Lunar Daytime: Behavioral Experiments in a Space Analog Living and Working Environment

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Abstract

The Lunar Daytime (LDT) concept addresses the challenge behavioral scientists and architectural researchers face in conducting research in space habitats or habitat analogs to produce scientifically valid and reliable results. Historically, researchers were limited to largely qualitative surveys. In order to address this limitation and produce better results, the Lunar Daytime team will demonstrate the efficacy of a modifiable environmental habitat analog laboratory capable of producing and analyze empirically quantitative data for such settings. To measure effects on crew performance and crew behavioral responses as a dependent variable, researchers must be able to make and control changes in the physical living and working environment as independent variables.

Keywords:

Architectural Research, Analog Habitat, Behavioral Science, Empirical Data, Environmental Psychology, Experimental Data, Human Factors, Human System Integration, Psychology, Scientifically Valid Results, Space Architecture, Space Habitat.

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Nomenclature:

EVA = Extravehicular Activity
HERA = Human Exploration Research Analog, NASA Johnson Space Center
HI-SEAS = Hawai'i Space Exploration Analog and Simulation, "Big Island" of HI
ISS = International Space Station
JSC = Lyndon B. Johnson Space Center, Houston, TX
LDT = Lunar Daytime
LMLSTP = Lunar Mars Life Support Test Project at JSC
MDRS = Mars Desert Research Station, Utah
MPRS = Multi-Purpose Research Station
NEEMO = NASA Extreme Environment Mission Operations
NDX = University of North Dakota spacesuit experimental prototype
UND = University of North Dakota, Grand Forks, ND

I. Introduction

Lunar Daytime refers to modeling an early human-tended lunar base. Because this surface mission depends on solar energy for power, which is available only during the lunar day, the time limit to the simulation is 14 days, but may run shorter. This LDT context provides the mission scenario to conduct these comparatively short-duration habitat analog studies. A benefit of two-week long simulations is that it becomes possible to conduct multiple test runs within the same time and budget that a much longer (i.e. Mars mission) scenario would require.

The LDT team has conducted extensive studies of space vehicle and habitat designs, conducted research in various analog habitats (e.g., MDRS, HERA, HI-SEAS, Concordia), and reviewed all existing space habitat analog facilities. Unfortunately, none of the current facilities allow for the degree of modification, flexibility and control necessary to experimentally address critical issues required to optimize the creation of sustainable space habitats.

A. Existing Space Habitat Analogs and their Limitations

The LDT team members have conducted extensive studies of space vehicle and habitat designs. We have participated in the design of several space habitat analog simulators (e.g. Human Exploration Demonstration Project/Controlled Environment Research Chamber (Cohen, 2012)). We have conducted crew performance research in various analog habitats (e.g., Human Exploration Research Analog (HERA), Hawai'i Space Exploration Analog and Simulation (HI-SEAS), Mars Desert Research Station (MDRS) and Concordia Station). We have reviewed all the existing space habitat analog facilities—that may be available for present use— such as the ones just enumerated. Most crucially, we have evaluated these analogs for their suitability to conduct the research for Lunar Daytime. .

The crucial analog facility characteristic for Lunar Daytime's purposes is ***flexibility***—flexibility mainly in two respects. These two experimental dimensions are the physical configurability of the habitat analog facility and the operational adaptability of how the experimenters may run it. Generally, the limitations on reconfigurability are that the analog is highly configuration-specific to a particular mission concept, that they facility was designed without any reconfigurability in the plan (pretty much all of them), or the bureaucratic strictures from the hosting organization do not allow for the degree of reconfigurability needed (if any at all) for Lunar Daytime. The prime example of a mission configuration-specific facility is the Flashline Mars Arctic Research Station (FMARS) and its near-twin the Mars Desert Research Station (MDRS) being modeled on the NASA Mars Design Reference Mission 1.0 (Hoffman, Kaplan, 1997)

Currently, none of the existing facilities allow for the degree of physical modification or operational variation necessary to experimentally address many of the critical issues surrounding creation of the optimal built environment for isolated, confined environments (ICEs). Consequently, the LDT team concluded that we need to find a host organization that will allow us to modify an existing habitat analog or build our own, or ideally perhaps some compromise between these two directions. For this reason—and many more—we found the University of North Dakota analog space habitat in Grand Forks offers the starting point to develop such an opportunity. We describe these reasons in greater detail in the Literature Review below.

B. Objectives

Therefore, the Lunar Daytime project seeks to accomplish two major objectives:

1) Create a space habitat analog research facility, specifically designed to accommodate flexible and repeatable modifications in the physical and perceptual living and working environment, and
2) Demonstrate the ability of such an environmental behavioral laboratory to investigate and address critical factors that are believed to play important roles in human health, performance and well-being in isolated and confined environments (ICEs).

C. University of North Dakota (UND) Analog Habitat

Toward that end, the LDT Team plans to implement adaptive modifications in the Multi-Purpose Research Station (MPRS) at the UND analog in Grand Forks. MPRS currently consists of a five-module lunar/planetary habitat analog complex originating from two NASA EPSCoR grants. The principal modification will be to design, build, and install a sixth module as a space habitat analog behavioral laboratory. The UND facility and institutional support will enable the LDT Team to develop a new framework and an enabling methodology for the design and assessment of human factors, architectural, and environmental experiments for environmental behavioral research.

D. Hypotheses

A set of exemplar hypotheses will be addressed, each requiring controlled testing with the specified modification(s) to the environment. Since the facility will be able to accommodate a wide variety of studies, we will seek to avoid redundancy with other habitat analog projects. So, the LDT Team will consult with NASA and Space companies on which hypotheses should rate the highest priority to pursue. Similarly, selection of crew response behavioral measures has been drawn from prior analog/simulation studies to provide for maximal cross comparison of results to bridge past and future studies.

E. Expected Results

The primary tangible result of Lunar Daytime will consist of a fully operational modifiable space analog behavioral laboratory. The series of suggested experiments will demonstrate the power and flexibility of utilizing a modifiable behavioral analog laboratory. It will set new standards for space analog habitat research. It will also initiate a NEW PARADIGM of behavioral research that moves beyond passive observation and "expert opinions" that have dominated past surveys and quasi-experiments. It provides for a heretofore unavailable degree of physical manipulation of the living environment that will lead to more definitive and sophisticated mission simulation research. These results will feed forward into the knowledge base for the design of future habitable structures and environments for humans off-Earth.

II. The Challenge

The great difficulty in conducting research on the effect of the spaceflight or planetary surface living environments upon behavioral health is the lack, in the Kuhnian sense, of a standard textbook or standard literature that reflects the "assent of the relevant community" [in this case, the human spaceflight community](Kuhn, 1970, pp. 94, 137, 149). Without such a community consensus on the effects of the off-Earth environments on crew behavioral health and performance, no baseline exists against which to test hypotheses. Currently the greatest knowledge base from which to draw is the 20 year of continuous space habitation aboard the International Space Station (ISS). In the absence of a consensus and standard research paradigm, researchers must draw from precedents and parallels from outside the history of human spaceflight, where the key variables and main problems may differ substantially, so the paradigms are incommensurable.

The specific challenge for Lunar Daytime is to create and run simulations of a crew mission on the lunar surface that lasts for the sunlight period of on lunar day: 14 Earth days. That is the realistic period of crew occupancy until there is permanent solar photovoltaic power beamed from the "peaks of eternal light" on the rim of Shackleton Crater or from other suitable high ground in the same vicinity of the Moon's South Pole. This power from the "peaks of eternal light" would enable crew habitation at a South Pole base permanently throughout every lunar month. Eventually, NASA or another exploration agency will produce a nuclear fission reactor that can fulfill that power requirement anywhere on the Moon or Mars, and it will become possible to locate a habitat anywhere on the Moon for permanent habitation.

Thus, in the development of the Lunar Daytime concept, it becomes necessary to pursue certain idealized conditions to simulate the 14-day sojourn on the Moon while at the same time be prepared to make certain compromises on other parameters. Architectural configurability of the physical environment is the idealized condition. Less than perfect isolation in a less than totally desolate landscape might constitute that type of compromise.

III. Literature Review: Research in Space Habitat Analogs

The study and utilization of space habitat analogs play an important role both in Space Architecture and in the broader human spaceflight community. Understanding the analog role in design, operations, and research is essential to comprehend the context not only of traditional analog use for scenario development and crew training, but also the analog's role in conceptualizing new concepts and experimenting with new techniques. This literature review summarizes the significance of a small number of analog overview studies that offer comparative analysis of selected analog facilities for their benefits, advantages, disadvantages, capabilities, and limitations. This Literature Review presents its discussion in two sections: first the characteristics of habitat analog simulators and second, the scientific and methodological essentials to research habitat effects upon crew health, performance, and well-being.

A. Analogs and Habitability Issues

Jack W. Stuster (1986) wrote the first such systematic comparative analysis. Stuster looked primarily at these analogs: Skylab, Sealab II, Project Tektite, fleet ballistic missile submarine, South Pole Station, and a commercial saturation diving chamber. Stuster framed his analysis in terms of the habitability issues that the "analogous conditions" affected. These issues included:

- Sleep,
- Clothing,
- Exercise,
- Medical Support,
- Personal Hygiene,
- Food Preparation,
- Group Interaction,
- Habitat Aesthetics,
- Outside Communications,
- Recreational Opportunities,
- Privacy and Personal Space,
- Waste Disposal and Management,
- Onboard Training Simulation, Task Management, and
- Behavioral and Physiological Requirements Associated with a Microgravity Environment,

The point of incorporating this list here is that the same issues—except microgravity—apply to Lunar Daytime. Lunar Daytime may identify some additional issues over its development and operation.

During the Space Station Advanced Development Program, it became necessary to forge a link between the habitability of the space living and working environment and the productive work that space crews were there to perform. That necessity led to this definition of habitability (Wise, et al, 1988):

A measure of the degree to which an environment promotes the productivity, well-being, and situationally desirable behavior of its occupants.

Mohanty, Fairburn, Imhof, Ransom, and Vogler (2008, 2009) have published a comprehensive comparative analysis of space habitat simulators. They established several sets of classification and key criteria for their evaluation. Their first classification system is temporal, dividing the analog simulators they considered into four groups: *Early, Recent, Present, Virtual,* and *Planned.* Across these five periods, the analog facilities that currently exist, are "still in business" and at least nominally available for outside experimental research are: Lunar Mars Life Support Test Project (LMLSTP) at JSC, MDRS in the Utah desert, NASA Extreme Environment Mission Operations (NEEMO), and the Concordia Antarctic Station.

Mohanty et al's second classification set covers "Scientific/Medical Investigation . . .Technology, Test and Development." This classification set reflects many of the same habitability issues that Stuster raises. It includes a wide range of medical support capabilities and research, including Human Factors and Psychology. The menu of habitability issues includes:

- Environmental Control and Life Support (System) (ECLS(S)),
- Hygiene,
- Waste Management,
- Food Preparation and Storage,
- Surgery/Dentistry,
- Extravehicular Activity (EVA),
- Interior Habitat Architecture And
- "Infotainment."

As with Stuster's enumeration, these issues hold significance for Lunar Daytime. Mohanty et al take their classification effort to a new level with an accounting of "Key Technical Data," which constitute in fact the main architectural and operational properties. These properties include:

- Simulation Duration (Days)
- Crew Size
- Gender
- Physical Dimensions
- Pressurized Volume
- Habitable Volume
- Floor Area
- Internal Pressure
- External Pressure
- Main Airlock Volume
- Number of Airlocks, and
- Number of Viewports

These criteria remain relevant to strategic planning for Lunar Daytime and for most crewed space missions. Mohanty et al's enumeration captures the defining physical parameters for pressurized space modules and habitats of all kinds.

Schlacht et al (2016) simplified the temporal framework from Mohanty et al's five categories down to two: "past and present" or "future." Among the habitat analogs they reviewed that might meet the baseline criteria: that they currently exist, are "still in business" and at least nominally available for outside experimental research, the few available analogs appear to be: MDRS, HI-SEAS, and NASA's Human Exploration Research Analog (HERA) at JSC (Cromwell, Niegut, 2014).

In their study, Schlacht et al published a comparative framework for space habitat analogs in which they compared candidate space habitat simulations across a small group of criteria for their characteristics:

- "Spin-In" vs. "Spin-Off,"
- Interior Analog
- Hybrid Habitat,
- Exterior Analog,
- Controlled Ecological Life Support System (CELSS)
- Food Production, and
- Human Isolation.

Perhaps the most significant aspect of this list of issues is the concern that the habitat analog includes an outside space as an exterior analog. The dichotomy "Spin-In" vs. "Spin-Off" refers in an arcane way to whether the analog project produces a spin-off technology or produces an innovation that can come down to Earth to improve life on Earth. These two attributes hardly seem to be mutually exclusive, and indeed some analogs display both properties.

The LDT team looked closely at all the habitat analogs above that were putatively "available" for outside research, but found that none of them or their owners would allow physical modifications to the extent required to conduct the Lunar Daytime experiments. Also, in some cases, particularly the NASA-owned NEEMO and HERA, the agency prescribes strict protocols for operational procedures, which would also be disabling for Lunar Daytime. Therefore, the LDT Team concluded that we need to construct our own habitat analog facility that will meet the LDT experiment requirements.

B. Scientific Experiment Approach, Methodology, and Requirements

Aside from historical studies of analogs (Stuster, 1996), or contextual compendia and reviews (Vakoch, 2011), most research of this kind takes the form of surveys or "quasi-experiments," that rarely yield quantitative or applicable results. Even so, over several decades, nearly all this research focuses upon the astronauts' or cosmonauts' experience of stress from the potential danger of the mission, the demands of its operational procedures and schedules, or the role of multicultural crews and their responses to them (Kanas,1985; Kass, Kass, Samaltedinov, 1995; Sipes, Vander Ark, 2005). Those social and behavioral scientists who have been fortunate to study space habitat analogs, actual space missions, or mission simulations up until now are able to do so most often only as a last-minute add-on or afterthought, always playing catch-up to the engineers and immutable environmental designs. Never have behavioral researchers enjoyed the opportunity to define and manipulate their own independent variables in the mission, the spacecraft, or its living environment to be able to study the effects on crew behavioral response.

NASA has been prolific in producing guidelines (Allen, 2003), handbooks (NASA, 2014, requirements documents (NASA, 2010, and standards (NASA, 1995), that (hopefully) help guide space vehicle/habitat design. Although seasoned by the experience of actual spaceflight, the prescriptive (but not the preventative) measures in these texts derive primarily from anecdotal evidence or speculation. Without experimental testing, the estimations in some of these "standards" historically have proven questionable or falsifiable, such as volumetrics (Cohen, 2009). The most recent NASA Standard 3001 tries to correct this shortcoming, but provides only this statement in Vol. 1 on crew health in space (NASA, 2015; NASA, 2011).

> **4.2.5.1** Pre-flight, in-flight, and post-flight crew behavioral health and crewmember cognitive state shall be within clinically accepted values as judged by behavioral health evaluation.

Vol. 2 is a little more expansive, touching on crew psychological health in relation to food and dining, privacy for hygiene functions and sleep, and sufficient volume. The companion handbook mentions privacy for hygiene and sleep (NASA, 2015, pp. 638-639).

However, all these documents predicate unexamined assumptions about the character of the living and working environment. Fortunately, the NASA *Evidence Report* (NASA, HAB-3, 2018; NASA, BMED-7, 2018) behind this research topic covers behavioral health: ". . . modifying the habitat/vehicle environment to mitigate the negative psychological and behavioral effects of environmental stressors (e.g., isolation, confinement, reduced sensory stimulation).

In the Space Architecture domain, practitioners and theorists have proposed numerous design concepts for a better space living and working environment, their technology readiness, and suitability for particular mission architectures (Mohanty et al, 2008 & 2009; Cohen, 2012 & 2016; Schlacht et al 2016; Cohen, 2015). These habitat concepts and the studies of them generally reflect the same deficiency as the NASA documents cited above; they do not address crew behavioral health or performance in any empirical, scientific, or systematic way.

IV. Design of Experiment

Although a stigma of mental illness plays a historical role, what is most important to the neglect of behavioral research for spaceflight environments is its lack of standing as a "hard" science that provides reproducible results with human subjects in the spaceflight domain. ***This project seeks to correct this deficiency by conducting controlled experiments in which we manipulate the physical environment as the independent variable and measure the crew behavioral responses as dependent variables.*** In this approach, the design of experiment dictates the design, layout, and outfitting of the analog habitat to the extent necessary to conduct the experimental runs.

A. Research Venue

Our institutional partner for this proposal is the University of North Dakota (UND) Space Studies Department in Grand Forks, ND. There, Dr. Pablo de Leon has overseen the design and construction of five modules in a lunar/planetary base simulation. The modules available in the present complex include the habitat, EVA module, greenhouse, and a geology lab module. The simulation includes UND spacesuits, Suitports through which to don and doff the suits, and a truck-like rover that integrates with the habitat and the suits. Dr. Cohen served as consultant to Prof. de Leon on the design and construction of the first analog habitat module, in FIGURES 1 and 2. FIGURE 3 shows the space habitat simulation analog complex in January, 2019. Prof. Pablo de Leon in the Space Studies Department at UND is supporting this effort as Facility CoI for the analog habitat adaptation to Lunar Daytime. the rover docked to the MPRS core habitat module.

FIGURE 1. Early Integrated Habitat Interior showing hatch, galley and group activity area. Photo: Marc Cohen.

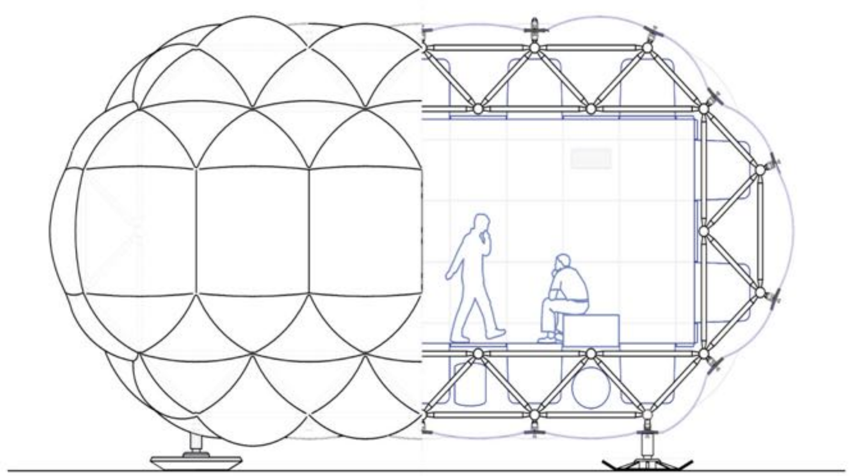

FIGURE 2. Early Integrated Habitat design concept: Partial Transverse Section through the inflatable Integrated Habitat Structure. Drawing credit: Andrew Daga.

To that end, the LDT will build a *sixth module* for the Multi-Purpose Research Station (MPRS) at the University of North Dakota (UND) in Grand Forks. MPRS currently consists of a five-module lunar/planetary habitat analog complex built from two NASA EPSCoR grants. PI Cohen served as consultant on the first EPSCoR. The expansion of the existing simulation facility is the most efficient path for realizing a true space habitat analog behavioral laboratory. The addition of a sixth module will accommodate a wide range of spatial and visual experimental configurations addressing various habitat design and psychosocial factors.

The MPRS research capabilities include the NDX spacesuits, Suitports to don and doff these EVA suits, and the lunar/Mars rover simulator, which can dock to the MPRS and carries Suitports for EVA access. FIGURE 4 shows the NDX suits with the rover. The rover has a pair of Suitports (Cohen, 1989) installed in the aft bulkhead, to which the suits seal for crew members to don and. Doff the suits. FIGURE 5 shows the rover docked by its side port to the "Integrated Habitat" via a flexible tunnel.

FIGURE 3. UND MPRS Space Habitat Analog Complex, January, 2019.

C. Specific Aims

The *Specific Aims* for this project address developing the research framework, the experimental methodology, the design of experiment including habitat analog module, running the experiments, and the data analysis.

FIGURE 4. NDX spacesuits with the UND lunar/Mars rover simulator with dual Suitports installed in the aft bulkhead. Photo credit: Pablo de Leon.

FIGURE 5. MPRS core habitat module with docking tunnel extended to the side-docking port on the lunar/Mars rover simulator. Pablo de Leon Photo credit.

1. Research Framework

The research framework refers to defining the relationship between the human spaceflight program, the evidence to date about crew behavioral response, and how our research will address the situation.

Significance: The framework scopes out the important environmental design issues or opportunities that may affect crew behavioral health and performance, and can be assessed based on experimental variables and controls.

Innovation: This approach is a new concept directed at how to research the human experience and prepare future behavioral scientists, training personal, architects, engineers and designers using a spaceflight analog.

Approach: These experiments propose designing and building an analog habitat to accommodate controlled experiments that involve making physical changes to the habitat's environment as an independent variable, and observing the behavioral and performance responses as secondary variables.

2. Research Methodology

Develop an experimental methodology that selects independent variables in the physical environment and how to manipulate, measure and evaluate their effects on behavioral and performance responses.

Significance: Only in this way can we begin to test concepts and countermeasures for architectural design of the crew living and working environment in a valid and repeatable scientific manner.

Innovation: Until now, all analog habitat research started from a predetermined habitat design that did not take this type of research into account. In *Lunar Daytime*, the researchers will modify the habitat based upon the desired independent variable to manipulate.

Approach: The experiments will start with small, couple day test runs before committing to a full 14-day simulation runs.

3. Design of Experiment

The Lunar Daytime team will take care to design scientifically valid and reliable experiments with sufficient ***n*** to give statistical power in testing our hypotheses. We can use a Bayesian Statistics analytical approach to reduce needed *n* so that short data run times are productive.

Significance: This "behavioral laboratory" in a habitat analog will respond to the design of experiment requirements, both in the facility and in operating the experimental runs.

Innovation: By basing the simulation on the comparatively short lunar daytime (i.e., 14 days) surface mission, it becomes affordable and feasible to schedule sufficient runs with multiple independent variables to achieve statistical power and means for observing and measuring crew response.

Approach: The LDT team will track behavioral response during the experiments through direct observation, RFID tracking, wrist-worn monitors, and various self-reporting tests (e.g., mood with the mobile app *Moodfit).*

4. Running the Experiments

Significance: Our experimental runs for Lunar Daytime are different from previous research in three substantive ways: First, we have sharp hypotheses about effects of environmental design interventions because we build on past research and design practice of our collaborators. Second, we will employ Bayesian statistical procedures to provide an estimate of the likelihood that an intervention is effective given the hypothesis, making the best of short data gathering sessions. Third, we can relatively rapidly redesign the simulated habitat to take advantage of design insights and emerging technologies and materials.

Innovation: Our prime innovation from previous habitability research is reconfiguration speed and creativity, optimal use of data regardless of size on *n*, and the ability to build upon lifetimes of experience in an expanded range of fields. We can find effective habitability design enhancers quickly and assuredly, and test them quickly. We consider this approach to be our way of introducing a 'rapid prototyping' design investigation into the space habitats field.

Approach: The LBT team will recruit subjects from the grad student population at the University of North Dakota who are the most "astronaut-like" that we can find. They will undergo a preparation and orientation period of up to 10 days before entering the analog habitat for the 10-day run. After the run, there will be a debriefing over two to three days.

5. Data Analysis:

Significance: Our innovation here is that we are ready to eschew the traditional 'significance test' approach and substitute Bayesian statistics as a preferred data analytical procedure. This has already been widely tested in medical and business fields and found to be extremely effective in finding answers to questions quickly. Bayesian statistics calculates the posterior probability that a design intervention is effective given its initial hypothesis. It does not look for an artificial 'significance'. Using Bayesian analysis, we can utilize the best of short run time data, and always provide a meaningful result in response to the effort extended. There are no 'lost runs' due to an unforeseen inability to continue to gather data.

Innovation: As stated above, we believe that the combination of rapid design prototyping and reconfiguration with this facility, combined with a statistical analytical approach that is idea for these types of tests will combine to provide a truly very large 'bang for the buck' outcome to this research, and become a new standard for other habitability research in the future.

Approach: Avoid confounding experimental results from running too many independent variables at the same time. Final run may include all the important environmental changes to see if they reinforce each other's effects or if the effects are the same.

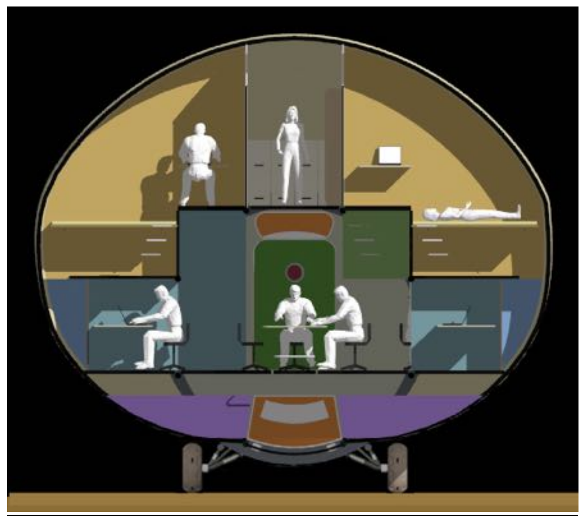

FIGURE 6. Cross-Section through the inflatable SEIM lunar-planetary habitat module. The private sleep compartments appear in the upper left and upper right. Courtesy of Constance Adams and Georgi Petrov.

C. Hypotheses

The Lunar Daytime team posits a set of hypotheses we plan to test in our experiments. We state these hypotheses here as examples of planned investigations, not as a comprehensive set. In all cases, the null hypothesis (allowed in Bayesian Statistics) states that there is no treatment effect. So, the hypotheses stated here are all alternate hypotheses. Also, our co-investigators have addressed all of these hypotheses in their prior work, ensuring that the sharpest tests will be done.

1. Hypothesis 1: Privacy of Sleep Quarters

Providing individual private quarters will produce better human performance and behavioral outcomes (e.g., lower stress, reduced interpersonal conflict, higher well-being, more positive moods, more restful sleep) than shared or common sleep quarters. Privacy and sleep comprise two distinct human needs. Together, they form a matrix of design challenges and expectations for a safe and healthy life. Privacy involves personal space and territoriality. Sleep hygiene involves isolation or protection from disruptive stimuli such as light, noise, nearby activity, vibration, smells and other distractions or irritants.

Configurations of sleep quarters to be tested include: individual, twin, and all-in-one/common sleeping arrangements. FIGURE 6 shows an example of private sleep quarters in a habitat module. The private sleep quarters appear on the upper level of the SEIM habitat, in the rooms with yellow ochre colored walls. These sleep quarters benefit from a positive physical separation from the work and group activity areas on the lower floor. This floor barrier appears as a solid black line running transversely across the module.

2. Hypothesis 2: Windows

Digital display "windows" will provide a sense of location as well as reductions in stress and the sense of confinement. Proposed characteristics to be tested include: geometry, lighting, scene, size, and location. Windows could also provide a sense of situational awareness for crew operations and systems. Actual physical windows will afford a basis of comparison. A compartment with no windows will provide a control. FIGURE 7 shows an example of a physical window in an International Space Station (ISS) module.

FIGURE 7. Astronaut Karen Nyberg at the window in the JAXA Kibo (Hope) module. NASA Photo.

3. Hypothesis 3: Circulation Pattern

A module traffic pattern that creates a circulation loop will elicit functional and crew interaction differences from a non-loop "tree" pattern. These differences include increased social interaction (positive or negative), and efficiency in response to emergency egress and access, and normal operation, and pose design questions regarding redundancy in design. FIGURE 8 shows the Mir space station with its tree-like single entry/single egress "dead-end" circulation pattern. FIGURE 9 shows the planned "racetrack" circulation loop for Space Station Freedom, the earlier name for the ISS.

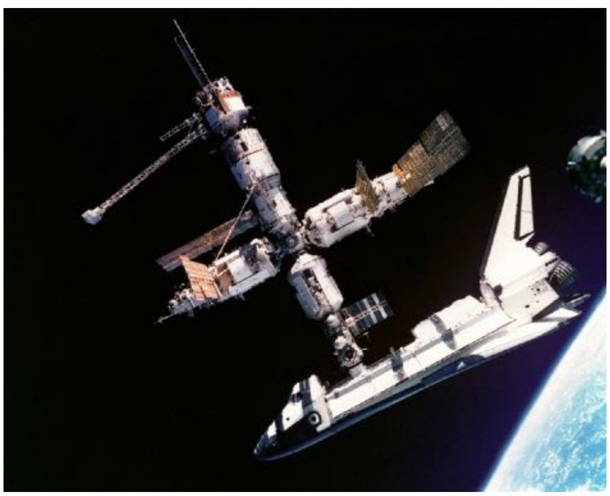

FIGURE 8. Space Shuttle Atlantis docked to the Mir space station. Photo Credit: Roscosmos,

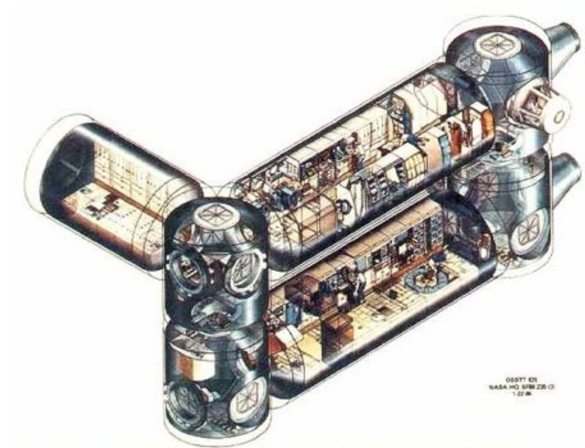

FIGURE 9. Space Station Freedom configuration showing four nodes connecting two long modules to create a circulation loop. Drawing Credit: NASA

FIGURE 10 shows the schematic concept for reconfiguring the MPRS at UND for the Lunar Daytime experiment to test Hypothesis 3. The upper drawing shows the existing MPRS plan layout for the view in FIGURE 3. The simulated pressurized rover appears in FIGURE 4 and the flexible tunnel to which it docks appears in FIGURE 5.

The lower drawing shows how we would rearrange the existing modules. Specifically, the LDT team proposes to relocate Lab 1 to connect to the distal end of Lab 2, using a node or hub. Then, between the distal ends of the Plant Growth Module and Lab 1, we would install the configurable and customizable Lunar Daytime Habitat module.

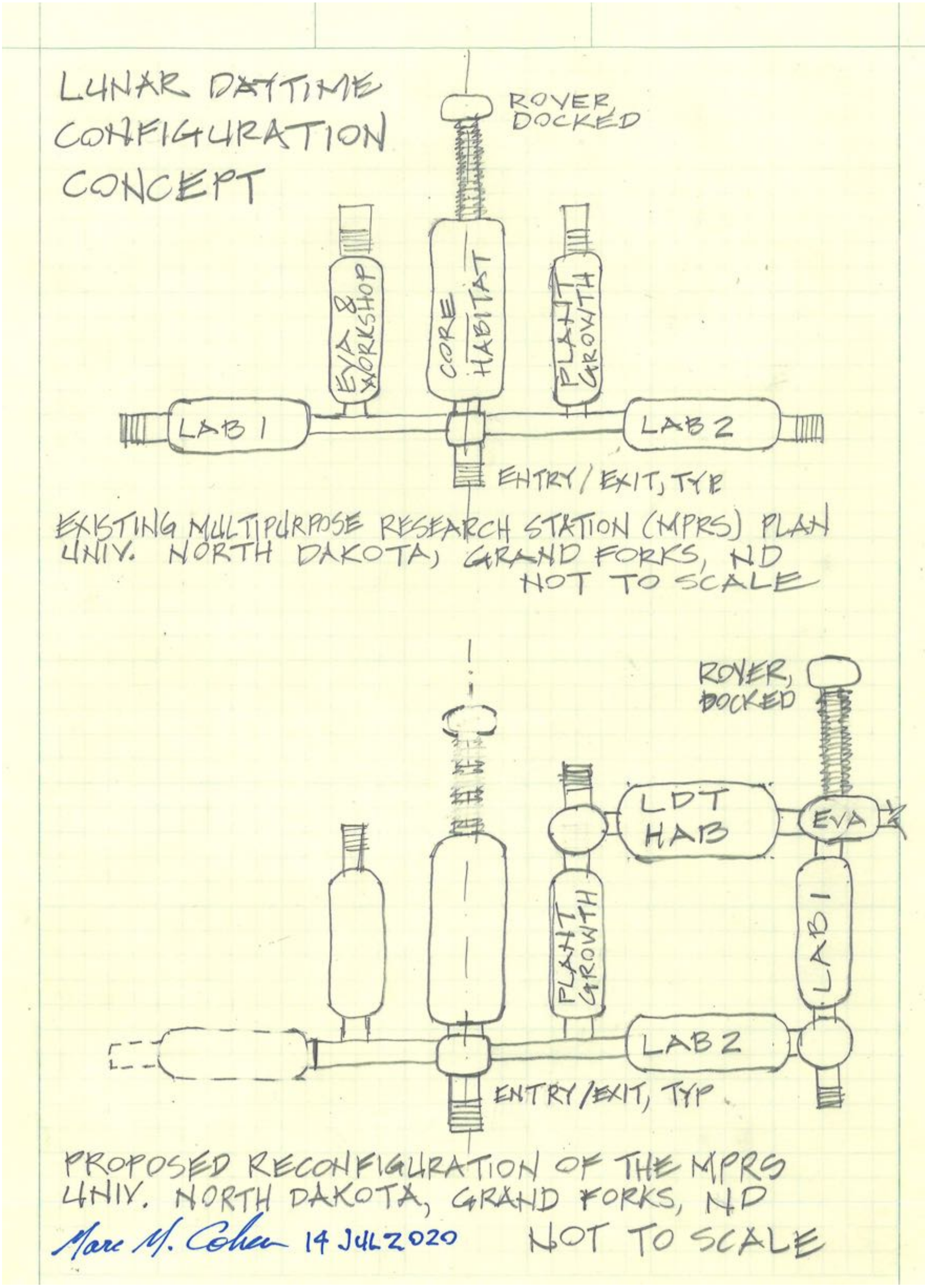

FIGURE 10. Two plans of the Multipurpose Research Station (MP/RS) at the University of North Dakota, showing the Lunar Daytime concept for a reconfigurable analog habitat. The LDT Habitat module constitutes a new addition that is internally reconfigurable to support the experiments. Drawing Credit: Marc M. Cohen.

The upper node in the right corner would consolidate all out-of-habitat activities within one integrated EVA Access Module. The capabilities incorporated in this node would include 1) the Rover flex tunnel, 2) the Suitport donning station that currently is installed in the EVA and Workshop module, and of course, 3) circulation between the two adjacent modules.

These four modules comprise the square: The Lunar Daytime Habitat, Lab 1, Lab 2, and the Plant Growth module. The square provides the circulation “racetrack” or loop reflected in FIGURE 9. This loop can afford through-circulation around the square in both directions. The control condition for Hypothesis 3 would consist of locking a door or “hatch” in one location between modules. This obstructed passage would effectively eliminate the “racetrack” dual access/dual egress circulation pattern. The experimental condition for Hypothesis 3 would be to leave this door or hatch unlocked to allow the full circulation to proceed during the test of the alternate hypothesis.

In the experiment for Hypothesis 3, the MDRS Core Habitat module (which appears in FIGURE 1) and the EVA/Workshop module would be closed off, as they do not fit into that experiment protocol. However, certain other Lunar Daytime hypotheses and their experiments may include those two modules in the protocol.

4. Hypothesis 4 Visual Order

A habitat with physical order and visually clean appearance will increase performance and, work output and positive effects in crew function, mood, performance, and productivity. FIGURE 11 shows the “normal view” of the physical disorder in the U.S. Destiny Lab module, where an astronaut is working among the tangle of cables and tubing. FIGURE 12 shows a view of a concept for an uncluttered new module for the Lunar Gateway Station. We hypothesize that there is a habitable distinction between visual complexity and visual clutter, and we intend to investigate it.

FIGURE 11. ISS: US "Destiny" Lab on Hawaiian Shirt Day. The shirt is the most orderly and visually readable item. NASA Photo.

FIGURE 12. Lockheed Martin “NextStep” Cislunar Habitat Mockup for Lunar Gateway. Photo Credit: Lockheed Martin.

D. Expected Results

This series of experiments will set a new gold standard for space analog habitat research. It will also begin a ***new paradigm*** of behavioral research for space habitability that moves beyond the passive observation and “expert opinions” that have dominated past surveys and quasi-experiments; it pioneers physical manipulations in the living environment that will blaze the path to more definitive and complex mission simulation research. It does this by actually manipulating critical habitability variables and assessing them with a statistical approach that has proven efficacy in environmental design research.

1. A fully operational flexible and modifiable off-Earth analog behavioral laboratory.
2. It provides a heretofore unavailable degree of physical manipulation of the living environment that will lead to more definitive and sophisticated mission simulation research and future design alternatives.

3. The empirical and theoretical framework for the habitation experiments.
4. A series of suggested experiments will demonstrate the power and flexibility of utilizing a modifiable behavioral analog laboratory.
5. It will set new standards for space analog habitat research, including reliability and validity metrics, relevant evidence for the habitat, research designs, operations, and behavioral measures.

V. Discussion

Every habitat analog simulation facility comes with its own—often unique—set of limitations. Providing a new analytical space and methodology for the Lunar Daytime experiments is thus not necessarily straight forward; the researcher may encounter some physical facility design and operational challenges to this analog-as-research lab approach. The MPRS presently is installed in a field that is separated from the main UND campus by a raised highway that shields the buildings from view. So, the ability to truly isolate the MPRS site is somewhat limited. In terms of providing physical windows to the outside, we may be constrained to limiting the view to seeing only other MPRS modules. However, it may be possible to change that scenery periodically. External views may also be augmented or substituted with digital scenes here which can also be investigated for efficacy.

On the plus side for this location, all the organizational and engineering support is readily available. Another consideration is the availability of medical support. This concern came to the fore after an incident during an isolation run at the Hi-SEAS analog habitat on Hawaii when a test subject suffered a minor injury. The HI-SEAS management had arranged for emergency medical support from a private provider, but when HI-SEAS tried to call them in this need, they did not answer. Consequently, they had to call 911 and wait for an ambulance. At UND, the University Hospital is roughly 1 km away, so that there will be very little risk of repeating the "non-response to injury" scenario experienced on HI-SEAS VI.

In order to conduct certain experiments, it will be necessary to rearrange or reconfigure some of the MPRS modules. For example, to conduct experiments for Hypothesis 3, Circulation, the LDT will rearrange the modules to form a circulation loop. The "sixth module," which will serve as a custom-reconfigurable interior would comprise part of each such configuration of modules.

An essential issue to consider concerns how to win funding for the Lunar Daytime program experiment. Historically, the engineering world has regarded the social sciences, including human factors, habitability, and psychology as afterthoughts. This attitude has begun to change in the new millennium in response to the need to the mitigate hazards and risks of all kinds, including human risks in crewed spaceflight. But much work remains in the proactive collection of information that will help architects and engineers design new off Earth systems and habitats, especially for long-duration sustainability. The hope—indeed, the purpose—of Lunar Daytime is to show that we can conduct this habitability research in a rigorous, scientifically valid and reproducible way.

VI. Conclusion

The Lunar Daytime concept presents the opportunity to move space exploration and habitation research forward to a rigorous basis that conforms with established scientific method. It will enable a giant step beyond conventional analog research that usually comes to little more than a collection of anecdotal reports. It will also free human factors research from the misuses and abuses of "expert opinion surveys" from so-called experts who usually have only the thinnest of familiarity with habitability as a research discipline and so only reinforce the "not invented here syndrome." The approach of using a customizable habitat as the behavioral laboratory means that it is possible to introduce real-world space habitat issues as independent variables and then measure their effect on crew behavior, performance, and sense of well-being.

VII. References

Allen, Christopher S. et al (2003). Guidelines and Capabilities for Designing Human Missions (NASA TM- 2003-210785). Houston, TX: Lyndon B. Johnson Space Center. https://spacecraft.ssl.umd.edu/design_lib/TM-2003-210785.pdf retrieved 2004.

Cohen, Marc M. (2009 April). Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume (SAE 2008-01-2027). In, *SAE International Journal of Aerospace* (vol. 1, no. 1, p. 107-142). Warrendale, Pennsylvania, USA: Society of Automotive Engineers. See Figure 7 (p. 10 and pages 20, 21, 32-33). http://www.astrotecture.com/Human_System_Integration_files/SAE-2008-01-2027%20%282%29.pdf

Cohen, Marc M. (2012 September). Mockups 101: Code and Standard Research for Space Habitat Analogues (AIAA 2012-5153). AIAA Space 2012 Conference & Exposition, Pasadena, California, USA, 11-13 September 2012. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics. http://spacearchitect.org/pubs/AIAA-2012-5153.pdf

Cohen, Marc M. (2015 August). First Mars Habitat Architecture (AIAA 2015-4517). AIAA Space 2015 Conference & Exposition, Pasadena, California, USA, 31 August - 2 September 2015. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics. http://spacearchitect.org/pubs/AIAA-2015-4517.pdf.

Cohen, Marc M. (2015 August). First Mars Habitat Architecture (AIAA 2015-4517). AIAA Space 2015 Conference & Exposition, Pasadena, California, USA, 31 August - 2 September 2015. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics. http://spacearchitect.org/pubs/AIAA-2015-4517.pdf

Cohen, Marc. M. (2016 June). Mockups 101: Technology Readiness Levels for Mockups and Simulators. In S. Häuplik-Meusburger, O. Bannova, *Space Architecture Education for Engineers and Architects: Designing and Planning Beyond Earth* (Section 3.5, p. 70-92). New York, New York, USA: Springer.

Kanas, Nicholas (1985, AUG). Psychosocial Factors Affecting Simulated and Actual Space Missions, *Aviation, Space, and Environmental Medicine* 56, no. 8. pp. 806–811.

Kass, J.; Kass, R.; Samaltedinov, I. (1995). Psychological Problems of Man in Space: Problems and Solutions, *Acta Astronautica* 36, pp. 657-660.

Kuhn, Thomas S. (1970, 2nd Edition). The Structure of Scientific Revolutions. Chicago, IL: University of Chicago Press. https://projektintegracija.pravo.hr/_download/repository/Kuhn_Structure_of_Scientific_Revolutions.pdf

Mohanty, Susmita; Fairburn, Susan M.; Imhof, Barbara; Ransom, Stephen; Vogler, Andreas (2009). Human-Space-Mission Simulators. In A. S. Howe, B. Sherwood (Eds.), *Out of This World: The New Field of Space Architecture* (Chapter 25, p. 333-354). Reston, Virginia, USA: American Institute of Aeronautics and Astronautics

Mohanty, Susmita; Fairburn, Susan M.; Imhof, Barbara; Ransom, Stephen; Vogler, Andreas (2008 June). Survey of Past, Present and Planned Human Space Mission Simulators (SAE 2008-01-2020). 38th International Conference on Environmental Systems (ICES), San Francisco, California, USA, 30 June - 2 July 2008. Warrendale, Pennsylvania, USA: Society of Automotive Engineers, . https://www.sae.org/publications/technical-papers/content/2008-01-2020/, retrieved 08 MAR 2020.

Mohanty, Susmita; Fairburn, Susan M.; Imhof, Barbara; Ransom, Stephen; Vogler, Andreas (2009). Human-Space-Mission Simulators. In A. S. Howe, B. Sherwood (Eds.), *Out of This World: The New Field of Space Architecture* (Chapter 25, p. 333-354). Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

NASA (1995). Man-System Integration Standards (NASA STD-3000/REV B). Vols. I & II. Houston, TX: Lyndon B. Johnson Space Center. https://msis.jsc.nasa.gov/, retrieved 06 JUN 2010

NASA (2010, NOV). Constellation Program Human System Integration Requirements, (NASA CxP-70024E). Houston TX: Lyndon B. Johnson Space Center. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120014522.pdf, retrieved 15 DEC 2011.

NASA (2011, JAN). NASA Space Flight Human-System Standard, Vol 2: Human Factors, Habitability, and Environmental Health (NASA-STD-3001A-1). Houston, TX: National Aeronautics and Space Administration. https://www.nasa.gov/hhp/standards, retrieved 21 FEB 2018.

NASA (2014, JUNE). Human Integration Design Handbook (HIDH) (NASA SP-2010-3407/REV 1), Washington DC: National Aeronautics and Space Administration. https://www.nasa.gov/sites/default/files/atoms/files/human_integration_design_handbook_revision_1.pdf, retrieved 21 FEB 2018.

NASA (2015, FEB). NASA Space Flight Human-System Standard, Vol 1, Rev. A: Crew Health (NASA-STD-3001A-1). Houston, TX: National Aeronautics and Space Administration. https://www.nasa.gov/hhp/standards, retrieved 21 FEB 2018.

NASA (2015, MAR). Human Research Program Requirements Document: Human Research Program Revision G (NASA-HRP-47052G). Houston TX: Lyndon B. Johnson Space Center. https://www.nasa.gov/sites/default/files/atoms/files/human_research_program_requirements_document_rev_g.pdf, retrieved 21 FEB 2018.

NASA (2018, JUL) Human Research Roadmap: BMed-7 Gap Analysis. Houston, TX: Lyndon B. Johnson Space Center https://humanresearchroadmap.nasa.gov/gaps/gap.aspx?i=402, retrieved 21 FEB 2018.

NASA (2018, JUL) Human Research Roadmap: HAB-03 Gap Analysis. Houston, TX: Lyndon B. Johnson Space Center. https://humanresearchroadmap.nasa.gov/Gaps/gap.aspx?i=603, retrieved 21 FEB 2018.

Schlacht, Irene Lia; Foing, Bernard; Bannova, Olga; Blok, Frans; Mangeot, Alexandre; Nebergall, Kent; Ono, Ayako; Schubert, Daniel; Kolodziejczyk, Agata Maria (2016 July). Space Analog Survey: Review of Existing and New Proposal of Space Habitats with Earth Applications (ICES-2016-367). 46th International Conference on Environmental Systems (ICES), 10-14 July 2016. Vienna, Austria, Lubbock Texas, USA: Texas Tech University. ICES2016_367_Space-Analog-Survey *(copy and paste into browser).*

Sipes, W. E.; Vander Ark, S. T. (2005, JUNE). Operational Behavioral Health and Performance Resources for International Space Station Crews and Families, *Aviation, Space, and Environmental Medicine* 76, no. 6, sec. II, pp. B36–B41.

Stuster, Jack (1996). Bold Endeavors: Lessons from Polar and Space Exploration. Annapolis, MD: Naval Institute Press. https://www.anacapasciences.com/staff/jstuster/index.html.

Stuster, Jack W. (1986 September) Space Station Habitability Recommendations Based on a Systematic Comparative Analysis of Analogous Conditions (NASA CR-3943). Washington, DC, USA: National Aeronautics and Space Administration. http://spacearchitect.org/pubs/NASA-CR-3943.pdf, retrieved Feb 22, 2020.

Stuster, Jack W. (1986 September). Space Station Habitability Recommendations Based on a Systematic Comparative Analysis of Analogous Conditions (NASA CR-3943). Washington, DC, USA: National Aeronautics and Space Administration. http://spacearchitect.org/pubs/NASA-CR-3943.pdf, retrieved Feb 22, 2020.

Vakoch, Douglas A., Ed. (2011). Psychology of Space Exploration: Contemporary Research in Historical Perspective, (NASA SP-2011-4411). Washington DC: National Aeronautics and Space Administration. https://history.nasa.gov/SP-4411.pdf, retrieved 01 SEP 2019.

Wise, James (1988 August). The Quantitative Modelling of Human Spatial Habitability (NASA CR-177501). Washington, DC, USA: National Aeronautics and Space Administration. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19890006159.pdf, retrieved 30 JUNE 2020.