

An Analysis of Exploration Capability Gaps for Future Habitation Systems to Inform Risk Assessment and Development Priorities

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Abstract— Within NASA, exploration capability gaps are defined as the difference between the current state-of-the-art in capabilities and the anticipated needs of future human spaceflight architectures. As NASA and its partners' capabilities for human exploration of deep space continue to mature, it is necessary to understand the capability gaps that require closure to support future habitation systems, such as the Lunar Surface Habitat (SH) and Mars Transit Habitat (TH) currently in concept development. This paper will identify high-priority capability gaps for exploration habitation and show potential options for gap closure through investment in technology, development, and testing. High-priority capability gaps are divided into the following general taxonomy areas: human health/life support/habitation systems, flight computing and avionics, power and energy storage, communications and navigation, thermal management systems, human exploration destination systems, autonomous systems, sensors and instruments, GNC (guidance, navigation, and control), robotic systems, ground and uncrewed surface systems, and materials/structures/mechanical systems/manufacturing. In the gap identification process, teams of discipline experts from across NASA reviewed the latest habitation architecture needs against current capabilities to understand where gaps may exist. The results of the assessment established a basis

for the current state-of-the-art within each gap and identified the capability needs of the proposed exploration missions the gap links to. An assessment of how each test platform (e.g., Ground, International Space Station (ISS), Commercial Low Earth Orbit (LEO), Gateway) may be leveraged to mature capabilities and potentially provide a route to gap closure will be discussed. The notional timeline for gap closure to support reference missions and impacts to overall schedule are also assessed where appropriate.

Based on the capability gap analysis described above, the paper summarizes important technology maturation considerations for human exploration architectures, with a focus on the Mars TH. The previously published NASA habitation ground rules and assumptions document is used as the basis to classify gaps as enabling, enhancing, or "push" opportunities for a particular architecture. Stepwise technology maturation plans/considerations are presented for some selected critical gaps. Overall, the analysis in this paper is intended to help influence development priorities for habitation systems, where high-priority, critical gaps are those currently assessed as having a low probability of closure by the anticipated need date. Capability gap analysis also informs the risk register for exploration habitation systems and mitigation strategies to ensure readiness of key technologies to support future

mission timelines. Linkage between capability gaps for Moon and Mars is noted, as closure of a gap at a Lunar destination may subsequently enable or enhance Mars TH architectures.

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1. INTRODUCTION

NASA’s Artemis program seeks to return humans to the moon and enable sustainable exploration of the Lunar surface, with the additional goal of using the moon to develop and advance technologies to support eventual Mars exploration. Elements of the Artemis program include the Space Launch System, an exploration class launch vehicle capable of sending humans to deep space which first flew in 2022 [1]. In its initial flight, SLS sent the uncrewed Orion capsule on an approximately three-week mission around the Moon and back to Earth. A subsequent Artemis II flight will send four crew around the Moon in 2024. With Artemis III, the Human Landing System (HLS) will land the first woman and person of color on the Lunar surface. HLS can also serve as an initial habitat for crew during short duration surface stays associated with early Artemis missions.

The Lunar Gateway is also a key piece of the Artemis architecture. Gateway is a Lunar outpost where crew can live and work in cisLunar space. Gateway’s near rectilinear halo orbit (NRHO) offers access to all of the Lunar surface. Gateway also serves as a waystation for vehicles in cisLunar space, including the Orion capsule, HLS, and the proposed Mars TH. Following establishment of the Gateway and initial Artemis Lunar missions, which will demonstrate the ability to safely land crew on the surface and return them to the Lunar orbiting outpost, buildup of the Artemis base camp at the Lunar south pole will begin. Planned elements of the base camp include the Lunar Terrain Vehicle, which transports two crew around the landing zone at distances up to 20 km without recharging. The pressurized rover will expand exploration ranges on the Moon and enhance Extravehicular Activity (EVA) science operations. The base camp would also include supporting infrastructure such as advanced robotics, power systems, communications systems,

and initial in-situ resource utilization capabilities to demonstrate production of oxygen and water from local resources.

The Lunar surface habitat represents the base camp’s core capability to support human exploration initiatives. The Apollo missions ranged from 7-12 days, with landing sites in the moon’s equatorial region. The Surface Habitat (SH) will support two crew initially for thirty days (with evolvability to sixty days) and be deployed in the more challenging polar environment. While the Apollo missions only landed and conducted operations during the period of Lunar day, the surface habitat must also operate during multiple days of Lunar darkness throughout the year, when temperatures can plummet to 120K (-153C) or below in some areas. Under current assumptions, the surface habitat (Fig. 1) will provide accommodations for nominally 2 crew. 4 crew can be supported for short durations, such as during crew swap-outs between SH and a pressurized rover [2]. The primary habitable volume is an inflatable softgoods structure.

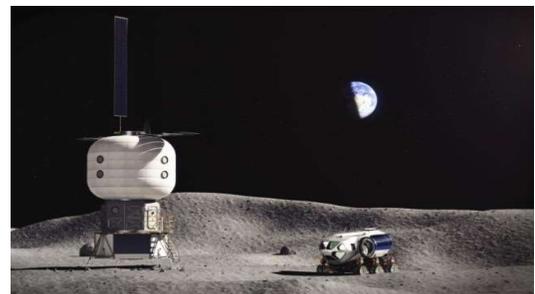


Figure 1: Concept rendering of the Lunar surface habitat.

The Lunar SH, in conjunction with the Lunar Gateway, will be used to mature systems and prepare crew for an eventual Mars mission. A key architectural element for any Mars mission scenario (and the focus of the analysis presented in this paper) is the Mars TH. Like the Lunar SH, the Mars TH consists of a metallic node and a primary habitable volume of inflatable softgoods (Fig. 2). As discussed later in the paper, this commonality in architecture enables materials and processes development for Lunar surface habitation to potentially be leveraged for a Mars TH. The TH will be designed to support up to 1,200-day Mars missions and will carry all food and supplies needed to support a crew of four for this mission duration.



Figure 2: Concept rendering of Mars TH. Image credit: NASA Langley Advanced Concepts Laboratory.

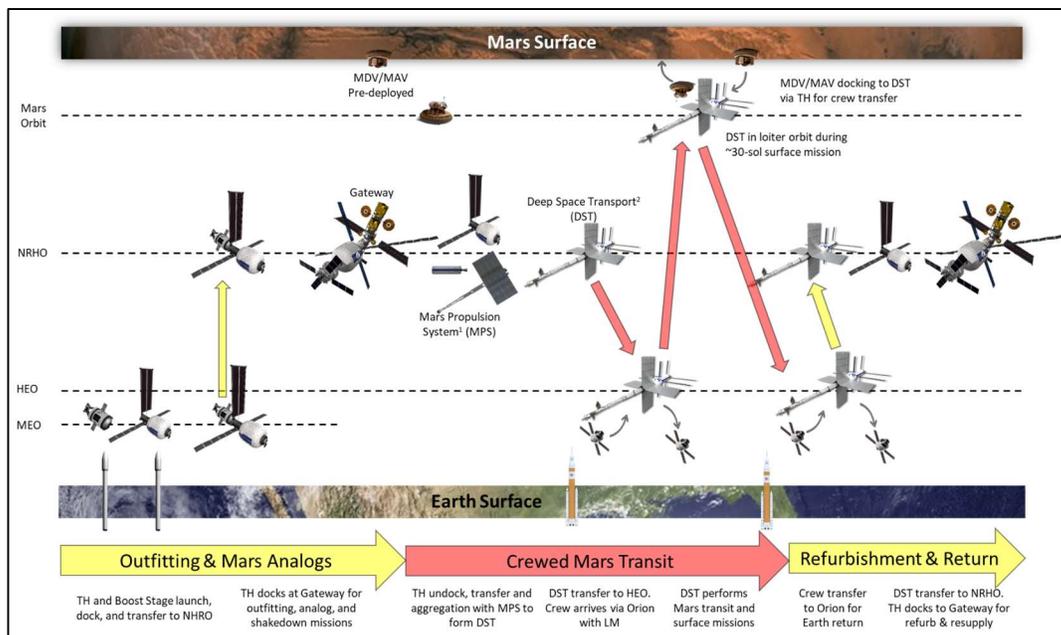
The capability gaps for a Mars TH can broadly be thought of as the gaps between our current state of the art habitation element, the International Space Station (ISS), and our future needed capabilities for longer duration Mars missions characterized by increased communication delay, no abort or resupply opportunities, and challenging combined microgravity and radiation environments. This paper first describes the planned TH missions which drive the needed habitation capabilities, then describes the process to identify and assess habitation capability gaps in Section 3. Then it provides a summary of the identified gaps in Section 4, followed by a high-level description of ways to close these gaps through technology development and testing efforts in Section 5. Finally, the role of Lunar SH to mature TH design is described.

2. CONCEPT OF OPERATIONS AND KEY CAPABILITIES FOR MARS TH

A detailed discussion of the concept of operations and ground rules and assumptions for Mars TH is helpful in understanding the technology gaps associated with it, specific risks, and the proposed technology maturation path for some areas which were identified in the subsequent gap analysis. Note that the Concept of Operations (ConOps) presented here is notional and subject to change as architectural trades and assessments continue. More detailed information on mission concepts under consideration can be found in “Reference Surface Activities for Crewed Mars Mission Systems and Utilization” [3, 4] and “NASA’s Strategic Analysis Cycle (SAC) 2021 Human Mars Architecture” [5]. The habitation ground rules and assumptions for Mars TH are identified in “Moon2Mars Habitation Considerations: A Snapshot as of January 2022” [6].

Following launch and transfer to near rectilinear

halo orbit (NRHO), the Mars TH will dock to Gateway as a visiting vehicle and conduct a series of outfitting and shakedown missions to demonstrate integrated systems and better understand reliability and sparing needs prior to departure on a Mars mission [7]. While docked at Gateway, the Mars TH can extend crewed missions for Gateway beyond 60 days. Durations for shakedown missions and the distribution of stays between Lunar surface and microgravity will be determined based on human research considerations for Mars transit and surface stays. Crew adaptation and transition between partial gravity (Lunar surface) and microgravity environments can be studied through these analog missions. During these shakedown missions, logistics for the eventual Mars missions are aggregated within the TH. Once the series of shakedown missions is complete, the TH departs uncrewed from Gateway and transits/docks with the Mars propulsion system, forming the Deep Space Transport (DST). After successful DST aggregation and transfer to the Lunar Distant High-Earth Orbit (LDHEO), a crewed Orion with a co-manifested logistics module docks via the TH radial port. Logistics and any remaining outfitting are moved into the TH; Orion and the logistics module depart. The crewed DST then transits from LDHEO to Mars orbit, where it then prepares for a 30-sol surface mission [5]. While in Mars orbit, the prepositioned Mars Descent Vehicle docks to the DST via the TH radial port. Upon return from the surface exploration mission, the crewed Mars Ascent Vehicle mates with the DST to transfer crew to the TH prior to ascent vehicle disposal. The DST then departs from Mars orbit and returns to LDHEO. The crew depart the TH via Orion and return to the Earth’s surface. The DST transits back to NRHO and the TH undocks and transits to/docks with Gateway for mission. A graphical representation of the mission which shows the order of operations in launch and aggregation appears in Figure 3. As noted in the ground rules and assumptions



¹ MPS notionally shown as Nuclear Electric Propulsion/Chemical (other options also in trade space)

² DST shown as notional Mars Propulsion System/TH configuration

Figure 2: Transit Habitat Concept of Operations with Mission Phasing [7]

(GR&A) [6], the 1,200-day mission length includes a 1,100-day nominal mission duration + 90 days for Space Launch System (SLS) crew launch timing + 10 days for rendezvous, proximity operations, and docking before and after the mission. Ultimately the selection of 1,200 days as a GR&A provides maximum flexibility in mission planning given uncertainties in trajectories and implementation timelines at this stage.

The TH is designed to have a 15-year lifetime, which includes shakedown missions and Mars transit mission(s). Planned system refurbishment needs and subsequent logistics operations are a topic for further study in development of the concept. The habitable structure for government reference Mars TH, like the Lunar SH, consists of both a metallic and inflatable softgoods compartment. The softgoods compartment in the present concept is divided into multiple levels with a central core passageway which extends through a hatch to the metallic airlock volume. Functional spaces are defined and arranged across multiple floors. Shown in Figure 4, the Mars TH layout contains private crew quarters, exercise and recreation areas, a galley, command and control center, medical systems, science utilization facilities, logistics stowage, and trash management. A trash management capability is crucial, as Mars TH must eject trash periodically along its trajectory to maintain propulsive performance with high specific impulse propulsion systems. Mars TH must also accommodate adequate crew quarters, environmental control and life support (ECLSS) systems, maintenance stations, exercise capabilities, hygiene/personal spaces, and two redundant universal waste management systems.

The government reference Mars TH also includes a metallic airlock for contingency EVAs. This volume may also operate as a safe haven in the event of an emergency in the primary habitable structure. Mars TH has two axial docking ports (1 active, 1 passive) and at least one radial port. This enables docking of TH to the Gateway and hosting of visiting vehicles including Orion, logistics modules, Mars propulsion systems, and future Mars ascent/descent vehicles as discussed in the concept of operations. The power system for Mars TH relies on solar arrays and batteries for energy generation and storage, with the ability to receive power from the Mars propulsion system in orbits beyond a certain threshold astronomical unit (AU). Thermal control components include both active (cold plates, heat exchangers, heaters) and passive (e.g., multi-layer insulation).

Together, the features of the functional layout ensure that Mars TH can provide volume for communications, thermal control, power management, environmental control and life support (ECLSS), docking interfaces, systems for crew health and hygiene/medical care, mission-specific onboard research capabilities, food storage and preparation, recreation, trash jettison, maintenance and repair, stowage, system monitoring, logistics management, and fire suppression. The full set of ground rules and assumptions shed greater lights on these functions (and systems to accomplish them) and are detailed in NASA TM2022-0000524: Moon2Mars Habitation: A Snap Shot as

of January 2022 [6].

Like the Lunar Surface Habitat and Gateway, TH is expected to have extended periods of quiescence. These periods would include launch and transit to Gateway, any period when crew are not in NRHO, transit and docking with the Mars propulsion system, uncrewed time at Mars orbit (if no crew remains aboard to operate Mars TH), and following departure of crew from the TH for earth after a Mars mission. These uncrewed periods, as well as the periods of communications blackouts identified in HEOMD-415 [4], drive the need for maximally autonomous systems and integrated vehicle management approaches.

Based upon these assumed functions and operations, subsequent sections of this paper assess the technology gaps for Mars TH within the context of habitation only (propulsion systems gaps are not discussed) and include thoughts on technology maturation needed to realize the concept as it is envisioned in the current architecture.

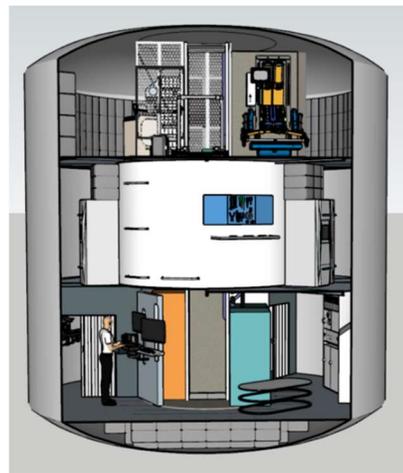


Figure 4: Notional concept rendering of three-story Mars TH layout.

3. METHODOLOGY: IDENTIFICATION AND CLASSIFICATION OF GAPS

Each element of the Artemis architecture has associated capability gaps, which define the difference between the current state-of-the-art and the maturity of the capability that is needed to enable or enhance the mission as it is currently envisioned in the government reference architecture. The habitation systems development team at NASA Marshall performed a capability gap analysis for habitation spanning multiple disciplines. For this assessment, a capability is defined as the ability to meet an objective for an element within the constraints and assumed level of risk of an assumed architecture [8, 9]. While capability gaps have linkages to multiple programs and even multiple habitation platforms, the primary focus of the initial capability gap analysis discussed in this paper was Mars TH.

A gap is defined as “the inability to complete a task or meet an exploration objective” [8]. Capability gaps were identified by discipline experts and grouped into the following subsystems: life support and human health;

materials, structures, mechanical systems, and manufacturing; autonomous systems; flight computing and avionics; exploration destination systems; thermal management; communications and navigation; power and energy storage; sensors and instruments; software, modeling, and simulation; robotic systems; ground and uncrewed surface operations; guidance, navigation, and control; entry, descent, and landing; and propulsion systems. These groupings are largely centered around NASA’s technology taxonomy [10]. The initial analysis activity linked each gap generated by subject matter experts across the agency to two future habitation platforms: Lunar Surface Habitat and Mars TH. Where a linkage to habitation was identified, the gap was further classified as a “need”, “want”, or “not required.” Gap categorization and definitions are consistent with the capability gaps framework established by NASA and detailed in references [8] and [9].

Table 1. Gaps Categorized as Need/Want/Not Required.

Gap categorization	Meaning
Need	Element cannot function or achieve mission success without closing this gap; there may be alternatives such as different operational approaches or accepting more risk but usually at additional cost/resources.
Want	Gap closure is not strictly required to function or achieve mission success, but closing this gap (potentially in combination with other gaps) improves the architecture by adding functionality or resiliency.
Not Required	Gap is not required in the current architecture but could provide value to a system or an architecture if the capability were fully developed.

Gaps are further classified into seven categories:

Table 2. Description of gap categories.

Gap category	Description
Technology	new and/or novel performance or function that has not been demonstrated (solutions to this gap type are generally technology readiness level (TRL) 1-4); this gap type aligns with the “New” Technology TRL 1-4 definition within the NASA Technology Readiness Assessment Report [11].
Development	At least one potential solution has been identified, but additional work is required to ensure feasibility of the new and/or novel performance or function

	in a specific operational application (solutions to this gap type are generally TRL 5-9); this gap type aligns with the “New” Technology TRL 5-9 definition within the NASA Technology Readiness Assessment Report [11].
Engineering	Performance or function is well accepted (not new or novel), but requires engineering development for a specific mission (solutions to this gap type are generally TRL 5-9).
Knowledge	Unknown data (e.g., chemical and physical properties) that will ultimately drive hardware requirements; these gaps typically require additional scientific research in order to close.
Architecture	Unknown mission parameters that will ultimately drive hardware requirements; further refinement of mission plans to clarify capability need.
Operations	Crewed and uncrewed mission operations considerations, including training and flight operations, that differ from current standards of practice and need to be defined and/or tested in order to enable the mission.
Policy	Policy or management issues that are needed to define closure of other gap types (e.g., risk postures, planetary protection policies, strategic mission objectives, etc.).

Note that the gap assessments in section 4 and 5 did not consider Operations or Policy gaps. However, all gap types are represented in the analyses in section 6. The gap assessment also considered current technology development and/or research efforts which would enable gap closure. Discipline subject matter experts (SMEs) representing various habitation subsystem backgrounds listed ongoing development work and associated technology readiness levels (TRLs) as part of the gap analysis. TRLs assess the maturity of a technology on a scale of 1 to 9, with 9 corresponding to proven technology that is ubiquitously used in missions. NASA systems engineering practices recommend that in the project lifecycle, mission technologies should be at a TRL of 6 by the preliminary design review (PDR) [12]. This corresponds to system or subsystem demonstration in a relevant environment (ground or space).

Where no current funded activities relating to the gap were able to be identified, subject matter experts (SMEs) identified potential activities to work toward gap closure. Test platforms for gap closure were also noted. For example, some gaps may be able to be closed with ground-based testing, while others require validation on the ISS or another in-space platform. Linkage of gaps to habitation systems and classification of gaps was rooted in the assumptions of the

current architectures for Lunar SH and Mars TH. As architectures change with further concept development, the habitation team must continually update the gap assessment, generate new capability gaps as they are identified, and assess the criticality of the gap and possible closure paths.

As the Mars TH concept matured through design and analysis cycles, a deep dive into gaps associated with this element was needed to inform subsequent development of an initial technology development plan. The purpose of this analysis was to assess which gaps are unlikely to close within the anticipated timeframe needed for delivery of the Mars TH and inform progressive technology investment to reduce identified development risks. The habitation systems development team initially narrowed the gaps linked to Mars TH to only those which were identified as required in the current architecture. Of the approximately 150 gaps linked to Mars TH, 86 were identified as a “need.” Of these, 16% were engineering gaps, 38% were development gaps, and 46% were technology gaps. High-priority gaps classified as a “need” and linked to Mars TH spanned the following areas (list is in order of frequency): life support and human health; flight computing and avionics; thermal management systems; materials, structures, mechanisms and manufacturing; communications and navigation; power and energy storage; exploration destination systems; autonomous systems; software, modeling, and simulation; and robotics. The analysis was restricted in scope to the Mars TH itself. While the TH requires significant propulsion system development to enable a Mars mission (and the specifics of this system are still the subject of active trades), propulsion systems gaps were not considered in this initial assessment.

SMEs were asked to revalidate the gaps identified and identify technologies which had a low likelihood of reaching TRL 6 by the currently anticipated timeframe for a transit habitat preliminary design review (PDR). TRL 6 means that the systems/subsystems model or prototype has been demonstrated in a relevant environment (ground or space). 21 gaps (24% of high-priority gaps for Mars TH) were identified as having a low probability of maturing to TRL 6 based on the schedule assumptions provided. Reasons for the low likelihood assessment for each gap were further analyzed and generally linked to one or more of the following:

- no current technology options exist
- technology options exist but need significant improvement and specific testing/ characterization for Mars TH (and this is unlikely to occur in timeframe needed given current funding levels and activities)
- flight demonstrations are planned but technology development is progressing slowly or is not anticipated to be demonstrated by timeframe needed
- lack of understanding of the requirements/use scenario for Mars TH (i.e. linked to an architecture/knowledge gap)
- funded work and demonstrations are ongoing but they do not align with Mars TH-specific needs

The remaining 52 high-priority gaps (76%) were assessed as having a medium or high probability of reaching TRL 6 within the timeframe anticipated for PDR. The breakdown of gaps with a low probability of closure by Mars TH subsystem were as follows:

Table 3. Frequency of Gaps by Technology Taxonomy.

Gap area	Number of gaps
Life support and human health	9
Flight computing and avionics	3
Power and energy storage	2
Thermal management systems	2
Exploration destination systems	2
Autonomous systems	1
Materials, structures, mechanisms, and manufacturing	1

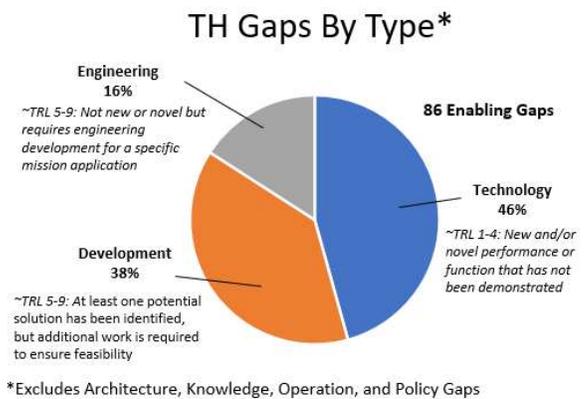


Figure 5: Summary of Transit Habitat Gaps by Type

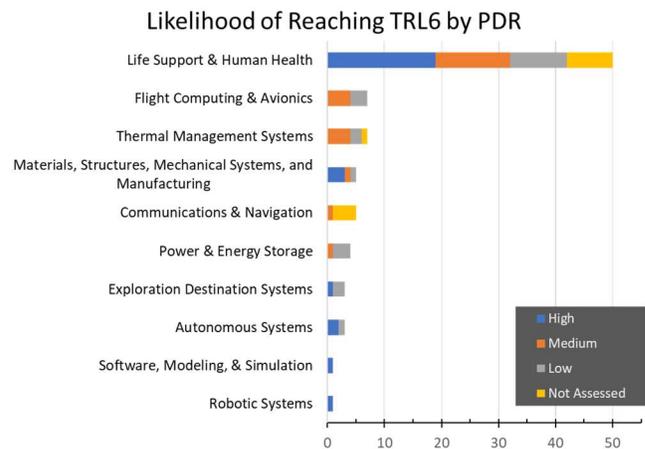


Figure 6: Summary of likelihood assessment.

The next section delves into specific gaps identified for each technology area and potential closure paths. Results of this analysis are intended to inform development of integrated roadmaps within specific technology areas and development

activity prioritization to best enable the current architecture for Mars TH.

4. GAP ANALYSIS FOR MARS TH AND RECOMMENDATIONS

Many technology gaps identified for the Mars TH with a low likelihood of closure are well-known and have been identified in development of Mars mission architectures for decades. Others are reflective of a potential mission dependency on emerging technologies which have not been sufficiently demonstrated for a Mars TH infusion (or are unlikely to be demonstrated within the timeframe currently anticipated for Mars TH deployment). In other cases, no identified technology solution exists. This section discusses the key gaps identified under each general technology area which were evaluated as having a lower likelihood of closure and their linkage to enabling the current concept of operations.

A. Avionics, Flight Software, and Autonomy

The transit habitat will require unprecedented levels of autonomy due to communications delays and communications blackout periods, the latter due to solar conjunction scenarios when the sun comes directly between Earth and Mars in opposition. While the communications delay is predictable, there will be significant periods (ranging from minutes to days to months) where communication with a ground-based mission control center is impeded or not possible at all. High-priority gaps under this category include:

- **Autonomy.** Autonomy is needed for periods of quiescence and communications delays and blackouts described in the concept of operations. Mars TH requires a paradigm shift in traditional approaches in mission management, with a much greater reliance on onboard software to manage the vehicle, intelligently monitor the health of systems to predict and detect anomalies, and inform crew actions when events occur.
- **High-speed Networks.** To best enable Mars TH operations, high speed networks need to be available with extremely high bandwidths to support the onboard instruments, video systems, and science equipment that transmit data to earth, other spacecraft, and potentially surface assets. Development of this capability requires new technology. While some confidence will be gained from Gateway usage and testing of network systems, the capability needed for Mars TH will be difficult to achieve with current wireless network architectures.
- **Enhanced Graphics Processing Systems.** Graphics processing systems also need to be matured for Mars TH, as current units are susceptible to radiation and may not survive in the

deep space environment associated with a long-duration transit.

- **Verification and Validation of Autonomous Systems.** Another major anticipated challenge with enabling autonomous operations is the need for autonomy verification and validation tools. Current verification and validation approaches are based on deterministic models. In autonomous systems, algorithms require the use of statistical/stochastic methods for verification.

B. Life Support and Human Health

The Mars TH also presents unprecedented human challenges in the level of radiation the crew will be exposed to and the length of time in a microgravity environment, which exacerbates deleterious physiological effects including muscle loss, bone atrophy, and space-induced neuro-ocular syndrome. Some effects can be mitigated using exercise protocols developed based on ISS experience. Any surface missions (either to the Lunar surface in a precursor analog mission at Gateway or to the Martian surface in a mission scenario) also require humans to adapt physiologically when transitioning between microgravity and reduced gravity environments.

High-priority gaps under human health (identified as having low likelihood of closure in timeframe needed) include:

- **Integrated System for Management of Crew Health and Performance Data.** Significant work is needed to ensure medical systems and crew expertise are adequate to provide the level of care required by human spaceflight standards. One potential technology solution is an integrated system for medical data that can predict crew health outcomes and advise on diagnosis and treatment when medical events occur. This is characterized as a need for Mars TH.
- **Food System for Mars TH (includes food storage and preservation).** On ISS, the crew has access to a large variety of foods and frequent resupply. Exploration missions such as Mars TH, where all food has to be launched in advance of the mission and sustain the crew throughout with no resupply opportunity, represents a fundamentally different scenario. Studies have shown that crew need a variety of food and a certain quality of food to meet nutritional needs and avoid food fatigue. A related gap is the need for refrigeration on Mars TH, which can include both active and passive approaches. While powered refrigeration equipment technologies are being flown on ISS, these have high total power/cooling demands and facility volumes for food preservation that may not

readily scale to a Mars TH scenario. A passive approach would leverage the external cold space environment to maintain a cold temperature for food. Both approaches for Mars TH require significant technology development and have a critical impact on risk if not closed, as crew performance is significantly impacted by food and nutrition. There could also be adverse health effects that derive from not meeting crew nutritional needs. Analog missions can also be used to explore food options for deep space missions and the relationship between food regimes and crew outcomes. The VEGGIE experiments on ISS have also demonstrated the ability to provide fresh food during missions via onboard crop growth, which may be required to maintain nutritional content in food systems.

- **Prevention of Microbial Growth.** Another health gap is the prevention of microbial growth in onboard systems and sterilization of support equipment. ISS experience has shown that microbial growth can become an issue over time and would likely manifest on a 1,200-day mission such as Mars TH. Testing of new and improved approaches to combat microbial growth in a flight scenario is needed, particularly given periods of quiescence which are inherent in Mars TH conops.
- **Radiation Monitoring and Shielding for Deep Space Environments.** Radiation is in many ways the overarching human challenge of a Mars mission. Currently radiation monitoring experiments are taking place on ISS and are slated for Gateway, but countermeasures and assessment tools may need to be developed specifically for the Mars TH environment. There is a need to monitor and predict solar particle events. Development of shielding for galactic cosmic radiation (GCR), which is pervasive and increases the risk of carcinogenesis in crew exposed to GCR over long durations, also continues to be highly challenging. GCR dosage varies with solar cycles [13]. Active shielding concepts for GCR may represent a substantial weight contribution. The efficacy of various passive shielding approaches and biological countermeasures will be assessed on existing and future habitation platforms.

There are also a number of challenging environmental control and life support system (ECLSS) gaps which may require significant development efforts to mature systems to meet mission needs within the timeframe currently anticipated:

- **Reliability Testing.** Testing of ECLSS systems and/or critical components is needed to adequately characterize system and component reliability, and that understanding of reliability is necessary to forecast failures and understand the optimal set of spares for the mission duration that is needed to ensure the required probability of sufficiency. System operating time at Gateway in analog missions, as well as from other orbital or ground-based test platforms, is a key piece of developing this understanding. ISS experience has shown that initial failure rate estimates are often incorrect, but that inaccurate estimates can be corrected, refined, and verified through test and operations [14, 15]. From a risk perspective, reliability testing prevents overallocation of spares on a Mars mission, perhaps allowing additional mass to be allocated to other systems where meeting mass targets is a challenge [16]. The level of reliability testing required for various systems and the distribution of where it occurs (ground-based, ISS, Gateway, commercial LEO platform, or a Mars analog at Gateway) is yet to be defined, and will depend on reliability targets, mission profiles, and risk postures.
- **Design for Maintainability (and Repairability).** Concurrent with reliability testing and overall system mass reduction is design of systems to enable lower-level replacement of failed items. The ISS maintenance strategy is based around the use of relatively large multi-component orbital replacement units which are stowed on ISS and replaced as single units rather than undertaking lower-level component repair. While this strategy can reduce maintenance crew time demands by simplifying interfaces and maintenance procedures, lower-level maintenance can reduce the mass of spares [15, 17]. Exploration missions stand to benefit from design for maintainability (“ease with which a system can be maintained” [18]) and design for repairability (“the ease with which components can be repaired by crew after a failure occurs” [18]). Migration away from an ORU design philosophy in this manner can considerably reduce overall logistics mass [18]. This design approach also helps enable the potential use/infusion of technologies like in-space manufacturing, which can provide small replacement parts for larger systems [17, 18]. Improved maintainability can also include improvements to interfaces, access, clearances, tool requirements, and other factors that affect maintenance crew time requirements.

- Enhanced Oxygen and Water Recovery and Food Hydration Reduction.** Enhanced Oxygen recovery and water recovery is needed to meet consumable mass limits and is also linked to the gap on providing a safe and nutritious food system for crew, as crew prefer higher levels of food hydration. Technologies or combinations of technologies/processes (including Plasma Pyrolysis Assembly (PPA) and Sabatier) for enhanced Oxygen recovery must be proven to meet the Mars TH performance targets. Increased oxygen and water recovery rates can reduce stored oxygen and water requirements; however, these reductions are limited by the amount of oxygen and water that is stored and whose mass can be reduced. In current food systems, the food itself is approximately 47% water by mass [19]. Integrated mission analysis shows that, once the water contained in the food is sufficient to meet stored water demands (along with a small contingency water supply), additional loop closure does not necessarily result in mass reduction. Once a certain level of water and oxygen recovery is reached, additional recovery capability results in a net increase in system mass because there is no additional water mass to reduce and the additional systems provided to achieve that recovery level result in increased system and spares mass [20]. However, increased water and oxygen recovery *and* reduced food hydration can result in net logistics reduction, because lower hydration food effectively shifts more water mass to stored water, which can be reduced by recovery systems that provide recycled water for food hydration [21].
- Operations during and following quiescence.** The ability to operate during and following periods of quiescence is a concern for any exploration habitation platforms, as ISS systems are designed with the assumption of continuous presence of crew. As discussed in section 2, the Mars TH concept of operations consists of multiple quiescent periods between crewed missions (both analogs at Gateway and Mars transit) [6, 7]. In particular, ECLSS systems may be susceptible to biomass formation and growth during quiescent periods, which poses a health risk to crew. Research to mitigate formation and inhibit this growth should be a priority. Technologies to enable and verify operation of systems after quiescent periods (which may require activation/re-start of systems in the absence of crew) is also key to the architecture.
- Design and Testing for Lower Pressure Environments.** TH is also anticipated to operate at lower pressure than ISS when docked at Gateway. ISS-derived systems that are being used for Mars TH thus must also be able to function in a lower pressure, higher oxygen environment. This environment also has implications for flammability of materials. Most heritage material testing was performed for the ISS environment; results of flammability testing cannot readily be extrapolated to other environments without a specific test-based evaluation. In addition to materials considerations, this will impose additional verification and performance testing for some systems. Testing must start early in the development to drive out any performance issues and identify modifications that may be needed for low pressure operations.
- In-flight Water Quality Monitors.** These monitors require a different approach for Mars TH, as currently samples for water quality evaluation are collected on ISS and returned to Earth for analysis. The ability to assess water quality in-situ for Mars TH is key to crew health and ensuring adequate water quality for onboard systems that require water as an input. Water quality monitoring also needs to be automated to support quiescent operations.
- Waste Jettison Technologies.** As discussed in the concept of operations for Mars TH, waste jettison technologies are needed in order to dispose of 2-3 kg of waste mass per person per day and achieve propulsive performance. Jettison does not negate the value of the conversion of waste materials through combustion (ex. “trash to gas”) [22], compaction [23], or recycling of materials into polymers for further use [24]. Ongoing work on jettison technology for ISS and in-flight demonstrations on the platform will help to close this gap, but the scale of systems needed for Mars TH is anticipated to be different than the scale tested on ISS and also needs to operate with reduced complexity. Jettison carries some risk in release of vapors and gases that can deposit on and contaminate sensitive surfaces that are in the line of sight. Crew time required for mass jettison is also currently an unknown and is dependent on frequency of jettison. NASA tournament lab recently ran a challenge on waste jettison, seeking concepts for a jettison mechanism to eject non-recyclable material from a crewed spacecraft during transit to and from Mars [25]. Reference [26] is a comprehensive look at potential jettison techniques and system design, including the consideration of the use of a crew airlock vs.

dedicated trash airlock and crew safety (risk of jettison material re-contacting the spacecraft).

C. Exploration Destination Systems

Challenging human considerations for Mars TH that fall under the heading of exploration destination systems include the incorporation of an EVA capability and outfitting. While EVA is not part of the nominal concept of operations, a contingency capability to repair external systems or respond to emergency scenarios is anticipated.

- **EVA Tools and Mobility Aids.** There is a need to develop specific tools and mobility aids for Mars TH, but a low level of understanding of needs and requirements for possible mission scenarios. There is also a question of whether existing suits and/or those in development for Lunar architectures would be able to fully support Mars TH EVAs without significant additional testing and/or modification. While primarily a concern for Lunar environments, dust cleaning of suits is also a consideration for crew returning to the Mars TH from Mars surface operations.
- **Outfitting of Inflatables.** Habitat outfitting transforms a structure into a usable system. Outfitting for Mars TH will take place at Gateway and also in LDHEO prior to Earth departure. While we have human spaceflight experience with outfitting in microgravity through ISS, the primary habitable structure for the Mars TH is a softgoods inflatable. As discussed in reference [27], inflatables have unique needs for outfitting relative to rigid metallic habitat structures, as they are launched in a stowed configuration and deployed at the point of use. Some outfitting can be pre-integrated in a metallic core, but elements may require migration to other portions of the habitat following habitat inflation and deployment of flooring. Some systems may also need to be positioned, installed, and activated in advance of the crew arrival. Research efforts are needed to develop specific approaches for outfitting of inflatable structures, identify crew tasks/timing/sequencing, and understand human factors considerations. Prototypes and demonstrators for inflatables would be key to developing and assessing outfitting approaches.

D. Power

High-priority power gaps that may require significant development for closure were identified as:

- **Power Management Systems with High Reliability and Radiation Tolerance.** Radiation hardening of electronics is a well-known and fully implemented approach to protect Electrical, Electronic, and Electromechanical (EEE) parts against space radiation. Technologies to impart radiation tolerance and reliability (circuit redundancy, staging) exist, but would need improvement for Mars TH's long-duration transit and sustained operations (spanning 15 years in deep space) as a baseline.
- **Development of a) Maintainable Power Management Systems Built from Common Components and b) Common Modular Building Blocks for Energy Storage.** Systems with common components greatly enhance interoperability, make planning for optimized sparing simpler and more efficient and minimize development costs by creating synergy/alignment across assets. There is significant work on modularity and interoperability considerations for power and other subsystems through the Modular Open Systems Approach (MOSA) working group within the Lunar Surface Innovation Consortium (LSIC) [28]. An alternative to commonality (if gap cannot be closed) is to design in several levels of redundancy as a feature, but this increases overall subsystem mass. In addition to commonality, systems with higher specific power, longer life, and greater reliability are needed, particularly for energy storage devices.

E. Thermal

Inherent in all of the thermal gaps identified is the design for the thermal environment of selected trajectories for Mars TH that may represent thermal extremes. The highest priority thermal gaps identified with a lower likelihood of closure both relate to management of coolant in a mission environment:

- **In-situ Analysis of Coolant Fluids.** On ISS, coolants are periodically assessed for microbial growth and contamination, both of which become a significant concern with mission of increasing duration. The coolant health assessment is not currently done in-situ, but relies on downmass of samples to Earth for analysis and determination of treatments. This is similar to the approach to water monitoring discussed under section B. In a Mars transit scenario, it could take months to years to know the results of the analysis. No access to comparable onboard capabilities to perform these assessments and a lack of identification of technologies for in-situ monitoring/evaluation that

would be applicable to Mars TH lead to this gap's classification as low likelihood of closure.

- **Location of Coolant Leaks.** An accompanying gap is the ability to locate coolant leaks during the mission and in particular in periods of quiescence anticipated in the current concept of operations. Leaks are serious events that could compromise mission success. Monitoring for both external and internal leaks currently relies heavily on crew; leak location via robotics will require advancements in the state-of-the-art. A workaround (as with some of the power system gaps) is to design for redundancy so there are multiple loops operating in the event of a leakage, but this also comes with a mass penalty. Detection of a leak on a space mission may also necessitate repair of the coolant lines and may require accompanying in-space repair technologies such as welding.

F. Materials and Structures

Materials gaps linked to Mars TH call for reduction of mass in structural systems and development of inflatable softgoods materials for use in a primary, habitable structure. Many of the softgoods gaps are development and engineering gaps that can be addressed with standard engineering approaches – these will be discussed in the next section as we roadmap the path toward a flight-certified material system.

- **Soft-hard structures integration.** The gap that is rated as unlikely to close within the needed timeframe without further investment is the integration of hard structures with inflatable softgoods. Integration of windows, hatches, airlocks, etc. into softgoods is challenging because these penetrations introduce discontinuities and stress points that can result in structural failure. The risk must be mitigated through additional testing of the structure with the penetration included to assess the impact of the discontinuity on the previously characterized material system performance. This testing is also architecture specific, so it cannot be worked as a general study that is then scaled or adapted to different designs based on analysis. The gap also includes hard/soft point connections such as handholds for EVAs and structural attachment points internal to the habitat for outfitting. Advancement toward gap closure may progress through development of other platforms that use softgoods prior to deployment of Mars TH, such as commercial LEO platforms and the Lunar Surface Habitat. Additionally, we can see how these critical gaps will first be tested, demonstrated, and validated in existing architectural elements to fulfill closure at the Mars TH.

5. TECHNOLOGY MATURATION CONSIDERATIONS

The initial gap analysis for Mars TH focused on gaps that were judged as high-priority (categorized as a need

for the architecture) and unlikely to close within the general timeframe currently assumed for launch of the Mars TH to Gateway. We further organized the gaps based on the reasons for the low probability rating and identified platforms that could be used as testbeds to move a gap toward closure.

A. Reasons for Low Likelihood of Gap Closure

Reasons for low likelihood of gap closure were also assessed and are noted below.

- Gaps for which no current technology options of a sufficient technical maturity were clearly identified, with the primary gap in this category being biomedical radiation countermeasures.
- Gaps for which technology options may exist (but trades are still ongoing) and would also need significant improvement and/or specific testing/characterization for the TH architecture include: high speed networks, graphics processing, autonomy verification and validation tools, development of EVA suits and tools for Mars TH, high reliability/radiation tolerant power systems, power management subsystems with commonality and modularity, and hard structure integration with inflatable softgoods.
- There were also gaps that are anticipated to be closed by flight demonstrations, but this testing will not be completed in the near-term. These include food systems for Mars TH (includes both flight demonstrations and results from analog missions), recovering and recycling additional oxygen from metabolic carbon dioxide (also relates to providing an adequate food system), in-flight water quality monitors, and habitat outfitting approaches. Work is ongoing in these areas, but SMEs assessed that it may not be progressing quickly enough to ensure infusion in the timeframe needed.
- EVA gaps for Mars TH and also Mars surface operations were judged to have a low likelihood of closure due to a lack of definition of requirements for EVA and corresponding mission scenarios. Within the Mars TH concept of operations, EVAs would be undertaken only in contingency scenarios, but these are not currently defined. Similarly, it is not understood what level of additional exploration EVA suit development and testing will be needed to support a Mars architecture. This knowledge/architecture gap may close with additional definition of the Mars TH architecture in future design and analysis cycles.

- Gaps for which technologies are identified and there is ongoing work but specific work for Mars TH would be needed to close the gap include: mitigation of microbial growth and biofilms, dust mitigation for EVA, ability to perform in-situ coolant health assessments, and automated coolant leak locating. In-flight waste mass jettison is a need that is defined within the Mars TH architecture, but currently planned ISS flight demonstrations are not at the scale which would be needed for Mars TH and are not subject to Mars TH-specific performance metrics (previously defined as 11.6 kg/day of waste jettison in reference [6]). There are opportunities to pivot or expand work in these areas of need to encompass Mars TH architecture-specific considerations.

B. Gaps and Technology Maturation Platforms

Additional analysis assessed the possible technology maturation platforms for the high-priority/low likelihood of closure gaps previously identified as well as other high-priority gaps for Mars TH. Many gaps related to networking, human/system integration, food/nutrition, system operations in lower pressure environments, and integrated reliability testing can be advanced toward closure on the ground, including through analog missions, prototypes, and environmentally relevant chambers and testbeds.

ISS is a critical testbed for regenerative ECLSS maturation and validation, assessment of the efficacy of countermeasures for radiation, and advancing exploration medical capabilities. Following de-orbit of ISS (potentially) by the end of the decade, NASA will lose access to a continuously crewed orbiting laboratory in microgravity necessary to test many of the capabilities needed for future exploration missions. NASA's Commercial LEO Destinations (CLD) program seeks to develop free-flyers with commercial partners which will serve as successor(s) to the ISS. The CLD program's goal is for these CLD platform(s) to be available to serve NASA, industry, and academia prior to the decommissioning of ISS [29]. Currently three companies (Blue Origin, Nanoracks, and Northrop Grumman) are developing free-flyer concepts which will support NASA as well as other potential markets such as space tourism. The goal is to support two crew at initial operational configuration with a capability for continuous crew stays (although this can be an evolvable capability). NASA calls for a flexible frequency of crew rotation, including occasional crew stays of six months, one year, or longer. Free-flyers should also accommodate payloads (both internal and external), with a stretch goal of providing a capability to conduct analog missions [30].

With the advent of these concepts and the end of ISS, CLD architectures may be needed to help finish proving out technologies which are currently envisioned as critical

elements of the Lunar surface habitat and Mars TH in a relevant environment. The gap analysis in this paper considered which technology gaps for Mars TH may be advanced toward closure through potential research and development activities which leverage CLD platforms. Some commercial LEO concepts may also rely on inflatable softgoods as a primary habitable structure for some portion of the platform, so design, development, and testing of these material systems for commercial LEO can serve to advance the technology for future exploration habitat applications. CLD platforms could also potentially be used to perform additional reliability testing for exploration ECLSS. CLD concepts can thus have a strong connectivity to future habitats beyond LEO and potential use to advance technologies for deep space exploration.

Gateway is a platform well-suited for understanding power management and distribution, dormancy operations, radiation effects and efficacy of countermeasures, environmental monitoring, exploration medical capabilities, and food/nutrition (in particular low water content food and a limited variety of food on crew performance and psychology).

C. Initial Perspectives on Technology Maturation

Beyond the initial assessment, the habitation team will use the gap analysis to inform the initial development of roadmaps and prioritization of potential future development tasks. One very prominent, critical task to support Mars TH development is the maturation of inflatable softgoods for use in a primary habitable structure. While Bigelow Expanded Activity Module (BEAM) has been tested on ISS, BEAM is a technology demonstration to better characterize the performance of softgoods materials in space and the accompanying internal radiation environment; the module is not used for sustained human habitation. As noted previously, inflatable softgoods are part of the current baseline architecture for both Mars TH and Lunar Surface Habitat. While the legacy of many current softgoods systems dates to the TransHab program at NASA Johnson Space Center [31], commercial companies are now developing softgoods habitation platforms and maturing these material systems. There is also continued in-house NASA research and development in this technology field, with the goal of transitioning advancements and innovations to the commercial sector. In recent years, softgoods technology has become a critical consideration for future habitation platforms, owing in part to its ability to provide a larger habitable volume for the same mass as a rigid metallic structure. The Bigelow Expandable Activity Module (BEAM) initially demonstrated the technology on ISS and has been used to assess the internal radiation environment and resistance of the material system to space environmental effects, but significant maturation and testing is still required to certify materials for use in exploration habitats [32]. Test programs toward certification must continue in a stepwise and logical manner to ensure the readiness of the material systems for use in a potential flight application by the late 2020s. Additionally, inflatable softgoods represent highly complex multi-material systems which will make

certification more challenging relative to heritage, monolithic metal structures (Fig. 7). As shown in the image, a typical inflatable layout is shown includes the following: a) inner liner layer, b) gas barrier bladder layer, c) structural restraint layer, d) micrometeorite and orbital debris protection layer, e) environmental protection layer, and f) deployment layer.

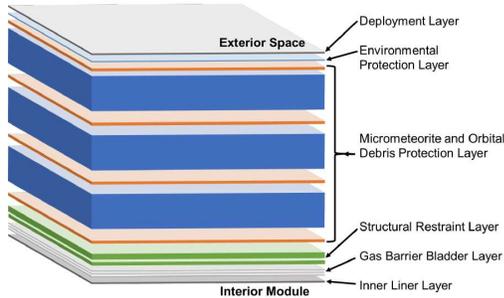


Figure 7: Illustration of softgoods material layup [29].

In August 2022, NASA published guidelines detailing the minimum testing needed to support certification

of a crewed inflatable structure [29]. This is not a requirements document itself, but is intended to guide development of programmatic requirements within the context of NASA-imposed standards for human rating of structures. The certification approach relies on testing at the component, subscale article, and full-scale article levels at ambient and (in some cases) conditions consistent with the space environment.

Within the gap analysis for Mars TH, subject matter experts mapped out the testing of softgoods within the context of phasing of a typical flight program. The image in Fig. 8 shows the phases of testing that are outlined in the softgoods certification guidance document. While this shows the sequence of testing and relationship between tests as precursors and successors, development of the testing requirements and timeline for execution would be highly program specific. The intent of the graphic is to show the steps needed to mature softgoods for flight and emphasize the reliance of the certification approach on testing due to their lack of heritage use in space structures and unique mechanical behavior, which is highly dependent on material and manufacturing process. Activities related to softgoods testing to mature the technology are being pursued for both

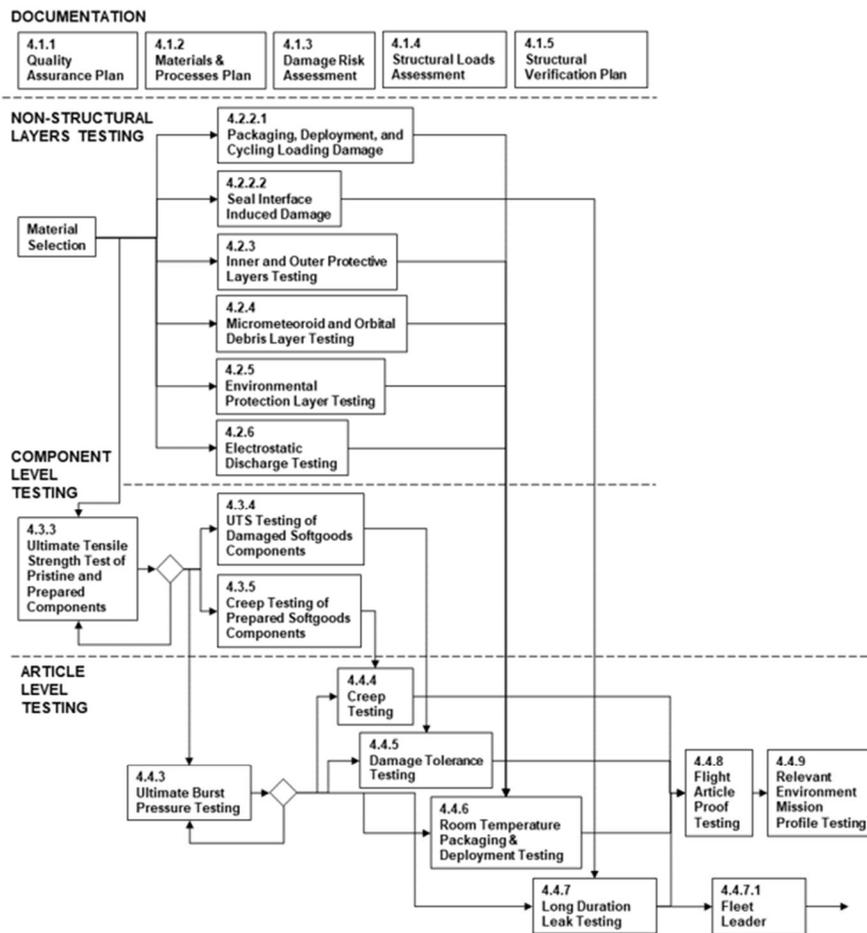


Figure 8: Testing flow for softgoods from [32]

commercial LEO and exploration habitat applications.

An ECLSS integrated roadmap and testing schedule for technologies in the Mars TH system trade space is also planned. There are numerous technologies from both open loop and regenerative ECLSS under consideration. There are also many platforms available for testing to validate the current assumptions of the architecture and inform future requirements. Platforms across all gap types include: Ground, ISS, CLD, Gateway, Other CisLunar Platforms, HLS, Robotic Lunar Surface, Human Lunar Surface, and Mars TH itself. The results of ongoing trade studies will determine the suite of ECLSS that can be incorporated into the Mars TH architecture and the level of loop closure associated with each. Generally speaking, regenerative ECLSS systems have immense potential to reduce logistics requirements (specifically the upmass for water, Oxygen, Nitrogen and other gases needed to run onboard systems). However, these systems may have a higher initial mass and higher volumes of spares relative to open loop systems; additionally, some are still in the technology development phase. Efforts are underway to make existing systems more reliable and less complex for exploration missions, with testing on ISS and Gateway informing modifications and redesign. Systems that have a high likelihood of achieving TRL 6 within the next few years for potential Mars TH implementation include an enhanced oxygen generation assembly, which electrolyzes water to supply Oxygen; water processing assembly, which purifies grey water into potable water; 4-Bed carbon dioxide removal assembly, which removes CO₂ from the atmosphere via passive sorbent beds that preferentially adsorb CO₂ and vent it to space or deliver it for postprocessing to other systems; urine processor assembly, which vaporizes and condenses pre-treated urine and recovers water for further processing; and the brine processing assembly, which increases water recovery from UPA by extracting it from the remaining urine brine. The Sabatier reactor uses hydrogen (from oxygen generation assembly) and carbon dioxide (from carbon dioxide removal assembly) to create gray water and waste methane. The Plasma Pyrolysis Assembly (PPA) then recovers further hydrogen from methane through recombination; the hydrogen can then be fed back into the Sabatier, reducing the need for it as an upmassed consumable. These systems have been proven/implemented on ISS. Environmental monitoring capabilities are categorized under ECLSS and were additionally assessed as having a high probability of closure for Mars TH, with systems having the ability to detect and control trace contaminants, detect/monitor/suppress fires, and identify and quantify microbes in the surrounding environment.

6. LINKAGE BETWEEN GAPS: LUNAR SURFACE HABITAT AND MARS TRANSIT HABITAT

While this paper focused specifically on Mars TH technology gaps, there are many gaps that apply to both the Lunar Surface Habitat and Mars TH due to the commonalities in architectures. Thus, advancement toward closure of a gap through Lunar surface habitation platforms, which may

include Human Landing System (serves as a habitat for short duration early Artemis missions), pressurized rover, and Lunar SH, also benefits Mars TH. One value proposition for a surface habitat (in addition to serving as a key element of a base camp) is that significant technology development can also be leveraged for Mars exploration.

Across all exploration capability gaps for all elements of the human spaceflight architecture, approximately 39% of gaps apply to both the Lunar SH and the Mars TH in terms of needs or wants. Approximately 14% of all gaps apply to both the Lunar SH and the Mars TH solely in terms of needs. Many of these gaps do not exclusively apply to these two architecture elements but to many other elements of the architecture as well, including other habitable elements that are beyond the scope of this paper. Furthermore, given the timing of campaign elements entering the overall architecture, most of the gaps applicable to Mars TH are first tested and closed on earlier Lunar elements. In fact, 2/3 of the gaps Mars TH needs to have closed are likely to be addressed earlier in the overall architecture than when Mars TH enters. In terms of gaps that are solely needed by both elements (rather than characterized as want *or* need), approximately 61% of the gaps applicable to Mars TH have closure pathways that may be addressed earlier by closing gaps with the Lunar SH. A further exploration of the commonalities between the Lunar and Mars exploration architectures and how development and testing at the Moon can enable Mars exploration can be found in reference [30].

We can further understand the commonalities of gaps between these habitable elements by understanding which parts of the taxonomy these gaps are classified under. The following are the applicable taxonomy areas as defined by NASA [10]: TX01 - Propulsion Systems, TX02 - Flight Computing and Avionics, TX03 - Aerospace Power and Energy Storage, TX04 - Robotic Systems, TX05 - Communications, Navigation, and Orbital Debris Tracking and Characterization Systems, TX06 - Human Health, Life Support, and Habitation Systems, TX07 - Exploration Destination Systems, TX08 - Sensors and Instruments, TX09 - Entry, Descent, and Landing, TX10 - Autonomous Systems,

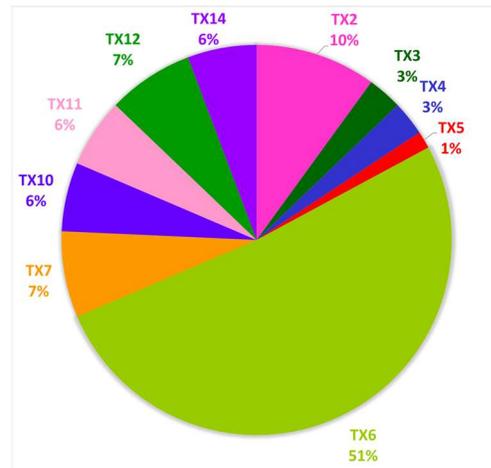


Figure 9: Overlapping Gaps Needed to Close Between Lunar Surface Habitat and Mars Transit Habitat by Taxonomy Classification.

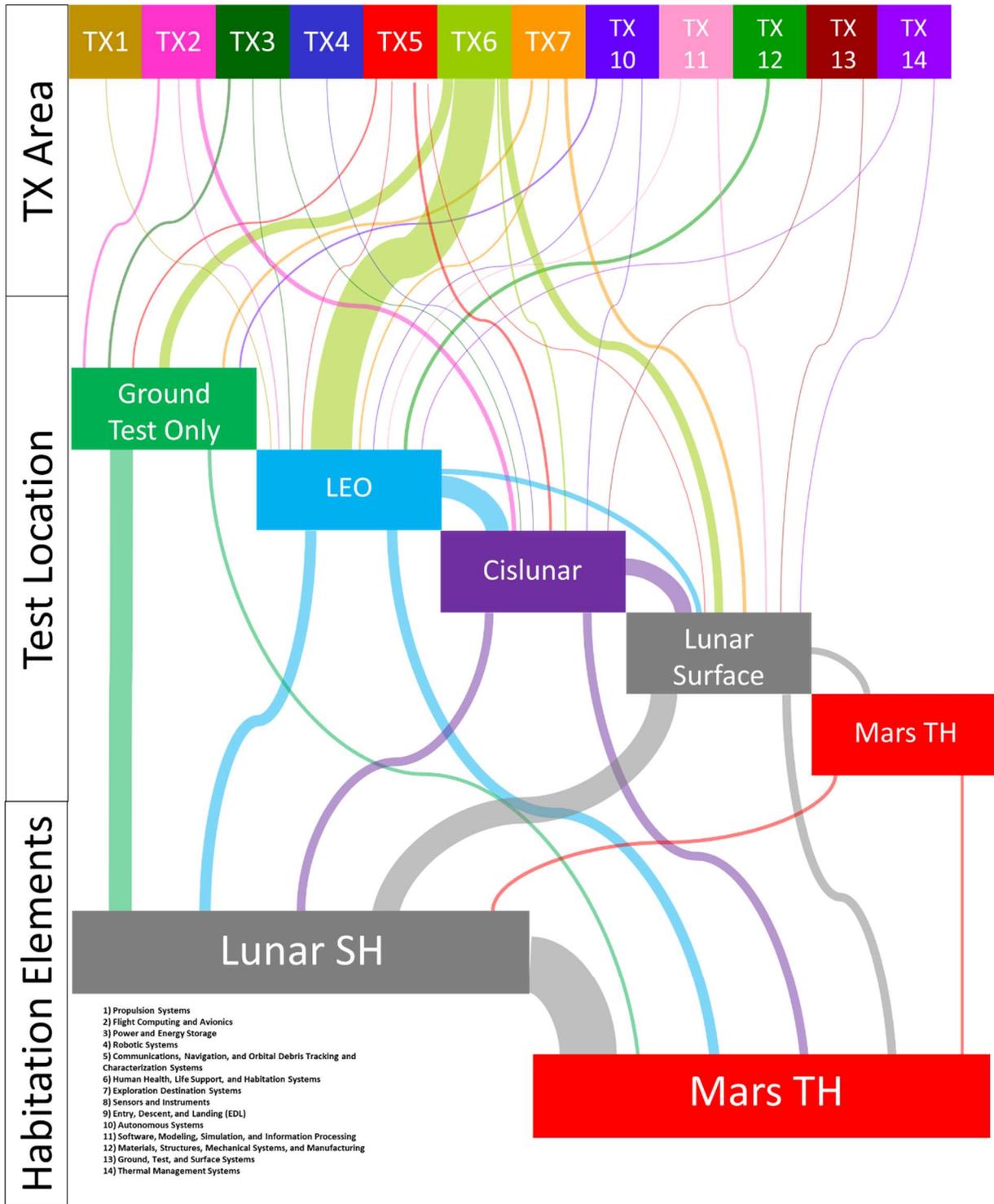


Figure 10: Sankey Diagram Demonstrating Capability Gaps by TX, Testing Locations, and Elements Enabled.

TX11 - Software, Modeling, Simulation, and Information Processing, TX12 - Materials, Structures, Mechanical Systems, and Manufacturing, TX13 - Ground, Test, and Surface Systems, TX14 - Thermal Management Systems, TX17 - Guidance, Navigation, and Control (GN&C). Figure 9 demonstrates this breakdown by TX area of common gaps that need to be closed between the Lunar SH and Mars TH.

As evidenced by this analysis, over half of all overlapping g needed for closure between these habitable elements are gaps pertaining to Human Health, Life Support, and Habitation Systems, with the remaining half being distributed amongst other technology areas. This result is intuitive, as all habitable elements would be expected to have significant overlap in terms of technical gaps and solutions.

A further breakdown of commonalities between habitable elements can be found in [33]. Of the 21 gaps listed in section 4 of this paper that are assessed to have a low likelihood of closure for Mars TH within the timeframe needed under current assumptions, 11 also need to be closed for the earlier Lunar SH. This further suggests that emphasizing closing gaps needed by multiple elements will have downstream enabling consequences for the exploration architecture. That these gaps need to be closed at an earlier state than the Mars TH suggests additional priority to these gaps, but also suggests perhaps that there might be additional closure pathways before the Mars TH.

There is a need for greater understanding of how gap closure testing, demonstration, and validation on platform locations already existing in the architecture will help to enable gap closure on subsequent architectural elements. Figure 10 shows gap closure pathways from the ground to the Mars TH by TX area. We can see in the top section how gaps that either Lunar SH or Mars TH need to be closed are broken down by TX area. The size of the flow lines correspond with how many gaps are tested, demonstrated, or validated at the various gap closure platform locations in the middle section. Note that some gaps require testing, demonstrating, or validating at multiple platform locations, which can be seen by the flow lines from one test location to another. While some gaps require only ground testing before being closed for Lunar SH or Mars TH, most require in-space testing. TX06 – human health, life support and habitation systems – has the most applicable gaps for both the Lunar SH and Mars TH. Most of these gaps are expected to be tested demonstrated, or validated in LEO. Some of these tests are satisfactory for gap closure of Lunar SH and Mars TH, but many others will require follow-on tests in cislunar, the lunar surface, or on the Mars TH itself before the gap is closed. Finally, we can see based on the size of the flow lines that while many gaps for Mars TH are closed at the various test platform locations, the majority of gaps closed for Mars TH are previously closed on the Lunar SH, as shown by the thick flow line from Lunar SH to Mars TH in the bottom habitation elements section, thus validating the discussion earlier in this section. Overall, gap closure for Mars TH will require tests across the rest of the human spaceflight architecture.

7. SUMMARY AND FUTURE WORK

Both the Lunar SH and Mars TH represent key elements of NASA's Moon to Mars approach. These advanced habitation concepts present new and unprecedented challenges due to the duration of the anticipated missions they will support and the environments they will operate in. The gap analysis summarized in this paper is intended to inform technology development prioritization and a technology development and assessment plan for Mars TH, which is currently assumed to support 4 crew on an up to 1,200-day mission. The technology assessment plan will identify technologies needed to close gaps and assess the maturity of these technologies. The plan will also include the stepwise development needed to raise their technology readiness level and infuse them into the habitation platforms

in time to support future missions. In some cases, fundamentally new technology may be required, while in other instances heritage technology may be used or modified. It is also possible that some CLD activities can “feed forward” into future habitation concepts, as testing on CLD platforms could become part of the closure plan for some technologies on the critical path to enabling the Mars TH architecture. Beyond identifying gaps that have a low likelihood of closure (and thus infusion) within the current anticipated timeline for Mars TH, an accompanying closure plan for each technology area needs to be developed. A deeper analysis into gaps that were categorized as a “need” but have a medium or high likelihood of closure is also planned. A closer look at ECLSS and integrated testing on various platforms to support Mars TH timelines is needed – the ability to obtain sufficient time on system by the Mars TH need date may be a consideration in trades and inform decision analysis for which systems to include in the architecture. A few other gaps were unable to be fully assessed within the context of Mars TH due to a lack of information on current state-of-the-art. These gap assessments may benefit from technology searches to identify ongoing work in government/industry/academia and potential applicability to NASA specific applications given the unique consideration of mission constraints.

As emphasized in this analysis, realization of a Mars mission in the near term requires fundamentally different technologies and accelerated approaches to technology development. The gap analysis presented in this paper is intended to be the start of a conversation on technology maturation for Mars TH and identify development efforts which will help close the architecture. With an ever-growing landscape for future habitation that also includes commercial providers, we will have increasing opportunities to test systems in relevant mission environments and better understand our capability needs relative to the current state-of-the-art for Mars TH. The future of habitation includes continued testing and development on ISS, the emergence of commercial LEO platforms through NASA's CLD program, sustained operation in cisLunar space (Gateway), Lunar surface habitation and the establishment of the Lunar base camp, and eventually transit and surface operations on Mars. Gap analysis will represent an ongoing activity as the Mars TH concept develops, with periodic re-evaluation and validation of gaps and updates to closure/maturation plans based on activities at NASA and in the commercial sector.

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BIOGRAPHY



Tracie Prater is in the habitation systems development office at NASA Marshall Space Flight Center, where she is a technical monitor for NextSTEP Habitat, supports habitation formulation activities and partnerships, and is engaged in the systems engineering and integration team for Mars TH. She joined NASA in 2013 and was an

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Quincy Bean is the Mars TH Deputy Tech Lead supporting the Habitation Systems Development Office at NASA Marshall Space Flight Center. In this role he supports the development of systems engineering documents pertaining to the Transit Habitat government reference design as well as leading the design of the Transit Habitat Propulsion System. He joined NASA in 2013 and has held various engineering leadership roles. He was the propulsion systems lead in the Advanced Concepts Office where he formulated Nuclear Thermal Propulsion System designs for Deep Space Transport concepts. He also served as the Principal Investigator and Discipline Lead Engineer for Technology Development for the In-Space Manufacturing Project. He received a Bachelor of Science in Engineering Physics from the University of Central Oklahoma (2010) and a Master of Science in Astronautical Engineering from the University of Southern California (2013).



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