

# Habitability Studies and Full Scale Simulation Research: Preliminary themes following HISEAS mission IV

Sandra Häuplik-Meusburger<sup>1</sup>

*Vienna University of Technology, space-craft Architektur, Vienna, Austria*

Kim Binsted<sup>2</sup>

*University of Hawai'i at Manoa, HI-SEAS*

Tristan Bassingthwaight<sup>3</sup>

*University of Hawai'i at Manoa, HI-SEAS IV*

The 'Hawai'i Space Exploration Analog and Simulation' (HI-SEAS) is a long duration Mars exploration analogue study run by the University of Hawaii at Manoa, funded by NASA. The first mission started in 2013. HI-SEAS mission IV included six crew-members, three male and three female. The mission began on 28 August 2015 and was scheduled to run for a year. HI-SEAS V began on January 19th, 2017 and is scheduled for 8 months. Research conducted during the missions includes research into food preparation and preferences, behavior, crew dynamics, group performance and other relevant issues for future missions to Mars and beyond, as well as our study on habitability.

This paper introduces the continuing 'HI-SEAS Habitability Study', which systematically investigates the relationship between the built environment (habitat) and its inhabitants. The term *habitability* describes the physical suitability and subjective value of a built habitat for its inhabitants within a specific environment. Along with human factors, habitability is critical for the design of an inhabited confined and isolated environment and thus the well-being of the inhabitants. The study uses a mix of methodologies for data collection, including monthly questionnaires during the mission and post mission interviews.

This paper introduces the topic of full scale simulation research and its relevance for habitability studies. Further, selected topics that emerged during the HI-SEAS mission IV are discussed in more detail. It is noteworthy that each isolated and confined environment (ICE) has its own limitations and strengths as an analogue environment for the development of future habitats. Therefore, this paper puts its findings into context with other relevant research in that field.

---

<sup>1</sup> Senior Lecturer, Institute for Architecture and Design, Department HB2, [haeuplik@hb2.tuwien.ac.at](mailto:haeuplik@hb2.tuwien.ac.at)

<sup>2</sup> [binsted@hawaii.edu](mailto:binsted@hawaii.edu)

<sup>3</sup> [tristanb@hawaii.edu](mailto:tristanb@hawaii.edu)

## I. Introduction

Isolated, confined and extreme environments (ICE) are environments, in which “*physical parameters [...] are [...] outside the optimal range for human survival [...] and which conditions [...] deviate seriously from the accustomed milieu of most [and further] involve physical remoteness [...] and a circumscribed spatial range*” (Suedfeld and Steel, 2000, 228).

Research on living and working conditions in ICE environments began earnest in the 1950s. The goal of “*understanding the physical and psychological components*” of such environments became important because of the increasing number of people exposed to such settings (Evans et al. 1988 p. 4). Naval submariners, oil company employees, polar station researchers and future inhabitants of the space station would soon be exposed to such remote and hostile environments, confining them indoors and isolating them from civilization. Polar-, underwater and also space habitats are examples for this building typology. Due to the specific characteristics of those environments, several physical and social factors can become stressors for the inhabitants. Table 1 lists a selection of physical and social stressors associated with ICEs.

Physical Stressors associated with ICEs	Social Stressors associated with ICEs
Limited available space	The feeling of being over-crowded
Constant confinement	The feeling of loneliness and separation from one’s normal social group
Irregular or unnatural light cycles	Reduction of privacy
Changes in pressure	The necessity of forced interaction with a small group of people
Extreme temperatures	Dependence on a limited community
Unusual environmental hazards (meteorites, radiation, etc.)	Disconnection from the natural world
Noise and Vibrations	No separation of work and social life
Poor ventilation	No family life
Sterile and monotonous surroundings	Repetitive and often meaningless tasks
Physical threat to life in exterior environment	
Restricted diet	

**Table 1. Physical and social factors that have been reported to cause stress.** (Evans et al. 1988 p. 4; Connors et al. 1985, Cohen and Häuplik-Meusburger 2015)

Behavioral changes associated with stress in ICE environments include a decline in alertness and mental functioning, lack of motivation, increases in somatic complaints (sleep disturbances, digestive problems, etc.), aggressive or depressed moods, psychotic episodes, social withdrawal, group splintering and polarization, and feelings of helplessness (Evans et al. 1988 p. 6, 11; Connors et al. 1985, p. 89; Suedfeld and Steel 2000).

Up to today, most research on ICE environments has focused on social stressors, with much less research examining the relationship between the physical environment and humans, and how their subjective experience affects life as an inhabitant. Examples for the later studies include: the effects of weather on psychological disturbances, the effects of crowding, and the role of privacy (cf. Evans et al. 1988 p. 9).

This paper introduces the topic of habitability and its relevance for the habitation of confined, isolated and extreme environments, followed by an introduction to the ongoing ‘HI-SEAS Habitability Study’, which systematically investigates the relationship between the built environment (habitat) and its inhabitants.

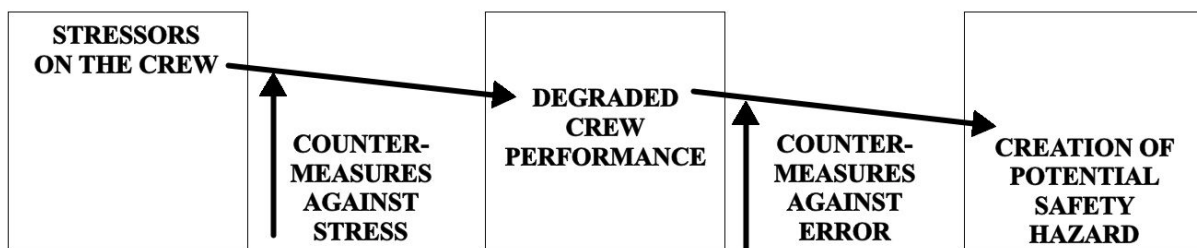
### I. ICE Research as Analogues for Habitability and Appropriate Design

The term *habitability* describes the suitability and value of a built habitat for its inhabitants in a specific environment. Along with human factors, habitability is a major factor in the design of an inhabited ICE environment, including its facilities. In that, habitability is critical for the well-being of the inhabitants and in the long-term for sustainable mission success.

In space and most of the environments characterized as ICE, the basic requirements of humans’ existence can only be secured by an additional technical envelope, such as the habitat or a space suit. Isolated from the Earth, astronauts must live for a long duration within a small and confined environment, completely dependent on mechanical and chemical life support systems. This building type is subject to careful design, planning and construction. Faulty or even inappropriate designs can have severe consequences on the inhabitants as well as for the overall mission. History has shown a number of examples of possible mishaps due to faulty design (cf.

Shayler 2000, Häuplik-Meusburger 2005) and the ‘*risk of incompatible vehicle or habitat design*’ has been identified by NASA as a recognized risk to human health and performance in space (NASA [Risk] 2013, p. 3).

Several incidents on past missions have shown that inappropriate design can lead to interferences with human activities, and a great deal of research has been conducted in so-called analogues. Polar (Arctic and Antarctic) areas are terrestrial locations to test human factors during winter-over operations and technological remote operations. Space habitats can also be considered analogues for future missions and are a relevant source for habitability research. In particular, a lot of research has been published on the habitability studies conducted during the Skylab missions (The Skylab Experience Bulletins, NASA 1973). NASA has evaluated the safety record, operations, and human factors of the Mir station and results have been published in the ‘Space Station Crew Safety Report (NASA 2004). In ‘Architecture for Astronauts’ (Häuplik-Meusburger, 2011), a cross-program comparison and analysis of all major inhabited human spacecraft and space habitats was made from a human perspective as a basis for the systematic assessment of existing and future living and working environments in space.



**Figure 1. The Crew Safety-Human Factors Interaction Model.** (Cohen, 2015)

Figure 1 shows a diagram, developed by Cohen and Junge (1984) for the early space station program. This model shows that a stressor can lead to degraded performance, which can in turn contribute to potential human error, unless appropriate countermeasures are available to the crew.

Habitability design has been envisioned as a viable contributor to both active and passive countermeasures for certain stressors. Particularly for long, remote mission scenarios, mission stress can be reduced through internal architecture and systems (Winisdoerffer & Soulez-Lariviere, 1992, p. 315, Bishop et al, 2016). Areas where appropriate design has already been employed as a countermeasure include:

- **Enhancing Performance:** Artificial and inadequate lighting can lead to fatigue, irritability and blurred vision. A potential safety hazard is mistaken perception. Appropriate lighting design can counteract degraded performance.
- **Enhancing psychological functioning:** Constant confinement and isolation as well as the decrease of privacy can lead to feelings of claustrophobia, loneliness and impaired judgment. Adaptable interior configurations allow for social group activities and changes in an environment characterized by monotony and over-familiarity.
- **Enhancing social cohesion:** The withdrawal from the normal social matrix and dependence on a small community can lead to depressed mood, social withdrawal or group splintering. Appropriate habitat layout can facilitate social interaction (e.g., events, group gatherings, shared activities) and as well as provide for private interactions (e.g., communications with family and friends, small groups/dyads) which can counteract the negative effects of isolated, confined environments.

In order to plan and test for building types in ICE environments, mock-ups and simulators are seen as appropriate ways to represent and understand the strengths and weaknesses of layout configurations and their effects on the crew.

## II. Full Scale Simulation Research - Examples

Full-scale mock-ups and analogs offer a wide range of testing capabilities for (almost) all systems including the habitat itself in an environment closest to the mission conditions before assembly. Multiple analog missions have been performed since the beginning of human space exploration. Space agencies and associated entities continue developing analog missions that are aligned with new space exploration road maps. An overview of

past and present simulators and simulation missions is given in Table 2. The facilities simulating long-term human space missions, exceeding 6 months are highlighted\* (underlined and marked with an asterix).

Past Simulators and Simulation Missions:	Current Simulators and Simulation Missions (as of 2015):
Regenerative Life Support Study by NASA Langley Research Center	Aquarius and NASA Extreme Environment Mission Operations (NEEMO)
Apollo Ground-based Tests	Mars Desert Research Station (MDRS)
Skylab Medical Experiments Altitude Test (SMEAT)	Flashline Mars Arctic Research Station (FMARS)
Skylab Mobile Laboratory (SML)	Concordia research station in Antarctica*
Ben Franklin Underwater Research Laboratory	NASA Fast Track Horizontal and Vertical Mock-Ups for lunar habitation
Tektite I and II Underwater Research Laboratories	Environmental Habitat (EnviHab)
BIO-Plex (Bioregenerative Planetary Life Support Systems Test Complex)	European Mars Analog Research Station (EuroMARS)
BIOS-3 (Institute of Biophysics, Krasnoyarsk, Russia)	Australian Mars Research Station (MARS-Oz)
<u>Biosphere-2*</u>	Virtual Simulators located at Industries, such as TAS-I VR Lab
Lunar Mars Life Support Test Project (LMLSTP)	<u>Mars 500 (RSA and ESA)*</u>
Closed Ecology Experiment Facilities (CEEF)	Human Exploration Research Analog (HERA)
	<u>HI-SEAS Hawaii Space Exploration Analog and Simulation *</u>

**Table 2. Past, Current and Planned Simulators.** *Relevant mission are highlighted\**. (Deems, Baroff, 2007; Mohanty et al. 2008)

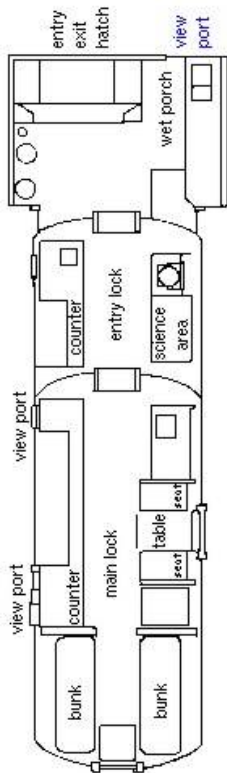
All space missions require the development of a combination of several analogs and test-beds in order to approve mission objectives. *“Because access to space is so difficult, dangerous, and expensive, the disciplines of engineering, operations and space architecture attempt to simulate every aspect of space habitats that they can before finalizing the design”* (Cohen, 2012 p.1). The selection of an appropriate mission analog depends on many factors, and not all conditions can be tested in analogs on Earth.

Full scale facilities involving human suspects usually start at a Technology Readiness Level (TRL) 4 or 5. TRL 4 relates to a relatively low-fidelity validation in a laboratory environment and includes mock-up evaluations. TRL 5 relates to a high fidelity validation in a relevant environment. TRL 4 and 5 correlate to the Habitation Readiness Level (HRL) 5-6. Those missions are typically using confined environment analogues, such as isolation chambers. Research usually focusses on psychological aspects of a long-term space flight and operational procedures including EVA operations.

The most relevant full-scale simulation research facilities relevant for habitability study are described below.

#### **A. NEEMO underwater facility**

Underwater facilities offer means for testing technologies, systems, tools, and operations of the habitat and EVA-related activities. Specifically they can test vehicles and crew operations in simulated micro-gravity conditions. In addition, the underwater environment allows simulating different gravity conditions. The only example of an underwater analog facility is the ‘NASA Extreme Environment Mission Operations’ project (NEEMO) Aquarius research station located underwater off the coast of Florida (Fig. 2 and 3). Underwater facilities such as NEEMO are used to test EVA equipment and operations.



**Figure 2. Floorplan of the underwater laboratory Aquarius. (NOAA)**

**Figure 3. Main lock, view to table and window. Aquanauts Tim Peake (ESA) and Steve Squyres (Cornell University) pose for a shot inside the Aquarius habitat with their iPads and some curious marine observers. (NASA)**

The 14m long and 3m in diameter sized facility was first deployed in 1988 and has hosted more than 20 crews of astronauts and space researchers since 2001. It requires total dependency on life support with “*significant restrictions to escape or access to immediate help*” (Vakoch 2011, 70). The missions are relatively short, between 7 to 14 days. A habitability survey including questions regarding the acceptability of the habitat was conducted during mission 1-5, for NEEMO 5 live feed from cameras was added.

Examples of the resulting video analysis are quoted as follows (NASA NEEMO-HABITABILITY 2004):

- Workstations were poorly placed and interfered with the flow of traffic in and out of the Main Lock. Particularly, the two workstations located near the entrances were problematic both for people trying to pass through, as well as for people working at them who were interrupted in their work.
- The table was an inappropriate size. Used for eating, working, meetings, and group teleconferences with ground, the table sometimes needed to accommodate up to six people at once. Even for four people, as was more often the case, the table was far too small and it was obvious from the video that the crew-members were uncomfortable.
- The food storage was poorly sited. Multiple instances were recorded where crew-members were seen reaching across the small galley, blocking traffic or standing precariously on the stepladder to reach the storage areas.
- The refrigerator and microwave/storage areas were located too far from each other, as lots of back and forth traffic occurred between them. Given the narrow passage, it was readily apparent that traffic within the Main Lock could be much ameliorated simply by moving these two areas closer together.

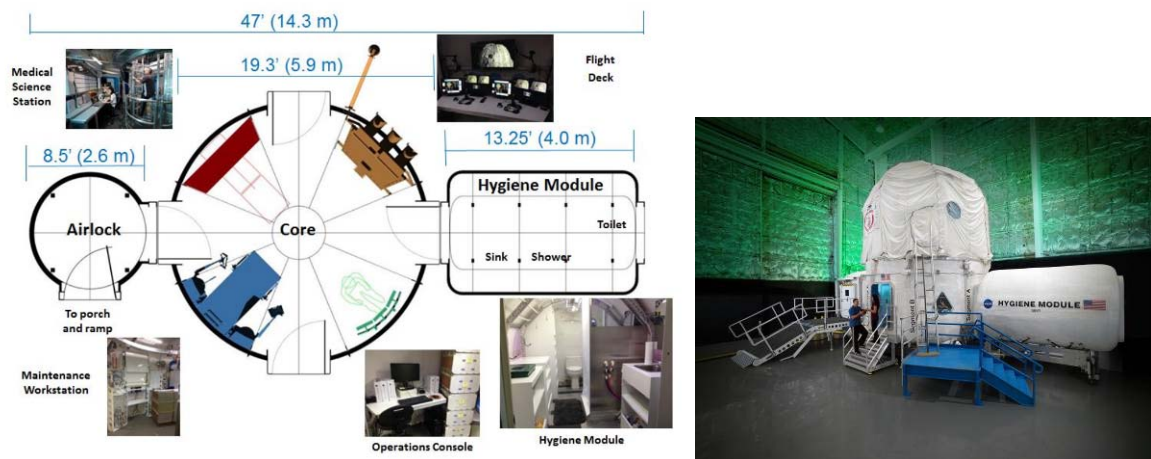
## **B. Human Exploration Research Analog (HERA)**

The Human Exploration Research Analog (HERA) is a modular three-story, four port habitat (Fig. 4 and 5). The ground floor comprises a medical science station, flight deck, maintenance workstation, operations console and the attached hygiene module and airlock. The upper floor houses a wardroom table, galley and aerobic exercise devices. The four crew quarters are on the top level.

HERA was formerly named ‘Deep Space Habitat’ and was developed by NASA, then enhanced via a series of university competitions. As such it was used in the desert research studies in the Arizona desert (NASA [HERA], 2014 and 2015). It is a high-fidelity research facility that is used as an analog for the simulation of isolation, confinement, and remote conditions of mission exploration scenarios. Its goal is to address risks and gaps associated with human performance during spaceflight. Standard simulation durations are 14, 30 and 60 days for a crew of 4, usually 2 men and 2 women.

Functional Area	Activities	Characteristics of Design Elements
HERA First Level	Airlock module, Core (Medical Science Station, Flight Deck, Maintenance Workstation, Operations Console, Hygiene Module)	Daily routine
HERA Second Level	Wardroom, Galley, Aerobic Exercise	Social and personal use
HERA Third Level	Crew Quarters	Personal use, items shall be personalized by crewmembers

**Table 3. Functional Overview of HERA.**



**Figure 4. The Human Exploration Research Analog in the HRP floor plan. (NASA)**

**Figure 5. The Human Exploration Research Analog in the HRP. (NASA)**

According to NASA the facility is suitable for studies that include behavioral health and performance assessments, communication and autonomy studies, human factors evaluations, and exploration of medical capabilities. Research areas include behavioral performance, team performance, crew medical and enabling technologies.

### C. Mars 500

An example of a terrestrial analog mission in preparation for a human mission to Mars was the Mars 500 experiment (IBMP, 2011), a collaborative project between Russian Space Agency (RSA) and European Space Agency (ESA). It was organized and planned through the Moscow Institute of Biomedical Problems (IBMP) and included a number of experiments starting in 2007. with completion of the 520-day mission in 2011. Later in 2015, an all-female crew mission that lasted eight days took place and longer missions (4, 8 and 12 months) are planned.

The isolation facility comprised of four hermetically sealed interconnected habitat modules, the Medical module, Habitable module, Storage module and Mars landing simulator (Fig. 5 and 6). In addition to one external module, which was used to simulate the ‘Martian surface’. The total volume of the habitat modules is 550m<sup>3</sup> (ESA [Mars500] 2012).

The crew for the 520-day mission was comprised of three Russian members, two from the European Space Agency, and a Chinese participant all male. The crew performed tasks planned according to a long-term mission timeframe.. Considerations taken into account included labor intensity, complexity of required methodologies,

crew members' specialties, and the possibility of experiments to cross-reference and influence each other, and observations if some special conditions are present during an experiment's implementation.

Stages of the experiments included a 14-day isolation (completed in November 2007); a 105-day isolation (completed in July 2009), and a 520-day isolation (April 2010 – October 2011).



**Figure 6. The Mars500 Isolation Facility Plan of the experimental complex.** *Module Simulator of Martian surface, Module EC-50 (Simulator of the landing Martian ship), Module EC-150 (Habitable module with 6 individual compartments, community room, main console, kitchen, lavatory), Module EC-250 (Utility module with gym, greenhouse, storage for resources, fridge, thermal chamber, lavatory), Module EC-100 ( Medical module with habitable compartment, kitchen-dining-room, working places with medical equipment and lavatory).* (Armael)

**Figure 7. Living room, view to the kitchen side.** *The Mars500 isolation facility in which the crew was based was located in a special building on the IBMP site in Moscow.* (IBMP/Oleg Voloshin)

Examples of the resulting video analysis are quoted as follows (Basner, 2014):

- Coping strategies to address monotony and boredom from low workload after the first mission quarter and to restricted social contacts are needed.
- A higher frequency of crew-perceived conflicts with mission control was reported in the first relative to the second half of the mission (being maximal during the period of the simulated landing on Mars).
- The number of crew interactions (overall amount of communication) with mission control and the number of negative and critical statements in crew messages increased during the simulated landing period. The researchers did not find a third quarter effect in any of the psychological or behavioral outcomes.
- Two crew-members were notable for showing no signs of behavioral changes or psychological distress during the mission; they were most often mentioned as the two people with whom the rest of the crew interacted; and they were the only two crew-members to suffer no changes in sleep duration, sleep-wake timing or sleep quality during the 520-day mission.

### III. The HI-SEAS Facility and Simulation Missions

The HI-SEAS facility started to run its first simulations in April 2013. Its missions place HI-SEAS in the company of a small group of analogs that are capable of operating very long duration missions (8-months and longer) in isolated and confined environments, such as Mars500, Concordia, and the International Space Station. Table 4 gives an overview of conducted missions.

<i>Mission</i>	<i>CM</i>	<i>Start of Mission / Duration</i>	<i>Habitability related research</i>
HI-SEAS I	6	April 2013; 4 months	Culinary and psychological aspects (temperatures in artificial habitats, variation of astronaut diets).
HI-SEAS II	6	March 2014; 4 months	Research on team cohesion and performance, use of 3D VR interactions with family and friends, emotional and effective states using automated analysis of textual communication to identify effective teamwork behaviors.
HI-SEAS III	6	October 2014; 8 months	Extended version of the HI-SEAS II research tasks, same focus for twice the duration.
HI-SEAS IV	6	August 2015; 12 months	Social and psychological effects of long-duration isolation on crew cohesion and task completion, the longest mission so far, extended version of HI-SEAS II and III.
HI-SEAS V	6	January 2017; 8 months	Team composition and dynamics, and their effects on performance.

**Table 4. HI-SEAS Mission Overview.**

#### **A. The Facility: Physical Space and Functions**

The HI-SEAS Habitat is located in a remote quarry on the northern slope of Mauna Loa, Hawaii. The geodesic habitation dome (Fig. 8) has an internal two-story open layout with a diameter of about 11m / 36ft. The ground floor is comprised of the communal areas with the kitchen, dining room, common work-space and lab, an exercise area and a small bathroom with a shower and toilet (Fig. 9).

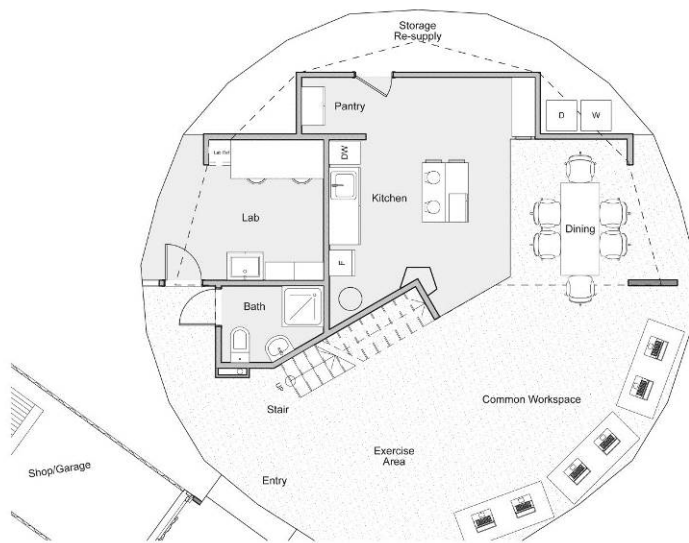


**Figure 8. The HI-SEAS habitat on Mauna Loa, Hawai.** (NASA Astrobiology Institute)

**Figure 9. The HI-SEAS habitat, view from the interior.** (HI-SEAS)

The ground floor has an area of 30.3 m<sup>2</sup> / 993ft<sup>2</sup> (usable 26,8m<sup>2</sup> / 878 ft<sup>2</sup>) with the second floor spanning an area of 39,4m<sup>2</sup> / 424ft<sup>2</sup> comprising 6 personal rooms and a small bathroom with toilet only. Attached to the exterior of the habitat is a single shipping container, providing storage for food and other supplies, as well as hosting the water and electrical systems.



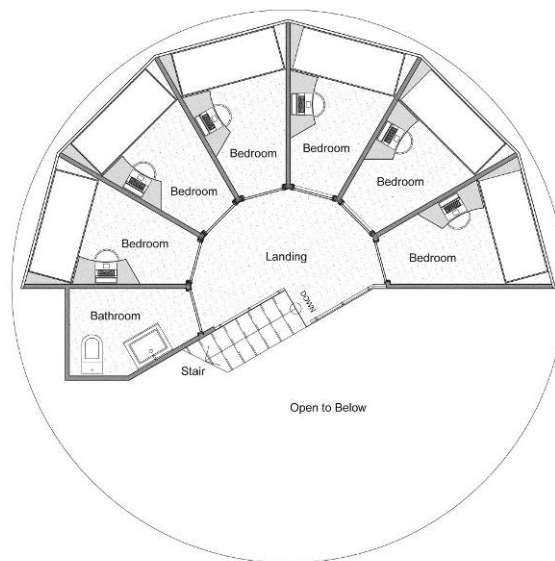


Envision Design, LLC



**Figure 10. Ground floor.** (HI-SEAS; Layout montage by Angelo Vermeulen)

The upper floor (12,9 m<sup>2</sup> / 424 ft<sup>2</sup>) accommodates six separate bedrooms and a bathroom with a toilet and washing basin. An additional 48,8m<sup>2</sup> / 160 ft<sup>2</sup> converted shipping container is attached to the dome.



Envision Design, LLC



**Figure 11. Upper floor.** (HI-SEAS; Layout montage by Angelo Vermeulen)

Table 5 shows a comparison of some of the habitat characteristics compared to other simulation habitats. Compared to other habitats (Table 5) the HI-SEAS Facility has a dome like structure, featuring different ceiling heights.

<i>Name of Facility</i>	<i>Module type</i>	<i>Additional modules</i>	<i>Total Area</i>	<i>Simulation duration</i>	<i>Features</i>
HERA	Vertical cylinder, two-story, four-port	Simulated airlock and hygiene module	148.1m <sup>3</sup> Core: 56.0 m <sup>3</sup> Loft: 69.9 m <sup>3</sup> Airlock:8.6 m <sup>3</sup> Hygiene Module: 14.1 m <sup>3</sup>	7, 14 and 30 days	Very short missions, limited suitability for human factors and habitability studies; Research on behavioral and team performance.
MARS 500	Horizontal cylindrical, one-story	Simulator of the landing Martian ship and landscape of Mars	550m <sup>3</sup>	520 days	Psychosocial isolation experiment of a simulated manned flight to Mars.
NEEMO	Horizontal cylinder, one-story	none	Entry lock: 14m <sup>3</sup>	7, 14 days	Total dependency on life support; experiments focus on isolation, confinement, communications, telemedicine, and remote health care technologies.
HI-SEAS	Dome, two story interior structure	Attached shipping container for additional storage	145,8 m <sup>2</sup> / 1462 ft <sup>2</sup> usable	4, 8, and 12 months	Studies psycho-social responses to extended isolation and confinement, crew cohesion, task performance, use of VR in maintaining social connections, and food study.

**Table 5. Summary and Comparison of Simulator Habitat Features.** Module Type, additional modules, total area and simulations duration of HERA, Mars 500, NEEMO and HISEAS missions are listed.

## B. Research at HI-SEAS

The conditions (habitat, mission profile, delayed communication, partial self-sufficiency) are explicitly designed to be similar to those of a planetary surface exploration mission. Daily routines include food preparation from only shelf stable ingredients, exercise, scientific research, geological field work carried out by humans or robots, equipment testing, and tracking resource utilization such as food, power, and water. These rigorous routines support a suite of behavioral and psychological tests and tasks performed by the crew that form the primary NASA behavioral research at HI-SEAS.

Behavioral research studies focus on the need to identify psychological and psycho-social factors, measures, and combinations that can be used to compose and support highly effective teams for future self-directing long-duration exploration missions. The primary research funded by the NASA Behavioral Health and Performance element is conducted by researchers from across the US and Europe who are at the forefront of their fields. The studies include: the Team Performance Task/Price of Cooperation Test, continuous monitoring of face-to-face interactions with sociometric badges, mitigation of the effects of isolation using immersive 3D Virtual Reality interactions with the crew's family and friends, measurement of emotional and effective states using automated analysis of multiple forms of textual communications provided by crew members to identify relevant and effective teamwork behaviors, and multiple stress and cognitive monitoring studies. (HI-SEAS [MediaKit] 2016)

During the first four month simulation mission (HI-SEAS I) diverse food preparation strategies for long-term space exploration were tested by the crew-members. As a result mission commander Angelo Vermeulen recommends to use spices and higher fiber foods. The importance of food systems has been confirmed early by astronauts during space missions and led to great improvement in food preparation as well as packaging.

Similarly, it has also been reported that food can get boring on long-term missions. The use of spices and the individual mixing ('cooking') of ingredients allows a lot of variation and adds to "renewed pleasure" (cf. Häuplik-Meusburger, 2011 p. 218). The second simulation mission HI-SEAS II was eight months. Data was collected on team cohesion and performance with various methods and technologies, such as sociometric badges and 3D Virtual reality applications. The second 8 months mission HI-SEAS III focused on identifying psychological and psychosocial factors, measures and combinations to be used to compose "highly effective crews for autonomous long duration and / or distance exploration mission" (HI-SEAS [MediaKit] 2016).

HI-SEAS IV will be described in more detailed in the following section.

#### IV. The HI-SEAS Habitability Study

With the beginning of the 4<sup>th</sup> mission, HI-SEAS IV, the 'HI-SEAS Habitability study' has been introduced. Dr. Sandra Häuplik-Meusburger is the principal investigator. Dr. Tristan Bassingthwaight was one of the crew members of the first mission. During his stay in the dome, he worked on his architectural thesis. The Habitability study was conducted on the mission for its duration of 12 months and is being continued with the ongoing mission HI-SEAS V that will last 8 months. In the following only HI-SEAS IV mission details will be explicated.

##### A. Preconditions for the study

All missions have a 20-minute time delay on all communications. Outside communication is strictly limited to email, for both sent and received messages. This results in a 40- minute time delay for a full cycle of back-and-forth communication to serve as an analogue for the longest expected delays in communicating with those on Mars. Additionally, crew did not come face-to-face or otherwise interact with other people while in-sim.

##### B. HI-SEAS IV Mission Crew

The HI-SEAS IV crew included six individuals; three women and three men. Crewmembers were from the US and Europe. Their professional background included an astrobiologist, astrophysicist, a soil scientist, engineer and an architect. Work tasks during the mission were distributed among the crew and included a commander, chief scientific officer, crew physician, crew engineer, crew biologist and EVA management.

##### C. Rational and Hypotheses

The rationale behind the ongoing 'HI-SEAS Habitability Study' is based on the strong assumption that habitability, along with human factors research, is of significant importance for living and working conditions, and thus the design, of an inhabited confined and isolated environment. The term *habitability* is used to describe the physical suitability and subjective value of a built habitat for its inhabitants within a specific environment. Previous research on habitability issues in remote places in Antarctica and during space missions (Stuster 1996, Bishop 1999, Häuplik-Meusburger 2011; Cohen 2015) has highlighted a direct influence between the habitability of the built enclosure and the well-being of the crew. Table 6 gives some examples how habitability and design issues can be related to crew activities.

<i>Relevant topics to be considered</i>	<i>Example of evidence</i>
Anthropometric and biomechanical limitations	A number of crew-activities (stowing equipment, translating, eating, etc.) have caused in-flight musculoskeletal injuries
Motor skill/coordination or timing	A microgravity environment leads to distortion of orientation and posture; the ability to avoid moving objects is impaired; reach envelope changes
Space and lunar visual environments	Improperly lit displays and controls may lead to mistakes and confusion. Within the space environment a lack of common orientation may contribute to nausea.
Noise interference	The detrimental effect on face-face speech communication at high noise levels has been reported
Seating, restraints, and personal equipment	Lower back discomfort and numbing of feet and legs has been reported
Design and placement of windows	Window watching (without a handle) was listed as

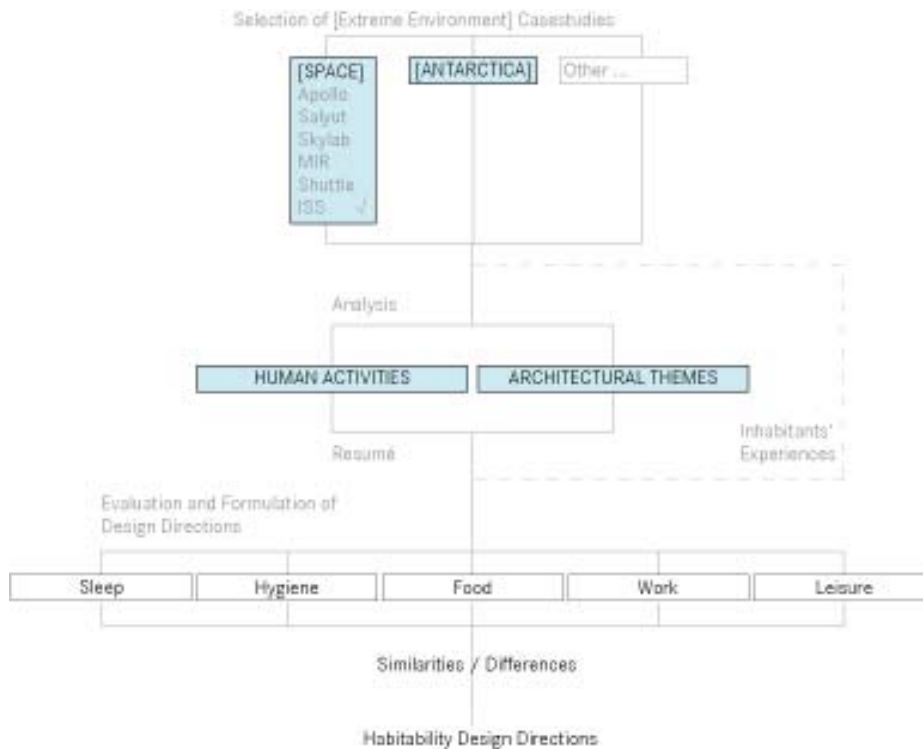
	probable cause for the leak of a flex hose used as a handle
Volume and layout of the habitat	Insufficient habitable volume and inappropriate layout can decrease functional productivity and habitability
Integration of communication technologies	Home and complex social networks are not available; this can lead to withdrawal from interpersonal connections.

**Table 6. Examples of key contributing factors to habitability design.** (adapted from NASA [Risk] 2013)

#### D. Research Methods

All of the six inhabitants of the HI-SEAS IV mission took part in this research. Three of them were female and three of them were male. Ages ranged between 26 and 37. All of the participants were students, professionals or scientists. All of them have some experience with space related science, research or missions.

The project uses several data-collection methods. The crew members of mission IV were asked to fill out a questionnaire with semi-open questions concerning selected habitability themes once a month. Some of the questionnaires included providing images in addition to written text. The preliminary themes for the questionnaire derived from previous research of living and working in space and in Antarctica (Häuplik-Meusburger, 2011; Häuplik-Meusburger Halley VI report) and are showcased in Figure 12.



**Figure 12. Schematic and major topics of a survey on Living in Antarctica and Space.** This schematic was adapted from the work on 'Architecture for Astronauts' (Häuplik-Meusburger 2011) for a comparison on living and working conditions at a European polar station.

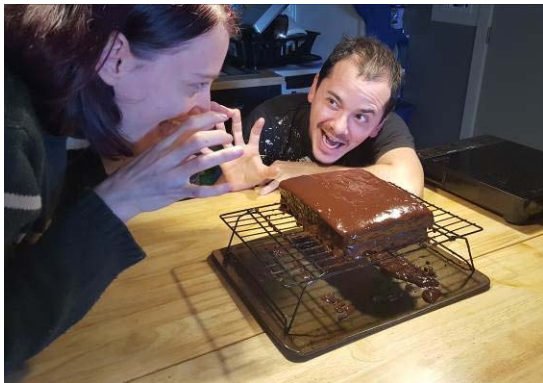
The research strategy follows a comparative approach with theoretical sampling. Based on the first interviews, questions and themes have been adapted. Following mission IV, a personal post-mission interview with each of the crew members was conducted via Skype. Additional information was retrieved from the crew's online blogs, the observation of the public representation of the living domain and selected emails, as well as a socio-spatial analysis. The surveys as well as the interview are being analyzed by qualitative methods.

## V. Observed phenomena and Discussion

The preliminary themes presented in this paper are based on research methods for qualitative and interpretative research with the goal to develop a theory from empirical data. Selected phenomena or ‘problems’ are systematically compared with each other and relevant phenomena in related environments. In the following selected socio-spatial phenomena are discussed:

### A. Enjoyable Social Activities and Situations

Enjoyable activities included cooking, group work outs and also games. Games were played alone and as a group (Pandemic, Cards Against Humanity, and Settlers of Catan are some examples). The crew organized special game nights about once a week. For some crew members, exercise was a predominant way in which to spend time off, also because it was a daily interaction, with three crewmembers training for and running marathons using the habitat treadmill. Often workouts were conducted with only 1-3 crew-members at a time, in part due to limited space, as well as varied exercise routines and interest, but also due to social conflicts between crew members. In general the ‘enjoyable social activities’ took place in the largest part of the habitat, around dinner time or in the private rooms. Although traditionally a work-related activity, some crewmembers engaged in EVA activities for leisure, in an attempt to explore the local geology, exercise out-of-doors, or take the time to experience the unique landscape and get ‘some fresh air’.



**Figure 13. Tristan Bassingthwaighte having fun with Christiane Heinicke and a chocolate cake. (HI-SEAS, Tristan Bassingthwaighte).**



**Figure 14. Treadmill in front of the dining room window, one of two available views to the outside. (HI-SEAS, Tristan Bassingthwaighte).**

### B. Unpleasant Social Activities and Situations

In contrast with previous research of extreme environment conditions, dinner was at times an unpleasant social activity, due either to the amount of work that needed review during the meal or social tensions between members of the crew. Activities which involved the whole crew were often forced or otherwise avoided, due to social rifts which formed very early in the mission and were exacerbated by continued time living within the dome. Crewmembers reported that, while all required and voluntary work was completed, this was at times a difficult proposition which required more effort than should have been necessary. Activities which had begun with a full crew, with movie-night being the most prominent example, deteriorated over time with 1-4 crewmembers choosing not to engage in the activity. In general situations triggering discussions or arguments were avoided, which often left disagreements open and, according to some crewmembers, affected activities negatively. Over the course of the simulation, work activities remained of high importance to the crew, at times disrupting crewmembers who wanted to relax. Personal hygiene activities were mentioned as potentially unpleasant due to the characteristics of the bathroom, with highly regulated water use that could result in cold showers or limited time for hygiene, as well as the smell of the composting toilet.



**Figure 15. Playing with other crewmembers can provide for social release and entertainment. “Some members are bigger pranksters than others”. (HI-SEAS, Tristan Bassingthwaighte).**

### **C. Privacy as opposition to Social Activities**

Over the duration of the mission privacy came to be of greater interest with the crew, often resulting in people spending 3-8 hours within their private quarters during the day to avoid social contact with other members of the crew.

According to the crew, sound proofing was non-existent, which negatively affected the quality of time spent alone, as the life of the habitat around a person severely intruded onto his or her subjective experience of privacy. As also reported on previous missions, the habitat has a lack of semi-private areas, with the most prominent spaces available being the airlock and the bio-lab. The bio-lab is adjacent to the kitchen and only separated by a partial wall, thus acoustically exposed. Obviously, this prevented comfortable small-group socialization or a sense of privacy.

Also per design, purely functional, the airlock was perceived as a more private space as it is partially isolated and able to be closed off with a zippered cover. However, the airlock also served as the sole entrance to the shipping container, where supplies and electronic equipment were located. This resulted in a great deal of “intrusions” on those within the airlock, or people attempting to conduct work being inconvenienced by needing to constantly move around resting people within a highly confined space.

### **D. Relationships and Personality**

A ‘splitting into small groups’ happened very early in the mission and continued or even intensified with mission length. Relationships within the dome came to be defined by friend-pairs, with people who were most similar bonding together and spending slightly more time in each other’s company, assisting with cooking, or generally being more available for work or social needs. Pairs were linked to previous experiences and interests, as well as cultural backgrounds. Pairs would often be buddies for longer EVA’s, exercise, or the de-facto teammate for games requiring such. Pairs also acted as motivation for personal projects within the dome, such as learning salsa, practicing art, or playing the ukulele. *“Friend-pairs only serves to imply the “best friend” of people within the dome, crew would still mix and spend a great deal of time with other configurations of crew members, especially during assigned tasks.”*(quote from a crew member) Relationships between all parties within mission VI tended to vary from best friends to forced professionalism as the mission duration extended. Friend pairs were very close, sharing interests in geology, music, exercise, and life stories from times prior to the time in the dome.

According to the crew members, personality played a distinct role in the relationships and also in the estrangement between those in the dome.

### **E. Architecture and Design**

In contrast to other simulation habitats, the design of the HI-SEAS habitat is based on a dome-like structure, which features different room heights in certain areas. The main area is the common first floor. It is a large double height space, which acts as the *“heart of the habitat”* (quote from a crew member). This characteristic was highly welcomed by most of the crewmembers, because it increases the sense of space (in an otherwise

highly confined environment). On the other hand, the design limits opportunities for privacy. The crew's private rooms, kitchen, dining room, and workout areas are directly visible from the common area, which lead to "a sense of observation which is difficult to escape from" (quote from a crew member). Soundproofing is perceived as non-existent, further decreasing the quality of 'feeling private' even within a private room with the door closed. A distinct lack of semi-private spaces for social use was reported as well as sufficiently isolated private areas for social decompression. Access to the shipping container is restricted to a single point, the airlock, which also happens to be a preferred social gathering spot due to access to natural light. This has caused conflict between those requiring access to the supplies within the shipping container and those utilizing the airlock to rest, especially when the airlock was zipped shut for privacy.

The amount of floor-space given to the common area provides ample room for flexible activities, with the area being employed for research, exercise, personal studies, movie-nights, or a host of other general purpose activities. Public areas would be used according to need on a daily basis, providing those needs didn't conflict with planned activities related to the mission. The included kitchen is also fairly expansive, with several cooking ranges, microwave, high quality cookware and accessories, and a full-size sink. This enabled the crew to engage in larger cooking projects, making food from home or for holidays, and served as a secondary social space.

## VI. Discussion

This paper is an introduction to the 'HI-SEAS Habitability study' and presents only preliminary results because both data collection and analysis are ongoing. The preliminary results have shown the consistent appearance of selected social phenomena. Further work will lead to a deeper insight into the mechanism of social and psychological boundaries in relation to the built environment.

The authors are convinced that full-scale simulations mission play an important role in the determination of relevant topics to be considered when planning future long-term missions beyond Earth. In order to research psycho-social-spatial issues, simulations lengths and number of people play an important role, as some issues are less evident in short missions or within a small crew.

## VII. Acknowledgments

Dr. Sandra Häuplik-Meusburger is the principal investigator of the HI-SEAS Habitability study. Dr. Kim Binsted is the principal investigator of the overall HI-SEAS simulation mission. Dr. Tristan Bassingthwaighte was a member of the HI-SEAS IV crew and just finished his thesis on the design of habitats in extreme environments. Dr. Häuplik-Meusburger would like to thank the crew-members of the HI-SEAS IV mission for their contribution to this study: Carmel Johnston, Christiane Heinicke, Sheyna Gifford, Andrzej Stewart, Cyprien Verseux and Tristan Bassingthwaighte. Special thanks go to Tristan for his initiative. Further I would like to thank Dr. Karl-Michael Brunner from the Department of Sociology and Empirical Social Research at the Vienna University of Economics and Business for his ongoing support in the research methodology. This research is supported in part by NASA Grants NNX11AE53G and NNX13AM78G.

## VIII. References

Basner Mathias, Dinges David F., Mollicone Daniel J., Savelev Igor, Ecker Adrian J. Antonio Adira Di, Jones Christopher W., Hyder Eric C. , Kan Kevin, Morukov Boris V., Sutton Jeffrey P. 2014. **Psychological and Behavioral Changes during Confinement in a 520-Day Simulated Interplanetary Mission to Mars**, *PLoS One*. 2014; 9(3): e93298., Published online 2014 Mar 27. doi: [10.1371/journal.pone.0093298](https://doi.org/10.1371/journal.pone.0093298)

Bassingthwaighte, Tristan. 2017. **The Design of Habitats for the Long-Term Health of Inhabitants in the Extreme Environments of Earth and Outer Space**, Doctoral Dissertation. To be published, retrieved from author.

Bishop Sheryl, Eckart Peter 1999. **Humans Living and Working in Space – The Interrelated Aspects of Physiology, Psychology, Human Factors and Life Support**, SAE Technical Papers.

Bishop Sheryl, Häuplik-Meusburger Sandra, Guined Jamie, Peldszus Regina. 2016. **Bionomic Design Countermeasures for Enhancing Cognitive and Psychological Functioning and Crew Performance in Isolated and Confined Habitats**, 46<sup>th</sup> International Conference on Environmental Systems (ICES 2016), Vienna, Austria, ICES-2016-375

Cohen, Marc. 2012. **Mockups 101: Code and Standard Research for Space Habitat Analogues**, AIAA Space 2012 Conference & Exposition, Pasadena, California, AIAA 2012-5153

Cohen, Marc M., Junge, Maria K. 1984. **Space Station Crew Safety: Human Factors Model**. In: Proceedings of the Human Factors and Ergonomics Society 28th Annual Meeting (vol. 28, no. 10, p. 908-912), San Antonio, Texas USA, 21-26 October 1984. Santa Monica, California, USA: Human Factors and Ergonomics Society.

Cohen Marc, Häuplik-Meusburger Sandra. 2015. **What Do We Give Up and Leave Behind?** 45<sup>th</sup> International Conference on Environmental Systems, Bellevue, Washington, US, ICES-2015-56

Compton William David, Charles D. Benson. 1983. **Living and working in space: A history of Skylab**. Scientific and Technical Information Branch, National Aeronautics and Space Administration.

Connors Mary M., Harrison Albert A., Akins Faren R. 1985. **LIVING ALOFT: Human Requirements for Extended Spaceflight**. Library of Congress Cataloging in Publication Data: NASA SP-483. <http://history.nasa.gov/SP-483/contents.htm>

Dudley-Rowley, Marilyn; Cohen, Marc M.; Flores, Pablo (2004, March). 1985. **Nasa-Rockwell Space Station Crew Safety Study: Results From Mir**, Presented at the Russian Academy of Science for the Institute for Biomedical Problems 40th Anniversary Conference, November 2003. Published in the (Russian). Moscow, Russia: Journal of Aerospace and Environmental Medicine.

Evans Gary W., Stokols Daniel, Carrere Sybil. 1988. **Human Adaptation to Isolated and Confined Environments: Preliminary Findings of a Seven Month Antarctic Winter-over Human Factors Study**, NASA Contractor Report NASA-CR-177499, University of California, Irvine, California

ESA [Mars500] 2012. **Mars 500 The Isolation Facility**. [online] [http://www.esa.int/Our\\_Activities/Human\\_Spaceflight/Mars500/The\\_isolation\\_facility](http://www.esa.int/Our_Activities/Human_Spaceflight/Mars500/The_isolation_facility)

HI-SEAS [Media Kit] 2016. **Hawaii Space Exploration Analog and Simulation. Media Kit. Mission Overview**. [online] [http://hi-seas.org/wp-content/uploads/2016/01/HISEASMediaKit\\_01132016.pdf](http://hi-seas.org/wp-content/uploads/2016/01/HISEASMediaKit_01132016.pdf)

Mohanty, Susmita; Fairburn, Sue; Imhof, Barbara; Ranson, Stephen; Vogler, Andreas. 2008. **Survey of Past, Present, and Planned Human Space Mission Simulators**, SAE 2008-01-2020. Warrendale PA: Society of Automotive Engineers

NASA [Bulletins]. 1974. **Skylab Experience Bulletins**, Houston, Texas, US, NASA Lyndon B. Johnson Space Center.

NASA [HERA] 2014. **Human Research Program Human Exploration Research Analog (HERA)**, Experiment Information Package. Flight Analogs Project Human Research Program. <http://www.nasa.gov/sites/default/files/atoms/files/hrp-hera-experiment-information-package.pdf> [cited 25 February 2016].

NASA [HERA] 2015. **Human Exploration Research Analog (HERA)**. <https://www.nasa.gov/hrp/research/analogs/hera> [cited 25 February 2016].

NASA [NEEMO-HABITABILITY] 2004. **Habitability Assessment: Habitat Utilization Analysis from Human Factors Perspective (NEEMO-HABITABILITY)**. [https://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp\\_index=1099](https://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp_index=1099) [cited 3 March 2017].

NASA [Risk]. 2013. **Evidence report: Risk of incompatible vehicle/habitat design**, Human Research Program, Space Human Factors and Habitability Element, National Aeronautics and Space Administration, Houston, Texas.



Shayler, David J. 2000. **Disasters and Accidents in Manned Spaceflight**. UK : Springer Praxis Books with Praxis, Publishing, 2000. ISBN 978-1-85233-225-9

Stuster, Jack. 1996. **Bold Endeavors: Lessons from Polar and Space Exploration**. USA : US Naval Institute Press, 1996. ISBN-10: 155750749X.

Suedfeld Peter, Steel Daniel G. 2000. **The Environmental Psychology of Capsule Habitats**. Annu. Rev. Psychol. 2000. 51:227-253

Vakoch, Douglas A. 2011. **Psychology of Space Exploration. Contemporary Research in Historical Perspective**. The NASA History Series, Washington DC