

Integrated Planetary Outpost Simulation to Assess Crew Psychophysiological Response as a First Approach to a Lunar/Mars Manned Base Settlement

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Abstract One of the most effective and complex concepts in planetary settlement is the integration of interfaces such as habitat modules, rover vehicles and space suits that can connect via airlocks, suitports and tunnels, and can disconnect to operate independently. This scenario is ideal to assess common symptoms during spaceflight missions such as fatigue, sleep loss, circadian desynchronization and work overload. This paper describes the main features of an integrated system built at the Human Spaceflight Laboratory from the Department of Space Studies at the University of North Dakota and a series of feasible measurements that can be conducted there to assess psychophysiological responses of a crew during confinement. This approach may contribute in the analysis of environmental mission conditions that interfere with sleep quality and individual vulnerabilities associated to sleep loss and circadian desynchronization.

Keywords: *space medicine, planetary outpost, circadian rhythm, sleep, confinement*

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1. Introduction

Planetary spaceflight missions will require the development of innovative capabilities including the design of new systems and processes according to mission objectives. In the case of Lunar/Mars base settlements many habitation approaches are being studied by means of terrestrial analogs around the world [1]. One of the most effective and complex concepts in planetary settlement is the integration of several interfaces such as habitat modules, rover vehicles and space suits that attach to each other through airlocks, suitports and tunnels and detach to operate independently. This concept offers advantages such as avoiding external dust/particles contamination of the living areas. The NASA-funded study, entitled “Integrated Strategies for the Human Exploration of the Moon and Mars,” is directed at advanced inflatable architectural concepts and its use for space analogs. The project is aimed at concurrently studying the habitat as well as other pressurized elements, including airlocks, pressurized connectors, pressurized rovers, and space suits,

all of which shall be tightly integrated to simulate long-term planetary missions.

This integrated planetary outpost makes up an ideal platform to assess the crew psychophysiological response as previously reported in other space analogues [2,3]. In addition, the specific design characteristics of this simulation outpost allow the operation in deserts, low temperature regions or high altitude sites. Thus, it offers the unusual possibility of studying human factors and mission operations with a design that allows the location of a semi-realistic space habitat in a real extreme environment. Fatigue resulting from sleep loss, circadian desynchronization, extended wakefulness and work overload are common during spaceflight missions [4]. During long-term missions on the Martian or Lunar planetary surface, the effect of prolonged confinement and isolation will be two major risk factors to which the crew will be exposed. These factors are associated with alterations in the circadian rhythm of the crew. Ground experience indicates that this may lead to performance errors, which could potentially compromise the entire mission. Thus, this paper describes the main characteristics of the UND Lunar Mars Integrated System

and a series of feasible measurements that can be conducted to assess psychophysiological responses of a crew during confinement. This approach can be used to analyze environmental and mission conditions that interfere with sleep quality and individual vulnerabilities associated to sleep loss and circadian desynchronization.

2. Basic Description of the Integrated Subsystems

2.1. The Inflatable Habitat (IH)

2.1.1. Structure

The IH consists of an inflatable structure that is stiffened and constrained by an internal rigid frame that is 13 m long, 3 m wide and 3 m high (Figure 1). This arrangement allows both tensile and compressive loads to be transferred from the soft fabric to the rigid frame, avoiding punctures and/or penetrations. The inflatable material is malleable and retains strength during folding. It is also lightweight and is stowed in a significantly smaller volume. The expandable soft goods structure such as the IH, offers a lower mass solution with increased volume compared to the ones based on metal or rigid composite materials.

The rigid structure portion of the habitat was designed in a common square-pyramid type space truss which has proved to meet the structural loading, low mass, and ease of erection requirements. The frame provides support for mounting interior architectural elements, such as floor and wall panels, life support equipment, and storage for food and scientific equipment. The IH was built for a crew of 4 occupants; it contains four sleeping compartments, one bathroom, one kitchen, one galley/dining room and one laboratory that can also be used as recreational area.

The required volume of the IH is a function of the crew size, layout efficiency, mission duration and objectives. It was determined according to the maximum usable volume and floor area for the associated structural mass [5].



Figure 1. Inflatable Habitat

2.1.2. Galley and Dining Area

The galley features a kitchen with cabinetry, counter space for food preparation, and sink. Directly across the food preparation area there is a fridge with a small freezer

space and a collapsible dining table to be used to dine, for meetings or recreational purposes. During the simulations, crew members are able to prepare and cook their meals based on frozen, canned, dehydrated ingredients, as well as fresh products. The kitchen subsystems include a microwave, a freezer and other basic electrical appliances. The galley, as well as the kitchen, is 2 m long, 1 m wide and 2m high.

2.1.3. Laboratory

The IH laboratory shall be used to conduct experiments similar to the ones that could be done on the Moon or Mars. Some of the research areas that apply are geophysics and geology, as well as closed-loop technologies such as physicochemical or biological processes.

The laboratory is 3.6 m long, 2.8 m wide and 2m high. It features two foldable tables, a large monitor for teleconferences & video, and a future greenhouse. The greenhouse, 0.7m long 0.5m wide, 1m high, shall be located adjacent to the bathroom in order to take advantage of the steam coming from the use of the shower and the water supply system.

Room is provided in the laboratory for special equipment such as microscopes for geological or mineralogical sample research, tools and such. While not conducting experiments, the laboratory can also be used for recreational purposes such as physical or recreational activities.

2.1.4. Sleeping Quarters

There are four private sleeping quarters in the IH with bed frames constructed by the team. The researchers on board can rest and are provided with ample room for stowing personal belongings. Each private quarter is approximately 2 m long, 1 m wide and 2 m high

2.1.5. Bathroom Area

The bathroom contains a shower adjusted to fit into the bathroom space, a small sink for hygiene and a standard toilet seat. A special pump was required to accommodate the different pressures produced when the toilet is flushed or water is used since the habitat is inflated while crew members live and work inside. Standard sized bathroom elements were selected since the analog seeks to imitate planetary surface subjected to partial gravity. The bathroom is 1.5 m long, 2 m wide and 2 m high.

2.2. The Electrical Rover (ER)

The ER is designed for a crew of two subjects and up to four members on emergency mode. It features a complete package of radio communication equipment, a rear-view back up camera, a 360° viewing cupola at a high vantage point, and illumination for traveling at night or during cloud cover and a sample return collection container to store up to 8 kg of rocks and soils from the external environment (Figure 2).

The structure of the vehicle was built by UND students with the cooperation of Cirrus Co. in Grand Forks, ND. The ER basic structure consists of a re-shaped commercially available electric vehicle, enclosed with a composite shell of fiberglass and epoxy resin [6]. The ER has been outfitted with tires designed for traversing

rugged terrain, which the crew may need to go through to get to geologically significant areas for rock and soil sample collection.



Figure 2. Electrical Rover

The vehicle is equipped with communication systems and experimental hardware to store soil samples for transportation back to the habitat by means of a sample return collection container.

2.3. The North Dakota Experimental 2 Analog Testing planetary suits (NDX-2AT)



Figure 3. NDX-2 ATs. North Dakota Experimental 2 Analog Testing Planetary Suits attached to the Electrical Rover.

The NDX-2 ATs are two space suit models based on the design of the original NDX-2 lunar prototype, built at the Laboratory of Space Suit at UND as well. The two-piece suits were built for planetary operations on the Martian surface. Based on the lessons learned while constructing and testing the NDX-1 suit, the Space Suit Laboratory then built the NDX-2 prototype which is a

one-piece rear-entry suit designed for planetary surface operations [7]. The NDX-2ATs are connected to the rear of the ER via the suit ports (Figure 3). The NDX-2 and NDX-2ATs were designed taking into account some requirements from lunar scenarios such as mobility as dust mitigation inside joints and mechanisms [8].

2.4. Additional Subsystems: ER Suit Ports, IH Tunnel from the IH to the ER

2.4.1. ER Suit Ports

The back of the ER is equipped with two suit ports that allow the NDX-2AT suits to be attached to the rover for use by the crews to conduct EVA (Figure 3). The suit ports are the interfaces that help this research project prove the feasibility of keeping space suits on the outside of the habitat, thus avoiding contamination by regolith/dust on a similar way than the NASA's Small Pressurized Rover Concept.

2.4.2. IH Airlock

On one end of the habitat is the airlock through which crew members will ingress and egress to conduct Extra Vehicular Activity (EVA) operations on foot. Traditionally, airlocks are used as a staging area allowing crew members to enter and exit the habitat without having to expose the internal environment to the external one.

The IH airlock consists of a free-standing structure that interfaces with the habitat through a small passageway. The tunnel will be thermally insulated via a heavy fabric segment that will wrap around and secure on the underside of the tunnel. The airlock structure will be complete with walls, insulation, and weather proofing material [9].

2.4.3. Tunnel Connecting the IH and the ER

The hatch and the tunnel that interfaces between the habitat and the rover are located on the opposite end of the habitat, in the laboratory section. Due to the difference in height of the habitat and the rover, the rigid portion of the tunnel will include a section which descends at a slight gradient to allow crews to easily move between the habitat and rover. The end portion of the tunnel is a moveable piece controlled from inside the habitat. When the rover returns to the habitat after completing an EVA excursion, the rover operator aligns the vehicle's hatch with the tunnel, while a crew member in the habitat controls that the end of the tunnel extends and docks along with the rover, providing a steady seal.

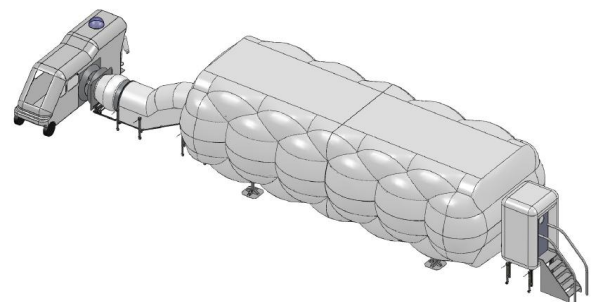


Figure 4. Additional subsystems. On one end of the habitat is the airlock through which crew members will ingress and egress to conduct Extra Vehicular Activity operations on foot. The hatch and the tunnel that

interfaces between the habitat and the rover are located on the opposite end of the habitat.

3. First 10-day Planetary Mission Simulation

During the first week of November, 2013 three UND graduate students tested the integrated analog base elements for the first time on a 10-day mission (Figure 4). The objective of this first experience was to test the performance of the IH connected to the tunnel, the airlock interface between the NDX-2 ATs and the ER and some EVA operations with the prototypes. The crew was able to adapt to their new environment rapidly. They were able to sleep between 6-8 hours a day and take 3 meals a day. The three subjects were enthusiastic, active and well-focused. Environmental, communication and operation systems functioned efficiently. Due to weather conditions (high winds, 50 mph and freezing temperatures), there was only one minor unpredicted event during one night, that led to the partial depressurization of the IH, as the air intake was obstructed by leaves and other environmental debris.



Figure 5. UND graduate students testing the integrated analog base systems. NDX-2 ATs, Electrical Rover and Inflatable Habitat can be seen from front to back.

4. Sleep and Circadian Rhythm Assessment in Space and Terrestrial Analogues

In this section, a series of measurements that can be used to assess the psychophysiological response to sleep loss of a crew in an integrated planetary outpost of this kind will be described. These measurements were previously used in space and space analogues, as it emerges from a non-exhaustive revision of literature and our own experience in Mars500.

5. Sleep and Circadian Rhythm Assessment

An optimal state of alert during daylight and a deep sleep during night time requires an adequate synchronization of a subject's biological rhythm. Isolation, confinement, stress and low artificial light intensity may affect a subject's biological "clock" leading it to receive inadequate environmental information required for the

normal synchronization of biological rhythms. In order to perform mission tasks astronauts are also frequently exposed to sudden changes in their sleep/wake cycles. These factors can cause poor crew performance during the space mission, as well as health problems. Among the instruments that can be used to assess the impact of sleep loss we can mention questionnaires, actigraphy, temperature sensors, cortisol and melatonin determinations, heart rate variability (HRV) analysis, and psychomotor vigilance task (PVT) tests.

Soft technologies such as questionnaires are designed and validated to measure certain aspects of sleep and circadian rhythms. Excessive somnolence can be assessed by means of the "Epworth Sleepiness Scale" [10]. The questionnaire features eight questions that define a scale with a maximum of 24 points. Values greater than 10 points are usually considered pathological. One of the most common tests that assess sleep quality is the "Pittsburgh Sleep Quality Index". It consists of 18 questions defining a 21-point scale, where values greater than 4 points are considered pathological [11].

During field work sleep-wake cycle can be evaluated with actimetry by means of wrist-watch-like actimetry sensors. This accelerometer offers a non-invasive method of monitoring the subject's rest/activity cycles. The instrument has two acceleration gauges relative to the horizontal and vertical directions and they registry intensity and movement amplitude with a resolution of 0.1G. The sensor can monitor for long periods of time (10 days for the most basic ones). Sleep data is registered in a diary by the subject, and then compared with the periods when he/she really slept according to the instrument [12].

Circadian rhythm main parameters can be analyzed by means of the recording of peripheral body temperature rhythm using a non-invasive sensor attached to the wrist of the subject (i-Buttons). This sensor is used for approximately 5 days. Skin body temperature data is registered every 10 minutes by the device and then transferred to a computer where these values are analyzed (mesor, acrophase, amplitude) [13,14].

The PVT is a reaction-time test that assesses alertness. It measures the speed with which subjects respond to a visual stimulus. Research indicates increased sleep debt or sleep deficit correlates with declined psycho-motor skills, deteriorated alertness, slower problem-solving, increased rate of false responding and circadian variations in performance. This test has been proven and validated in our laboratories for its use with netbooks [15,16].

The autonomic nervous system (ANS) controls the non-voluntary processes of the subject. Sympathetic division dominates during stressful situations, while parasympathetic division prevails during rest or sleep. Sympathetic-parasympathetic interactions determine heartbeat variations that can be analyzed to assess autonomic activity. These oscillations are associated to different frequencies. High frequency (HF) oscillations are associated to the respiratory sinus arrhythmia and reflect parasympathetic modulation. Low Frequency (LF) oscillations are related to the baroreflex, and reflect sympathetic and parasympathetic stimuli [17].

Regarding hormonal biomarkers of the sleep-wake cycle, melatonin begins to rise in the evening and peaks after midnight. It is recognized as a stable marker of the circadian phase position. Cortisol starts to ascend before

waking and peaks around half an hour later. It is recognized as a biological marker of stress. Both hormones can be measured in blood, saliva or urine samples [18,19].

6. Use in Space and Terrestrial Analogues

In space, sleep-wake cycle has been evaluated by means of actigraphy along with body temperature measurements and levels of urinary cortisol. In a sample of five astronauts, a decrement in the amplitude of the body temperature rhythm and a misalignment of the circadian rhythm of urinary cortisol relative to the imposed non-24-h sleep-wake schedule was observed during short-term (up to 16 days) space missions. Sleep duration was of 6.5 hours with subjective sleep quality reduction [20]. In reference to alertness and performance assessment, a tracking task and psychomotor tests of different complexities were conducted on three crew members aboard the ISS before, during and after a 6-month stay. The tracking task showed an error rate increment while reaction times maintained constant values. These results were attributed to difficulties related to astronaut sensor-motor adaptation or stress due to the mission [21]. ANS evaluation through HRV was documented in a limited amount of studies. An increment in parasympathetic activity during control breathing tests in prolonged flights on board of the ISS (196 days) was observed [22]. This tendency has been reported by other authors as well [23,24].

The Antarctic continent is considered one of the most suitable terrestrial analogues to study bio-social issues that challenge space exploration. Some of the technologies hereby exposed were used in this continent, where sleep-wake cycle misalignment is frequent. As an example, the importance of morning bright light exposition as a mean for sleep-wake synchronization was verified by actigraphy. Additionally, improvement in cognitive performance was demonstrated through questionnaires (Corbett et al., 2012). HRV and hormonal studies demonstrated a decrement in the sympathetic activity after a 40-day mission [25]. Studies conducted in Antarctica revealed a phase delay during winter for both melatonin [26] and cortisol [27]. Also, it was reported that cortisol levels during winter and summer were comparable, but winter melatonin level was markedly higher than summer level. The values of morning melatonin were positively correlated with better sleep quality, memory and arithmetic test performance [28]. However, the impact of circadian rhythm alteration in performance has not been yet well established [3].

Mars500 project was a space analogue whose main objective was to simulate a full-length mission to Mars in order to analyze biological, psychological and social factors of the crew that could be affected by long-term confinement. To this end, six subjects were confined for a period of 520 days inside the facilities of the Institute of Biomedical Problems of Moscow. In a study that included measures of wrist actigraphy, light exposure and weekly computer-based neurobehavioral assessments, it was reported that crewmembers experienced altered sleep-wake periodicity and timing, disturbances of sleep quality and vigilance deficits, suggesting inadequate circadian entrainment [29]. In the Mars500 pilot study, we reported

that autonomic changes measured by HRV were consistent with an increase in parasympathetic activity during wake periods [30]. In the full-length 520-day mission we observed diminished amplitude of the rest-activity pattern of the autonomic nervous system parasympathetic function, with decreased parasympathetic activity during the night and increased parasympathetic activity during the day. Reduced daylight exposure and mood changes could account for this observation [2].

7. Conclusions

Future plans regarding planetary exploration shall require the combination of effective and reliable life support system design aimed to integrate specific hardware to countermeasure depressurization and dust contamination. In parallel, further psychophysiological, social and biological studies should be conducted to gain a better understanding of human performance in altered ecologies.

The described approach of a hybrid inflatable habitat structure along with complementary simulation hardware located in terrestrial extreme environments, may offer plausible mission constraints and operation scenarios similar to those that a real Moon/Mars crew would experience. Thus, it will constitute an ideal platform for the study of psychophysiological aspects of adaptation to isolation and confinement.

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Statement of competing interests

None declared.

List of abbreviations

ANS: autonomic nervous system.
 ER: electrical rover
 EVA: extra vehicular activity
 HF: high frequency
 HRV: heart rate variability
 IH: inflatable habitat.
 LF: low frequency
 NDX-2AT: North Dakota Experimental 2 Analog Testing Planetary Suits
 PVT: psychomotor vigilance task
 UND: University of North Dakota.

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