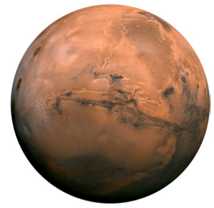
The Sixth Community Workshop for Achievability and Sustainability of Human Exploration of Mars (AM VI)
Final Report





Lunar Operations, Technologies, and Capabilities to
Enable Human Exploration of Mars

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Hosted by Explore Mars, Inc. and The American Astronautical Society

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AM VI Executive Summary

Approximately 70 subject matter experts on astronaut lunar and martian exploration, science, operations, and key technologies assembled in late August 2018 at The George Washington University to critically assess how operations, technologies, and facilities for the Moon and its vicinity might feed forward to astronaut missions to the martian surface before the end of the 2030s. This workshop was the sixth 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. Reports from previous workshops are posted at https://www.exploremars.org/affording-mars.

Using Mars exploration scenarios and enabling technologies from, respectively, the fifth (AM V) and fourth (AM IV) workshops, we summarize in this report those lunar activities that show promise in enabling Mars exploration. Specifically:

A. **Prioritized Space Transportation and Propulsion Systems, Technologies, and Operations:**

1. **Long-term cryogenic fluid management:** Long-term storage of cryogenic propellants (LOX, LCH_4, LH_2), passive/active reduced boiloff tanking, liquid acquisition, tank mass gauging
2. **Lander development** (e.g., propulsion, precision & autonomous landing, hazard avoidance): Cryogenic engines in the 40 - 100 kN range, deep-throttling engines, cryogenic reaction control system (RCS), precision landing, hazard avoidance
3. **Vehicle aggregation** (e.g., refueling, refurbishing, checkout): Vehicle servicing, cryogenic refueling, refurbishment, repair, cleaning, re-certification for flight readiness
4. **Human health and biomedicine** (e.g., radiation, psychosocial): Deep-space behavioral health monitoring, deep-space radiation

B. **Surface Systems/Technologies/Operations:**

Highest priority (in alphabetical order):
- **Human health and biomedicine** (e.g., psychosocial, food & medicine)
- **Power systems** (e.g., fission for primary power, radioisotope power for mobility)
- **Rovers for human exploration** (e.g., operations, energy storage, airlocks, suitlocks)
- **Surface suits** (e.g., pressure garment, environmental protection layer, maintenance)

Next highest priority (in alphabetical order):
- **Communication systems** (e.g., orbital assets, local communication)
- **In-situ resource utilization**
- **Surface habitats and laboratories** (e.g., systems availability, operations)

Our workshop produced a series of findings and observations, including:

- Early Mars missions do not necessarily require precursor lunar surface activities. However, our workshop identified various potential and important human and robotic operations, technology developments, and demonstrations on the surface of the Moon that would contribute in varying degrees to the Mars scenario adopted here (Field Station) during the 2030s.

- A successful and sustainable Moon-to-Mars human space flight program requires a single "integrating" NASA Headquarters office with budget authority to apply the results of technology, operations, and science trade studies [emphasis added]:
  - *Lunar and martian priorities should not be assessed independently of one another.*
  - *Future priorities for Mars exploration may levy requirements on lunar exploration.*
- The profound environmental differences between the Moon and Mars must be fully incorporated into scenarios that intend for the former to enable the latter.
- The Gateway may be an important test-bed for Mars transportation architectures, if the final design includes that requirement.
- Using the International Space Station (ISS) or a similar Low Earth Orbit (LEO) platform, where crews are continuously present using systems intended for Mars, is key for understanding how these systems will perform and potentially need to be maintained for a three-year Mars mission. In addition, permanent presence by crews in a zero-g and relatively isolated and stressful environment is critical for reducing human health and biomedicine risks for long-duration missions.
- Two martian engineering or technology "long poles" – Crew and Cargo Landers and Martian System Reconnaissance – have very long development times. If development of these "long poles" is delayed, the goal of landing humans on the surface of Mars will likewise be delayed.
- Our workshop found significant value in the Moon and Mars communities working together to understand how lunar operations and capabilities can feed forward to Mars. We recommend a more extensive assessment with increased joint participation by these communities.

Finally, the AM VI workshop recommended that several important studies be undertaken, one by the National Academies, as well as a series of trade studies that could be carried out by a broad community of subject matter experts. The proposed National Academies study would evaluate in-situ resource utilization (ISRU), especially of surface/shallow geological deposits containing extractable water, as to the potential to enable affordable and sustained human occupation of both the Moon and Mars. At present, certain critical information about these resources is not yet available and, consequently, how and when such resources might be exploited is unclear, specifically:

- *What are the priority surface and orbital reconnaissance programs of potential lunar and martian resources to assess their potential?*
- *What is the degree to which lunar resource exploration, production, beneficiation, and commodity storage processes enable and feed forward to Mars?*
- *What are the anticipated effects of declining launch costs and development of lunar resource extraction capabilities?*

The proposed series of additional trade studies are (not in priority order):

- Comparison of end-to-end costs of resources extracted from the Moon with those supplied from terrestrial sources
- Lunar ascent vehicle/lander extensibility to Mars ascent vehicle/lander
- Pros/cons of different cryogenic propellant combinations (i.e., LOX/CH_4 versus LOX/H_2) for lunar and Mars scenarios
- Value of remotely operated robots versus on-site astronaut operations on the lunar surface to feed forward to human missions to Mars
- Airlock versus suitlock, including planetary protection, habitat access, and cognizance of different environment
- Common development paths for Mars and Moon surface suit thermal systems
- Long-lived pressurized rover energy production and storage [e.g., Kilopower versus radioisotope power system (RPS), fuel cells versus batteries]
- Rover needs on the two worlds [e.g., duration of trips, what rovers are used for (science, construction, maintenance, transportation), day-night cycle, and crew size]
- Study of ISRU-based site preparation and construction for landing, lift-off, and surface transportation operations on lunar and martian terrains

AM VI Report

Background: The Achieving Mars ("AM") Workshops and the Motivation for AM VI

The exploration of Mars by astronauts 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.

Our series of community-based *Affording, Achieving, and Sustaining Human Exploration of Mars Workshops* (collectively referred to as the "AM Workshops") was initiated in the spring of 2013 and was designed to build upon the growing number of scenarios for the human exploration of Mars that were being developed by the government and commercial sectors, as well as one by the NASA Jet Propulsion Laboratory (JPL), each of which appeared to offer far lower-cost missions than previously envisioned. Moreover, these community-based workshops promised direct involvement and alternative perspectives by highly capable individuals, organizations, and/or institutions external and a complement to the long-running design work by NASA and other space agencies. That is, disparate industries, academia, and experts would be given the opportunity to contribute in the early stages of formulation to proposed architectures for human exploration beyond the Earth-Moon system. Thus, the overarching goal of the AM Workshops from the start would be the development of a public, private, and international consensus on human Mars exploration that is not otherwise being pursued.

Since the time of our first workshop in December 2013, and in the five 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 reports from all the AM Workshops are hosted on the Explore Mars, Inc. web site at https://www.exploremars.org/affording-mars.

Summary Descriptions of the AM Workshops

Our first Affording and Sustaining Human Exploration of Mars Workshop (**AM I**) was held in December 2013 at The George Washington University (GWU) 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.

Our second workshop (**AM II**) was held at the Keck Institute for Space Studies in Pasadena, CA 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.

The George Washington University's Space Policy Institute hosted **AM III** in December 2015. This third AM Workshop conducted 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.

Technology investment strategies and priorities, including a detailed timeline for key milestones, were the major activities for **AM IV**, held at the Doubletree Hotel in Pasadena in December 2016. AM IV concentrated on achieving various critical capabilities (or technology and engineering "long poles") in the human exploration of Mars.

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

- Scenario 1: Initial exploration analogous to the Apollo sorties or the Lewis and Clark "Corps of Discovery"
- Scenario 2: Semi-permanent base or "field station" on the martian surface, analogous to early Antarctic exploration
- Scenario 3: Building toward sustained, permanent habitation analogous to current Antarctic exploration

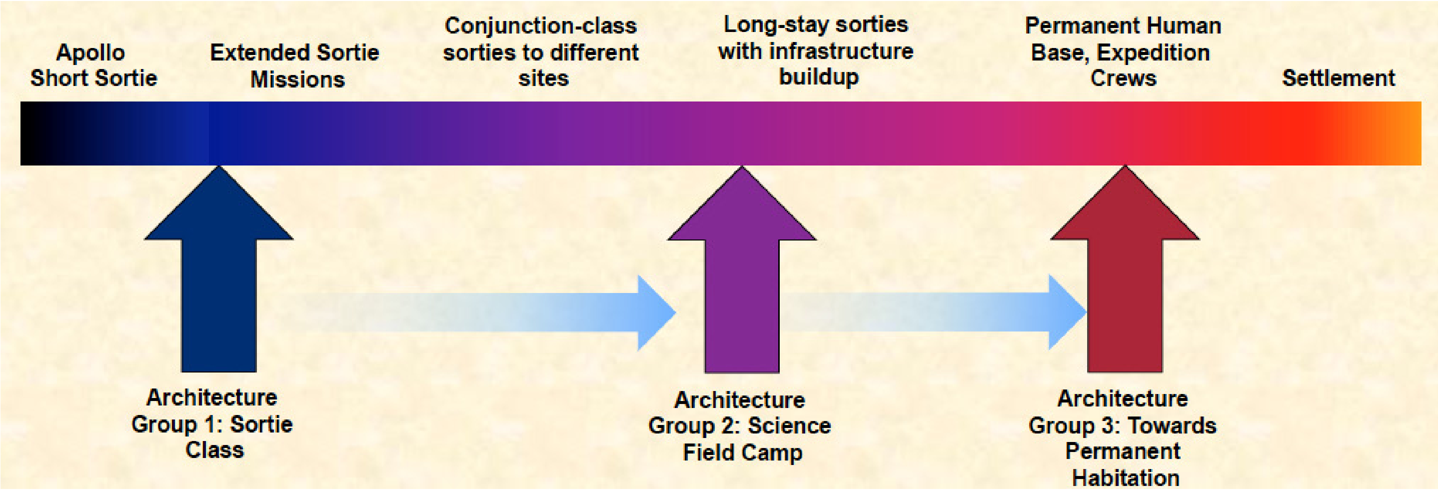

Figure 1: Three "end state" architectures assessed in AM V along the continuum of plausible astronaut exploration scenarios.

Motivation for the Sixth Community Human Mars Exploration Workshop: Critically Assessing How Lunar Operations and Capabilities Can Feed Forward to Human Missions to Mars

The space community has long debated whether or not 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. However, to our knowledge such a discussion of a return to the Moon to enable subsequent Mars exploration has rarely if ever been subjected to a critical assessment via comparison with sufficiently detailed Mars exploration scenarios.

With a renewed emphasis by NASA on human lunar exploration, the AM VI meeting included members of the lunar community, which allowed for substantive discussions of Moon-to-Mars development synergies. With our previous workshops' extensive analysis of Mars technology "long poles" and strategy (AM IV) and of three distinct Mars exploration scenarios (AM V), our *Affording, Achieving, and Sustaining Human Exploration of Mars* team was uniquely well-positioned in AM VI to critically examine and analyze in some depth frequently advocated lunar operations and capabilities and as to whether they, in fact, may enable subsequent human exploration of Mars.

Adopted Mars Scenario: Field Station and Activities

The previous AM workshops developed and advocated major technological "long poles" necessary for achievable, affordable, and sustainable human exploration of Mars. The AM IV workshop developed and advocated major technological "long poles" necessary for achievable, affordable, and sustainable human exploration of Mars. These eleven technology "long poles" for the human exploration of Mars were:

1. Mars System Reconnaissance
2. Aggregation, Refueling, and Resupply Capability (ARRC)
3. Transit Habitat and Research Laboratory
4. Crew/Cargo Lander: Entry, Descent, and Landing
5. Surface Habitat and Research Laboratory
6. Mars Surface Power
7. Mars Ascent Vehicle (MAV)
8. Human Health/Biomedicine
9. Sustainability of NASA Mars exploration results from its value to stakeholders
10. Planetary Protection
11. Lunar surface operations in advance of human missions to Mars

During our AM V workshop, held in December 2017, workshop participants developed in detail three distinctly different scenarios for the human exploration of Mars. The requirements placed on these three scenarios (Figure 1) were human missions to Mars during the 2030s that would be affordable with budgets growing only at the rate of inflation.

For our AM VI workshop, we decided that workshop participants would adopt the “Surface Field Station” as the Mars architecture representative scenario. The details of such a field station are given below, although we note that the actual requirements for each of the three scenarios are not significantly different. The Field Station scenario is similar to NASA’s Evolvable Mars Campaign (EMC) (https://www.nasa.gov/sites/default/files/files/NextSTEP-EMC-Reference.pdf) study from 2014-2016, and has the goal of learning how to live and operate on Mars in preparation for eventual continuous human presence via the deployment of a temporary Mars surface field station that is visited by multiple crews over the lifespan of the infrastructure.

Activities associated with the field station include:

- **Engineering testing** of surface hardware [e.g., ISRU, in-situ materials, civil engineering, pressurized rovers, etc. (Figures 2 and 3)]
- **Environmental monitoring and characterization** (e.g., ground-truthing of orbital recon datasets such as water mapping and surface winds, better informing planetary protection practices)
- **Understanding long-term human health impacts** of long duration deep space and surface missions and demonstrating appropriate countermeasures
- **Learn how best to do in-situ science** with human crewmembers as a resource (e.g., to address MEPAG science goals)

The intended end state for the field station is:

- When sufficient knowledge and operational experience is gained to decide on the location and architecture of the first continuously occupied permanent base on Mars.
- Chosen to occur at the same time that Mars surface equipment wears out, thus avoiding the need for system recertification and/or replacement.

Figure 2: Field station establishment and testing of habitat construction, life support, and ISRU. See image source in footnote.

The features of the field station are built upon NASA’s Evolvable Mars Campaign (EMC) study (2014-2016) with additional options considered to increase program sustainability:

- **Conjunction-class missions** with gradually increasing time spent on the Martian surface as more surface capabilities are delivered and more experience is gained
- **Baseline atmospheric O2 ISRU** with water-based ISRU considered within the trade space depending on selected landing site and precursors/field station activities
- **Reuse of Transit Habitat and in-space propulsion** for crew and cargo transit, which are sent back to lunar gateway for refurbishment
- **Reuse of Mars Surface Habitat**

Additional features include

- **Modular build-up** of in-space and Mars surface assets, including human habitat and laboratory modules using multiple commercial and international providers
- **Small/mid-size Mars landers** derived directly from lunar surface program
    - Develops experience base and distributes costs for Mars program across longer timeline

Fig 2a Image credit: Mars Ice ISRU, NASA LaRC Advanced Concepts
Fig 2b Image credit: Mars hab, Steve Burg/The Martian

- Smaller, modular payloads (~10 mT) allows for **increased commercial / international participation** (e.g., launch vehicles, landers, and payloads, which increases cost sustainability and political sustainability)
- Allows deployment of **larger science payloads** than currently considered with increased opportunities for scientific discovery and public engagement
- Increases **system flexibility and robustness** by allowing individual components to be repaired and/or upgraded as they degrade, or as more experience is gained in their operations

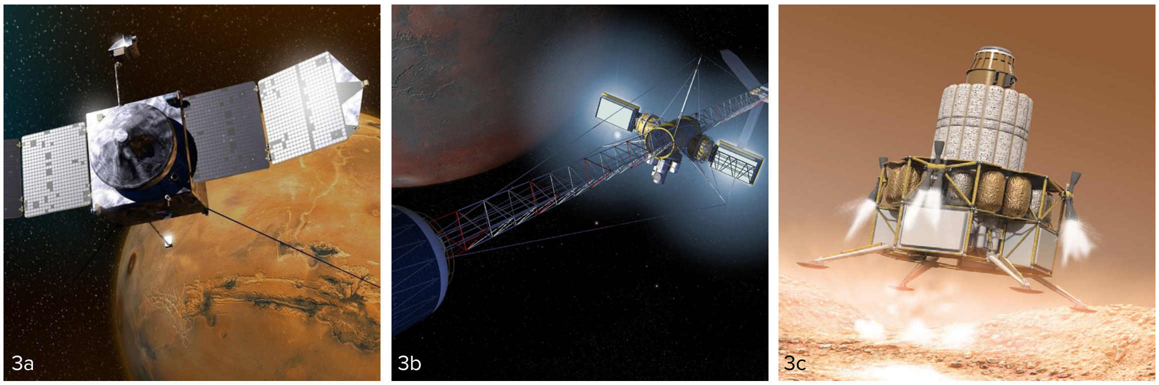

Figure 3: Features of the Field Station architecture. Courtesy: NASA. See image source in footnote.

Prior to the start of the AM VI workshop, a planning group re-examined the AM IV "long poles" and identified all those appropriate in a discussion of lunar feed-forward activities. Based on this analysis, a revised set of "long poles" and "driving gaps" were identified for study during the AM VI workshop. This revised list, and the extent to which activities near and on the Moon would potentially retire risk and cost for future Mars human exploration, became the major focus of the workshop.

For the AM VI workshop, the "long poles" and "driving gaps" were

1. In-Space Aggregation/Refuel/Resupply
    - Design of logistical architecture and demonstration in deep space
    - Autonomous operations at Mars
    - Xenon and cryogenic transfer
2. Transit Habitat and Research Laboratory
    - Radiation protection
    - Crew autonomous operations
    - Crew health
    - Crew activity
    - Vehicle maintenance
    - Reliable life support
    - Crew privacy and habitable volume
    - Logistics and storage
    - Thermal
    - Reduced power
    - Deep-space navigation
    - Quarantine/isolation/privacy capability

Fig 3a Image credit: MAVEN, NASA/Planetary Society
Fig 3b Image credit: Mars Trasnfer Vehicle, NASA/Planetary Society
Fig 3b Image credit: Mars Lander, NASA/Planetary Society

3. Solar Electric Propulsion
    - 300 kW-class solar array
    - Power and Propulsion Element (PPE)-derived power distribution
    - 12.5-kW electric propulsion thruster
    - Low-thrust navigation
4. Mars System Reconnaissance
    - Resource reconnaissance for landing site selection
    - Ground truth of resource mapping
    - Round-trip demo/sample return
    - Extant biology in soil
    - Atmospheric reconnaissance for entry, descent and landing
5. Crew/Cargo Lander: Entry, Descent, and Landing (EDL)
    - Human-scale Mars EDL system
    - Cryogenic propulsion and cryofluid management
6. Mars In-Situ Resource Utilization (ISRU) Technology Development
    - Convert CO2 to O2
    - Dust effects on ISRU
    - Oxygen extraction from CO2
    - Access H2O subsurface ice/minerals
    - Resource acquisition
    - Liquefaction and cryofluid management
7. Surface Habitat and Research Laboratory
    - Surface habitation
    - Systems availability (e.g., mean time between failures; system reliability + repair +supply of parts)
    - Fundamental and applied research objectives
8. Mars Surface Power
    - Surface solar arrays
    - Lightweight fuel cell/battery storage
    - High-power/high-efficiency radioisotope power systems
    - 10s of kW fission power
    - Power management and distribution
9. Mars Ascent Vehicle
    - Cryogenic propulsion and cryofluid management
    - Habitability
    - Guidance, navigation, and control
    - Integrated systems
    - ISRU conversion: CO2 to O2
10. Mars Communication Network for Human Exploration and Science
    - Deep-space, high-rate forward link downlink
    - High-rate proximity communication
11. Human Health/Biomedicine
    - Risk of spaceflight-induced intracranial hypertension/vision alterations
    - Risk of cardiac rhythm problems
    - Risk of cardiovascular disease cardiovascular disease, and other degenerative tissue effects from radiation exposure
    - Risk of unacceptable health and mission outcomes due to limitations of in-flight medical capabilities; health outcomes of concern include spaceflight associated neuro-ocular syndrome (sans), bone fracture, and renal stone, and dust exposure
    - Risk of adverse cognitive or behavioral conditions and psychiatric disorders

- Risk of ineffective or toxic medications due to long term storage
- Risk of performance decrement and crew illness due to an inadequate food system

12. Surface EVA Suit
    - Pressure garment suit
    - EVA system mobility, durability, and environmental protection layer (e.g., dust management)
    - EVA total system mass (Mars gravity appropriate)
    - System maintenance and repair (garment and life support system)
    - System thermal management
13. Pressurized Surface Rover (for multi-day excursions)
    - Autonomy/dormancy
    - Power/energy storage
    - Maintenance and repair
    - Operations
    - Habitability
    - Ports and air locks: versatile suits, habitation systems, other rovers
    - Range, speed

During our AM VI workshop, the participants were divided into two teams, with one team focusing on the transportation elements and propulsion, notably involving travel from the Earth and cis-lunar space to Mars, as well as onto the lunar and martian surface, while the other team focused on surface activities. Both teams addressed a number of the "long poles" and "driving gaps" from their respective perspectives, while a number were only addressed by the appropriate team.

Adopted Lunar Scenarios and Activities

As NASA's human exploration priorities move beyond low-Earth orbit and deeper into space, NASA is proposing significant robotic and human exploration activities on the lunar surface and its vicinity (e.g., orbit) utilizing both government and commercial resources. Major investments include the development of a new launch capability and a human transportation vehicle in the form of NASA's Space Launch System (SLS) and Orion crew capsule.

In considering potential lunar activities that could feed forward to enable future Mars human activities, we assumed that SLS, Orion, and the lunar Gateway (Figure 4) will all be operational to support lunar exploration and science by the mid-2020s. In addition to this infrastructure, we considered three potential scenarios for human exploration of the lunar surface, summarized in Table 1.

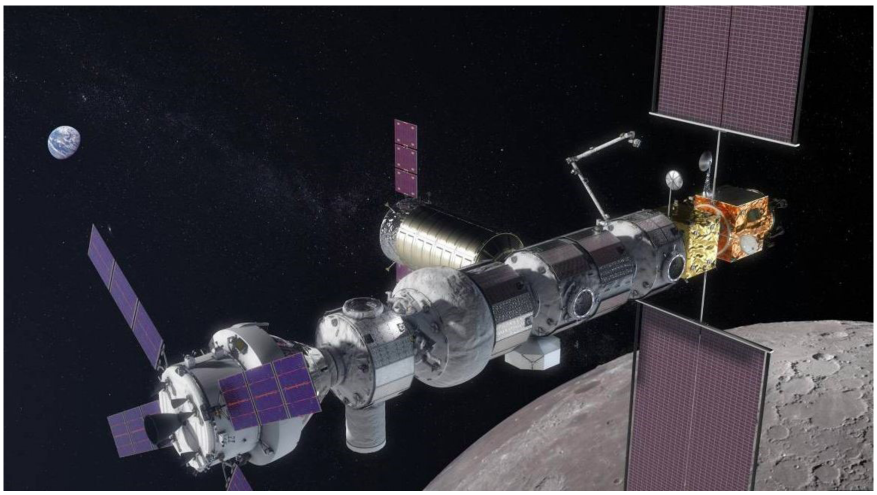

Figure 4: Artist's conception of the lunar Gateway on orbit at the Moon. Source: NASA.

TABLE 1: Key Characteristics of Adopted Lunar Exploration Scenarios

Lunar Attribute	Gateway-Only	Sortie-Class	GER-Class	Field Station
All options assume Gateway staging, heavy lift, and 11 km/s return vehicles				
Human Surface Mission?	No	Yes, Multiple Sites	Yes, Multiple Sites	Yes, Fixed Base Site
Crew to Surface	0	2-4	4	4+
Surface Exploration Duration	n/a	3-5 Days	42 Days	6 Months
Pre-Deployed Surface Assets	No	No	Yes	Yes
Key Attributes	• Earth or Gateway tele-operated robotic science & demonstrations	• Unpressurized rover for local exploration	• Pressurized Rover • Cryogenic lander/ascent • Reusable ascent stage • KiloPower	• Pressurized Rover • Cryogenic lander/ascent • Reusable ascent stage • KiloPower • Habitat • ISRU
Exploration Range	n/a	<10 km per site	100 km per site	100 km from base

A range of lunar missions was considered in order to help drive key capability and technology needs and potential applicability toward future Mars missions

These three surface scenarios, which are described in detail by Connolly *et alia* (2018)[1], varied from brief visits to the lunar surface that would last for less than a lunar day (~14 Earth days) up to extended human presence at a lunar field station, with all the necessary infrastructure for long-term habitation. The table provides basic information and attributes for each of the lunar scenarios. The sortie-class scenario is essentially a more advanced and sophisticated version of the Apollo missions. The intermediate scenario is derived from the architecture defined by the Global Exploration Roadmap (GER)[2] developed by the International Space Exploration Coordination Group (ISECG), where pressurized rovers became mobile habitats. The Field Station scenario provides a more robust exploration capability similar to that required for future landed human missions to Mars. The workshop showed that in varying degrees all three of these surface scenarios fed forward to the human exploration of Mars, although with the Gateway as presently conceived being of more limited value. The task of the AM VI teams was to assess the extent to which activities enabled under each of these scenarios would potentially retire risk and cost, and reduce development times, for human missions to Mars.

Workshop Process

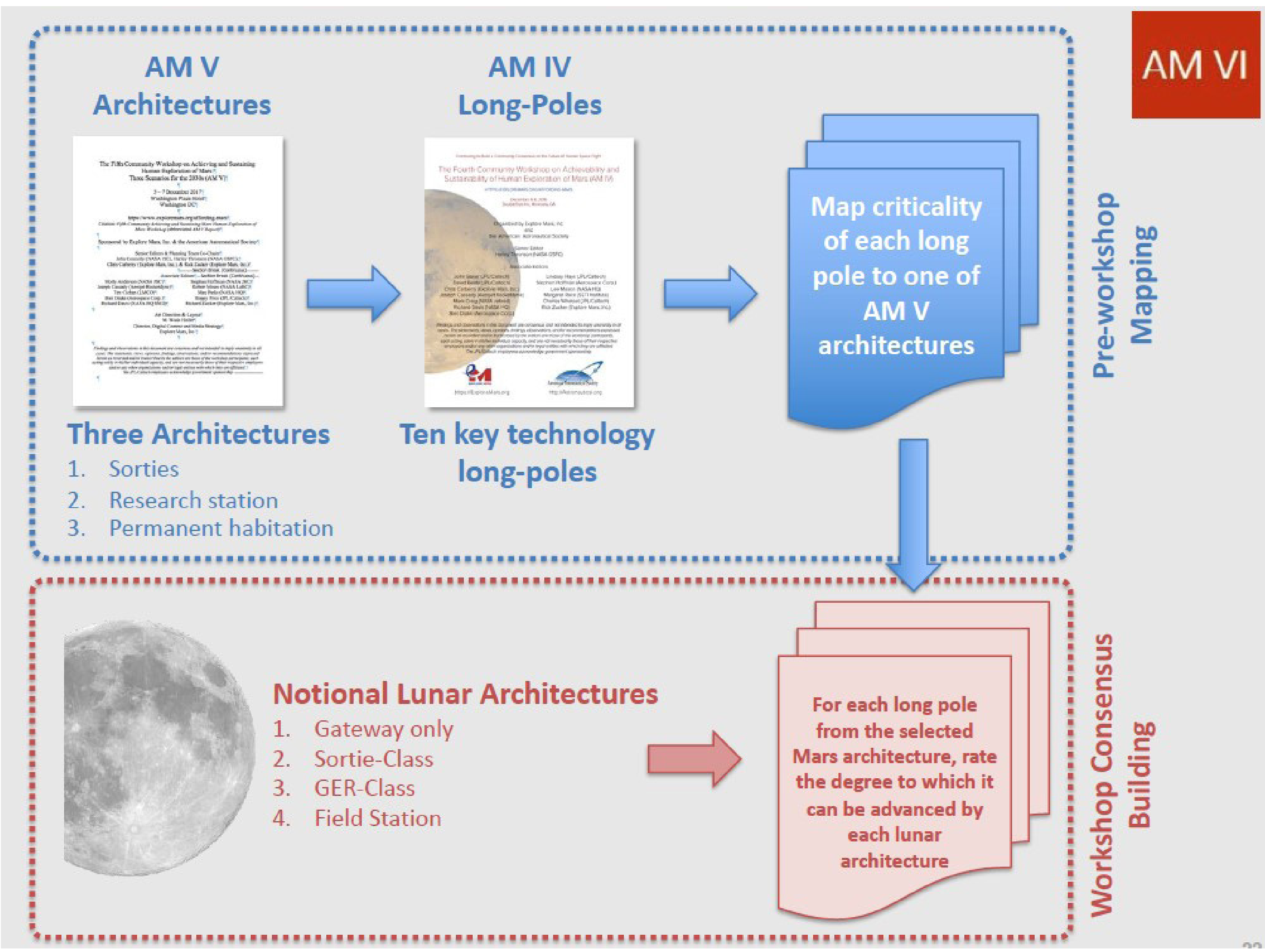

Figure 5: Process to assess candidate lunar operations for relevance to human Mars exploration

[1] Connolly, J.F., B. Drake, B.K. Joosten, N. Williams, T. Polsgrove, R. Merrill, M. Rucker, J. Stecklein, W. Cirillo, S. Hoffman, and T. Percy (2018) The Moon as a stepping stone to human Mars missions. 69th International Astronautical Congress, IAC-18,A3,1,3,x43905.

[2] https://www.nasa.gov/sites/default/files/atoms/files/ger_2018_small_mobile.pdf

Our process for assessing how astronaut and robotic operations on the lunar surface and its vicinity may feed forward to enable subsequent human exploration of the surface of Mars builds upon our previous AM workshops (https://www.exploremars.org/affording-mars) following the process summarized in Figure 5 .

Three independent scenarios for the human exploration of Mars were developed in our AM V workshop, each of which had a different 'end state' for astronaut operations, from simple sortie missions to elaborate permanent habitation. The four adopted lunar scenarios summarized in Table 1 were evaluated in our AM VI workshop on the degree to which they served as a plausible demonstration or development site for the AM IV technological "long poles" that were determined to be necessary to achieve the Mars scenarios. As we describe below, in practice we adopted only a single Mars scenario – the Research Station – as the sortie mission did not require lunar operations or demonstrations. Furthermore, for the purpose of our study, the Mars Permanent Habitation scenario was nearly equivalent to the Research Station.

To better manage this assessment process during the workshop, the participants were divided into two somewhat-overlapping groups of about equal size: one emphasized surface operations and capabilities on the Moon and Mars and the other concentrated on in-space transportation and propulsion systems. The two teams communicated regularly during and after the workshop and shared membership, so that the final set of observations and findings are internally consistent. However, as the two topic areas are separable, we present and discuss their findings separately

The most significant and actionable output of this process is discussed below and is reflected in the pair of technology and engineering "long pole" matrices in our appendix, where we tabulate our assessment of the degree to which several dozen proposed lunar technologies, operations, and infrastructure enable human exploration of the surface of Mars during the 2030s.

Workshop Ground Rules and Assumptions

To manage the process and, especially, to encourage convergence on conclusions and findings, several ground rules and assumptions were required for the workshop. These were similar to those adopted for the previous AM workshops:

- The first human mission to the surface of Mars will take place before during the 2030s. Budgets for space agencies will grow approximately with inflation. Modestly greater budget growth is possible in response to broad public and stakeholder support for lunar exploration and travel to Mars.
- No technological, political, or budget "miracles" are permitted or, if so, they must be clearly identified and justified.
- SLS, Orion, the Gateway, and commercially available medium-lift launch vehicles will be available during the time period considered here, so will not be assessed in depth in this workshop.
- The presented Moon and Mars scenarios may not be altered in significant ways.
- Teams are not to advocate for any lunar scenario, but rather accept the scenarios as presented.
- There will be a continuous human presence in low Earth orbit to provide research and development opportunities via the ISS and/or other (e.g., commercial) platforms throughout the timeframe considered in this workshop.
- Partnerships (international, industrial, commercial, academic . . .) will be an essential component of human exploration.

Matrix-Filling Approach

Each team was provided with a matrix of suggested technology "long poles" that were developed in our fourth (AM IV) workshop. These "long poles" were evaluated against the four lunar mission categories that were adopted in the current workshop (AM VI): Gateway only, lunar sortie, GER-class, and Field Station (Table 1). For each of the mission categories, the teams were tasked with specifying whether or not the category had feed-forward applicability to the human exploration of Mars. The general ranking terms to be applied were: low, medium, and high.

This process involved first analyzing each "long pole" with respect to the four lunar scenarios. The pair of teams (Surface and Transportation/Propulsion) determined[3] whether the "long pole" was included or would be a capability that was required for the particular lunar scenario. If so, then the teams were required to also assess the extent of its applicability to future Mars scenarios. The rankings are described in the opening of each of the two sets of matrices and are reflected in the color coding on the matrix blocks (**red** for low, **yellow** for medium, and **green** for high) and comments were included in the blocks to explain the rationale for each ranking. An example output is shown in Figure 6.

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew explora-tion	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[1]
1: Aggregation/Refuel/ Resupply **(11)**									
Design of logistics architecture and demonstration in deep space	Demonstrate the autonomous delivery and transfer of fuel and cargo in deep space	Med: Aggregation, assembly and refueling/ resupplying of the Gateway will inform Mars mission assembly Small quantities and scale	Low: Assuming expendable descent and ascent stage	Med: Assuming at least a reusable ascent stage. Vehicle Refurbishment at Gateway High: If descent stage (cryo) is fueled at Gateway Med scale logistics	High: Assuming fully reusable lander. Long duration operations on the surface of the Moon will help refine future Mars logistics strategies. Large scale logistics	N/A	*Note: Focus only on logistics here since fuel is covered below.	ISS analog possible	No Most of this work can be done in LEO and/or Gateway
Autonomous operations at Mars	*Operations of systems at Mars distance with limited/no Earth support	Med: Uncrewed/ autonomous operation at Gateway provides an analogue for autonomous operation at Mars Transition from autonomous to crewed operations Demonstration of Comm Ops through Comms relay	Med: Autonomous mating of lander with Gateway and checkout prior to human arrival Potential autonomous landing operations	High: Repeated/ extended autonomous operation of lander at Gateway	High: Assume field station is permanently occupied (less autonomous than previous). Initial operations similar to GER class	Time lag may influence autonomous operations		ISS analog possible (Proposed)	No

Figure 6: Example engineering long pole matrix for Mars ascent vehicle (MAV) assessed by the Transportation team.

As seen in the figure, the long pole of converting CO2 to oxygen does not apply in any way to lunar missions so it was ranked "low" and color-coded red. On the other hand, the "long pole" of Guidance, Navigation, and Control was found to apply directly to all lunar surface scenarios and was correspondingly ranked high because techniques such as Terrain Relative Navigation could be demonstrated on the Moon very effectively and would also support all our adopted lunar activities, except a Gateway-only scenario. The long pole of cryogenic propulsion and storage, however, was seen as being capable of being demonstrated at the Gateway and used for all lunar surface scenarios, although only required for a "field station" scenario with much higher landed mass requirements. It was therefore ranked as a "medium".

[3] These assessments continued for several weeks after the workshop ended.

Workshop Outcomes, Driving Gaps, and Priorities

Transportation/Propulsion Team:

The Transportation breakout group debated the most relevant transportation-related systems and technologies needed to be tested or demonstrated on the Moon to feed forward to Mars, using the "long poles" matrix to guide the discussion. The team considered all of the "long poles" identified in the AM VI candidate matrices with the exception of Surface Habitats and Research Laboratories, Surface Power, Surface EVA Suit, and the Pressurized Surface Rovers, which were felt to be only appropriate for surface systems evaluation. Four topic areas emerged as the priorities for using lunar operations to address the most critical transportation segment (risks): long-term cryogenic fluid management, lander development, vehicle aggregation, and human health and biomedicine.

Long-term cryogenic fluid management is critical to the storage of cryogenic propellants (LOX, LCH_4, LH_2) needed to provide the impulsive propulsion for human Mars missions. Lunar missions will require similar cryogenic propulsion systems for lunar landers, and these elements will have a high degree of commonality with Mars transportation systems including passive and active thermal control of cryogenic propellants, low- or no- boiloff systems, liquid acquisition and tank mass gauging.

The development of lunar and Mars landers will share a great deal of common technology. Though the landing sequence is different, both require propulsive landing, precision guidance, hazard detection and avoidance, and autonomous landing systems. Both lunar and Mars landers will require deep-throttling cryogenic engines in the 40 - 100 kN range, and (likely) cryogenic reaction control system (RCS).

The cislunar Gateway, while not assessed in this workshop, was assumed to be available for both lunar and Mars missions, and can serve as an important node for vehicle aggregation for both destinations. Initial assembly, refueling, refurbishment and checkout of both lunar and Mars vehicles can be performed at the Gateway, and will be enabling for reusable transportation elements. A large part of vehicle servicing focuses on refueling of lunar and Mars landers, but will also include vehicle maintenance, provisioning and re-certification for flight. The operational experience gained during the lunar phase of exploration will feed directly into the vehicle reuse operations for future Mars missions, and contribute to the sustainability of both programs.

Transit durations to and from Mars will place astronauts in a deep space environment for between six and ten months, both Mars-bound and Earth-bound. Multiple human health and biomedical challenges exist, with radiation and psychosocial issues topping the list. Monitoring deep-space behavioral health will extend cislunar operations as the distance from Earth and mission duration increase isolation and confinement of the crew. Similarly, monitoring for and protecting from radiation exposure on cislunar missions will greatly reduce the uncertainties in risk projections for Mars mission radiation exposure.

Surface Team:

The Surface Operations team focused on the following "long poles": In-Situ Resource Utilization (ISRU), Surface Habitats and Research Laboratories, Surface Power, Communications, Human Health and Biomedicine, Surface EVA Suit, and the Pressurized Surface Rovers. We approached each "long pole" in terms of how the four lunar scenarios would contribute to their shortening. The Surface Team found that the highest priority systems/technologies that could be tested/demonstrated on the Moon to reduce risk in implementation on Mars were the following:

- Human Health and Biomedicine (e.g., psychosocial, food, medicine). Here, we focused on humans in partial gravity, which meant the Gateway scenario was of minimal use (except for testing the longevity of food and medicine in the space environment).

- Surface Power (e.g., fission for primary power, radioisotope power for mobility). The Field Station scenario was again the most relevant to shortening this long pole. The GER-Class and Field Station scenarios were best suited to shortening this long pole, with the Sortie and GER Class scenarios being of some use. The Gateway scenario was not relevant here. Fuel cell – battery trade for power/energy storage in the rover – should be considered.
- Pressurized Surface Rovers (e.g., operations, energy storage, airlocks, suit ports). For this long pole, both the GER Class and Field Station scenarios were very relevant, while the Gateway and Sortie scenarios were considered not applicable. Power/Energy Storage trade for the Rover was considered important because of the different environments and use cases for Moon and Mars.
- Surface EVA Suits (e.g., pressure garments, environmental protection layer, maintenance). The GER-Class and Field Station scenarios are the most relevant to shortening this long pole with Sortie missions being somewhat relevant because the longevity of the suits was considered to be the most important. Thermal management was considered an important issue for the Moon. It would be very attractive if a solution could be developed for the Moon that is also technologically viable for Mars. While the martian environment is more thermally benign than that of the Moon, Mars has an atmosphere, which may preclude some thermal solutions that could work on the Moon due to the lunar vacuum environment. We note that a trade study for suit ports versus airlocks for the rover/field station EVA system still needs to be done.

The next highest priority included:

- Communications (e.g., orbital assets, local/regional/global communication networks). All scenarios were considered important for shortening this long pole.
- Surface Habitats and Research Laboratories (e.g., systems availability, operations). The Field Station scenario was the most relevant to shortening this "long pole."
- SRU was highlighted as a "notable topic" because of the synergies in local resources on the Moon and Mars, specifically surface water ice. However, critical information about these resources (e.g., abundance, composition, accessibility & extractability, storage & transport) is still needed, as well as verifying the potential for lunar water ice ISRU technologies, processes, and operations to feed forward to the human exploration of Mars. (See also the next section and appendix.)

Major Conclusions – Transportation/Propulsion Team:

Comparing the various lunar scenarios, the "Gateway only" had zero low feed-forward ratings, eighteen mediums, and ten highs. The Lunar Sortie scenario had one low, twelve medium, and nine high ratings. The GER-class surface mission scenario had zero lows, thirteen medium, and thirteen high ratings and the Field Station scenario had zero lows, twelve medium and sixteen high ratings. From this comparison the lunar Sortie scenario was clearly the least useful for achieving risk reduction of "long poles" leading to human Mars missions. The GER-class and the lunar Field Station were comparable and the most applicable. The Gateway-only scenario accomplished an equivalent number of risk reduction activities, although had more ratings classified as medium than high. Gateway was therefore found to have real benefit to feed-forward risk reduction for Mars, especially for one of our priority driving gaps: vehicle aggregation. We also noted that the Mars Ascent Vehicle (MAV) had strong benefit from use of cryogenic engines in the lunar exploration campaign and that a single lunar ascent/descent vehicle is directly applicable to a MAV.

Major Conclusions – Surface Team:

In each of the seven areas listed above, it was the lunar Field Station scenario that was the most relevant in terms of using the Moon to shorten these technology "long poles" in each case. This scenario reduces the most risk for human permanence on Mars and could facilitate synergistic developments to facilitate human presence at both destinations, with the Moon as the risk reduction proving ground (as long as funding is still available for Mars exploration in a reasonable timeframe).

A. Suggested Trade Studies – Transportation/Propulsion Team:

Our assessment activities identified several trade studies that we urge be carried out by a community of subject matter experts supported by and reporting to NASA:

- What are the priority surface and orbital reconnaissance programs of potential lunar and martian resources to assess their potential?
- What is the degree to which lunar resource exploration, production, beneficiation, and commodity storage processes enable and feed forward to Mars?
- Pros/cons of different cryogenic propellant combinations (i.e., LOX/CH_4 versus LOX/H_2) for lunar and Mars scenarios
- What are the anticipated effects of declining launch costs and development of lunar resource extraction capabilities, including comparison of end-to-end costs of resources extracted from the Moon with those supplied from terrestrial sources
- Lunar ascent vehicle/lander extensibility to Mars ascent vehicle/lander

In addition to these suggested trade studies, a potential National Academies study could examine the mitigation of environmental damage to human health (e.g., radiation, psychosocial, zero g, partial g) for lunar and Mars missions. Questions, such as those below, would need to be addressed in such a study:

- What needs to be carried out at ISS and Gateway, and what can be learned on the Earth?
- How will long-duration stays on the lunar surface (i.e., partial g) inform us about developing mitigation strategies for maintaining human health and performance?
- What capabilities can be supported within mass and volume limitations?

Furthermore, as described below in our section on in-situ resource utilization (ISRU) and in the appendix, we urge a National Academies study to assess this issue in the near term.

B. Suggested Trade Studies – Surface Team

In addition to ISRU, our Surface Team found the following trade studies would be important in defining the magnitude, and a pathway to shortening, of a "long pole," as well as reducing risk for a human presence on the surface of Mars:

- Value of remotely operated robots versus on-site astronaut operations on the lunar surface to feed forward to human missions to Mars.
- Airlock versus suitlock, including planetary protection, habitat access, and cognizance of different environment.
- Common development paths for Mars and Moon surface suit thermal systems.
- Long-lived pressurized rover energy production and storage (e.g., Kilopower versus radioisotope power system (RPS), fuel cells versus batteries).
- Rover needs on the two worlds [e.g., duration of trips, what rovers are used for (science, construction, maintenance, transportation), day-night cycle, and crew size].
- Study of ISRU-based site preparation and construction for landing, lift-off, and surface transportation operations on lunar and martian terrains.

Future Joint Workshops and Assessments: Subject Matter Experts on the Moon and Mars

In addition to these proposed trade studies, our workshop found significant value by having the Moon and Mars communities work together to understand how lunar operations and capabilities can feed forward to Mars. We recommend a more extensive assessment with increased joint participation by these communities. This collaboration, under NASA leadership, should commence **as soon as possible** and use the ongoing NASA *Engineering Long Poles for Getting Humans to the Surface of Mars* effort as the basis for the activity.

In-Situ Resource Utilization: The Key for Sustainable Exploration

Two constants in all planning efforts for NASA's human space exploration program have been both **sustainability** and **affordability**. One approach NASA has pursued that can significantly change how systems required for space transportation and infrastructure are designed and integrated, as well as potentially break our reliance on Earth-supplied logistics and enable space commercialization, is ISRU or "living off the land". Specific to the AM VI workshop, and contained in our recommendations, was evaluating potential synergies between ISRU development at the Moon that would directly feed forward to Mars.

Mineral and Water Ice Resources of the Moon

During the Apollo era, the Moon rocks that were returned to Earth by the astronauts gave rise to the concept that the Moon was extremely dry. However, the regolith of the Moon contains many light elements (O, C, N) and oxides of Si, Fe, Ca, Al, Mg, etc., that may be possible sources for utilization.

The Apollo picture of a very dry Moon began to change in the mid-1990s. Beginning with the bistatic radar hints from the Clementine mission in 1994 and confirmed by the gamma-ray and neutron spectrometers aboard the Lunar Prospector (LP) launched in 1998, what appear to be water ice deposits of ~2-4% in the permanently shadowed polar regions were detected. Though the spectrometers aboard LP could not distinguish between implanted/cold-trapped hydrogen and water ice in the form of H_2O, the discovery set the stage for more sophisticated missions: NASA's Lunar Reconnaissance Orbiter (LRO), the Lunar Crater Observation and Sensing Satellite (LCROSS) impactor and the Chandrayyan project from India, with its U.S.-supplied instrument, Moon Mineralogical Mapper (M^3).

Figure 7 shows a recent integration of data sets from instruments aboard LRO as well as M3. As shown, the figure contains the provocative finding of water ice at the surface of the Moon up to 30% by weight. If confirmed by a landed mission and found to be accessible via **affordable** mining techniques, these deposits could represent a very substantial resource for human exploration. Conservative estimates on the basis of current data indicate >1 billion mT of water ice is available at the lunar poles. This requires verification through surface exploration that would also test the purity and extractability of this resource.

Mineral and Water Ice Resources of Mars

A long series of spacecraft beginning with the twin Viking orbiters and landers in 1976 have sought to characterize the martian surface and atmosphere. With the arrival of Mars Global Surveyor in 1997, Odyssey in 2001, Mars Reconnaissance Orbiter (MRO) in 2005, Phoenix in 2007 and a series of rovers (Spirit, Opportunity, and Curiosity) in 2004 and 2012, the elemental and mineralogical composition of most of the martian surface and some of the subsurface has received at least an initial examination. Data from the instruments aboard the MRO spacecraft shows hydrated minerals are present across much of the surface of Mars, in principle providing significant ISRU locations. We note that Mars 2020 will contain an ISRU technical demonstration experiment, the Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE), to harvest oxygen from the Martian atmosphere, a resource beyond Earth that is unique to Mars.

Perhaps even more compelling for ISRU and future human exploration and habitation are the results of the Odyssey mission. Using high-resolution gamma-ray and neutron spectrometers, this mission created a whole-planet map of Mars' surface chemical composition. One of the most surprising findings (Figure 8) is the presence of hydrogen in the form of water ice distributed across most of the Red Planet. From a few percent by weight at the equator to more than 80% at the poles, water ice appears to be ubiquitous in the first meter of the regolith. This discovery immediately suggested a follow-up landed mission to check the veracity of the orbital remote-sensing measurement. That opportunity came through NASA's Phoenix mission that landed at 69 degrees North latitude. Using a scoop and on-board evolved gas analyzer, the detection of water ice was confirmed.

Measurements of the subsurface of Mars have been conducted using ground-penetrating radar on the MRO mission [via the Shallow Subsurface Radar (SHARAD) instrument] and the European Mars Express mission [via the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) instrument]. Data from the two suggests far more ice on Mars at depths well below one meter. Recent measurements from SHARAD indicate a buried glacier the size of New Mexico. In addition, MARSIS investigators recently published data showing a liquid water lake at the depth of 1 km that is about 20 km in size. Clearly, Mars appears to have enormous reserves of water ice and perhaps even liquid water.

Specific Lunar ISRU to Feed Forward to Mars Exploration

We believe that by conducting revealing studies and demonstrations, ISRU at the Moon may pave the way for humans exploring Mars, studies that include (1) Identify, characterize, quantify, acquire and utilize resources/volatiles for future applications; (2) define a lunar-landed mission that will travel to the regions of the lunar poles where water ice may be present in quantities up to ~30% by weight; and (3) demonstrate ISRU concepts, technologies, and hardware that reduce the mass/cost/risk of human Mars missions. This would include ISRU for propellant production, cryogenic storage and transfer to refuel an ascent vehicle as well as site engineering and infrastructure emplacement for repeated landing/ascent at the same location. Another important area of synergy is utilizing the Moon for operational experience and mission validation for Mars, such as (1) pre-deployment and remote/autonomous activation and operation of ISRU assets without crew or (2) landing crew with empty tanks with ISRU propellants already available; and (3) examining long-duration surface operations to increase duration and autonomy, possibly at a polar location due to more benign solar/thermal environment.

Trade Studies Relevant to ISRU

As discussed earlier, there is a large number of trade studies that we recommend NASA conduct to validate the proposition that conducting demonstrations at the Moon will plausibly and substantially advance the journey to Mars. A subset of those trades directly affects ISRU, including (1) comparison of end-to-end costs of resources extracted from the Moon with those supplied from terrestrial sources, (2) value of remotely operated robotic versus on-site astronaut operations on the lunar surface to feed forward to human missions to Mars, and (3) ISRU-based site preparation and construction for landing, lift-off, and surface transportation operations on lunar and martian terrains.

National Academies Studies

In recognition of the long-term importance of ISRU, we recommend a National Academies study of ISRU for the Moon and Mars. Beyond the fundamental importance of "living off the land" for sustainability, there are several reasons why such a study is required:

- National Academies studies are the "gold standard" for advice to the Nation. Great care is given to selection of a panel with the relevant expertise and in balancing perspectives and achieving consensus.
- Sufficient time (usually three to five multi-day meetings, plus months of writing and editing) is devoted to hearing from advocates/experts in a public setting as well as opportunities for deliberation and (often) intense debate internal to the panel.
- An ISRU study would serve as a practical bridge between the robotic science and human

spaceflight (HSF) communities, a collaboration that has long been sought by many. The science community would learn about the special constraints that accompany human exploration and the HSF groups would similarly learn what scientists and mission data say (and do not say) about the composition of the Moon and Mars.

- All consensus reports of the National Academies go through a peer-review process by a completely separate panel of experts, just as is done for top-quality journal articles.
- The Statement of Task for such a study is beyond the scope of this report, although we suggest that some combination of the high-level investigations along with the detailed recommendations for demonstrations and trade studies would serve as an excellent starting point. ISRU in some form will be critical to future exploration.

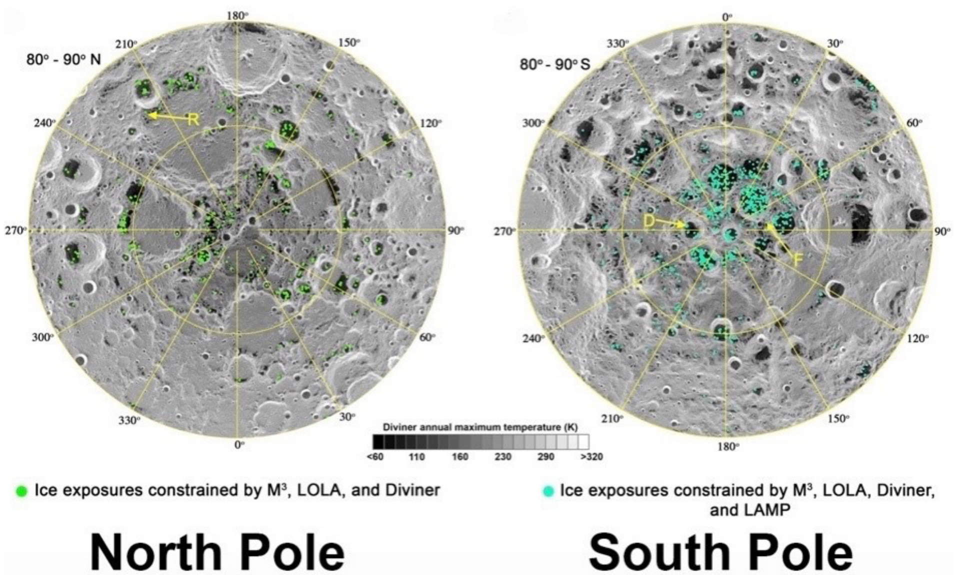

Figure 7: Polar water ice: up to 30% by weight at the surface. Li S. et al. (2018) PNAS 115, 8907-8912

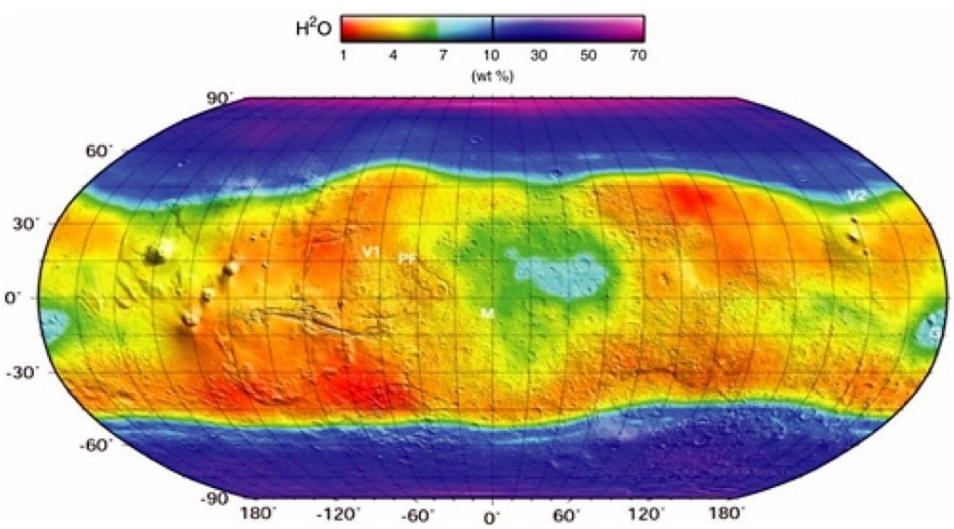

Figure 8: Water ice distributed across Mars, up to 80% wt.

Appendix A: Mars Engineering Long Poles – Surface Team

<u>Feed Forward Assessment</u>

- For each viable lunar capability, or operational need, assess how well it feeds forward to each of the three example Mars scenarios and capture the rationale for each rating in a narrative form:

Low: Within this rating level it was viewed by the assessment team that even though the capability may play a very important role in lunar exploration, the specific system or capability in question provided very little risk reduction or no feed-forward to the Mars basis of comparison.

Medium: With this rating level the capability was viewed as being on the path to Mars, but differences in the capability performance level, operational characteristics, or environment would allow mitigation of some risks associated with capability readiness for Mars. After a lunar mission, these capabilities would require modification. Additional testing would also be required before it would be fully applicable to a Mars mission.

High: This capability was viewed as being on the path to future human Mars missions “as is”, or with few or even no modifications, and demonstration in the lunar environment would significantly or fully mitigate risks associated with Mars missions. After a lunar mission the emphasis would be on certification to the Mars environment and operational requirements.

**Please note content marked with an * has been added by the Achieving Mars VI preparation team*

Long Poles and Associated Driving Gaps	**Minimum Success Criteria and *other information**	**Gateway**	**Lunar Sorties**	**GER Class**	**Field Station**	**Key environmental differences that impact Long Pole/driving gap reduction**	**Other Considerations**	**Capabilities which can be matured in LEO (e.g. ISS) now**	**Capabilities with long lead times which must be developed specifically for Mars[1]**
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
1: In Space Aggregation/ Refuel/ Resupply (11)									
Design of logistics architecture and demonstration in deep space *Please Note: This row has been filled in as an example	Demonstrate the autonomous delivery and transfer of fuel and cargo in deep space	Somewhat: As currently envisioned Gateway operations are limited in duration (~42 days) requiring less logistics than a Mars mission	n/a	Somewhat: As currently envisioned GER operations are limited in duration (~42 days) requiring less logistics than a Mars mission	High: Long duration operations on the surface of the Moon will help refine future Mars logistics strategies.		*Note: Focus only on logistics here since fuel is covered below.	No	
Autonomous operations at Mars	*Operations of systems at Mars distance with limited/ no Earth support		n/a						
Xenon & cryogenic transfer	*Transfer of high pressure He and cryogenic propellants in zero-g		n/a						
Footnotes	Secondary objective compared to Surface systems.								

[1] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/ driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Radiation Protection	*Provide adequate protection from GCR and SPE						* **Secondary.** Look at commonalities in radiation protection.* Gateway can be useful for Mars transit hab information. Can put sensors on Gateway to gather more information – human presence not required. LRO has already been collecting data for 9 yrs! Useful to send a surface asset to collect info there before people land? If surface missions are short duration, then less knowledge. But could add sensors to surface assets to gather the information.		
Crew autonomous operations	*Demonstrate the capability of operating habitat systems at Mars distance with limited/no Earth support (e.g., simulated time delay)		n/a						

[2] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/ driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Crew health	*Provide the ability to adequately maintain crew health		n/a						
Crew activity	*Demonstrate the ability to autonomously plan and execute crew activities during the mission								
Vehicle maintenance	*Demonstrate maintenance and repair including internal- and external-mounted equipment		n/a						
Reliable Life Support	*Demonstrate the ability to support long duration (1000+ day) Mars missions including 500 days of dormancy be-tween crew visits		n/a						
Crew Privacy and Habitable Volume	*Provide adequate human factors concepts		n/a						
Logistics and storage	*Ability to store and manage adequate supplies for a round-trip Mars mission		n/a						

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	**Gateway** Lunar orbit only with surface telerobotics	**Lunar Sorties** Short duration stays with local crew exploration	**GER Class** Medium duration with local exploration, relocatable	**Field Station** Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/ driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Thermal	*Habitat thermal control for cis-lunar, deep space, and Mars orbit operations								
Reduced power	*n/a						*Mars architectures has the transportation system provide power to the habitat, thus this sub-pole is n/a		
Deep Space Navigation	*Ability to autonomously navigate in deep-space at Mars distance						*For the Mars architecture the transportation system can perform this (cargo vehicle), thus habitat would be backup		
Quarantine/Isolation/Privacy Capability	*Adequate provisions for crew privacy accommodations		n/a						
Footnotes	Does it apply? You may want to have commonality between your transit habitat and labs and your surface systems. So while not necessarily part of the surface system, it should be considered due to the likely commonalities between transit and surface.								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[3]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
3: Solar Electric Propulsion Cargo Tug									
300-kW Class Solar Array	*Ability to produce 300-400 kw of electric power at Mars distance		n/a						
Asteroid Retrieval Vehicle-derived Power Distribution	*Ability to condition and transfer 300-400 kWe power to the thrusters		n/a				*This should now read Gateway derived		
12.5-kW Electric Propulsion Thruster	*Xenon Thruster performance for long durations		n/a						
Low Thrust Navigation	*Ability to autonomously navigate during long-thrust arcs necessary for electric propulsion		n/a						
Footnotes	Not applicable								

[3] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[4]
4: Mars System Recon (12yrs)							Long pole 4 is Mars specific and thus all sub-poles are n/a		Yes
Resource Reconnaissance for Landing Site Selection	Minimum success criteria can be met with at least one new focused orbital mission and one new surface precursor ground-truth mission.	n/a						No	See above
Ground truth of resource mapping	*Correlation of orbital reconnaissance with surface mission	n/a						No	See above
Round-trip Demo / Sample Return	*Return of sample from the surface of Mars which demonstrates key human-forward capabilities	n/a	n/a	n/a	n/a			No	See above
Extant biology in soil	*Analysis of materials to be returned to Earth to identify potential extant biology	n/a	n/a	n/a	n/a		*In-situ?	No	See above
Atmospheric recon for Entry Descent and Landing	*Ability to predict local atmosphere conditions to improve EDL capabilities	n/a	n/a	n/a	n/a			No	See above
Footnotes	Also driven by science questions Informing landing site as well as human space flight design (dust for suits, surface integrity for landing, etc) Weather sensing also important for making sure you have the right prop/system design for landing given variations in atmospheric density. "n/a" above are related to whether you can learn about Mars surface from the Lunar surface.								

[4] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[5]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
5: Crew/Cargo Lander: Entry, Descent, and Landing (EDL) (13)	Perform a precursor mission to demonstrate EDL, prior to delivery of mission-critical cargo								
Human-scale Mars EDL system)	30 t, <100 m precision	n/a					*Consider lunar propulsion landing and Mars terminal landing phases		
LOX/Methane Propulsion and Cryofluid Management	*Demonstrate a relevant LOX/ Methane propulsion system and long-term cryogenic storage in Mars –like surface environmental conditions	n/a	n/a				*Assume hypergolics for lunar sortie missions		
Footnotes	Make sure that this design takes into account everything that is needed by humans and surface systems. ? Add plume excavation? May also include landing site preparation.								

[5] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[6]
6: Mars In-Situ Resource Utilization (ISRU) Tech Development **(8) ** PRIMARY**								No	No
Convert CO_2 to O_2	Demonstrate the capabilities on Earth in Mars environmental chamber at rates of 2.2 kg/hr			n/a	n/a		Not relevant to lunar missions, so remove.	See above	See above
Atmospheric dust effects on ISRU	*Demonstrate the ability to accommodate expected dust conditions on Mars	n/a	n/a	n/a	Med - More general dust mitigation commonalities.	No atmosphere on Moon, but other methods to kick up dust (landers landing, mining activities, etc.) Important to figure out design of filters and "fowling" of filters, catalysts, joints, bearings, etc.	Dust is an issue in all cases, but specific mitigations may vary significantly.	See above	See above
Oxygen extraction from CO_2.	*Production of oxygen from the atmosphere of Mars at a scale required for human missions (2.2 kg/hr)	n/a	n/a	n/a	n/a		Assumes getting O_2 from CO_2 because we have not ground truthed ice presence on Mars (bring methane from Earth). We know how to do this. Is this a long pole?	See above	See above

[6] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[6]
6: Mars In-Situ Resource Utilization (ISRU) Tech Development **(8) ** PRIMARY**								No	No
Access H2O--sub-surface ice/minerals (mining)	*Demonstrate the ability to access and acquire useable H2O sources on Mars	n/a	n/a	n/a	Med – depends on nature of ice deposit.	Mars site may have pure ice, which may drive Rod well vs processing very dirty ice on Moon. Acquiring ice at 40K (Lunar poles) may be intrinsically different.	Mining at lunar conditions (e.g., 40 K) is quite different from Mars conditions.	See above	See above
Resource Acquisition (processing)	Perform subscale demo with soil and water analysis capabilities on Mars with similar feedstock material	n/a	n/a	n/a	Med– depends on nature of ice deposit.	Processing 40K ice is different. Different type of "dirty" ice, so processing may be somewhat different.	Fluids aspects can be modeled. Geological specifics need testing.	See above	See above
Liquefaction & Cryofluid Management	*Demonstrate the ability to store O2 and CH4 for long periods in Martian surface environmental conditions	n/a	n/a	n/a	Component - High System – Med	Where is the cryo prop stored – permanently shadowed or not? What is energy input and what cryocooling (or heating?) is required?	Thermal environment different between Moon & Mars.	See above	See above
Footnotes	This ISRU is not the recon part – it's the actual infrastructure and whole system buildup. If GER-class goes back to the same site, then it could become relevant. Add water electrolysis. Is this really a long pole? We already know how to do it. ISRU for habitat construction added? Also for landing site preparation and others. Do we need ISRU For Mars surface exploration? Liquefaction & storage important. Prospecting aspect is captured in site recon. Robotics precursors as part of CLPS program could be a good synergy. Understanding lunar ice deposits does not translate to understanding Mars ice deposits.								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[7]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
7: Surface Habitat and Research Laboratory **(~5-17yrs) ** Primary**								No, can anyone think of any meaningful feed forwards?	No, there are feed forwards from the moon
Surface habitation	Integrated test (with appropriate fidelity including environment, subsystems, layout, procedures, duration, etc.	n/a	n/a	n/a	Med - environment is different, though can learn about layout, procedures, duration, and some subsystems, etc.	Significant effect required to mitigate differences due to environment, dealing with waste, recycling, motivation for design.	*Testing can be performed on Earth Many discussions of the details of the designs – commonality and feed forward depends on more design specifics.	See above	See above
Systems availability (mean time between failures – system reliability + repair + supply of parts)	*Demonstrate system availability is sufficient to meet mission objectives (i.e., crew does not spend all of its time maintaining the system)	n/a	n/a	n/a	Med– learn about concepts of how to do this, as well as for some systems that are (close to) common; but many system details may be different due to different environments.	For Moon, can bring repair parts on relatively short timeline, while for Mars need to make decisions far ahead of time.	*Demonstration can be performed on Earth. Design of systems to be repairable overarching. Reliability vs repairability – increasing both may not always be compatible.	See above	See above

[7] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[7]
7: Surface Habitat and Research Laboratory **(~5-17yrs) ** Primary**								No, can anyone think of any meaningful feed forwards?	No, there are feed forwards from the moon
Fundamental and applied research objectives	*Demonstrate the ability to meet the functional and operational needs of surface missions	Med (in situ investigations and glovebox, but very different between zero g and Martian g)	Low	Med	**Most** (monitoring human health-type investigation should be identical)	Mars may have indigenous biology	Accommodate field science investigations. Planetary protection must be accommodated	See above	See above
Extended periods of dormancy	*Demonstrate the ability to place the surface systems in a dormant (uncrewed) state and revive it remotely/ autonomously between crew visits.	Low – e.g., biology-related systems, radiation. Operational experience: how to shut down system, reactivate it.	n/a	Low – depends on systems used.	Med – some level of overlap, but specific to the systems used.	Mars vs Moon environment different (e.g., dust, thermal control)	What are situations where you have to put a system/ habitat/ rover in dormancy? Depends on system details.	See above	See above
Surface operations	*Demonstrate the ability to meet the functional and operational needs of Mars surface missions	n/a	n/a	Low (for hab) – due to different drivers in operations. (assume has little/no lab)	Med – difference in time delay for comms back to Earth, etc causes a number of changes. Some aspects are high.		Little definition of what lab capabilities are in GER missions. Level of applicability to Mars depends on that.	See above	See above
Footnotes	Food was here but has been moved to crew health to avoid double book-keeping. Commonality of having humans involved in research both at Moon and Mars is an opportunity to develop operational experience and system maturation (risk reduction) for research and hab ops. Similar ideas and general requirements for both Moon and Mars, but the subsystem design is quite different between the two due to the very different environments.								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/ driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[8]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
8: Mars Surface Power **Primary (8-12yrs)								No	No, there are feed forwards from the Moon
Surface Solar Arrays	Demonstrate a combined PV array and energy storage system suitable for Mars surface environment, producing at least 40 kW of electrical power, with RPS for emergency backup and keep-alive.	n/a	n/a	n/a	Low	Surface environments very different. Configuration, day night cycle. Pointing at Sun more important for Moon.	How do implement "surface" and required size? Solar array issues: dust, deployment, tolerant to environment (e.g., wind survival).	See above	See above

[8] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/ driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[8]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
8: Mars Surface Power **Primary (8-12yrs)								No	No, there are feed forwards from the Moon
Lightweight fuel cell/ battery storage	*Demonstrate power storage system capable of meeting crew mission needs during night and extended dust storms	n/a	Med	Med	Med	Environmental differences: temperature, needing batteries to last for 14 days in lunar night. KiloPower system might be used directly or to recharge batteries (e.g., if kilopower is sized for ave power vs peak power).	A lot of lack of clarity on what lunar architecture would be. That makes it hard to answer applicability to Mars. Energy density and duration of cycle may change what components you choose. Implementation of KiloPower in GER and Field Station architectures determines rest of that design too.	See above	See above
High power/ high efficiency Radioisotope Power Systems	Demonstrate at least several kW, and enhance operational flexibility with safe human proximity operations (e.g., rover power) and possibly, heat for the habitat or ISRU and science instruments	n/a	n/a (exception: could be used for long-lived experiments)	n/a (assumption that kilopower is sole power source and (exception: could be used for long-lived experiments)	High (assumption – RPS used fpr secondary)	No significant differences	*All missions may include RPS for science instrument packages	See above	See above

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/ driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[8]
8: Mars Surface Power **Primary (8-12yrs)								No	No, there are feed forwards from the Moon
10s kW Fission Power	A fission reactor compatible with the Mars surface environment and capable of producing up to 10 kW that can be integrated with multiple like-modules to provide 40 kW total.	n/a	n/a	High	High	No differences		See above	See above
Power management and distribution (PMAD)	Connecting sources and loads separated by significant distance (>1 km)	n/a (no long distance)	n/a (no long distance)	Med - dust resistance connectors, and robotic manipulation of cables (maybe shorter cables but similar robotic manipulation required).	High – laying cables, manipulating voltage for transmission efficiency, dust-resistant connectors.	Shielding of cables may be similar between Moon and Mars, while thermal considerations are different, and those can affect power loss.	Need dust proof connectors, extend & retract long cables, boost and buck voltage to help with transmission (transmit at high voltage).	See above	See above
Footnotes	Power management and distribution (PMAD) O2 & CH4 can be energy storage or backup power; similar to fuel cells.								

Long Poles and Associated Driving Gaps	**Minimum Success Criteria and *other information**	**Gateway** Lunar orbit only with surface telerobotics	**Lunar Sorties** Short duration stays with local crew exploration	**GER Class** Medium duration with local exploration, relocatable	**Field Station** Long duration with regional exploration, single site	**Key environmental differences that impact Long Pole/driving gap reduction**	**Other considerations**	**Capabilities which can be matured in LEO (e.g. ISS) now**	**Capabilities with long lead times which must be developed specifically for Mars[9]**
9: Mars Ascent Vehicle (MAV) (13)									
LOX/CH4 Propulsion and Cryofluid Management	Successful qualification test program, for integrated propulsion system and the demonstration of long- duration (1000 sols), minimal-loss cryogenic propellant storage	n/a	n/a						
Habitability	*Demonstrate the ability to accommodate 4-6 crew, for up to 43 hours, mitigate dust, and support adequate ingress/egress	n/a							
Guidance Navigation & Control	*Demonstrate the ability to autonomously navigate and rendezvous in highly elliptical orbit								
Integrated System	Key architecture decisions made. Development of a comprehensive T&V plan.								
ISRU Convert CO2 to O2	Demonstrating the capability of maintaining "zero-boil-off" during long duration periods (1000 sols) as well as liquefying oxygen produced by ISRU systems at rates of approximately 2.2 kg/hr.	n/a	n/a						
Footnotes	More about capability, than specifically MAV architecture. Can we learn from MSR MAV to develop human MAV? MSR MAV uses storables – is that compatible with human & in situ propellant production tech? Also given our current max down mass, we cannot land a wet MAV.								

[9] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/ driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[10]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
10: Mars Communication Network for Human Exploration & Science **PRIMARY								No	No, there are feed forwards from the moon
Deep Space, High-Rate Forward Link / Downlink	*Demonstrate sufficient high data bandwidth for both down and uplink at Earth-Mars conjunction distances	High – similar/ same operations and needs; system can be built to be similar to that needed for Mars.	High – similar/ same operations and needs; system can be built to be similar to that needed for Mars.	High – similar/same operations and needs; system can be built to be similar to that needed for Mars.	High – similar/ same operations and needs; system can be built to be similar to that needed for Mars.	Need planet-synchronous comms satellites for both Moon and Mars to support operations goals.	Gateway is x-band, with laser comm demo. Are we using x-band or laser comm for Mars? Some lack of clarity of the architecture for both Moon and Mars. Lunar system could be designed to Mars requirements (more stringent) such that we can use the same system in both places. Commercial opportunities to provide comm.	See above	See above
High Rate Proximity Communication	*Demonstrate local proximity vehicle-to-vehicle and vehicle/base to EVA crew communications; includes comms through orbiters.	n/a	High – similar/ same operations and needs; system can be built to be similar to that needed for Mars.	High – similar/same operations and needs; system can be built to be similar to that needed for Mars.	High – similar/ same operations and needs; system can be built to be similar to that needed for Mars.			See above	See above
Footnotes	Comms rates affect architecture significantly.								

[10] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
11: Human Health & Performance						Medical capability will be different on Moon due to different mass and volume constraints there.			No, there are feed forwards from the moon
Risk of Radiation Carcinogenesis Cardiovascular Disease, and Other Degenerative Tissue Effects from Radiation Exposure	*Reduce the uncertainties in risk projections for radiation exposure; investigate pharmacologic countermeasures and biomarkers	Somewhat – Limited by short mission duration. Need humans to measure properly (can't just do tissue simulant)	Low – Limited by short mission duration.	Med – Limited by short mission duration.	High – Longer mission duration allows for study of effects of radiation exposure and investigation of countermeasures.	Radiation environment, mission duration		Yes	See above

[11] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
11: Human Health & Performance						Medical capability will be different on Moon due to different mass and volume constraints there.			No, there are feed forwards from the moon
Risk of Unacceptable Health and Mission Outcomes due to Limitations of In-Flight Medical Capabilities; Health outcomes of concern include Spaceflight Associated Neuro-ocular Syndrome (SANS), bone fracture, and renal stone, and dust exposure.]	Pre-flight health status assessment, including new technological approaches, and development of a systematic approach to a more comprehensive autonomous health care system in space	Somewhat – Change in paradigm for medical provision given lack of timely medevac, additional constraints on mass and volume, and Gateway dormancy periods. Care Level 4	Low, Limited by short mission duration.	Med – Limited by short mission duration.	Med – gain knowledge regarding extended periods in partial gravity. DRM may lack extended period in microgravity pre-field station (to simulate mars transit). Different fractional gravity may produce different physiologic effects.	Distance from Earth limits opportunities for timely medevac and medical consumable resupply. Change in philosophy from "stabilize and evacuate" to "stay and treat". Physiology of partial gravity may influence occurrence of medical conditions – renal stones, SANS, fracture. Mission duration is a driver in applicability to Mars. Comms delay is different between Mars and Moon, which also significantly changes medical care.	Being at the Moon automatically changes Level of Care from 3 (ISS) to Level 4 (>2ish days away). In Level 4 the local medical person is in charge of care. What capabilities can be supported within mass and volume limitations? Big jump from Level 4 to Level 5 in terms of capability requirements.	Yes	See above

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
11: Human Health & Performance						Medical capability will be different on Moon due to different mass and volume constraints there.			No, there are feed forwards from the moon
Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders	Development of cognitive and behavioral degradations or a psychiatric condition that could seriously harm and negatively affect the individual or the crew. Includes risks to behavioral and psychological health resulting from inadequate cooperation, coordination, and communication and psychological adaptation within a team.	Med – Applicability limited by mission duration	Low – Applicability limited by mission duration, but commonality of time to get back, radiation, distance from Earth.	Med – Applicability limited by mission duration	High – Extended mission duration in isolation and confinement with distance from Earth.	Isolation, confinement, distance from Earth, mission duration	Not having Earth in sight makes a big difference psychologically, being at Moon with only Blue Marble is very different, hence learning from lunar missions. Having a place to hang out on your own on ISS is very helpful. Most of these have not been (well) measured in this environment, so a lot of unknowns on what effects will be, over what timeframe, etc.	Yes	See above

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
11: Human Health & Performance						Medical capability will be different on Moon due to different mass and volume constraints there.			No, there are feed forwards from the moon
Risk of Ineffective or Toxic Medications Due to Long Term Storage	*Demonstration of medication stability for long periods. in micro- and partial-gravity environments with radiation exposure	High - Medications can be left on the Gateway for extended periods and tested later)	Low –limited by short mission duration.	Low–limited by short mission duration	High – Longer surface stays and ability to leave medications on the surface for extended periods. There will also be ingestion of the drugs past their expiration date.	Reduced gravity; Radiation; Limited resupply		Yes	See above
Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System	Identify vitamins and amino acids at risk for degradation in the space food supply, and characterize degradation profiles of the unstable nutrients in-situ food production	Med – limited mass and volume allocation may result in manifest of sub-optimal food system	Low – relatively short mission duration	Med - Relatively short mission length; some may have been prepositioned so running up to shelf life.	High – Need for in-situ food production to supplement food systems for longer missions; increased variety needed to ensure adequate caloric intake	Limited resupply; Physiologic changes of reduced gravity affecting food acceptability; Limited mass and volume for food system drives need for in-situ production		Yes	See above
Footnotes									

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[12]
12: Surface EVA Suit **PRIMARY							How do we operate EVAs on the two surfaces? That can drive differences (relevant for all categories).	No	No, there are feed forwards from the moon
Pressure Garment Suit	Addresses abrasiveness and mobility to meet desired maintenance cadence and operations.	Low – elements of next gen Space Suit will provide learning for Surface Suit.	High *We would like it to be high. Depends on design decisions made for the suit. If suit is designed for longer duration mission, then High. Risk posture is different due to different levels of infrastructure available nearby.	High – Moon is a more extreme environment in terms of dust environment; the operations and methodology will be somewhat different but overall similar knowledge gain.	High – Moon is a more extreme environment in terms of dust environment; the operations and methodology will be somewhat different but overall similar knowledge gain.	Best practices of being dust tolerant are very common; some details may be different. Can get a lot of benefit by making Mars and Moon pressure garment same/very similar.	Assuming that this is just pressure garment and does not include the environmental protection layer. Want to be tolerant to suit damage – astronauts will kneel. For short duration missions (Sorties) astronauts can deal with more load and discomfort, so may be a different suit. In Apollo suit there was an environmental protection garment over the pressure garment.	See above	See above
EVA system mobility, durability, and environmental protection layer (e.g., dust management)	Needs to include being able to accomplish science objectives.	n/a	Med – Depends on suit requirements and thus design decisions.	High – design suit to have mobility to accomplish science goals; not need maintenance for 40 days (limited by space, spare parts, etc).	High – design suit for repeated (about daily) use over 6mo, and to have mobility required to accomplish science and other field goals; maintenance possible on the station.	Sortie requirements on the suit are much less, due to ability to maintain it after just ~5 EVAs, back on Gateway or Earth, so meeting requirements will result in a different suit; *could* be designed for long duration use and the community recommends that a long surface duration suit is designed from the beginning. Do science and field operations have similar mobility needs?	This specifically addresses the durability of joints and other mobility-related components.	See above	See above

[12] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[12]
12: Surface EVA Suit **PRIMARY							How do we operate EVAs on the two surfaces? That can drive differences (relevant for all categories).	No	No, there are feed forwards from the moon
EVA total system mass (Mars gravity appropriate)	Specifics of meeting capability, operations, safety, etc requirements while being usable by the crew.	n/a	Med – can take shortcuts. But would be great if it's high.	High – mass could be higher for lunar suits, but makes sense to have similar development to Mars – increases lunar productivity, a lot of commonality in development, significant feed forward to Mars.	High – mass could be higher for Lunar suits, but makes sense to have similar development to Mars – increases lunar productivity, a lot of commonality in development, significant feed forward to Mars.	Different gravity, so more stringent mass requirements for Mars.	Mars suit likely derived from Moon suit & learnings, but will be a new development – maybe 60-80% commonality? Would make sense for lunar program to design for Mars. Lower mass lunar suit is likely to increase productivity on Moon.	See above	See above
System maintenance and repair (garment and life support system)			Low – expect low maintainability.	High – strong recommendation for this suit design to be consistent with a Field Station and Mars suit, where being able to maintain the suits will be critical. Expect this suit to be developed for little/no Maintenance for 40 days, which is consistent with capabilities needed for Field Station and Mars; future crews may need to bring repair parts and repairs that can be executed can be limited by GER capabilities.	High – expect this suit design to be consistent with a Mars suit, where being able to maintain the suits will be critical. Need long duration between maintenance cycles. Have parts and capabilities for maintenance and repair.		Life support systems are well developed; not a significant gap. But maintenance and repair of overall system needs significant development.	See above	See above

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[12]
12: Surface EVA Suit **PRIMARY							How do we operate EVAs on the two surfaces? That can drive differences (relevant for all categories).	No	No, there are feed forwards from the moon
system thermal management		n/a	Need to do trade study – many uncertainties in Mars designs.	Need to do trade study – many uncertainties in lunar and Mars designs.	Need to do trade study – many uncertainties in lunar and Mars designs.	Cooling systems for Moon will not work on Mars. Expect design of this system to have a big impact on the Suit.	Currently no good Mars cooling system design.	See above	See above
Footnotes	Added after AM IV. This is important part of architecture. What about different classes of rovers? Smaller robotic, unpressurized, and larger like Athlete. Or is the main difference pressurized vs unpressurized? Power (different between Moon and Mars b/c of long Lunar night) Thermal environment (esp. different between Moon and Mars) What is the appropriate range? What is the overall rover surface mobility system? Comm is important in rover operations (and architecture); covered in Comms section.								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Medium duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[13]
13. Pressurized Surface Rover (for multi-day excursions) **PRIMARY								No	No, there are feed forwards from the moon
Autonomy/ Dormancy		n/a	n/a	High – for dormancy Somewhat – for autonomy. Hazard are different, as well as people being able to bail out the rover through teleoperations.	High – for dormancy Somewhat – for autonomy. Hazard are different, as well as people being able to bail out the rover through teleoperations.	Lunar rovers can be teleoperated vs Mars missions have significant time delay.	Capability and system design sets commonality (do you teleoperate rovers between crews to do science, or do you make them dormant? Are they autonomous or teleoper-ated?)	See above	See above
Power/ Energy Storage		n/a	n/a	High – Kilopower as a charging station for rovers works same on Mars; other power sources (e.g., RPS) works as well.	High – Kilopower as a charging station for rovers works same on Mars; other power sources (e.g., RPS) works as well.	Differences in heat rejection radiators (~20%) will be req'd; will affect power generation. Storage trade must be done; affected by different environ-ments and use cases for Moon and Mars (could be Somewhat or High).	Key is that nuclear power is Mars forward. Assume that Mars rovers will also be kilopower charged. Some uncertainty in operations of when you charge and whether power source is moving with rover or rover has to come back to the same site (every ~1day?). Should also consider fuel cell and battery trade**.	See above	See above

[13] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[13]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
13. Pressurized Surface Rover (for multi-day excursions) **PRIMARY								No	No, there are feed forwards from the moon
Maintenance and Repair		n/a	n/a	Med – due to differences in environmental damage/impacts; can replace with spares.	High – can do more repairs, more similar to Mars, but environmental impacts on rover systems will be different. Gain valuable operational experience.	For GER can't do inside repairs (bring something into the hab & repair).	IVA repairs quite similar?	See above	See above
Operations		n/a	n/a	High – for operations and various overall system commonalities	High – for operations and various overall system commonalities		Experience with similar systems can buy down risk. Overall difference in operations due to environmental protection, time delay to Earth, difference in size due to difference in duration? Assume rovers the same for "Field Station" and GER.	See above	See above
Habitability		n/a	n/a	Med – learn overall about implementing concepts and risk buydown; difference in thermal design different, environment different, different duration of stay in rover (diff mass of consumables, range).	Med – learn overall about implementing concepts and risk buydown; difference in thermal design different, environment different, different duration of stay in rover (diff mass of consumables, range).	Different environments and somewhat different goals imposed on rovers for Moon and Mars.	Given a lot of similarities, may be warranted to develop a rover that works both on Moon and Mars (to extent possible). Assume rovers the same for "Field Station" and GER.	See above	See above

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[13]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Medium duration with local exploration, relocatable	Long duration with regional exploration, single site				
13. Pressurized Surface Rover (for multi-day excursions) **PRIMARY								No	No, there are feed forwards from the moon
Ports & air locks – versatile (suits, habs, other rovers)		n/a	n/a	High – trade for Mars architecture still needs to be done, but overall expect that applicability will be High.	High – trade for Mars architecture still needs to be done, but overall expect that applicability will be High.	Use of ports vs air locks for Mars architecture? Open question whether dust effect on Moon and Mars are same to sealing mechanisms and surfaces.	Assumes same rovers for GER and Field Station. Suit ports do not eliminate need for airlocks.	See above	See above
Range, Speed		n/a	n/a	High – similar science, safety, etc requirements for both Mars and Moon.	High – similar science, safety, etc requirements for both Mars and Moon.	Is trafficability on Moon and Mars similar?	Going over different geological terrains between Moon & Mars. Range of temperature of operation affects design. Software should be designed in from the beginning to get maximum effectivity. Navigation sensors used are also a critical part of this package.	See above	See above
Footnotes	Added after AM IV. This is important part of architecture. What about different classes of rovers? Smaller robotic, unpressurized, and larger like Athlete. Or is the main difference pressurized vs unpressurized? Power (different between Moon and Mars b/c of long Lunar night) Thermal environment (esp. different between Moon and Mars) What is the appropriate range? What is the overall rover surface mobility system? Comm is important in rover operations (and architecture); covered in Comms section.								

Appendix B: Mars Engineering Long Poles – Transportation/Propulsion Team

Feed Forward Assessment

- For each viable lunar capability, or operational need, assess how well it feed forwards to each of the three example Mars scenarios and capture the rationale for each rating in a narrative form:

Low: Within this rating level it was viewed by the assessment team that even though the capability may play a very important role in lunar exploration, the specific system or capability in question provided very little risk reduction or no feed-forward to the Mars basis of comparison.

Med: With this rating level the capability was viewed as being on the path to Mars, but differences in the capability performance level, operational characteristics, or environment would allow mitigation of some risks associated with capability readiness for Mars. After a lunar mission, these capabilities would require modification. Additional testing would also be required before it would be fully applicable to a Mars mission.

High: This capability was viewed as being on the path to future human Mars missions "as is", or with few or even no modifications, and demonstration in the lunar environment would significantly or fully mitigate risks associated with Mars missions. After a lunar mission the emphasis would be on certification to the Mars environment and operational requirements.

**Please note content marked with an * has been added by the Achieving Mars VI preparation team*

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[1]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
1: Aggregation/Refuel/ Resupply **(11)**									
Design of logistics architecture and demonstration in deep space	Demonstrate the autonomous delivery and transfer of fuel and cargo in deep space	Med: Aggregation, assembly and refueling/ resupplying of the Gateway will inform Mars mission assembly Small quantities and scale	Low: Assuming expendable descent and ascent stage	Med: Assuming at least a reusable ascent stage. Vehicle Refurbishment at Gateway High: If descent stage (cryo) is fueled at Gateway Med scale logistics	High: Assuming fully reusable lander. Long duration operations on the surface of the Moon will help refine future Mars logistics strategies. Large scale logistics	N/A	*Note: Focus only on logistics here since fuel is covered below.	ISS analog possible	No Most of this work can be done in LEO and/or Gateway

[1] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[1]
1: Aggregation/Refuel/ Resupply **(11)**									
Autonomous operations at Mars	*Operations of systems at Mars distance with limited/no Earth support	Med: Uncrewed/ autonomous operation at Gateway provides an analogue for autonomous operation at Mars Transition from autonomous to crewed operations Demonstration of Comm Ops through Comms relay	Med: Autonomous mating of lander with Gateway and checkout prior to human arrival Potential autonomous landing operations	High: Repeated/ extended autonomous operation of lander at Gateway	High: Assume field station is permanently occupied (less autonomous than previous). Initial operations similar to GER class	Time lag may influence autonomous operations		ISS analog possible (Proposed)	No
Xenon & cryogenic transfer	*Transfer of high pressure Xenon and cryogenic propellants in zero-g	Med: Transfer of all fluids (propulsion and consumables) Gateway does not use Cryogens.	n/a	High assuming Cryo transfer of lander prop at Gateway, otherwise Med Potential storage of Cryo at Gateway (lander/tanker)	High: Surface production, storage and transfer to landers of cryofluids	Mars transit/orbit cryo management is less challenging than in the lunar environs		Yes	Much of this work can be done at LEO or Gateway, but MAV requires multiyear storage due to prepositioning requirements Cryo Fluid Management needs to start immediately.
Footnotes	Cryogenic commercial resupply tugs could provide additional expertise for cryofluid transfer/management Possibility of cryo production at Gateway from delivered feedstocks. A single stage lunar ascent/descent vehicle is directly applicable to a Mars ascent vehicle.								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Radiation Protection	*Provide adequate protection from GCR and SPE	High: Biological experiments to validate protection and avionics exposure/recovery (SPE protection must be equivalent to transit) High fidelity Mars transit analogue	High: Biological experiments to validate protection and avionics exposure/ recovery (SPE protection must be equivalent to transit) High fidelity Mars transit analogue N/A for transportation	High: Biological experiments to validate protection and avionics exposure/ recovery (SPE protection must be equivalent to transit) High fidelity Mars transit analogue N/A for transportation	High: Biological experiments to validate protection and avionics exposure/ recovery (SPE protection must be equivalent to transit) High fidelity Mars transit analogue N/A for transportation	The lunar surface and in space testing can provide adequate risk reduction	Gateway is not designed to have SPE shielding, but can provide opportunities for testing of shielding concepts	No	No, these can be tested at the Gateway and lunar surface

[2] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Crew autonomous operations	*Demonstrate the capability of operating habitat systems at Mars distance with limited/no Earth support (e.g., simulated time delay)	High if time lag is simulated, but low otherwise. ISS may be a better test bed. Gateway is the most recent experience with longer abort timelines than ISS	High if time lag is simulated, but low otherwise. ISS may be a better test bed. Gateway is the most recent experience with longer abort timelines than ISS N/A for transportation	High if time lag is simulated, but low otherwise. ISS may be a better test bed. Gateway is the most recent experience with longer abort timelines than ISS N/A for transportation	High if time lag is simulated, but low otherwise. ISS may be a better test bed. Gateway is the most recent experience with longer abort timelines than ISS N/A for transportation	No significant differences for transportation issues		Yes, doesn't cover all aspects	No

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Crew health	*Provide the ability to adequately maintain crew health	Med: Days away from Earth medical facilities Closed environments Behavioral health issues. Isolation and confinement	Med: Days away from Earth medical facilities Closed environments Behavioral health issues. Isolation and confinement N/A for transportation	Med: Days away from Earth medical facilities Closed environments Behavioral health issues. Isolation and confinement N/A for transportation	Med: Days away from Earth medical facilities Closed environments Behavioral health issues. Isolation and confinement N/A for transportation	No significant differences for transportation other than the length of time in space, and the limitations on evacuation back to Earth in case of emergencies. Resupply of medications etc. will be more challenging at Mars.		LEO analog possible	Yes, in work
Crew activity	*Demonstrate the ability to autonomously plan and execute crew activities during the mission	Med: Human/ robotic interactions especially in human-tended situations	Med: Human/ robotic interactions especially in human-tended situations N/A for transportation	Med: Human/ robotic interactions especially in human-tended situations N/A for transportation	Med: Human/ robotic interactions especially in human-tended situations N/A for transportation	No significant differences for transportation.	Advanced crew planning is being implemented on ISS now (Playbook).	Yes	Yes, in work

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Vehicle maintenance	*Demonstrate Maintenance and repair including internal- and external-mounted equipment assuming a logistics lean environment	Med: Need to incorporate lessons learned from ISS and increased autonomy	Med: Need to incorporate lessons learned from ISS and increased autonomy N/A for transportation	Med: Need to incorporate lessons learned from ISS and increased autonomy N/A for transportation	High: Human maintenance of cryogenic systems.	Challenges with resupply and maintenance will increase with distance from Earth.	May not need to be a driving gap.	Yes	No
Reliable Life Support	*Demonstrate the Ability to support long duration (1000+ day) Mars missions including 500 days of dormancy between crew visits	Med: ECLSS activity during unoccupied intervals	Med: ECLSS activity during unoccupied intervals N/A for transportation	Med: ECLSS activity during unoccupied intervals N/A for transportation	Med: ECLSS activity during unoccupied intervals N/A for transportation	Challenges with resupply and spare parts increase with distance from Earth.	Long duration/ more reliable ECLSS being demonstrated on LEO platforms	Yes	Yes, In work
Crew Privacy and Habitable Volume	*Provide adequate human factors concepts	Med: Data to anchor models of crew behavioral health and performance for longer duration	Med: Data to anchor models of crew behavioral health and performance for longer duration N/A for transportation	Med: Data to anchor models of crew behavioral health and performance for longer duration N/A for transportation	Med: Data to anchor models of crew behavioral health and performance for longer duration N/A for transportation	No significant differences.		LEO analog possible	No

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Logistics and storage	*Ability to store and manage adequate supplies for a round-trip Mars mission	Med: Pharmaceuticals and Food nutrition (including seeds)	Med: Pharmaceuticals and Food nutrition (including seeds) N/A for transportation	Med: Pharmaceuticals and food nutrition (including seeds) N/A for transportation	Med: Pharmaceuticals and Food nutrition (including seeds) N/A for transportation	Main difference is length of time and stability of food and drugs in space environment; availability of spare parts an issue.	Covered under previous long pole	LEO analog possible, but does not address radiation effects	No
Thermal	*Habitat thermal control for cis-lunar, deep space, and Mars orbit operations	High: Deep space thermal environment	High: Deep space thermal environment N/A for transportation	High: Deep space thermal environment N/A for transportation	High: Deep space thermal environment N/A for transportation	No significant differences.	Assumes storable prop for DST	No	No
Reduced power	*n/a					n/a for transportation.	*Mars architectures has the transportation system provide power to the habitat, thus this sub-pole is n/a		No

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	**Gateway** Lunar orbit only with surface telerobotics	**Lunar Sorties** Short duration stays with local crew exploration	**GER Class** Med duration with local exploration, relocatable	**Field Station** Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other Considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[2]
2: Transit Habitat and Research Laboratory	All the critical subsystems (e.g., life support, water recycling) have been operated successfully in the deep space environment of cislunar space for at least one Earth year with and without astronauts on-board.								
Deep Space Navigation	*Ability to autonomously navigate in deep-space at Mars distance	High: Gateway uses X-ray pulsars for DSN independent navigation	N/A	N/A	N/A	No significant differences.	*For the Mars architecture the transportation system can perform this (cargo vehicle), thus habitat would be backup	No	No
Quarantine/Isolation/Privacy Capability	*Adequate provisions for crew privacy accommodations	Med: Lunar/Mars/ Asteroid sample return missions	N/A	N/A	N/A	Main difference is the time required for evacuation and isolation.	Gateway may not be optimal Mars sample return waypoint Quarantine should be separated from Isolation/Privacy		No
Footnotes	Operational experience identifies unknown unknowns								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[3]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
3: Solar Electric Propulsion Cargo Tug									
300-kW Class Solar Array	*Ability to produce 300-400 kw of electric power at Mars distance	High: 50kW arrays for Gateway PPE	N/A	N/A	N/A	No significant differences		LEO analog possible	No, but scaling breaks at about 500kW
PPE-derived Power Distribution	*Ability to condition and transfer 300-400 kWe power to the thrusters	High: Power distribution for 40kW Hall thrusters, may need higher voltage bus	N/A	N/A	N/A	No significant differences	*This should now read Gateway derived	LEO analog possible	No, but state of the art breaks at about 250V
12.5-kW Electric Propulsion Thruster	*Xenon Thruster performance for long durations	High: Baselined for Gateway, may need higher power thrusters for Mars mission	N/A	N/A	N/A	No significant differences		LEO analog possible	No
Low Thrust Navigation	*Ability to autonomously navigate during long-thrust arcs necessary for electric propulsion	N/A	N/A	N/A	N/A	N/A	Already demonstrated on previous missions	N/A	No
Footnotes	Removed from AMIV final report due to advanced development to be inserted in Gateway Asteroid Retrieval Vehicle reference deleted and PPE substituted Alternative Propulsion methods should be considered for Mars mission cargo and crew								

[3] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[5]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
5: Crew/Cargo Lander: Entry, Descent, and Landing (EDL) **(13)**	Perform a precursor mission to demonstrate EDL, prior to delivery of mission-critical cargo								
Human-scale Mars EDL system)	30 t, <100 m precision	Med: Aeromaneuvering of Commercial Logistics/Earth Return	High: Precision landing and hazard avoidance Med: Abort scenarios	High: Critical infrastructure near landing zone	High: Abort to surface. Humans present near landing site	Mars has an atmosphere and higher gravity. Dust may also be a factor for atmospheric drag on Mars (not on the Moon).	*Consider lunar propulsion landing and Mars terminal landing phases	Commercial Resupply for atmospheric entry	Yes
Cryo Propulsion and Cryofluid Management	*Demonstrate a relevant Cryo propulsion system and long-term cryogenic storage in Mars –like surface environmental conditions	N/A Gateway does not use Cryogens Med: If commercial logistics vehicles use cryo propulsion	N/A	High: Strong similarity between lunar descent and Mars lander propulsion Med: Potential storage of Cryo at Gateway (lander/tanker)	High: Strong similarity between lunar and Mars lander propulsion Surface production, storage and transfer to landers of cryofluids	If the same cryogens are used for both destinations, the major differences are mostly in the surface handling environments.	*Assume hypergolics for lunar sortie missions	No	Yes, depending on whether the propulsion system is the same for both destinations. In any case Cryo Fluid Management needs to start immediately
Footnotes	GER class missions may have some abort to surface capability								

[5] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[6]
6: Mars In-Situ Resource Utilization (ISRU) Tech Development (8)									
Dust effects on ISRU	*Demonstrate the ability to accommodate expected dust conditions on Mars	n/a	n/a			Not relevant for transportation	MOXIE demonstrating at small scale on Mars 2020 lander	No	Yes
Oxygen extraction from CO2.	*Production of oxygen from the atmosphere of Mars at a scale required for human missions (2.2 kg/hr)	n/a	n/a			Not relevant for transportation	MOXIE demonstrating at small scale on Mars 2020 lander	Have demonstrated on ISS at smaller scale	Yes
Access H2O--subsurface ice/ minerals	*Demonstrate the ability to access and acquire useable H2O sources on Mars	n/a	n/a	n/a for transportation	Med: Potential applicability to lunar, MAV, cislunar and Mars transfer stages	Much colder in the lunar polar craters than Martian deposits; higher thermal variance in other regions.		No	Yes, Need to verify presence of accessible water; needed to inform architecture.
Resource Acquisition	Perform subscale demo with soil and water analysis capabilities on Mars with similar feedstock material	n/a	n/a	n/a for transportation	Med: Potential applicability to lunar, MAV, cislunar and Mars transfer stages	Much colder in the lunar polar craters than Martian deposits; higher thermal variance in other regions. Gravity differences.		No	No

[6] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[6]
6: Mars In-Situ Resource Utilization (ISRU) Tech Development (8)									
Liquefaction & Cryofluid Management	*Demonstrate the ability to store cryogens for long periods in Martian surface environmental conditions	Med: Assumes production of prop at Gateway from delivered feedstocks	n/a	n/a for transportation	Med: Potential applicability to lunar, MAV, cislunar and Mars transfer stages	CO2 atmosphere on Mars as a source of oxygen; potential CH3 for propellant		LEO analog possible	Yes, for O from atmosphere / CH3 for propellant Cryo Fluid Management needs to start immediately
Footnotes	This working group focused on propulsion centric perspectives of ISRU Lunar ISRU supports MAV propellant and alternative propellant architectures. Also benefits cis-lunar transportation infrastructure. Potential for ISRU on the Moon to supply propellant for Mars transfer Water mining for large scale production may be robotic								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[9]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
9: Mars Ascent Vehicle (MAV) (13)									
Cryo Propulsion and Cryofluid Management	Successful qualification test program, for integrated propulsion system and the demonstration of long-duration (1000 sols), minimal-loss cryogenic propellant storage	Med: Potential commercial cryo logistics tug	Med: Potential commercial cryo logistics tug	Med: Potential storage of Cryo at Gateway (lander/tanker)	High: Surface production, storage and transfer to landers of cryofluids. May use permanently shadowed regions to facilitate.	CO2 atmosphere makes CH3 potentially viable as propellant; not so for the Moon.	For early Mars missions, baseline assumes bringing cryo fuel from Earth for the MAV requires minimal loss deep space cryo storage.	LEO analog possible	Yes Cryo Fluid Management for Mars specific cryogens and environments needs to start immediately
Habitability	*Demonstrate the ability to accommodate 4-6 crew, for up to 43 hours, mitigate dust, and support adequate ingress/ egress	N/A	High: Similar duration and crew size from surface to orbiting hab.	High: Similar duration and crew size from surface to orbiting hab.	High: Similar duration and crew size from surface to orbiting hab.	Dust environment is different on Mars; dust is lofted high into the atmosphere during seasonal dust storms.		No	No
Guidance Navigation & Control	*Demonstrate the ability to autonomously navigate and rendezvous in highly elliptical orbit	N/A	High: GN&C system similar to lunar lander. Lander navigation linked through Gateway	High: GN&C system similar to lunar lander. Lander navigation linked through Gateway	High: GN&C system similar to lunar lander. Lander navigation linked through Gateway	No significant difference		No	No

[9] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[9]
9: Mars Ascent Vehicle (MAV) **(13)**									
Integrated System	Key architecture decisions made. Development of a comprehensive T&V plan.	N/A	N/A	Med or high: Depends upon commonality level of ascent vehicle	High: Long surface stay prior to activation and departure	No significant difference		No	No
ISRU Convert CO2 to O2	Demonstrating the capability of maintaining "zero-boil-off" during long duration periods (1000 sols) as well as liquefying oxygen produced by ISRU systems at rates of approximately 2.2 kg/hr.	N/A	N/A	N/A	N/A	No CO2 at the Moon.	Moon does not have accessible CO2 See ISRU section MOXIE demonstrating at small scale on Mars 2020 lander	LEO analog possible	Yes
Footnotes	For MAV, there is a big payoff if there is high commonality between lunar and Mars vehicles. A hopper style surface mobility vehicle could provide operational experience to MAV.								

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[10]
10: Mars Communication Network for Human Exploration & Science									
Deep Space, High-Rate Forward Link / Downlink	*Demonstrate sufficient high data bandwidth for both down and uplink at Earth-Mars conjunction distances	High: Gateway demonstrates high- bandwidth, two-way comms. (Cat videos, etc.). Privacy of comms.	High: Delay Tolerant Network demonstration	High: Delay Tolerant Network demonstration	High: Delay Tolerant Network demonstration	Greater distance to Mars requires demo of optical comm		No	No
High Rate Proximity Communication	*Demonstrate local proximity vehicle-to-vehicle communications.	N/A	N/A	N/A	N/A	No significant difference	Assumes a surface Wide Area Network Assuming this is not related to vehicle rendezvous proxops since already demonstrated at ISS.	LEO analog possible	No
Footnotes									

[10] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
11: Human Health/ Biomedicine									
Risk of Spaceflight-Induced Intracranial Hypertension/Vision Alterations	A set of preventative and treatment countermeasures	N/A	N/A	N/A	N/A	Longer time in transit		LEO analog possible (partial gravity mitigation?)	Yes, in work May require advanced countermeasures
Risk of Cardiac Rhythm Problems	*it is the "total spaceflight environment" (i.e. accumulation of all risk factors listed) that contributes to long-term cardiovascular disease risk	N/A	N/A	N/A	N/A	Longer time in transit		Yes	No
Risk of Cardiovascular Disease Cardiovascular Disease, and Other Degenerative Tissue Effects from Radiation Exposure	*Reduce the uncertainties in risk projections for radiation exposure; investigate pharmacologic countermeasures and biomarkers	Med: Potential animal studies	Med: Potential animal studies	Med: Potential animal studies	Med: Potential animal studies	Longer time in transit		No	yes

[11] Development time takes more than 10 years and there are very little feed forwards from Moon to Mars

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway Lunar orbit only with surface telerobotics	Lunar Sorties Short duration stays with local crew exploration	GER Class Med duration with local exploration, relocatable	Field Station Long duration with regional exploration, single site	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
11: Human Health/ Biomedicine									
Risk of Unacceptable Health and Mission Outcomes due to Limitations of In-Flight Medical Capabilities; Health outcomes of concern include Spaceflight Associated Neuro-ocular Syndrome (SANS), bone fracture, and renal stone, and dust exposure.]	Pre-flight health status assessment, including new technological approaches, and development of a systematic approach to a more comprehensive autonomous health care system in space	Med: Increased level of care over ISS; Evac times vs ISS	Med: Increased level of care over ISS; Evac times vs ISS	Med: Increased level of care over ISS; Evac times vs ISS	Med: Increased level of care over ISS; Evac times vs ISS	Longer time in transit; time lag issues with medical support from Earth; resupply challenges.		Yes	No
Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders	Development of cognitive and behavioral degradations or a psychiatric condition that could seriously harm and negatively affect the individual or the crew. Includes risks to behavioral and psychological health resulting from inadequate cooperation, coordination, and communication and psychological adaptation within a team.	Med/High: Effects of isolation confinement and radiation on the Central Nervous System. Sensory Motor component as well.	Med/High: Effects of isolation confinement and radiation on the Central Nervous System. Sensory Motor component as well.	Med/High: Effects of isolation confinement and radiation on the Central Nervous System. Sensory Motor component as well.	Med/High: Effects of isolation confinement and radiation on the Central Nervous System. Sensory Motor component as well.	Evacuation to Earth more of a challenge from Mars; resupply of medications and food more challenging.		Yes (Proposed)	Yes

Long Poles and Associated Driving Gaps	Minimum Success Criteria and *other information	Gateway	Lunar Sorties	GER Class	Field Station	Key environmental differences that impact Long Pole/driving gap reduction	Other considerations	Capabilities which can be matured in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[11]
		Lunar orbit only with surface telerobotics	Short duration stays with local crew exploration	Med duration with local exploration, relocatable	Long duration with regional exploration, single site				
11: Human Health/ Biomedicine									
Risk of Performance Decrements & Adverse Health Outcomes Resulting From Sleep Loss, Circadian Desynchronization, & Work Overload	*Other potentially relevant countermeasure strategies, such as stress management, diet, and exercise, may also be assessed.	N/A	N/A	N/A	N/A	Resupply of medications and food more challenging.	Better done at ISS	Yes (currently)	No
Risk of Performance Errors Due to Training Deficiencies	Develop an understanding of how training can be tailored to better support long-duration deep space operations	Med: May demonstrate JIT training and guided procedures.	Med: May demonstrate JIT training and guided procedures.	Med: May demonstrate JIT training and guided procedures.	Med: May demonstrate JIT training and guided procedures.	No significant differences for transportation.		Yes (Proposed)	No
Risk of Ineffective or Toxic Medications Due to Long Term Storage	*Demonstration of medication stability for long periods.	High: Storage demonstration during unoccupied portions	High: Storage demonstration during unoccupied portions	High: Storage demonstration during unoccupied portions	High: Storage demonstration during unoccupied portions	Resupply of medications and food more challenging.	Ground testing may assist in knowledge capture	No does not include radiation effects	No
Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System	Identify vitamins and amino acids at risk for degradation in the space food supply, and characterize degradation profiles of the unstable nutrients	High: Storage demonstration during unoccupied portions	High: Storage demonstration during unoccupied portions	High: Storage demonstration during unoccupied portions	High: Storage demonstration during unoccupied portions	Resupply of medications and food more challenging.	Ground testing may assist in knowledge capture	Yes, but does not include radiation degradation	No
Footnotes	Current transportation architecture does not include artificial gravity capability.								

Lunar ISRU and Preparation for Mars Human Exploration

While the focus of NASA's next steps in human space exploration has changed over the past few years from Near Earth Objects, to Mars, and recently to the Moon, a constant in all planning efforts has been that human space exploration needs to be sustainable and affordable, and that new and innovative technologies and infrastructure are required. One approach NASA has pursued, which can significantly change how systems required for space transportation and infrastructure for sustained human presence are designed and integrated, as well as potentially breaks our reliance on Earth supplied logistics and enable space commercialization, is In-Situ Resource Utilization (ISRU). ISRU, or "living off the land", involves the identification, extraction, and processing of resources at the site of exploration into useful products and services. In particular, the ability to make propellants, life support consumables, fuel cell reagents, and radiation shielding can significantly reduce the cost, mass, and risk of sustained human activities beyond Low Earth Orbit (LEO). In addition, the ability to modify planetary surface material for safer landings, lower maintenance of surface transportation, dust mitigation, and infrastructure protection, placement, and buildup, are also extremely important for long-term planetary surface operations. At first glance, it appears that the resources available and the environmental conditions on the Moon and Mars are different enough that close synergism between lunar and Mars ISRU technologies and systems and how they are incorporated into mission scenarios is not possible. However, upon closer examination, it can be shown that there are significant synergisms in ISRU technologies, systems, and operations between the Moon and Mars. Incorporating ISRU capabilities into lunar missions and utilizing the Moon as a test platform for future Mars missions may also significantly reduce the cost, mass, and risk for both human exploration destinations while providing a logical stepping stone approach to achieving sustainable and affordable human exploration.

I. Introduction

The purpose of In-Situ Resource Utilization (ISRU) is to harness and utilize resources at the site of exploration (both natural and discarded) to create products and services that reduce the mass, cost, and risk of robotic and human exploration as well as increase performance or enable new mission concepts compared to bringing everything from Earth. The immediate goal of ISRU is to greatly reduce the direct expense of humans going to and returning from the Moon and Mars, and then to build toward self-sufficiency of long-duration crewed space bases to expand our exploration efforts and possibly to return energy or valuable resources to Earth.

The benefit of incorporating ISRU into mission plans is directly related to the extent to which it is used and when it is used. Because human exploration missions require significant amounts of oxygen, water, and hydrogen and/or methane fuels for propulsion, life support, and fuel cell power systems, incorporation of ISRU into missions has primarily focused on extracting or producing these mission critical consumables. However, the ability to create parts locally through in-situ manufacturing and infrastructure from local materials and resources is also considered extremely important for sustained human surface operations.

During NASA's Constellation program (2005 to 2010), a significant amount of work was performed on developing and testing lunar ISRU technologies and systems associated with excavating and processing lunar regolith to extract oxygen and metals, and work started on developing civil engineering capabilities for area clearing, berm building, and landing pad construction. Work also began at this time on how to obtain 'ground truth' data on potential volatile and water resources that could exist in permanently shadowed craters at the lunar poles through the Regolith & Environment Science and Oxygen & Lunar Volatile Extraction (RESOLVE) experiment project, which eventually became part of the Resource Prospector mission.

During NASA's Evolvable Mars Campaign (EMC) and particularly in the last two years, significant advancements were achieved on developing and testing Mars ISRU technologies associated with Mars atmosphere collection, pressurization, and processing into oxygen or oxygen/methane, and the extraction of water from Mars resources. A small ISRU flight demonstration, called MOXIE (Mars Oxygen ISRU Experiment), will fly on the Mars 2020 rover to test a Mars atmosphere compressor and solid oxide electrolysis technologies to make oxygen (at 10 grams of oxygen/hour rate). In addition, human mission scale technologies are being designed, built, and tested for dust filtration, carbon dioxide separation and pressurization from the Mars atmosphere, oxygen and oxygen/fuel production, and water extraction. The Mars Water ISRU Planning (MWIP) Study and subsequent analyses showed human missions would obtain significant mass benefits from excavating and processing granular surface soil with low weight percent water (1.36 wt%) to obtain and use the water for subsequent oxygen/methane production for crewed ascent vehicles

II. Lunar ISRU Strategy That Feeds Forward Moon-to-Mars

Since the first paper on the concept of using the Mars atmosphere to make propellants was published in 1976, the incorporation of Mars ISRU into both robotic and human exploration missions has been studied numerous times. In the late 1990's NASA initiated a series of Mars Human Design Reference Missions (DRMs) that started to quantify the benefits of Mars ISRU in human missions, the first of which was released in 1997. These studies primarily focused on evaluating the impact of making propellants on Mars for crew ascent to Mars orbit, but creating large caches of life support consumables (water & oxygen) as a backup for regenerative life support systems for long-duration surface stays (>500 days) was also considered in Mars DRM 3.0. The Mars Design Architecture 5.0 (DRA 5) was the first human mission architecture to evaluate the impact and benefit of utilizing water from surface materials besides just processing Mars atmospheric carbon dioxide on its own or with hydrogen brought from Earth. While Mars DRA 5.0 selected the oxygen-only approach from Mars atmosphere resources as the baseline for the mission, the study recommended that NASA should pursue further characterization of Mars water resources and to develop technologies for excavation and water extraction from Mars soils. The MWIP study in 2016 and Kleinhenz-Paz Mars ISRU study in 2017 further confirmed this recommendation, and the mission benefits associated with Mars water extraction and processing.

To date, no robotic or human mission flown has relied on ISRU derived products for mission success. Therefore, mission planners are hesitant to incorporate ISRU into mission critical roles until adequately demonstrated. This is particularly true for human Mars missions since the long-trip times and communication time delays mean recovering from failures is much more difficult and potentially catastrophic for mission success. The current approach to incorporating ISRU into human lunar architectures is to demonstrate ISRU capabilities and incorporate ISRU products when available, but not to rely on ISRU products and services for mission critical applications or mission success until they have been adequately demonstrated. Incorporation of ISRU into human Mars missions may also require one or more successful precursor demonstration missions. With short trip times (days) and short communication time delays (seconds), using the Moon as a testbed for Mars ISRU offers several significant benefits:

- Ability to demonstrate instruments and capabilities for identifying, characterizing, and quantifying resources

- Ability to demonstrate ISRU concepts, technologies, and hardware that can reduce the mass, cost, and risk of human Mars missions
- Ability to use the Moon for operational experience and mission validation
- Ability to use the Moon to demonstrate long-duration surface operations and autonomy

A. Identify and Characterize Available Resources

While rover-based science missions may incorporate similar instruments to understand and characterize surface and subsurface physical, mineral, and volatile resources present, prospecting and mapping resources for subsequent extraction planning involves different measuring and operation techniques. Hardware and instrument procedures developed for characterizing lunar regolith physical and mineral deposits and volatiles/water concentrations in lunar polar regions along with terrestrial practices and software for mine planning can be applied to Mars soil/water resource assessment. Surface and subsurface sample acquisition and transport will have to be modified to deal with the differences in soil mechanics between lunar and Mars soils, but lessons learned from current and planned Mars surface science missions and Earth analog and lunar prospecting system development activities, such as Resource Prospector, can reduce the uncertainties and risk. Since the availability of water resources on both the Moon and Mars will strongly influence ISRU process selection and mission implementation, water/volatile characterization should be the primary focus of lunar and Mars resource characterization efforts. To minimize cost and risk, partnerships between Exploration and Science objectives and hardware development should be strongly encouraged. Resource prospecting missions should also be performed well in advance of human exploration missions to maximize the benefits and minimize the risk of water-based ISRU process implementation.

B. Demonstrate ISRU Technologies, Hardware, and Concepts

While the Moon does not have an atmosphere, lunar ISRU processes, such as oxygen and volatile extraction from regolith, involve excavation and material transfer, soil processing reactors, gas processing reactors, gas product cleanup and drying, gas/water separation, water cleanup and electrolysis, and product drying and storage. Upon examination of the functional block diagrams for lunar ISRU (Figure 5) and Mars ISRU (Figure 7) it should be noted that many of the boxes are similar. Besides similarity, an important factor to consider in examining lunar and Mars ISRU is commonality in scale of operation. With initial Mars ISRU systems required to produce ~20 to 25 MT of oxygen over 480 days and lunar ISRU systems required to produce ~10 MT per year, overall processing rates are similar so commonality in components is possible. Even if there is a large difference in production rates for lunar and Mars ISRU applications, pre-planning may still allow for modularization of systems to eliminate or minimize the scaling of hardware required for both destinations. This may again increase mass over size-optimized systems, but could significantly reduce human exploration life-cycle costs, increase mission flexibility and failure recovery options.

Lunar and Martian soils have been modified by different processes. Excavating and processing lunar regolith is both easier and harder than Mars soils due to the fact that they were modified by different processes. Mars soils were created through weather, volcanic, and water processes creating highly oxidized, fine-grained, and rounded dust, while lunar regolith was created through volcanic, bombardment, and solar radiation processes creating extremely fine-grained, jagged minerals, glasses, and agglutinates. Lunar regolith may be more difficult to deal with than Mars soil due to the jagged, abrasive nature of lunar regolith. The lower lunar gravity as well as potential electrostatic aspects of lunar regolith due to the vacuum and radiation environment on the lunar surface further complicates regolith excavation and granular flow through hoppers and reactor systems. Mars soil excavation and processing will be more difficult than for lunar regolith since Mars water modified materials such as clays cannot be sieved and size sorted like lunar regolith, and the water will cause particle binding making material transport into reactors difficult. To properly design excavation and granular flow transport systems, both lunar regolith and Mars soil physical (shape, size distribution, density, and hardness) and mineral/chemical characteristics need to be determined. Apollo mission samples give excellent data for equatorial and some highland locations on the Moon, but regolith property uncertainties still exist for regolith at the polar regions, especially in permanently shadowed regions. Mars surface robotic assets are providing crucial data on Mars soil properties but more is required, especially on water content and form, to properly design ISRU soil excavation and handling systems. There is great synergism in the instruments that can be used to take these measurements as well as commonality in measurement goals between ISRU and science objectives such that costs can be reduced if these are taken into consideration from the start.

C. Utilize the Moon for Operational Experience and Mission Validation

While the environments and ISRU feedstock resource on the Moon and Mars are different, there is significant commonality between lunar and Mars ISRU technologies, processes, and operations in the following areas that make operation on the Moon relevant to future Mars missions:

- Excavation and material handling & transport
- Volatile/water extraction from soil
- Thermal/chemical processing subsystems for oxygen and fuel production
- Product and reactant fluid storage & transfer
- Site civil engineering and infrastructure emplacement for repeated landing/ascent at the same location

A significant percentage of the costs associated with developing and deploying hardware for flight applications is associated with development, qualification, and flight certification testing of the hardware under mission environments and operation scenarios. Therefore, even if the initial resources and the end-to-end processing systems are different for lunar and Mars applications, the tele-operated and autonomous operations, controls, and communications associated with lunar ISRU systems are similar enough to provide direct benefits to Mars ISRU development and deployment. Performing these operations on the Moon could increase confidence that similar processing and applications on Mars will be successful. Lessons learned from Earth and lunar testing and operations would reduce risk for initial Mars deployments. In addition, successfully demonstrating systems that utilize ISRU products, such as fuel cells, EVA suits, and propulsion systems would likewise provide confidence in ISRU performing mission critical functions.

Since there are risks and uncertainties associated with material handling, chemical processing, and product storage and transfer technologies and techniques associated with the lower gravity on the Moon and Mars, sustained operation of ISRU resource extraction, handling, processing, and product management on the lunar surface at 1/6th gravity would provide relevant data on Mars technology and hardware performance. Lunar ISRU demonstrations and systems can provide long-term operation data at low gravity that can reduce similar operation duration and low gravity impact concerns for Mars ISRU applications.

Besides the technologies and systems incorporated into ISRU systems, how ISRU systems are deployed, operated, and integrated into surface system exploration plans are important aspects that can be demonstrated on the Moon before use on Mars. Since ISRU for Mars must be pre-deployed and operated for extended periods of time before the crew leaves Earth, techniques and procedures for pre-deployment and activation of ISRU assets can be demonstrated in Earth analog field tests and on the Moon. Making, transferring, and using ISRU products, such as water and oxygen, for mission critical applications such as radiation protection, life support, EVA, and propulsion can provide confidence in the quality of ISRU products as well as concerns with how ISRU systems can be effectively integrated into human Mars exploration plans.

D. Demonstrate Long-duration Surface Operations and Autonomy

Utilizing planetary material simulants, analog test sites, vacuum and environmental chambers, and low-gravity aircraft for Earth testing can provide critical data for verifying technology and system performance in mission environments. However, facility costs, the limited range of environmental conditions that can be simulated, and the limited amount of time environment simulation testing can be performed restricts the effectiveness of Earth-alone testing. Therefore, long-duration operation on the Moon, especially at polar locations where near permanent sunlight and more benign thermal environments exist, can allow for better understanding of hardware life and performance that can be applied to Mars ISRU hardware design and operations. The short time delay in communications also allows for gradual development of autonomous control and remote operations capabilities that are critical for the success of Mars ISRU systems.

III. Lunar ISRU Overview

A. Lunar Resources

Lunar missions that have included ISRU systems have considered the use of lunar regolith, solar wind implanted volatiles, and potentially water ice and other volatiles at the lunar poles for the production of propellants, life support consumables, radiation shields, and habitat/infrastructure construction. Before findings of water on the Moon (starting with the Clemantine mission), most lunar mission trade study and design efforts that included ISRU focused on the production of oxygen from oxygen-bearing ores in lunar regolith and removal of solar wind-deposited elements. The lunar regolith is primarily made up of four major mineral types, pyroxene, anorthite, olivine, and ilmenite, and more than 42% by mass of lunar regolith is oxygen. Table 1 depicts the major constituents of lunar mare samples and solar wind volatiles released from the Apollo samples. Because iron oxide reduces at lower temperatures than the other mineral oxides, ilmenite and pyroclastic glasses are the most preferred mineral in the lunar regolith. While data before and during the Apollo program provided a picture of a very dry Moon, this began to change in the mid-1990's. Beginning with the bistatic radar hints from the Clementine mission in 1994 and confirmed by the gamma-ray and neutron spectrometers aboard the Lunar Prospector (LP) project launched in 1998, what appear to be water ice deposits of ~2-4% in the permanently shadowed regions were detected. Though the spectrometers aboard LP could not distinguish between implanted/cold trapped Hydrogen and water ice in the form of H2O, the discovery set the stage for more sophisticated missions: Lunar Reconnaissance Orbiter (LRO), the LCROSS impactor and the Chandrayyan project from India with its US instrument Moon Mineralogical Mapper (M^3). The table also depicts the major volatiles released after the impact of the lunar crater observation and sensing satellite (LCROSS). Recently, composite data compiled with measurements from instruments aboard LRO as well as M^3 (Li et al., 2018). As shown in Figure 1, the provocative finding of water ice at the surface of the Moon up to 30 wt.%

Mare Regolith		
Mineral	Concentration	
Pyroxene	50%	
CaO*SiO_2		36.7%
MgO*SiO_2		29.2%
FeO*SiO_2		17.6%
Al_2O_3*SiO_2		9.6%
TiO_2*SiO_2		6.9%
Anorthite	20%	
CaO*Al_2O_3*SiO_2		97.7%
Olivine	15%	
2MgO*SiO_2		56.6%
2FeO*SiO_2		42.7%
Ilmenite	15%	
FeO*TiO_2		98.5%

Solar Wind Volatiles	
Volatile	Concentration
Hydrogen	50-150 ppm
Helium	3-50 ppm
Helium-3	10^{-2} ppm
Carbon	100-150 ppm
Major Volatiles from LCROSS	
Carbon Monoxide	5.70%
Water/Ice	5.50%
Hydrogen	1.40%
Hydrogen Sulfide	0.92%
Mercury	0.48%
Ammonia	0.33%

Table 1. Lunar Regolith and Volatile Constituents (Heiken et al. and Colaprete)

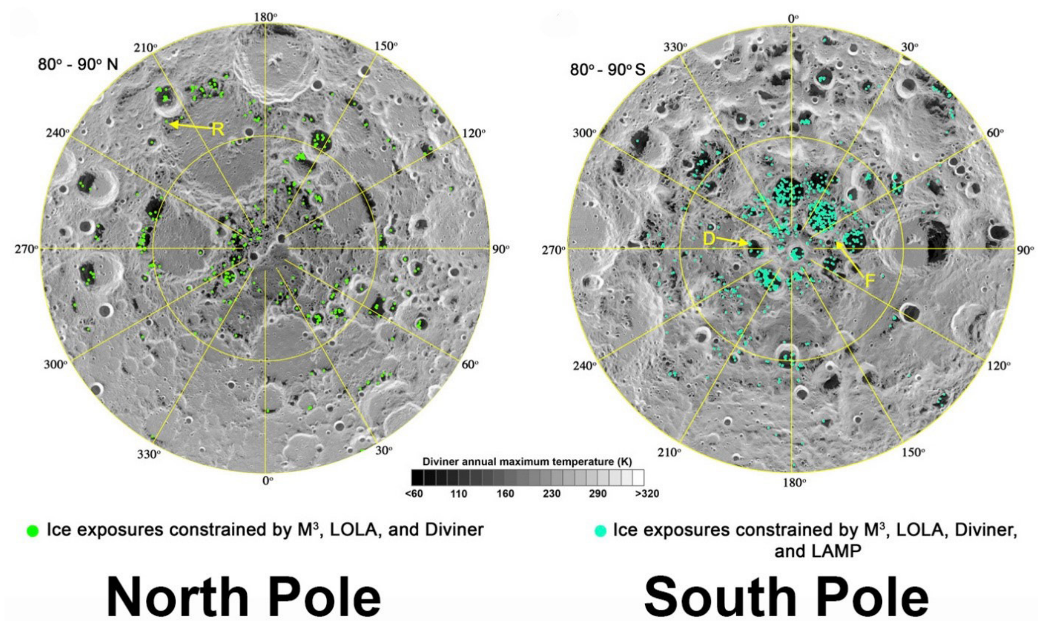

Figure 1. Composite data from instruments aboard LRO as well as M3 (Li et al., 2018).

B. Oxygen Extraction from Regolith

Since the 1970's numerous methods have been considered and examined on how to extract the oxygen bound in lunar minerals. Based on past oxygen extraction process evaluation studies and small scale laboratory experiments performed over the last 40 years, NASA chose three processes for detailed development during the Constellation program: Hydrogen (H_2) Reduction, Carbothermal Reduction, and Molten Oxide Electrolysis (MOE). Each of these processes have strengths and weaknesses with respect to extraction efficiency, complexity, and development risk.

Of the three processes selected for development, H2 Reduction is the simplest but least efficient. When regolith is heated between 800 and 1000 °C and mixed with hydrogen gas, iron oxide-bearing minerals and glasses in the lunar regolith, such as ilmenite ($FeTiO_3$) and pyroclastic glasses are reduced to produce water vapor. The water is condensed and electrolyzed to produce oxygen and to regenerate the reactant hydrogen for subsequent processing. While H2 Reduction is not the most efficient process because the amount of iron oxide in lunar regolith is low (1 to 5%, ie 1 to 5 kg oxygen for every 100 kg of bulk regolith), it does have the advantage of lower temperatures that keep the lunar regolith in granular form, which greatly simplifies material handling. To increase the performance and extraction efficiency of H2 Reduction, it has been found that feeding a specific size range of regolith particles can reduce the amount of time required to process the regolith. In addition, by increasing iron oxide material concentration through mineral beneficiation reduces the amount of regolith that needs to be processed to produce the same yearly production rate, thereby reducing the size of the reactors. Because of the low efficiency of the H2 Reduction process, a lot of regolith is heated up to 1000 °C, and because lunar regolith is a poor conductor of heat, it must be mixed and/or fluidized to speed up the reaction. In November 2008, two pilot-scale H2 Reduction systems were designed, built, and tested at an analog field site in Hawaii to allow comparison of different approaches for regolith feed and removal, regolith mixing and heating with H2, water vapor removal and collection, water electrolysis, and oxygen storage. One system developed by Lockheed Martin Astronautics, under a contract called 'PILOT' for Precursor ISRU Lunar Oxygen Testbed, uses a 'cement mixer' approach with a tumbling reactor to mix and heat the regolith, and was sized to produce 250 kg of oxygen per year (nominal early Outpost production need is ~1000 kg of oxygen per year). The second system development by NASA, called 'ROxygen', incorporated a vertical reactor with both fluidization and an internal auger to stir and heat the regolith to produce ~660 kg of oxygen per year. The purpose of these 1st generation hardware systems was not to build a system that meets flight mass or power requirements, but rather to provide the first end-to-end integration and test of excavation, oxygen production, and product storage in an automated system configuration at a relevant scale for human exploration. Based on lessons-learned from both system development and test activities, development of a 2nd generation ROxygen system was initiated that included regolith transfer via pneumatic lift techniques, pulse-stirred fluidization within the reactor, and internal reactor heat exchange from processed regolith to fresh regolith before reaction begins to minimize operation time and energy. The Constellation program was cancelled before this 2nd generation system could be completed.

The second oxygen extraction process selected for development, the Carbothermal Reduction process, is a more efficient oxygen production technique compared to H2 Reduction because it will also reduce some of the silicates found abundantly in the lunar regolith. However, the process requires much higher temperatures (>1600 °C) with the regolith becoming molten. When methane is introduced into the melt chamber, the methane reacts with the molten regolith and carbon monoxide is produced. The carbon monoxide is fed with hydrogen into a methanation reactor where the methane is regenerated and water is produced. The water is electrolyzed to recover the hydrogen and produce oxygen. This process can achieve efficiencies of 10 to 14% or greater (i.e. 10 to 14 kg of O2 for 100 kg of bulk regolith), but the process is more complex than H2 Reduction. The main challenges of this approach are delivering the energy needed to form the melt and developing techniques to deal with molten materials. Orbital Technologies Incorporated, now Sierra Nevada Corp., developed a Carbothermal Reduction system under contract to NASA, that utilized concentrated solar light channeled through fiber optic cables, (built by Physical Science Inc.), to melt the regolith and incorporated the ingenious concept of using the regolith's inherent insulation properties to contain the localized melts. Once the reduction reaction is complete, the melts are allowed to cool, and once solid can be removed from the regolith bed with an automatic rake mechanism, thereby avoiding reactor wall material and molten material handling issues. The combined PSI solar concentrator system with Orbitec Carbothermal Reactor and NASA water electrolysis and oxygen storage system were also successfully tested during analog field site in Hawaii on the slope of Mauna Kea in February 2010.

Figure 2 depicts the ROxygen and Pilot Hydrogen Reduction systems tested in Hawaii in 2008. Figure 3 depicts the Carbothermal Reduction system tested in Hawaii in 2010. Figure 4 depicts the functional block diagrams for both H2 Reduction and CH4 Reduction systems.

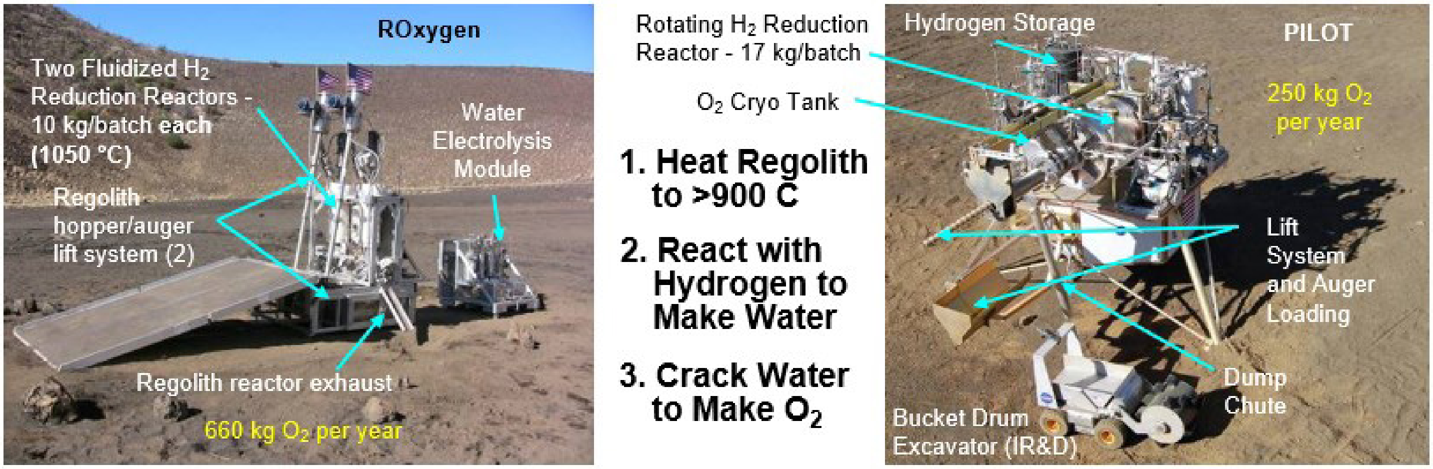

Figure 2. ROxygen and PILOT Hydrogen Reduction Systems

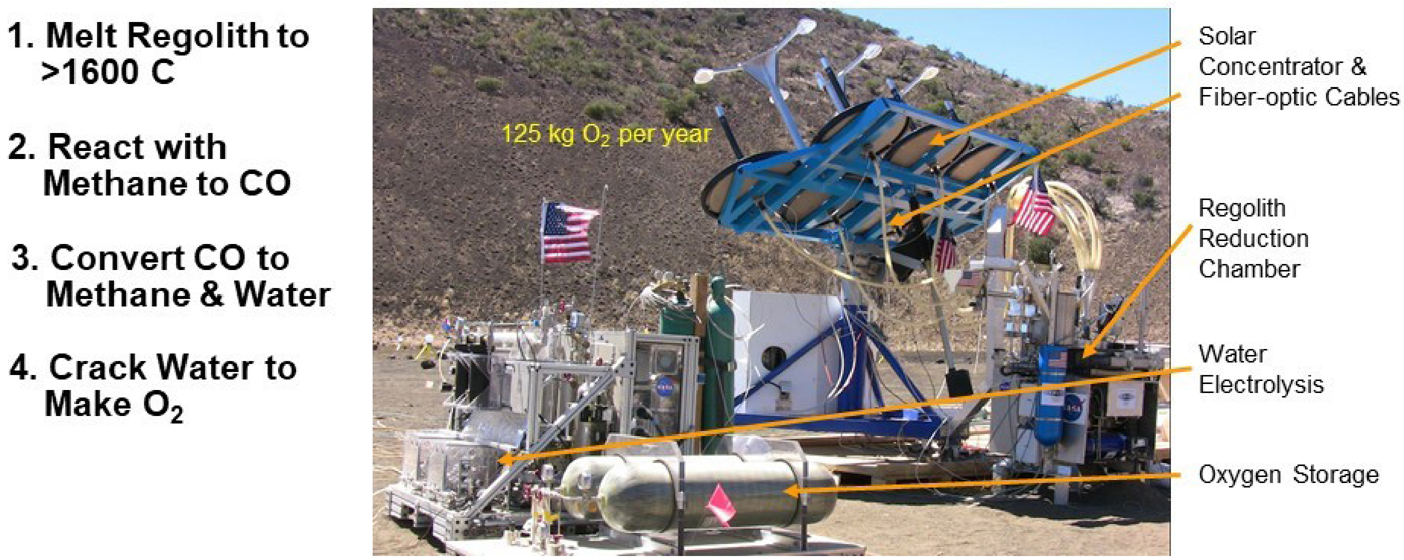

Figure 3. Carbothermal Reduction System

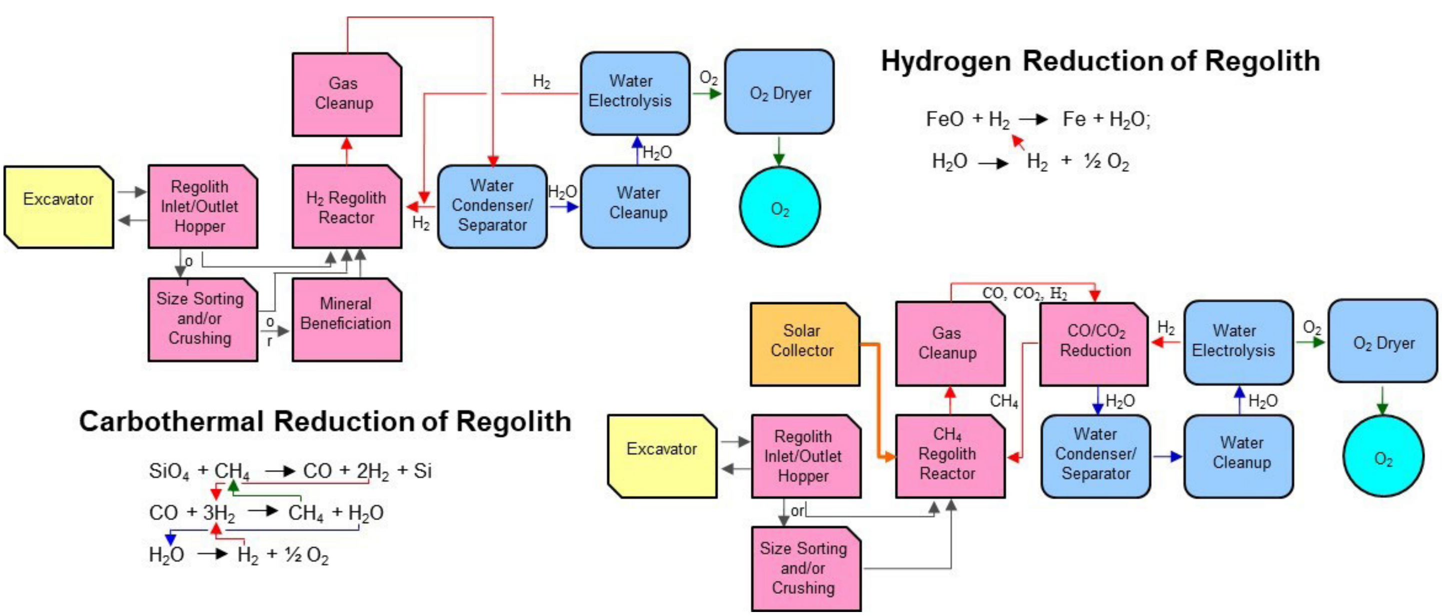

Figure 4. Functional Block Diagram for H2 and CH4 Reduction of Regolith

C. Polar Ice/Volatile Extraction

At this time, it is not possible to design pilot or full-scale polar ice/volatile mining equipment due to the large uncertainties associated with the depth, lateral distribution, and concentration of ice and volatiles in the permanently shadowed craters and regions of the lunar poles. Should the concentration of water ice be low (<5%), the regolith/ice resource may be granular in nature so excavation and regolith heating/ water extraction technologies developed for hydrogen reduction and Mars low water weight percent extraction may be applicable. If the water concentration is higher and the regolith/ice resource is hard and consolidated, material excavation by auger or subsurface extraction techniques may be required.

IV. Mars ISRU Overview

A. Mars Resources

Unlike the Moon. Mars has an atmosphere - which has long been a target for ISRU advocates. A long series of spacecraft beginning with the twin Viking orbiters and landers in 1976 have sought to characterize the Martian surface and atmosphere. With the arrival of Odyssey in 2001, Mars Reconnaissance Orbiter (MRO) in 2005, Phoenix in 2007 and a series of rovers (Spirit, Opportunity and Curiosity) in 2003 and 2012, the elemental and mineralogical composition of most of the Martian surface and some of the subsurface has received at least an initial examination. With high-resolution gamma-ray and neutron spectrometer data from the Mars Odyssey spacecraft, a whole planet map of Mars' chemical composition was created. One of the most surprising findings was of hydrogen (in the form of water) distributed across most of the Red Planet from a few percent by weight (wt%) at the equator to more than 80 wt% at the poles in the first meter of the regolith. Figure 5 depicts hydrogen (water) concentration across the Mars surface, and Figure 6 depicts hydrated minerals present in the mid-latitudes based on composite data from the instruments aboard the MRO spacecraft, particularly HiRISE and CRISM. The mission instrument data and figures depict that water content varies from a low of <1 wt% to >10 wt% in the mid latitude band of Mars (-30 to +30 degrees) in the upper 1 meter of Mars surface material. Also, that located deposits of phyllosilicates, carbonates, sulfates, and silica bearing deposits should contain enhanced water content from 6 to 10 wt%. Information from Viking I and II and the Sample Analysis on Mars (SAM) instrument on the Curiosity rover show that even the loose granular soil found across Mars is expected to contain 1 to 3 wt% water. From Mars orbital radar measurements (SHARAD and MARSIS), and from locating and imaging recently formed craters on the surface of Mars, more and more evidence suggests that vast subsurface ice deposits may exist near the Mars surface (top 10 m) in the mid to mid-upper latitudes (+/- 35 to 60 degrees). Therefore, Mars ISRU systems can consider three different forms of water for system designs depending on landing site location: granular low water weight percent surface soils, consolidated hydrated minerals with 6 to 10 wt% water, and near pure subsurface ice.

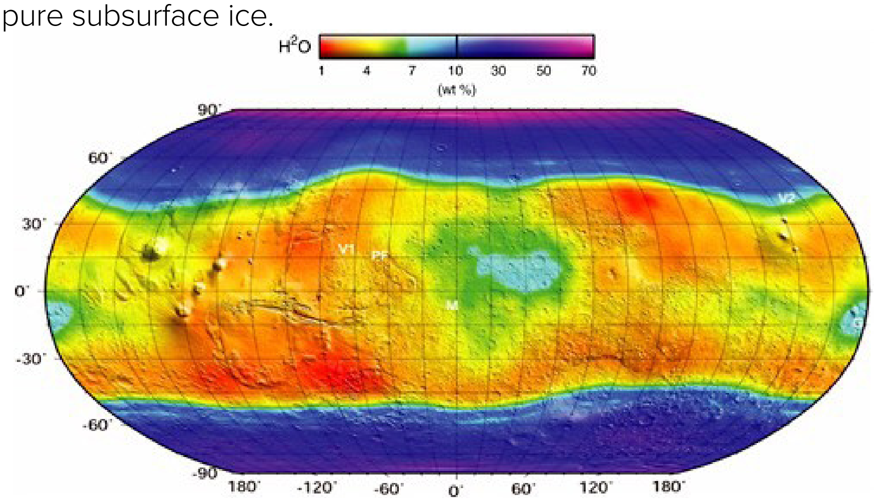

Figure 5. Water ice distributed across Mars, up to 80% wt <1m depth at poles

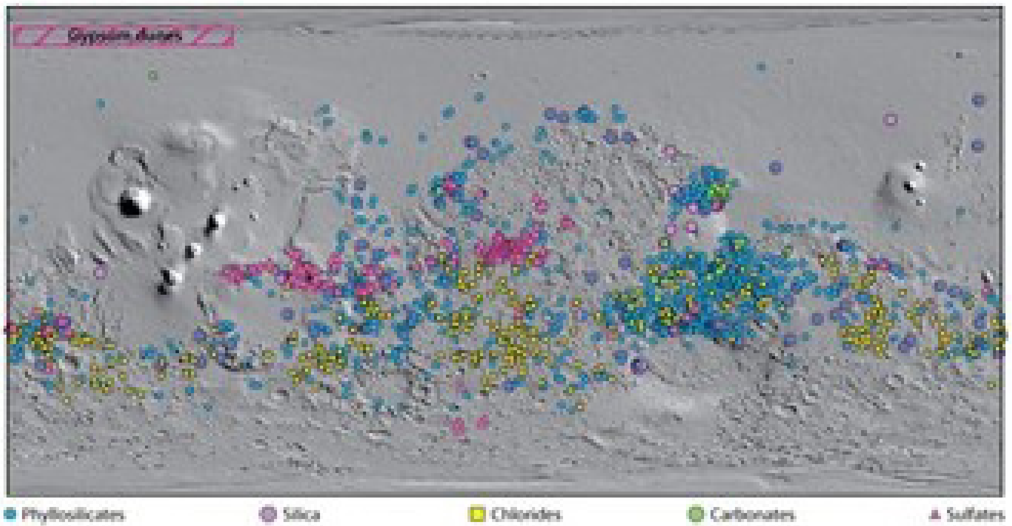

Figure 6. Mid-Latitude Hydrated Minerals

B. Oxygen and Oxygen/Methane Production from Mars Atmosphere Carbon Dioxide

Since the first paper on the concept of using the Mars atmosphere to make propellants was released in 1976, the incorporation of Mars ISRU into both robotic and human exploration missions has been studied numerous times. In the late 1990's, NASA initiated a series of Mars Human Design Reference Missions (DRMs) that started to quantify the benefits of Mars ISRU in human missions, the first of which was released in 1997. These studies primarily focused on evaluating the impact of making propellants on Mars for crew ascent to Mars orbit, but creating large caches of life support consumables (water & oxygen) as a backup for regenerative life support systems for long-duration surface stays (>500 days) was also considered in Mars DRM 3.0. The Mars Design Architecture 5.0 (DRA 5) was the first human mission architecture to evaluate the impact and benefit of utilizing water from surface materials besides just processing Mars atmospheric carbon dioxide on its own or with hydrogen brought from Earth. While Mars DRA 5.0 selected the oxygen-only approach as the baseline for the mission since it was considered the lowest risk due to water resource uncertainties on Mars (the study was performed in 2007), the study recommended that NASA should pursue better knowledge of water resources on Mars and to develop technologies for excavation and water extraction from Mars soils. The MWIP study in 2016 and Kleinhenz-Paz Mars ISRU study in 2017 further confirmed this recommendation and mission benefits .

To make oxygen from CO_2, two primary processes have been pursued and developed for ISRU applications: i) CO_2 electrolysis via Solid Oxide CO_2 Electrolysis (SOCE), and ii) CO_2 reduction via Reverse Water Gas Shift (RWGS) with Water Electrolysis (WE). It should be noted that while life support systems have also considered and pursued methane pyrolysis and the Bosch process for CO_2 reduction, these techniques were not considered viable candidates for ISRU applications due to the added complexity and need to handle solid carbon.

Carbon dioxide electrolysis involves the breakdown (or dissociation) of carbon dioxide into carbon monoxide (CO) and O_2. There are a number of different material and electrode options and methods for supplying energy to disassociate the CO_2 molecule: glow discharge, radio frequency electro-magnetic radiation, thermal, and catalytic. The method with the best results to date is a combined thermal/catalytic reactor using yttria-stabilized zirconia (YSZ) with platinum (or platinum alloy) catalyst/electrodes, commonly known as Solid Oxide CO_2 Electrolysis (SOCE). The SOCE process is fairly simple. CO_2 is supplied to the solid state ceramic reactor where energy is supplied to the gas to disassociate the CO_2 molecule into oxygen ions and CO via a platinum electrode applied to the surface of the YSZ. The oxygen ions produced are conducted through a YSZ membrane with a voltage potential and combine with another oxygen ion on the other side of the membrane to form an oxygen molecule. A solid oxide electrolysis device using a nickel electrode was selected for the MOXIE flight experiment on the Mars 2020 rover. Human mission scale versions of this technology were recently selected for development through the Small Business Innovation Research (SBIR) and NextSTEP ISRU Broad Agency Announcement (BAA) solicitations.

The RWGS reactor operates by taking H_2 and CO_2 and combining them in an endothermic catalytic reaction ($\Delta H = +9$ kcal/mole) to form H_2O and CO. The catalytic process is most efficient above 400ºC. Using conventional catalyst beds, the RWGS process only converts about 10% of the CO_2 in a single pass, so CO/CO_2 separation and recycling of CO_2 is required to minimize the mass and power associated with Mars atmospheric CO_2 collection system. Both NASA and Pioneer Astronautics developed and built first generation RWGS/WE systems that provided significant design and operational lessons-learned. Work by the Pacific Northwest National Laboratory (PNNL) using microchannel RWGS reactors have demonstrated CO_2 conversion from 40 to over 60% with selectivity to carbon monoxide of >99.99% and minimal pressure drop. A multi-stack RWGS microchannel reactor can potentially increase the conversion efficiency above 80%.

To produce both oxygen and methane on Mars requires both a Sabatier reactor and Water Electrolysis unit (depicted in Figure 7). The ISRU system is very similar to life support systems where a Sabatier reactor catalytically converts hydrogen and CO_2 into methane and water in a self-sustaining, exothermic reaction that converts >99% of CO_2 into methane at moderate temperature (200 to 250ºC). Since only half of the H_2 needed in the Sabatier reaction is recovered from the subsequent WE process, extra hydrogen is required to complete the process (either brought from Earth or from water obtained on Mars). The difference between an ISRU and life support system is that ISRU systems can operate at higher pressures and at higher hydrogen-to-carbon dioxide ratios than life support systems to increase chemical processing efficiencies.

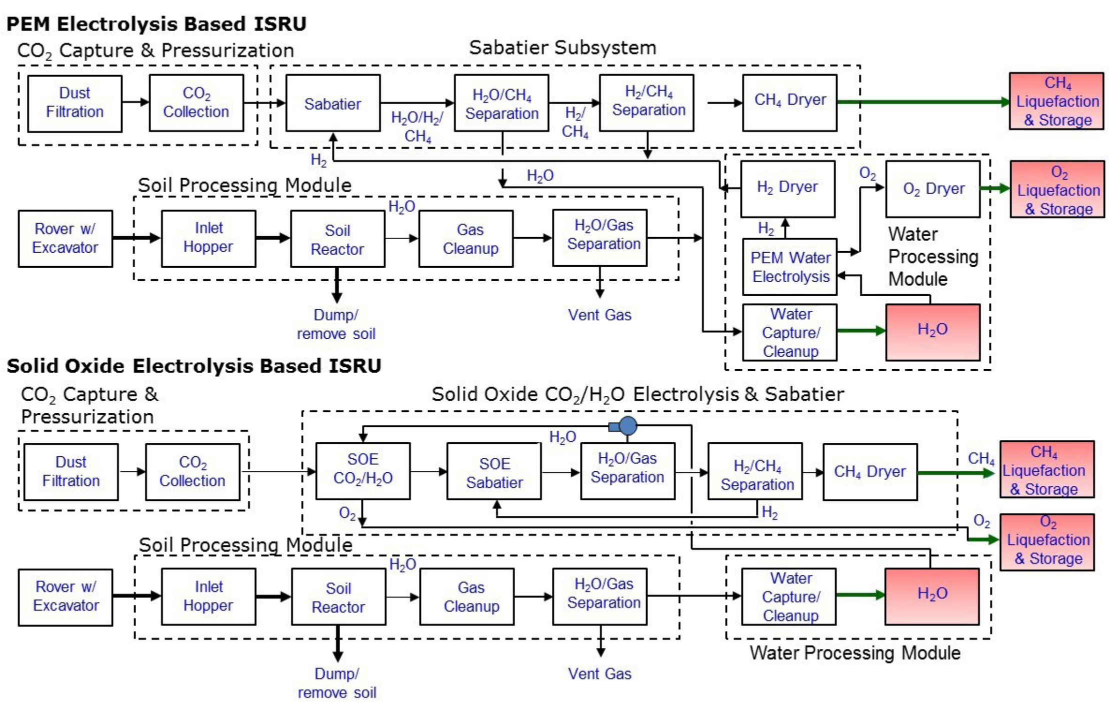

Figure 7. Functional Block Diagram for Oxygen/Methane Production from Mars CO_2 and H_2O

C. Water Extraction from Mars Resources

As stated in Section A (Mars Resources) above, Mars ISRU systems can consider three different forms of water for system designs depending on landing site location: granular low water weight percent surface soils, consolidated hydrated minerals with 6 to 10 wt% water, and near pure subsurface ice.

For water extraction from granular and hydrated minerals, several technology options have been studied, and have or are being evaluated including 1) a fluidized bed, internal auger/heater based on lunar hydrogen reduction reactor experience, 2) a microwave heating device, 3) an auger screw soil dryer, and 4) an open reactor heating concept. Each of these technologies show promise, and further work and testing is required before downselection of a baseline approach will be made. For excavation of surface granular material, numerous excavation concepts exist and have been considered and evaluated; however, NASA has primarily focused on bucketwheel or bucketdrum excavation concepts due to their efficiency and simplicity in excavating and transferring this type of material. The most developed excavator to date for ISRU is the Regolith Advanced Surface Systems Operations Robot (RASSOR) version 2 dual-bucketdrum excavator. The non-flight RASSOR excavator weighs approximately 66 kg but can carry an equal weight or more of granular material. It was estimated that only 3 of these excavators would be needed (due to redundancy requirements) to support crewed ascent vehicle propellant production. Based on these studies, it is estimated that the mass of excavation and processing hardware to extract water from low weight percent water granular material on Mars is around 0.8 to 1.0 mT for production of 15.7 mT of water over 480 days of operation.

For permafrost or ice relatively close to the surface, drilling into the material and applying microwave energy down the hole to cause the water to vaporize and be collected has been examined, but concerns continue to exist that water vapor released will recondense elsewhere in the hole before being collected. To overcome the concern about water vapor released recondensing below the surface, Honeybee Robotics has developed and demonstrated two near surface water extraction concepts; the Mars In Situ Water Extraction (MISWE) and Planetary Volatile Extractor (PVEx). The MISWE concept utilizes an auger to bring subsurface material into a heating chamber for water extraction. This approach can obtain material progressively deeper below the surface in batches. The PVEx concept utilizes a double walled corer with a perforated inner wall to allow material to be heated within the corer while below the subsurface. For cemented icy soils, both approaches require significantly less energy for material penetration and removal then other excavation approaches. However, both concepts rely on the icy resource to be near the surface.

For deeper subsurface ice layers, a terrestrial water extraction approach developed for the artic regions of Earth called the Rodriquez Well (or Rodwell for short) is being examined. The Rodwell concept first utilizes a drill to create a shaft from the surface into the subsurface ice sheet. Tubes with a water pump and/or heater unit are lowered into the subsurface ice sheet. Heat is then applied (via hot water or heater) to liquefy the ice into a pool of water which can then be pumped to the surface. This concept requires a significant amount of thermal energy, but can allow for significant amounts of water to be extracted *in situ* with minimal excavation and drilling compared to the open pit mining and MISWE/PVEx extraction concepts. Preliminary analyses of the Rodwell concept suggest that the complete amount of water needed for production of crewed ascent vehicle propellant could be obtained in less than 60 days of water extraction operation. The ability to utilize thermal energy from planned nuclear fission power reactors would make this extraction concept extremely attractive for long-term human exploration objectives, but would require careful selection and evaluation of potential landing sites. Honeybee Robotics was recently selected for award of a contract to develop a drilling system that could create a Rodwell up to 25 meters below the Mars surface through the NextSTEP ISRU BAA.

The Sixth Community Workshop for Achievability and Sustainability of Human Exploration of Mars (AM VI)

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