The Sixth Community Achieving, Affording, and Sustaining Human Exploration of Mars Workshop (AM VI)

AM VI

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

28-30 August 2018, The Elliott School
The George Washington University
Sponsored by Explore Mars, Inc. & the American Astronautical Society

Harley Thronson (NASA GSFC), Richard Davis (NASA HQ SMD), & Steve Mackwell (AIP)

NASA GSFC Systems Engineering Seminar: July 9, 2019

Reports available at https://www.exploremars.org/affording-mars

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Background to the Series of AM Workshops

AM VI

A series of informal discussions in early 2013 among a half-dozen or so academics, industry reps, and NASA civil servants led to a series of workshops unique in the development of strategies for human exploration.

Specifically . . .

- **Multi-institution** participation intended to be broader than the usual processes adopted for many years by NASA-developed/initiated architectures
  - *Significant leadership by non-NASA architects, scientists, engineers*
- **Transparent** workshop structure invited open debate
  - *Last decade's ESAS architecture was developed at NASA HQ behind locked doors, no external review . . . .*
- **Deliberate** collaboration of disparate communities: science + human space flight, Moon and Mars advocates
- **Community-developed** findings, observations, proposed investments
- Deliverables reported largely **independent of NASA** to Congress, professional conferences, Space Council, the Agency . . .

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Relevant Previous AM Community Workshops

AM VI

AM III (December, 2015 at the Space Policy Institute, GWU)

Integration of priority science goals with increasingly detailed human space flight scenarios: modify science goals and elements of human exploration to improve integration. Included planetary protection.

AM IV (December, 2016, Doubletree Hotel, Pasadena)

Critical comparison of major technological “long poles” necessary for achievable, affordable, and sustainable human exploration of Mars.

AM V (December, 2017, Washington Plaza Hotel, Washington, DC)

Developed in detail three distinctly different scenarios for human exploration of Mars by the end of the 2030s that were required to be affordable.

AM VI

The Challenge to AM VI

NASA, international, and commercial partners have proposed systems, technologies, and operations in the lunar vicinity that are proposed precursors to eventual human missions to the surface of Mars.

To enable near-term investments in critical technology capabilities, design studies, demonstration missions, and scientific precursors, it is necessary to critically examine those proposed lunar systems and activities that show the greatest promise to support humans-to-Mars during the **2030s,** the period of time assessed by our previous five workshops.

Our presentation today*:* Our workshop identified those activities proposed for lunar exploration that have the **strongest justification** for development in support of a human Mars mission within about two decades.

Our presentation will be limited to top-level findings, observations, etc. The complete, detailed report is available on-line and has been submitted to NASA HQ for consideration.

An additional goal of the workshop was face-to-face transfer of knowledge about human exploration of Mars to developers of scenarios for lunar exploration.

Workshop VI Assessments:
How Valuable to Mars Exploration is The Moon?

AM VI adopted the three scenarios for exploration of Mars within the 2030s as developed in our previous workshop (AM V).

A range of lunar scenarios established context for subsequent Mars missions. Each of these lunar studies will be assessed with respect its ability to enable or enhance **martian exploration**.

Deliverables to space agency stakeholders and professional colleagues will be the answers to major questions, including

1. What capabilities proposed for human missions to Mars during the 2030s will be important — or useful — to develop via astronaut and/or robotic missions in the lunar vicinity, including its surface and orbit? Which enabling activities for Mars exploration are the most desirable to include in existing lunar scenarios?

2. To what degree do lunar activities, systems, technology demonstrations and/or mission operations contribute to the reduction of risks for future human Mars missions?

3. What are the priority technology capabilities or activities **in common** among human lunar operations and Mars operations?

4. How can the government encourage commercial and international partnerships that will contribute to the efforts?

Workshop Process

The Human Exploration of Mars Mission Continuum From AM V

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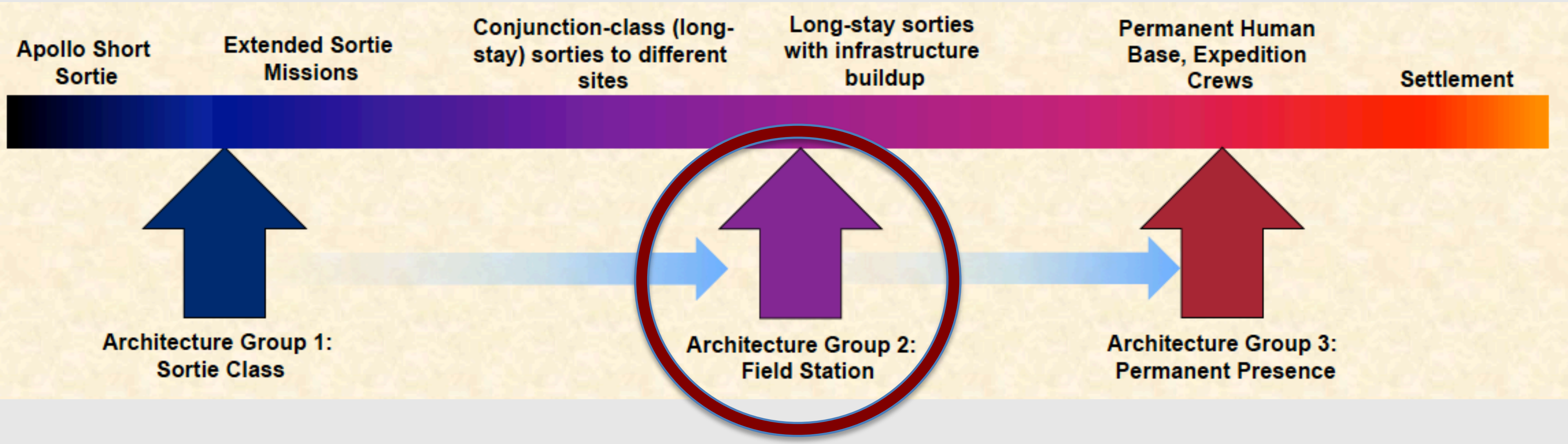
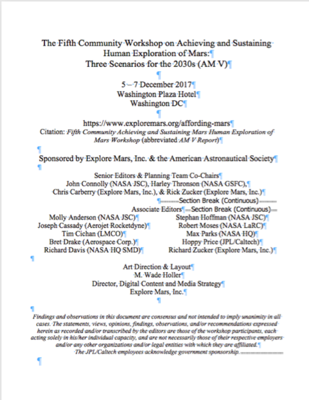
Three different "end states" for human exploration of Mars were adopted in AM V as representative of the goals widely identified and an architecture was developed that sought to achieve each of them under common ground rules and constraints.



<u>Adopted for AM VI Assessment</u>:
The engineering/technology Long Poles were essentially the same in the medium to long term across all three scenarios examined at the AM V workshop. For this reason, the Field Station was used as the baseline for AM VI.

AM VI

AM V Architectures


The Fifth Community Workshop on Achieving and Sustaining Human Exploration of Mars: Three Scenarios for the 2030s (AM V)

5 – 7 December 2017
Washington Plaza Hotel
Washington DC

https://www.exploremars.org/affording-mars
Citation: *Fifth Community Achieving and Sustaining Mars Human Exploration of Mars Workshop* (abbreviated *AM V Report*)

Sponsored by Explore Mars, Inc. & the American Astronautical Society

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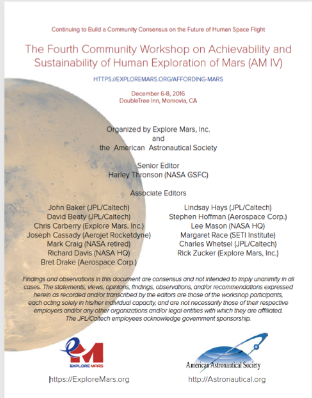
Three Architectures

1. Sorties
2. Research station
3. Permanent habitation

AM IV Long-Poles


Continuing to Build a Community Consensus on the Future of Human Space Flight

The Fourth Community Workshop on Achievability and Sustainability of Human Exploration of Mars (AM IV)

HTTPS://EXPLOREMARS.ORG/AFFORDING-MARS

December 6-8, 2016
DoubleTree Inn, Monrovia, CA

Organized by Explore Mars, Inc.
and
the American Astronautical Society

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Ten key technology long-poles

Map criticality of each long pole to one of AM V architectures

Pre-workshop Mapping

Notional Lunar Architectures

1. Gateway only
2. Sortie-Class
3. GER-Class
4. Field Station

For each long pole from the selected Mars architecture, rate the degree to which it can be advanced by each lunar architecture

Workshop Consensus Building

Adopted Mars Architecture

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AM V Team 2 (2018)

Looked for ideas to enable an "enterprise sustainable" architecture for an initial human Mars Field Station.
Do not necessarily represent completed trades.

- Conjunction Class
- Pre-deployed cargo on a range of lander sizes
- ISRU O_2, but also include H_2O as early as possible
- Long surface stay
- Round-trip crew vehicle

- Examine crew of 6
- Cost profile – long medium
- In-space prop: NTP, Minimum energy SEP/Chemical, Chemical
- No orbital only missions; All crew to surface
- Vehicle assembly in cis-lunar, HEO departure and arrival
- Launch cadence depends on commercial landers
- Aim for frequent opportunities
- Minimize crew space exposure (surface stays + NTP)
- Modular habs and labs likely have redundancy
- Single site with broad science exploration
- Reuse of habitat, transport, and surface & examine MAV reuse

Key Characteristics of Lunar Activity Categories

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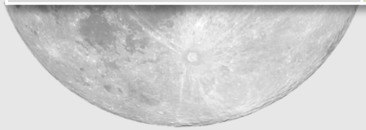
Lunar Attribute	Gateway-Only	Sortie-Class	GER-Class	Field Station
All options assume Gateway staging, heavy lift, and 11 km/s return vehicles				
Human Surface Mission?	No	Yes, Multiple Sites	Yes, Multiple Sites	Yes, Fixed Base Site
Crew to Surface	0	2-4	4	4+
Surface Exploration Duration	n/a	3-5 Days	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

Workshop VI Scenario Ground Rules

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- First human mission to the surface of Mars will occur **during the 2030s.**
- Budgets for the space agencies will grow approximately with inflation.
- 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.
- The **presented** Moon and Mars scenarios may not be altered in significant ways.
- 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.
- Partnerships (international, commercial, academic . . .) will be an essential component of human exploration.

Breakout with Two Teams: Assess Using the Moon to Enable Mars Exploration

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Transportation/Propulsion Systems And Operations

Heavy lift/Earth re-entry, on-orbit aggregation, Gateway, landers for crew and cargo, ascent vehicles, radiation, human resources/ECLSS

Surface Systems and Operations

Reconnaissance, habitats, suits, rovers, intelligent systems, ISRU, surface power, communications, human resources/ECLSS

Overlap among the topics assessed by each team was accepted.

The breakout teams reported and discussed progress, challenges, uncertainties, etc. every few hours in plenary.

Example: Long Pole Matrix
Mars Ascent Vehicle Assessed by Transportation Team

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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 mature in LEO (e.g. ISS) now	Capabilities with long lead times which must be developed specifically for Mars[6]
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	Previous column applies	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.		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 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.	Previous column applies	Previous column applies			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	Previous column applies	Previous column applies			No	No
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	No

Most Relevant Systems and Technologies (aka, "Long Poles") to Test/Demonstrate on the Moon to Feed Forward to Mars

AM VI

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

Most Relevant Systems and Technologies (aka, "Long Poles") to Test/Demonstrate on the Moon to Feed Forward to Mars

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Surface Systems/Technologies/Operations

Highest priority (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 (Alphabetical Order)

- **Communication systems** (e.g., orbital assets, local communication)
- **In-situ resource utilization**
- **Surface habitats and laboratories** (e.g., systems availability, operations)

Lunar ISRU Strategy That Feeds Forward Moon-to-Mars

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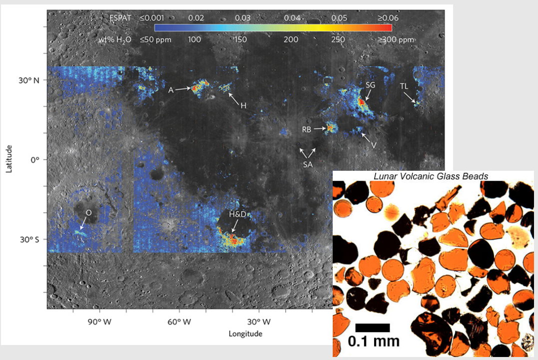
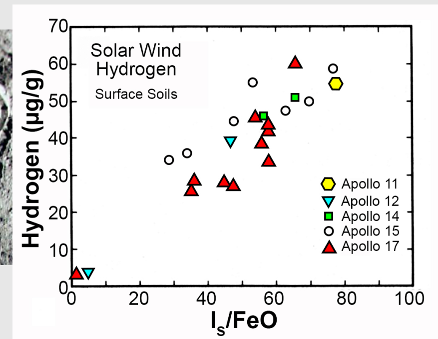
Potential Resources on the Moon and Mars

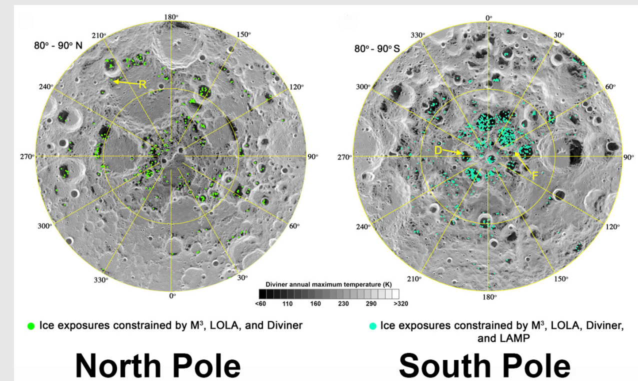
Water Resources on the Moon



Volcanic glasses: ≥0.3 wt.% H_2O

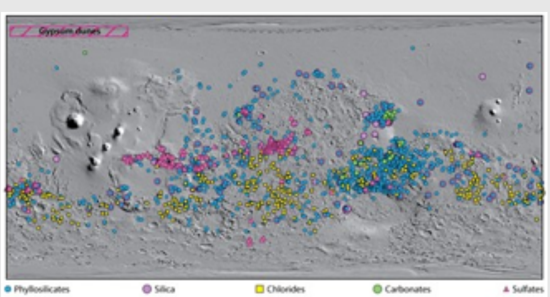


Regolith: solar wind implanted H

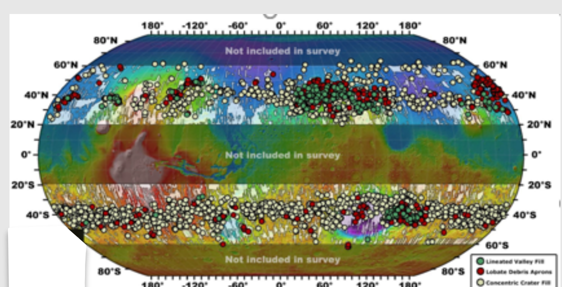


Polar water ice: up to 30 wt.% water ice at the surface

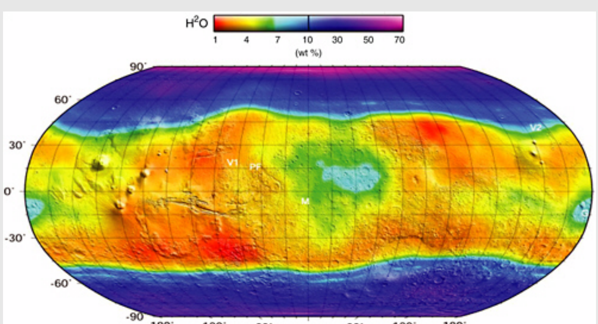
Water Resources on Mars



Mid-latitudes: Hydrated Minerals



Potential near-surface ice >1m depth



Massive ice <1m depth at poles

Mars-Forward Lunar ISRU Role & Focus

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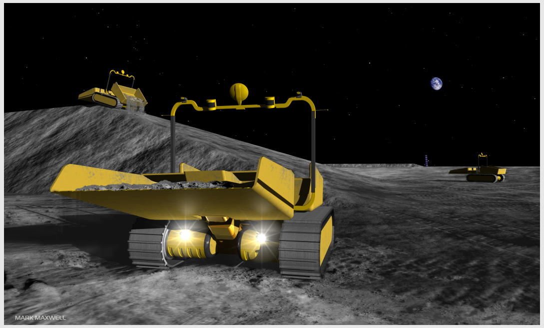
Identify/characterize/quantify resources/volatiles for future uses

- Robotic prospecting is an urgent requirement on the Moon and Mars.
- Data needed: form, abundance, extractability, purity, etc.
- Prospecting campaigns on Moon and Mars – multiple deposits.

ISRU – Moon-to-Mars

- Demonstrate ISRU concepts, technologies, hardware that reduce the mass/cost/risk of human Mars missions:
  - ISRU for propellant production; Cryogenic storage & transfer to refuel ascent vehicle and orbiting refueling depot
  - Site engineering and infrastructure emplacement for repeated landing/ascent at same location
- Use Moon for operational experience and mission validation for Mars:
  - Pre-deployment & remote activation and operation of ISRU assets without crew
  - Landing crew with 'empty' tanks with ISRU propellants already made and waiting



Selected Workshop Observations

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- An **important number** of possible human and robotic operations, technology developments, and demonstrations on the surface of the Moon and its vicinity were identified that would contribute to the Mars scenario adopted here (Field Station).
- 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:
  - *Lunar & martian priorities should not be assessed independently*.
  - *Future priorities for Mars exploration may levy requirements on lunar exploration.*
- The **Gateway could be an important test-bed** for Mars transportation architectures.
- Using the **ISS or a similar 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.
- 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.

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Priority Follow-on Activity to AM VI:

Selected Trade Studies (Not in Priority Order)

1. Comparison of end-to-end costs of resources extracted from the Moon with those supplied from terrestrial sources
2. Lunar ascent vehicle/lander extensibility to Mars ascent vehicle/lander
3. Pros/cons of different cryogenic propellant combinations (i.e., LOX/CH_4 versus LOX/H_2) for lunar and Mars scenarios
4. Common development paths for Mars and Moon surface suit thermal systems
5. Long-lived pressurized rover energy production and storage (e.g., Kilopower versus radioisotope power system (RPS), fuel cells versus batteries)
6. 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)
7. Study on ISRU-based site preparation and construction for landing, lift-off, and surface transportation operations on lunar and martian terrain.

Proposed Assessments of the Extent to which the Moon may be used to Further Mars Exploration (II)

AM VI

Potential National Academies Studies

- ISRU has the potential to enable affordable and sustained human occupation of both the Moon and Mars (and beyond). However, certain critical information about these resources is not yet available.
  - *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 feed forward to Mars?*
  - *What are the effects of declining launch costs and development of lunar resource extraction capabilities?*
  - *What are the roles of federal, commercial, and international partners?*
- Characterization and mitigation of the adverse space environment on human health (e.g., radiation, psychosocial, zero g, partial g) for lunar and Mars missions:
  - *What needs to be carried out at ISS and Gateway, and what can be learned on the Earth?*

Questions?

Opening talk by Dr. Jim Green (NASA Chief Scientist)
Closing talk by Dr. Ellen Stofan (Director, NASM)

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Back Up

Engineering Long Poles to Enable Mars Exploration

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About a dozen engineering Long Poles required for eventual human missions to the martian surface were identified and assessed in our 2016 AM IV workshop.

In AM VI, these were used to assess the content of the lunar scenarios that most enabled exploration of Mars in the 2030s.

Long Pole [1]	Yrs to close [2]	Driving Gaps [3]	Long Term Goal	Enabled Human Missions				
			Mars Surface Long Stay	Cislunar Shakedown Cruise	Mars Fly-By [4]	Mars Orbital	Orbital + Martian Moon Sortie	Mars Surface Short Stay
3. Aggregation and Refueling / Resupply Capability	11	Design of logistics architecture and demonstration in deep space, Autonomous operations at Mars. Xenon & cryogenic transfer.	X	X	X	X	X	X
4. Mars Transfer Vehicle (hab & Propulsion)	HRP roadmap green + ? years	Hab: Space radiation protection for crew,	X	X	X	X	X	X
5. Solar Electric Propulsion Cargo Tug		300-kW Class Solar Array, ARV-derived Power Distribution, 12.5-kW Electric Propulsion Thruster, Low Thrust Navigation	X			X	X	X
6. Martian System Recon for Human Operations	12	Resource Reconnaissance for Landing Site Selection, ground truth of resource mapping Round-trip Demo / Sample Return, extant biology in soil (?), atmospheric recon for EDL,	X				X	X
7. Mars Crew / Cargo Lander(s) [5]	13	Mars EDL system (30 t, <100 m precision), LOX/Methane Propulsion and CFM	X					X
8. Mars ISRU Tech Development	6 (atmos) 8 (water)	Convert CO2 to O2, Dust effects on ISRU hw. Oxygen extraction from CO2. (DRM 5.0) Access H2O-- subsurface ice/minerals. Resource Acquisition, Liquefaction and CFM	X					
9. Mars Surface Hab / Science Lab	~5 -- 17	Surface Habitation (architecture for livability and usability)	X					X
11a. Mars Surface Power - Solar + RPS	8 - 10	SEP-derived Solar Arrays, lightweight fuel cell/ battery storage, high power/high efficiency RPS	X					X
11b. Mars Surface Power - Nuclear Fission	10 - 12	10s kW Fission Power, Heat pipe thermal transport, high efficiency energy conversion	X					
13. Mars Ascent Vehicle (MAV)	13	LOX/CH4 Propulsion and CFM, habitability, GN&C, Integrated System, ISRU Convert CO2 to O2,	X					X
14. Mars Communication Network for Human Expl and Science		Deep Space, High-Rate Forward Link / Downlink and High Rate Proximity Communication	X			X	X	X

Example Long Pole Matrices

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Transportation Team - Crew/Cargo Lander

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 at the ISS now	Capabilities with long lead times which must be developed specifically for Mars
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	Medium: Aeromaneuvering of Commercial Logistics/Earth Return	High: Precision landing and hazard avoidance Medium: Abort scenarios	High: Critical infrastructure near landing zone	High: Abort to surface. Humans present near landing site		*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 Medium: If commercial logistics vehicles use cryo propulsion	N/A	High: Strong similarity between lunar descent and Mars lander propulsion Medium: 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		*Assume hypergolics for lunar sortie missions	No	Yes Cryo Fluid Management needs to start immediately
Footnotes	GER class missions may have some abort to surface capability								

Surface Team – Mars Communications

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
12: Surface EVA Suit **PRIMARY							How do we operate EVAs on the two surfaces? That can drive differences (relevant for all categories).
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.
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.

Proposed Assessments of the Extent to which the Moon may be used to Further Mars Exploration (II)

AM VI

National Academies Studies

- In-situ resource utilization (ISRU), especially of surface/shallow geological deposits containing extractable water, has the potential to enable affordable and sustained human occupation of both the Moon and Mars. However, certain critical information about these resources is not yet available and, consequently, how and when such resources might be exploited. Therefore,
  - *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 feed forward to Mars?*
  - *What are the effects of declining launch costs and development of lunar resource extraction capabilities?*

- Mitigation of environmental damage to human health (e.g., radiation, psychosocial, zero g, partial g) for lunar and Mars missions:
  - *What needs to be carried out at ISS and Gateway, and what can be learned on the Earth?*