Recommended Crew Systems Capabilities for a 30 to 90 Day Four-Crew Lunar Surface Mission

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Abstract— **For any given surface mission duration, there exists a set of surface capabilities necessary to sustain a four-person crew for the length of time the crew is on the surface. Identifying these capabilities is important to mission planners and spacecraft design engineers responsible for lunar surface habitation elements, who need to know which systems and capabilities must be prioritized for the vehicles they are designing. However, simply identifying the surface capabilities does not necessarily equal a viable surface configuration. These capabilities may or may not satisfy stakeholder expectations or even permit completion of mission objectives. Lunar lander cargo mass constraints are a powerful forcing function that requires significant efforts to reduce the mass of all surface elements, including those supporting crew habitation. The required capabilities do increase as a function of mission duration, but it is a nonlinear growth. There are key points in mission duration, beyond which certain additional capabilities are needed. This forms bands of capability between each point. Within a given band, the same functional capabilities are needed, and the only scaling is that associated with daily consumables. The next higher band requires additional capabilities. This paper will focus on those capabilities needed for missions of 30-90 days. It should be noted that there are some uncertainties interpreting NASA requirements that require capabilities after a certain number of days, as typically this refers to number of days in space, not number of days on the lunar surface. Depending on transportation architecture, the number of days between Earth launch and lunar surface landing may vary, therefore impacting when certain required capabilities are implemented. However, activities to prepare humans for missions to Mars and commercial interest in lunar development may drive progressive increases in surface duration. Missions up to 30 days are expected to follow the initial 6.5-day surface missions and there may be commercial interest in extending to even greater durations. This paper will examine the potential case of a 30-90-day surface mission duration with respect to the systems necessary to support crew living and working on the lunar surface.**

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1. INTRODUCTION

Overview

Now that NASA is planning missions to the lunar surface, mission planners are working to match targeted surface element capabilities with the mass and volume constraints and system availability of lunar landers. As is often the case in human space flight, there are limits on the number of flights available and the amount of material that can be delivered on each flight. Consequently, mission planners ask what are the minimum surface capabilities required for a given crew size and mission duration?

Unfortunately, there is only limited guidance available in existing human spaceflight standards (e.g. NASA Standard 3001, Human Integration Design Handbook, etc.) There have only been six human landings on the lunar surface, the longest of which was only three days, and thus the experience base to derive detailed standards simply does not exist.

Additionally, the definition of "minimum" is difficult to determine. For instance, does a minimum capability mean that the crew does not die? is uninjured? does not develop long-term medical conditions upon return to Earth? is able to complete a predetermined set of mission objectives? experiences a difficult to quantify level of comfort or personal comfort, actualization, or other psychological state? Is what will be considered "minimum" influenced by other factors such as program budget, launch vehicle or lander mass or volume constraints, allocation of element development to specific providers?

This paper will develop a framework of recommended capabilities that mission planners can use to derive minimum surface capabilities for a 30-90-day lunar surface mission.

The paper will not spell out an exact solution but will provide assumptions and caveats that can help guide vehicle development efforts.

Mission Duration

The initial Artemis missions are expected to be up to 7-day missions with the crew living inside the lunar lander. Once additional surface assets are deployed, the crew will use the lander only as a taxi, with surface habitation occurring inside a pre-deployed asset such as a habitat or pressurized rover. At this point mission durations can increase. Missions as short as 30 days and up to 90 days generally fall within the same spectrum with respect to human performance needs and the associated crew systems capabilities the surface habitation system should provide. The deltas of different durations within this class of mission are primarily logistical supplies. Those can potentially be stored in a separate logistics module instead of in the habitat.

It is important to note that a 30-day mission is not a short duration. Missions of this duration begin what is defined by NASA as long duration. [1] The Skylab space station was designed essentially for this regime, with Skylab 2 having a 28-day mission, Skylab 3 a 60-day mission, and Skylab 4 an 84-day mission.

A single mission of this class exceeds the total surface stay time of the entire Apollo lunar program. Even the longest space shuttle missions were shorter than this mission duration and crew expeditions to the International Space Station are significantly longer in duration. In United States human spaceflight history, only the Skylab program had crew missions in the 30-90-day range.

Additionally, the surface duration is only part of the crew's space mission. The astronauts will spend several days in transit between the Moon and Earth, and possibly some additional period of time at an intermediate location such as the Gateway spacecraft in Cislunar space. Thus, a 30-day surface mission may be a 35, 45, or 60-day total space mission, or even greater.

There is a risk that missions in this duration class may underestimate the habitation capabilities needed by the crew, as this mission class is long enough to introduce mission objectives that may place significant demands upon the astronaut crew. Yet it is significantly shorter than a six-month ISS crew rotation, or the ~300-500-day Mars surface missions typical to conjunction class mission concepts that many people have erroneously used to define long duration.

Volumetric Challenges

NASA-STD-3001 requires that the spacecraft have the volume necessary to accommodate both the number of crew and mission tasks and support behavioral health, [2] but the smaller the volume, the greater potential impact to crew survival. Lunar surface 30-90-day missions are likely to utilize both mass and volume constrained habitation systems so it is important that mission goals not exceed the ability of the associated habitation system to support. Because most 30-90-day lunar mission conceptual studies are considering spacecraft far smaller than Skylab, it will be critical to ensure that the necessary crew systems can indeed be accommodated within the available volume.

Beyond those that directly cause mission failure, any deficiencies in volumetric accommodation will be increasingly annoying to the crew over time. In short duration missions, the crew may tolerate adverse conditions in ways that cannot be sustained in long duration missions. While not volume driven, the famous example of crew intolerance is the alleged "crew mutiny" of the 84-day Skylab 4 mission [3] when the crew was out of contact with mission control for approximately 90 minutes. This incident centered around crew work schedules, but numerous factors including flight experience, work schedule, hygiene, clothing, and flight crew equipment [3] were collectively adding stress to the crew leading up to the incident. For long duration missions, care must be taken to eliminate "nuisance factors" as they can have a cumulative degrading effect on the crew over time. Forcing the crew to endure adverse conditions over a protracted period can have unintended consequences.

2. GUIDING DOCUMENTS AND EXPERIENCE

Recommendations within this paper are gleaned from multiple NASA documents and habitat prototype field testing experience.

NASA-STD-3001

NASA-STD-3001 [2], [4], Space Flight Human-System Standard, is a two-volume set of National Aeronautics and Space Administration (NASA) Agency-level standards established by the Office of the Chief Health and Medical Officer, directed at minimizing health and performance risks for flight crews in human space flight programs. It is applicable to programs and projects that are required to obtain a human-rating certification

NASA/SP-2010-3407

The Human Integration Design Handbook (HIDH), NASA/SP-2010-3407 [1], provides guidance for the crew health, habitability, environment, and human factors design of all NASA human space flight programs and projects. It is a resource document for NASA-STD-3001. It is intended to help designers develop designs and operations for human interfaces in spacecraft and for requirement writers to prepare contractual program-specific human interface requirements.

EVA-EXP-0031

The Extravehicular Activity (EVA) Airlocks and Alternative Ingress/Egress Methods Document [5] is intended to record and organize trades for future exploration EVA capability that address needs for ingress/egress methods and vehicle impacts. The NASA EVA Office, EVA System Maturation Team (SMT), and the Human Exploration Office have identified exploration EVA suits as a high priority requirement to support many of the Design Reference Missions (DRMs) currently under consideration, many of which include alternative ingress/egress methods which aim to provide the capability for high frequency EVAs, or readily available EVA capability, with dust mitigation.

HRP Risks

The Human Research Program (HRP) investigates and mitigates the highest risks to human health and performance, providing essential countermeasures and technologies for human space exploration. [6] HRP maintains a list of thirty-four human spaceflight risks [6] that must be mitigated in the design and operation of human spaceflight systems.

DRATS Field Tests

Initially under NASA's Constellation Program (cancelled lunar program established in the early 2000s to further human presence on and exploration of the Moon) and later under the NASA Johnson Space Center's Advanced Exploration Systems program (no relation to the current NASA Headquarters program of the same name), habitat testing was conducted through the Desert Research and Technology Studies (DRATS).

The Constellation Program planned to send four-person crews to the Moon, initially for 7-day missions operating out of the Altair lunar lander, but leading up to a continuous lunar presence featuring 180-day missions with potentially overlapping crews operating from a lunar base at the south pole of the Moon.

Three test campaigns conducted human-in-the-loop analog tests of a prototype habitat. These tests occurred in parallel with DRATS test campaigns of the Small Pressurized Rover (SPR) / Space Exploration Vehicle (SEV), All-Terrain Hex-Legged Extra-Terrestrial Explorer (ATHLETE), and other subsystems and robotic systems being developed for future exploration missions.

2010 DRATS – Black Point Lava Flow, AZ

The habitat prototype was the Habitat Demonstration Unit (HDU), a medium fidelity spacecraft mockup. The HDU was outfitted as the Pressurized Excursion Module (PEM), a field transportable lunar habitat module that could be carried by the ATHLETE on ~30-day traverses away from a lunar base. The PEM was a laboratory module and relied on two accompanying SPRs for crew habitation.

Figure 1. PEM with Airlock and Two SPRs

For most of the 14-day test the SEV crews were away from the PEM, conducting rover excursions. During this time subject matter experts performed checkouts and evaluations on the PEM. However, on days 7 and 14, the SEV crews docked to the PEM as shown in Figure 1 for PEM operations and logistics resupply of the rovers.

2011 DRATS – Black Point Lava Flow, AZ

The Constellation program was cancelled during the buildup towards the 2011 DRATS field test. NASA was redirected to instead formulate a plan to send a human crew to a Near Earth Asteroid. Consequently, the HDU was repurposed as a Deep Space Habitat (DSH) to simulate portions of a 400-day mission to a Near Earth Asteroid. The DSH was the transit habitat to conduct the voyage while the SEV was an excursion spacecraft intended for geologic survey of the asteroid. Two four-person test crews occupied the DSH, one spending four days and three nights in the habitat and the other spending three days and two nights (the latter mission being cut short by severe weather). The DSH prototype, shown in Figure 2, consisted of a lab deck and airlock (the former PEM), habitation deck, loft, and external waste and hygiene module.

Figure 2. DSH Prototype in Arizona Desert

2012 RATS – Building 220, NASA Johnson Space Center, Houston, TX

The 2012 test dropped the "D" from DRATS, becoming simply RATS as the test occurred onsite at Johnson Space Center, shown in Figure 3. With Constellation clearly cancelled there was no justification to test rover and habitat prototypes in a lunar-like landscape. The 2012 DSH test was a 10-day test, divided into two 5-day periods. A single four-person crew lived in the habitat for this test, staying overnight Monday-Thursday nights of the first week, emerging Friday afternoon for a weekend break, and then resuming the test the following Monday morning staying overnight through Friday afternoon. The 2012 Mission Operations Test simulated two five-day excerpts of a 400-day expedition to the Near Earth Asteroid 2008 EV 5. Thirty-five subjective questionnaires examined the habitability of the DSH prototype and its suitability for living and working in the context of a long duration, deep space mission.

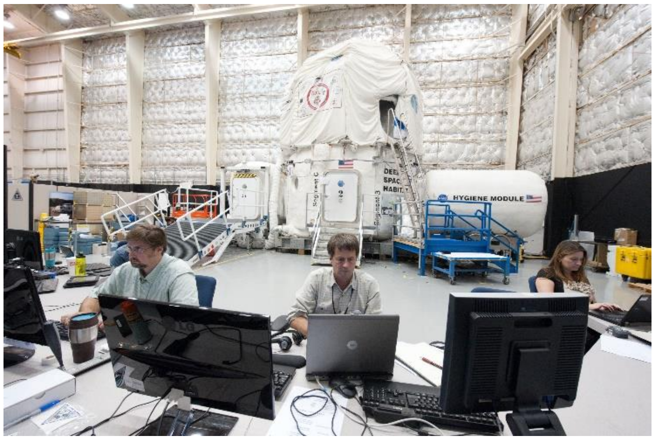

Figure 3. DSH Prototype at Johnson Space Center for 2012 Mission Operations Test

3. APPROACH TO CAPABILITIES

Discontinuity of Capabilities

NASA-STD-3000, the predecessor to the current NASA-STD-3001, featured a table (removed in NASA-STD-3001) that expressed habitable volume as a continuous function of duration. This was a convenient idea, but the reality is that capabilities (and volume) are more complex than this. One cannot add or subtract to the volume of a sleeping volume, for instance, because a day has been added or subtracted from the mission duration. For a two-hour mission no sleep volume is required at all. By comparison, for a 1000-day mission an entire private room is needed. (But a room of what size?) Capabilities cannot be reduced to a continuous function on a graph.

Ranges of Capabilities

This nonlinearity makes it desirable to address duration in the context of ranges. Given the caveat that we have little experience with human life beyond Earth, subject matter expertise suggests that habitation can be considered within certain duration bands. Clearly there is overlap between them – the needs at 60 days is presumably pretty close to the needs at 59 or 61 days, but probably nothing like the needs at 6 days or 600 days.

Duration

Many NASA standards have requirements for habitat systems based on mission duration. For instance, NASA-STD-3001 requires private habitation for missions greater than thirty days. [2] However, it is unclear if this means 30 days from Earth launch or 30 days from crew ingress to the particular spacecraft.

For instance, if the crew launches from Earth and spends 5 days in the Orion Multipurpose Crew Vehicle traveling to Gateway, 25 days at Gateway, and 5 days in Orion returning to Earth, the crew spent 35 days in space. This is a space mission greater than 30 days, but where is private habitation required? Orion certainly cannot provide private habitation and Gateway could argue that crew were only onboard for 25 days, falling below the 30-day threshold.

Vehicle and Habitat Occupancy

Even if a mission duration is clearly defined, how can capabilities be addressed if the crew is away from the spacecraft for significant portions of the mission?

Even when only the surface destination is considered, the multi-element surface architectures for the Moon and Mars create additional uncertainty. Most historic spaceflight experience can be described as either a short duration mission where the crew launches, flies, and lands in the same spacecraft, or a mission where a short duration spacecraft is used to transfer crew to/from a long-duration destination (e.g. ISS). But that is no longer the primary mission paradigm.

Consider, for instance, a surface architecture involving multiple short duration spacecraft. Such as a crew spending 5 days in a lunar lander, followed by 14 days in pressurized rovers, followed by 10 days in a surface habitat, followed by another 14 days in pressurized rovers, concluding with 10 more days in the habitat. The crew will have spent 53 days on the lunar surface – clearly not a short duration mission, but was never in any one spacecraft for greater than 14 days at a time. Which vehicle or vehicles are responsible for providing private habitation and with what capabilities?

Approach

This paper will assume that the crew lander has anytime abort capability, does not have medical evacuation capability (it is not an ambulance), but delivers a fresh, rested crew to the lunar surface and fully accommodates the crew's nominal habitation needs during both ascent and descent.

This paper will make an assumption with regard to the crew time spent in space. In order to reach the lunar surface, the crew may either employ a direct flight from Earth, as was done with Apollo, or the crew may take an indirect path that involves transfers, layovers, or secondary missions at other locations (e.g. Low Earth Orbit, a Gateway-type space station in Cislunar space, Low Lunar Orbit, etc.).

The direct route may involve a 2-4 day period in microgravity, while the indirect route may be twice as long or even longer, if additional mission activities occur along the way. This paper will assume that the crew will have spent anywhere from 2-8 days in space by the time they reach the lunar surface and will spend another 2-8 days in space returning to Earth at the end of the lunar mission. The presence or absence of a short stay at Gateway is irrelevant as long as the total in-space time falls within this range. Scenarios that involve significantly greater time in space will require specific microgravity capabilities to maintain the health and safety of the crew and may have implications for the surface habitation, but those lie outside the scope of this paper and will not be discussed.

4. CREW SYSTEMS FUNCTIONS

Crew systems can generally be divided into living functions and working functions. Crew Function refers to the habitat's accommodation of a general crew task, such as meal consumption or maintenance. [7]

Living functions can be defined as the functions that must occur as a consequence of the crew being alive, irrespective of the mission of the spacecraft. [7] Living functions considered in this paper are: private habitation, hygiene, waste collection, meal preparation, meal consumption, group socialization and recreation, exercise, medical operations, and radiation protection.

Working functions can be defined as those as that derive directly from the mission of the spacecraft. [7] Working functions considered in this paper are: scientific research, robotics/teleoperations, spacecraft monitoring and commanding, mission planning, maintenance, logistics operations, and EVA operations.

Crew functions heavily affect overall spacecraft volume and configuration because each function occupies physical space in the spacecraft and depending on the capabilities of these functions, they may or may not be able to share volume with other crew functions.

Each living or working function has associated capabilities. The capabilities of a given crew systems function describes the level of performance (capacity, features, efficiency, etc.) of that particular function. [7] For instance, one habitat might support the function of meal preparation with only a food warmer, while another might support the same function of meal preparation with a fruit and vegetable greenhouse module, multiple food warmers, rehydration stations, food processors, and convection ovens. The two habitats support the same function, but with very different capabilities

5. RECOMMENDED 30-60-DAY LUNAR SURFACE CAPABILITIES

Living Function Capabilities

Private Habitation

Sleep accommodation is required [2], regardless of mission duration. Adequate crew sleep is necessary to prevent the risk of fatigue-induced errors. Quality sleep is an important safety feature that cannot be discounted as a non-minimal capability, especially given that crew tasks at this mission duration may involve complex and mentally or physically demanding tasks, such as driving rovers and manipulating drilling or cutting tools. Private habitation may have an impact on several HRP risks, including risks 5, 10, 26, and 28 as listed in Appendix A.

Visual privacy, and perhaps to some extent auditory privacy may be achievable with very lightweight partitioning curtains or other low-mass solutions and should not be automatically overlooked in the design process.

While it is clear that astronauts will conduct more activities in their private quarters than just sleep and various activities have been recommended [7], there are no requirements in the standards to define specifically what must exist within those private quarters, only that they exist. It is believed by some that shorter long duration missions can be satisfied with extremely small private quarters (e.g. on the order of the Space Shuttle sleep stations – shown in Figure 4), though there is anecdotal speculation that the small sizes of these sleep stations are likely to trigger feelings of claustrophobia among some astronauts. (It is worth noting that while these shuttle sleep stations have flown in space, the longest shuttle mission in history was 17.67 days and is thus not even in this class of mission duration.)

The bunks shown in Figure 4 were used on STS-59, an 11-day mission. Anecdotally, some astronauts have disdainfully referred to these bunks as coffins, due to their small size. Thus, while there is no clear experimental data, there is at least this anecdotal comment to suggest that these bunks may be too small for use in a lunar habitat. Space Station Freedom initially planned for 3.2 m^3 crew quarters and ISS eventually flew 2.1 m^3 crew quarters. [8] The NASA Center for Design and Space Architecture is currently developing 2 m^3 private quarters (1m x 1m x 2m) for use in a ground test analog. Data from this test, once available, may help provide guidance for lunar surface crew quarters for 30-90-day missions.

Figure 4. STS-59 Shuttle Sleep Stations

Hygiene

The crew could be exposed to any number of substances (whether biological in nature or from the lunar environment) that require immediate cleaning in order to prevent the creation of additional hazards. The hygiene capability impacts HRP risks 7 and 10.

Privacy is also required for hygiene, which must include oral hygiene, personal grooming, and body cleansing. [2] HIDH requires [1] that hygiene facilities must be designed to accommodate partial-body or full-body cleansing before and/or after these functions:

- Urination and defecation
- Exercise
- Medical activities
- Experimentation or other work requiring specialized washing
- Meal consumption
- Accidental exposure to toxic substances
- Eye contamination

Hygiene should be a dedicated volume, not co-located with other capabilities. The Waste and Hygiene Compartment (WHC) on ISS has received negative crew comments for combining waste management and hygiene into a single compartment. In verbal conversation, one astronaut compared it to placing a shower in the same stall as a public restroom toilet. There is anecdotal evidence that some ISS crew members will conduct hygiene operations in other areas of the space station (e.g. logistics modules) that were not designed for hygiene tasks in order to avoid having to use the WHC for this purpose. While this is not captured in a NASA standard, separating the waste and hygiene functions into separate compartments may be a minimum capability in order to meet crew behavioral needs.

Waste Management

Privacy is also a requirement for body waste management at all mission durations. [2] This must include visual privacy and to the extent possible should include auditory and olfactory privacy. [1] A limitation of the Space Shuttle toilet was that the compartment included a door, but the design was such that the door could only close when the compartment was unoccupied. A privacy curtain was added, but visual gaps could allow a direct view from the compartment interior to the Shuttle flight deck. Additionally, HIDH requires that the waste management system be both psychologically and physiologically acceptable for use. [1] The risk in an undesirable system is that the crew may alter their diet in an effort to avoid or minimize system use, resulting in nutritional deficiencies. [1] The waste management enclosure must be sized for all body postures throughout the process of male or female waste activities (not just while seated). It must also be sized for servicing of the toilet and other equipment located within the enclosure. Finally, some stowage volume should be within the waste management enclosure for supplies needed during waste activities. HRP risks 7, 10, and 21 are impacted by waste management system design.

Meal Preparation

For missions beyond three days, NASA-STD-3001 requires hot water for hot food and beverage hydration and cold water for cold beverages. [2] Including hot water increases the range of hot food available, enables faster preparation of hot food and beverages, and in some cases provides more acceptable (e.g. taste) food options. Food variety is important in order to continue to meet the requirement for food acceptability. This may impact food stowage, meal preparation, and meal consumption equipment and configurations. The design of the food preparation system should allow all crew meals to be prepared together without creating bottlenecks. [9] Meal preparation impacts HRP risks 10, 21, and 27.

Meal Consumption

The HIDH indicates that the spacecraft should be sized and designed such that all crew members are able to eat meals together at the same time. [1] This crew dining area should be located in an area that is conducive to relaxation and not in a high traffic location. [1] The dining area should also be close to the meal preparation [10] but should provide enough volume to comfortably accommodate all four crew with no crew blocked in by each other or other spacecraft components. It further should be isolated from waste and hygiene areas. [1] Locating meal consumption from areas with potentially hazardous chemicals such as science, maintenance, and medical areas is also reasonable. There are behavioral health benefits if the crew can all view a movie or other video data form the dining area. [10] Design for meal consumption is directly related to HRP risks 10, 21, 26, and 27.

Group Socialization and Recreation

There are vague standards in place with respect to crew recreation. NASA-STD-3001 requires that recreational capabilities be provided, but does not state what they must be, indicating that the nature and duration of the mission may play a role. [2] HIDH indicates that recreation is especially important for long duration missions. [1] The simplistic solutions acceptable in short duration missions (such as looking out a window or enjoying the reduced gravity environment) are likely no longer sufficient [1] and recreational materials and games – both team-oriented and individual [2] – should be assessed as potential minimum capabilities. HRP risks 5, 10, and 26 are impacted by group socialization and recreation capabilities.

Exercise

NASA-STD-3001 requires countermeasures to meet crew bone, muscle, sensory-motor, and cardiovascular standards. [2] The E4D (formerly known as Tarzan or as the Potential European Device) [11] exercise device, or a lunar gravity adaptation/derivation of it can likely be used for missions of this duration. Exercise capabilities impact HRP risks 10, 16, 17, 23, and 32.

It is worth noting when making trades that some conventional wisdom may be in error when considering deconditioning effects on the lunar surface. The HIDH notes that "greater loss of leg muscle strength than arm muscle strength is expected because locomotion is performed with the upper body during spaceflight." [1] This is true for microgravity spaceflight, where virtually all prior human spaceflight experience lies. But locomotion on the Moon will involve the legs and may involve a combination of upper and lower body muscle groups. There is a possibility that exercise subject matter experts (SMEs) who have a microgravity mindset may underestimate the upper body deconditioning on the Moon, which may create a risk for crew members being unable to perform critical tasks requiring upper body strength. And given the longer duration of this mission class (as compared to 0-7 day durations), there is a greater likelihood that key mission tasks or even crew survival operations may require upper body performance. (e.g. EVA activities, incapacitated crew member scenarios, etc.)

Medical

At minimum, the medical system must have adequate volume and surface area to treat a patient and allow access for the medical care provider and medical equipment. [1] For missions above 30 days, the NASA-STD-3001 medical care requirement is Level of Care IV, which includes space motion sickness, first aid, private audio, anaphylaxis response, clinical diagnostics, ambulatory care, private video, private telemedicine, trauma care, medical imaging, sustainable advanced life support, limited surgical, and dental care. [2] The longer the surface stay, the more opportunities exist for activities – both IVA and EVA – that could result in crew injuries.

Additionally, the mission-specific objectives influence the potential range of crew injury. The injury risks of a 30-day rover field survey mission, for instance, will be different from those of a 30-day outpost assembly mission. While both missions will involve significant levels of EVA, field survey EVAs will involve more intensive walking on more irregular terrain, while outpost assembly EVAs will involve more lifting and climbing tasks.

Almost all HRP risks are impacted by medical capabilities. These risks include 1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13. 14, 15, 16, 22, 23, 24, 25, 27, 30, 31, and 33.

It can be beneficial if the medical capability employs visual privacy to isolate it from the remainder of the spacecraft. The Habitat Demonstration Unit (HDU) added privacy curtains to its Medical Operations Workstation (MOWS) prior to the 2012 test, thereby allowing telescience or telemaintenance activities to proceed without risk of inadvertent camera views of parallel activity occurring in the medical workstation. Test subjects also noted that the curtains could be a mounting location to temp stow medical items by hanging them on the curtains. [12] However, test subjects noted that the lack of auditory privacy was problematic. [12] Incorporating sound suppression into the curtains would have improved MOWS acceptability.

Finally, care should be given if this medical capability shares its volume with other spacecraft functions. An obvious concern is cross-contamination with co-located capabilities, but this is not the only design consideration. The PEM MOWS was a dedicated medical facility in 2010, but in the 2012 DSH test it shared its volume with the Life Science Workstation. Crew noted frustration with medical tasks due to the need to stow life science equipment before performing patient care. [12] Crew also commented on the need for more room [12], which appeared to be both a consequence of sharing the volume with life sciences and the geometric constraints of the DSH's PEM heritage. (A vertical passageway was added in the conversion from PEM to DSH and this passageway claimed volume that had previously been available to the MOWS.)

Radiation Protection

Radiation cannot be addressed without giving consideration to the August 4, 1972 solar particle event (SPE). [13] This event was significant because it occurred between the landing of Apollo 16 (April 24, 1972) and the launch of Apollo 17 (December 7, 1972). With the uncertainties in both launch scheduling and space weather forecasting in the 1970s, no mission planner could have planned to miss the August 4 event. It was simply luck that neither mission was in space on August 4 – or said differently, it was luck that the SPE occurred on August 4 instead of during either of the two missions.

The principle of As Low as Reasonably Achievable (ALARA) does allow mission developers to trade the use of dedicated radiation shielding in this class of mission. Some vehicle concepts have employed protection, while others have not. The NASA Constellation program contained examples of both – the Altair lunar lander did not provide radiation protection against SPEs, while the Lunar Electric Rover did. Altair assumed that it would have crew onboard for at most a 7-day sortie mission and could thus leverage space weather forecasting to target Earth launch times less likely to experience solar events. Alternately, the Lunar Electric Rover assumed its long-term use on the surface (in the context of a permanent outpost) meant eventually a solar event would occur while the vehicle was in use. It therefore incorporated shielding into its structure and thermal control system. The Orion spacecraft assumed a radiation posture that is somewhat of a compromise of the two. The Orion carries no dedicated radiation shielding, but in the event of a SPE, the crew empties out the lockers beneath the seats and takes shelter in them, relying on that displaced stowage above them and the mass of the Service Module beneath them to provide radiation protection.

There is a significant consideration here where multi-element surface architectures are concerned, particularly if the surface includes mobile elements that can travel more than a few days away from each other. NOAA currently provides a three-day space weather forecast [14] for geomagnetic activity, solar radiation activity, and radio blackout activity. When considering radiation protection in a surface architecture with mobile assets, the three-day forecast capability may influence which assets should receive sufficient protection to serve as a safe haven, such that the crew are not separated from a safe haven by a greater travel time than the forecast time.

Long duration missions generally cannot make the assumption that an SPE will not occur during the period of crew occupancy. Thus, SPE protection is a minimum capability. Vehicle designers may trade between a permanent SPE shelter or one that is constructed – such as by moving stowage items to build a temporary shelter. Radiation protection impacts HRP risks 3, 4, 10, and 16.

Practices from current and in-development spacecraft include providing shielding built into the crew quarters walls (ISS) or reconfiguration of stowage and stowage volumes into temporary radiation shelters (Orion). Other options proposed for the lunar surface include burying the habitat under regolith our surrounding it with water or propellant tanks, though both options are extremely unlikely for the early lunar missions typically associated with 30-90-day missions.

Working Function Capabilities

Lack of meaningful work is considered a psychological stressor that should be considered in long duration human spaceflight. [1] From a crew health perspective it is not a sound option to provide only living functions and engage in no meaningful work inside the habitat. Even taking EVAs into consideration, the human body cannot tolerate being in a spacesuit often enough for EVA tasks to constitute all meaningful work.

For long duration missions, meaningful work and contingency response impose significant volume drivers and can become the dominant driver for vehicle volume (as is the case for ISS). It is worth noting that four modules in the ISS US operational segment (Destiny, Centrifuge Accommodation Module, Japanese Experiment Module, and Columbus Module) are devoted entirely to scientific research. [15] Crew work may encompass scientific research, robotic teleoperations, EVA operations, spacecraft monitoring and commanding, mission planning, maintenance and repair, and logistics operations. Mission objectives, crew size and workload, maintenance/repair/abort trades, and vehicle volume are interrelated drivers that will determine the minimum capabilities for meaningful work.

Scientific Research

Preparing for, conducting, and recovering from EVAs and monitoring/maintaining the spacecraft will not consume all of the astronaut's available work hours, suggesting a need for some form of scientific intravehicular activity (IVA). Additionally, the limited human experience in 1/6 gravity will produce decades worth of scientific questions if not more, thus elevating the priority of IVA research further.

While aboard the Mir space station, US astronaut Norm Thagard had the undesirable experience of having to wait for many of his science experiments to be delivered to the station. [16] NASA psychologist Al Holland stated, "The situation of work underload is one of the worst situations you can ask a high-achieving, bright, interested astronaut to subject himself to." [16] NASA-STD-3001 indicates that with respect to cognitive workload, too little and too much load can affect crew performance. [2] The crew must be given something to do.

While this is reasonable given that the point of human spaceflight should relate to some mission objectives that require a crew presence, standards do not currently exist that would help estimate the number and type of scientific work stations or work areas for a given crew size, mission duration, or mission objective. But it is clear that the productivity among space crews is directly tied to crew morale, cohesion, sense of efficacy, work structures, schedules, and reward practices. [2] Consequently, an IVA science capability should be sized to properly engage the crew. Scientific research has direct and indirect tie-ins to HRP risks 5, 10, 19, 20, 28, and 29.

Robotics/Teleoperations

Remote operations – whether a robot arm, science rover, remotely commanded crew rover, or other vehicle – is a likely activity for a 30+ day lunar surface outpost.

Maintaining optimal workload levels for similarly complex tasks is a known challenge in human spaceflight [2] and a key cause of inadequate workload related to crew systems capabilities is poor equipment design, including inappropriate or incompatible control-display relations. [2] Both underload and overload are significant problems that can lead to mission-threatening errors. Relevant HRP risks include 10, 18, 19, 20, 28, and 29.

In general, workstation designs are difficult to plug into a parametric sizing tool, making it challenging to size this capability in early trade studies. A workstation to support robotic/teleoperations activity is especially challenging because the necessary display real estate may depend on specifics of the robotic system(s) and teleoperations tasks that may not be known at the time of habitat design. NASA-STD-3001 recommends combinations of human-in-the-loop simulations, task analyses, and timeline analyses to measure workload, which can help size the necessary workspace.

Spacecraft Monitoring and Commanding

NASA-STD-3001 requires that the design provide sufficient situational awareness for efficient and effective task performance for all levels of crew capability and all levels of task demands. [2] The arrangement of displays and controls within the internal architecture must also result in a workload that does not overload or underload the crew. [2]

At this mission duration, it is increasingly likely that there may be multiple habitable spacecraft (at minimum an ascent vehicle and a habitat, along with waiting orbital assets – e.g. Orion and potentially Gateway) and an increased spectrum of vehicle capabilities and crew activities. With a potential increase in the number, interactions, and complexity of surface assets as mission duration increases, the amount of data and information posed to the crew may likely increase, which will impact the ultimate design solution.

Psychological drivers may also impact spacecraft monitoring and commanding capabilities. It is well known that one of the psychological stressors of human spaceflight is a sense of isolation. This will likely be increased in long duration missions on the lunar surface. This will make the need for situational awareness and control (of the habitat and associated orbital and surface assets) become not just a mission performance and safety issue, but also a behavioral health issue. The crew will need to know that they have all needed insight into the state of their exploration outpost and the level of control to initiate any intervention necessary to operate and maintain their system. This will imply multiple means of conveying information, both as high-level summaries and as deep dives into specific subsystems or components. This may also imply just-in-time training capabilities to expand crew member skill sets on an as-needed basis. HRP risks impacted by spacecraft monitoring and commanding include 10, 16, 18, 19, 20, 28, and 29.

Mission Planning

Even with real-time Mission Control support, the crew needs some level of independent mission planning capability. [3] The crew will need operator volume and input/display access to make any needed real-time modification of onboard procedures. [2] The crew will also need display real estate to obtain information management data. [2] Related HRP risks are 10, 18, 19, 20, 26, 28, and 29.

Maintenance

Onboard maintenance capabilities are necessary to ensure survivability. Survivability refers to the fact that the vehicle and crew should be expected to continue to function throughout the mission. This may be addressed in ways that do or do not utilize crew intervention. Appropriate risk trades should drive the inclusion or exclusion of redundancy, reliability, maintainability, and reparability of vehicle components. Any components that are to be accessed by the crew – whether nominally or otherwise, whether designed for maintenance or not – must have sufficient access volume for the crew to perform the necessary tasks and any needed tools, spares, personal protective equipment, and other items must be manifested and stowed onboard.

NASA-STD-3001 includes requirements for physical, electrical, fluid and gas hazard minimization, durability, assembly and disassembly, cable management, design for maintainability, and protective/emergency equipment. [2] A 30+ day surface mission implies potentially available time for crew intervention to recover vehicle functionality. Further, the longer duration implies increased complexity of habitat subsystems and also means that surface elements will experience greater use and thus be more likely to experience failures due to wear and tear. Consequently, an increased repair capability is likely to be a minimum capability. HRP risks related to or impacted by maintenance include 6, 10, 16, 17, 18, 19, 20, 22, 23, 28, and 29.

NASA Desert RATS field tests explored increased maintenance capabilities to support surface infrastructure including maintenance of habitat systems, spacesuits, EVA equipment, and pressurized rovers. [17], [10] Insufficient volume can substantially increase the time requi red to complete maintenance task, particularly if the crew member has to maneuver around equipment or deployed surfaces. [18] Also, work surfaces must be sized appropriately to the entire range of potential maintenance tasks. [18]

Logistics Operations

Logistics operations essentially encompass the stowage and transportation of material within the spacecraft. Stowage systems may be either integral components of work stations and crew stations or separate areas apart from normally occupied areas. [1] Most spacecraft should be expected to have combinations of both. The HIDH also indicates that insufficient or inefficient stowage systems will negatively impact crew operations and efficiency, promote stress and irritation, and may even pose a danger in emergency situations. [1] Stowage "keep out" zones must be enforced around critical equipment and controls, [1] which means that the sum total of stowage requirements must be less than or equal to the designed stowage capabilities – in other words, the volume allocated to stowage must be greater than the volume of items to stow, or there will be overflow into aisles, work spaces, and living areas. This must remain true even in the face of spacecraft/mission expansion or changes in stowage performance. Generally, the crew should not have to move stowed cargo in order to use any work station or crew station. Trash is often grouped as part of the stowage system, which may include food system wet and dry trash, waste management system human waste, completed science payloads, failed or otherwise unneeded hardware, stowage packaging, particulates or other generated/shedded debris, and material from the external environment unintentionally brought into the cabin. [1] Most things brought into the cabin (e.g. food, logistics, packaging) at some point become trash. The stowage system must be able to isolate and accommodate this trash from the time of its generation until its removal from the spacecraft, including mitigation against contamination and odor. [1] HRP risks related to logistics include 10, 20, 21, and 22.

EVA Operations

EVA operations will require spacecraft volume for suit donning/doffing, EVA stowage (inclusive of suits and suit components, EVA-related tools), suit maintenance, and for any equipment transferred between the spacecraft interior and exterior. [5] In that vein, NASA-STD-3001 specifically requires that accommodation be made for efficient and effective donning and doffing of spacesuits for both nominal and contingency operations. [2] Insufficient volume can lead to a loss of crew scenario, as was demonstrated in a 1966 Honeywell mockup evaluation of a 1.86 m^3 pressurized lunar rover airlock involving two suited, pressurized test subjects. The scenario involved was an incapacitated crew member scenario where crew member "A" rescues crew member "B." In the test, crew member A partially succeeded in pulling crew member B into the airlock (B's legs were still sticking out, projecting from the airlock to the outside – simulated lunar environment). Crew member A then tried to step over B to improve his position, but instead fell, pinning him against the wall where his PLSS wedged. This rendered A immobilized (while B was incapacitated) and A had to depressurize his suit in order to get up – an act that would have been fatal on the Moon. [19]

Post-EVA, the spacecraft will need to enable removal of waste from the spacesuit, which may include urine, feces, menses, and vomitus [2] and recharge consumables, including resources for hydration [2] and potentially medication [2] and/or nutrition. [1] Additionally, HIDH indicates that IVA crew members may need to be able to see biomedical telemetry during EVA. [1]. HRP risks related to EVA operations include 10, 14, 20, 23, 28, 29, 31, and 32.

6. ARCHITECTURAL CONSIDERATIONS

Architecture encompasses the development and integration of overall size and configuration, location and orientation aids, traffic flow and translation paths, hatches and doors, windows, and lighting. [1] The previously recommended capabilities must be integrated into what will undoubtedly be a smaller than desired pressurized volume. This volume is not acceptable unless it can provide the operational envelopes and interior configuration necessary for the crew to perform all mission tasks while also supporting human performance and behavioral health. [2] Consequently, the architectural layout must give special consideration to the human experience.

Arrangement of functions is driven by use of common equipment, interferences, and the sequence and compatibility of operations. [2] Key considerations include separation of public from private spaces, work areas from off-duty areas, noisy areas from quiet areas, clean areas from dirty areas, and functional arrangement. Translation paths and hatches must consider not only individual crew members, but crew motion as a group, crew members carrying or otherwise manipulating other items, traffic flow, etc. [2], [1] Restraints and mobility aids must enable the crew to properly perform tasks. [2] Windows and lighting must be provided in the habitat [2] and the design of all interior components must promote standardization while minimizing hazards. [2] And while implementing all of the above, the spacecraft must address psychological stressors. [1]

The layout must avoid trip hazards and other sources of congestion that could cause astronauts to lose their balance at critical moments (e.g. while working with hazardous tools), become trapped, or otherwise fall into positions that could cause harm to themselves or the vehicle.

The HIDH provides representative operator volumes [1] that can be used to help estimate workstation, crew station, and translation volumes. However, these volumes are based on a zero-gravity environment and must be adapted for lunar gravity. Examples of historic techniques used to estimate required volumes are also provided in the HIDH. [1]

Additionally, as the design matures, there may be changes in the level of capability accepted by the program. Modifications in selection and placement of components, ways of utilizing them, operator volumes, and translation spaces may have ripple effects on the layout, creating different design solutions.

7. CONCLUSIONS

In many cases there are no explicit standards that can be relied upon to deterministically predict a spacecraft volume. Additionally, the standards that do exist are not necessarily the key driving capabilities with respect to mass, volume, cost, or timetable.

There are also significant risks in the popular philosophy of designing for “minimum” capability. Unexpected interactions between multiple elements and crew may create instances where a capability that was presumed to be minimum is actually insufficient.

Obviously, there is a cost for any given capability – in mass, volume, dollars, and timetable. The sobering reality is that if a capability is critically needed and the resources are not available to provide it, program cancellation can occur…and has occurred repeatedly since the Apollo program.

A program will have to set requirements and engineers will have to identify design solutions based on the risks and associated considerations and opportunities. As previously mentioned, the NASA Human Research Program has identified 34 risks [6] listed in Appendix A that they consider to be the highest risks to astronaut health and performance. Any given capability that is being traded as “minimum” or not should be assessed in light of its potential contribution or impact to one or more of these risks.

Care must be taken to ensure that the absence of a requirement does not immediately trigger a default to the zero capability solution (perceived minimum mass, minimum power, minimum volume, etc.). The absence of a requirement may reflect the lack of human experience with operations beyond low Earth orbit more so than an indication of a lack of need for any given capability.

It is a delicate balancing act to consider stakeholder expectations and return on investment, subject matter expertise, test data (where available), known risks, and constraints. Arguably, the minimum surface capabilities are those which are satisfactory in light of each of these domains.

In general, any selection of capabilities should be tested in human-in-the-loop evaluations. The higher the fidelity of the test the greater confidence can be held in the results. Virtual Reality testing can be used to narrow down a trade space of competing architectures. However, this will never eliminate the need to proceed to medium to high fidelity mission simulations. The interrelations between crew and architecture become most realistic when the crew is fully embedded in a functional representation of the system with an appropriate spectrum of both nominal and contingency crew tasks. Data from such tests will provide an assessment of the adequacy or limitations of the capabilities in the system under development.

The capabilities in this paper are focused on missions of approximately 30 to 90 days. Additional capabilities are important for significantly longer missions (e.g. 120 days, 500 days, etc.) and fewer for significantly shorter missions, but those are beyond the scope of this research.

APPENDICES

A. HUMAN RESEARCH PROGRAM RISKS

1. Concern of Clinically Relevant Unpredicted Effects of Medication
2. Concern of Intervertebral Disc Damage upon and immediately after re-exposure to Gravity
3. Risk of Acute (In-flight) and Late Central Nervous System Effects from Radiation Exposure
4. Risk of Acute Radiation Syndromes Due to Solar Particle Events (SPEs)
5. Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders
6. Risk of Adverse Health & Performance Effects of Celestial Dust Exposure
7. Risk of Adverse Health Effects Due to Host-Microorganism Interactions
8. Risk of Adverse Health Event Due to Altered Immune Response
9. Risk of Adverse Health Outcomes & Decrements in Performance due to Inflight Medical Conditions
10. Risk of an Incompatible Vehicle/Habitat Design
11. Risk of Bone Fracture due to Spaceflight-induced Changes to Bone
12. Risk of Cardiac Rhythm Problems
13. Risk of Cardiovascular Disease and Other Degenerative Tissue Effects From Radiation Exposure and Secondary Spaceflight Stressors
14. Risk of Decompression Sickness
15. Risk Of Early Onset Osteoporosis Due To Spaceflight
16. Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Spaceflight
17. Risk of Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance

18. Risk of Inadequate Design of Human and Automation/Robotic Integration
19. Risk of Inadequate Human-Computer Interaction
20. Risk of Inadequate Mission, Process and Task Design
21. Risk of Inadequate Nutrition
22. Risk of Ineffective or Toxic Medications Due to Long Term Storage
23. Risk of Injury and Compromised Performance Due to EVA Operations
24. Risk of Injury from Dynamic Loads
25. Risk of Orthostatic Intolerance During Re-Exposure to Gravity
26. Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team
27. Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System
28. Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload
29. Risk of Performance Errors Due to Training Deficiencies
30. Risk of Radiation Carcinogenesis
31. Risk of Reduced Crew Health and Performance Due to Hypobaric Hypoxia
32. Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity
33. Risk of Renal Stone Formation
34. Risk of Spaceflight Associated Neuro-ocular Syndrome (SANS)

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