiments. However, there will still be plenty of down-time. The daily routine with the same small crew will begin to grow old. Not only will each crewmember have just 5 other people to physically interact with, but these will also be the same 5 people that they will have to physically see every day whether they want to interact with them or not. Small nuances can quickly become major interpersonal arguments and conflicts.[6,7] Tension can then easily result in grudges, lack of communication, low morale, depression, anxiety, poor sleeping patterns, and other detrimental conditions. The intensity of these collective psychosocial issues may ultimately impact the success of the mission. Thus, the ability for crewmembers to have their own personal space and time to get away from the rest of the crew will be crucial.

III. Net Habitable Volume (NHV)

As defined in the NASA Human Integration Design Handbook (HIDH), *net habitable volume* (NHV) refers to:

> "The functional volume left available to the crew after accounting for the loss of volume due to deployed equipment, stowage, trash, and any other structural inefficiencies and gaps (nooks and crannies) that decrease the functional volume."[8]

Furthermore, *minimum acceptable net habitable volume* was defined by subjects matter experts at NASA's Behavioral Health and Performance Element as:

> "The minimum volume of a habitat that is required to assure mission success during exploration-type space missions with prolonged periods of confinement and isolation in a harsh environment [and that is acceptable by human factors and behavioral health standards such that it is unlikely to produce] negative consequences for psychosocial well-being and performance of the crew."[5]

This value of the minimum acceptable NHV for any particular spacecraft depends on its mission parameters and objectives.[8]

Using the parameters outlined in Table 3 the recommended minimum acceptable NHV for a Mars habitat was derived to be 25 m^3 per crewmember, or a total of 150 m^3 for a crew of 6.[3] This *minimum* acceptable NHV for a Mars habitat is proposed with basic functional area caveats in mind (crew quarters, workstations, dining and communal area, exercise area, hygiene area, stowage access, and translation portals), and assuming reasonable flexibility and overlapping uses for certain areas without significantly compromising behavioral health.[3] The volume delegated to each area is shown in Figures 1a and 1b as proposed in NASA/TM-2015-218564.[5]

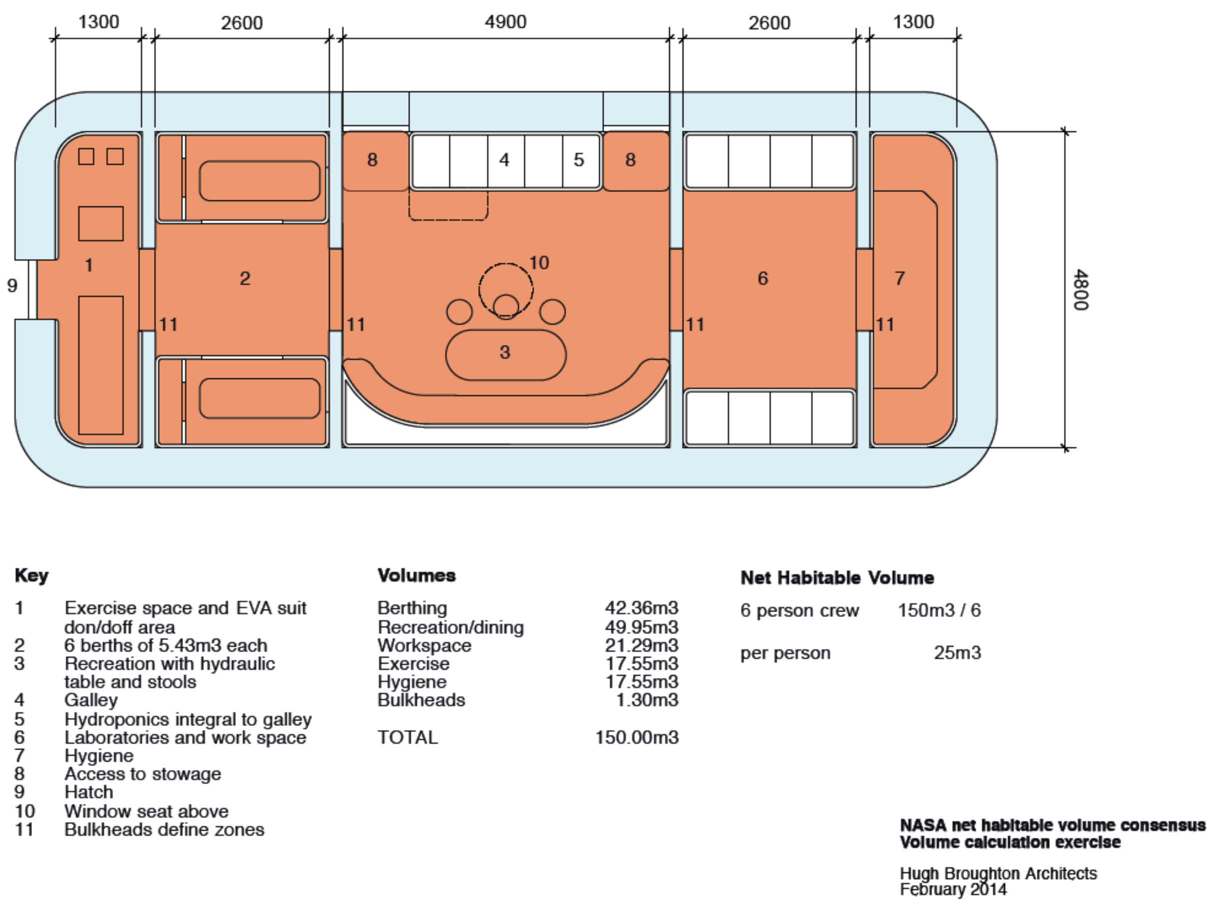

Figure 1a. An example of volume distribution for each functional area of a proposed Mars habitat with acceptable NHV.[5]

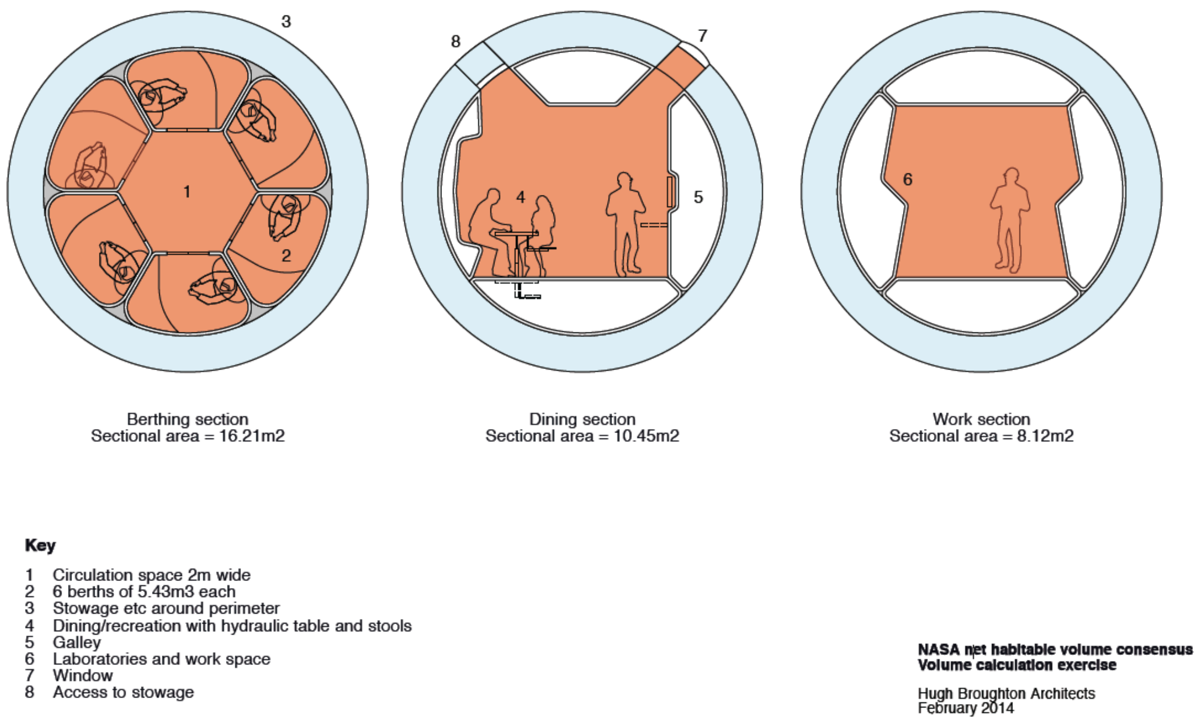

Figure 1b. Cross-sections of the major functional areas of a proposed Mars habitat with acceptable NHV.[5]

For comparison, Table 4 shows the net habitable volume of Skylab, ISS, Salyut, and Mir with respect to each of their longest mission durations. At one end is the aforementioned Mars habitat with 25 m^3 per person and a maximum mission duration of 912 days. Sitting at the other extreme, with the greatest NHV and smallest maximum mission duration, Skylab has been described as a roomy space home in LEO, with a generous amount of volume to move about and conduct activities in freely. However, for missions to Mars (more than 900,000 times farther on average), we may not be able to afford such a luxurious spacecraft. The Mars vehicle/habitat may have to be minimal at best in order to accommodate all of the necessary equipment for a successful deep-space mission and first human landing on Mars.

Table 4. Previous NHV for long-duration space missions compared to the proposed Mars habitat NHV. (Source: NASA/TM-2015-218564).[5]

Long Duration Mission	Hab Volume (m^3/person)	Hab Volume (ft^3/person)	Maximum Mission Duration
Skylab	120.33	4249.41	84 days
ISS	85.17	3007.75	196 days
Salyut	33.50	1183.04	237 days
Mir	45.00	1589.16	438 days
Proposed NHV	25.00	882.87	912 days

IV. Major Spacecraft Emergencies

With regard to the last stressor from Table 2, the possibility of a compromise in the structure, volume, or systems of a spacecraft as a result of an off-nominal event may force the crew into reduced or limited living quarters for an indefinite amount of time. Four major types of these spacecraft compromises include:

A. Fires

In February 1997, a fire broke out in the Mir Space Station with 6 crewmembers onboard. The fire stood in the way between the crew and an escape vehicle. One of the crewmembers, American astronaut Jerry Linenger, described the dense smoke as having spread "10 times faster than I would expect" due to the air circulation fans on Mir.[5] Another crewmember, Russian cosmonaut Aleksandr Lazutkin, claimed that, "When I saw the ship was full of smoke, my natural reaction was to want to open a window. And then, I was truly afraid for the first time. You can't escape the smoke."[9] Because a fire behaves much more unexpectedly in space than it does on Earth, it is harder to control, and even more so when dealing with a closed-environment. As the smoke grew in thickness, the crew managed to don their oxygen masks, ultimately saving them serious respiratory issues. The fire, originating from an oxygen canister, burned for 15 minutes. Luckily, the station suffered no major damage and the crew was able to continue on with their respective missions.

B. Gas Leaks

In January 2015, an alarm indicated a potential ammonia leak onboard the International Space Station (ISS).[10] Because the deadly gas is only used on the American segment of the ISS, the safety protocol for this situation led to an emergency evacuation of the entire crew to the Russian segment and sealing off the connecting node. At this point, the crew was safe and still had the same fundamental resources and support available to them in the Russian segment just as they would with access to the entire station. Ultimately, the event was said to have been a false alarm triggered by a malfunctioning sensor. The crew were allowed back into the U.S. segment and operations resumed as normal.

C. Depressurization

In July 2015, impending space debris caused three ISS crewmembers to seek emergency shelter.[11] Scott Kelly, Mikhail Korienko, and Gennady Padalka had 90 minutes from learning of the nearby debris to prepare for contingencies by closing hatches to isolate potential loss of pressurization, heading to a docked Soyuz capsule, and getting ready to evacuate the station if necessary. Luckily, the debris narrowly missed them, and the all-clear was ultimately given. This was the fourth time in ISS history that such a safety protocol was implemented for similar reasons.

D. Solar Particle Events

In August 1972, an unusually intense solar particle event (SPE) was recorded.[12] Coming only 5 months after the return of the Apollo 16 crew, this sudden SPE was large enough to potentially be considered lethal to life outside of the protection of Earth's magnetosphere, whose "tail" only covers the Moon once a month. Although not necessarily a permanent compromise to spacecraft volume, such an SPE of this magnitude (or any galactic cosmic ray event) may certainly drive the crew into a designated "radiation shelter" within their vehicle for several days.

All four major spacecraft compromises are examples of situations in which it may be necessary for the entire to crew to move to a specific module or vehicle closed off from the potential danger. The Mars mission, however, lacks in its contingency plan what all four aforementioned incidents had available to them, and that is: relatively quick communication and coordination with ground control, and quick vehicle transit times back to Earth for abort scenarios.

V. Analogs

In an effort to better understand how teams will interact and coexist on long-duration space flight missions, space habitat analogs located around the world (Table 5) host several crews per year to simulate aspects of an actual Mars mission.

Table 5. Some of the space habitat analogs in current operation.

Analog	Location	Maximum Crew Size Supported	Longest Mission Duration	Net Habitable Volume	Operated By
Hawai'i Space Exploration Analog and Simulation **(HI-SEAS)** – (Figure 2)	Mauna Loa, Hawai'i, USA	6	365 days	368 m^3	University of Hawai'i
Mars Desert Research Station **(MDRS) –** (Figure 3)	Hanksville, Utah, USA	6	80 days	250 m^{3*}	Mars Society
Human Exploration Spacecraft Testbed for Integration and Advancement **(HESTIA) –** (Figure 4)	Houston, Texas, USA	4	90 days	210 m^{3*}	NASA
Human Exploration Research Analog **(HERA) –** (Figure 5)	Houston, Texas, USA	4	45 days	148 m^{3*}	NASA
Aquarius Reef Base – (Figure 6)	Key Largo, Florida, USA†	6	31 days	53 m^{3**}	Florida International University
Self-Deployable Habitat for Extreme Environments **(SHEE)** – (Figure 7)	(Varies – Transportable)	2	14 days	50 m^3	International Space University

As in an expected Mars mission, these analogs typically hosts 4-6 crewmembers, with the exception being the SHEE. At its fully-expanded state, the design of the SHEE incorporates only 2 crew quarters. However, given its NHV, it is likely to be able to accommodate up to 4 more crewmembers, trading for a more confined and less private habitat similar to the Aquarius Reef Base. Incidentally, Aquarius is one of the most high-fidelity analogs in terms of recreating ICE-conditions that mirror those experienced on the ISS. Sunken well below sea level, an immediate evacuation or return to "Earth" is not as simple as just opening the door and walking away and requires the logistical support and coordination of several operators. Psychologically, this real-life risk enhances the accuracy of the data collected. Similarly, the HESTIA facility is in unique in that it recreates airtight conditions such as those present in any space habitat or vehicle, potentially providing a more accurate simulation of air quality and its related effects on crew performance.

[*] Estimated NHV

[†] Located at Conch Reef, 19 m underwater and 9 km off of the coast of Key Largo

[**] Excluding Wet Porch

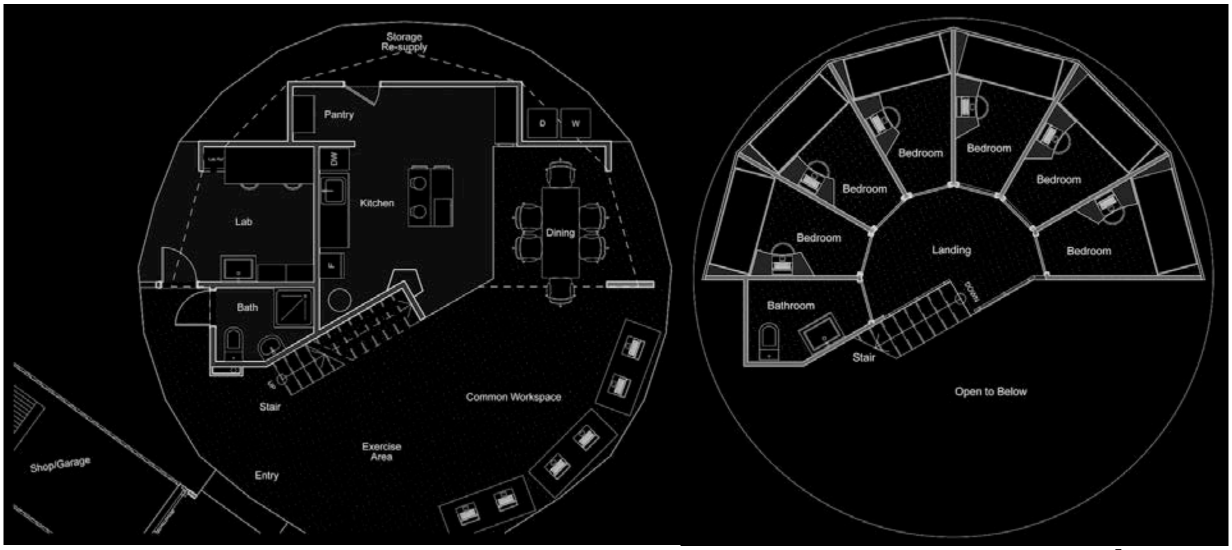

Figure 2. Layout of HI-SEAS. First floor (bottom); second floor (top). (Source: HI-SEAS[5])

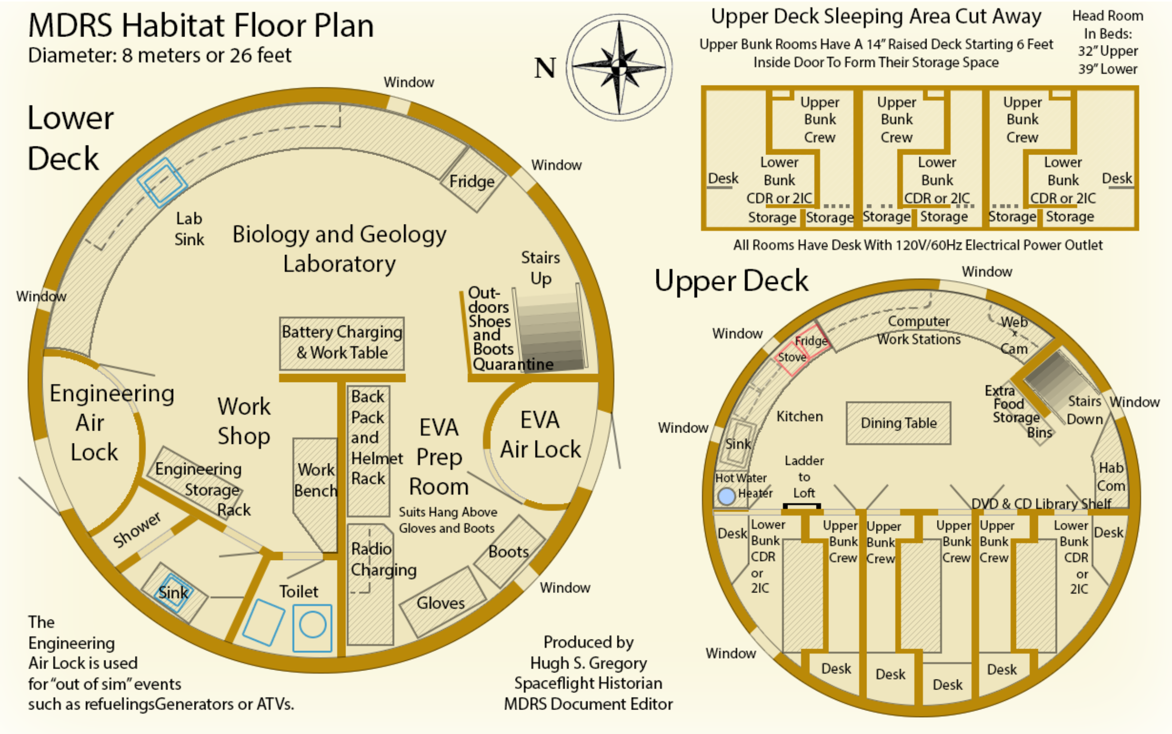

Figure 3. Layout of MDRS. (Credit: Mars Society[6])

[5] https://hi-seas.org/?p=1278
[6] http://mdrs.marssociety.org/about/

Figure 4. Layout of HESTIA. (Source: NASA[7])

Figure 5. Layout of the HERA. Back-side view (left); front-side view (right). (Sources: NASA[8,9])

[7] https://www.nasa.gov/analogs/hestia

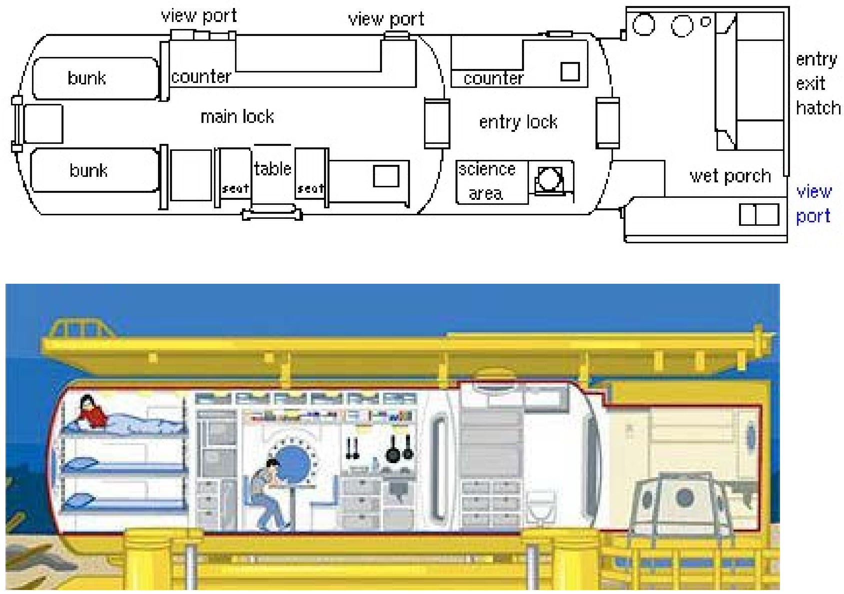

Figure 6. Layout of Aquarius Reef Base. (Source: Florida International University[10])

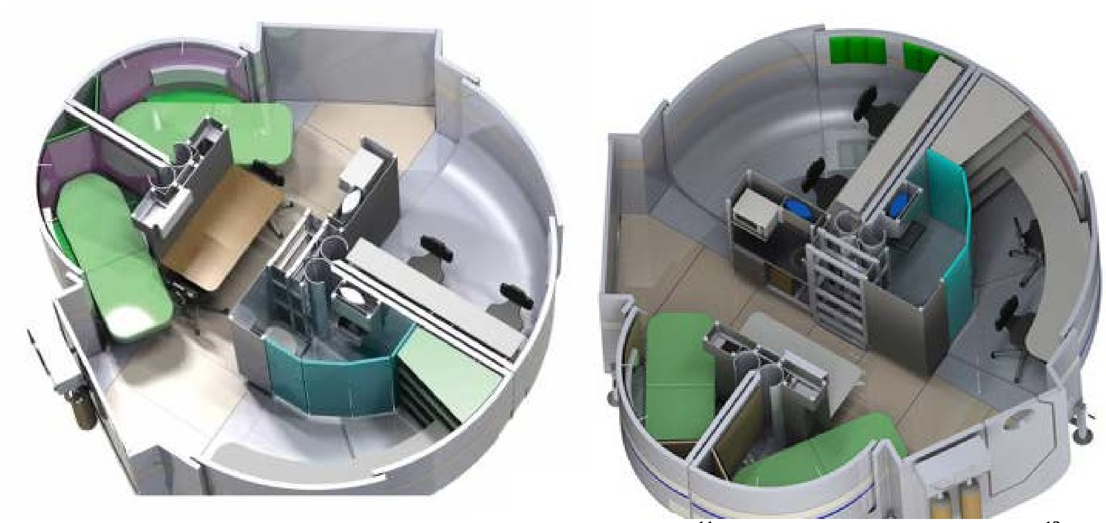

Figure 7. Layout of the SHEE. (Sources: ASB-Portal,[11] Tiroler Tageszeitung Online[12])

[8] https://www.nasa.gov/content/exploring-an-asteroid-without-leaving-earth
[9] https://nasa3d.arc.nasa.gov/detail/nmss-hdu
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VI. The Mobile Extreme Environment Research Station (MEERS)

A team of interdisciplinary graduate and undergraduate students at Embry-Riddle Aeronautical University have been applying a human-centered approach to designing and developing the Mobile Extreme Environment Research Station (MEERS). Inspired by NASA's Apollo-era Mobile Quarantine Facility, the MEERS team has been retrofitting an Airstream trailer into a mobile laboratory and ICE analog for research on human factors and team performance as they apply to long-duration space flight (Figure 6).

Figure 6. MEERS required deep-renovation after its acquisition in 2013.

Having been completely gutted of interior fixtures and furniture for a clean slate in design (Figure 7), the MEERS team has contemplated several fixed layout configurations for optimal crew health and performance (Figure 8). However, it was decided that a basic, yet flexible and re-configurable design would be best in order to better accommodate a larger range of research studies, as opposed to limiting researchers and crew in the ways that they can use the station's functional areas (Figure 9).

Figure 7. The MEERS frame cleared out of its original interior. All windows will be completely tinted so as to reduce connections to the external environment.

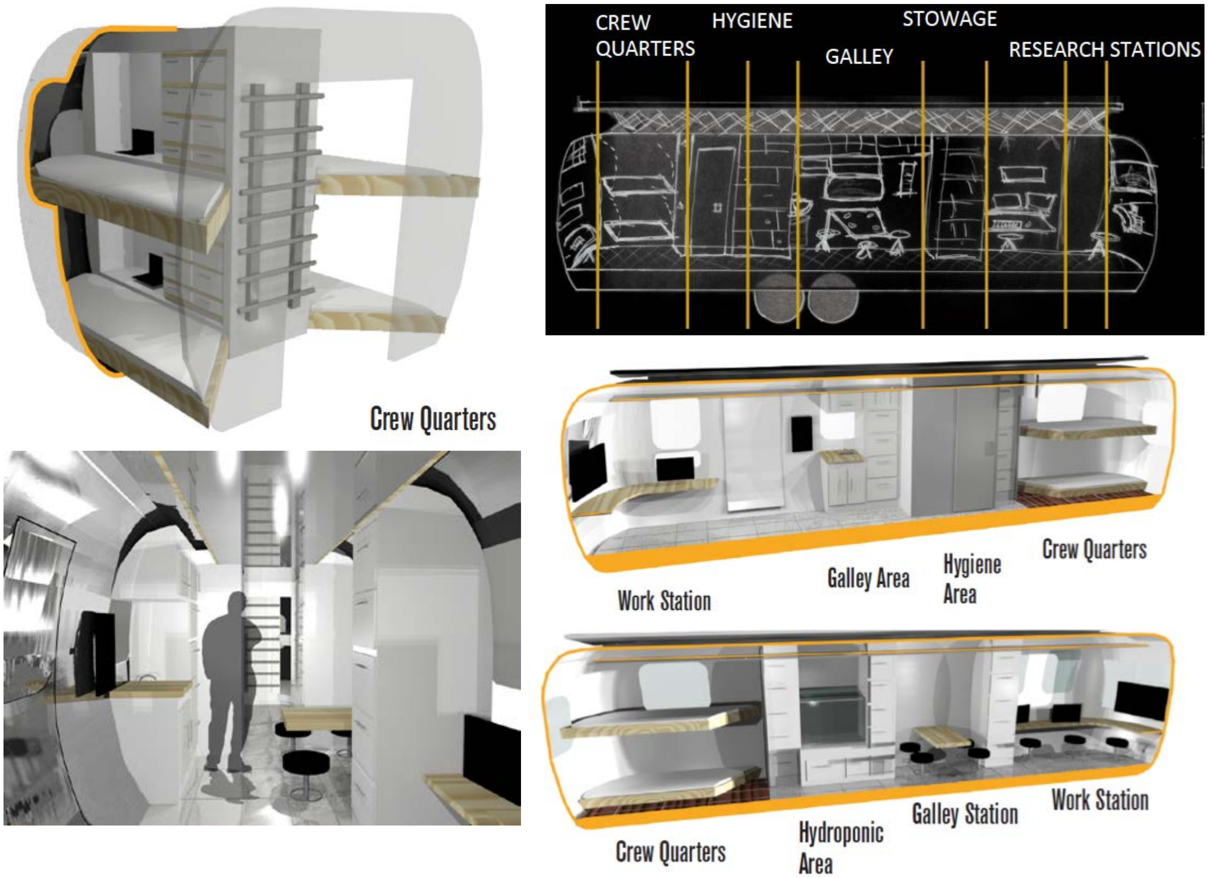

Figure 8. An example of a fixed-configuration layout for MEERS. (Credit: Michael Fehlinger, ERAU, 2013)

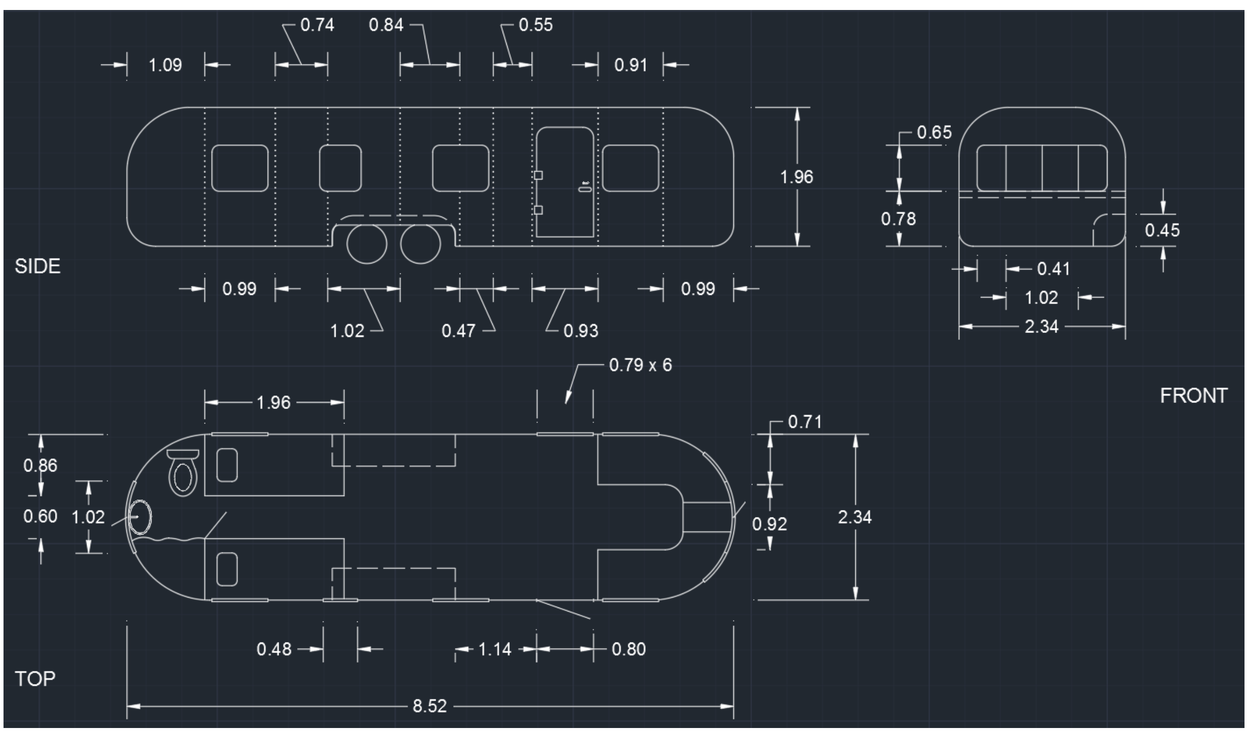

Figure 9. Approximate dimensions (in meters) and basic layout for MEERS

When complete, the station will be capable of hosting 4-6 crewmembers in a net habitable volume of approximately 40 m^3 for up to 2 weeks. Most analogs in current operation are easily 3 or more times larger in volume. With less than half of the recommended minimum NHV per person for a Mars mission, MEERS would be the ideal analog to study human factors and behavioral health for temporary, off-nominal safety habitation. The SHEE facility is the only analog that compares to MEERS in the sense that it is similar in volume, has a reconfigurable interior, and is capable of being transported to space-analogous environments. Otherwise, the only other current analog most similar to MEERS is the Aquarius Reef Base located underwater off of the Southern coast of Florida, which is not easily accessible. In contrast, MEERS will allow greater access for researchers focusing on this critical long duration spaceflight (LDSF) safety topic by being towable to any research location of interest (i.e., volcanic terrain, sedimentary deposits, and other areas analogous to celestial surfaces such as Mars). The benefit of a mobile habitat is the reduction of cost for operating in a wide-range of relevant analog environments (Figure 10). Furthermore, MEERS may potentially be used as an auxiliary emergency module in conjunction with larger analogs such as HI-SEAS or MDRS. In this mode of operation, researchers at these facilities could simulate a random emergency and have the crew evacuate to MEERS and conduct the rest of the mission using the resources and reconfigurability provided within its habitable volume. Not only will researchers be able to study team cohesion and performance for emergencies in ICE, they will also be able to analyze the influence and improvisation of reduced functional area, use of resources, effects of lighting, communication delays with mission control, changes in schedule programming, drone/robot teleoperation, regenerative life support systems, and other critical factors.

Figure 10. A recent photo of MEERS with solar panels installed (left). The rendered image of what MEERS may look like when complete (right) (Credit: Michael Fehilinger, ERAU, 2013).

VII. Conclusion

As history has shown us, unanticipated emergency scenarios are bound to occur on our endeavor to explore Mars and deep space. Not only is it critical to prevent behavioral health decrements for LDSF by incorporating human factors into the design of deep-space vehicles and habitats, but it is absolutely necessary to at least consider and plan for low probability/high consequence emergency scenarios such as a compromise in spacecraft that results in reduced habitable volume for the crew. A close-quarter habitat analog with less-than-recommended minimum NHV (by Mars mission standards), such as MEERS or SHEE, would be the ideal training facility and research test-bed to learn best practices and procedures for emergency safety habitation, and may also help in narrowing down a consistently accepted definition of habitable volume. Unlike the options that astronauts have had in the past for dealing with off-nominal events, the Mars crew will not have the convenience of being able to quickly return home, nor the real-time guidance from experts at ground control. Though the technology and procedures have been refined and improved over the course of human spaceflight, it is well known that the risk of catastrophic failure will always be present in the uncharted and unforgiving environment of space, and ever more so the farther humanity spreads.

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