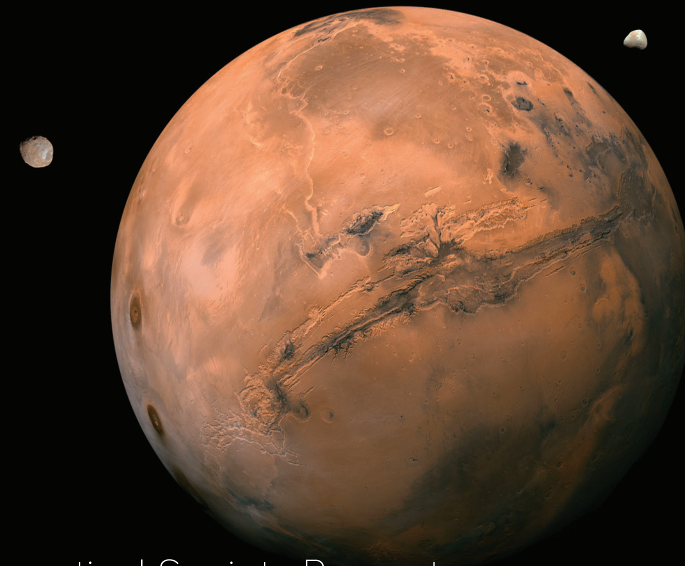

Explore Mars, Inc. and the American Astronautical Society Present

The Seventh Community Workshop for Achievability and Sustainability of Human Exploration of Mars

19-21 November 2019
Universities Space Research Association
Columbia, MD

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The Seventh Community Workshop for
Achievability and Sustainability of Human Exploration of Mars

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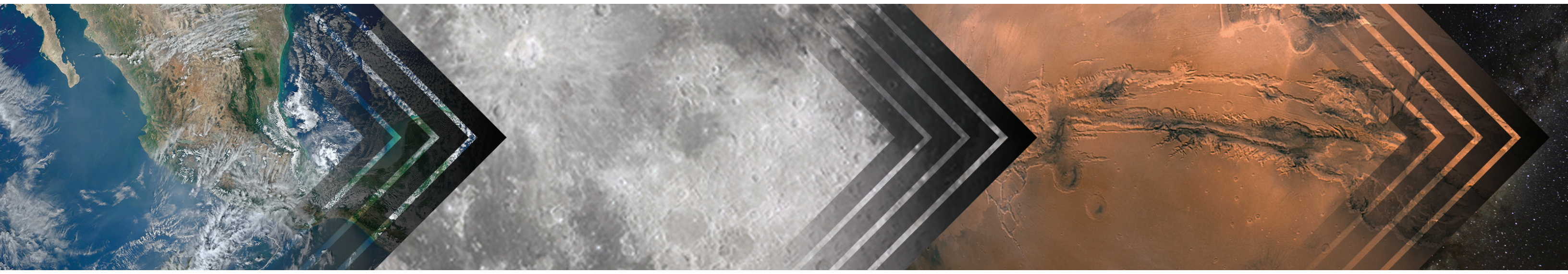
The Seventh Community Workshop for Achievability and Sustainability of Human Exploration of Mars



EXECUTIVE SUMMARY

Approximately 50 subject matter experts on human and robotic lunar and martian exploration, science, operations, key technologies, and policy assembled in mid-November 2019 at the headquarters of the Universities Space Research Association (USRA) in Columbia, Maryland to critically assess how operations, technologies, and facilities for the Moon and its vicinity might feed forward to human missions to the martian surface before the end of the 2030s. This workshop was the seventh in the series of community workshops on *Achieving, Affording, and Sustaining Human Exploration of Mars* (a/k/a AM Workshops) hosted since 2013 by Explore Mars, Inc. and the American Astronautical Society. Appendix A includes brief summaries of previous workshops, while the full reports for the workshops are posted online at https://www.exploremars.org/affording-mars/.

Building upon the work and findings of the previous AM Workshops, particularly the Mars exploration scenarios and enabling technologies analyzed in the sixth (AM VI), fifth (AM V), and fourth (AM IV) workshops, this report of the seventh workshop includes the findings of its two Working Groups that were focused on various lunar activities that show varying degrees of promise in enabling Mars exploration. The Capabilities Working Group addressed the "feed forward" characteristics of several key capabilities identified in the AM VI Workshop, and the In-Situ Resource Utilization (ISRU) Working Group addressed the "feed forward" characteristics of ISRU, which was identified in AM VI as an area warranting future study. The findings of the two Working Groups are described in the following sections, and further discussion of the process and additional details that support the findings for each Working Group are included in Appendices B and C.

BACKGROUND AND MOTIVATION FOR AM VII

Putting humans on Mars has been the long-range goal for NASA and partnering space agencies for many decades. However, the perception that such journeys would require overcoming daunting technological challenges and be exceedingly costly (and therefore unaffordable) has been a severe limiting factor in developing the necessary consensus plan for exploration among governments, industry, and the general public.

The participants of the seventh *Achieving, Affording, and Sustaining Human Exploration of Mars Workshop* (AM VII) were specifically tasked with critically assessing how performing lunar tests and/or pathfinding operations, such as In-Situ Resource Utilization (ISRU), might reduce the cost, technical risk, and schedule for human missions to Mars, that is, "feed forward" to human missions to Mars.

Since the time of our first workshop in December 2013, and in the six annual AM Workshops that have followed, hundreds of technologists, engineers, scientists, policy experts, senior managers, and stakeholders have participated as representatives of their respective communities. Explore Mars, Inc., a 501(c)(3) nonprofit organization, has been the host organization of these workshops, joined by the American Astronautical Society. These workshops have been designed from the very beginning to be a series, with each subsequent workshop building upon the previous ones while responding to changing political, technological, and scientific developments.

The space community has long debated whether the development of capabilities, technologies, and operations that would enable returning astronauts to the vicinity of the Moon and/or to its surface would feed forward to subsequent human missions to Mars. In our sixth workshop, this discussion of a return to the Moon to enable subsequent Mars exploration was subjected to a critical assessment via comparison with sufficiently detailed Mars exploration scenarios. In that sixth workshop, we identified seven high-priority capability areas. In addition, a key area that was implicit, but not discussed in detail, in AM VI, was operations across all major areas that might feed forward. In our seventh workshop, therefore, we not only continued to focus specifically on several of the key capabilities that had been identified in the sixth workshop but also focused on operations, as follows:

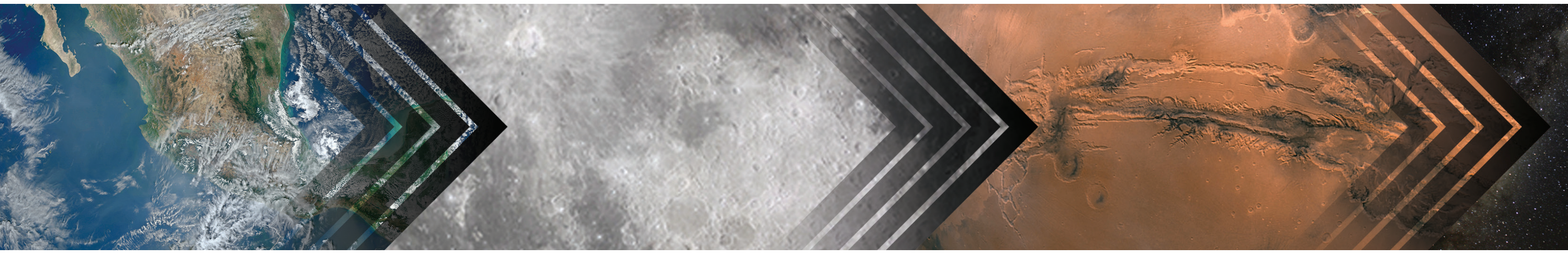
1. Lunar ascent vehicle/lander extensibility to Mars ascent vehicle/lander, including propulsion and cabin
2. Surface infrastructure for ISRU and other operations, including surface suits, power and emplaced assets
3. Mars and lunar rover similarities and differences, including functional requirements for science and human support, resource needs, and trafficability
4. Operational strategies such as:

» Human and system health and maintenance, particularly life support, extravehicular activity (EVA), and on-demand training
» Cryogenic fluid management on orbit and during surface operations
» Logistics tracking, location, and management
» Vehicle aggregation

Our seventh workshop also devoted substantial participant resources to a focused in-depth analysis of another capability that our previous workshops had identified as relevant to any consideration of “feeding forward” to Mars missions, but one that had not yet been analyzed in depth, and that is In-Situ Resource Utilization (ISRU). It was called out in the report of the sixth workshop as a “notable topic” deserving of special attention due to the shared presence of water ice on the Moon and on Mars. We believe that our workshop was the first of its kind to bring the lunar and Mars communities together to jointly examine and analyze the “feed forward” characteristics of lunar ISRU capabilities to human missions to Mars. This activity was accomplished through a separate breakout session that was devoted solely to ISRU, which leveraged strongly the results of the Lunar ISRU 2019 workshop, held four months prior to AM VII.


Group Photo of AM VII Participants, Novmeber 2019

The Seventh Community Workshop for Achievability and Sustainability of Human Exploration of Mars



REPORT

During our AM VII Workshop, the participants were divided into two breakout sessions (Working Groups): The Capabilities Working Group focused on the "feed forward" characteristics of several of the key capabilities that had been identified in the AM VI Workshop. The In-Situ Resource Utilization (ISRU) Working Group focused on the "feed forward" characteristics of ISRU, identified in the AM VI Workshop as deserving of further study. The following sub-sections of this report include background material as well as a description of the approaches each group used in assessing operations, technologies, and proving ground venues that would feed forward to Mars exploration. They also include a list of the participants in each Working Group. Major findings are then provided with short descriptions justifying each finding. Appendices B and C provide additional details supporting the findings of the two Working Groups.

AM VII CAPABILITIES WORKING GROUP

CO-LEADS: **Joe Cassady** (Aerojet Rocketdyne), **Michelle Rucker** (NASA JSC)

WORKING GROUP PARTICIPANTS:

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Len Dudzinski - NASA SMD
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Steve Hoffman – Aerospace Corp
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Bob Moses – NASA LaRC
Rich Phillips – Phillips & Company
Hoppy Price – Jet Propulsion Laboratory, California Institute of Technology
Sam Scimemi – NASA HQ

Successfully sending humans to the surface of Mars in the 2030s and returning them in a healthy state to Earth is a major challenge that requires a reasonable assessment of the risks involved and mitigation of those risks on Earth, in Earth orbit, in cis-lunar space, and on the surface of the Moon. In past AM workshops, we identified critical areas of technological and operational importance for the success of human missions to Mars. The development of key technologies and operational requirements necessitates demonstration in space or on the lunar surface prior to committing to a long-duration human exploration mission to Mars.

The Capabilities Working Group was tasked with assessing the applicability of the activities that are currently planned in preparation for human Mars missions in the 2030s. The current activities assumed for this assessment included continued operations on the International Space Station (ISS), the Artemis activities focused on a return to the Moon, including the Commercial Lunar Payload Services (CLPS) and Human Landing System (HLS) programs, and other Mars precursor missions. The assertion is that performing tests or pathfinding operations during these activities can significantly reduce the cost, technical risk, and schedule for human missions to Mars. It is also true that many of these technologies and operations are currently required for human missions to the Moon and synergistic benefits can be realized for both Moon and Mars exploration.

In order to evaluate the applicability of current and planned efforts to human missions to Mars, it is important to first understand what is needed for those missions. This activity resulted in development of a list of required functions to prepare for and execute a human Mars mission. These functions are listed in Table 1 below. We then determined that there were three broad categories of testing venues that could be used: the ISS and other Low Earth Orbit (LEO) platforms, the Gateway and cislunar space, and the lunar surface.

Table 1 Mars Mission Functions

Human Health
Entry, Descent, and Landing
Surface Operations
In-Situ Resource Utilization (ISRU)
Ascent
Off-Nominal Operations
Precursors

During AM VII, time was allotted for brainstorming the activities and technologies associated with each of the functions listed in **Table 1**. While these lists are not exhaustive, they are representative of activities and/or technologies that will be part of human Mars missions. The detailed activity/technology lists are given in Appendix B, organized by the main functions listed in Table 1. Since this was a brainstorming activity, the Capabilities Working Group did not filter the list too critically. However, the group did recognize the need to establish some priority within this list. It was felt that it was important to distinguish between activities that are required before we can accomplish the first human mission to Mars (enabling) and activities which would make human missions to Mars (or the Moon) more sustainable (enhancing).

The Capabilities Working Group sought to show how performing tests in these locations can significantly reduce the cost, risk, and schedule for human missions to Mars. The group also wanted to define what cannot be done at the Moon and identify precursor Mars activities that must be performed in parallel with Artemis.

NASA is conducting studies of robotic precursor missions focused on identifying and characterizing regions of the martian surface that would be optimum locations for human landing sites. One of these missions under study is the Mars Ice Mapper, a remote sensing mission intended to map and profile the near-surface water ice, primarily at mid-latitude regions. Other examples of Mars precursor missions that will provide valuable data ahead of human exploration include the Climate Orbiter for Mars Polar Atmospheric and Surface Science (COMPASS), Mars Sample Return (MSR) and the Deep Space Optical Comm (DSOC) project.

As the basis for determining the technologies and operations that need to be further developed or demonstrated, the Capabilities Working Group used the report of the sixth Achieving Mars Workshop (AM VI), which identified seven high-priority capability areas. The Capabilities Working Group focused on the following key capabilities that were adapted from that list:

- Lunar ascent vehicle/lander extensibility to Mars ascent vehicle/lander, including propulsion and cabin
- Surface infrastructure for ISRU and other operations, including surface suits, power, and emplaced assets
- Mars and lunar rover similarities and differences, including functional requirements for science and human support, resource needs, and trafficability
- Operational strategies such as:
  - » Human and system health and maintenance, particularly life support, EVA, and on-demand training
  - » Cryogenic fluid management on orbit and during surface operations
  - » Logistics tracking, location, and management
  - » Vehicle aggregation

Upon convening the working group, it was determined that the best approach to obtaining a full set of the critical technologies and operations was to define the activities and technologies required to carry out a human mission to Mars. These were grouped into the major functions shown previously in Table 1.

After the group established a complete list of activities and technologies, it broke into smaller groups and evaluated the applicability and appropriateness of the potential venues for proving out each activity/technology. There was a great deal of discussion about providing an assessment of the degree to which the risks were retired through tests or operations in the various venues.

After further discussion with the small assessment groups, it was agreed to characterize their applicability as follows: Venues could be said to provide some additional benefit, a substantial additional benefit, or complete reduction of the risk for Mars missions. The characterization of each venue is summarized in the tables in Appendix B. In those tables, an unfilled circle represents some benefit, a half-filled circle represents substantial benefit and a completely filled circle represents complete risk burn-down. No mark indicates either that there is no benefit to performing testing in that venue or that the group felt that another venue (such as testing at high altitudes in Earth's atmosphere) would provide a higher-fidelity test.

FINDINGS

The Capabilities Working Group produced the following major findings:

APPLICABILITY: Of the 85 activities or functions, a significant number benefitted to at least some significant degree from some aspect of Artemis and ISS mission plans. (See details in Appendix B) The group concluded that planned Artemis and ISS activities either naturally contribute directly to progress towards sending humans to Mars or could be easily modified to do so. While some technology or process maturation would remain to address Mars-specific requirements, it is clear that he path to Mars is facilitated by certain activities at the Moon and in LEO.

MODIFICATIONS: As an adjunct to the above finding, some planned ISS and Artemis activities could better serve to prove out Mars systems and operations if slightly modified. For example, Gateway crew stays could be extended to more accurately simulate transit durations, and communications delays could be introduced to demonstrate operations and crew performance with variable communications latency. Also, combined activities such as long duration crew stays on Gateway, followed by descent to and activity on the lunar surface could be used to effectively simulate Mars transit and crew functions after landing on Mars.

OPTIMIZING RISK REDUCTION: All venues (ISS, Gateway, the lunar surface) provide important risk reduction activities – in other words, surface missions alone are not sufficient to reduce risk for Mars. It is important to review the specific risk-reduction objectives and determine the best venue for achieving them. Leveraging all possible options helps to constrain costs and enable progress in parallel. It also avoids straining resources at any given venue to accommodate a risk reduction activity that could be better accomplished elsewhere.

CREW HEALTH AND PERFORMANCE: Many crew health issues would benefit from coordinated mission planning between venues. For example, it is possible to address aspects of crew health and performance on the round-trip to/from Mars through long duration stays on Gateway followed by lunar surface deployment and activities followed by return to Gateway for another stay before returning to Earth.

ISRU PATHFINDERS: Lunar surface activities can be pathfinders for many key techniques and technologies required for ISRU. The group noted that there are differences in environments that would have to be accounted for when developing Mars-specific hardware and processes. (The other Working Group - the ISRU Working Group - focused specifically on these similarities and differences. Their findings are in the following section.

MARS PRECURSORS: A handful of activities or functions will require actual robotic Mars precursor missions to adequately perform risk mitigation before sending humans. These include identification and characterization of special regions and development and demonstration of communications infrastructure.

OPERATIONS: Operations issues are potentially more numerous and important to resolve through Artemis and ISS missions than technology demonstrations. While specific technologies and capabilities need to be matured to enable Mars missions, operations on the surface, autonomous operations, and other crew procedures including preparing for and conducting ascent from the surface can and should be tested and refined using venues closer to home. Additionally, the concept of vehicle aggregation can be proven through operations at the Gateway, including assembly, servicing, and refueling of modular vehicles that could provide a basis for a Mars deep space transport.

AM VII ISRU WORKING GROUP

CO-LEADS: **Dave Beaty** (Jet Propulsion Laboratory, California Institute of Technology), **Clive Neal** (University of Notre Dame)

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The AMVII workshop focused on the synergistic resource utilization activities to enable humans to survive and thrive on the Moon that could enable similar activities on Mars. These include the need to:

1. the need to acquire oxygen,
2. the need to acquire water, and,
3. the need to avoid possible harmful effects (such as rocket exhaust cratering) and/or to make beneficial use of local construction materials (sand, gravel, rocks, regolith, etc.) for civil engineering purposes from these materials.

ISRU activities at the Moon, depending on how they are conducted, have the potential to establish extremely valuable engineering heritage for all of the above. The benefits are most obvious for #2 and #3 above. However, even though the production of oxygen from the martian atmosphere and from anhydrous lunar regolith are quite different pathways, there are at least some important engineering elements in common.

In addition, recent discussions both in the literature and in the press emphasize the potential value to human Mars missions of obtaining certain commodities (e.g. fuel, water, etc.) at the Moon (rather than at the Earth) to support crew on an ~1,100 day mission to the Red Planet. Although the production of these commodities falls within the general banner of ISRU, the argument related to whether this leads to an optimized solution or not depends on a number of factors that were well outside the scope of this workshop, including minimum required resource availability, production rates, delivery requirements, expected commodity demand, regulatory environment, and other factors. Thus, the ISRU Working Group did not contribute an opinion on how impactful obtaining resources at the Moon might be for Mars exploration.

There are several important ways in which a lunar ISRU program could/would contribute to a human mission to Mars. These include developing essential exploration methodologies, establishing valuable engineering heritage (risk reduction), and building relevant operational experience for a subsequent Mars ISRU program. Specific components are summarized as follows (listed in approximate priority order):

FINDINGS

The ISRU Working Group produced the following major findings.

1. Lunar mission results to date imply the existence of several different kinds of water resources* on the Moon. Elevating some subset of these resources to the status of reserves will require (1) more detailed/ focused exploration (to further define location, spatial extent, heterogeneity, purity, and other attributes), (2) development of the technologies needed to extract/process them, and (3) agreement on risk tolerance and strategies for risk management. The process by which we define lunar reserves will be directly applicable to Mars, even though the underlying geology is different. The resource exploration program for the Moon will require more than a single mission--it will require a campaign of multiple missions; this is also certainly true for Mars. Mars explorers will benefit from the experience gained in the resource exploration process on the Moon.
   - Definition of Resources vs Reserves:
     - » Resources are defined as occurrences that may or may not be collected or viable for use.
     - » Reserves are defined as resources that have known location, spatial extent, volume, and have a technology system(s) that can perform extraction and processing to the point of sustaining human exploration and stimulating commercial development.

2. Because of its distance from the Sun and its surface conditions, sustainable human exploration (including ISRU) on Mars will require nuclear power. Using the Moon as a testbed to develop nuclear power systems would therefore be a particularly valuable feed forward to Mars. In addition, ISRU systems for sustainable human missions to both the Moon and Mars will require power systems that are scalable, where the demand changes greatly with time. Power generation systems at both locations likely will need to be diverse (e.g., a mixture of solar power, nuclear power, and radioisotope power) and include a variety of power storage systems (e.g., batteries, regenerative fuel cells) to meet ISRU and broader mission power requirements.

3. Several technology developments/demonstrations at the Moon would be highly valuable to Mars. The development of autonomous capabilities as part of an overall ISRU system will be extremely important for Mars, and all developments at the Moon in this area would constitute valuable heritage. The group encourages leveraging existing industry experience on Earth (e.g. in reliability, applications, challenges) in the area of autonomous mining/processing operations. Because of the strong interest in water resources on Mars, another obvious benefit from the Moon would be in the areas of water clean-up, water electrolysis, product liquefaction and storage techniques. Finally, depending on which martian water resources are utilized, valuable heritage at the Moon may be established in the areas related to materials handling (excavation, transport, transfer systems, and water-regolith reactors). Learning to operate and maintain ISRU systems on the Moon will uncover unknown-unknowns that will directly inform operations planning for Mars.

4. Both methane and hydrogen (pending the development of zero-boil-off storage) should be considered viable propellant options for human missions to the Moon and Mars, and for heritage reasons it would be valuable to use the same propulsion system in both places. The trade between these two is larger than just ISRU, but ISRU planning (on both target objects) will be strongly influenced by the outcome of this decision.

5. ISRU construction (of roads, landing pads, and radiation and thermal protection) will be critical for long-term sustainable habitation on both the Moon and Mars. Plume-surface interaction in particular poses potentially major threats to mission hardware, and experience developed at the Moon will be a critical input to Mars mission designers.

6. There will be legal ramifications for commercial and potential multi-national resource extraction activities on both the Moon and Mars. Precedents established at the Moon are very likely to carry forward to Mars, and Mars planners should stay engaged in the discussions.

APPENDIX A

SUMMARY DESCRIPTIONS OF PREVIOUS AM WORKSHOPS

Our first ***Affording and Sustaining Human Exploration of Mars Workshop*** (**AM I**) was held in December 2013 and consisted of a community-based critical assessment of the affordability of non-NASA scenarios for human missions to Mars, the case for science as a key element in the human exploration of Mars, opportunities for international partnerships, precursor missions, and building on the International Space Station (ISS) experience in the management of complex programs.

AM II was held in October 2014 and continued critical assessments of Mars exploration scenarios that were updated in response to AM I findings and observations. Scientific exploration of Mars using astronauts was introduced as a priority activity for the proposed scenarios.

AM III took place in December 2015 and focused on side-by-side comparisons of potential Mars mission architectures and strategies, and integrated specific science goals with increasingly detailed human space flight scenarios that would modify the science goals to be consistent with human space flight goals, and vice versa. Planetary protection considerations were also incorporated in the goals.

AM IV, held in December 2016, involved an assessment of technology investment strategies and priorities, including a detailed timeline for key milestones. AM IV participants assessed the achievability of various critical capabilities (or technology and engineering "long poles") in the human exploration of Mars.

During **AM V**, held in December 2017, participants developed and critiqued three distinct scenarios (Figure 1) for human exploration of Mars that were distinguished by their final "end states." These three scenarios were used to identify common technology investments, as well as those investments that were unique to each end state.

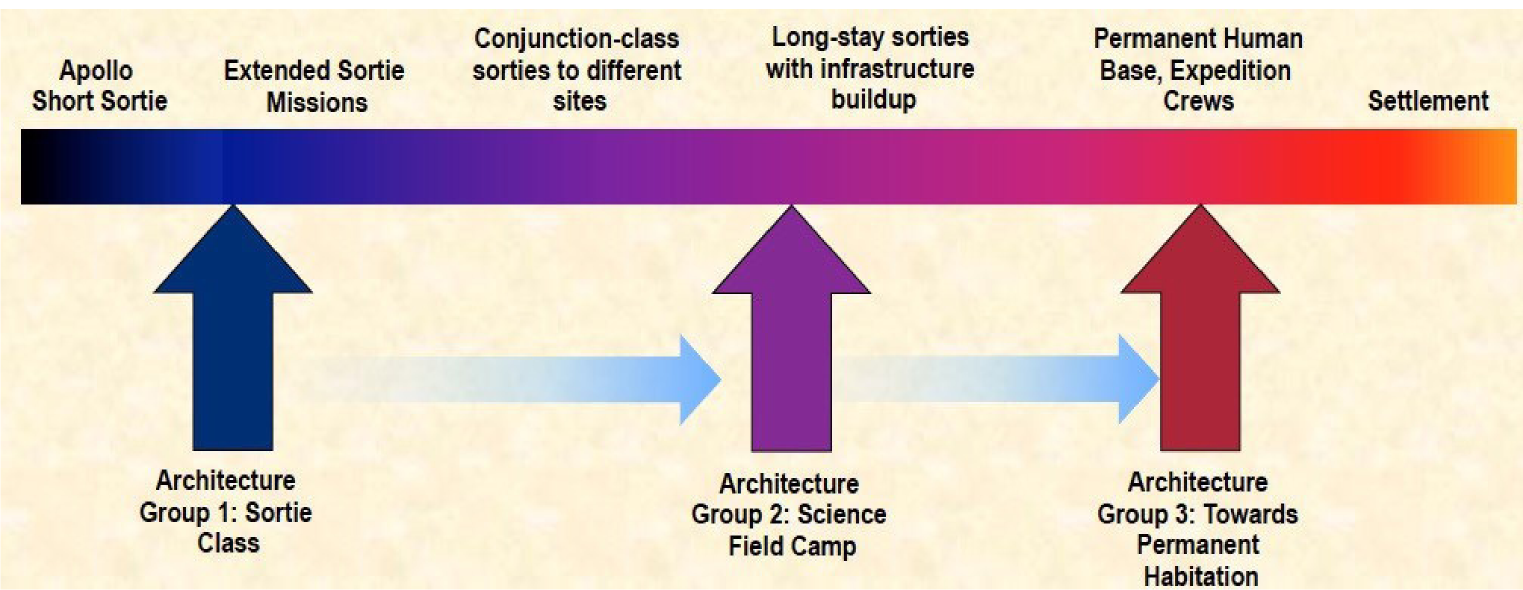


***FIGURE 1:** Three "end state" architectures assessed in AM V along the continuum of plausible astronaut exploration scenarios.*

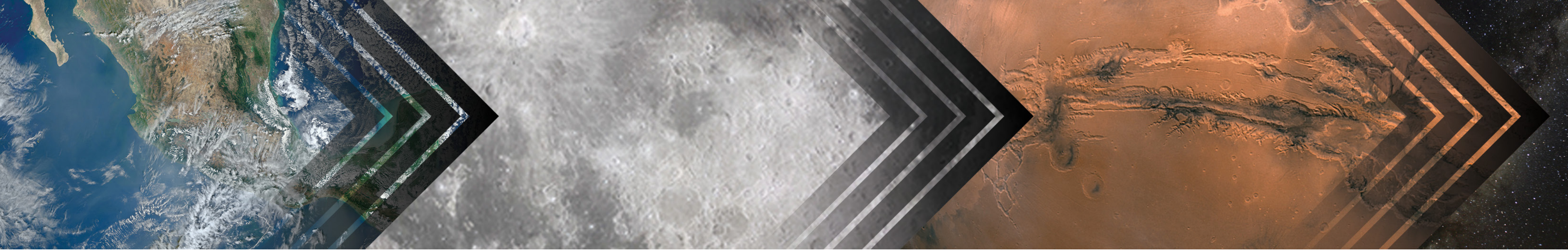
With a renewed emphasis by NASA on sustainable human lunar exploration, AM VI, which was held in August 2018, included members of the lunar community, permitting detailed discussions of Moon-to-Mars development synergies. The extensive analysis of Mars technology "long poles" and strategy from AM IV and the three distinct Mars exploration scenarios assessed during AM V positioned the AM VI team well to critically examine and analyze commonly advocated lunar operations and capabilities and to determine whether they could enable subsequent human exploration of Mars.

APPENDIX B

ADDITIONAL DETAILS SUPPORTING MAJOR FINDINGS OF THE CAPABILITIES WORKING GROUP

The summary assessment of the Capabilities Working Group is provided in the following set of tables. Key outputs are the functions and operations that show some degree of benefit to reducing risk for Mars from the planned NASA activities under the ISS and Artemis human spaceflight programs. Prior to each table a brief description of the Working Group's thought processes and main points of emphasis for each area is given. Within the tables, comments are included to explain the rationale for the rating given to each venue. The column **Mars Precursor** refers to a robotic precursor mission to Mars that might be either an uncrewed orbiter or uncrewed lander with limited capability. Such a mission might include elements of the Mars Sample Return (MSR) architecture.

N/A indicates that this platform is not applicable for this activity.



The top concern addressed, linking back to the findings of the AM VI workshop, was Human Health. This also proved to be an area where the Capabilities team saw many opportunities for lunar activities to benefit Mars missions. In fact, the Artemis program was shown to benefit all of the 17 individual activities / technologies examined.

Table B-1 Assessment of Human Health Activities and Technologies

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
HUMAN HEALTH ACTIVITIES AND TECHNOLOGIES						
Human Response to Galactic Cosmic Radiation (GCR)	Need to expand database with more people, diversity, and duration.	○	◑	◑	N/A	• You can measure in-space GCR exposure better at Gateway (correct GCR environment), but you can't test its long-term effects on crew because of duration • You can measure surface GCR exposure on lunar surface, but can only test long-term effects if surface duration is long • The only way to mitigate crew exposure to GCR is to use significant mass (e.g. blocks of concrete or water), which is inefficient for in-space exposure • Can test potential GCR mitigation on Gateway or lunar habs • On lunar surface, you have unlimited mass (civil engineering), but only provided appropriate material handling equipment are part of surface infrastructure
Latent Communications	How does crew deal with ops with up to 40 minute time delays?	○	◑	◑	N/A	• Simulated on ISS and/or Gateway by putting in communication delay – also test psychological impact • Not a clear difference between Gateway or Lunar – higher bandwidth from lunar surface activity? • Need both Gateway and lunar surface to accurately represent Mars, where both the transfer vehicle in orbit and the surface infrastructure need to communicate with Earth. Gateway can be analog for the transfer vehicle while lunar surface is analog for Mars surface.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
HUMAN HEALTH ACTIVITIES AND TECHNOLOGIES						
Intermittent Loss of Communications	How does crew deal with ops during communications interruption?	○	◑	◑	N/A	• This is part of the human performance and should test the psychological impact • Loss of communications is both a test of the technical issues as well as a test of impact on the crew psychological well-being • Can't get high-fidelity test on ISS – doesn't feel real (MCC can always hear the crew) • If you have relays you won't have long-term loss of comms at Mars, but worst case with no relays (solar conjunction) is 70 days • Surface rover loss of communications (due to terrain) can be tested on the lunar surface
Crew Isolation Mitigation	How will crew react to being in a small confined space so far from Earth for long duration?	○	◑	◑	N/A	• Some difficulties in simulating effects on Moon due to large difference in proximity of Moon and Mars to Earth; can be partially mitigated if communications time delay is incorporated • Modifications could be made to the ISS to make it more realistic, however, this is difficult to do without cutting crewmembers off from the cupola and other needed equipment and supplies; confine crew to smaller region to understand the psychology. Additionally, ISS has restrictions associated with utilization priorities – programmatically challenging to implement • Gateway does not have a national lab component – ~1/9th the size of ISS – or at a maximum it is smaller platform than ISS – feels more confined than the ISS and lacks a cupola With a split crew between Gateway and lunar surface, the crew on surface experiences a similar isolation environment to that of Mars mission (crew cut off from return vehicle) • The lunar surface more closely resembles that of the martian environment because you can have control over the platform and create a purposeful smaller hab to conduct test. Split crew between the habitat and in the rover • If the habitat volume and configuration is not representative of the Mars habitat then it's not relevant to Mars

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
HUMAN HEALTH ACTIVITIES AND TECHNOLOGIES						
Crew-to-Crew/ Crew-to-Ground Interactions	How much do we need? How much is too much?	N/A	◑	◑	N/A	• Long-term interpersonal interactions/conflict can be simulated to analogs (the accuracy of the simulation is highly dependent on the four people and the fidelity of the mission operations and the habitat environment –individuals with psychological and personality characteristics similar to those of astronauts are required for testing – astronauts like to be busy and useful) Rotation of crews occur frequently on the ISS – interpersonal conflicts don't last for the duration of a Mars mission • Gateway (and ISS) mission duration may not be long enough to be representative of Mars – which at a minimum would be 1,100 days • Lunar surface has the appropriate level of crew isolation and the architecture of the hab must be relevant, the duration may not be long enough • Comm delays similar to those for Mars could be partially, but not fully, simulated.
Habitat layout and design (transit and surface)	How should it be designed for optimum mission performance and crew health and safety?	N/A	◑	◑	N/A	• ISS design is most likely not relevant, and can't be modified Gateway is an opportunity to represent the transit vehicle design, but requirements must be written to represent the MTV design. • Same thing for lunar surface if designed to the requirements to represent Mars • This may not be required for Moon operations alone, but Mars testing requirements should not be excluded
Crew quarters/ sleep systems	How much space and what design is required?	N/A	◑	◑	N/A	• ISS is good simulation for transit hab sleep situations assuming representative crew quarters are available. • ISS is a good place to research sleep disorders associated with weightlessness, lighting, and noise, even if the crew quarters are not representative • Gateway has the same issues as ISS; but more flexibility to remodel the Gateway crew quarters to resemble the MTV • Lunar surface provides an excellent opportunity to learn differences between microgravity and low gravity. Surface crew quarters should be equivalent to expected Mars configuration

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
HUMAN HEALTH ACTIVITIES AND TECHNOLOGIES						
Human/machine interaction (HMI)	How are effective interactions designed into systems?	N/A	◑	◑	○	• Includes computer systems, robotics, hardware, and mechanisms • Commanding robotics on the Moon from Gateway will be relevant to Mars telerobotics from orbit • ISS and Moon can be used to develop a set of standards that will inform Mars requirements • Possible testing of wearables (haptics and position tracking) on lunar surface for testing HMI for Mars • Opportunity to test safety questions as well • Mars surface HMI (offloading equipment, rovers, mechanisms, habitat systems) will be relevant to lunar surface HMI if surface infrastructure is similar. • Starting to find the unintended consequences of AI that we don't understand – NASA does not need to invest in AI – private sector off-the-shelf • Most airline accidents are due to failed HMI or overriding of machine learning • Crew will be in direct contact with surface assembly robots
Long-duration zero-g exposure	How do humans adapt and function in zero-g?	●	◑	N/A	N/A	• ISS is an ideal platform and Gateway can be modified if duration is extended, lunar environment can be simulated from low g to zero-g • But interpolation between them is possible
Human response to partial gravity	How do humans adapt and function in 1/6 or 1/3 gravity?	N/A	○	●	N/A	• ISS not a good platform to test partial gravity • Transition can be tested at the Gateway • Lunar surface depending on mission duration you can understand physiological impact of partial gravity
Crew reconditioning after landing	How long does it take the crew to recover to be able to perform required activities?	○	○	◑	N/A	• Some testing possible as crew members return from ISS on commercial crew vehicles • Include more advanced medical tests • Possible testing on Gateway if stay time is extended– ideal duration similar to Mars mission transit. • To test reconditioning the duration should be similar • Allows opportunity to contrast new exercise system against legacy systems – on ISS or Gateway but Gateway more constrained • Impact of reconditioning in low gravity environment can be measured on lunar surface.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
HUMAN HEALTH ACTIVITIES AND TECHNOLOGIES						
Food Systems	What effects does deep space environment have on nutrition?	N/A	◑	◑	N/A	• ISS enables testing of food growth – and the impact on crew – including psychological • Extensive prototyping on ISS
Waste management	How is this best facilitated?	◑	○	◑	N/A	• Lot of this on ISS – this includes metabolic and non-metabolic waste • ISS can help with transit testing, but human waste is different in zero-g vs. low-g • Universal waste management system designed for low gravity too • Gateway will allow for testing in smaller spaces – you could test ejection of waste • Planetary protection concerns can be tested and evolved on Lunar – but this is a policy restriction but this is different for Mars
Personal Hygiene	How is this best facilitated?	N/A	◑	◑	N/A	• For ISS is limited but ability to add • Personal hygiene taking care of body maintenance, washing • Gateway may be opportunity to separate waste and personal hygiene management • Lunar in low gravity environment allows us to test showering and other hygiene environments • Clothing is a challenge because ISS we can logistically send clothes. Laundry depends on separation – so testing on Lunar service in partial gravity – ISS provides opportunity for testing but lunar surface give opportunity to laundry testing
Medical diagnosis and Treatment	How do we deal with not being able to bring someone home right away?	○	◑	◑	N/A	• ISS is where we are testing most of this. Both monitoring vital statistics and general health. With doctor consultation. But also detection of anomalies and on-orbit. • The tools for the crew to do that autonomously can be testing on the surface of the Moon but you could go through those operations on Gateway or the Moon. • Body posture issues better testing on Lunar Medical treatment procedures and potential crew injuries in low gravity will be different than in zero gravity – lunar surface will help prepare for Mars surface

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
HUMAN HEALTH ACTIVITIES AND TECHNOLOGIES						
Crew Health Countermeasures	What steps can be taken to counter effects of radiation exposure/ micro-g duration?	◑	◑	◑	N/A	• Includes exercise equipment, medication, and more research needs to be done • Test fluid shifts in eyes and potential site degradation – need to test on lunar surface for low gravity • Issue is around radiation exposure for the most part – around cancer and woman already at higher cancer – overexposure limits much lower for women • Can you take drugs that can be protective? • With long duration we can develop protocols for Mars • You need the low-gravity to test exercise
In-flight Fabrication and Repair	What steps can be taken to counter effects of radiation exposure/ micro-g duration?	◑	○	◑	N/A	• Important to ensure that medical equipment continues to function • Low gravity fabrication environment (including particle mitigation) will be different than in zero gravity or 1G

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

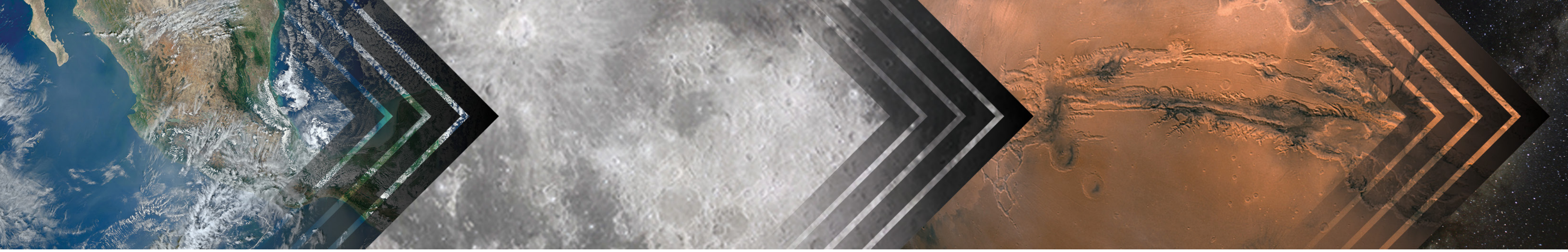


Table B-2 describes the sequence of functions required to successfully touch down on the surface of Mars. This includes some technologies, such as supersonic retro propulsion, which have not been implemented on previous Mars landings.

Table B-2 Entry Descent and Landing Activities and Functions Assessment

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
ENTRY DESCENT AND LANDING ACTIVITIES AND FUNCTIONS						
Long-duration environmental exposure of materials and systems	How do we ensure that deployables that have been stored in space for long durations will deploy as expected?	○	◑	◑	N/A	*Context: Must ensure that subsystems such as inflatables will deploy correctly after years of being packed and exposed to space environment.* • Where should testing be conducted? Vacuum and thermal cycling testing can be done on Earth or on the ISS, but cis lunar environment is required for radiation exposure testing. Must be long-duration testing (years). Must perform testing after deployment, so it's necessary to return to Earth's atmosphere. • Gateway is likely the optimum place to test (plume impingement, radiation, thermal cycling, loads) if it's possible to return test articles to Earth
Thermal protection system function	How do we test TPS materials in realistic environment?	○	N/A	N/A	●	• Same rationale as above. Could be done as re-entry portion of the previous test.
Aerocapture	How do we test aerocapture in realistic environment?	○	N/A	N/A	●	*Context: Must validate the theory.* • Must test at Mars because of unique aerodynamics. Some level of Subsystems testing can be done in high Earth orbit.
Hypersonic aero-maneuvering	How do we test hypersonic aero-maneuvering in realistic environment?	○	N/A	N/A	●	*Context: Must validate that the aerodynamics theory works in practice with a very large vehicle* • Conduct final testing at Mars, but should also conduct LEO testing

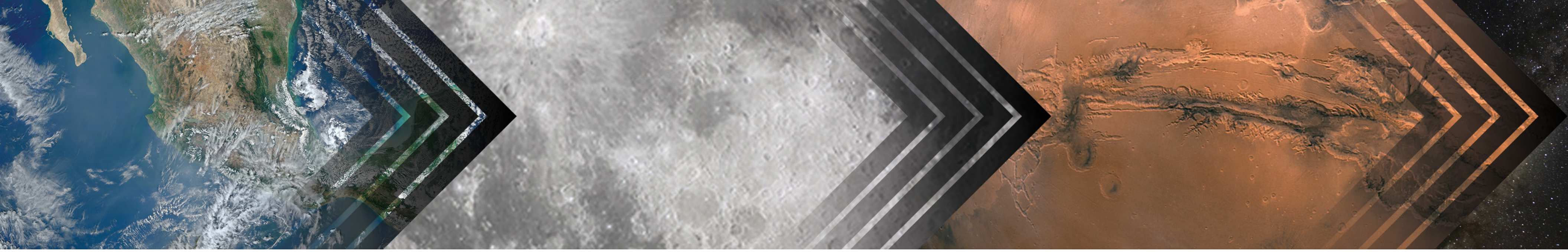
LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
ENTRY DESCENT AND LANDING ACTIVITIES AND FUNCTIONS						
Supersonic Retro-Propulsion	How do we test supersonic retro-propulsion in realistic environment?	○	N/A	N/A	●	Can do some testing on Earth (SpaceX Falcon 9), but optimal location is Mars,
Separation events	How do we test separation events in realistic environments?	○	○	N/A	●	*Context: separate heat shield, backplane, so some atmosphere is required* • Can't conduct testing on moon (no atmosphere), but can do some at high atmosphere Earth, LEO, but still need to go to Mars. • Entry velocities for testing in Earth atmosphere can be achieved via secondary payloads released from Cislunar trajectories (e.g. logistics flights)
Sensor operation	Test of sensor suite under actual landing conditions	N/A	N/A	◑	●	• Testing at the Moon provides risk reduction because of Mars-like terrain and descent profiles.
Terrain Relative Nav & precision landing	Test of TRN under actual landing conditions	N/A	N/A	◑	●	• Same as above
Guidance, Nav and Flight Control	Test of GN & FC under actual landing conditions	N/A	N/A	◑	●	*Context: integration test* • LEO, Earth, don't need to go to Moon, but can piggyback on HLS
Terminal constant V descent	How do we test terminal constant V descent?	N/A	N/A	●	◑	*Context: terminal descent phase;* • could test on Earth, can piggyback onto HLS or CLPS – free with Artemis; could partially test on robotic precursor landers at Mars
Landing gear deploy	How do we test landing gear deployment in a realistic environment?	N/A	N/A	◑	●	• Can't test in Earth upper atmosphere because of atmospheric friction
Landing attenuation systems	How do we test landing attenuation systems in a realistic environment?	N/A	N/A	●	N/A	• Will be used on HLS.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
ENTRY DESCENT AND LANDING ACTIVITIES AND FUNCTIONS						
Touchdown and soil interaction	How do we evaluate effects of propulsive landing on surface and nearby objects?	N/A	N/A	◑	●	*Context: plume/surface interaction* • Moon will help but gravity, atmosphere and surface are all different on Earth/moon vs. Mars. Need some data from a robotic precursor at Mars to determine whether or not you need a prepared surface.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN



The list of primary surface operations is presented in Table B-3. These functions are assumed to begin immediately after landing and to continue through the lift-off of the ascent element.

Table B-3 Assessment of Surface Operations Activities and Functions

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
SURFACE OPERATIONS ACTIVITIES AND FUNCTIONS						
Post landing configuring	Doffing suits, stowing items, throwing switches for systems, etc.	◐	N/A	●	N/A	• Can use ISS as an analog and test productivity recovery on Earth for 3/8g Mars human conditioning • Some added benefit to performing this on the moon (has to be done anyway on the moon) and can compare to results from ISS analog • With extended duration Gateway missions prior to lunar descent can assess task performance with deconditioned crew • Because of the differences in gravity environments, post-landing ISS testing in conjunction with lunar surface testing can completely burn down the risk for Mars
Solar array and other deployments	How do deployable elements such as solar arrays and radiators function in the surface environment (partial-g, thermal, etc.)?	N/A	N/A	◐	N/A	• Gravity will be a factor here, so can gain knowledge from moon. • Has to be done anyway on the moon and can compare to results from Earth • Somewhat dependent on surface infrastructure, but solar power for rover systems is unprecedented in gravity environments. Testing on the Moon is critical to prevent total mission failure on Mars.
Cabin systems surface operations	Surface systems checkouts	N/A	N/A	◐	N/A	• If ISS system, then you know microgravity and Earth, checkout on Moon will give you further validation of system checkout • Has to be done anyway on the Moon and can compare to results from ISS and Earth • Operating in partial g could reveal operating modes not possible in 0g and 1g

LEGEND	○ SOME BENEFIT	◐ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
SURFACE OPERATIONS ACTIVITIES AND FUNCTIONS						
Crew preparation for EVA	EVA suit assembly and checkout, prebreathe	N/A	◑	◑	N/A	• Prebreathe protocol (saturation) can begin partially on Gateway, then demonstrated on the lunar surface for improved prebreathe duration • Mass reduction, mobility, crew time for checkout and prebreathe can all be demonstrated on the lunar surface • Gateway and lunar will greatly benefit prebreathe
EVA egress and ingress	Getting in and out of lander, hab, rover, etc.	N/A	N/A	◑	N/A	• Testing and validation can be accomplished on Earth (e.g. NBL) • EVA egress and ingress on the lunar surface will provide lessons learned for Mars procedures and architecture beyond what can be accomplished in a laboratory setting
Surface EVA equipment and mobility	How do crews use surface EVA equipment and what items are used to assist in surface mobility?	N/A	N/A	◑	N/A	• Walking lower torso cannot be effectively demonstrated on ISS and Gateway as there is no way to walk in microgravity • Lunar surface will provide lessons learned with respect to hand holds, rover crew restraints, tool/sample stowage and retrieval, even walking, etc. in relevant field environments – Apollo data is very limited • Mobility, informatics, crew autonomy on the lunar surface can inform Mars surface capability • Tools operation
Cargo transport	How do we get cargo off a lander and moved where it is required?	N/A	N/A	◑	N/A	• EVA tools • Logistics transfer
End to End surface telecom	How do we talk to crews on the surface even in EVA situations?	N/A	N/A	●	N/A	• Assuming Artemis uses EVA with point-to-point telecom, lunar surface will fully retire risk for Mars (suits and rovers)
Deployment and ops of unpressurized rover	How is unpressurized rover deployed? How will we operate it?	N/A	N/A	◑	N/A	• Testing in partial gravity and dust and electrostatic environment will help inform Martian con ops for unpressurized rover as well as maintenance/repair

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
SURFACE OPERATIONS ACTIVITIES AND FUNCTIONS						
Deployment and ops of pressurized rover	How is pressurized rover deployed? How will we operate it?	N/A	N/A	◑	N/A	• Testing in partial gravity and dust and electrostatic environment will help inform martian con ops for pressurized rover as well as maintenance/repair • Could test out pressurized transfer to other pressurized modules (e.g. tunnels or direct docking) • Could test out concepts of ingress/egress and/or logistics transfer between pressurized and vacuum environments
Deployment and ops of habitats	How do habitats deploy and set up in preparation for crews?	N/A	N/A	◑	N/A	• Testing in partial gravity and dust and electrostatic environment will help inform martian con ops for habitats as well as maintenance/repair • Ingress/egress methods can be tested • Dust mitigation protocol performance
Surface assembly and check-out	How do crews function on the surface while performing assembly and check-out of systems?	N/A	N/A	◑	N/A	• Can help inform line between what is automated robotically, remotely operated, teleoperated and IVA/EVA performed • Testing in partial gravity and dust and electrostatic environment will help inform martian con ops as well as maintenance/repair
Crew surface science operations	How effective are the crew members at achieving science objectives while wearing EVA suits under microgravity conditions?	N/A	N/A	◑	N/A	• Performing surface science operations with latency will help inform what is performed by IV crewmembers, science teams, etc.
Surface dust mitigation	Systems and procedures to mitigate dust impacts	N/A	N/A	◑	N/A	• A dust mitigation protocol is currently being worked and will be incorporated in operation on the lunar surface • Suit ports on pressurized rovers on the Moon will validate dust mitigation techniques for Mars rover operations • Sending components to the lunar and Martian surface will provide information on materials regarding dust and radiation • Lunar surface dust mitigation protocol will help inform the Planetary Protection and dust mitigation protocol Mars

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
SURFACE OPERATIONS ACTIVITIES AND FUNCTIONS						
Crew post-EVA operations	EVA suit cleanup, suit maintenance and repair, stowage	N/A	N/A	◑	N/A	• Suit maintenance on the lunar surface will help inform dust mitigation and planetary protection protocols on Mars and logistics and sparing philosophies for Mars
Prep for ascent	Procedures required to prepare vehicle for ascent from surface	N/A	N/A	◑	N/A	• *Some added benefit to performing this on the moon (has to be done anyway on the Moon) and can compare to results from ISS analog*

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

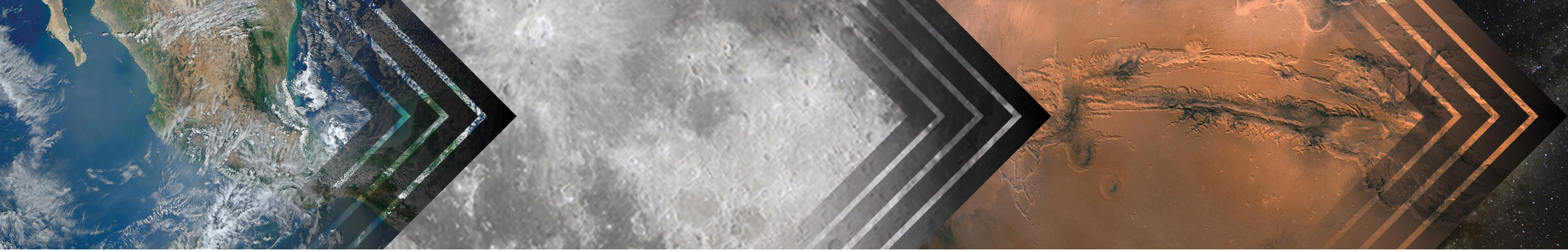


Table B-4 presents the functions that were directly related to the utilization of in-situ resources. While this was primarily taken to be volatiles that can be processed to make rocket propellants and other consumables such as oxygen and water, there were also functions associated with use of resources to build structures, provide radiation shielding, etc. Landed Mars Precursor robotic missions could make contributions if appropriately instrumented.

Table B-4 Assessment of In-Situ Resource Activities and Functions

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
IN-SITU RESOURCE ACTIVITIES AND FUNCTIONS						
Resource Identification and Characterization	What steps are required to understand the quantity and quality of the resources? How can this be done with robotic missions? How can it be done with astronauts?	N/A	N/A	◑	◑	• Landed lunar mission that prospects the available resources is applicable to Mars, but only partially, depending on the resource being assessed. Some of the equipment and techniques could be common or related.
Surface Power for ISRU	What power levels will be required to achieve significant production of useful resources? What types of power sources should be used?	N/A	N/A	◑	N/A	• Landed lunar mission is needed. Directly applicable. Different diurnal and thermal environment make it only a partial qualification, but could be high fidelity for some applications like fission reactors.

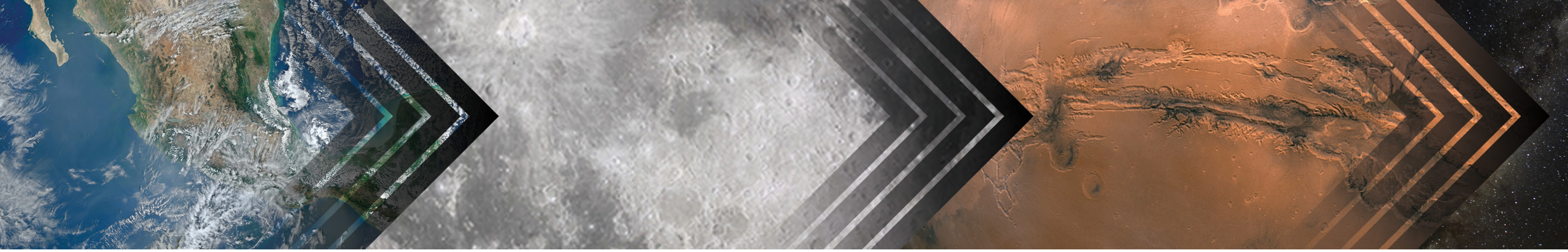
LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
IN-SITU RESOURCE ACTIVITIES AND FUNCTIONS						
Regolith Excavation	What methods of extracting regolith will be most effective? How can these be used to support human missions?	N/A	N/A	◑	◑	• Landed lunar mission needed. May be common techniques and equipment, but only a partial qualification due to the different environments.
Subsurface Water Extraction	What options exist to extract subsurface water and how can these be tested?	N/A	N/A	◑	◑	• Landed lunar mission needed. May be common techniques and equipment, but only a partial qualification due to the different environments. Sublimation issues in both locations.
Water Extraction and Purification	What processes are involved in extraction and purification of water?	N/A	N/A	◑	N/A	• Landed mission only way to do this . Could be a high fidelity qualification for Mars. Might even use common equipment.
O_2 and H_2 Production from Water	What processes are involved in producing O_2 and H_2 from water?	N/A	N/A	◑	◑	• Landed mission only. Could be a complete qualification. The main difference is 1/6 vs. 1/3 g.
Lox and LH_2 Liquification	What process is involved in liquefaction of O_2 and H_2?	N/A	N/A	◑	N/A	• Landed mission only. Different thermal environments, but could possibly use some common equipment. High fidelity qualification.
Cryogenic Propellant Storage	What technologies and processes will be required to achieve near-zero boiloff cryogenic propellant storage?	N/A	N/A	◑	N/A	• Only a partial lunar surface qualification for cooling pumps and maybe some other components.
Cryogenic Propellant Transfer	What processes are required to transfer large amounts of cryo fluids in partial gravity?	N/A	N/A	◑	N/A	• Landed mission only. Potentially a complete qualification.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
IN-SITU RESOURCE ACTIVITIES AND FUNCTIONS						
Atmospheric Lox Generation	A key for Mars since atmosphere can be accessed globally.	N/A	N/A	N/A	●	• Mars precursor: Probably can best be qualified by Earth testing and analysis on a best effort basis and accepting the risk for Mars. Cannot be effectively qualified by Artemis elements.
Civil Engineering	How do you prepare sites for more sustainable human presence?	N/A	N/A	◑	N/A	• Bulk regolith movement, sintering, etc. could be broadly similar. May or may not be high-fidelity.
Regolith Shielding	How do you move regolith to provide effective radiation shielding for habitats?	N/A	N/A	◑	N/A	• Regolith movement hardware could be similar. Structural loads could be different due to different partial gravities.
In-Situ Manufacturing	What resources could be used for manufacturing? What processes are required?	N/A	N/A	◑	N/A	• Secondary consideration but will likely be needed for sustainable "outpost" mission operations.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN



Ascent functions and applicable venues are listed are listed in Table B-5. One comment of note is that much of the actual engine operation and function can be adequately and fully tested on Earth, thus it does not require actual testing in the cislunar environment. The exception to this is orbital operations and rendezvous and docking operations in deep space. Both of these functions are fully demonstrated by missions to the Gateway or by multiple vehicle aggregation in lunar orbit, especially NRHO or other high lunar orbits.

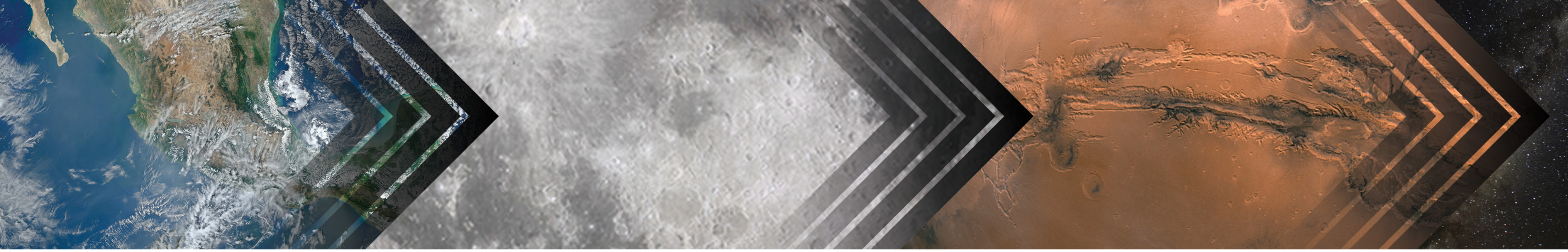
Table B-5 Ascent Activities and Technologies

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
ASCENT ACTIVITIES AND TECHNOLOGIES						
MAV autonomous spacecraft health monitoring and maintenance		N/A	N/A	◑	◑	• May belong in general capability gaps. • Situational self-awareness to adjust to variations in the martian atmosphere. • Gateway: Untended operations could be relevant to dormancy and self-monitoring, but there are no active environment variations. • Similar systems on both the unpressurized and pressurized rover will be directly relevant to MAV • MSR MAV: Could prototype some sensor technologies, but propulsion systems and scale are different.
MAV ignition and separation		N/A	N/A	○	◑	• Can test on Earth, can test in Earth atmosphere. If you have requirement for ascent abort, can test in Earth or lunar orbit. Will get some piggyback from HLS if they have ascent abort. • Could get aspects of this from lunar surface missions and MSR

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
ASCENT ACTIVITIES AND TECHNOLOGIES						
MAV ascent propulsion	Operation of the propulsion for the ascent stage through the complete profile required to return from the surface to an orbiting vehicle.	N/A	N/A	◑	◑	• Can test on Earth. Note that there might be some benefits to reduced gravity operation with ascent from lunar surface. Could get aspects of this from MSR
MAV orbital operations	Maintaining station on orbit, orbital maneuvers to approach orbiting vehicle.	N/A	●	N/A	◑	• Context: spacecraft functional verification (i.e. plane change maneuvers: have to take data, make decisions, fire thrusters, operate systems, etc.) • May get this for free from HLS; otherwise can test anywhere in cis lunar space (no lunar surface). Can take advantage of Artemis infrastructure. • May get aspects of this from MSR
Rendezvous and Proximity and docking operations with Deep Space Transport (or boost stage)		N/A	●	N/A	◑	• Get this for free at Gateway with HLS • Could get aspects of this from MSR on orbit rendezvous at Mars

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN



Part of the workshop charter was also to provide inputs to the planning for precursor missions and the functions that could be potentially tested in these missions. Table B-6 lists the output for precursors.

Table B-6 Precursor Activities and Technologies

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
PRECURSOR ACTIVITIES AND TECHNOLOGIES						
Radiation tolerant components	Use of deep space missions (Gateway, Mars probes) to test radiation tolerance and to look for alternative methods (dis-similar redundancy)	○	◑	◑	◑	• Earth – No. Cannot simulate GCR on Earth at the present. • ISS/LEO – No. Is not a good test point given that Van Allen belt filters away charged particles • Gateway/Cislunar – Yes. Provides excellent proving ground as it is beyond Van Allen belts and is representative of radiation levels in martian environment. • Lunar Surface – Yes. Accurate simulation for Mars surface components since the planet blocks half of the radiation. • Note: We should consider future deep space missions as testing venues for modern electronics. Alternative methods for determining acceptable radiation tolerance (dissimilar redundancy).
Build-up of communications infrastructure	Place relays in lunar orbit to test methods for Mars relays	○	◑	◑	◑	• Earth – Yes. Can complete some ground testing (Environmental, EMI) of communications equipment on Earth • ISS/LEO – Yes. Experimental platform for next gen technologies • Gateway/Cislunar – Yes, will develop comms infrastructure in cislunar vicinity that will prove out technologies for martian orbit, including optical communications and delay-tolerant networking. • Lunar Surface – Yes. Demonstrate installation of ground communication systems on lunar surface will prove out ground communication systems on martian surface including potential communications through a commercial relay satellite network.

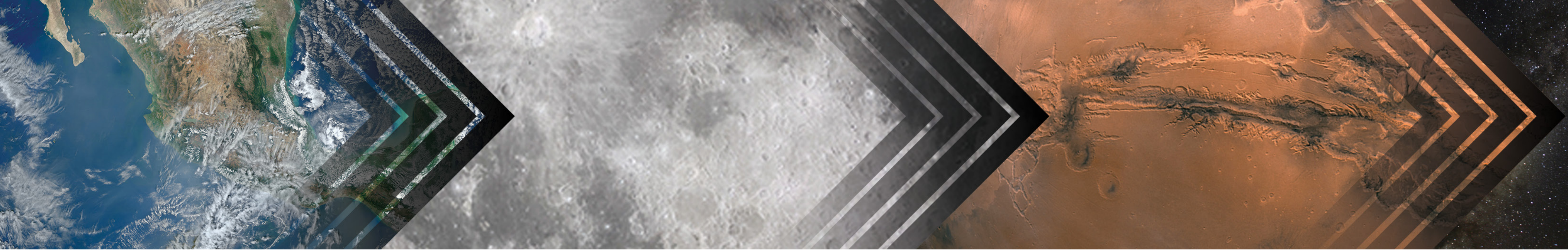
LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
PRECURSOR ACTIVITIES AND TECHNOLOGIES						
Latent communications	How to deal with the long delay in communications between the ground and the crew?	○	◑	◑	N/A	• Earth: Latency can be incorporated into analog missions • ISS: Latency could also be incorporated into ISS operations. • This will simulate the effects of delayed communications on psychology. • Moon: Latent communications during lander unloading or outpost assembly.
Loss of communications	How to operate in situations where communications is interrupted for a period of time?	N/A	◑	◑	N/A	• ISS: A loss of communications could be simulated onboard. • Moon: Lost communications during lander unloading or outpost assembly.
Special regions identification and characterization	How to deal with areas characterizered as special regions, which could potentially harbor life.	N/A	N/A	◑	●	• ISS/LEO – Maybe. Might be able to prototype surface observing technologies of Earth from LEO • Gateway/Cislunar – Yes. Developing mapping capabilities of Moon will help develop mapping capabilities for Mars • Lunar Surface – No. Requirements for biological sensors or planetary protection protocols are not defined. • Mars Precursor mission – May be required to map special regions in higher resolution.
Telerobotic operations and remote assembly	How to use teleoperated systems to prepare for crew arrival.	N/A	◑	◑	◑	• ISS/LEO – Yes. Can include remote control from ISS to Earth or vise-versa • Gateway/Cislunar – Yes. Earth to Gateway, Gateway to Lunar Surface • Lunar Surface – Yes. Earth to Lunar surface, lunar surface to lunar surface
Deployment of ISRU systems	What operations are required to get ISRU systems up and running?	N/A	N/A	◑	◑	• ISS/LEO – No. not related to ISRU operations • Gateway/Cislunar – No. not related to ISRU operations • Lunar Surface – Yes. Best environment for testing equipment and tech prior to Mars.
Cargo offloading and deployment	How do operations deal with getting cargo offloaded and for those systems requiring it, deployed?	N/A	N/A	◑	◑	• ISS/LEO - No. Not relevant due to microgravity environment • Gateway/Cislunar – No. Not relevant due to microgravity environment • Lunar Surface – Yes. Best environment for robotic capability and tech prior to Mars.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
PRECURSOR ACTIVITIES AND TECHNOLOGIES						
Remote/ autonomous habitat deployment	What operational considerations arise from preparing systems for arrival of crew?	N/A	N/A	◑	N/A	• ISS/LEO – No. not relevant • Gateway/Cislunar – No. not relevant • Lunar Surface – Yes. Best environment for testing equipment and tech prior to Mars.
Remote/ autonomous maintenance and repair of systems	How do you deal with required maintenance and unplanned repairs in the absence of crew?	○	◑	◑	N/A	• ISS/LEO – Yes. Can test capability of intelligent robotic systems in micro g environment • Gateway/Cislunar – Yes. Must test capability of intelligent robotic systems in micro g environment including potential comm delays (robotically maintained ECLSS, etc.) • Lunar Surface – Yes. Best environment for testing robotic systems and tech prior to Mars.
Dormancy	What special operational considerations arise from prolonged periods of untended systems?	N/A	◑	◑	◑	• ISS/LEO – No. Not good candidate for dormancy testing as always occupied. • Gateway/Cislunar – Yes. Will have lots of opportunity for no habitation in between rotations. Life support systems are harder to drain in microgravity (preparing for dormancy). • Lunar Surface – Yes. Will have lots of opportunity for no habitation in between rotations

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN



Finally, the working group felt that it was important to develop a set of off-nominal operations, which are shown in Table B-7. Off-nominal operations will be simulated, rehearsed, and potentially executed during the course of the Artemis lunar program. Lessons learned from these activities in the cislunar environment can contribute directly to the planning and improved safety of Mars missions.

Table B-7 Off-Nominal Operations

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
OFF-NOMINAL OPERATIONS						
Post-landing abort to orbit	Similar to above, but immediately after landing	N/A	N/A	◑	N/A	• Moon: Only environment with a surface to land and abort from. HLS will already need to test this since it automatically will return to orbit.
Failed deployments	Activities to address failed deployment of deployable systems such as solar arrays, radiators, antennas, etc.	N/A	◑	◑	N/A	• ISS: ISS EVAs (AMS repair, battery swap, ammonia coolant leak, etc.) prepare us for deployment problems and repairs on the MTV before departure for Mars. All MTV components will be deployed before departure.
Subsystem failure	Activities to address failure of one or more subsystems	◑	◑	◑	N/A	• ISS: Components such as ECLSS are repaired by astronauts. Systems on a Mars mission will be overall similar, although they will differ in detail. • Gateway: Testing internal component replacement to minimize the number of EVAs. Some external components will be serviced with robotic elements (CanadaArm 3). Gateway systems must be able to autonomously transition into safe mode. • Moon: Fixing subsystems on the exterior of a lander in an EVA suit/partial gravity.
Rover breakdown	Repair or rescue activities	N/A	N/A	◑	N/A	• Moon only (you can only drive rovers on the Moon). Repairs must be performed in an EVA suit in partial gravity.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

ACTIVITY/ TECHNOLOGY	DESCRIPTION	ISS/ LEO	GATEWAY/ CISLUNAR	LUNAR SURFACE	MARS PRECURSORS	COMMENTS
OFF-NOMINAL OPERATIONS						
EVA suit failure	Repair or rescue activities	◑	N/A	◑	N/A	• Much less risk to practice this on Earth than in space in the Neutral Buoyancy Lab. • ISS: Should be sufficient to practice in-space repairs (the suits break all the time naturally). We are assuming a modular suit design that does not need to be returned to Earth.
Medical (urgent care)	Treatment of non-acute injuries or illness	◑	◑	◑	N/A	• Medical information/delivery systems will be developed on Earth (they are already used in hospitals on Earth). • ISS: During closed-module, long-duration testing, someone will have a minor health issue and access the above database. • Gateway: Small, confined space to practice medical procedures; experimentation with a small medical kit. • Planetary surface introduces new risks (surface-related injuries) requiring medical procedures not used on ISS or Gateway.
Injured/ Incapacitated crew member	Transport, treatment, and securing crew member who cannot move or respond on their own	◑	N/A	◑	N/A	• ISS: Can be used to practice injury procedures during an interplanetary transit. • Moon: Practice moving an incapacitated crew member into the lander during an EVA. Can only be practiced in EVA suits and a low-g environment. The configuration of a lander will be different from anything on orbit: how do you bring an injured crewmember to the lander's habitable volume? Does astronaut selection need to include a fitness test for moving an incapacitated crewmember?
Fire detection, suppression, and clean-up	Locating the fire, isolating it, securing crew safety, and cleaning up areas impacted by fire	◑	N/A	◑	N/A	• ISS: Fires are currently being ignited on Cygnus cargo ships leaving the ISS to test how various compounds burn. These experiments could be enhanced by experimenting with the baseline habitat pressure for Mars missions. • Moon: A Cygnus-like experiment on a CLPS lander could test fire suppression in closed, partial-g environments.
Toxic atmosphere	Procedures related to detecting and responding to toxic atmosphere inside elements (habitat, rover, etc.)	●	N/A	◑	N/A	• ISS: Sensors in the space station already monitor for leaks of hazardous chemicals such as ammonia. • ISS procedures (e.g. evacuate) will not work for Mars transit or Mars surface. Alternate procedures can be developed with lunar infrastructure.

LEGEND	○ SOME BENEFIT	◑ SUBSTANTIAL BENEFIT	● COMPLETE RISK BURN DOWN

APPENDIX C

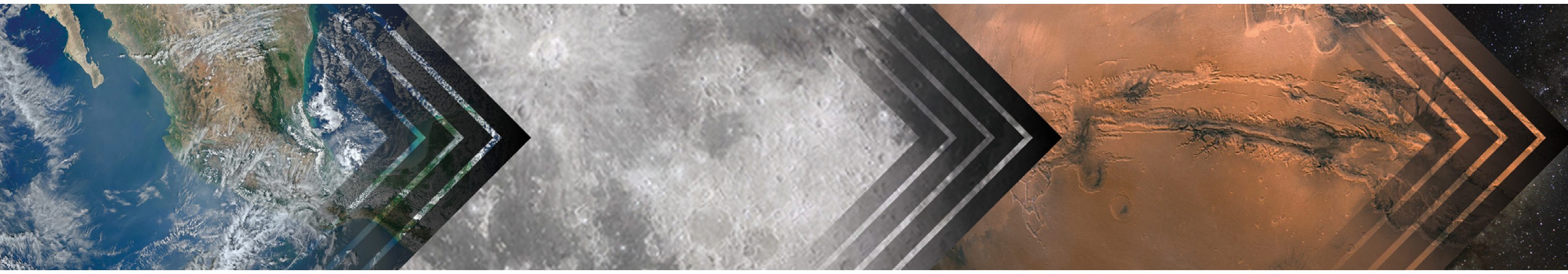
ADDITIONAL DETAILS SUPPORTING MAJOR FINDINGS OF THE ISRU WORKING GROUP

INTRODUCTION:

A premise of the anticipated upcoming Artemis program relating to the renewed human exploration of the Moon is that its ISRU program will serve two purposes: (1) Meet the needs of the human explorers at the Moon, and (2) Establish engineering heritage and operational experience that would benefit follow-on human missions to Mars. While recognizing that the systems developed as part of Artemis will need to be 100% functional in the lunar environment (in support of #1 above), there may be more than one way of doing things, and these differences may translate to different degrees of Mars-relevant heritage (#2 above). Although Topic #2 above has been espoused as a general strategy by the political side of the process, there has been a shortage of specific technical detail. The purpose of the discussion at AM VII, therefore, was to focus on Topic #2 above, so that as the science/engineering trade-offs are worked, the priorities and perspectives of the Mars system designers and explorationists can be considered. Our goal is that the final designs and strategies for use at the Moon include an appropriate mix of inputs from #1 and #2 above.

THIS DOCUMENT:

The discussions that are summarized in this report were carried out over a 2-day period, on Nov. 20-21, 2019. Each of the discussion topics listed below were debated orally, and the discussion's conclusions were summarized in one or more essential findings. Significant group effort during the workshop itself was devoted to the phrasing of the 24 findings listed in this report, so they represent the most refined aspect of this document. For convenience, a listing of all findings is presented in Appendix 1. As the discussion of each topic was brought to completion during the workshop, one or more documentarians from the group were identified, and those individuals were asked to summarize in writing, at the scale of a couple of paragraphs, the essential logic that led to the findings. These documentarians were additionally encouraged to identify 1-2 pre-existing figures to illustrate the key points, and to add a few references. Most of this writing took place in real-time, during the course of the workshop, while the main discussion group moved on to the next topic. There was not an opportunity for these paragraphs to be heavily edited, and the figures are mostly drawn from the personal knowledge of the documentarian(s) rather than the wider collective knowledge of the group. Post-meeting processing consisted of formatting, the addition of some introductory and context material, the reconciliation of inconsistencies, and importantly, the addition of the Executive Summary. However, in the post-meeting editing we have minimized the changes to the paragraphs, findings statements, or figures that were prepared while the group was together on Nov. 20-21. As such, this document should not be interpreted as a research paper—its purpose is to provide a scoping of the problem(s), some preliminary analysis to help guide further planning, and serve as a launching point for follow-on detailed analysis, potentially in the form of focused workshops or other group-level activities. Our intent is that the aspect of this document that should be extracted and used in other planning processes is the Executive Summary.



BREAK-DOWN INTO COMPONENT QUESTIONS:

In pursuing its charge, this AM VII working group first broke the problem into seven specific and manageable questions, on which it planned to spend time. The following primary component questions were identified (listed in priority order):

1. Which lunar resources exist that could be used to lower cost and/or risk for human missions to Mars and *on what timescale*? What are the knowledge gaps that stand in the way of a detailed plan for utilization of such resources for future Mars missions?
2. How do we progress from lunar resources to reserves?
3. What is the power architecture to support ISRU?
4. What opportunities to test technologies and operations for resource prospecting, characterization, extraction, and processing exist on the Moon that can reduce risk and cost for use in support of the human program on Mars?
5. What are the pros and cons of different cryogenic propellant combinations (e.g. methane, hydrogen, etc.) for lunar and Mars scenarios?
6. What are the applications and potential of ISRU-based site preparation and construction for landing, lift-off, and surface transportation operations in lunar and martian environments?
7. What are the ramifications (e.g. legal, operational, for partnerships, etc.) of commercial and international resource extraction on the Moon and Mars? How do any precedents that might be established by what we do at the Moon inform what we do at Mars?

In discussing these questions, the team chose to work from the following assumptions and definitions:

1. Public-private partnerships will be feasible and available for both lunar and martian human exploration efforts.
2. Given our current understanding, oxygen from lunar regolith is (mostly) a reserve.
3. Resources are defined as geological occurrences/deposits that may or may not be harvested or viable for use.
4. Reserves are defined as resources that have known location, spatial extent, volume, and technology systems that can perform extraction and processing to the point of sustaining human exploration and stimulating commercial development.
5. Dust suppression and control is a high priority for construction and mining on Earth as well as surface and infrastructure improvement around settlements and will be even more important on the Moon and Mars.

With these assumptions in mind, we relied on the expertise of our team to consider each of the above knowledge gaps in turn to arrive at concise findings. Herein we provide a summary of the discussions and background that support these findings as well as the findings themselves.

DISCUSSIONS AND FINDINGS

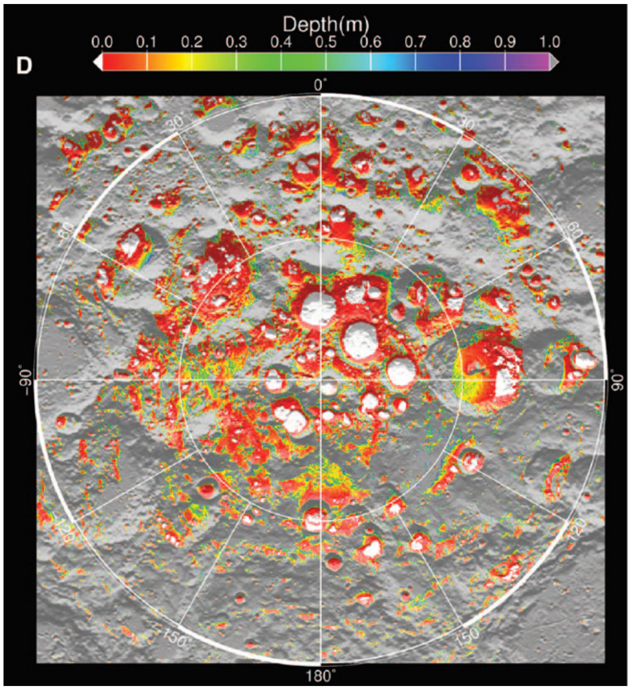
QUESTION #1

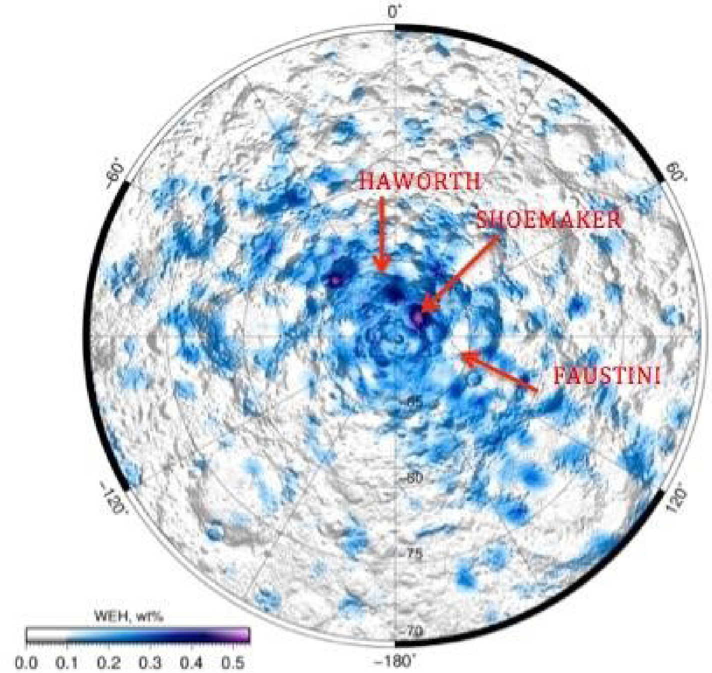
1. a. Which lunar resources exist that could be used to lower cost and/or risk for human missions to Mars and *on what timescale*?
   b. What are the knowledge gaps that stand in the way of a detailed plan for utilization of such resources for future Mars missions?

INTRODUCTION: Hydrogen and oxygen on the Moon offer significant potential to support human exploration of Mars in at least one, and possibly, two ways: (1) The Moon can be a useful proving ground for development and demonstration of ISRU technology and operations, which can then later be used in modified form for Mars. (2) ISRU production of propellant using hydrogen and oxygen and life support consumables on the Moon may potentially facilitate the transfer of human mission elements to Mars. For both of these purposes, the most promising resource is water and/or water ice found in the subsurface across lunar polar regions. As it applies to propellant, it is the resource with the greatest potential of becoming a reserve. In addition, as it applies to testing resource exploration technologies and operations, lunar subsurface water-ice may be similar to subsurface water-ice on Mars.

FINDING 1a: Rovers and instruments developed to identify and characterize near surface (within 1-2 meters) water-ice on the Moon would be immediately applicable to resource exploration on Mars.

BACKGROUND: If it exists, water-ice in the top 1-2 meters of regolith will be the most accessible on the Moon and Mars (***Fig. 1***). Quantification of (in terms of both values and uncertainties) the abundance, spatial distribution, depth distribution, mechanical properties, physical form, and presence of contaminants of either lunar or martian water-ice is lacking on the relevant spatial scales needed to design ISRU systems. The instruments and strategy for acquiring those data on the Moon are directly applicable to Mars. For example, both environments require a mobile surface asset to provide the appropriate spatial resolution, which is on the order of 1-10 meters (areal), to assess the heterogeneity of the surface material. Because the ice exists beneath the surface, we need instruments capable of exploring at depth to assess the amount of water-ice in a given region. Neutron spectrometers are useful for this purpose. Further, we will need a method to access the subsurface to directly sample the composition, determine the depth distribution, and measure the mechanical properties of the water-ice deposits. Possible methods of doing this are currently under discussion by the Lunar Water ISRU Measurement Study (LWIMS) team, under the leadership of Julie Kleinhenz and Amy McAdams. Developing either neutron spectrometers or subsurface drills for lunar exploration are just a few examples of the resource exploration technologies that would feed forward directly to martian exploration efforts.





[LEFT] from Paige et al. (2010) A thermal model is used to estimate the depth beneath the surface of the Moon where water is stable against sublimation loss over billion-year times. In illuminated polar regions, water ice is stable within tens of cm of the surface. In some permanently shaded regions, water ice is stable on the surface or near the surface. [RIGHT] from Sanin et al. (2017) LRO LEND measurements of the abundance of hydrogen in the lunar south polar region. [BOTTOM] from the Subsurface Water-Ice Mapping Team (SWIM) (2018), map showing the equatorward extent of locations on Mars where multiple datasets are consistent with the presence of near surface water-ice.

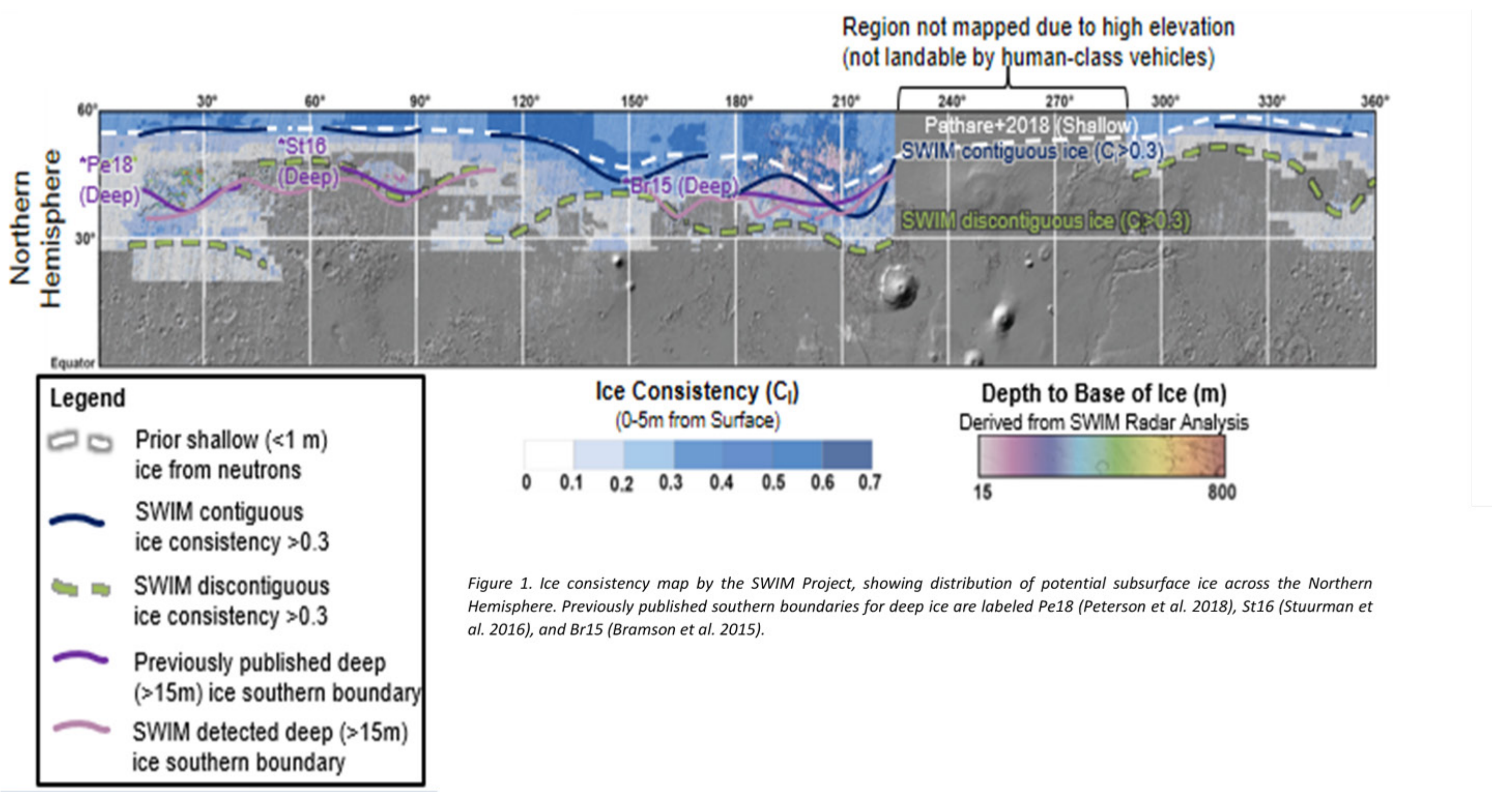


Figure 1. Ice consistency map by the SWIM Project, showing distribution of potential subsurface ice across the Northern Hemisphere. Previously published southern boundaries for deep ice are labeled Pe18 (Peterson et al. 2018), St16 (Stuurman et al. 2016), and Br15 (Bramson et al. 2015).

FINDING 1b: We do not yet understand the mechanical properties of water resources in lunar permanently shadowed regions (PSRs). If they exist and are found to be similar to the water-ice deposits on Mars, learning how to deal with hardened ice/regolith mixtures on the Moon will inform resource extraction techniques on Mars.

BACKGROUND: On both the Moon and Mars, it is possible to find water frozen between the individual grains of regolith, known as ice-cemented regolith. Additionally, water on Mars exists beneath the subsurface in enormous ice sheets and trapped as part of the molecular structure of rocks known as hydrated minerals. We do not yet understand the mechanical properties of these water resources, but assessment of ice-cemented regolith at the Moon could improve our understanding of similar water resources at Mars. In particular, we need to know how the mechanical properties of ice-cemented regolith change at different water concentrations and temperatures. We expect, for instance, that ice-cemented regolith is extremely hard at cold temperatures and at high water concentrations (***Fig. 2***). This will affect the design and requirements for extraction systems. Once we assess the material characteristics of ice-cemented regolith at the Moon, we can evaluate the feed-forward potential of extracting similar water resources on Mars.

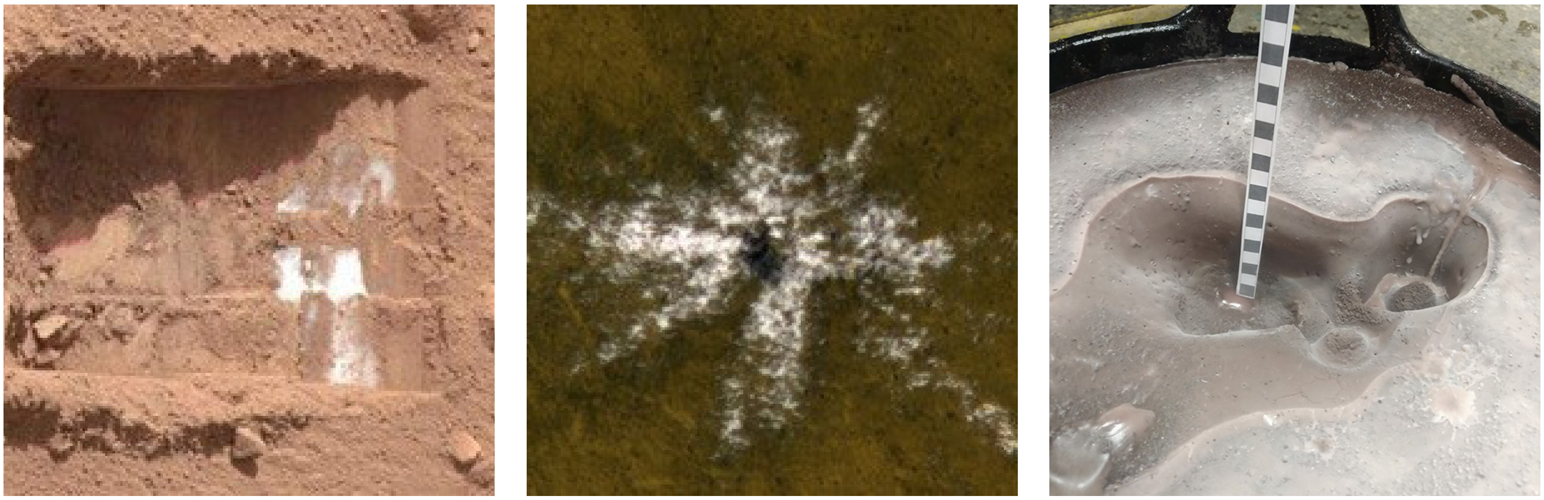


Figure 2: *Ice-regolith mixtures. The images show subsurface sheet-ice deposits from the Phoenix Lander[LEFT] and a HiRISE image of an impact crater [CENTER]. on Mars. [RIGHT] Image of ice-laden regolith produced in the laboratory for geotechnical investigations (courtesy of Paul van Susante)*

FINDING 1c: Architectures for sustainable human exploration of the Moon and Mars should be designed to be evolvable such that they can incorporate locally derived resources (e.g. water, oxygen, propellant) as the infrastructure necessary to access and process resources becomes available.

BACKGROUND: ISRU is critical for an affordable and sustainable exploration program. However, it will take time to develop the ISRU systems. While products derived from local resources will not be available by the time humans first get to the Moon and probably Mars, it is important that the human exploration architectures allow the use of locally derived products for life support, propellant, construction, etc., if and when they become available. Designing systems for the eventual incorporation of local resources will facilitate early incorporation of this asset and long-term sustainability.

QUESTION #2

2. How do we progress from lunar resources to reserves?
    a. Is there enough water on the Moon in a useable form to progress to a reserve?
    b. What form (e.g. blocks, mixture, layer, etc.) is it in? (see Findings 1a and 1b above)
    c. Does the technology exist to extract/process it?
    d. What measurements and knowledge are needed in order to make a decision about the viability of these resources?

INTRODUCTION: We do not currently have the knowledge necessary to classify any subset of the total volume of lunar water-ice resources to the status of reserves. Orbital InfraRed (IR) measurements suggest that in approximately 5% of lunar cold traps (regions where the annual maximum temperature is less than 110 K and water-ice is stable) and up to 30% of the total exposed surface mass is water ice [*Li et al.*, 2018]. The state of knowledge implied by the term "reserve" requires multiple kinds of information about the material to be acquired and processed, including the depth of the upper and lower boundaries, the stripping ratio, the nature of the non-ice waste components (gangue) of the ore, the ice concentration and its heterogeneity, chemical purity, the mechanical properties of both ore and overburden, and many other factors. That said, the limited sensing depth of IR instruments cannot directly determine the thickness, or by extension the total volume, of these ice exposures. The thickness of these deposits could be much thicker than millimeters (mm). At present, we do not yet understand enough about the physical characteristics of lunar water-ice deposits to consider them reserves for future exploration efforts.

FINDING 2a: Exploration to date supports the existence of several different kinds of water resources on the Moon. Elevating some subset of these resources to the status of reserves will require (1) more detailed/focused exploration (to further define location, spatial extent, heterogeneity, purity, etc.), and (2) development of the technologies needed to extract/process it. The process by which we assess the potential of lunar resources to become reserves will be directly applicable to martian resources, which will require the same kind of assessment.

Background: Data (specifically epithermal neutron data (***Fig. 3***) gathered from observations of surface-level water-ice deposits on the Moon suggest these may also exist in the subsurface. However, the thickness of these subsurface-ice deposits is still the biggest unknown. The total mass of lunar water ice has been estimated to be anywhere between 10 to 100 million tons at each pole, if the thickness of the ice deposits is about 0.5 m (***Fig. 4***).

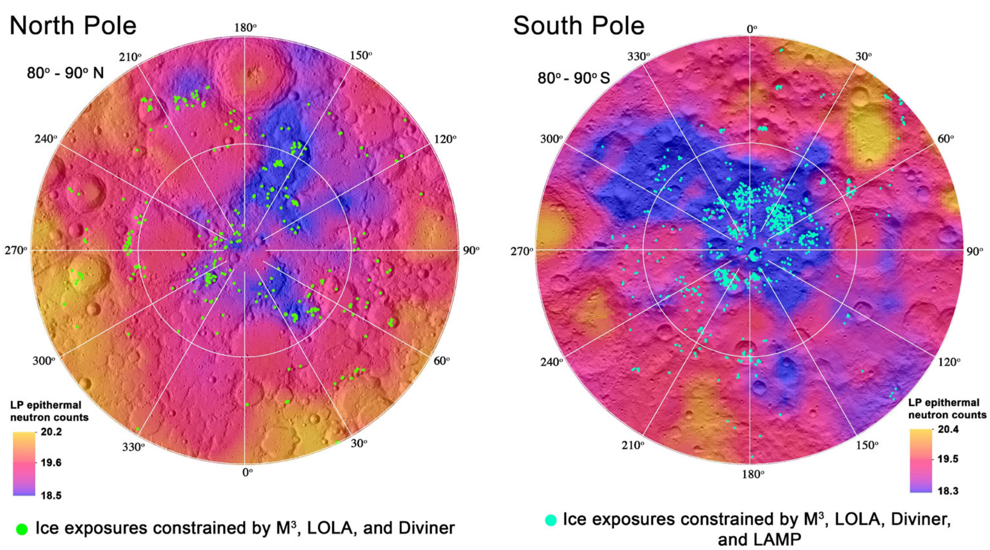


Figure 3: *Surface ice exposures observed in IR spectral data overlain on the epithermal neutron maps; lower epithermal neutron counts indicate more buried Hydrogen bearing species (e.g., water ice); the ice exposures are from [Li et al., 2018] and the epithermal neutron maps are from [Lawrence et al., 2006].*

Unfortunately, the low quality of IR data limits the detections of ice exposures. These data rely on the extremely weak stray light in lunar cold traps, only 1% or less intensity compared to illuminated regions on the Moon [*Li et al.*, 2018]. As a result, it is difficult to determine which of the ice detections are false positives or to determine the location and spatial extent of surface exposed ice in lunar cold traps. Further, IR measurements only sense at most the upper few mms. It is impossible to determine the vertical distribution of ice in lunar cold traps by IR observations alone. Missions designed to access the ice and verify the spatial and vertical distribution of ice in lunar cold traps are necessary to progress these resources to reserves.

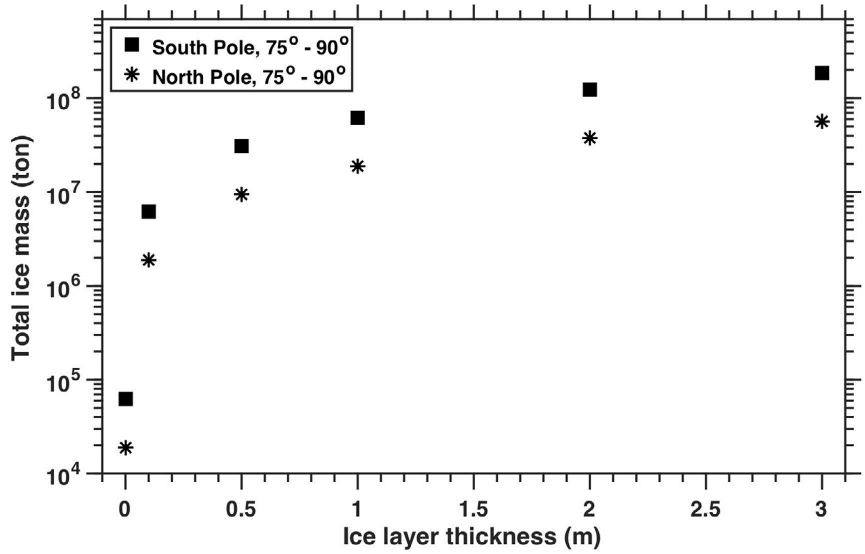


Figure 4: *Estimation of total ice mass in the lunar polar regions by assuming a wide variety of thickness of ice deposits, from 1 mm to 3 m; the ice content is assumed as 30 wt.% [Li et al., 2018].*

FINDING 2b: Answering knowledge gaps pertaining to the reserve-potential of water-based resources on the Moon will require more than a single exploration mission; it will require a campaign of multiple missions that includes ISRU technology demonstration.

BACKGROUND: Although orbital reconnaissance provides preliminary information on the abundance and distribution of water ice, determining if that water ice constitutes a reserve will require a surface exploration campaign. Critical knowledge gaps include: the vertical distribution of ice (in particular, the thickness of a superficial desiccated layer), the extent or patchiness of ice and local abundance (known to a few percent at locations of interest) within a region that is of a scale relevant to mining, and the geotechnical properties of the regolith–ice mixture to be excavated. In order to locate a deposit that meets threshold requirements for ISRU (i.e., a reserve), a *campaign* built on the example of terrestrial resource exploration is required. Lessons learned from terrestrial resource exploration include:

- regional reconnaissance to address the critical knowledge gaps and prioritize candidate target sites,
- more detailed exploration at prioritized sites to determine if they meet requirement thresholds set by mission needs, and
- demonstration of excavation and extraction techniques at an extraction site.

FINDING 2c: The existence of a stable market (e.g. government commitments to sustain a presence on the lunar surface) for the resource is necessary (but probably not sufficient) to enable commercial development. The same considerations will apply to Mars.

BACKGROUND: ISRU is necessary to establish a sustainable presence on the Moon and Mars. ISRU requires systems for excavation, processing, and storage of resources, cutting across many different terrestrial industries (e.g., mining, water purification, cyrogenic storage, etc.). The lunar exploration community should define a stable, long-term market to promote development of multiple innovative approaches to ISRU. To that end, we should explore lunar and martian resources and demonstrate ISRU concepts on the Moon and Mars to establish them as reserves. After establishing reserves, we can estimate the amount of material required for sustainable human exploration efforts over a defined period. Bids from commercial companies for different aspects of the ISRU infrastructure to meet the agency's estimated demand could then be solicited. This approach will not only stimulate innovation in the commercial space industry, it will also result in lower lifetime costs due to competitive pressure. *Committing to a sustainable program of exploration with long-term resource needs is key to stimulate participation from commercial providers.*

QUESTION #3

3. What is the power architecture to support ISRU on the Moon and Mars?
   a. What is the composition of the power system?
   b. How can we accommodate for increased power demand over time?
   c. How can power system architecture on the Moon inform that of Mars?
   d. What is the amount of power required for ISRU activities?

INTRODUCTION: The amount of power needed for sustained human presence on either the Moon or Mars is likely on the order of 100s to 1000s of Kilowatts (kW) whereas initial power needs are likely to be closer to 10s of kW. Although it may be feasible to meet initial power demands on the Moon with solar energy alone, it is unlikely that solar power could provide 1000s of kW of energy, especially on Mars. Exploration of Permanently Shadowed Regions (PSRs) on the Moon or anywhere on Mars needs a power source that is unaffected by the diurnal cycle of light and dark, as well as weather events (i.e., dust storms) that can significantly impact the local solar flux. In both cases non-solar power sources either alone or in combination with solar provide significant advantages over solar power alone.

FINDING 3a: Solar power alone is not sufficient to meet power needs of sustained human missions on either the Moon or Mars. Power generation systems at both locations will need to be diverse (e.g., a mixture of solar power, nuclear power, and radioisotope power) and include a variety of power storage systems (e.g., batteries, regenerative fuel cells) to create a resilient and robust power system for long-term habitation.

Background: Diversification of supply is a method to introduce inherent margin into the power system. We recommend that lunar and martian exploration architectures incorporate multiple power sources, both in number of sources as well as types of generation, to ensure redundancy if any one system goes down. Mission architects are currently examining multiple sources of power to provide the necessary power on the Moon and Mars. Power systems under consideration include solar power, nuclear power, radioisotope generators, and potentially others.

Power backup capabilities are critical to mitigating risk in emergencies. For instance, a base relying on solar power needs stored energy to maintain base functions for times when sunlight is not available. But in this case, other systems will place their own demand on stored power in addition to maintaining base functions. More specifically, exploration, logistics and ISRU vehicles will require some power storage systems on board to enable long-term mobility. Diverse power generation and storage ensures that the power infrastructure can meet the power needs of human exploration efforts even when one system is unable to meet demand or disabled.

FINDING 3b: ISRU systems for sustainable human missions to both the Moon and Mars will require scalable power systems to meet the demands of increased exploration activities without replacing infrastructure.

BACKGROUND: Initial missions will require much less power than a long-term, sustained human presence, and ISRU and habitat capabilities will require significantly more power than sortie exploration missions. Therefore, a scalable power generation system and power grid is essential to allow for increases in demand over time. We must consider scalability when designing initial power systems to create a system design that allows for additional connections over time. This is something that both solar and nuclear can do currently. That said, while we can adapt solar power to the lunar environment near PSRs, when looking to Mars, decreased solar intensity compared to the Moon and detrimental environmental conditions (e.g. dust storms) challenge the notion that solar power could meet human exploration needs. Nuclear power provides a constant, reliable energy source unaffected by most external conditions. While solar power may be sufficient (at least in the near-term) for lunar operations, we recommend integrating nuclear systems into the lunar architecture to verify their performance and concept of operations before deploying them at Mars. Nuclear energy provides a scalable power source to provide increasing levels of power over time as demand increases.

FINDING 3c: Because of its distance from the Sun and surface conditions, sustainable human exploration of Mars requires nuclear power. Using the Moon as a testbed to develop nuclear power systems would directly feed forward to Mars.

BACKGROUND: Determining a viable power source requires understanding the magnitude of the power required for a lunar or martian base. Unfortunately, no study that estimates the total power demand of human missions to the Moon and Mars currently exists. However, some studies do estimate the power required for ISRU activities to produce, store, and transfer fuel for a Mars ascent vehicle (MAV), or the craft that will return human explorers from the surface of Mars to orbit. Based on current NASA studies (Kleinhenz 2017), the amount of power needed for an MAV is 10s of kilowatts, when assuming one ascent vehicle per 26-month period. A lunar ISRU demonstration system could be useful to validate the reliability of both the power grid and the ISRU plant components and to size both the eventual Mars ISRU plant in terms of both mass and power. This information is vital for defining the total amount of power required for sustained exploration of the Moon and Mars.

FINDING 3d: Current sustainable human missions to Mars envision ISRU as a means of fueling the MAV. A demonstration of the primary ISRU production units (water clean-up, water electrolysis, and product liquefaction and storage techniques) on the Moon would have a strong feed forward to Mars. Any demonstration system will likely require 1s to 10s of kilowatts of power.

Background: As stated above, no published studies estimate the total amount of power required for sustained lunar or martian exploration. As such, we identified two outstanding questions that need to be answered as we develop the power infrastructure for future human exploration efforts: (1) What is the total per mission/per day power demand for sustainable human missions to the Moon and Mars? (2) How frequently do you need to meet the total power demand identified in question 1? These power demand estimates are critical to the design of power infrastructure. Activities at a lunar base could determine and/or verify total power demand estimates for future lunar and martian missions. In the meantime, research into the total power demand will help close this knowledge gap and inform the design of power infrastructure at both the Moon and Mars.

QUESTION #4

4. Identify opportunities to test technologies and operations for resource exploration, characterization, extraction, and processing that can happen on the Moon, to reduce risk and cost for use in support of the human program on Mars.
    a. Which technologies developed for the Moon can apply to Mars with minimal modifications?
    b. If Mars designers could levy requirements on lunar development, what are the development requirements for martian technologies that can be incorporated into technologies required for lunar exploration?
    c. Are the scales (e.g. demand, distances travelled, etc.) similar or different at the Moon and Mars?
    d. How do we develop the autonomy (e.g. sensing, operations, decision-making) and automation necessary to collect and process resources (end-to-end) at the Moon and Mars – particularly in areas that require human labor on Earth?

INTRODUCTION: While environmentally different, the Moon and Mars contain similar resources that can be used to sustain and support human life – water and regolith. Characterizing such deposits to understand their reserve potential requires autonomy of operations for mobility and operations that are repeated over an area of interest. Understanding the composition, form, extractability, extent, etc., of such deposits will be required on the Moon and Mars. Extraction capabilities will likely be very similar at both locations, as will processing. The Moon may have more challenging in storage of refined products relative to Mars, especially in terms of storage cryogenic propellants, although use of permanently shadowed craters at the lunar poles could mitigate this.

FINDING 4a: Engagement with terrestrial industries could potentially enhance or enable autonomous ISRU technology development if we leverage industry experience and developments (e.g. in reliability, applications, challenges) in the area of autonomous mining/processing operations. Coordination between the space exploration and mining industry stakeholders would help identify the areas with the most feed forward to the Moon and Mars.

BACKGROUND: In recent years, private industry prototyped and tested a number of new autonomous technologies for terrestrial mining operations. Leveraging the experience of terrestrial industry may help identify key autonomy knowledge gaps and technologies that may serve as a springboard to develop initial concepts for mining-autonomy on the Moon and Mars. System design should incorporate lessons learned by the terrestrial mining industry and the state-of-the-art currently used on Earth.

FINDING 4b: Water clean-up, water electrolysis, and product liquefaction and storage techniques developed for all ISRU processes at the Moon have direct feed forward to Mars.

BACKGROUND: An ISRU system consists of many components and subsystems. A number of these are independent of the resources and needs of a particular planetary body and exploration site, whereas others are resource- and destination-specific. Those components and subsystems that are applicable to both the Moon and Mars, such as water clean-up, electrolysis, liquefaction, and storage techniques, are the best candidates for having feed-forward applicability to Mars. An example of a process that is only applicable to Mars would be methane production from the Martian atmosphere.

FINDING 4c: If lunar ISRU systems target icy-regolith with either a low ice content or icy-regolith with a high enough ice content that it is a cemented material, the excavation, transport, transfer systems, and water-regolith reactors would directly feed-forward to martian ISRU systems.

BACKGROUND. See ***Figure 5***

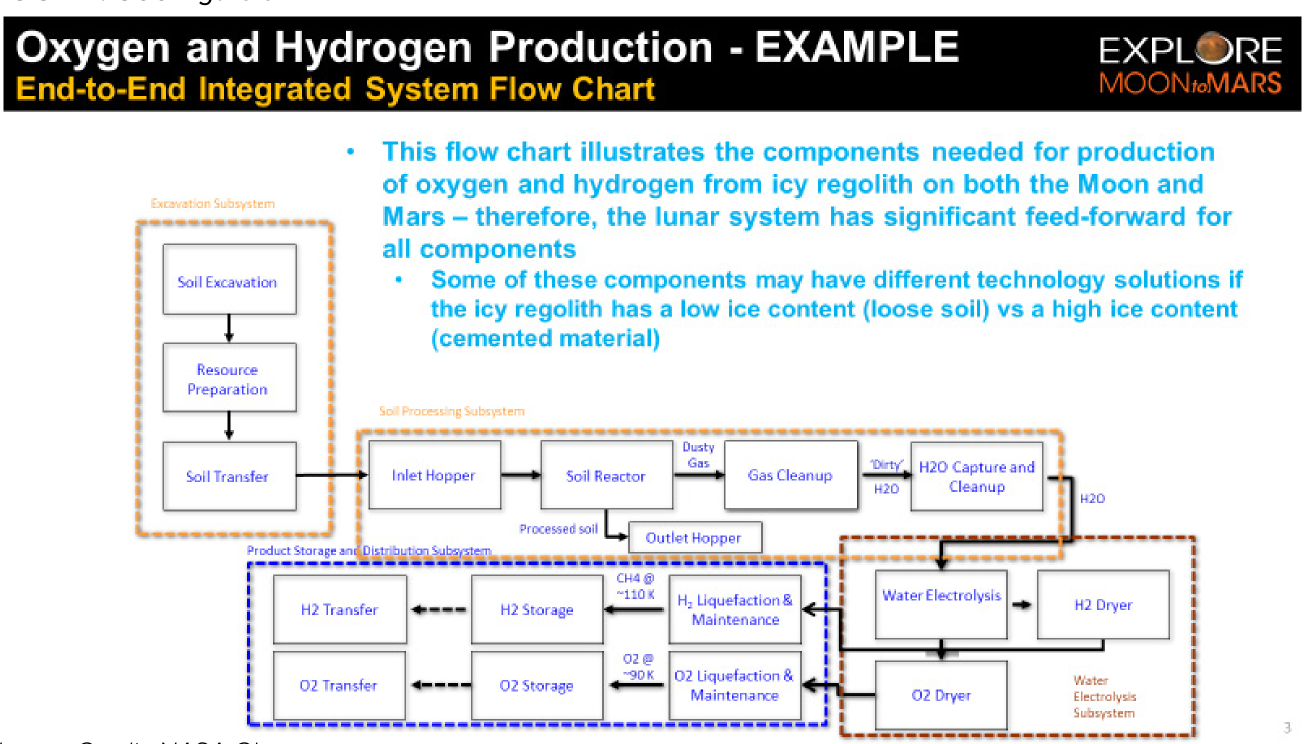


Figure 5. *Image Credit: NASA Glenn*

FINDING 4d: If we extract oxygen from lunar regolith and we choose to use a carbo-thermal reactor to process it, then the methanation reactor, species separators, and gas recycling system developed for this process could feed forward to production of methane and oxygen from the atmosphere and water on Mars if similar systems are employed there.

BACKGROUND: On the Moon, we can use various processes to produce oxygen alone from regolith (*Figs. 6, 7*) and liquid water from near-surface ice. The composition of the lunar regolith is variable in terms of metals but is approximately constant in terms of oxygen content so the regolith is a reserve in this case. However, we do not understand the form and concentration of water ice on the Moon. Knowing the form(s) lunar water ice is in (see findings under question 2) will drive key design tradeoffs for water ISRU processes. Ground truth data on the form and concentration of lunar water-ice will determine the extent of feed forward to Mars.

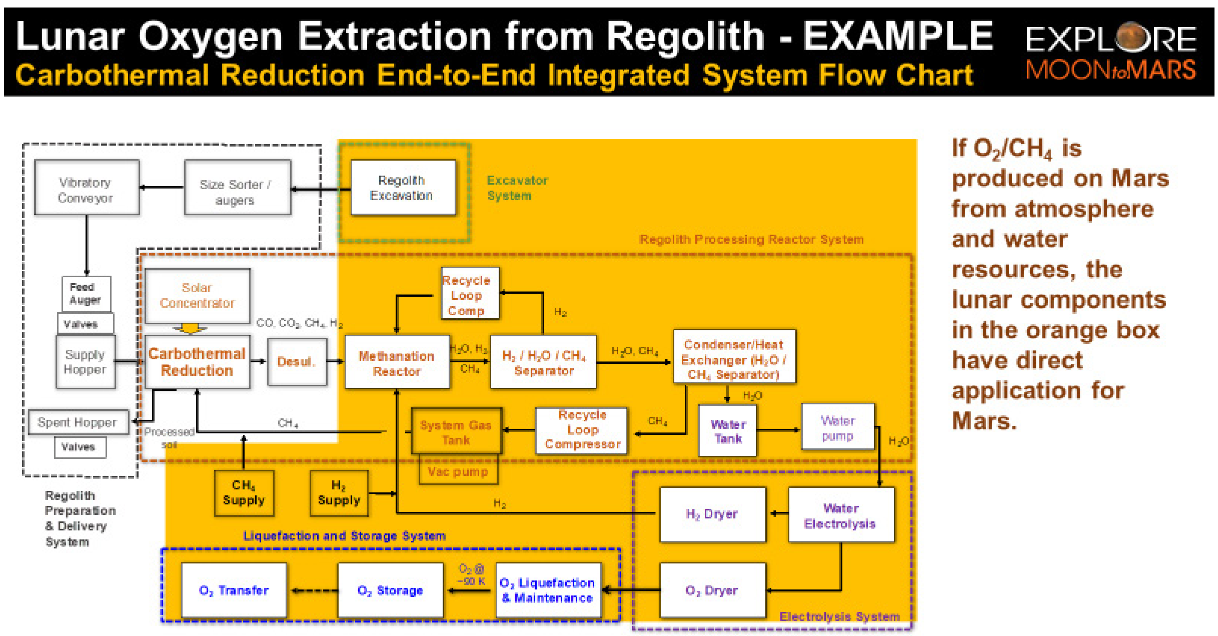


Figure 6

FINDING 4e: Learning to operate and maintain both ISRU systems and facilities (e.g. autonomy, automation, reliability, durability, contaminant build-up, etc.) on the Moon will uncover unknown-unknowns that will directly inform and reduce the risk of operations on Mars.

Background. An ISRU system consists of many components and subsystems (*Figs. 5-7*). Terrestrial analogs of these systems rely on extensive human support for operations, maintenance, failure-recovery, and interactions among the various components. However, the Earth is a limited platform for testing long-term and robust ISRU operations on other planetary bodies. Independent of specific technological solutions, the experience of setting up and operating such a system on the Moon would provide invaluable experience and expose "unknown-unknowns" that may be applicable to human missions to Mars.

FINDING 4f: At current envisioned human mission rates (e.g. 1 Lunar landing/year and 1 Mars Ascent Vehicle Fueling/26-month synodic period) ISRU extraction and production rates would be similar at both the Moon and Mars. These similarities may translate into similar sizing of ISRU systems.

BACKGROUND: Besides technological similarities, an important facet of feed-forward is the similarity in operational and production scale. The size of a planetary body's gravity well and the expected launch cadence drive propellant requirements for missions there. While the gravity on Mars is twice the gravity on the Moon, the expected lunar mission cadence is twice that of Mars. Therefore, necessary propellant production rates to get a vehicle off the surface up to orbit are similar on each planetary body.

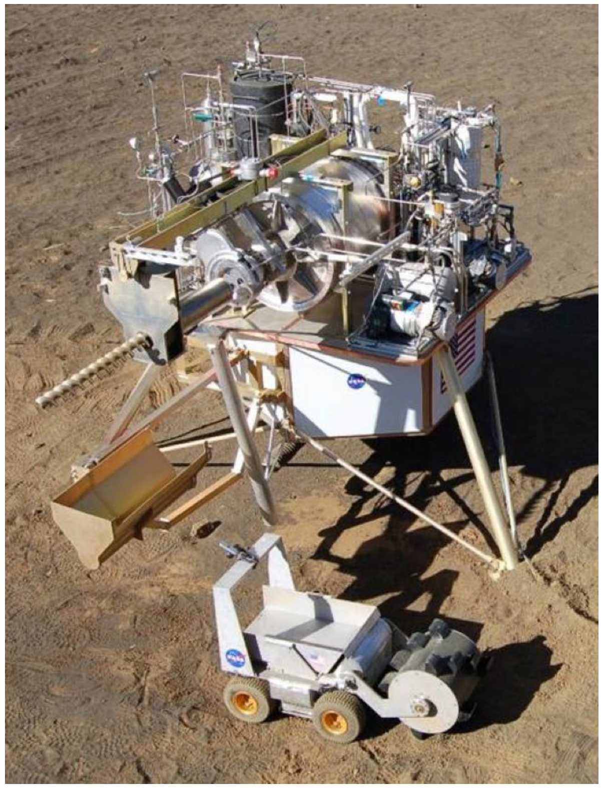


Figure 7. *PILOT (Precursor In-situ Lunar Oxygen Testbed),*
Image Credit: Lockheed Martin

QUESTION #5

5. Assess the pros and cons of different cryogenic propellant combinations (e.g. methane, hydrogen, etc.) for lunar and martian scenarios
   a. Do the issues associated with liquefying and storing hydrogen (e.g. technology, power, etc.) hinder its potential as a fuel? How does it compare to methane?
   b. Do you need to use methane at all locations or can hydrogen be incorporated into the system?
   c. How would nuclear thermal propulsion (NTP) affect these trades, considering that straight water vapor can be used as fuel?

INTRODUCTION: Hydrogen/oxygen is the most efficient chemical propellant combination, but access to and storage of sufficient quantities of hydrogen presents significant challenges. Hydrogen is widely available around the Solar System – including at the Moon and at Mars – although not always in a useful form. Methane/oxygen, on the other hand, is a useful propellant combination from a Mars standpoint in that all of the resources needed to produce methane and oxygen are available on or near the martian surface. While methane is present in the martian atmosphere at the low parts per billion by volume level, this is an insufficient reserve for rocket propellant. However, on Mars C can be generated from the splitting of atmospheric CO_2 and combined with H from water ice to form methane.

That said, the specific impulse of methane is roughly 18% lower than that of hydrogen. Still, the storage requirements for methane more closely match the requirements for oxygen, simplifying the overall infrastructure and power requirements as compared to hydrogen.

FINDING 5a: Although other propulsion technologies exist (e.g. CO/O_2, etc.), methane and hydrogen fueled propulsion are currently the most mature, and we should therefore consider them as the most viable propulsion systems for near-term exploration of the Moon and Mars.

FINDING 5b: As a propellant, hydrogen produces the greatest efficiency for nuclear thermal propulsion (which offers the best specific impulse compared to other propulsion options).

BACKGROUND: The boil-off of stored hydrogen is a significant challenge for long-term storage. Current flight-proven coolant technologies cannot meet the needs for a zero boil-off system, but recent ground tests of the technology show significant progress. For example, cryogenic storage and boil-off capture technologies indicate for >2,000 kg storage capacities, losses are currently <0.7% (e.g., Petitpas, 2018) Hydrogen has advantages over methane for a long-term exploration especially when used in conjunction with non-chemical propulsion technologies (e.g., nuclear thermal propulsion), which can significantly reduce the trip-time to Mars. If a mission is in a “power rich” environment (reaching “power rich” may be too demanding for early missions), long-term storage of water, oxygen, and liquid hydrogen is feasible, especially in permanently shadowed craters of the Moon. Initial estimates of the power required for an ISRU plant designed to convert water into 1.7 tons of H_2 and 10 tons of O_2 per year (one descent module refueling) suggest that roughly 50kW of power are needed (produced over 220 days). To store water as a feedstock and complete the production of the hydrogen and oxygen in the month prior to the need, roughly 7 times the power (~350kW) would be needed for electrolysis, liquefaction and storage.

FINDING 5c: Both hydrogen and methane should be considered as viable propellant options for human missions to the Moon and Mars. Hydrogen can be produced from the locally available resources at both the Moon and Mars; methane can be produced from locally available resources on Mars. Any methane production on the Moon would require the importation of a carbon source.

FINDING 5d: Regardless of which cryogenic liquefaction, storage, and volume technology (whether for hydrogen or methane) is explored at the Moon, such will feed forward to hydrogen and/or methane handling technologies developed for Mars.

BACKGROUND. The long-term demand for propellant on the Moon would be 1.7 tons of H_2 and 10 tons of O_2 per year assuming the refueling of one descent module per year. Relevant long-term demand for a MAV on Mars would be roughly 30 tons of propellant (fuel/oxygen) per MAV launch per 26-month synod. As technological development progresses the competitive process may drive toward a certain solution.

6. Study on ISRU-based site preparation and construction for landing, lift-off, and surface transportation operations on lunar and martian terrain.

INTRODUCTION: Sustainable operations at any landing site, whether on the Moon or Mars, requires infrastructure to mitigate the effects of and exposure to dust and to prevent wear and tear from long term use. In the short term, we need to learn how to mitigate plume effects from landing/launching spacecraft on surface infrastructure on the Moon and Mars as well as orbital infrastructure around the Moon (***Fig. 8***). The risk of plume effects on the lunar surface to the infrastructure is primarily from plumes during landing and launch ejecting regolith particles accelerating at up to 3 km/s and potentially sandblasting any surface and possibly orbital infrastructure. On Mars, when landing on unconsolidated material the effects of the plume interaction can also lead to the excavation of a large crater directly under the lander which can lead to possible loss of vehicle and/crew. Proposed solutions include berms, infrastructure requirements and placement, landing pads and other possible solutions. There is not yet sufficient testing for any of these solutions, however. Work on this subject matter is coordinated through a newly formed landing team: https://sciences.ucf.edu/class/landing-team/.

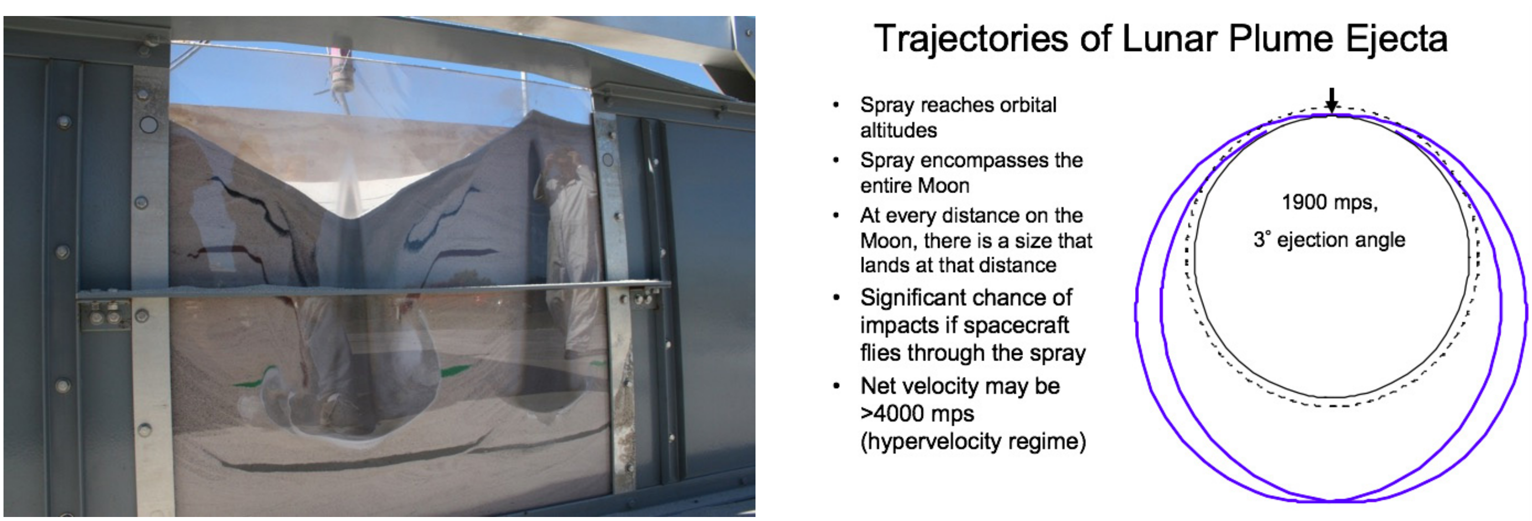


Figure 8. *Left: Illustration of plume interaction with unconsolidated regolith. Right: Lunar plume trajectories based on a 3˚ ejection angle*

FINDING 6a: ISRU site construction (of roads, landing pads, and radiation and thermal protection) will be critical for long-term sustainable habitation on both the Moon and Mars.

FINDING 6b: Although there are environmental differences (e.g. atmosphere, geochemistry, etc.) between the Moon and Mars, the lessons we can learn at a systems level for construction ISRU on the Moon will directly feed forward to Mars.

FINDING 6c: Plume surface interaction poses threats to mission hardware, but how we solve that problem is unclear at this time and needs further study.

BACKGROUND: Longer term, the wear and damage to mobility and ISRU systems can be mitigated by establishing roads, landing pads, and other infrastructure. Despite differences in gravity and atmosphere, most mitigation strategies and technologies for the lunar surface have commonalities and thus feed forward to Mars application. Still, we need to understand what ISRU construction capabilities we need and the schedule for phasing these capabilities into mission architectures to inform studies into civil engineering moving forward.

QUESTION #7

7. What are the ramifications (e.g. legal, operational, for partnerships, etc.) of commercial and international resource extraction on the Moon and Mars? How do any precedents established by what we do at Moon inform what we do at Mars?

INTRODUCTION: The successful development of in-situ resources on the Moon and Mars will require a framework that encourages ISRU. Questions of ownership, jurisdiction, and liability for extraterrestrial operations are currently unanswered and need to be resolved, preferably well in advance of a sustained mission to either planetary body.

FINDING 7a: There are ramifications (e.g. legal, operational, for partnerships, etc.) of commercial and international resource extraction on the Moon and Mars. The precedent set at the Moon could likely carry forward to Mars.

Models and mechanisms for risk-sharing and collective decision-making between a variety of private and public stakeholders will enable ISRU on the Moon, and will feed forward to Mars. In particular, the standardization of materials, components, protocols, and interfaces will enable the transfer of materials and responsibilities between the various actors. It is not yet clear who will be authorized to make and modify such standards.

In addition, if extant martian life is found to exist, there is a question about humanity's responsibility towards those lifeforms. What rights if any do extant martian lifeforms have? Precedent from Earth suggests that non-human lifeforms do not have any legal rights (see recent presentation by Kramer, 2019). How this question will be addressed for potential extant life on Mars will likely have a spillover effect for any lifeforms found in the rest of the Solar System. These questions may be good starter material for one or more successor workshops.

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APPENDIX 1. COMPILATION OF FINDINGS

Findings related to lunar water resources

FINDING 1a: Rovers and instruments developed to identify and characterize near surface (within 1-2 meters) water-ice on the Moon would be immediately applicable to resource exploration on Mars.

FINDING 1b: Rovers and instruments developed to identify and characterize near surface (within 1-2 meters) water-ice on the Moon would be immediately applicable to resource exploration on Mars.

FINDING 1c: Architectures for sustainable human exploration of the Moon and Mars should be designed and/or evolvable such that they can incorporate locally derived resources (e.g. water, oxygen, propellant) as the infrastructure necessary to access and process resources becomes available.

Findings related to reserve definition

FINDING 2a: Exploration to date supports the existence of several different kinds of water resources on the Moon. Elevating some subset of these resources to the status of reserves will require (1) more detailed/focused exploration (to further define location, spatial extent, and heterogeneity), and (2) development of the technologies needed to extract/process it. The process by which we assess the potential of Lunar resources to become reserves will be directly applicable to Martian resources, which will require the same kind of assessment.

FINDING 2b: Answering knowledge gaps pertaining to the reserve-potential of water-based resources on the Moon will require more than a single exploration mission; it will require a campaign of multiple missions that includes ISRU technology demonstration.

FINDING 2c: The existence of a stable market (e.g. government commitments to sustain a presence on the lunar surface) for the resource is necessary (but probably not sufficient) to enable commercial development. The same considerations will apply to Mars.

Findings related to power

FINDING 3a: Solar power alone is not sufficient to meet power needs of sustained human missions on either the Moon or Mars. Power generation systems at both locations will need to be diverse (e.g., a mixture of solar power, nuclear power, and radioisotope power) and include a variety of power storage systems (e.g., batteries, regenerative fuel cells) to create a resilient and robust power system for long-term habitation.

FINDING 3b: ISRU systems for sustainable human missions to both the Moon and Mars will require scalable power systems to meet the demands of increased exploration activities without replacing infrastructure.

FINDING 3c: Because of its distance from the sun and surface conditions, sustainable human exploration of Mars requires nuclear power. Using the Moon as a testbed to develop nuclear power systems would directly feed forward to Mars.

FINDING 3d: Current sustainable human missions to Mars envision ISRU as a means of fueling the MAV. A demonstration of the primary ISRU production units (water clean-up, water electrolysis, and product liquefaction and storage techniques) on the Moon would have a strong feed forward to Mars. Any demonstration system will likely require 1s to 10s of kilowatts of power.

Findings related to opportunities to test technologies and operations

FINDING 4a: Engagement with terrestrial industries could potentially enhance or enable autonomous ISRU technology development if we leverage industry experience and developments (e.g. in reliability, applications, challenges) in the area of autonomous mining/processing operations. Coordination between the space exploration and mining industry stakeholders would help identify the areas with the most feed forward to the Moon and Mars.

FINDING 4b: Water clean-up, water electrolysis, and product liquefaction and storage techniques developed for all ISRU processes at the Moon have direct feed forward to Mars

FINDING 4c: If Lunar ISRU systems target icy-regolith (with a low ice content) or icy-regolith (with either a high enough ice content that it is a cemented material) the excavation, transport, transfer systems, and water-regolith reactors would directly feed-forward to Martian ISRU systems.

FINDING 4d: If we extract oxygen from lunar regolith and we choose to use a carbo-thermal reactor to process it, then the methanation reactor, species separators, and gas recycling system developed for this process could feed forward to production of methane and oxygen from the atmosphere and water on Mars if similar systems are employed there.

FINDING 4e: Learning to operate and maintain both ISRU systems and facilities (e.g. autonomy, automation, reliability, durability, contaminant build-up, etc.) on the Moon will uncover unknown-unknowns that will directly inform and reduce the risk of operations on Mars.

FINDING 4f: At current envisioned human mission rates (e.g. 1 Lunar landing/year and 1 Mars Ascent Vehicle Fueling/26-month synodic period) ISRU extraction and production rates would be similar at both the Moon and Mars. These similarities may translate into similar sizing of ISRU systems.

Findings related to cryogenic propellants

FINDING 5a: Although other propulsion technologies exist (e.g. CO/O_2, etc.), methane and hydrogen fueled propulsion are currently the most mature, and we should therefore consider them as the most viable propulsion systems for near-term exploration of the Moon and Mars.

FINDING 5b: As a propellant, hydrogen produces the greatest efficiency for nuclear thermal propulsion (which offers the best specific impulse compared to other propulsion options).

FINDING 5c: Both hydrogen and methane should be considered as viable propellant options for human missions to the Moon and Mars. Hydrogen can be produced from the locally available resources at both the Moon and Mars; methane can be produced from locally available resources on Mars. Any methane production on the Moon would require the importation of a carbon source.

FINDING 5d: Regardless of which cryogenic liquefaction, storage, and volume technology (whether for hydrogen or methane) is explored at the Moon, such will feed forward to hydrogen and/or methane handling technologies developed for Mars.

Findings related to site preparation and other civil engineering issues

FINDING 6a: ISRU construction (of roads, landing pads, and radiation and thermal protection) will be critical for long-term sustainable habitation on both the Moon and Mars.

FINDING 6b: Although there are environmental differences (e.g. atmosphere, geochemistry, etc.) between the Moon and Mars, the lessons we can learn at a systems level for construction ISRU on the Moon will feed forward to Mars.

FINDING 6c: Plume surface interaction poses threats to mission hardware, but how we solve that problem is unclear at this time and needs further study.

Findings related to legal issues

FINDING 7a: There are ramifications (e.g. legal, operational, for partnerships, etc.) of commercial and international resource extraction on the Moon and Mars. The precedent set at the Moon could likely carry forward to Mars.