

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)

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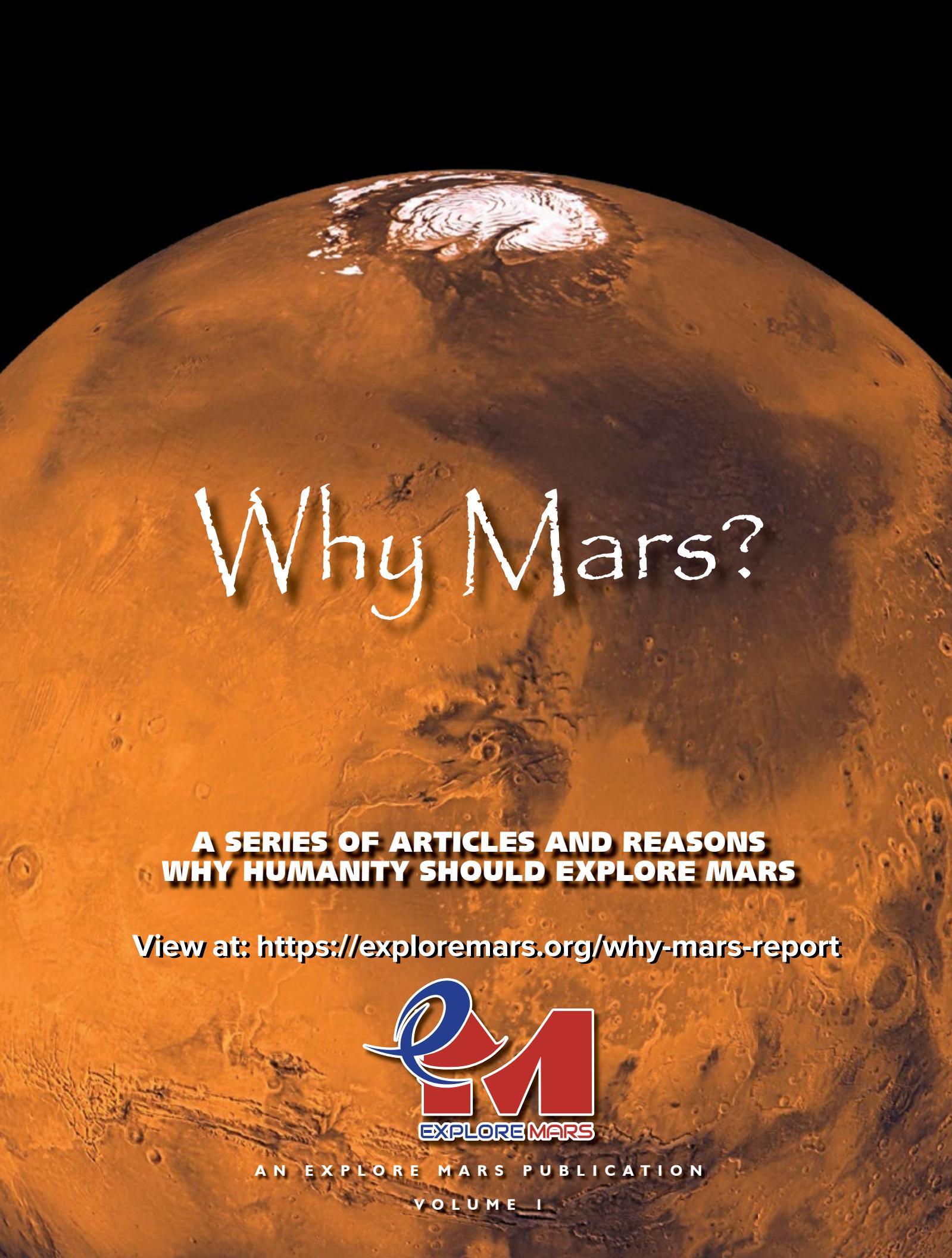


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The Fourth Community Workshop on Achievability and Sustainability of Human Exploration of Mars (AM IV)

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

In December 2016, approximately 60 invited professionals from the industrial and commercial sectors, academia, and NASA, along with international colleagues, assessed the *achievability and sustainability* of critical capabilities (or “long poles”) necessary for human exploration of Mars. These individuals were chosen to be representative of the breadth of interests in astronaut and robotic Mars exploration. Ten expert teams were assembled and each was charged with assessing the achievability of one major element common among scenarios for initial human missions to Mars. The long poles assessed at the workshop include:

1. Mars System Reconnaissance
2. Aggregation, Refueling, and Resupply
3. Transit Habitat and Research Laboratory
4. Crew/Cargo Lander: Entry, Descent, and Landing
5. Surface Habitat and Research Laboratory
6. Surface Power
7. Mars Ascent Vehicle
8. Human Health/Biomedicine
9. Sustainability
10. Planetary Protection

The role of planetary protection policy in human exploration was also considered. Long poles such as the Space Launch System and Orion Multi-Purpose Crew Vehicle were considered by the workshop participants as key critical elements of future human exploration of Mars, although were not addressed at the workshop as they are currently under development and making good progress.

In general, the workshop participants concluded that the estimated length of time to retire the long poles strongly suggests that a human mission to the surface of Mars could be accomplished in the early to mid-2030s with sufficient funding. A human orbital mission to Mars does not require retiring as many long poles as a landing to be closed and could be attempted as early as 2026 or 2028. Such a mission could substantially inform subsequent missions. *That is, engineering and technology are not the factors limiting initial human missions to Mars*, although major decisions are required in the near future about the exploration architecture. In addition, it will be important to ensure that international planetary protection policy and requirements are integrated into the system designs and operations plans in the early phases of planning.

The workshop participants produced several additional conclusions, including

- Risks associated with entry, descent, and landing (EDL) systems of human-class payloads are the major long pole in initial missions to the surface. With increased funding and a fast-track approach, this might be achieved in as little as 13 years, although these risks may require up to 17 years to retire without funding greater than the conservative assumption in our assessment. These capabilities do not need to be in place prior to attempting orbital missions.
- The Mars Ascent Vehicle drives the size of the landing vehicle. Further refinement of the overall Mars architecture is required before the ascent vehicle can be properly defined, including the degree to which in-situ resources will be assumed.
- Robotic reconnaissance over the next two decades is an essential element of preparing for human missions, predominately for landing site selection and potential subsurface resource characterization, as well as analysis of samples returned from the Martian surface.
- The role of logistics support, supply nodes, refueling and aggregation needs to be studied in more detail and could be enabling of sustained human missions.
- There is potential synergism among the transit and surface Habitat and research modules. The value of modularity and commonality needs to be assessed as a priority.
- Providing the necessary surface power will be challenging, although there are developments that might lead to the availability of small nuclear fission reactors.
- Operations with astronauts on the lunar surface were not identified as offering value to initial human missions to Mars given the associated costs and risks of those missions, as well as the absence of detailed engineering analysis.



Preface

To continue to build broadly based consensus on the future of human space exploration, the *Fourth Community Workshop on Achievability and Sustainability of Human Exploration of Mars (AM IV)*, organized by Explore Mars, Inc. and the American Astronautical Society, was held at the DoubleTree Inn in Monrovia, CA., December 6–8, 2016. Approximately 60 invited professionals from the industrial and commercial sectors, academia, and NASA, along with international colleagues, participated in the workshop. These individuals were chosen to be representative of the breadth of interests in astronaut and robotic Mars exploration.

AM IV built upon the three previous *Affordability and Sustainability Workshops* (i.e., AM I–III) held in 2013, 2014, and 2015 respectively. Those previous workshops assessed and reported on the affordability and sustainability of multiple scenarios for human exploration of Mars. For that reason, our organizing committee concluded that the 2016 workshop would concentrate specifically on *achieving* critical capabilities (or “long poles”) in human exploration of Mars. Ten expert teams were assembled and each was charged with assessing the achievability of one major element common among scenarios for initial human missions to Mars. Included in each assessment, each of which was critically reviewed during the workshop and which is reported on here, are such characteristics as key elements of the long pole and the length of time required for development, venues for demonstration, precursors, and scenarios that take advantage of the long pole.

The output of the workshop consists of observations, findings, and recommendations that will be presented to space agency leadership, policymakers, and at professional conferences.



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Mars Exploration “Long Pole” Thumbnails: Abbreviated Findings and Observations

There are a relatively small number of major elements (“long poles”) required to enable initial human missions to the surface of Mars in the mid-2030s. Ten long poles were assessed in depth before and during this workshop and all were found to be achievable. That is, with sustained and focused investment, they all would be available for deployment within about fifteen years or less.

Given the complexity and required long development time of several of these long poles, the highest-priority finding of this workshop is that initiation in the very near term of design work, trade studies, and key technology investments is necessary to achieve the goal of a landed human mission on Mars within two decades.

1. Mars System Reconnaissance: Higher-fidelity data on the martian surface environment and its impact on crew and hardware operations are needed to guide architectural and engineering design decisions. The global and local distribution of water deposits (in the form of hydrated minerals or subsurface ice), planetary protection special regions, and local surface terrain and topography affect the selection of the landing site, its surface operations, and the systems that may benefit from its resources (e.g., life support, Mars ascent). Moreover, the local dust toxicity, particle size distribution, and extant biological potential characteristics can impact the health of the crew and the reliability of their supporting systems. Gathering sufficient data to inform these decisions requires supplementing existing datasets with at least one new focused orbital mission and one new surface precursor ground-truth mission, as well as the analysis of samples returned from the martian surface.

2. Aggregation, Refueling, and Resupply Capability (ARRC): Limitation on overall launch performance and launch rate requires aggregating of Mars stack elements. Refueling and resupply is an effective strategy to mitigate undesirable mass growth of individual elements. To take advantage of this long pole, a logistics architecture needs to be defined, including locations, launch infrastructure, docking concept of operations and refueling. Operations in the martian system are part of the challenge. ARRCs are achievable in the near term with current technology already in development. The primary challenges are: operations in deep space, including navigation and autonomous rendezvous and larger quantities of propellant, and different types such as xenon and cryogenic propellants. A pressing concern is the development of an overall strategy for using ARRCs, notably to ensure adequate and diverse supply chains to support crews in the martian system. It is our assessment that a robust strategy will add to mission flexibility and crew safety and may be critical to reducing the overall costs of Mars mission. Given NASA’s current plans for missions in the Proving Ground of cislunar space, this long pole will be closed in about ten years. However, given technology readiness levels at present, acceleration could reduce this time to about 7-8 years.

3. Transit Habitat and Research Laboratory: The long pole for transit habitation is an integrated design within a limited volume that protects the crew from increased radiation, keeps them healthy and productive, stores all the logistics they will need for the trip (>500 days) and in the harsh environment of deep space. While building on lengthy experience from the ISS, NASA has done extensive studies and even built mockups to test different approaches. Public-private partnerships are in place to further develop this area.

4. Crew/Cargo Lander: Entry, Descent, and Landing: Entry, descent and landing (EDL) is a challenging problem today for science-class payloads such as the Mars 2020 rover. It is a long pole for human-class missions because the payload mass that must be safely landed is much greater than the approximately one ton that is characteristic of current robotic missions and closer to 20–40 t for human-scale missions. Simply scaling up the current approach will not work because of launch vehicle fairing diameter limitations. This requires examination of different approaches to decelerate and guide the payload to the surface. At the same time, current exploration plans require that multiple payloads be landed in close proximity to one another, requiring much greater precision in the landing guidance and control. There are many approaches under consideration to address this (deployable heat shields, inflatables, and mid-L/D entry body designs) and it is imperative that decisions be made soon about the architecture to allow the concept selected to be matured in time for human missions in the mid-2030s.

5. Surface Habitat and Research Laboratory: This is a long pole for much the same reasons as the in-space habitat. However, there is also a tightly coupled relationship between the capabilities of the surface habitat and science laboratory and the capabilities of other systems (e.g., lander, EDL, etc.) that could lead to different or additional capabilities compared to the in-space habitat. The surface habitat and laboratory will build on experience gained from the development and operation of the transit

habitat: both will build on the 15+ years of experience with ISS from which we learned that the primary challenge is habitability. That is, the system must be designed such that the small crew complement can live comfortably, accomplish all the research and exploration tasks assigned to the mission, and recover from unexpected occurrences. At present, there is little confidence that the results of studies of short duration – several weeks to several months – habitation tests extrapolate to a 500- to 1000-day mission. A longer-duration habitation capability will be required to be demonstrated in the 2020s to enable initial missions to Mars in the 2030s.

- 6. Mars Surface Power:** The decision on surface power technology will depend heavily on the expected longevity of the outpost, the extent of in-situ resource utilization (ISRU), and the landing location. For shorter missions near the equator with minimal ISRU, solar power systems with nighttime energy storage seem sufficient. Solar power systems will be limited by reduced solar insolation and extended-duration dust storms, making radioisotope power systems an attractive emergency backup. If the outpost is planned as a permanent staging node for repeated visits with a strong dependence on ISRU, nuclear fission is favored. The long pole for Mars surface power spans both solar and nuclear options since no current technological solution exists to supply the 10s of kilowatts that will be needed for human missions given the challenging Mars environment.
- 7. Mars Ascent Vehicle (MAV):** There is an increasing need for critical decisions to be made soon for those related to the overall Mars exploration architecture operational concept, functions, and performance requirements that impact the MAV: e.g., rendezvous orbit, the need for and availability of aborts during descent, reliance on ISRU. Resolution of these architectural-level issues for initial human missions are necessary to close long poles associated with the MAV.
- 8. Human Health/Biomedicine:** Crew health and performance are critical to successful human exploration beyond LEO. The work of NASA’s Human Research Program (HRP) is essential to enabling extended periods of space exploration through research and technology development activities that are aimed at mitigating risks to human health and performance. This program delivers human health and performance countermeasures, knowledge, technologies and tools to enable safe, reliable, and productive human space exploration. The achievability of this long pole – meaning adequate health and performance protection of astronauts during future deep space long duration missions – is expected to be possible based on a risk mitigation strategy that is very focused and applied. Human spaceflight risks include physiological and performance effects from the hazards of spaceflight, such as altered gravity, space radiation, and hostile environments, as well as unique challenges related to medical support, human factors, and behavioral health support. Risks and Concerns in the HRP research portfolio are within NASA’s Office of the Chief Health and Medical Officer. Priority research is a major component of the mitigation strategies and is assigned to an element within the HRP to quantify, mitigate, or monitor.
- 9. Sustainability of NASA Mars exploration results from its value to stakeholders:** value built into the enterprise to enable continuity after a few human missions, the case with Apollo. This requires creating a critical mass of international partner and in-space economic private sector stakeholders. It will require sustained leadership and an architecture that returns value to these stakeholders, even if it involves intermediate destinations or new business models to do so. Potential intermediate destinations need to be part of an ever-expanding base of international partnerships among in-space private-sector stakeholders for an exploration of Mars founded upon mutual value.
- 10. Planetary Protection:** Although planning for Mars missions can build upon a long history of policies and practices used for robotic exploration missions, human missions beyond LEO have been limited to the small number during the Apollo Program. There is a recognized need to update, adapt and replace Apollo-era planetary protection practices in ways that reflect advances in science understanding about planetary environments, recent information about the human microbiome, technological improvements in many areas, and legal/policy changes. Considerable cross-cutting R&TD are needed for integrating planetary controls and requirements into plans for future human missions to Mars.
- 11. Lunar surface operations in advance of human missions to Mars:** In our series of four community workshops, there was little or no support expressed for either demonstration programs with humans on the lunar surface nor for the search for usable resources to enable initial human missions to Mars. Both were judged unnecessary, costly, and at present almost entirely devoid of sufficient engineering designs, trade studies, comparison with terrestrial supply, technology development plans that included launch vehicles in the lunar environment, and return on investment.

Background, Goals, and Structure

Planning for the fourth in our unique series of community-based workshops on affordable, achievable, and sustainable scenarios for human exploration of Mars began shortly after the third workshop concluded in December 2015. These workshops, organized jointly under the auspices of Explore Mars, Inc. and the American Astronautical Society, bring together experts from industry and commerce, academia, government, and other space communities. These individuals were selected as representative experts in their respective fields.

The first three workshops concentrated on assessing and reporting on the affordability and sustainability of scenarios for initial human exploration of Mars as developed by industry and NASA. AM I, which was held in Washington, D.C. in December 2013, evaluated industry and government policies and practices that limit cost and seek schedule savings for initial human missions to Mars¹. Building upon the findings and recommendations from this first workshop, AM II, which was held at the Keck Institute in Pasadena in October 2014, compared and contrasted scenarios, architectures, and sample strategies developed by industry, academia, and NASA that are intended to significantly reduce costs for human space flight (HSF) beyond low-Earth orbit (LEO), especially to Mars. At that second workshop, a team of experienced Mars scientists was included in a breakout session to assess the role of human-enabled science exploration as an integral part of proposed HSF architectures. Involving scientists in assessing HSF scenarios was found to be so valuable in AM II that AM III, which was held at The George Washington University in Washington, D.C. in December 2015, included an even larger contingent of practicing scientists in the planning, execution, and reporting from the workshop.

Formal reports from all of these workshops are widely available, briefed to senior NASA leaders, and presented at numerous professional conferences. [More information about all workshops and their deliverables may be found at <https://exploremars.org/affording-human-exploration-of-mars> .]

Following AM III and based on discussions held there, the organizing committee concluded that for the fourth community workshop in the series, participants should concentrate on the achievability, as well as the sustainability, of major elements (i.e., “long poles”) of published Mars exploration scenarios. Specifically, the motivating principle behind AM IV was that it would be of little value to human exploration stakeholders to consider scenarios for human exploration that are not plausibly achievable over the time period of the next two decades.

Approximately sixty professionals participated in this invitation-only workshop, including senior NASA and non-government managers, scientists, engineers, technologists, as well as international colleagues. Individuals were chosen to be representative of stakeholders in astronaut and robotic exploration of Mars. Sponsors of the workshop once again were Boeing, Lockheed Martin, Orbital ATK, Aerojet Rocketdyne, and MDA.

To make progress in a relatively short workshop, even with several preparatory and follow-on tasks, the organizers adopted a handful of guiding assumptions and ground rules, including:

- It is the stated goal of Congress and NASA leadership that the exploration of Mars with astronauts will take place before the mid-2030s.
- Early and focused technology investment, including robotic and human precursors and demonstration missions, is essential for the timescale for Mars exploration adopted here.
- Technical/engineering solutions exist for landing and long-duration operations on the martian surface; that is, no “miracles” are required for successful Mars exploration.
- Partnerships (international, industrial, commercial, academic, government and others) will be an essential component of human Mars exploration.
- Research and development will continue on the International Space Station (ISS) at least through the mid-2020s.
- The Space Launch System (SLS) and Orion will be available during the time period considered here, so will not be assessed in depth in this workshop.
- The budgets for space agencies will be approximately flat in real dollars at least for the next few years. Budget growth is possible in response to an international commitment to travel to Mars.
- Venues proposed for demonstration or precursor activities in advance of human missions to Mars in the 2030s must be assessed critically.

Preparation for the workshop included agreeing upon definitions that would be used throughout this activity, including

An **affordable program** is an activity that stakeholders are willing to support because it returns value commensurate with its cost. A Level 0 requirement for credible Mars human exploration architectures must be identification of the sustaining sources of funding and how the architecture will return value to stakeholders. An **achievable element** of an exploration scenario is one that, given sufficient funding, can be developed and deployed for operation sufficiently in advance of early human missions to Mars in the early- to mid-2030s. A **sustainable campaign** is one that is affordable with returned value sufficient to ensure stakeholder support over decades. Specifically, what will enable human Mars missions to endure after the first several missions, unlike the case with the Apollo Program? And what will overcome a “been there, done that” response to initial human missions? A sustainable program is by definition affordable, although an affordable program is not by definition sustainable.

Preparation for AM IV began about three months in advance of the workshop by identifying and defining various “long poles” that are major elements necessary for the early human exploration of Mars (see below). Each long pole was assessed by a team of workshop participants who were charged with producing a description of how, when, and why each pole will be achieved over the next decade or two. The assessment teams, which also contributed to the chapters in this report, are listed at the start of this report. At the workshop, each of the long pole justifications was critically reviewed in plenary and in more focused breakout sessions. The team responsible for each pole then revised their presentations in response to input from workshop participants. Revised assessments were presented in plenary to close the meeting. As part of the workshop, current scenarios or proposals about human exploration of Mars were briefly presented by representatives from NASA HQ, Orbital ATK, Boeing, JPL, Aerojet Rocketdyne, Lockheed Martin, SpaceX, and Blue Origin.

Major Capabilities Necessary to Human Exploration of Mars (“Long Poles”)

“Long Poles” Considered by AM IV

Ten major capabilities (i.e., “long poles”) were assessed in depth by their respective assessment team in advance of the workshop. They were then presented and critiqued in plenary during the workshop, with updates and revisions made during extensive breakout sessions. The following chapters, one for each of the long poles, were developed from the input from participants during, as well as after, the workshop. The specific capabilities initially chosen for consideration by our workshop satisfied three criteria: (1) each is a significant element within current human Mars exploration scenarios, (2) its development has proceeded far enough at this time that input from AM IV would be meaningful, and (3) significant contribution to its development could be achieved by a three-day workshop that included extensive pre- and post-workshop work.

The ten capabilities discussed in depth in the following chapters are listed in our table of contents.

“Long Poles” Not Considered by AM IV

A number of major human exploration capabilities were not considered at AM IV, primarily because these were deemed to be already in advanced development or were not found critical to enable early human missions to the Red Planet’s surface. These long poles were (1) Mars transfer propulsion (i.e., solar electric propulsion (SEP) and high-thrust), (2) heavy lift (i.e., Space Launch System), (3) Orion crew vehicle (i.e., an Earth launch and re-entry vehicle), (4) Mars human-class surface rover, and (5) space suits: surface and in-space.

Notional “Long Pole” Report Contents

Although the long poles considered by AM IV are a disparate group, as guidance to the ten assessment teams, the workshop organizing team requested each assessment team to incorporate, if applicable to the long pole, the following contents in their presentations.

¹All four workshops emphasize, unless otherwise stated, initial human missions to Mars with the goal of a landed mission by the mid-2030s.

1. Major elements and key characteristics of the “long pole” (assuming a long-stay surface mission):
 - Basic description: “sub-poles,” key technologies/capabilities
 - Why this is a “long pole” and why this needs to be developed
 - Why this is challenging and why this is achievable (with substantive reasons: e.g., high TRL/SOA, advanced SOA, few or no “miracles” required)
2. Development plan(s) or options, if any, to make this achievable:
 - Milestones, investment strategy and priorities
 - Precursor and demonstration site(s), where is this being developed (US aerospace, NASA, academia, internationals?)
 - Time to close “long pole”
 - Planned or expected time to close, including “sub-poles”
 - Required time to close, if different from above
 - Creative alternatives, if any, for accelerating closing
3. Gaps, shortcomings, or missing elements, so far as is known, in current “long poles” and their plans (e.g., lack of precursors/demos, disconnect among schedules, irrelevance to scenarios)
4. The role in enabling early human mission to the surface of Mars, if any, of human operations on the lunar surface.

Human Operations on the Lunar Surface to Enable Human Exploration of Mars

The scientific importance of lunar exploration is persuasive, has been identified as a high priority by multiple space agencies, and has been discussed extensively elsewhere. These scientific merits were not discussed at AM IV. A largely independent issue is whether, as asserted by some advocates, human operations on the lunar surface are either required or highly desirable in advance of initial human missions to the vicinity of or to the surface of Mars. This topic was discussed in advance of the AM IV workshop and in plenary at the workshop. In each of the following chapters, venues – including the vicinity and surface of the Moon – identified as necessary to retire risk for individual “long poles” are included as concluded by each of these expert groups.

These discussions did not assess the value of astronauts on the lunar surface for other purposes, such as scientific exploration, nor was the relative value of sustained human occupation of the Moon versus Mars discussed. Assessment at this AM IV workshop, and the three preceding AM workshops, was focused solely on the assertion that lunar surface operations with astronauts was necessary in advance of initial human missions to the Red Planet.

Arguments as to the value of lunar surface operations by humans in support of eventual human missions to Mars generally fall into three broad categories:

1. the lunar surface is claimed as a necessary demonstration site,
2. lunar surface resources, specifically water ice, could be extracted and turned into rocket fuel as a priority justification for eventual lunar industrialization, and/or
3. lunar surface missions could create international partner and in-space economic private sector stakeholders that would strengthen sustainability of the Mars exploration program.

The first justification is widely considered of minimal value, at best, by experts on Mars exploration, as the two worlds are so profoundly different. For example, the existence of an atmosphere has substantial implications on the entry phase of a Mars mission, as well as requiring different approaches for thermal control for habitable elements and long-term storage of cryogenic propellants. Although both planets have a dusty environment, the dust properties are significantly different, leading to different operations and mitigation approaches.

Complex systems, such as EVA equipment and surface rovers, designed for optimal use in a martian gravity environment, will be over-designed for a lunar environment. These examples, among others, indicate that, although certain subsystems could be designed and used at both locations, the system-level designs will have significant differences. This means separate design and development phases for lunar systems and martian systems. It also calls into question the degree to which design lessons learned on the Moon will be relevant on Mars.

The second justification is frequently criticized for its lack of sufficient detail for a credible cost and feasibility comparison with, for example, supplying resources from the Earth’s surface. This shortcoming includes a lack of verification that the ice resources are actually present and accessible in a usable form in sufficient quantities. In addition, many current scenarios for human missions to Mars do not make extensive use of the fuel that could be derived from hypothetically available lunar water ice. Furthermore, anyone familiar with the time and resources needed to develop a promising resource feedstock into a reliable source of propellant that will be in the critical path for any major endeavor, will realize that industrialization of lunar water ice will require a sustained investment of time, resources, and refinement of operations likely lasting for many decades before propellants in a usable amount might be available.

The third justification is not unique to the lunar surface, but rather is expected to be applicable to any destination for human space flight as demonstrated by the wide-ranging and long-term support for the ISS among international partners and more recently by commercial entities. Potential intermediate destinations need to be used as a mechanism to build an ever-increasing base of international partner and in-space economic private sector stakeholders for sustained Mars exploration founded on mutual value. It will be NASA leadership via a national policy of commitment to in-space economic development and international partnership(s) that will lead to a sustainable program of human exploration throughout the solar system, not the order in which future destinations for these human exploration missions are carried out.

To summarize, at AM IV, as was the case at AM I–III, there was little or no support among participants for either demonstration programs with humans on the lunar surface nor for the search for possible suitable water ice fuel stocks and subsequent industrialization to extract it to substantially reduce risk or reduce the overall time or resources needed. Both were judged unnecessary, costly, and – in the case of lunar industrialization – at present almost entirely devoid of sufficient engineering designs and milestones, trade studies (e.g., robots versus astronauts, source(s) of water ice), comparison with terrestrial supply, technology development plans including launch vehicles in the lunar environment, and a credible return on investment for governments and/or industry that indicate this approach would improve the prospects for initial human missions to Mars.

Planetary Protection and Mars Exploration

Given that achievability of Mars human exploration is the primary focus of the workshop, planetary protection is a critical element for consideration, to identify priority near-term actions and investments necessary to ensure effective integration into relevant future activities on the appropriate timescales. Overview information on planetary protection for human Mars missions is summarized below, with additional information provided in the Appendix.

Planetary protection supports multiple human exploration objectives at Mars, including assuring astronaut health and minimizing the potential for Earth invasive species to disrupt future exploration. The ten-identified future “long poles” focus largely on important science and technology needs for realizing achievable and sustainable human missions. In addition, the existing international and NASA policy and implementation requirements for planetary protection also need to be included, because they represent challenges to different phases of mission planning that cut across the long poles already identified. Consequently, a summary of the important planetary protection issues was presented at the workshop, to educate participants and sub-groups about current and potential future consequences of planetary protection policies for mission architecture and future implementation. Integrating such information in the early planning phases is important to encourage cross-cutting deliberations and planning that will help avoid costly re-designs in later mission phases.

For both NASA and international space missions beyond Earth orbit, integration of planetary protection considerations is considered mandatory under Article IX of the UN Outer Space Treaty², which stipulates that

“... Parties to the Treaty shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose . . .”

In addition, Article VI of the Treaty indicates that signatory States

“...bear international responsibility for national activities in outer space, whether such activities are carried on by governmental agencies or by non-governmental entities...” and must assure that ... “national activities are carried out in conformity with the provisions set forth in the ...Treaty.” In addition, “The activities of non-governmental entities in outer space, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.”

Since the earliest days of space missions, planetary protection policies have applied to both robotic and human missions beyond Earth orbit. During the Apollo Program, concerns relating to assuring Earth safety were addressed more effectively at a policy level than during actual implementation. Internationally, policies and frameworks for planetary protection are currently maintained by the Committee on Space Research (COSPAR)³. In the United States, NASA develops and oversees the implementation of planetary protection policies and controls on missions launched using NASA assets⁴.

Fortunately, planning efforts for Mars human missions can borrow and build upon decades of successful planetary protection implementation. NASA and other space agencies have extensive experience applying planetary protection measures to robotic exploration missions to the Moon, Mars and other celestial bodies. However, to date, the only times that planetary protection controls were applied to *human missions beyond low Earth orbit* occurred during the Apollo Program, when Apollo 11, 12, and 14-17 landed on the lunar surface.⁵ Significant improvements in understanding since that time are being incorporated into planetary protection for human missions to Mars, including advances in scientific inquiries into planetary environments and Earth biology (e.g., the human microbiome); major technological improvements in many systems; and revisions of environmental, health and safety laws/policies in the U.S. and internationally.

While an overview of current planetary protection information and research priorities was presented to AM IV workshop participants, there is undoubtedly a need for more detailed discussions at future workshops. At the very least, each subgroup needs to determine to what extent planetary protection policies and requirements may impact their long pole. It is also important to consider how integration of planetary protection controls and requirements might alter their assessments of challenges, data gaps, design options, mission alternatives, and timetables for achieving future human missions.

Based on current COSPAR Principles and Guidelines for Planetary Protection and Human Missions, there are many aspects of missions that likely will need special attention, including: habitation and laboratory elements –both in transit and on the Mars surface; assessment of possible ISRU areas, landing zones and Special Regions on Mars; a range of human health and biomedical systems applicable in transit and on the surface; back contamination controls, quarantine capabilities, and microbial monitoring; and development of national and international requirements associated with return of astronauts and sample materials to Earth. Accordingly, as the space community sets its sights on achievable, affordable, sustainable future human Mars missions, it should also be mindful of the need to integrate into all mission phases the broad range of new and changing information about planetary protection policies and implementation controls.

²UN Outer Space Treaty: <https://www.state.gov/t/isn/5181.htm>

³COSPAR Planetary Protection Policy: <https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf>

⁴NASA Planetary Protection Website: <https://planetaryprotection.nasa.gov/documents>

⁵While there is considerable useful information from ISS and other orbital platforms in Earth orbit, none of these earlier orbital human missions had to address planetary protection concerns, which specifically apply to harmful contamination delivered *to or from* extraterrestrial bodies beyond Earth orbit.



Exploration of the lunar surface enabled by a cis-lunar Gateway: telerobot descends from an expandable habitation and operations facility at an Earth-Moon libration point. [Source: Future In-Space Operations Working Group (2007)]

Long Pole 1: Mars System Reconnaissance

The Long Pole

Certain specific data sets are needed to guide architecture and engineering design of a long-stay mission to the martian surface that require reconnaissance activities *at Mars*, specifically ground truth for resources, surface mapping, and linkage to orbital data; knowledge of atmospheric dynamics; surface dust environment; health considerations (toxicity, extant biological potential); mapping of special regions for potential “forward” planetary protection/contamination concerns; and demonstration of proof-of-concept hardware systems, such as in-situ resource utilization (ISRU) production, in the relevant environment interacting with indigenous materials.

Major Elements of the Long Pole

- A. Biological, geochemical, and atmospheric reconnaissance to retire strategic knowledge gaps
- B. In-situ resource utilization
 - i. Reconnaissance to determine where minimally acceptable resources are located and their attributes
 - ii. Development of technology needed to use those resources
- C. Reconnaissance to establish/optimize astronaut-enabled science program (now largely complete)
- D. Landing site selection

Statement of Achievability

Full set of measurements can be collected via (1) a focused set of observations from future robotic orbiter(s) to identify most promising candidate resource deposits; (2) at least one robotic surface mission to the intended crew landing site to provide site-specific ground-truth measurements; (3) other opportunistic measurements to fill remaining priority strategic knowledge gaps, which could be combined with either #1 or #2 above and should not need a separate mission, if appropriately planned and funded; and (4) analysis of martian materials (from any site) already to be returned to Earth for other scientific purposes for exploration measurements such as toxicity, extant biological potential, dust particle size distribution of the general Mars environment (not site specific).

Primary challenge to closing long pole: Identify from orbit and characterize/demonstrate resource extraction feasibility from surface sites with adequate resource potential to support long-term sustained exploration operations.

Secondary challenges to closing long pole: (1) Demonstration of ISRU and off-Earth mining techniques and technologies and (2) filling of other strategic knowledge gaps required to enable design of the crew landing and surface systems.

Time to close long pole: 10-12 years: 6-8 years for orbital asset to identify sites and 4-6 years for surface ground truth from robotic precursor from landing site. This assumes missions that enable analysis of returned samples, if needed (e.g. dust characteristics, toxicity, particle size distribution, etc.), occur in parallel over similar time frame.

Closing long pole requires access to (at a minimum): Surface of Mars

Primary Challenge to Achievability: Identify from orbit and characterize/demonstrate resource extraction feasibility from surface sites with adequate resource potential to support long-term sustained exploration enterprise.

Current State of Knowledge and Practice for Primary Challenge: Potentially promising sites with ice deposits at TBD depth and hydrated minerals of uncertain water content and material properties have been detected using prior orbital missions and data sets.

Current Strategies to Close the Long Pole and Minimum Success Criteria

Minimum success criteria can be met with at least one new focused orbital mission and one new surface precursor ground-truth mission.

- Concept development work for orbital mission to collect data sets specific to identifying places with the most promising resource potential for human exploration.
- Concept development work for future surface precursor ground-truth mission.
- Ongoing plans for scientific sample return.

Innovative Strategies to Close the Long Pole Primary Challenge

- Combination of mission objectives to improve cost-effectiveness: e.g. combine resource prospecting measurements from either orbit or surface with other robotic missions such as Mars sample return orbiters or landers.

Secondary Challenge to Achievability (1): Demonstration of ISRU and off-Earth mining techniques and technologies.

Current Strategies and Priorities to Close the Long Pole Secondary Challenge: Investment in ISRU technology maturation in terrestrial laboratories and mission concept development work for future in-situ demonstration/ proof-of-concept robotic precursor mission.

Innovative Strategies to Close the Long Pole Secondary Challenge:

- Conduct as much ISRU proof-of-concept development and testing as possible in terrestrial environmental chambers using analog materials before deploying systems to Mars surface.

Secondary Challenge to Achievability (2): Filling of other strategic knowledge gaps required to enable design of the crew landing and surface systems.

Current Strategies and Priorities to Close the Long Pole Secondary Challenge:

- List of strategic knowledge gaps and measurements required to fill them being maintained and coordinated through the Mars Exploration Program Analysis Group (MEPAG).
- Instruments incorporated into ongoing robotic missions as technical and budget resources permit. However, planetary protection requirements need to be considered for contamination control/cleaning/ reuse of instruments for sampling in subsurface or special regions.

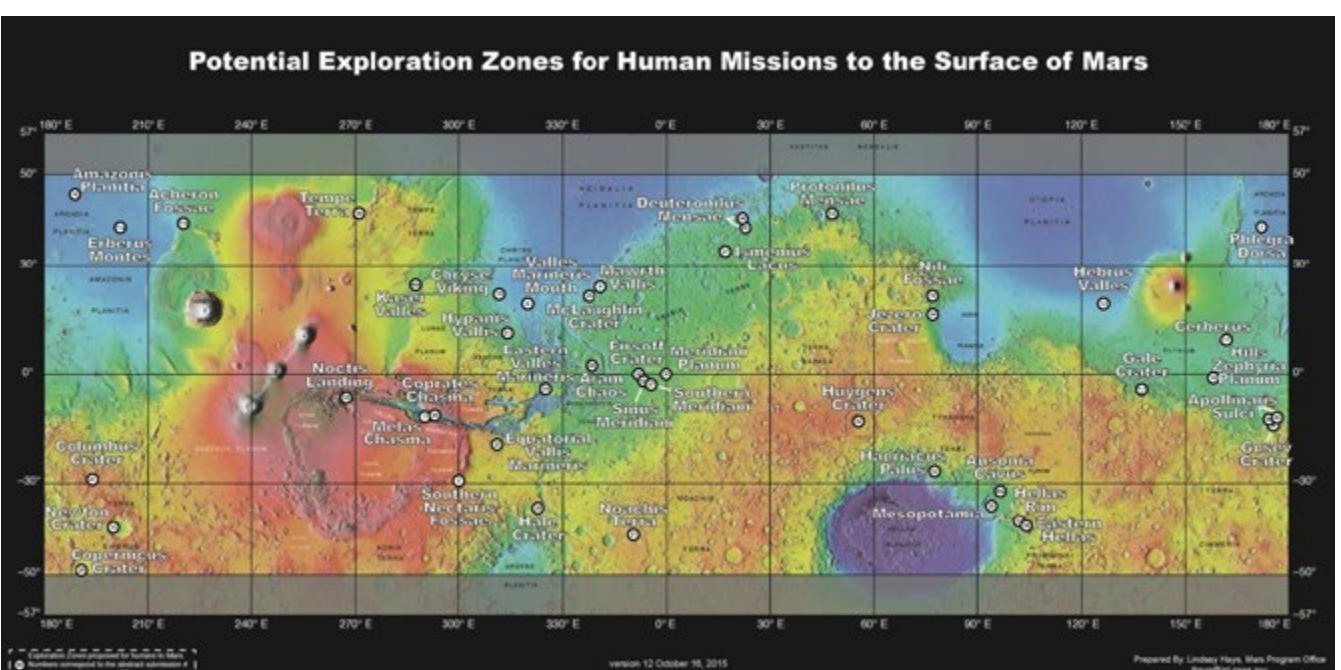


Figure 1. Potential exploration zones for human missions to the surface of Mars

Long Pole 2: Aggregation/Refueling/Resupply

The Long Pole

Limitation on overall launch performance and launch rate require aggregating of Mars stack elements. Refueling and resupply is an effective strategy to mitigate individual element mass growth. Furthermore, a logistics architecture needs to be defined, including locations, launch infrastructure, docking concept of operations and refueling. Operations in the martian system are part of the challenge.

Statement of Achievability

ARRCs are achievable in the near term with current technology already in development. The primary challenges are:

- Operations in deep space, including navigation and autonomous rendezvous
- Larger quantities of propellant, and different types such as xenon and cryogenic propellants

Given NASA's current plans for missions in the Proving Ground of cislunar space this long pole will be closed in about ten years, although given technology readiness levels at this time an acceleration could reduce this time to about 7-8 years. Figure 1 shows an example schedule for development of the ARRC concept.

Primary Challenge to Achievability

Long Pole 2: Aggregation and Refueling / Resupply Capability

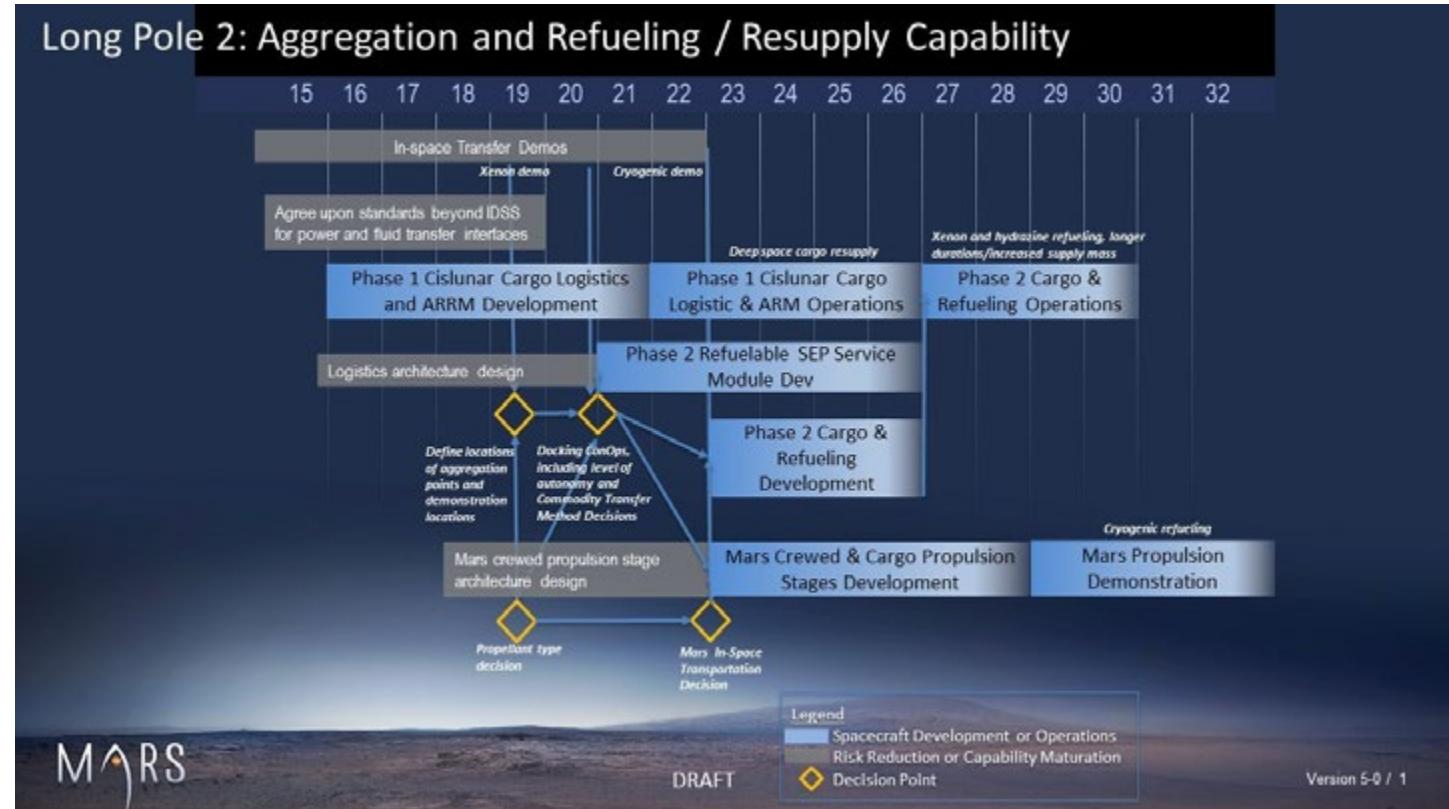


Figure 1. ARRC development schedule

A most pressing concern from our perspective is the development of an overall strategy for using ARRCs, most notably to ensure adequate and diverse supply chains to support our crews in the martian system. It is our assessment that a robust strategy will add to mission flexibility and crew safety and may be critical to reducing the overall costs of Mars missions.

In the following section, it is our goal to start that conversation and outline a number of key considerations.

A Preliminary Look at How Logistics Nodes Can Help Enable Successful and Sustainable Human Missions to Mars

Logistic supply chains are a critical component of any human operation occurring over large distances. The importance of these supply chains has routinely been seen in military campaigns as well as in all major exploration efforts ranging from the Lewis & Clark Expedition to Antarctic expeditions to the International Space Station. A robust logistics system is a key difference between initial exploration and later sustained operations and is vital to risk reduction.

A comprehensive plan for caching supplies, such as consumables and spare parts, can be critical for ensuring mission success and minimizing risk to human lives. Missions to Mars are no different.

For Mars missions, there are basically three general locations where supplies can be aggregated/cached besides the surface of the Earth. They are Earth orbit/cislunar space, Mars orbit, and the martian surface, which includes sub-surface, if applicable.

As was the case with Antarctic exploration, nodes allow stockpiling critical supplies and react to unexpected events such as mechanical failures or medical emergencies. Diversity of the supply chain is critical for ensuring a steady stream of supplies, and certain nodes should be multi-modal, supporting multiple types of transportation. In the case of Antarctic support, Christchurch, New Zealand is such a node where the efficiencies of aircraft, trucks, trains, and ships can all be exploited and merged for the final leg of re-supply to the Antarctic. Analogous lesson have been learned on the International Space Station (ISS).

In the following sections, these lessons learned are assessed as to their application to Mars mission designs.

For the potential orbital supply caching/re-supply nodes at Earth/cislunar space and at Mars, we refer to such a node as an Aggregation, Refueling, Resupply Capability (ARRC). For the node on the martian surface, it is assumed to be a semi-permanent base. This base is referred to as the Human Exploration Zone (EZ), as was defined in the recent Mars Human Landing Sites Study (HLS2) workshop.

The existence of a logistics node does not mean that all logistics go through that node; we would, in fact, expect several different paths for delivering logistics to the end goal, the martian base. However, we would expect a significant percentage of the logistics to pass through most if not all of the nodes. The total logistics system supports all vehicles, even if they bypass a node.

Characteristics of an ARRC

An ARRC is primarily a series of nodes with core capabilities such as attitude control and power generation. Figure 2 shows that logistics nodes are differentiated by both location and operational intent.

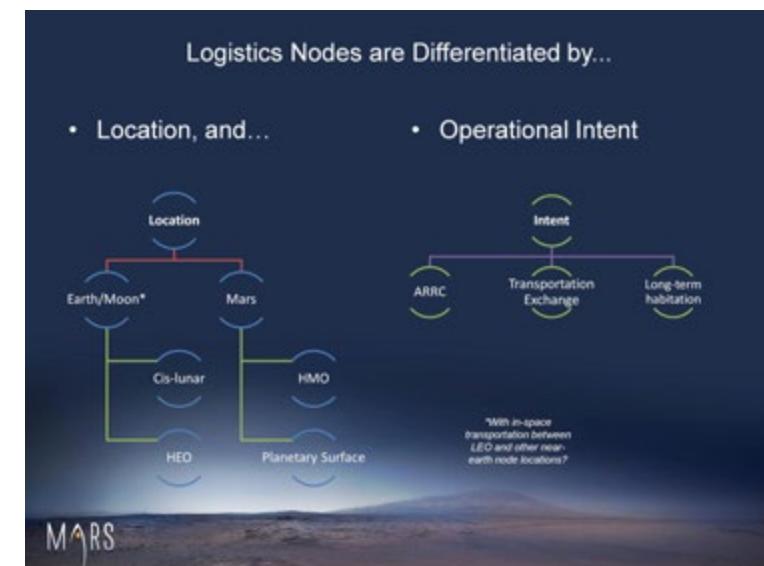


Figure 2. Logistic node differentiation

We envision there definitely being an ARRC in high Earth orbit (HEO) or cislunar space. The case for an ARRC in Mars orbit, probably high Mars Orbit (HMO), needs to be studied more extensively and may offer some very interesting options. An ARRC in HMO could conceivably be a sub-set or smaller version of the one in cislunar/HEO.

In HEO/cislunar space, the ARRC is where the Mars Transfer Vehicle (MTV) is initially aggregated. It is also where the MTV may dock upon returning from Mars and is refurbished and resupplied for the next mission to Mars.

In HMO, the ARRC would be where logistics modules with critical supplies, consumables and spare parts are docked awaiting the MTV. An appropriately designed ARRC could also serve as a safe haven for crews on their missions to Mars if repairs cannot be affected on the outbound leg or while in the martian system. This potentially increases overall system safety. The safe haven concept may obviate the need to develop certain technologies prior to embarking on the first human missions to Mars. A critical purpose of this section is to begin examination of this potential.

The ARRC in HEO/Cis-Lunar Space

The optimal location of an ARRC in the Earth-Moon system needs to be assessed. Current NASA Mars architectures assume that the aggregation would occur in a stable lunar orbit like a Distant Lunar Retrograde Orbit (DLRO). There were two principal drivers for this: the Space Launch System (SLS) will be able to place usable masses this far out, and the orbit that is stable for parking any parts of an asteroid retrieved from an Asteroid Redirect Mission (and thus keeping them from potentially impacting the Earth).

However, for a humans-to-Mars focused architecture it is not clear that this is the optimal orbit for aggregating. Increasingly it appears that robustness of supply chain may be more important and that having an ARRC that multiple launch providers, both commercial and international, can reach with usable payloads may be enabling. If one accepts this logic, then it would be critical to optimize on the orbits that can be reached by the different launch providers, while keeping the location as far out of Earth's gravity well as possible.

For cargo missions using solar electric propulsion (SEP) to get to Mars, the ARRC would also be a logical place to hand off to a re-usable SEP tug. Cargo can be aggregated at the ARRC (if needed) and then pushed out to the martian system using these efficient tugs. This is very analogous to using ships to efficiently deliver large amounts of cargo from Christchurch to McMurdo in Antarctica. These SEP tugs themselves can be re-fueled and serviced at the ARRC.

While perhaps not meeting the standard for a true ARRC node as defined here, we recognize that low Earth orbit (LEO) represents a special location in cislunar space as the "least common denominator" access point for space. Incorporating an in-space logistics transfer capability between LEO and the location of the ARRC in HEO/cislunar space could be an extremely valuable service, potentially commercial or international, that would open up participation in Mars exploration to any organization who has the ability to access LEO. Combined with the development of other standards such as docking/grappling approaches and standard volumes/dimensions, the use of LEO as a "bus stop" on the way to a larger "station" could greatly increase the number of pathways and providers available to get materiel into the overall logistics chain.

The ARRC in High Mars Orbit

The ability to efficiently pre-emplace cargo and propellant and to have diversity of supply chain is equally important, if not more so, in the martian system.

Because of the large amounts of cargo that have to be shipped out to the martian system to support human operations and the associated large quantities of propellant needed to do that, most Mars architectures try to send as much cargo as possible out via electric propulsion given its greater efficiency over high-thrust propulsion. Solar electric propulsion is significantly more efficient than high-thrust propulsion, but has much lower levels of thrust and therefore longer transit times. An Earth-based analogy would be sending cargo via ship and people via airplanes. Fundamentally, the goal is to keep the size of MTV as small as possible and use less efficient, but higher-thrust, propulsion to get the crew there as quickly as possible.

There is also a tradeoff between keeping the MTV as small as possible and its capability for keeping the crew safe. With an ARRC in high Mars orbit (HMO), the propellant mass problem may be a little easier to solve, allowing the MTV to be a little more robust.

Additionally, for delivering cargo, having multiple entities (commercial or international) delivering logistics modules to the ARRC may be enabling. The key point is that the docking adapters on the ARRC would support these different types of logistics modules arriving at different times and effectively being aggregated in one place awaiting a crew arriving on the faster, but less-efficient, MTV. We have begun to see this capability emerge with the International Space Station where several different types of spacecraft have docked with it.

An ARRC in HMO would also function as a safe haven. The key here, from a mission-planning standpoint, is that we stop thinking of the Earth as the only safe haven. We can over time build up safe havens at other nodes to allow us to better handle contingencies. On the outbound leg or while in orbit at Mars, the underlying assumption may be that if something goes wrong, we plan to handle it at the ARRC in HMO.

With such a safe haven concept, it is not necessary to have equipment and machinery that works flawlessly for a typical full Mars mission of 1000-1100 days. So, for life support, the equipment does not need to be fully closed-loop. If the crew experiences a failure and cannot repair it in transit to Mars, they can make use of spare parts at the ARRC to accomplish the repair. The utilization of standardized modules, for bulk cargo, life support, etc., can offset the need for major tech developments to occur prior to a human Mars mission. For example, the need to develop a life-support backbone that will survive an entire mission duration may be obviated if a "standardized" plug-and-play life support module can be substituted if there is a component fault. This concept can be extended for all of the major mission elements that would comprise an MTV: the module concept can be extended to either extreme, large or small, when trying to determine the standard module(s) configuration. This could range from entire redundant habitation modules, down to modular individual components.

This overall capability can also be augmented with 3D printing capabilities. While this technology is still developing, we need to realize that it has heavy commercial involvement already and that counting on significant gains in overall capability by the time we execute the first human Mars mission is reasonable.

In such an approach, we fundamentally are breaking up a Mars mission into segments where the management of the segments and the equipment designs begin to be more like ISS-duration missions. This, if done aggressively and creatively, but with adequate attention to risk, can substantially reduce the overall cost of Mars missions. In other words, we may not need significant advances in all systems needed for a MTV. We can start contemplating using systems not much improved over what we use already on ISS, with the attendant cost savings in immediate research and development.

Besides being an aggregation point for logistics and safety reasons, having a capability in Mars orbit provides other benefits. Crewed sortie missions to one or both of the martian moons from the aggregation point would be enabled depending on the orbit selected. Exploring the moons can achieve science and possibly in-situ resource utilization (ISRU) objectives. Tele-operation of rovers, and maybe aircraft, from orbit would accelerate the amount of science these assets could perform. The facility, during crewed and un-crewed portions, can be a platform for science instruments and experiments. Additionally, an ARRC in HMO could act as an integral component of the overall communications network, utilizing the power-rich infrastructure that is required to support a logistics node/safe haven. Orbital mechanics and mission coverage may influence the importance of an ARRC node in the overall communications network, but the inclusion of the capability should not be overlooked.

A high Mars orbit aggregation point may be not be necessary anymore, once the capabilities on the surface are completed. By the time a permanent exploration zone is established, the technology for landing large payloads directly on the surface of Mars will likely be proven and available for cargo resupply. At this point logistics could be delivered directly to the surface of Mars and the orbital aggregation point may be used solely for scientific and communication relay purposes.

Establishing a Logistics Node on the Surface of Mars

Ultimately, the goal is to establish a permanent base or Exploration Zone (EZ) on the surface of Mars. In many respects, a surface base is akin to the South Pole research station. It is at the end of a very long supply chain. It will take some time to build up sufficient infrastructure and logistics for it to become a true safe haven for crews.

Furthermore, we understand how to live in space. We do not know how to live on Mars. While Mars may look like Earth, there are significant hazards there (dust, toxicity of dust, lack of access to resources, ubiquity of oxychlorine compounds, potential biological hazards, temperature extremes, etc.) that will take time to be assessed. Just because Mars looks like Earth, does not mean it is as safe as Earth.

It may be that in off-nominal situations, the default down mode for some time may to return to the MTV docked to an adequately provisioned ARRC.

Having said that, we do envision EZ becoming a robust logistics node in time. We would also envision commercial entities and international partners delivering cargo and eventually crews to the base.

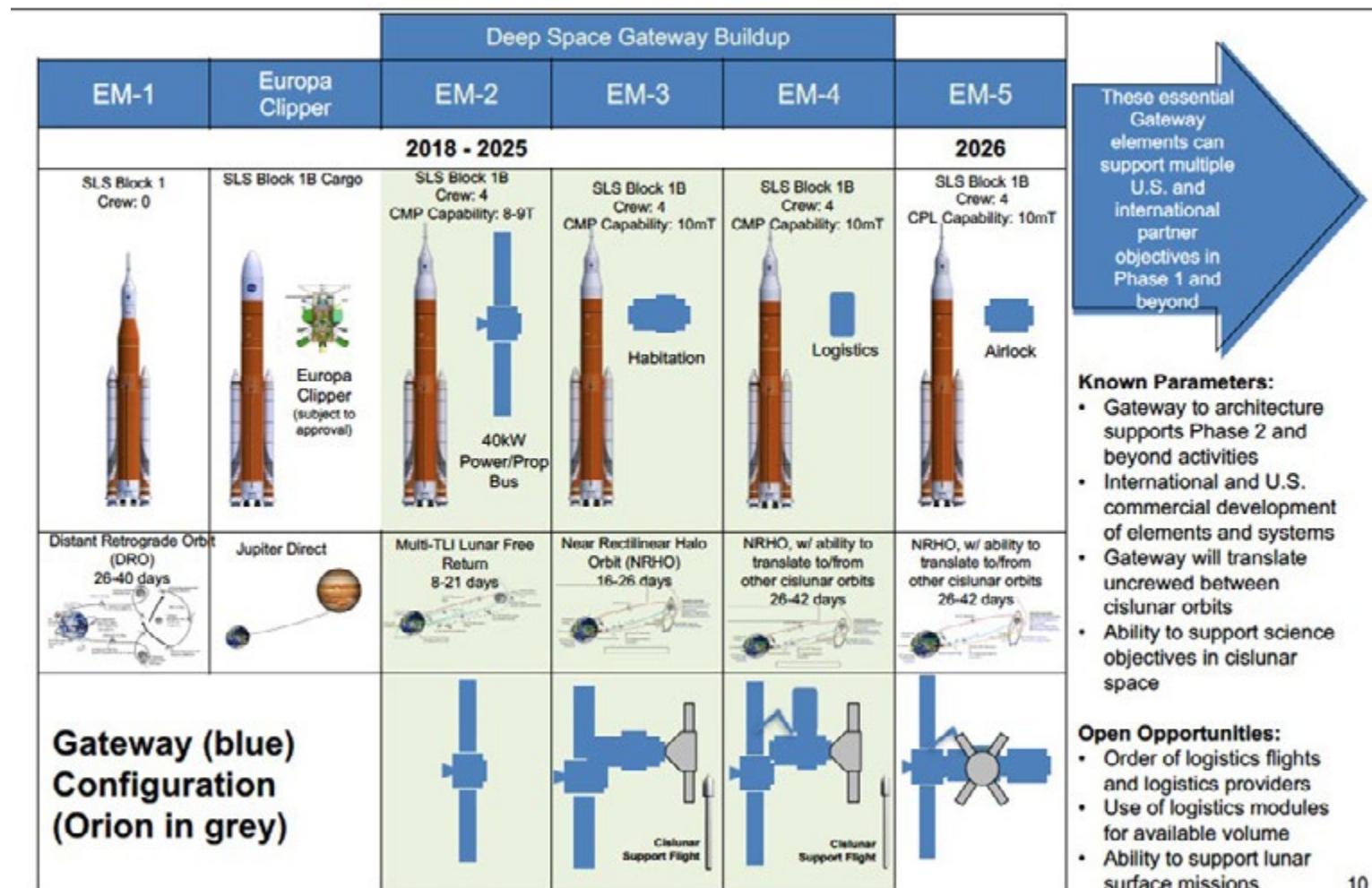
Costs Associated with an ARRC

While an ARRC may be mandatory in HEO/cislunar space, it is not proven yet that an ARRC is required in HMO. Any capability and associated equipment has to be maintained. Propellant may also be needed to maintain the orbits of these ARRCs. Rendezvous with a fixed asset will also entail orbital plane changes, particularly at Mars with the greater tilt of its polar axis relative to Earth's. While such plane changes can probably be managed, the actual costs in terms of propellant need to be fully understood.

With an ARRC architecture in place, it may enable individual in-space vehicles to be simpler and have fewer redundant systems, since the failure of one vehicle carrying supplies would more easily be mitigated by other supply vehicles.

Summary

A robust Mars Aggregation, Refueling, Resupply Capability is a key difference between exploration and sustained operations and is vital to risk reduction across the human Mars exploration architecture. There is immense value in having a robust logistics supply chain and safe havens for our crews in contingency scenarios, offsetting an increase in cost or complexity of the architecture, if there even is an increase.



Current NASA scenario for assembling a cis-lunar Gateway. [Source: "Progress In Defining the Deep Space Gateway and Transport Plan," NASA Human Exploration and Operations Update to the NASA Advisory Committee (March 2017).]

Primary challenges to closing long pole

Each of the challenges is listed in the following table, which includes why it is a challenge, what the current state of practice is, options for mitigation and recommendations.

Sub-pole	Why	Current State	Current Options	Recommend
Radiation Protection	Meet 5% increase in cancer risk requirement. Increased exposure to PSEs and GCRs has known effects on CNS, cardio vascular and other body systems. However, some animal research suggests there may be unknown effects such as nerve damage, cardiac issues, cognition and early onset dementia risks as well.	ISS missions in LEO are limited to six months which is inside the Earth's Magnetosphere so radiation levels are reduced	Water bags and other shielding solutions can be used to mitigate PSE effects. Some studies are being done on supplements and diets that can reduce susceptibility	Detailed study looking at radiation energy spectrum and corresponding medical risks and how to mitigate them. Most risk comes from SPEs but some risks remain from GCRs.
Reliable High-efficiency ECLSS	To significantly reduce the logistics mass to go to Mars, the biggest challenge for Mars class regen life support is closing the loop at high efficiencies and increasing the reliability and maintainability of hardware, reducing the mass and volume of the hardware, reducing the dependency on ground control to monitor and operate the hardware.	ISS systems require frequent maintenance and are too bulky for the limited volume available on a deep space hab. Current water recycling is up to 90%, with newly implemented pre-treatment, Air is ~40%.	Some research and ISS demonstrations are being funded by AES and ISS but additional funding is needed in FY18+ for Mars-class ECLSS systems to be sufficiently matured prior to use in Cis-Lunar and beyond	The NASA ECLSS System Maturation Team has a plan to design, build and test Mars-class ECLSS components on ISS before 2024 if resources are secured. Technologies that drastically reduce ECLSS MPV and/or drastically increase reliability are still sought.
Crew Health	To mitigate the debilitating effects of zero-g on the crew and to keep the crew healthy during the 30 month mission	ISS has done work and has demonstrated that through modified diet and exercise, the effects of zero-g can be mitigated but the exercise equipment is very heavy and large. Additionally, the medical equipment is also very bulky and needs miniaturization.	Some lite weight prototypes are being funded by HRP but there is insufficient funding to produce the flight equipment needed.	ISS should continue to be used for demonstrations of Exploration systems/equipment.
Crew Autonomy	Current ISS flights have a near continuous dialog between flight controllers and the crew and a constant telemetry stream that will be impossible for Mars missions. Those missions will require a degree of crew autonomy and operations for which there is no precedent and no appropriate Flight Rules. This represents a huge paradigm shift for the Agency.	The current paradigm where the crew continuously interacts with the ground and flight controllers monitor a continuous telemetry stream must change. This means not only different flight operations and Flight Rules, but different astronaut selection criteria with different astronaut skill sets, and different crew training. NASA has not always found change like this easy and it will take time.	Some research and studies have been done but there is insufficient funding to produce the required system	TBD
Crew Activity	There has been no attention given as to what the crew members will actually do during the long transits to and from Mars. Inactivity can have very serious effects in missions of these durations especially with limited hab volume. And creating a "make work" program, just to keep the crew busy, is very transparent to the crew and counterproductive.	The tools we use on ISS to maintain crew psychological health (constant/real-time comm, large bandwidth comm, IP phone, privacy, family conferences, the view out the window etc.) will not all be available on a Mars transit, and the mass penalty will prevent carrying a lot of supportive resources such as a suite of science experiments for the transit. This suggests alternate approaches to crew well being are needed.	There is not a comprehensive solution yet. Some studies suggest a 'texting' style of communication can be used but that is a limited answer to a complex problem.	Additional study is needed
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Long Pole 3: Transit Habitat and Research Laboratory

The Long Pole

As we expand our exploration of the solar system with humans, the extreme environment of deep space presents challenges to the designing and building a habitat that would take humans safely to and from Mars. The highly successful International Space Station (ISS) has provided a wealth of lessons learned from the past 20 years of development and operations experience that can be used to further our goals. The transit habitat specifically will be required to keep four astronauts healthy for up to 500 days, provide high-efficiency life support (air and water), have equipment that allows for a crew of four to exercise, be fairly autonomous, allow the crew to conduct research during their trip in a limited volume and protect them from the harsh radiation of deep space. The transit habitat should also allow for resupply and potentially for reuse and refurbishment as well. These challenges are solvable but require focused funding.

Statement of Achievability

While there are engineering challenges to designing a reliable deep space transit habitat, the work to date on the International Space Station and data from the robotic Mars Program have allowed scientists to conclude it is possible to live and work in space for an extended period of time. To further reduce the risks and cost, NASA is developing new technologies in the HEOMD Human Research Program (HRP; see long pole 8 in this report) and in the Advanced Exploration Systems (AES) Program in the areas of life support, crew health and habitation. Finally, NASA's NextSTEP-2 studies have shown that there are a range of solutions available to support crews in cislunar deep space, a proving ground for longer-term human exploration of Mars.

While the long-pole itself is transit habitation, there are a number of contributing characteristics that contribute to the challenge in the area. Those challenges are summarized in the list below.

Radiation protection: long term crew health and safety vs increased mass and volume

Crew autonomous operations due to communication delays

Crew health: compact and robust exercise and medical equipment

Crew activity: the crew needs sustained meaningful activities during the trip

Vehicle maintenance, including internal- and external-mounted equipment

Reliable Life Support: serviceable/maintainable with much lower power and volume compared to the ISS

Crew Privacy and Habitable Volume and other human factors (configuration and total volume)

Logistics and storage: storage of supplies and waste in a limited volume

Thermal in the range 1 AU-1.5 AU

Reduced power at 1.5 AU: only 43% of available solar power at Mars compared to Earth.

Navigation

Quarantine/Isolation/Privacy Capability

Time to close long pole: Each of these challenges will need to be addressed before sending humans to Mars in the 2030s and, as such, should be demonstrated effectively in cislunar space in the mid-2020s.

Closing long pole requires access to (at a minimum): Still several days away from Earth, cislunar space is the closest available similar environment that would allow for validation of each of the solutions to these challenges. Getting to cislunar space requires a heavy lift launch capability such as the Space Launch System (SLS) currently under development by NASA.

Primary Challenge to Achievability

The main issue with achievability is available budget and organizational structure. At present, the funding to address the long poles in habitation is limited. While there is work on some of them, the current funding level is insufficient to be ready for a mission to Mars in the 2030s. Additionally, habitation design work within NASA is limited to a small closed team. A private-public partnership arrangement with a more open acquisition process that would overlap the goals of government and private industry would be mutually beneficial allowing for more innovation to address the challenges and to lower development costs.

Current State of Knowledge and Practice

Some relevant examples of current long-duration habitat work includes the International Space Station (ISS) – prior to that, NASA spent time on the Russian Mir space station – NASA's Human Research Program (including its Human Exploration Research Analog (HERA) facility), the University of Hawai'i's Space Exploration Analog and Simulation (Hi-SEAS), the Japanese Controlled Ecological Experiment Facility (CEEF), as well as studies funded through NASA's Next Space Technologies for Exploration Partnerships (NextSTEP-2).

Trade studies by the NASA teams have identified two alternate habitat configurations, one derived from ISS and the alternate derived from SLS. Both are driven by available manufacturing tooling, which determines the outside diameter of the module. The ISS configuration (Figure 1), with its 4.2 m diameter, has the principal orientation horizontally for all the crew equipment. The SLS 8.2 m diameter module (Figure 2) is also horizontal, although multi-level. This in contrast with Skylab, which had all the crew decks oriented vertically within the habitat shell.



Figure 1. ISS module-derived deep-space habitat

The ISS has been a very valuable asset for dealing with long-term crew health in microgravity. However, the ISS is considerably larger, is regularly resupplied from the Earth and relies heavily on ground controllers to keep it running smoothly. A Mars habitation vehicle will have to operate in a much different radiation environment and will be much further from Earth.

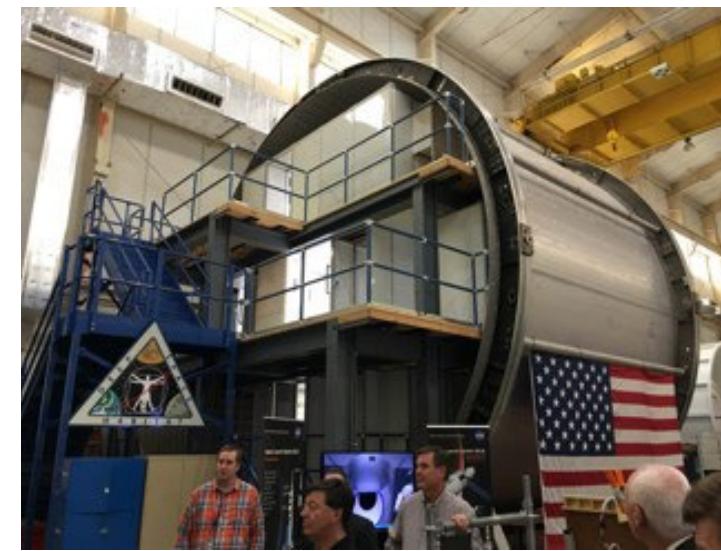


Figure 2. SLS-derived deep-space habitat

Current Strategies to Close the Long Pole and Minimum Success Criteria

The current strategy is for NASA to develop and fly a deep space habitat to cislunar space. The environment is similar enough to deep space that many of the proposed solutions can be tested in cislunar space before sending astronauts on a 30-month journey to Mars. The minimum success criteria should be that 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. This is very similar to how they would be operated for an actual Mars mission.

Innovative Strategies to Close the Long Pole

Public-private partnerships should be exploited to the maximum extent possible. Open architecture developments have repeatedly demonstrated enormous innovation and cost savings over time. NASA could share lessons learned from ISS development and operation while private companies could bring clever and less expensive ways of accomplishing the objectives. In short, a public-private partnership for the design and eventual build of deep space habitation modules would accomplish this approach.

Long Pole 4: Crew/Cargo Lander: Entry, Descent, and Landing

The Long Pole

The entry, descent, and landing (EDL) long pole for a crewed Mars mission is the selection, development, and qualification of an EDL architecture capable of precisely landing payloads over an order of magnitude heavier than present capability allows that also fit within possible launch vehicle fairings. The first long-duration (~300 days) Mars human surface missions will require delivery of nearly all supplies necessary for survival. Total payload estimates are on the order of 80 t, which is not feasible to deliver in a single lander. Therefore, current concepts divide the total payload into four separate 20-ton units that must be delivered in close proximity (~1 km) of one another with high precision (<50 m) at a single location over several launch opportunities to minimize the distance humans must travel to access surface assets. Current technology can only land payloads of approximately one ton within a landing radius of approximately 20 km. We require an order-of-magnitude increase in payload capability and a nearly three order-of-magnitude reduction in landing radius, thus necessitating new vehicle systems with significantly improved deceleration, payload volume, guidance, navigation, control and landing capabilities.

Simply scaling current designs to the larger masses required by human missions requires capsule diameters larger than those that can be accommodated by current or planned launch vehicle fairing dimensions. Thus, capable atmospheric entry technologies that can be packaged into a more compact and efficient form at launch are being explored. Similarly, present supersonic parachute technology is near its scale limit and cannot be extended to the deceleration of payloads in the mass range required for a human mission. Supersonic retropropulsion is the present descent mode of choice, although very limited Mars descent developmental analysis and testing has been performed for this technology. The development and qualification of the EDL systems required for human Mars missions will take significant time to complete. Figure 1 shows at a top level what it will take to get a human mission to Mars using conservative assumptions about both funding levels, as well as the pace of future technology development.

Statement of Achievability

Although EDL of human-class missions for crew and cargo to the surface of Mars represents a significant long pole to future Mars missions, the challenges can be mitigated with proper and timely decision making, planning, and funding. As can be seen in Figure 1, we estimate that, with development at current funding levels, approximately 17 years is required to prepare a landed human-class cargo mission on Mars. The challenge of landing human-scale payload masses on the Martian surface is daunting. Many of the configurations being considered offer key trade-offs in terms of reducing risk, mass, cost and schedule. The key to achieving human scale EDL is making early architecture decisions to narrow the trade space and proceeding down the path of design solutions and testing to verify these solutions.

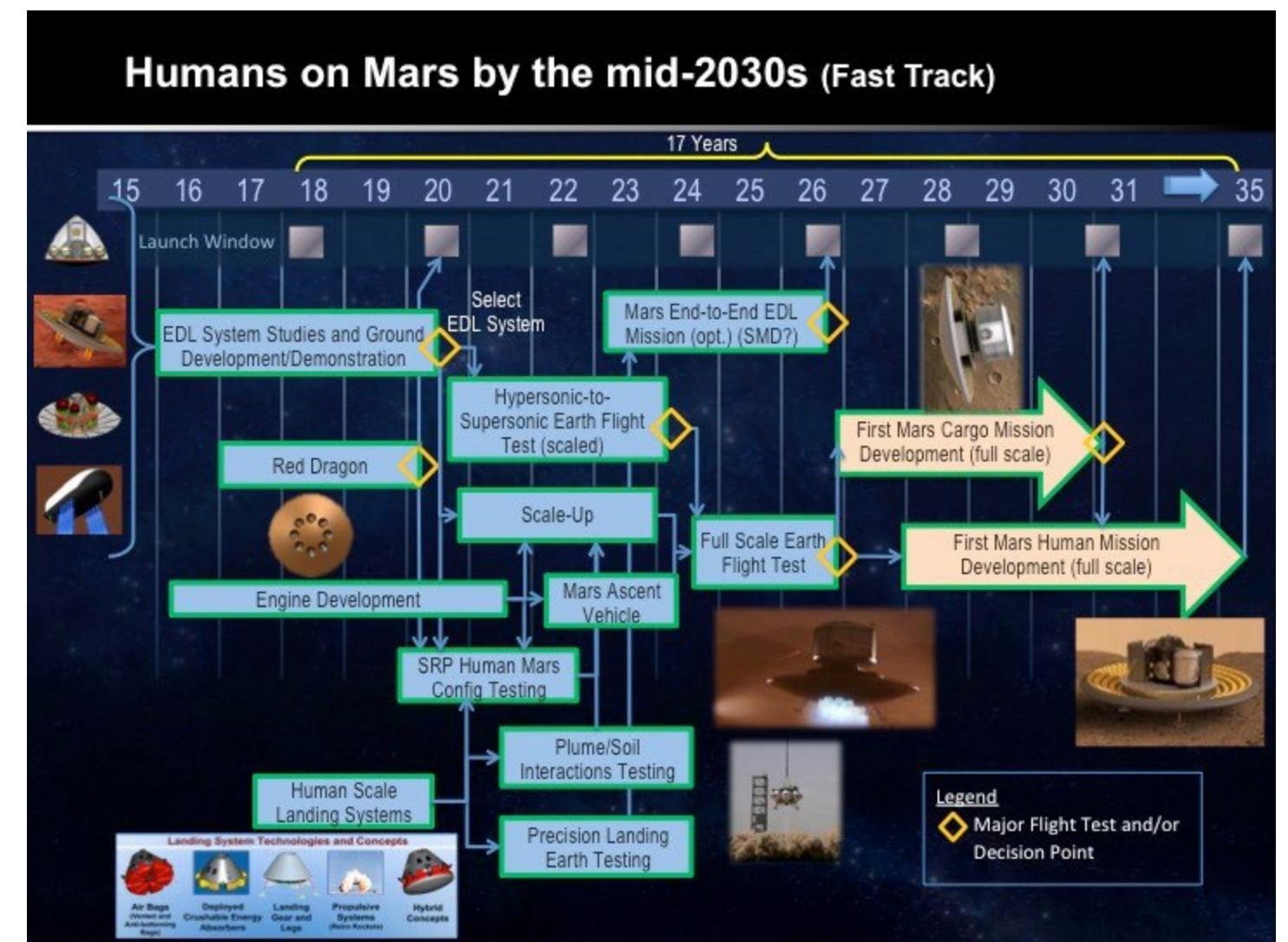


Figure 1. Fast track to Mars by mid-2030s

Key characteristics of long pole and its challenges

- **Primary challenge to closing long pole:** Early selection of lander design and EDL architecture in the context of the entire mission – Earth launch to Earth return – to allow sufficient testing and data for each flight regime.
- **Secondary challenges to closing long pole:** Techniques to allow pinpoint landing
- **Time to close long pole:** 13 years with early architecture decisions and enhanced funding and up to 17 years with more conservative assumptions.
- **Closing long pole requires access to (at a minimum):** High-Earth atmospheric regions simulating Mars atmospheric density; precursor mission to Mars surface demonstrating full scale, full system EDL prior to human crew flight.

Primary Challenge to Achievability: Scale of EDL Human-Class Missions (volume and mass)

The Apollo missions used retropropulsion alone to land on the moon, although when they returned to Earth, they used the atmosphere to decelerate. Use of atmosphere for deceleration is much more practical than retropropulsion alone mainly due to the huge mass savings realized by not carrying the additional propellant. Mars is a particularly difficult destination for achieving a soft landing. Its atmosphere is too significant to ignore, but too thin to use the same systems that work at Earth. Furthermore, Mars is a much larger gravity well than the Moon. Carrying enough propellant to Mars to allow a retropropulsion-only approach for even the smallest usable payloads becomes prohibitive. The challenges are greater as payload masses increase toward human-class missions.

An atmospheric EDL system is comprised of several distinct technologies employed in sequence: (1) An entry vehicle whose drag removes more than 99 % of the vehicle's kinetic energy, (2) supersonic decelerators to reduce the vehicle's velocity further in preparation for terminal descent, and (3) a landing system to provide a soft touchdown. Current state-of-the-art for EDL at Mars is a rigid blunt aeroshell, followed by a supersonically deployed parachute, and then a propulsive system to remove the remaining kinetic energy achieving a soft touch down. At Mars, such a system can land 1-1.5 t vehicles with an accuracy on the order of a 20 km \times 6.5 km ellipse.

Recent NASA studies indicate human-scale missions may require payloads between 15 t and 40 t, depending on the architecture selected. Landing precision needs to improve to be able to safely deliver multiple payloads within 50 m of their target. And the system must be "human-rated." NASA's current Mars EDL capability will not meet these requirements. If a common EDL architecture is assumed for cargo and crewed entries, early cargo missions could be used to "human-rate" the system at Mars.

For the hypersonic phase, rigid blunt bodies have been used for every successful landing on Mars. Such entry vehicles must tolerate the high temperatures of hypersonic flight. Increasing the size of the heatshield allows for targeting higher altitudes, or delivery of heavier payloads, or both. Unfortunately, the diameter of rigid blunt body heatshields is limited to the diameter of the launch vehicle. This will not be sufficient to decelerate these larger masses nor will the capsule accommodate the required payload volume. Other entry technologies, such as rigid slender aeroshells or deployable/inflatable heatshields to allow blunt body diameters beyond the limitations of the launch vehicle shroud, will be required. Launching a rigid blunt body aeroshell in a "hammerhead" configuration, making it the launch shroud, is possible but poses many aerodynamic, structural and verification difficulties.

Supersonically deployed parachutes are not feasible for human-class entry masses. However, supersonic decelerators other than parachutes have been investigated. One of those, supersonic retropropulsion, can be employed with any of the hypersonic technologies currently being considered. Data is needed in the flight regimes and pertinent environments to verify its performance. A current activity that is gathering this type of data is the flyback of Falcon 9 boosters by SpaceX. Data from these flights will inform the design of future Mars EDL systems.

Our state-of-the-art landing system for Mars to date, the Sky Crane system used for Curiosity in 2012, and baselined for the Mars 2020 mission, does not scale efficiently to human-class missions. Completely new systems, utilizing lander legs, single-stroke airbags, or crushable materials (or some combination of these) will be required. The terminal decent through landing will likely require hazard avoidance and hazard tolerance. Thruster-terrain interactions will also require study, as significant material will likely be excavated during high-mass mission propulsive landings.

EDL technologies can be developed to some degree with ground-based efforts. Although flight testing at Earth is required in order to match all design conditions concurrently for a given EDL phase, they cannot be matched at Earth for the entire EDL sequence. Thus, end-to-end testing of an entire Mars EDL system at Earth is not currently possible. So, we build complex simulations of the vehicle systems to do the end-to-end testing (see Figure 2). Retiring as much risk at Earth as possible, then human-rating the vehicle system at Mars via the cargo delivery missions required prior to human arrival, is one approach. It does put valuable cargo at risk for the first high-mass landing attempt at Mars, but that is the trade for getting humans to Mars sooner for less funding.

However, an optimal EDL system may not result in an optimal overall Earth-to-Mars human mission architecture. Therefore, efforts to understand whole mission architecture and early decisions regarding engine selection, propellant type, launch vehicle fairing diameter and even in-space transportation options will have a significant impact and guide EDL architecture decisions.

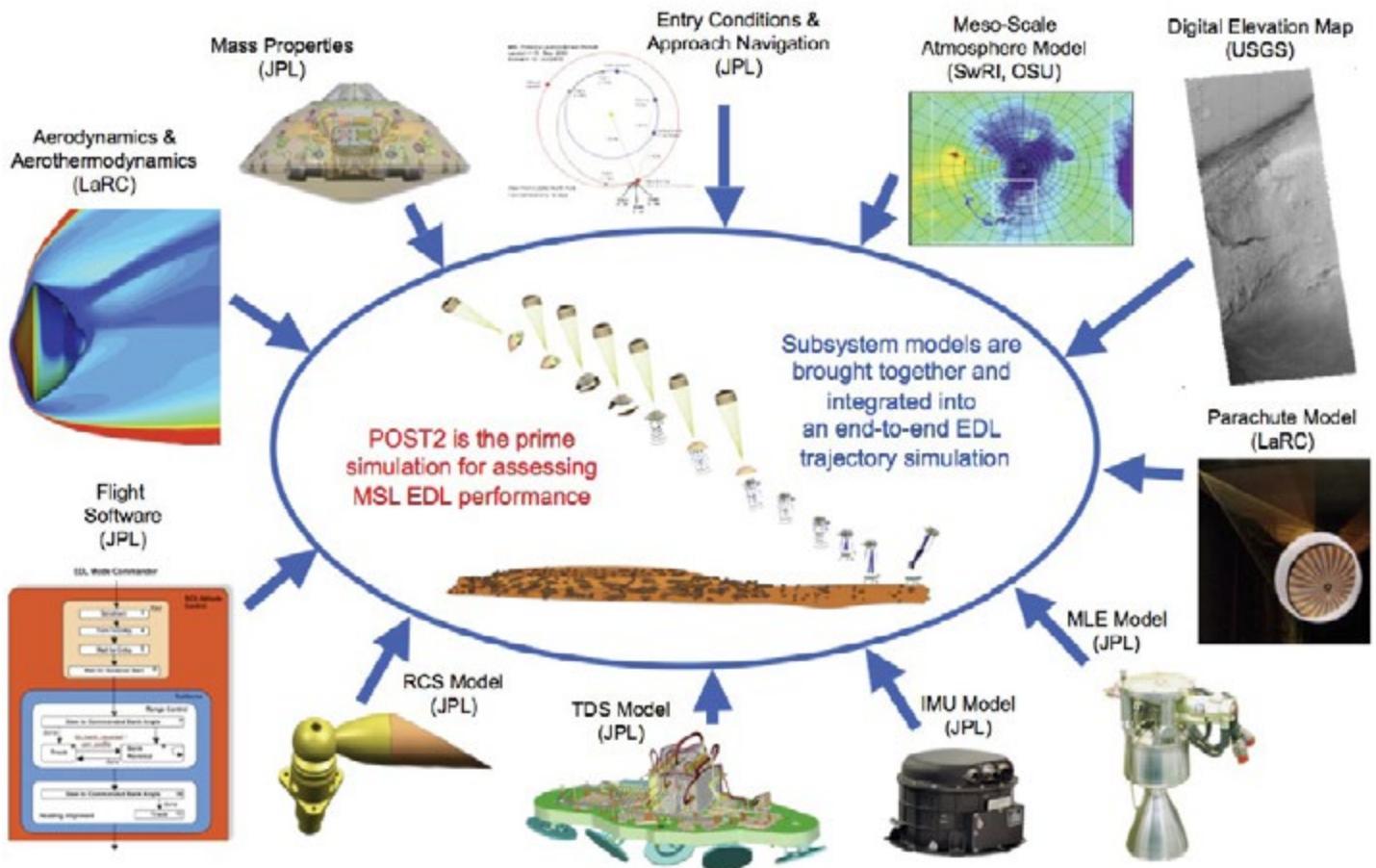


Figure 2. End-to-end simulation of human-scale EDL

Secondary Challenge to Achievability: Pinpoint Landing

The Mars Science Laboratory (MSL) mission used a combined aeroshell/supersonic parachute/powered descent (subsonic) with a hovering Sky Crane to lower the approximately one ton Curiosity rover onto the surface. The landing ellipse achieved through bank angle guidance was 20 km \times 6.5 km. This system will also be used for the upcoming Mars 2020 mission, and is likely capable of landing a 1.5 t payload.

To minimize the distance humans must travel to access the surface assets, current requirements are to land the vehicles within 50 m of a designated target. Due to the unknown interaction between the engines and the surface at landing, and based on lunar experience where surface assets were "sandblasted" by debris lifted by engines, there is also a requirement for the individual landers to maintain a 1 km separation zone from any other landed asset. Surface plume interaction studies are being conducted to see if that separation zone can be reduced. Approaches to evaluate more favorable engine orientations at landing and the use of surface preparation approaches (i.e., landing pads) are also being considered to reduce or eliminate the need for a separation zone.

To achieve the secondary challenge of pinpoint landing several advancements are needed. The first is in the entry guidance and control approach. Bank angle control used on MSL has an open loop phase during reversals that increases landing dispersions. Other control approaches should be considered. Additionally, innovative guidance/vehicle integration and mechanisms need to be traded against propellant-based options that minimize targeting errors (e.g., invest in deep-throttling engines vs. developing a movable flap system for control). Also, the geometry and flight profile of supersonic retropropulsion trajectories is very different from heritage parachute trajectories necessitating the investigation of new landing sensors suites.

Current State of Knowledge and Practice

- No launch vehicle exists to launch the payloads needed to support humans on the surface: EDL design and capability is strongly coupled to the diameter of the launch vehicle.
- Viking-heritage EDL technology (parachutes) does not extend to payload masses beyond two tons: human-scale payloads will be much greater than two tons.
- Requirements for landing sensors that can enable landing precision within 50 m have not been identified: no lander mission to date has flown with the geometry that a SRP mission will require or had such stringent requirements for landing (<50 m).
- An architecture strategy has not been selected. That affects in-space transportation, parking orbit, duration on the surface, and delivered payload requirements: no clear picture of what payloads are, how they integrate with the entry system, or how much propellant and control authority will be needed to meet landing requirements.

Current Strategies to Close the Long Pole and Minimum Success Criteria

Several private industry, academia, and government studies are underway to assess various hypersonic entry technologies, GN&C strategies, supersonic retropropulsion performance, engine options and landing sensors. All make assumptions regarding the launch-vehicle diameter and in-space transportation options. These are two key factors that can impact the selection of the entry system. Therefore, until a decision is made, continued evaluation of the strengths and limitations of various entry configurations (e.g., capsule, deployable, and mid-L/D) is encouraged.

The sooner an EDL system downselect can be made and testing of elements at flight regimes of interest commences, the sooner the technologies will be available. Efforts to perform a precursor mission to demonstrate EDL, long-term cryogenic storage, in-situ resource utilization (oxygen), fission power or other subsystems required for human-scale missions are also encouraged to enable a full-scale cargo lander in the early 2030s.

Innovative Strategies to Close the Long Pole

- Deployable and Mid-L/D entry technologies
- Use of ISRU to produce LOx for MAV (limits upper bound of landed mass)
- Guidance algorithms for Direct Force Control
- ALHAT-like landing sensors
- Aerocapture
- Landing pad preparation

Long Pole 5: Surface Habitat and Research Laboratory

The Long Pole

The surface habitat and research laboratory facilities will build upon lessons learned from the International Space Station (ISS), a series of field and laboratory tests at NASA Centers, as well as lessons learned and design of the in-space transit habitat that should be, at a minimum, designed and likely already flown, if only in a test flight. The surface habitat discussed here should be designed to eventually support a crew of six astronauts for a long-duration mission at the start as opposed to a short stay, with possible allowance for gradually building up to longer durations. The habitat should support multiple visits as an outpost, as opposed to Apollo-style landings at multiple sites. We are also assuming that the primary power source and the primary communication infrastructure for communication with Earth are both external to or separate from the habitat and its design.

This is a long pole partly for the same reason that the in-space habitat is a long pole: while there are many components of this complex project that are being assessed independently, there is at present no centralized budget and organizational structure to develop it. In addition, there is a tightly coupled relationship between the capabilities of the surface habitat and research laboratory and the capabilities of other systems (e.g., the lander). For example, total surface mission duration, the degree of in-situ resource utilization (ISRU) dependence, and desired science investigation capabilities will drive total habitat mass that could, in turn, become a driving requirement for the lander. But factors unrelated to the habitat (or other payloads), such as entry, descent, and landing (EDL), could lead to constraints on the lander's mass delivery capability or payload volume capability, which could then become a driving requirement on the surface habitat and laboratory. Because of this dilemma, specific choices were made in this assessment. The reader should keep in mind that alternative adopted implementations or architectures would lead to different long poles.

Statement of Achievability

The surface habitat and laboratory will build on experience gained from the development, and possible operation, of the transit habitat. Both the transit and surface habitats will build on the 15+ years of experience with ISS habitats and laboratory experience, likely 20+ years of experience by the time either of these systems are developed, as well as ongoing insight gained from technology developments, such as NASA's NextSTEP-2 and other international and commercial efforts. The experienced design/development workforce, established manufacturing base, and cumulative operational experience will provide the best possible foundation to extend this capability to the surface of Mars. But the specific design and development of the surface habitat and laboratory will still face challenges unique to this portion of a human Mars mission, influenced predominantly by landing constraints, interactions with other surface assets, and Mars environmental effects.

Challenges to closing long pole:

- Surface habitability: defined as a system designed such that the small crew complement can live comfortably and accomplish all of the research and exploration tasks assigned to the mission, as well as recover from unexpected occurrences.
- Systems availability: defined as the fraction of time that a system is operational as compared to the total time that it is deployed
- Mitigating detrimental martian natural surface environmental effects, while leveraging beneficial effects, and predicting potential environmental changes due to human presence
- Definition of the fundamental and applied research objectives to be carried out on the martian surface, along with the systems and operations needed to achieve them
- Extended periods of dormancy followed by successful startup
- Surface operations
- Close coordination with lander and entry/descent/landing (EDL) design
- Food: providing food that remains nutritional after a very long shelf life

When discussing the challenges faced by the surface habitat and laboratory, this group considered the relative magnitude of the challenge presented by the environmental control and life support system (ECLSS) compared with the items listed above. The consensus was that, although a critical component of the surface habitat and laboratory system, several factors were identified indicating that ECLSS would not be as daunting as other challenges identified in this section. These other factors include: (1) the International Space Station (ISS) ECLSS is already at roughly 50% recovery of O₂ from CO₂ and roughly 75% recovery of H₂O⁶, recognizing that this performance is likely to improve even more before the ISS is decommissioned; (2) ISS ECLSS reliability numbers are also relatively high and will continue to improve through end-of-life, although we recognize that these numbers are probably not yet good enough for a Mars mission; (3) ECLSS technology development work is going on now in NASA's NextSTEP activity, both for the habitat modules and separately for ECLSS itself; and (4) by the time the surface module is in development, the transit habitat should have been built and may have been operating, experience from which will feed directly into the surface habitat development. Given these factors, our group decided that a usable form of ECLSS would be a low-risk development item for early Mars surface missions. This does not mean that more advanced forms of ECLSS, such as bioregenerative types (e.g., incorporating crop growth), would not be mature enough for early Mars surface missions. However, these advanced forms of ECLSS were not absolutely required for initial Mars surface missions, although potential Mars surface environmental impacts are uncertain at this time and are still being assessed.

Time to close long pole: There are several areas of research currently under study by NASA's Human Research Program (HRP; long pole 8 in this report) that will affect the detailed design of the surface habitat and research laboratory. Once these HRP issues are resolved or understood to an acceptable level of risk, it is our assessment that surface habitation will require a minimum of five years for design/development/test (an aggressive timeline that accepts high levels of risk for cost, schedule and achieving mission objectives) to as much as 16 years (a more traditional timeline that allows for resolution of issues described below).

Closing long pole requires access to (at a minimum) the following venues for development and test: Earth surface

Primary Challenge to Achievability: Surface habitability (architecture for livability and usability)

The concept of surface habitability incorporates multiple architectural aspects within the habitat that are specifically designed for its livability and usability. This includes (a) adequate volume for the size of the crew and their supplies (e.g. crew consumables, supplies, commodities buffer (e.g., water, gases, etc.), spares), (b) the interior layouts of the space within the habitat, (c) design of the individual workstations throughout (including those research disciplines that are included within the habitat, and their level of functionality), (d) design of lighting architecture to augment the natural environment, and (e) the hatch size and docking system to other modules or transport vehicles. Additionally, this includes important practical techniques such as repair techniques and tools.

Why this Long Pole is Challenging

Gap: We have no validation that results of studies of short duration (several weeks to several months) habitation tests extrapolate to a 1000-day test or mission

- There is limited human expertise in long-duration habitation in remote locations: there is no practical study to predict the volumes, layouts, tools, etc. needed for this type of excursion
- Some close-analogs exist (e.g., Arctic and Antarctic stations, submarines, small surface vessels, aircraft), although there are many differences between those environments and Mars surface habitats
- Example: Submarines have small crew quarters, but large crew size and numerous/diverse facilities, plus periodic surfacing and ocean access
- Example: Arctic and Antarctic stations had deep isolation, although evacuation possible and access to large surface areas outside habitat
- Example: ISS had similar mission durations, although greater breadth of science functionality and <1 day evacuation to Earth, plus resupply during crew expedition
- Human behavior is non-deterministic and difficult to predict: different crew makeups can experience the same environments differently
- Historically, each space flight mission has been a custom solution for the vehicles used.
- Largely unexplored challenge will be months-long voyages that will require significant activities, attractive challenges, substantial accommodation for privacy, isolation, and/or quarantine.

Current State of Knowledge and Practice

Some examples of current long-duration habitat studies include the International Space Station, NASA's Human Research Program (including its Human Exploration Research Analog (HERA) facility), the University of Hawai'i's Hawai'i Space Exploration Analog and Simulation (Hi-SEAS), the Japanese Controlled Ecological Experiment Facility (CEEF), as well as studies funded through NASA's Next Space Technologies for Exploration Partnerships (NextSTEP-2).

The challenge with these current studies is that there is no agreed-upon relationship that can be used to scale them up to a size relevant for a martian surface habitat design for either different crew sizes or longer mission durations. In order to properly close this challenge, a representative analog of the mission would need to be performed that would address issues such as maintenance, medical, egress, and food/consumption, which could be somewhat independent of research science goals and operations. Although a "good-enough" surface habitat and laboratory design may be possible based on our understanding today, or it may be possible to build a "modular" habitat system that incorporates aspects of testing, at this stage more work needs to be done in order to fully assess the challenge of surface habitability.

Current Strategies to Close the Long Pole and Minimum Success Criteria

- Perform psychological studies with focus on limited volume and long duration
- Study modular habitat design and standard interfaces
- Test intermediate-length duration isolation
- Evaluate options to address environmental impacts

The primary strategy for closing the long pole would be to conduct mission simulations with relevant Mars mission durations in multiple existing and future analog facilities to identify trends or relationships impacting Mars surface habitat design with respect to volume, layout, workstation design, crew size, hatch size and docking system, mission objective (science, ISRU, technology testing, robotics, etc.) disciplines included, and repair techniques and tools.

Key Test Elements

- Supportability (combining maintenance, repair, and fabrication)
 - Planned and unplanned activity (habitat, spacesuits, other surface elements)
 - Time-critical subsystem repairs
 - Component versus replacement-unit sparing; material recycling/recovery versus raw material for on-site manufacturing
- Preventative and Emergency Medical Care
 - Consumables mass/volume/access implications
 - Long term recovery, including possible isolation and quarantine
- Long-Term Habitation
 - Habitat quality
 - Crew psychology/teaming
 - Logistics translations, including across hatches
 - Transitions across habitable elements: lander, habitat, rover
- Meaningful Crew Work
 - Degree of crew scheduling authority/mission design
 - Manpower assessment
 - Work disciplines: science, ISRU, technology testing, robotics, etc.)
 - Quality and quantity of work achieved in each domain

Innovative Strategies to Close the Long Pole

- Allowing for higher risk
- Design/build/test methodology (field tests/analogs)
- Repurposing items: dual-use items and logistics-to-living concepts, including trash
- Continuing mission simulations in even-more realistic simulated environments
- Leveraging commercial capabilities

Secondary Challenge to Achievability: Systems Availability

The concept of availability as used here is intimately tied to the system reliability concept of operation (CONOPS), and maintainability (preventative and corrective). This means that a system, in this case the surface habitat and research laboratory, is functioning properly when needed and that availability is achieved through a combination of highly reliable subsystems/components and a reasonable level of planned maintenance. System availability is formally defined⁷ as the fraction of time that a system is operational as compared to the total time that it is deployed. That is, 100% system availability means that a system is operational for the entirety of a mission. Conversely, 50% system availability means that it is only operational half the time. Note that operational does not necessarily mean “running”: a system can be operational but not “ON”. The Mars surface habitat and research laboratory is currently envisioned to be a facility used by multiple crews over the course of a Mars surface exploration campaign. This implies a useful lifetime for this facility that is comparable to that of the ISS. But logistical support, in this case in the form of spare parts, will be much more expensive to provide and there will be very few opportunities to deliver these spare parts. Planned (or unanticipated) maintenance is facilitated by the presence of a crew, although only to the degree that they have the spare/replacement components needed.

Current Strategies and Priorities to Close the Long Pole

Improvements in the current level of availability for key habitat systems as exemplified by the ISS are readily apparent. Continued operation of the ISS, as well as technology development efforts such as NASA’s NextSTEP, will lead to improvements that will be incorporated into both the transit habitat and the surface habitat and laboratory. Extended duration simulations identified above for the habitability challenge will incorporate availability testing and validation, in many cases focused specifically on those areas of emphasis identified for habitability. Some specific examples include:

- Long-life testing of all hardware to characterize mean time between failure (MTBF), failure modes, and logistics demands
- High-fidelity tracking of ISS maintenance and logistics in the ISS Maintenance Analysis Data Set (MADS)
- 3D printing in zero-g experiments on the ISS, using 3D printers and material recyclers: for example, systems developed and flown by Made In Space, Inc.; see www.madeinspace.us) and their adapted use in 0.38 g.
- Flight of the Mars Oxygen ISRU Experiment (MOXIE) on the planned Mars 2020 rover to characterize performance of a 1% scale ISRU system in the martian environment
- Lifecycle testing of exploration class ECLS systems on the ISS (e.g., CO₂ and Moisture Removal Amine Swingbed (CAMRAS) for the Orion Multi-Purpose Crew Vehicle (Orion MPCV)). Note that CAMRAS is based on similar technology used on the next generation Portable Life Support System.

Innovative Strategies to Close the Secondary Long Poles

- Continuing mission simulations in increasingly realistic simulated environments
- Continued lifecycle testing of hardware under operational conditions and in relevant operating environments to characterize MTBF, spare parts demands, and repair times to enable trades between spare parts mass and level of repair and, hence, crew time and required diagnostic equipment and tooling for each system
- Investigate potential of material recovery from failed parts to begin closing the “material loop” where the material from yesterday’s failed component can be recovered and manufactured in situ into today’s spare part.
- Investigate opportunities for system redesign that takes advantage of the benefits of in-situ manufacturing (ISM). For example, designing components that use lighter materials as ISM means that they no longer need to withstand launch loads and can hence be lighter. Similarly, investigate opportunities for system redesign with materials that are amenable to material recycling and ISM.
- Investigate opportunities for commonality in component design and material across the system to take advantage of either common parts and/or common ISM and material recovery opportunities. This may potential lead to a more robust system, with higher system availability, at a lower total system mass.

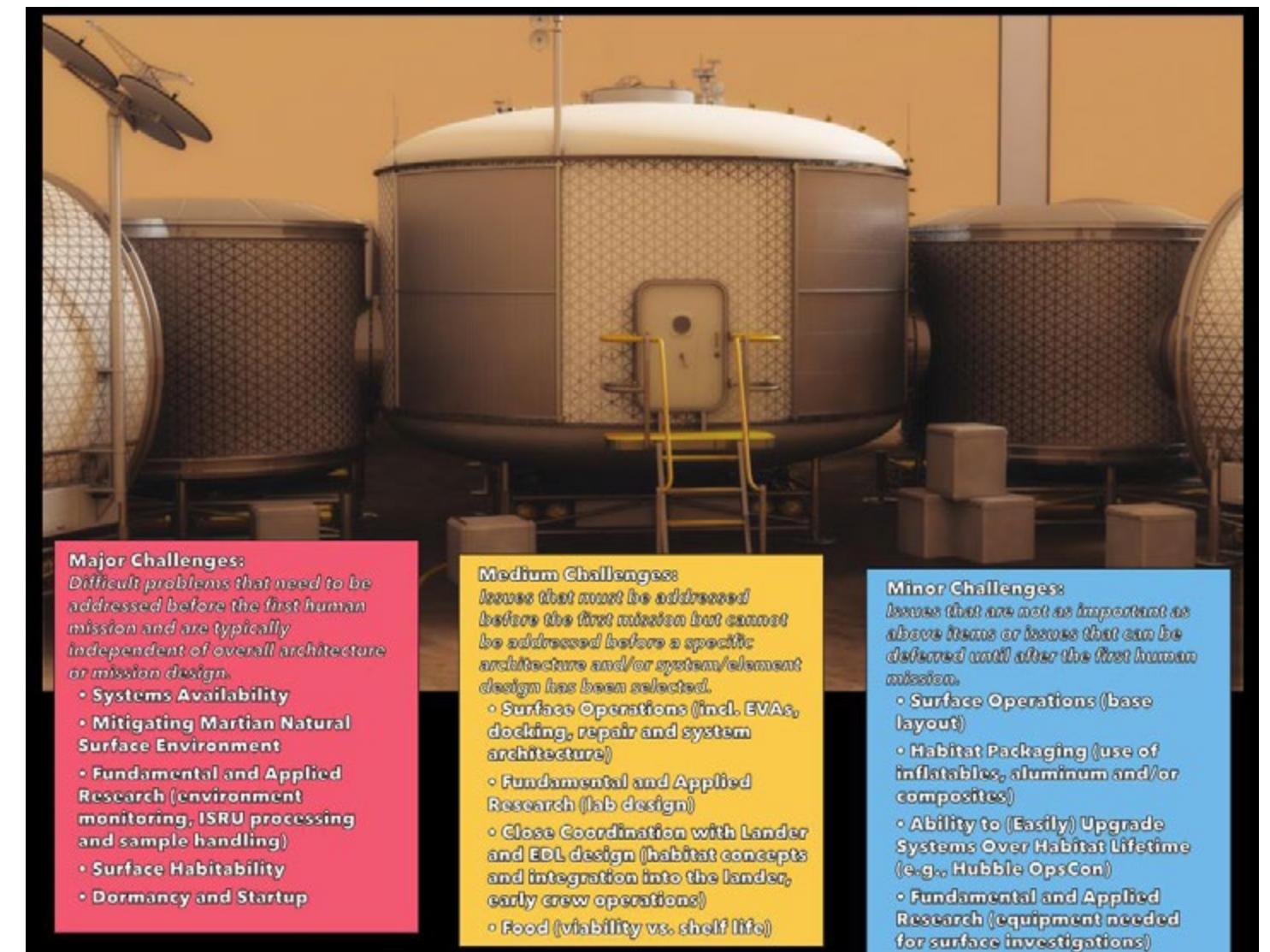


Figure 1. MSFC Advanced Concept Office deep space habitat



[HTTPS://EXPLOREMASR.ORG](https://exploremars.org)

⁷Federal Standard 1037C Telecommunications: Glossary of Telecommunication Terms, August 1996.



[HTTP://ASTRONAUTICAL.ORG/](http://astronautical.org/)

Long Pole 6: Surface Power

The Long Pole

There are many long poles that must be overcome in order to successfully land humans on Mars. To keep the astronauts alive and well, and all of their necessary equipment functioning for the time periods involved in extended stay missions, the generation of sufficient and dependable power on the martian surface is a critical need. As stated in the critically acclaimed movie, *Apollo 13*, "Power is everything".

Surface power needs for human Mars missions will require large-scale power generation, far larger than is currently required for robotic missions. Instead of power measured in mere watts, human missions will require supplying tens of kilowatts of power, with power systems that can initially be deployed robotically and that will remain functional for multiple crew campaigns. Overcoming the Mars surface power "long pole" involves the development and/or scaling up of (1) deployable solar arrays with energy storage, (2) compact fission reactors, and/or (3) radioisotope power systems (RPS).

Statement of Achievability

Current and/or under development solar electric propulsion (SEP) solar array technology may be adaptable for use on the martian surface (e.g., the Megaflex Solar Array or the Roll-out Solar Array). In addition, there is potential to leverage current terrestrial investments in lightweight batteries (e.g., lithium-ion) that would provide the necessary energy storage capability during periods when the solar arrays are offline entirely or are otherwise operating at less than peak efficiency, such as during nighttime or due to dust storms.

There are also promising prospects for the development of small, affordable fission reactors using Kilopower technology (see below). Such a system could be used at any location on the Mars surface and provide continuous day/night power at a sufficient scale for human missions. Furthermore, past successes of radioisotope thermoelectric generators (RTGs) on Mars, such as in the Viking missions and in the Mars Science Laboratory's Curiosity rover, as well as solar power (Pathfinder, Mars Exploration Rover's Spirit and Opportunity, and Phoenix) also speak to the possibility of scaling up these technologies to more robust power levels.

Challenges to Closing the Mars Surface Power Long Pole

There is no current off-the-shelf power solution available at sufficient scale that can operate for long durations in the martian environment. Current RTGs, for example, are limited to an output of approximately 100 watts. Solar Photovoltaic (PV) systems are adversely impacted by reduced solar flux, by dust storms, by seasonal changes, and by non-equatorial latitudes. There are also other environmental factors that would have to be taken into consideration, such as Mars' carbon dioxide atmosphere, 0.38 gravity, dust, wind, diurnal cycle, and surface temperature extremes (-140 C to 35 C). The current lack of availability of Plutonium-238 (Pu-238) would have to be addressed for the use of larger radioisotope power systems (RPS) on Mars.

Closing the Mars Surface Power "Long Pole" Requires Access to the Martian Surface

Because the equipment and machinery that will be needed for surface power is so critical to mission success, and has never been tested under the harsh conditions that exist on the martian surface, closing this particular long pole will require extensive testing, including Mars simulated environmental tests on Earth and under actual conditions; that is, on the martian surface.

Primary Challenge to Achievability

Accelerated development of Kilopower technology for Mars surface operations is needed. In addition, studies must be undertaken to examine the adaptability of SEP arrays designed to operate in-space to the conditions that exist on the martian surface. Finally, the potential for scaling up of RPS output to kilowatt-class must also be determined, including the impact on Pu-238 fuel production.

Other Design Considerations

Mars surface power requirements for expanded robotic systems and human habitation are not well-defined at present. For example, power requirements for in-situ production may be significant.

In order to generate the same power on Mars as on the Earth, a solar array would have to be three to four times larger in area. In addition, dust storms are frequent and can develop anywhere on Mars at any time, and landings on the surface will produce dust plumes that may damage nearby solar arrays and radiator surfaces. Dust particles will obscure the Sun for extended periods of time, thus requiring backup power for PV arrays.

Nuclear power systems offer performance advantages, although have unique safety and policy issues including those related to launch. A cold reactor, however, presents minimal risk to the public if the fuel is dispersed during a launch accident. Radioactivity is an issue only after the reactor is turned on, which would not occur until the reactor is safely away from the Earth. Nuclear reactor shielding mass could be significant and will be dependent on proximity of crew and duration of stay; the use of in-situ materials for shielding may be a possible solution to reduce the delivered mass.

Multiple, distributed landing sites, and multiple, time-phased crew campaigns will complicate the power distribution network: A large, centralized power station may have to be oversized for initial use and require long-distance cabling to connect loads. On the other hand, a distributed power architecture may require the delivery of many, smaller power modules with greater complexity of operations. There is also a theoretical potential for power beaming for surface-to-surface power transmission (instead of cabling) or orbit-to-surface, via laser or microwave.

Time to Close the Mars Surface Power Long Pole

A notional development approach for Mars surface power is shown in Figure 1. Parallel development of solar and nuclear technology options is required for the next ~3-5 years to support informed decisions on a preferred flight system approach, followed by a full-scale engineering unit design/fabrication/test in a Mars simulated environment in the next ~6-8 years. A full-scale power module flight demonstration on a robotic Mars lander in the next ~9-10 years could provide significant risk reduction for later human systems. Following the robotic demonstration, continued development of human-rated flight systems would be required in order to support human missions to Mars in the 2030s.

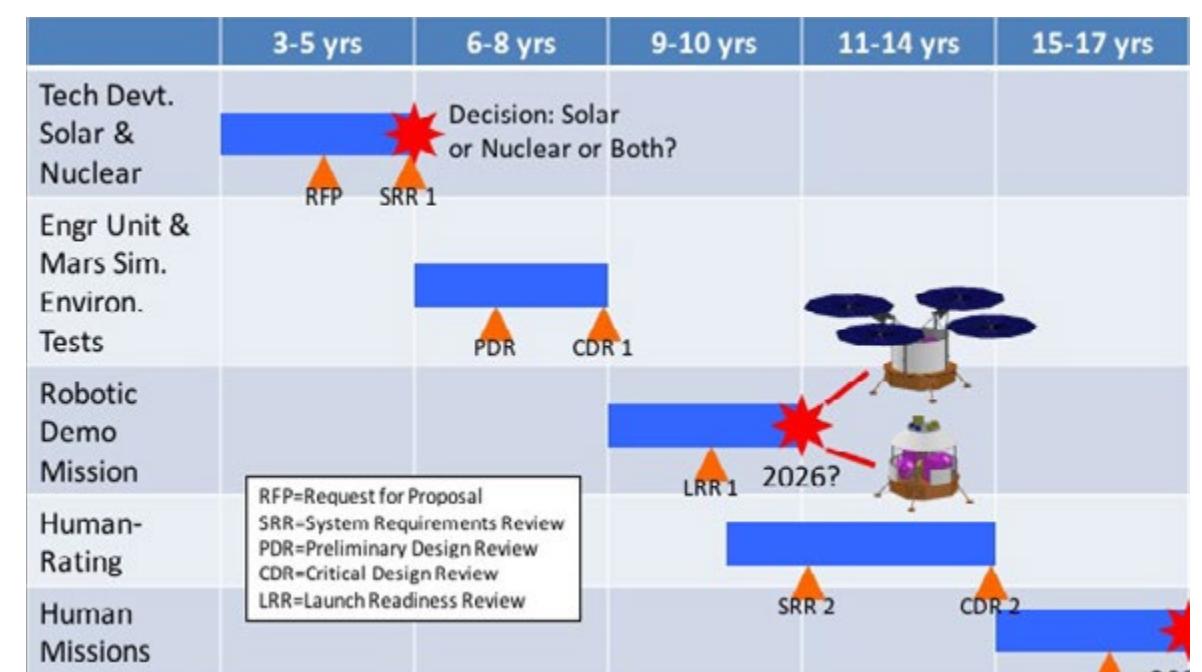


Figure 1. Mars Surface Power Development Timeline

The time to close this long pole would be approximately 8-10 years for solar and/or RPSs and approximately 10-12 years for nuclear fission.

DISCUSSION

A. Solar and RPS:

1. Overview of the Challenge:

Solar-based power architectures may require a combination of PV arrays, energy storage, and RPS for reliable power generation. Large Mars surface PV arrays could be derived from SEP or Orion systems, modified for use under martian g-loads, wind, and insolation. For example, landing and take-off dust plumes could impact array design and concept of operations. In addition, the latitude of the landing site will impact the daylight period, and the season (aphelion as opposed to perihelion) will impact the available solar flux. Lightweight batteries or regenerative fuel cells (RFC) will be needed for night power. Unfortunately, the projected Pu-238 supply under current production scenarios would be insufficient to support large-scale RPS use for both human Mars missions and robotic science. However, a combination of dynamic conversion and production scale-up could address this issue.

2. Power Requirements, and Advantages of this Option:

Human missions are expected to require 30 to 40 kW of reliable power for pre-crew in-situ resource utilization (ISRU) propellant production and post-landing crew operations, possibly over multiple crew campaigns. Combined power systems must provide power throughout the day-night cycle on the surface, including dust storms. Even if ISRU is not utilized to make return propellant, the Mars Ascent Vehicle (MAV) keep-alive alone requires 4 to 7 kW. RPS can provide up to several kW, and enhance operational flexibility with safe human proximity operations (e.g., rover power) and possibly, heat for the habitat or ISRU.

Solar PV and energy storage would provide a mass and cost-effective surface power solution with flexible multi-role architecture, one that could be robotically installed/repurposed, with flexible use, and one that would be immune to terrain variance. The dust environment (periodic dust storms, daily build-up) is, however, a major driver. Advanced energy storage solutions would also be required.

3. Current State of the Art:

A human-scale solar/RPS Mars power architecture has a strong link to prior robotic missions with relevant state-of-the-art (SOA) systems shown in Figure 2. Mars Exploration Rovers (MER) Spirit and Opportunity, and the Phoenix Lander, used PV arrays and batteries on Mars. Mars Science Laboratory's Curiosity rover and the Viking Landers used RPS.



Figure 2. Mars SOA power examples: MER, Phoenix, and Curiosity

4. Why is it Not Sufficient to Use Current State of the Art?

Solar arrays and rechargeable energy storage must be sized for 30-40 kW on Mars and designed for the Mars environment. Larger, dynamic RPS must be developed to minimize Pu-238 load, and Pu-238 production must be scaled up from $<1 \text{ kg yr}^{-1}$ as currently planned to 5 kg yr^{-1} .

5. What is Currently Being Done to Close this Long Pole?

NASA's SEP effort seeks to develop large-scale in-space arrays. The Space Technology Mission Directorate (STMD) Game Changing Development (GCD)'s Advanced Energy Storage Systems (AESS) Project is developing high energy-density batteries. STMD/GCD has also initiated a Solar Array With Storage (SAWS) Seedling Study for Mars-specific PV arrays (possibly adapted from SEP) and RFCs. The RPS Program is developing advanced dynamic power conversion, and the Department of Energy (DOE) is funded to produce $\sim 1 \text{ kg yr}^{-1}$ of Pu-238.

6. What is the Minimum Success Criteria?

A combined PV array and energy storage system suitable for Mars surface environment, producing up to 40 kW of electrical power, with RPS for emergency backup and keep-alive, is required.

7. Other Efforts to Close This Long Pole (Other than NASA)

Commercial interests are driving high W-hr-kg^{-1} energy storage for aviation and automotive applications. Large photovoltaic arrays are being developed for SEP and commercial space applications, as well as for terrestrial use. ARPA-e is developing kilowatt-class power conversion for residential combined heat and power (CHP) applications. These efforts might be adapted/leveraged for the Humans to Mars campaign.

8. Creative Ideas That Might Help to Reduce the Length of this Long Pole

Smaller, modular PV arrays could be deployed from landers and delivered on multiple landers for gradual power buildup. RFC energy storage could use ISRU reactants and share ISRU components. The DOE is considering alternative Np-237 target designs and commercial fuel production options that could allow easier scale-up to 5 kg yr^{-1} Pu-238.

9. Commonality with another Long Pole

SEP vehicles and the in-space habitation module require large-scale solar arrays. Kilopower fission technology requires dynamic power conversion.

10. Other Relevant Factors

High-capacity power management and distribution (PMAD) systems are needed to connect the distributed landing sites and integrate the multiple, diverse power generation sources, with suitable safety and fault tolerance for human missions.

11. Access and Time for Closure

This long pole requires access to the martian surface in order to test out the equipment/machinery under the harsh conditions that they will be subjected to on Mars. This could be accomplished through a Mars surface robotic lander mission to demonstrate large-scale deployable solar arrays with sufficient nighttime energy storage, and possibly, a kilowatt-class RPS. It is estimated that the solar PV/RPS long pole can be closed within the next 8-10 years.

12. Additional Information

Hibbard, K., et al., "Stirling to Flight Initiative", IEEE AERO.2016.7500818, 2016 IEEE Aerospace Conference, March 5-12, 2016.

Rucker, M.A., et al., "Solar vs. Fission Surface Power for Mars", AIAA 2016-5452, AIAA SPACE 2016, SPACE Conference and Exposition, 2016.

B. Nuclear Fission

1. Overview of the Challenge:

Due to the power levels required, day-night cycle on the surface, dust storms, and the low solar flux at Mars, nuclear fission is an attractive power option that would offer global Mars access. For human Mars missions, this would require the development and deployment of compact, human-rated fission surface power systems in the 10 kW-class that are suitable for the Mars environment. Through the use of multiple power modules, these systems could provide 30 to 40 kW of power for surface operations, as shown in Figure 3. A modular system that can be autonomously deployed, remotely started, and turned off/transported/turned back on would also enhance operational flexibility and allow a greater exploration range. A key first step is a low-cost nuclear ground test of a prototype reactor, which is slated to occur under the STMD/GCD Kilopower Project in 2017. Dynamic conversion scale-up, reactor heat pipe integration, and launch safety certification are the primary challenges to be resolved after the reactor prototype test. Planetary protection must also be considered in the design process, possibly through the use of thermal insulation to prevent local surface heating.

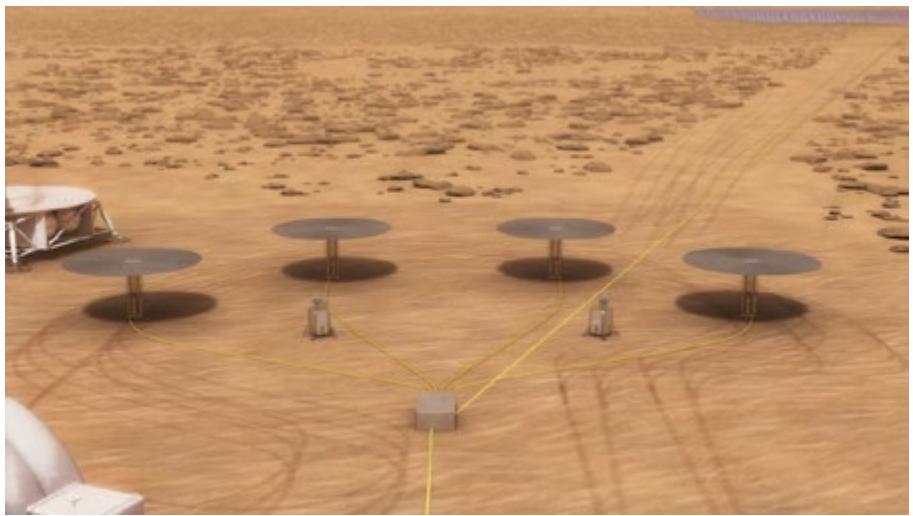


Figure 3. Multiple fission power units deployed on the martian surface

2. Power Requirements, and Advantages of this Option

Human missions are expected to require 30 to 40 kW of reliable power for pre-crew ISRU propellant production and post-landing crew operations, possibly over multiple crew campaigns. Combined power systems must provide power throughout the day-night cycle on the surface, including dust storms. Even if ISRU is not used, the Mars Ascent Vehicle keep-alive alone requires 4 to 7 kW.

Nuclear fission reactors can be deployed at any martian latitude including locations near the poles where water is present. They can also operate continuously, including during the nighttime and during dust storms. The reactor has an extremely long life due to the low-fuel burnup, and the power system can be designed for many years of reliable operation, without crew interaction, using automated control.

Fission reactors provide a very compact energy source: a 10 kW reactor core is about 15 cm in diameter and about 28 cm tall. At this small size, the reactor thermal energy can be delivered to the power conversion equipment using passive heat pipes. The enriched-uranium fuel (core) can be made in advance and stored until needed without any performance decay.

3. Current State of the Art

Previous missions have been one-way robotic missions, requiring relatively low power levels achievable with solar arrays and batteries or radioisotope power systems. Nuclear submarines use a pressurized-water reactor that is not applicable for space use. The only U.S. reactor flown in space (SNAP-10A) was discontinued in the late 1960s. Other space reactor projects (e.g., SP-100, Prometheus) were never completed due to cost and/or technical difficulty.

4. Why is it Not Sufficient to Use Current State of the Art?

Solar arrays with energy storage may not scale to the power levels needed for human missions, and RPS are probably limited to about 1 kW, whereas nuclear fission reactors do not have such limitations. Space reactors derived from shipboard nuclear systems may seem like a logical path. However, naval reactors are not relevant to space due to their large size and low operating temperature.

5. What is Currently Being Done to Close this Long Pole?

As part of the STMD/Game Changing Development Program, the Kilopower Project will perform a nuclear-heated reactor test at the Nevada Test Site in 2017, establishing TRL 5 for small fission space reactors as shown in Figure 4. The next phase is Kilopower II Engineering Development Unit and simulated Mars environment testing. The commonality between Kilopower and nuclear thermal propulsion reactor development could reduce the combined overall cost.

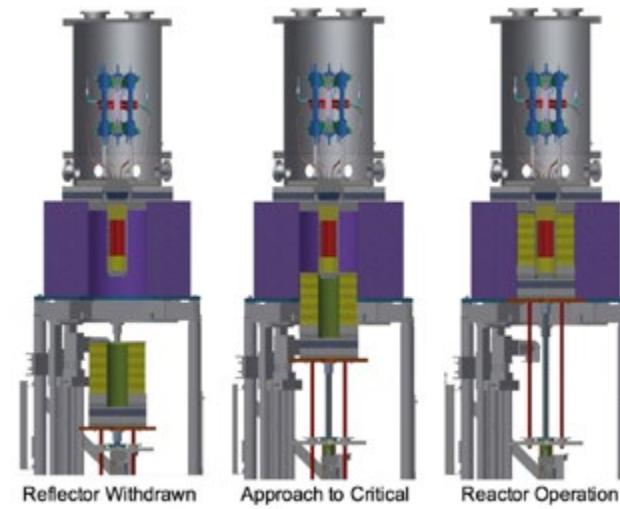


Figure 4. Kilopower reactor prototype test

6. What is the Minimum Success Criteria?

A fission reactor compatible with the Mars surface environment and capable of producing up to 10 kW, that can be integrated with multiple Imodules to provide 40 kW total, is required.

7. Other Efforts to Close This Long Pole (Other Than NASA)

The DOE is developing Small Modular Reactors for terrestrial applications, but their large size (10s of MW) is too big for currently foreseeable Mars missions. The Department of Defense (DOD) is exploring small reactors in the 100 kW to 1 MW class for forward operating bases and unmanned underwater vehicle applications. These systems may have some commonality with Mars surface reactors.

8. Creative Ideas That Might Help to Reduce the Length of this Long Pole

The fission power unit could be integrated with ISRU to provide both electricity and heat, with thermal energy supplied at either 600°C (reactor heat) or 100°C (waste heat). Fission reactors could use Low Enriched Uranium (LEU) rather than High Enriched Uranium (HEU) as a means to reduce security costs during launch processing, but the LEU systems would have significantly higher mass.

9. Commonality with another Long Pole

Nuclear thermal propulsion could use common infrastructure (e.g., test facilities), engineering practices (e.g., modeling, materials handling), and components (e.g., neutron reflectors, shielding, control drive motors). Dynamic power conversion technology supports both fission and RPS.

10. Other Relevant Factors

High-capacity power management and distribution (PMAD) systems are needed to connect the distributed landing sites and integrate the multiple power generation sources, with suitable safety and fault tolerance for human missions. Fission systems also introduce the need for radiation shielding and radiation-hardened electronics near the reactor. Launch certification process will require combination of analysis and testing to assure launch safety and prevention of inadvertent reactor criticality during a launch failure.

11. Access and Time for Closure

This long pole requires access to the martian surface in order to test out the equipment/machinery under the harsh conditions that they will be subjected to on Mars. This could be accomplished through a Mars surface robotic lander mission to demonstrate the Kilopower design, possibly in combination with an ISRU plant. It is estimated that the nuclear fission long pole can be closed within the next 10-12 years.

12. Additional Information

Gibson, M, et al., "Development of NASA's Small Fission Power System for Science and Human Exploration." NASA/TM-2015-218460.

Mason, L., et al., "Kilowatt-Class Fission Power Systems for Science and Human Precursor Missions" NASA/TM-2013-216541.

Rucker, M.A., et al., "Solar vs. Fission Surface Power for Mars", AIAA 2016-5452, AIAA SPACE 2016, SPACE Conference and Exposition, 2016.

SUMMARY

Mars surface power requirements for human-scale missions (10s of kW) presents a major development challenge or long pole. The Mars environment, as well as distributed, time-phased landing sites, pose significant challenges to surface power architectures. Although no off-the-shelf solutions currently exist, there are several promising options. These include solar PV with energy storage or nuclear fission.

The solar PV option could leverage SEP investments. The nuclear fission option will be better understood after the Kilopower nuclear test in Nevada in 2017. RPS is well-suited for low power (less than 1 kW) emergency backup.

Technology gaps can be closed with focused, sustained investments. The STMD/GCD Program provides a good starting point with Kilopower and SAWS. Funding augmentation is needed, however, to accelerate technology maturation to allow informed decisions on flight system approach, and a Mars simulated environment test, followed by an actual environment test, is crucial for technology validation. A mid/late-2020s robotic surface demonstration of ISRU/power is highly desirable in order to reduce risk for human missions. In addition, work must begin in the very near term, without delay, in order to ensure technology readiness for human landings in the 2030s.

Long Pole 7: Mars Ascent Vehicle

The Long Pole

Round-trip missions from the Earth, to the surface of Mars, and back will require overcoming a number significant challenges. Perhaps one of the greatest challenges is that of ascending from the surface of Mars to return the crew to their transportation system for return to Earth. There have been multiple mission, architecture, and system concept studies conducted over the past several decades and each of these studies have helped formulate a set of key characteristics for the Mars Ascent Vehicle (MAV) including:

- Typical Mars architectures are designed with the MAV serving as an unoccupied payload with periods of long dormancy. These periods of dormancy include the transit to Mars, loiter in Mars orbit, landing on the surface, operations on the surface prior to and during exploration on the surface by the crew prior to the final active ascent from the surface to orbit. This dormant duration is typically measured in years of operation.
- Operation in various environments including launch, deep-space transit, entry, landing, surface, and ascent.
- The MAV must be capable of operating in the various remote environments and performing as needed with limited maintenance and repair capabilities by the flight crew.
- Ascent to Mars orbit requires fairly significant change in velocity to achieve orbital conditions, typically $4\text{-}6 \text{ km s}^{-1}$ depending on the chosen rendezvous orbit, which results in a large propellant load.
- The MAV may utilize cryogenic propellants to improve performance (reduce the propellant load) as well as enable the use of propellants generated in-situ at Mars.
- The MAV must provide the ability to support multiple crew members (typically 4-6) through multiple operational phases (ingress, egress, high acceleration, docking, etc.).
- As one part of a multi-part systems-of-systems architecture, the MAV must have the ability to integrate with multiple separate assets of the overall Mars architecture including items such as power systems, propellant production, and crew ingress including ensuring compliance with planetary protection protocols.
- In order to reduce development as well as recurring costs, it is desired to drive commonality of the MAV with other Mars architecture elements (e.g., propulsion, propellant choices, power systems, crew support systems, etc.).

Statement of Achievability

It was the consensus of our MAV team that, although ascent from the surface of Mars represents a significant long pole to future Mars missions, the challenges can be mitigated with proper and timely decision making, planning, and funding. Our team concluded that the efforts required to ensure that the integrated system will perform as needed represents the primary challenge for Mars ascent. As can be seen in Figure 1, we estimated that approximately 17 years may be required to close the set of integrated MAV long poles. This time includes approximately six years for the development and testing of the integrated system and is preceded by approximately seven years of effort associated with the secondary long poles including cryogenic fluid management, engine development and crew systems (see discussion below). As part of the deliberations of the MAV team, it was determined that most of the integrated testing of the system can be achieved on Earth, although testing of the cryogenic fluid management system will require access to low-Earth orbit in order to perform long-term testing in the space environment.

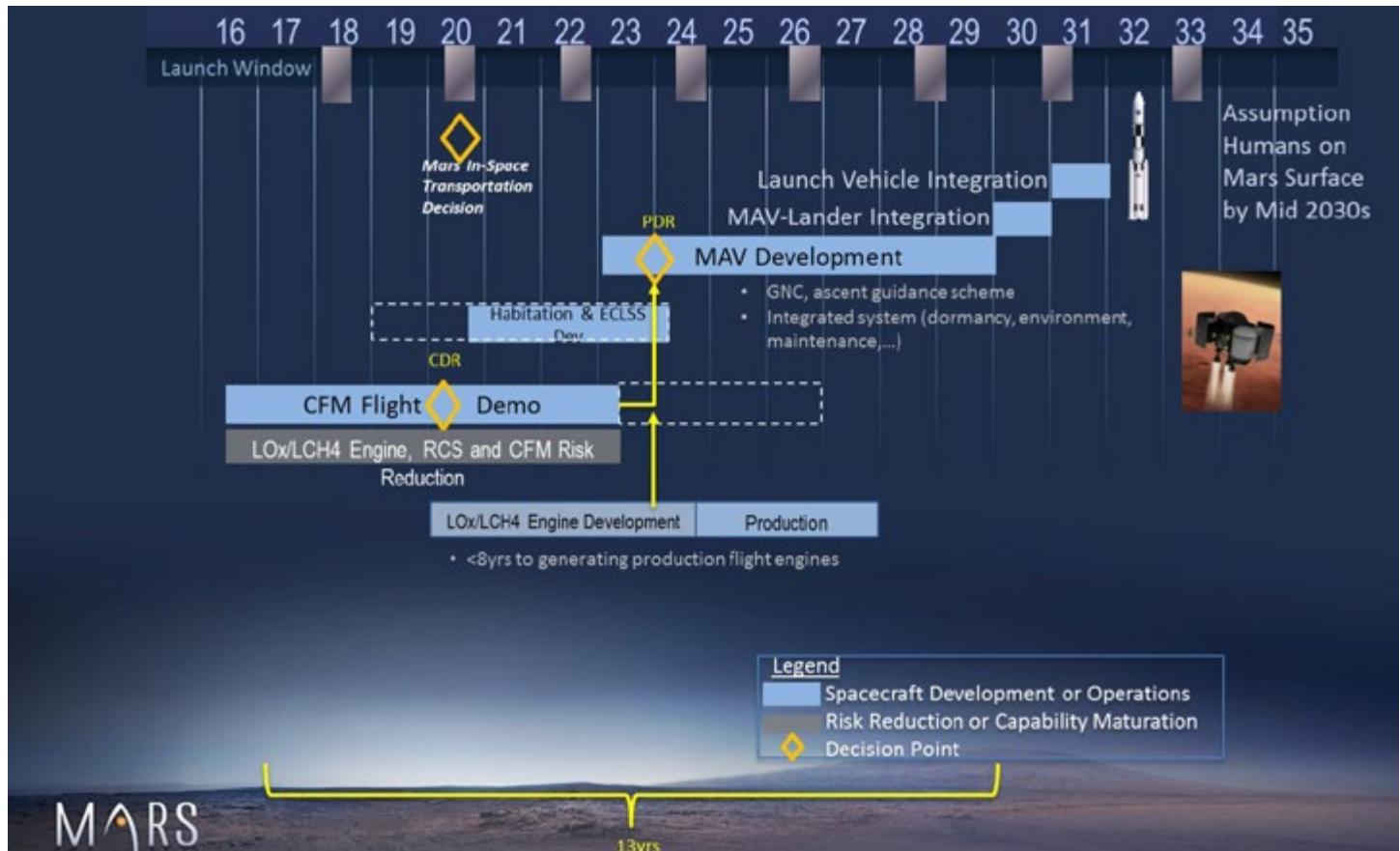


Figure 1. MAV integrated schedule

Primary Challenge: MAV Integrated System

1. Current State of Knowledge and Practice

Although there is an established experience base of crew launch from the Earth, the unique characteristics of ascent from a planetary body represent a significant challenge for human space flight. Unlike crew launches from Earth, where the support staff can easily number in the thousands, the crew on the surface of Mars will be alone with limited access to maintenance tools, facilities, and information from the team on Earth. The current state-of-the-art for human ascent from a planetary body is limited to the six Apollo missions. As can be seen in Table 1, although the previous lunar Apollo missions provide some foundation for future Mars missions, the magnitude of differences illustrate significant challenges ahead. Most of these challenges for the MAV are associated with the unavoidable long-duration remoteness of Mars missions.

2. Current Strategies to Close the Long Pole and Minimum Success Criteria

It was a consensus of the MAV team that key impediments to closing the integrated system long pole include those associated with performing key technical trade studies and making and maintaining decisions associated with those trades. Multiple critical decisions are required first to define the overall architecture operational concept, functions, and performance requirements including the mission architecture rendezvous orbit, the need for and availability of aborts during descent, reliance on in-situ resource utilization (ISRU), propellant type, and surface operational concepts, before efforts on closing the MAV long poles can be made. All of the decisions are critical for defining the MAV in the overall system-of-systems architecture, but those decisions impact identified secondary long poles as well (Figure 2). For instance, depending on final decisions such as mission payload size, crew size, and mission architecture, the utility and strategic implications of hypergolic fuels as a fallback solution from ISRU-enabling cryogenic propellants cannot be determined. Adequate progress cannot be made until key architecture decisions are made and the necessary test and verification plan is developed.

3. Innovative Strategies to Close the Long Pole

A significant challenge to mitigating the risks associated with the MAV long pole is uncertainty in the overall Mars architecture. There are numerous integrated architecture issues related to the MAV that require further definition and decision to narrow the trade space and enable meaningful advancement. It is essential that NASA management establish and implement a focused decision-making process for moving the Mars architecture, including the MAV, forward.

Table 1 Ascent vehicle characteristics comparison: Moon (Apollo) vs. Mars

Driving Characteristics	State of the Art	Example MAV
Crew size	2	4-6
Ascent Delta-v	2 km/s	4-6 km/s
Ascent Rendezvous Time	2 hours	43 hours
Dormant Duration	4 days	~2000 days
Propellant Load	2.5 mt	30 mt
Propellant Type	Earth Storable	Soft Cryogenic
Environmental Exposure	Deep Space / Limited Dust	Deep Space / Dust
External Interfaces	Minimal	Multiple Interfaces
Mission Mode	Brought with the crew	Pre-deployed ahead of crew
Communication lag with Earth	2.5 seconds	480-2400 seconds

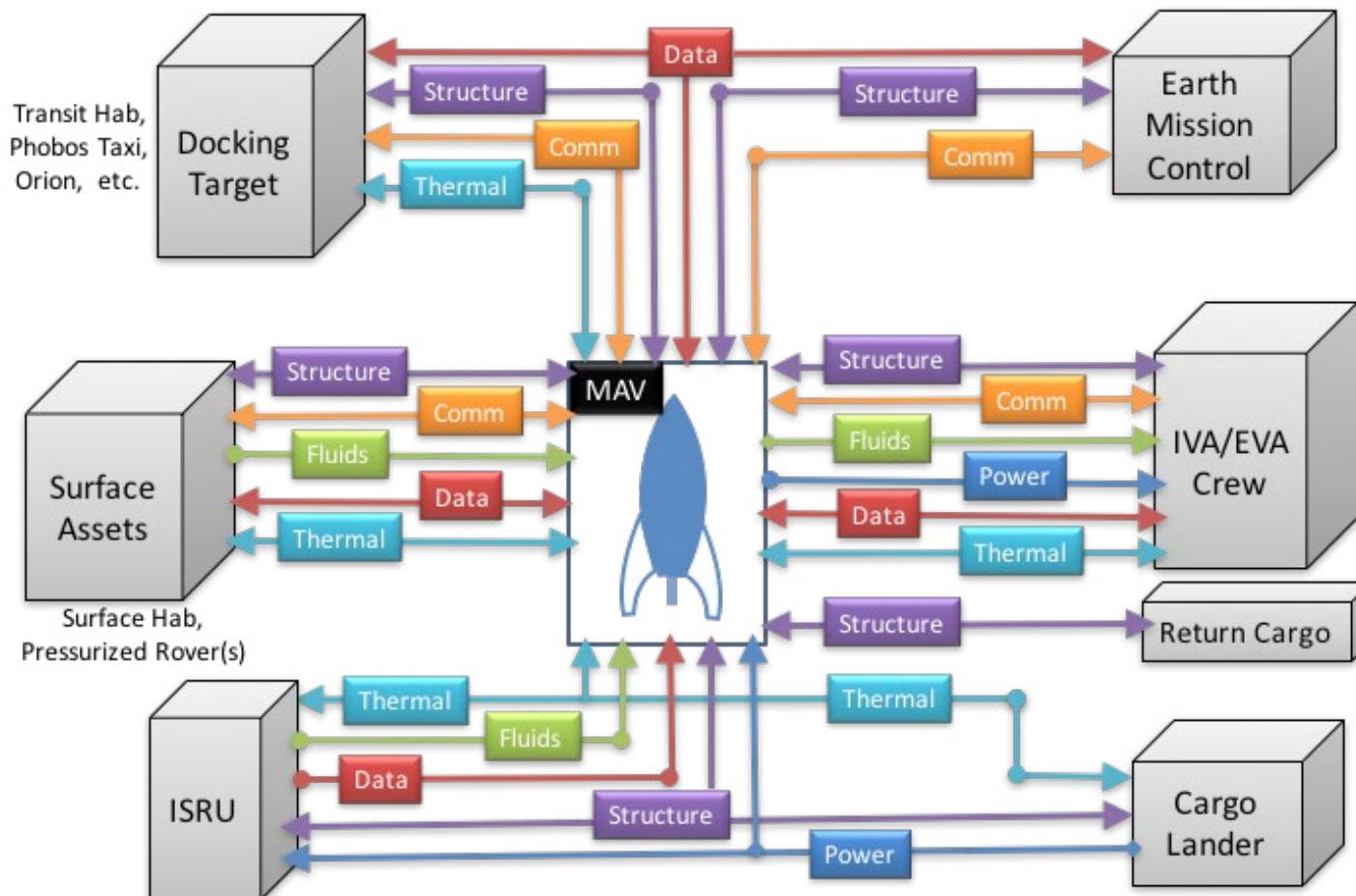


Figure 2. MAV interfaces within the system-of-systems architecture

Secondary Challenges

1. Cryogenic Fluid Management

Cryogenic fluid management (CFM) is a key feature of NASA's long-term mission to Mars. Current mission architectures require that cryogens be stored for extended periods of time, up to nine years. Active cooling (cryocoolers), passive storage (insulation, low conductivity structure, etc.) and low leakage components are needed for long term storage of cryogens, and to efficiently liquefy ISRU-generated propellants for tank replenishment on the martian surface. There are three elements of propellant management which require further technology development efforts to mature the technologies prior to an integrated system demonstration or flight demonstration: (1) High-efficiency, high-capacity cryocoolers, (2) Soft vacuum insulation for Mars environments, and (3) Operational considerations for liquefaction. Only the cryocoolers would need to be tested in space in order to demonstrate long-duration storage of cryogenic propellants.

a. Current State of Knowledge and Practice

The current state-of-the-art (SOA) in CFM technology is spray-on foam insulation (SOFI), multi-layer insulation (MLI), cryogenic flight valves with leakages on the order of 100 cubic inches per minute (CIM) and low-capacity (20 watts) cryocoolers (both 20 and 90 K).

SOFI is only effective at atmospheric conditions and MLI requires a low-vacuum environment. The martian atmosphere unfortunately is a soft-vacuum CO₂ (5-7 Torr) limiting the usefulness of MLI. Several vendors have looked at concepts that could potentially be used for a MAV application, although all are in the early phases of development. SOA cryocoolers do not have the refrigeration capacity needed. The refrigeration capacity needs to be increased at least an order of magnitude from the existing 20 W capability. Valves need to be developed to lower the SOA leakage rates while maintaining low heat loads into the tank and lightweight actuation devices to assure propellant is preserved long enough to meet mission requirements. Non-cryogenic propellants could be a credible fallback technology, depending on final mission payload size, crew size, and mission architecture.

b. Current Strategies and Priorities to Close the Long Pole

NASA is working with industry via Small Business Innovative Research (SBIR) activities for the development of high-efficiency, high-capacity cryocoolers and advanced insulation concepts. NASA has begun working in-house on the development of long-duration cryogenic valves and actuators including funding multiple external efforts as well. NASA is also beginning the development of technologies and planning demonstrations under NASA's Lander Technologies Advanced Exploration Systems project, which includes the liquefaction of "ISRU-like" propellants and maintaining zero boil-off during long-duration storage.

c. Innovative Strategies to Close the Long Pole

Maximizing the cooling efficiency of the integrated system is key for long-duration storage. Liquefaction demonstration will include integrating the cryocooler heat exchanger into the tank wall to maximize heat exchanger surface area. Advanced insulation concepts are being examined which make use of MLI, but in configurations which make it effective in atmosphere and allow it to withstand the aero-thermal loads associated with a launch environment.

2. Engine Development

NASA's and industry's mission architecture and system trade studies have shown that propellant choice and specific impulse (Isp) capability have a strong impact on the size and mass of the ascent vehicle or stage. The most recent trades have indicated that a liquid oxygen (LOx) and methane (CH₄) propellant choice provides adequate Isp, minimizes the tankage volume, has a higher cryogenic storage technology readiness, and can provide additional mission benefits when combined with Mars ISRU plans. The predominate system benefits at the propulsion level are the elimination of heaters typical for storables

propellants and avoiding the use of extreme (20 K) active cooling as with liquid hydrogen (LH₂). The Mars ascent vehicle is assumed to use LOx/CH₄ as the primary and RCS propellants in the context of the following discussion.^{8, 9, 10, 11}

a. Current State of Knowledge and Practice

The current state of knowledge (i.e., 2016) with LOx/CH₄ rocket engines in the 22 to 155 kN size is limited to component design and testing applicable to ascent and descent propulsion for a Mars lander. Several engine thrust chambers, between 0.5 and 22 kN thrust size, have been run with GOx/CH₄ or LOx/CH₄ propellants by NASA and industry during 2010 and 2011. NASA and industry have tested pressure-fed gaseous thrusters and recently, under the Morpheus Lander project, where a 24 kN pressure-fed engine was operated. Current pressure-fed engine approaches by the NASA Morpheus lander and the RS-18 demonstrators are in the 20 kN class and are pressure-fed. Larger booster engines are in development by Space X and Blue Origin, but their thrust is between 2,000 to 3,500 kN and are not being designed for multiple start, in-space operation. Legacy work has been performed on engine systems in the 66 kN size derived from the RL10 LOx/Hydrogen (H₂) engine used with LOx/CH₄ propellants in the late 1960s. The performance for a fully loaded MAV that is between 30 to 40 mt will most likely require a pump-fed gas generator or expander cycle engine approach. No such engine is currently in development nor have LOx/CH₄ propellants been used operationally.

If non-cryogenic propellants were chosen as a fallback technology, then a new engine development could be based on a scaled-up and throttleable version of the RS-72 engine. The performance is lower than LOx/CH₄ and selection would be dependent on the mission architecture solution.¹²

b. Current Strategies and Priorities to Close the Long Pole

A strategy should be put in place that starts technology development activities aligned with MAV propulsion needs for a pump-fed, 20-30 kN engine system immediately if humans are to be on the Mars surface by the 2030s. These activities should build off recent lower thrust chamber work by NASA and extend the testing to higher thrust levels to confirm LOx/CH₄ engine control systems, combustion stability, turbopump operability, robust ignition systems, and throttling range. Other areas that should be addressed are reducing or minimizing valve and chill-down conditioning leakage and limiting environment exposure and engine seal conditioning for long-term dormancy on the Mars surface. These should be a priority for testing.

c. Innovative Strategies to Close the Long Pole

To reduce the engine cost, the strategy should build off recent advances in additive manufacturing by NASA Marshall on LOx/CH₄ engine components, recent work by industry such as the Common Extensible Cryogenic Engine (CECE) based on the LOx/LH₂ RL10, as well as other propulsion being developed for commercial launch upper stages. Testing at NASA facilities on LOx/CH₄ engine components should continue and new elements such as turbopump systems, main combustor cooling rigs for gas generator and expander designs, and robust injector designs to reduce the engine development risk should also be added. This provides benefits in several areas for

⁸ Grayson, Gary D., "Propellant Trade Study for Crew Space Vehicle," AIAA 2005-4313, AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 10 -13 July 2005, Tucson, Arizona, 2005.

⁹ Drake, Bret, G., and Kevin D. Watts, ed., "Human Exploration of Mars Design Reference Architecture 5.0, Addendum 2," NASA SP-2009-566-ADD2, National Aeronautics and Space Administration, NASA Johnson Space Center, Houston, Texas, March 2014.

¹⁰ Polsgrove, Tara, D. Thomas, S. Sutherlin, W. Stephens and M. Rucker, "Mars Ascent Vehicle Design for Human Exploration," AIAA 2015-4416, AIAA Space 2015 Conference and Exposition 31 Aug.-2 Sept., Pasadena, California, 2015.

¹¹ Sanders, Gerry, A. Paz, L. Oryshchyn, K. Araghi, A. C. Muscatello, D. L. Linne, J. E. Kleinhenz, and T. Peters, "Mars ISRU for Production of Mission Critical Consumables-Options, Recent Studies, and Current state of the Art," AIAA 2015-4458, AIAA SPACE 2015 Conference and Exposition 31 Aug.-2 Sept., Pasadena, California, 2015.

¹² Dressler, Gordon, L. W. Matuszak, and D. D. Stephenson, "Study of a High-Energy Upper Stage for Future Shuttle Missions," AIAA 2003-5128, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 20-23 July 2003, Huntsville, AL, 2003.

obtaining LOx/CH4 propulsion in the thrust-class required for the MAV such as reducing the cost for full scale development, gaining experience with in-space operability, and reducing the technical risk with early use on other stage applications or on an in-space demonstrator before the MAV is needed. The LOx/CH4 propulsion technology is around Technology Readiness Level (TRL) 4 to 5 and simply needs some additional design efforts focused on the MAV application to get it to TRL 6-7. Flying the propulsion on a demonstrator stage that provides integrated testing to verify the cryogenic fluid management systems with LOx/CH4 is another key area that has synergy with any effort to mature a LOx/CH4 propulsion system for the MAV or any in-space stage.^{13,14}

3. Habitation Systems and Crew Access

For the most part, habitation and crew access technologies are either available or being developed for other elements of a Mars architecture, such as a surface habitat. The long pole for habitation and crew access is dependent upon decisions on three key MAV functional requirements: how many crew the MAV will carry, how long crew will live inside the MAV, and what restrictions will be placed on martian dust brought into the MAV cabin from the surface. The design of a two-crew, one-day MAV with few planetary protection restrictions will be significantly different from a six-crew, three-day MAV with no allowable reverse contamination.

Deciding how many crew the MAV must accommodate is likely to depend on many factors including international partnership agreements made at the Agency level, and may be influenced by other programs, such as how many crew Orion can launch and subsequently return to Earth. The duration that crew must be sustained inside the MAV is a function of Mars destination orbit, which in turn is a function of in-space architecture, which may well be influenced by the introduction of new commercial providers. Destination orbit may also be influenced by surface landing site selection, which in turn will be influenced by the science community as well as by surface resource needs such as in-situ resource utilization propellant production. Habitable duration will also be influenced by whether the crew lands on Mars inside the MAV and how long they would have to remain in the MAV after landing, which is a function of surface architecture and crew physical condition.¹⁵ Any requirements for abort to orbit during EDL and the ability to survive off-target landing anomalies could also be factors in MAV habitation specifications. The level of planetary protection imposed on the MAV will be determined by the international community, with reverse contamination back to Earth a primary consideration.¹⁶

a. Current State of Knowledge and Practice

b. MAV habitability and crew access drives MAV cabin size,¹⁷ which in turn drives MAV propellant load, and together these set the minimum Mars lander mass (Figure 5). For this reason, MAV habitability cannot be patterned after the relatively large Orion capsule. Even with Earth-reentry equipment stripped out, Orion would require an enormous quantity of ascent propellant and drive the Mars lander size. If the MAV carries more than three crew members, neither a Soyuz- nor Apollo-style capsule would be large enough, even for a short ascent. If the MAV's destination is a five-sol orbit, a Soyuz descent capsule would not be large enough for the estimated Mars ascent period, even with only two or three crew, and an Apollo-style capsule would be limited to three crew. Current state-of-the-art vehicles

use ingress/egress hatches, although Apollo experience shows this will make planetary protection dust abatement difficult,¹⁸ and studies indicate it may add unnecessary mass to the MAV. Heritage life support systems designed to work in the hard vacuum of low-Earth orbit or the Moon would work well for the in-flight portion of a Mars ascent, but pre-ascent time on the surface will require slightly different technologies that are compatible with the martian atmosphere.¹⁹ Although those life-support technologies would have to be developed for a long-duration Mars surface habitat anyway, the MAV application may be unique. For example, regenerative life support systems make sense for a very long-duration surface habitat, but may not trade well for mass on a very short ascent-duration MAV.

c. Current Strategies and Priorities to Close the Long Pole

A number of studies have evaluated exploration crew complement, with recommendations pointing to a minimum of six crew for long-duration missions.²⁰ The most recent MAV conceptual designs have been limited to four crew, but could be expanded to six crew. NASA's Evolvable Mars Campaign traded numerous architecture options, destination orbits, and operational schemes to determine break points for various destination orbits, and the Mars Study Capability Team is continuing this work. As a general rule of thumb, the lower the destination orbit, the lower the MAV mass will be, but lower orbits will push in-space transportation masses up. The planetary protection community conducted a workshop in October, 2016 to begin refining Mars human mission requirements. Commercial launch providers are developing Earth launch/entry crew capsules that could potentially be paired with a Mars ascent propulsion system.

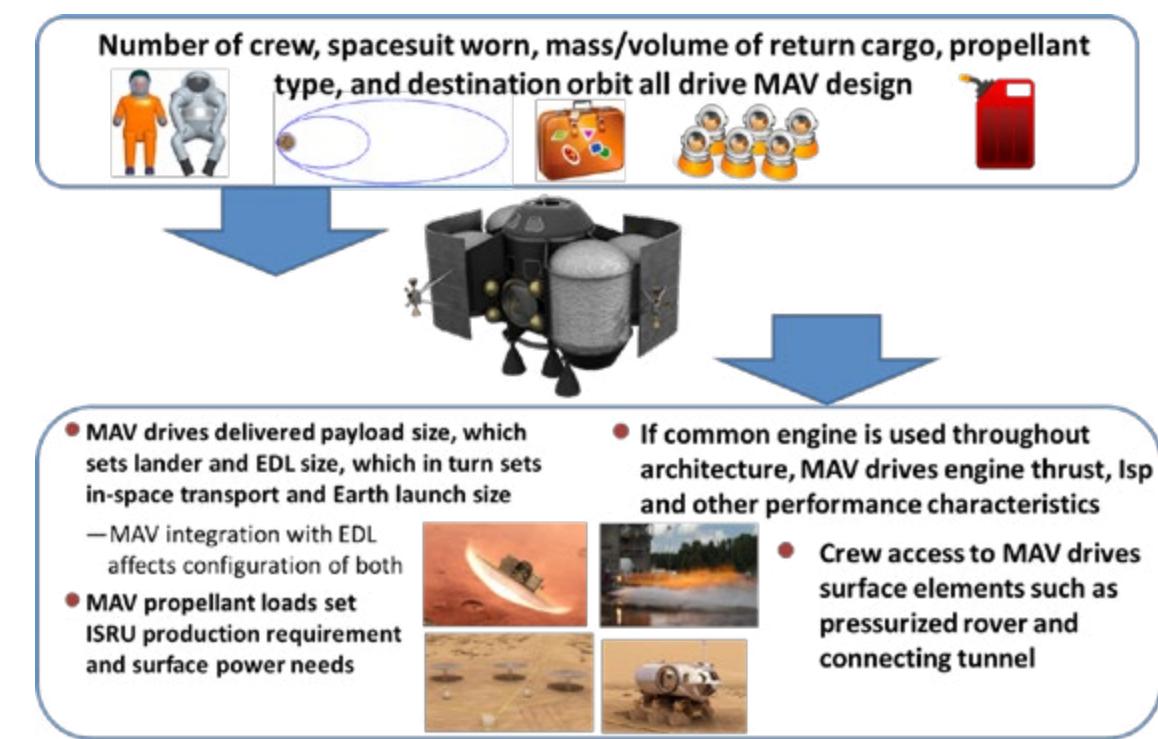


Figure 5. MAV decisions drive much of the overall architecture.

¹³Crocker, Andrew, Peery, S., "System Sensitivity Studies of a LOX/Methane Expander Cycle Upper Stage Engine," AIAA 1998-3674, 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit 13-15 July 1998, Cleveland, Ohio, 1998.

¹⁴Posgrove, Tara, et. al., "Human Mars Lander Design for NASA's Evolvable Mars Campaign," IEEE M16-5076, 37th IEEE Aerospace Conference, 5 – 12 March, Big Sky, Montana, 2016.

¹⁵Moore, S.T. and H.G. MacDougall, *Journey to Mars: Physiological Effects and Operational Consequences of Long-Duration Microgravity Exposure*, Journal of Cosmology, 2010, Vol 12, 3781-3793.

¹⁶NPI 8020.7, NPD 8020.7G, NASA Policy on Planetary Protection Requirements for Human Extraterrestrial Missions, National Aeronautics and Space Administration, Washington, 2014.

¹⁷Rucker, M.A., Mars Ascent Vehicle Design Considerations, AIAA-2015-4518, American Institute of Aeronautics and Astronautics (AIAA) SPACE 2015, Pasadena, 2015.

¹⁸Wagner, S.A., *The Apollo Experience Lessons Learned for Constellation Lunar Dust Management*, NASA/TP-213726, National Aeronautics and Space Administration, Johnson Space Center, September 2006.

¹⁹Schneider, W.F., et al., ICES-2016-40, NASA *Environmental Control and Life Support Technology Development and Maturation for Exploration: 2015 to 2016 Overview*, 46th International Conference on Environmental Systems, Vienna (2016).

²⁰Drake, Bret, G, editor, *Human Exploration of Mars Design Reference Architecture 5.0, Addendum*, NASA SP-2009-566-ADD, National Aeronautics and Space Administration, NASA Johnson Space Center, Houston, Texas, July 2009, pages 148-154.

Long Pole 8: Human Health/Biomedicine

The Long Pole

Crew health and performance are critical to successful human exploration beyond low-Earth orbit (LEO). The work of NASA's Human Research Program (HRP), see <https://www.nasa.gov/hrp>, is essential to enabling extended periods of space exploration through research and technology development (R&TD) activities that are aimed at mitigating risks to human health and performance. This program delivers human health and performance countermeasures, knowledge, technologies and tools to enable safe, reliable, and productive human space exploration.

This chapter of the AM IV report is derived from the Integrated Research Plan (IRP), see https://humanresearchroadmap.nasa.gov/Documents/IRP_Rev_H.pdf, as maintained by the Human Research Program. The IRP is updated on a regular basis as the evidence base changes, and describes HRP's approach and R&TD activities that are intended to address the needs of human space exploration. As new knowledge is gained, the required approach to R&TD activities may change.

The IRP serves the following purposes for the Human Research Program:

- Provides a means to ensure that the most significant risks to human space explorers are being adequately mitigated and/or addressed.
- Shows the relationship of R&TD activities to expected deliverables.
- Shows the interrelationships among R&TD activities that may interact to produce deliverables that affect multiple HRP Elements, Portfolios, Projects or research disciplines.
- Accommodates the uncertain outcomes of R&TD activities by including milestones that lead to potential follow-on activities.
- Shows the assignments of responsibility within the program organization and, as practical, the proposed acquisition strategy.
- Shows the intended use of research platforms such as:
 - The International Space Station (ISS);
 - NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory on Long Island, NY; and
 - Various spaceflight analog environments including the Human Exploration Research Analog (HERA) at Johnson Space Center (JSC).
- Shows the budgeted and unbudgeted R&TD activities of the Human Research Program, but does not show all budgeted activities, as some of these are enabling functions, such as management, facilities, and infrastructure, and others are internal/discretionary tasks.

Statement of Achievability

The achievability of this long pole – meaning adequate health and performance protection of astronauts during future deep space long duration missions - is expected to be possible based on a risk mitigation strategy that is very focused and applied. Human spaceflight risks include physiological and performance effects from the hazards of spaceflight, such as altered gravity, space radiation, and hostile environments, as well as unique challenges related to medical support, human factors, and behavioral health support. Risks and Concerns within the HRP research portfolio are identified by the Human System Risk Board (HSRB), a function of NASA's Office of the Chief Health and Medical Officer (OCHMO), as those for which research activity is a major component of the mitigation strategies, and are assigned to an Element within the HRP to quantify, mitigate, or monitor.

The HSRB uses the following broad categories of Design Reference Missions (DRM) to provide flexibility in risk characterization and assessment that will be applicable to human space exploration missions yet to be defined:

- Low-Earth Orbit;
- Deep Space Sortie;
- Lunar Visit/Habitation;
- Deep-Space Journey/Habitation; and
- Planetary.

A Risk has a clear likelihood and consequence supported by evidence. Risks in the IRP are assigned Likelihood and Consequence (LxC) ratings (see Figure 1, below) and Risk Dispositions (see Figure 2, below) either from the HSRB or HRP. The LxC ratings are assessed for two consequence categories (in-mission health and performance outcomes [Operations], and long-term health) based on scales defined by the HSRB and have associated colors (red, yellow, green) based on where the scores fall within the risk matrix. A Concern currently does not have sufficient evidence to perform an LxC assessment or determine a risk disposition for a given DRM; the objective of ongoing research is to assemble the evidence necessary to generate an LxC assessment.

HSRB Risk Matrix

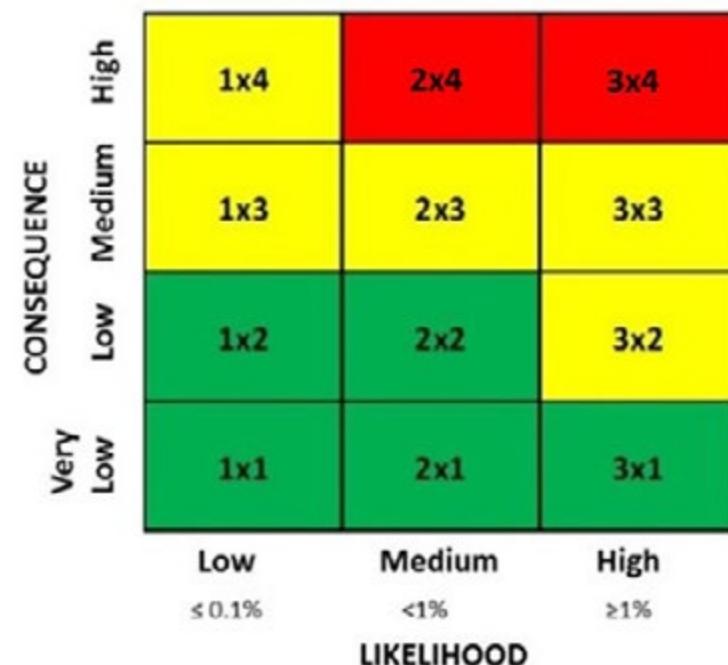


Figure 1. Likelihood by Consequence (LxC) Matrix; Source: Human System Risk Management Plan – JSC 66705

The HSRB maintains a risk record system for approved risk summary reports and supporting evidence for all the risks (including those not assigned to HRP) in its portfolio. This set of information is used by the HSRB to track and monitor the status of the risks, and to inform its decisions. HRP utilizes the HSRB as a forum to communicate updates to risks resulting from HRP R&TD activities.

For each risk, the responsible HRP Element identifies gaps in knowledge that are germane to characterizing the risk and the ability to mitigate the risk. Gaps represent the critical questions that need to be answered to mitigate a risk and therefore serve to focus the areas of research work to address risk reduction milestones. In some cases, a gap may map to more than one risk.

Red Risks For Future Manned Deep Space Missions

1. Risk of Spaceflight-Induced Intracranial Hypertension/Vision Alterations

Astronauts working and living in space during long duration ISS missions have experienced ophthalmic anatomical changes and visual performance decrements of varying degrees, which are hypothesized to be related to increased intracranial pressure secondary to the headward fluid redistribution of weightlessness. Presently these symptoms have manifested themselves as changes in eye structure such as optic disc edema, globe flattening, choroidal folds, cotton wool spots, increased nerve fiber layer and/or decreased near vision along with post-mission spinal opening pressures ranging from 18-28.5 cm H₂O for symptomatic astronauts. Present pre-, in-, and post-flight data indicate that after approximately six months of space flight,

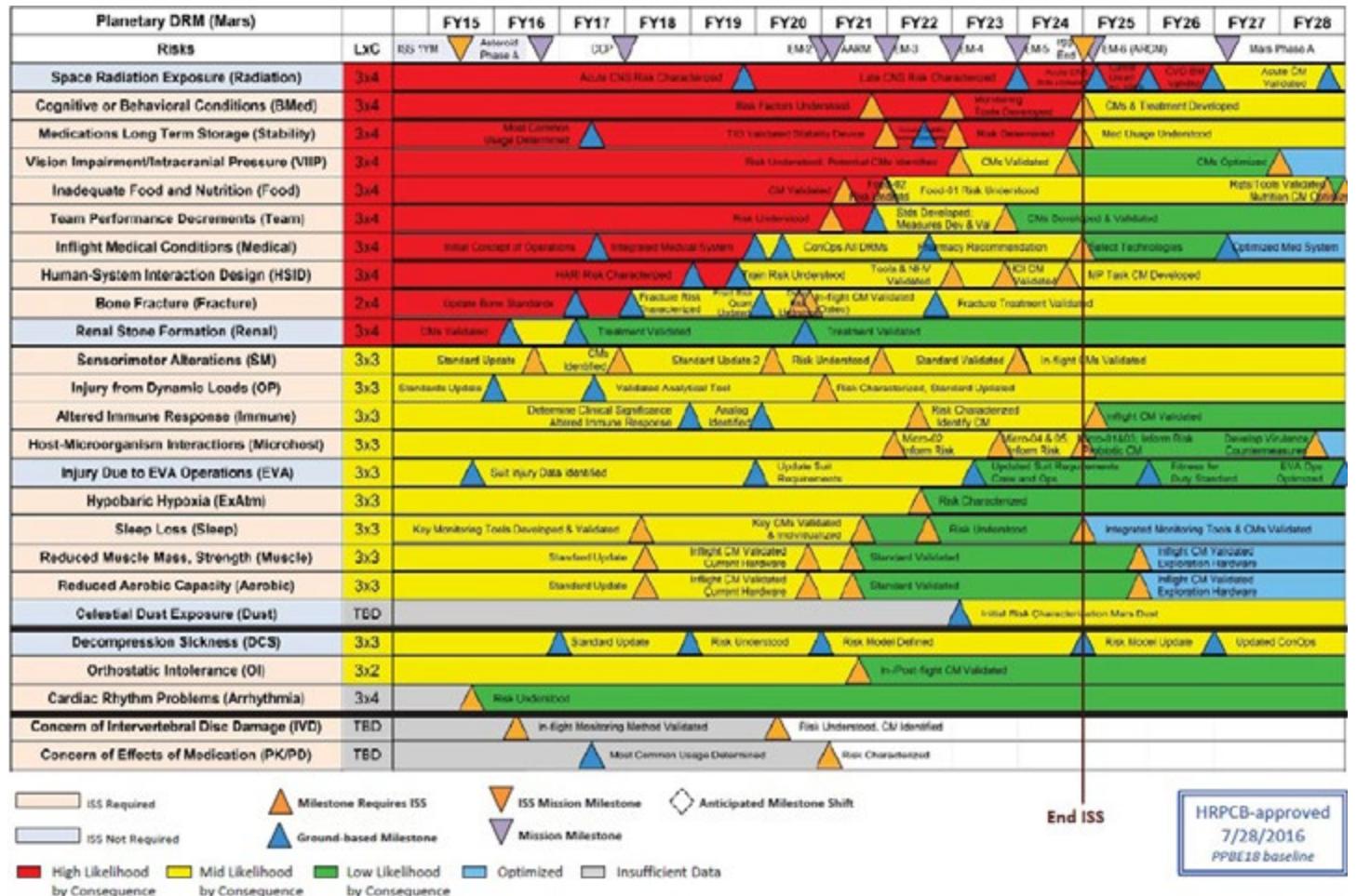


Figure 2. Risk Dispositions as Depicted by HRP's Integrated Path to Risk Reduction (PRR)

21 of 30 U.S. crewmembers that have been evaluated have shown symptoms of the Visual Impairment/Intracranial Pressure (VIIP) syndrome. The cases are graded based on the criteria in the VIIP clinical practice guidelines. The symptoms considered are refractive changes, presences of globe flattening, choroidal folds, cotton wool spots and/or increased retinal nerve fiber layer along with the severity of optic disc edema (using the Frisen Scale). Incidence to date has shown a rate of 70% of those tested with a 20% rate for the most severe clinically significant classes (i.e., so-called classes 3 and 4).

Leading hypotheses for the VIIP syndrome are currently being investigated with a series of ground and flight studies. Ultimately, the goal of both Space Medicine Operations and HRP is a set of preventative and treatment countermeasures for the syndrome. The VIIP Research and Clinical Advisory Panel, comprised of recognized experts in fields relevant to VIIP, monitors progress and provides guidance to NASA.

2. Risk of Cardiac Rhythm Problems

There have been several reports of cardiac arrhythmias during long-duration spaceflight, the most serious being the case of a Russian cosmonaut who was deorbited due to a serious arrhythmia. Some cardiac rhythm problems have been related to cardiovascular disease (CVD), but it is unclear whether this was due to pre-existing conditions or to the effects of spaceflight. It is believed that advanced screening for coronary disease has greatly mitigated this risk. Other heart rhythm problems, such as atrial fibrillation, can develop over time, necessitating periodic screening of crewmembers' heart rhythms. Beyond these terrestrial heart risks, exposure to certain elements of space flight, such as radiation, stress, and altered diet and exercise may potentiate both rhythm disturbances and vascular disease, not only during flight, but for years post-flight.

Limited data are available to definitively establish the individual roles of spaceflight stressors (i.e., exposure to microgravity, radiation, oxidative and mental stress, or lifestyle alterations in diet and exercise) on short-term and

long-term cardiovascular health outcomes. Existing evidence suggests increased vascular stiffness and carotid intimal media thickness immediately post-flight, but it is unclear if these effects persist or resolve over time. It is hypothesized that the cumulative effect of spaceflight stressors might increase the long-term cardiovascular disease risk for crewmembers, although the role of the individual risk factors and the scope of these long-term effects are insufficiently understood. In regard to this cardiac rhythms risk, the research approach of HRP includes retrospective data mining and flight and ground studies to identify the role of the risk factors outlined above. Importantly, many questions regarding these risk factors can only be answered using actual space flight exposures, because it is hypothesized that it is the "total spaceflight environment" (i.e. accumulation of all risk factors listed) that contributes to long-term cardiovascular disease risk. As such, preflight, in-flight, and post-flight crew testing is currently being performed to ameliorate this important risk to crew member health.

3. Risk of Cardiovascular Disease and Other Degenerative Tissue Effects from Radiation Exposure

Recently, several epidemiological studies, including results from atomic-bomb survivors and nuclear reactor workers, have identified an increased risk of stroke and coronary heart disease from low-linear energy transfer (LET) radiation at doses comparable to those of a Mars mission, or a large solar particle event (SPE) during a lunar mission. Because the risk of heart disease as a result of exposure to space radiation has only recently been identified, preliminary studies in these areas are seeking to establish possible distinctions in mechanisms for this risk, between protons, high charge and energy (HZE) nuclei, and gamma rays. As an adjunct, HRP will take advantage of studies by the European Union in this area. These studies should present new insights into the nature of the low LET (e.g., gamma-ray) radiation risk at low dose-rates comparable to space conditions, and should identify appropriate mouse strains to be used in future studies.

Exposure to ionizing radiation is associated with an increased risk for development of heart disease, stroke and other degenerative tissue diseases such as cataracts later in life or well after flight. It is currently unknown whether there are significant synergistic effects from other secondary spaceflight factors (i.e., altered and reduced gravity, stress, immune status, bone loss, etc.) that may alter morbidity and mortality estimates for late effects resulting from space radiation exposures. Once the pathophysiology of radiation-induced CVD is established and well-characterized, research to test potential interactions between radiation exposure and other identified spaceflight factors will be performed as required.

4. Risk of Radiation Carcinogenesis

Near-term goals for cancer research focus on reducing the uncertainties in risk projections through the development of tissue specific models of cancer risks, and the underlying mechanistic understanding of these models, and appropriate data collection at NSRL. In the long term, extensive validation of these models with mixed radiation fields and chronic exposures is envisioned, and research on biological countermeasures and biomarkers will be pursued. Research on improving cancer projections has two major emphases, as follows:

- (1) Testing the correctness of the National Council on Radiation Protection (NCRP) model; and
- (2) Reducing the uncertainties in the coefficients that enter into the cancer projection model.

Research on the validity of the NCRP model relies on studies at the NSRL observing qualitative differences in biological damage - comparing the effects of HZE nuclei and gamma rays (low LET radiation) and the establishment of how these differences relate to cancer risk.

There are distinct mechanisms of cancer induction across and within major tissue sites, and uncertainty reduction requires tissue specific risk estimates. Proposal selections through the NASA Research Announcement (NRA) and NASA Specialized Center of Research (NSCOR) mechanisms focus on cancer affecting the following major organs and sites: lung, breast, colon, stomach, esophagus, the blood system (leukemias), liver, bladder, skin, and brain. There are differences in radiation sensitivity based on genetic and epigenetic factors and research in these areas aids the development of tissue-specific cancer models.

The approach to risk quantification and uncertainty reduction is based on modifying the current model for projecting cancer incidence and mortality risks for space missions. The cancer rate is the key quantity in the evaluation, representing the probability of observing a cancer at a given age and time period (i.e., the number of years) since exposure. The life-span study of the Japanese survivors of the atomic bomb is the primary source for gamma ray data. More recently, however, meta-analysis of data for several tissue types from patients exposed to radiation or reactor workers has become available.

These newer data are being used to check or replace the Japanese atomic bomb survivor data. Other assumptions in the model are made with regard to the transfer of risk across populations, the use of average rates for the U.S. population, age, and age-after exposure dependence of risk on radiation quality and dose rate, etc.

Collaborative research with the Department of Energy's (DOE) Low Dose Research Program remains a key component of the strategy. The DOE program focus is on low LET irradiation; and collaborative grants have been selected from proposals that contain one or more specific aims addressing NASA interests using the NSRL. This research augments research funded by NASA's HRP with a number of grants that use state-of-the art approaches, i.e., genetics, proteomics, and transgenic animal models, etc.

Determining the shape of the dose-response model for cancer induction is a near-term focus that is enumerated in biological terms through various cancer gaps. In the NCRP model, the relationship between dose and response is linear and the slope coefficient is modulated by radiation shielding. Models of non-targeted cancer risk describe processes by which cells traversed by HZE nuclei or protons produce cancer phenotypes in regions of tissue not limited to the traversed cells. Non-targeted effects are the major mechanism that has been identified that is in disagreement with the NCRP model, and they show a sub-linear dose response. The implications of such a dose response for cancer risk are large since such a model predicts a reduced effectiveness for radiation shielding. The importance of mission length is also affected by the sub-linear dose response. For some cancer sites and exposure conditions, for example proton exposures, the NCRP model may be adequate. NSRL research is focused on reducing the uncertainties in the model through the establishment of tissue-specific models of human cancers, and on collection of data at NSRL for a variety of ground-based analogs simulating solar particle events (SPE) and galactic cosmic rays (GCR).

Systems biology models provide a framework to integrate mechanistic studies of cancer risk across multiple levels of understanding (i.e., molecular, cellular, and tissue), and are the most likely approach to replace the NCRP model. Systems biology models are being developed by the Risk Assessment Project and several NSCORs, and, in conjunction with data collection, will improve the descriptions of cancer risk, laying a framework for future biological countermeasure evaluations and biomarker identification.

5. Risk of Unacceptable Health and Mission Outcomes due to Limitations of In-Flight Medical Capabilities

One objective of the HRP is to minimize or reduce the risk of unacceptable health and mission outcomes due to limitations of in-flight medical capabilities on human exploration missions. Medical conditions of varying complexity are expected to occur during these long-duration missions outside of LEO to destinations such as the Moon, asteroids, or Mars. Several factors necessitate increased medical capabilities on such missions. Mission lengths for these missions may range from several weeks to several years, and the number of medical events is expected to increase with mission length. Additionally, mission architecture and orbital mechanics may preclude timely evacuation during certain phases of exploration missions. Further, consultation with medical experts on Earth may be hindered by communication delay or blackout periods. Thus, medical care, including emergency treatment and psychological support, will be rendered by the crew in an autonomous fashion during certain periods.

Genuine difficulties in providing medical care on exploration missions include, but are not limited to, the following:

1. Resource constraints resulting from the boundaries of the mission design and architecture (volume, mass, power) dictating that only the most critical medical equipment can be stored onboard the space vehicles and delivered to the space habitats;
2. The potential for delivery of medical care by a non-physician for missions outside of LEO less than 210 days in length;

3. Limited pre-flight crew training time necessitating tailoring of training to the medical knowledge, techniques and procedures that address the medical situations most likely to occur;
4. The need for crewmembers to be prepared to respond to emergency medical conditions without real-time support from Earth; and
5. The possibility of encountering unpredicted common illnesses, as well as ailments that may be unique to the space environment.

HRP seeks to ensure crew health and secure mission success on exploration missions through:

1. Thorough pre-flight health status assessment, including new technological approaches, and
2. Development of a systematic approach to a more comprehensive autonomous health care system in space.

A first step in mitigation of human health and performance risks is the establishment of human spaceflight health standards. These standards are designed to address acceptable levels of human health and performance risks for exploration missions of varying complexity and duration. The OCHMO has established an initial set of standards that serves to guide the HRP in the expansion of its evidence base regarding human spaceflight health and performance risks. HRP sponsors research and technology development that may require modification or development of OCHMO maintained standards. Additionally, NASA exploration missions may require new knowledge and/or new technology development either to support current standards or to modify standards for mission success. In either situation, HRP in working with the Medical Operations Lead for standards, will determine gaps in knowledge in the current standards and identify tasks to close those gaps.

Incidence rates and outcomes for relevant medical conditions have large uncertainties associated with them due to limited available operational and research data. The Exploration Medical Condition List (<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110008645.pdf>) was created and is analyzed regularly to determine gaps in knowledge about the incidence rates and outcomes of various medical conditions during spaceflight. Tasks are then assigned to further study, model, and use analog population data to better quantify these medical conditions.

In addition, the Exploration Medical Condition List is analyzed for the capabilities required to monitor and treat the conditions based on the DRM defined within the HRP PRR. An analysis is performed to determine where gaps exist in current medical system capabilities and where efficiencies could be realized in the future. Based on when a capability or technology is needed, a technology watch is implemented or a capability development project is initiated.

6. Risk of Bone Fracture Due to Spaceflight-Induced Changes to Bone

The Fracture and bone demineralization (osteoporosis) risks are interrelated by sharing the physiological outcomes of fracture. However, the type of fracture, the causality of fracture, the timing of the fracture incidence and the mitigation approach and resources for the two fracture related risks may be different. The definition of skeletal changes due to spaceflight will inform both risks. The combined research risk approaches are presented below.

To address these risks, it is currently possible to:

1. Track the effect size of long-duration missions by changes in bone mineral density, in biomarkers of bone turnover and in bone structure for the hip and spine,
2. Project if bone losses will occur during a Mars visit, and
3. Use such information to estimate the risk of fracture upon return to Earth after a Mars mission.

However, these capabilities are not part of any requirements documents for lunar or Mars missions. Currently there are indications that, after 6-month missions, bone quality, and thus bone strength, does not recover as quickly as bone mineral density. This discordant recovery dynamic may influence skeletal health after return to Earth and contribute to osteoporosis and fracture risk. Continuing to collect bone quality and bone mineral density data and analyze this information is essential for assessing long-term health risks to returning crew.

In spite of the long history of collecting bone relevant data, there are still gaps in knowledge. Bone atrophy during spaceflight is well recognized and may require mitigation to prevent fractures, but the time course of in-flight bone changes has not been determined. Furthermore, the time course of post-flight recovery and the individual susceptibilities to multiple risk factors have not been defined well enough to assess the probability of fractures. Therefore, NASA solicits and selects proposals to gather these data. In addition, work is ongoing with the Space and Clinical Operations Division to obtain bone surveillance data. This is complicated by the fact that the current bone standards based upon diagnostic guidelines for age-related osteoporosis are not acceptable for assessing skeletal integrity in the younger-aged astronaut following prolonged spaceflight exposure. Thus, per the recommendation of clinical experts, an evidence base from population studies with fracture outcomes is being assembled and analyzed to generate a modified set of operating bands for skeletal integrity in astronauts. Finally, to address early-onset osteoporosis, methods to monitor the combined skeletal effects of spaceflight with effects of aging are required to predict fractures and to determine an intervention threshold to prevent premature, age-related fractures in the astronaut. Overall, the long-term goals of HRP are to develop and deliver countermeasures for long-term missions and to establish the efficacy of countermeasures according to the newly formulated standards for skeletal integrity.

The risk for fracture, however, requires integrating a biomechanical component. The Factor of Risk for fracture is defined as the ratio between the applied load vector to bone and the bone fracture load (which captures both magnitude and direction of load). Thus, the increased fracture risk induced by spaceflight is inferred collectively from the accelerated loss of bone mass, the changes in hip bone structure, and the probability that bones will be overloaded while working and performing tasks in an encumbered, atypical, unknown risk environment. The most critical work needed for this risk requires assessing in-flight changes in bone mass and structure over the course of ISS missions. This increased understanding of spaceflight effects on bone (particularly of hip, wrist, and spine) in LEO is limited but can help inform the probabilistic assessment of fracture risk for a future planetary mission, e.g., to Mars. These data will provide a basis for evaluating whether the expected loads/torques to bone during human performance on a mission will exceed the failure load of bone (i.e., fracture load). This knowledge can be used to direct mission operations planning.

Notably, the Risk of Bone Fracture deals with fractures occurring during a mission up until landing on Earth. The incidence of fractures occurring after return to Earth, in contrast, are the domain of The Risk of Early Onset Osteoporosis Due to Spaceflight. The modalities and medical tests used to assess changes to bone mineral density and bone quality are applicable to both the Fracture and Osteoporosis risks. The independent gaps in the Risk of Bone Fracture address fracture healing and estimating fracture risk during a mission.

7. Risk of Renal Stone Formation

Research into nutrition and in anti-resorptive pharmaceutical agents is evaluating modifications to bone turnover - an established risk factor for renal stone formation. Ultrasound artifact diagnostics are being explored to improve early detection of kidney stones in the renal pelvis. The potential for moving renal stones through application of ultrasound is being developed as a non-invasive approach to providing clinical mitigation of renal stone risks.

8. Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders

Given the isolated, extreme and confined nature and extended duration of future space exploration missions, there is a possibility that

1. Adverse behavioral and cognitive conditions will occur; and
2. Behavioral and cognitive disorders could develop, should adverse behavioral and cognitive conditions be undetected and unmitigated.

We do not have a full understanding of the detrimental impact that spaceflight missions of one-year and longer will have on behavior and performance. Evidence from ground-based analogs suggests there is a significant impact on the performance and behavioral health of individuals. Early detection of risk factors such as increased stress and decrements in cognition due to a variety of spaceflight stressors (e.g., high workload, circadian desynchrony, elevated carbon dioxide [CO₂] levels, space radiation, diet and nutrition, separation from family, limited volume, confinement

and isolation) during spaceflight is important to deter development of cognitive and behavioral degradations or a psychiatric condition that could seriously harm and negatively affect the individual or the crew, and pose serious consequences for accomplishing mission objectives or jeopardizing the mission altogether. Toward this end, HRP is developing methods for monitoring cognitive and behavioral health during long duration exploration missions, and adapting and refining various tools and technologies for use in the spaceflight environment. These measures and tools will be used to monitor, detect, and treat early risk factors. Analogs are utilized to test, further refine, and validate these measures for exploration missions. Countermeasures are also being developed for maintaining and enhancing behavior and performance and for treating cognitive and behavioral problems during and after long-duration isolated, confined, and highly autonomous missions.

9. Risk of Performance Decrements and Adverse Health Outcomes Resulting From Sleep Loss, Circadian Desynchronization, and Work Overload

Objective and subjective evidence indicates that during ISS missions, as on Space Shuttle missions, sleep is reduced and circadian rhythms are misaligned. The average nightly sleep duration of crewmembers for both short and long duration missions is around six hours, with crewmembers showing a significant increase in sleep duration once they return to Earth, indicating a sleep debt may have accrued on orbit. Ground evidence clearly demonstrates that performance impairments can occur when sleep is only attained in restricted quantities similar to that attained by astronauts in flight. While a correlation between sleep quantity and performance during spaceflight has not yet been established, HRP is characterizing the relationship between sleep quantity and vigilance and attention during spaceflight. Future data mining efforts may also yield insights into the relationships between sleep duration and circadian phase with other outcomes (e.g., immune health, operational performance).

Research aims to further characterize and quantify this risk by implementing studies on the ISS using standardized measures to evaluate performance relative to fatigue. Planned data mining efforts seek to further investigate contributors to sleep loss, fatigue, circadian desynchronization, and work overload, by evaluating environmental factors, individual vulnerabilities, and mission timelines. Ground assessments incorporating head-down tilt, varying CO₂ levels and other factors can allow for systematic assessment of additional stressors. The role of sleep and circadian phase in other outcomes will also be further evaluated through research in Earth analogs such as the HERA at JSC.

Such investigations help to inform the optimal countermeasure strategy for mitigating the health and performance effects of sleep loss and related issues in flight. As an example, studies indicate that properly timed exposures to light of appropriate wavelengths can help maintain circadian alignment, and facilitate schedule shifting, performance and alertness. Current efforts aim to determine the operational protocols and technical requirements for lighting systems on the ISS, as well as future exploration vehicles. Other countermeasures that are currently being investigated include recommendations around sleep education and training; sleep-wake models of performance that can inform real time scheduling decisions as well as optimal ways to individualize countermeasure regimens; and investigations that seek to provide educational materials related to sleep-wake medications. The effectiveness of other potentially relevant countermeasure strategies, such as stress management, diet, and exercise, may also be assessed.

10. Risk of Performance Errors Due to Training Deficiencies

This risk focuses on the training of crew and mission support operators, both prior to and during flight, be it in microgravity or on another partial gravity surface. Currently, the training flow begins years before the mission, and crews have commented on the impact of early and drawn-out training on the level of training retention. Historically, spaceflight operations have mitigated potential execution errors in at least two ways: specially-trained crewmembers are assigned to missions or rotated into the operational environment when complex, mission-critical tasks must be performed; and, execution of tasks are closely monitored and supported by ground personnel who have access to far more information and expertise than an individual operator. However, emerging future mission architectures include long-duration operations in deep space. Simply increasing the pre-mission ground training time will not address the need for increased training retention, and may even exacerbate the issue. Deep space operations do not allow for assignment of new crew or rotation of crew to ground for training. Further, delays in communication will have a disruptive effect on the ability of Earth-

based flight controllers to monitor and support space operations in real time. Consequently, it is necessary to develop an understanding of how training can be tailored to better support long-duration deep space operations. This includes appropriate methods for Just-In-Time training, and the extent to which materials, procedures, and schedules of training should be modified. Performance errors of critical tasks may result in crew inefficiencies, failed mission objectives, and both short and long-term crew injuries.

11. Risk of Ineffective or Toxic Medications Due to Long Term Storage

The risks associated with use of expired or degraded medication are well-established. A special area of concern with respect to exploration missions is the safety and efficacy of medications throughout extended missions. HRP seeks to understand how medications are currently being used in spaceflight through a retrospective review of medication use and developing a dose tracker application that is currently in use on the ISS. Direct assessment of medication stability will be performed through a stability study including assessments of effects from room temperature, refrigerated, and radiation environments. Additionally, an in-flight medication analysis device is being developed which could provide point of use assessments for medication.

12. Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System

HRP is optimizing methods to prepare, preserve, package, stow, and ship space food while preserving the nutritional value and acceptability - and minimizing use of flight resources. The retort, irradiation, and freeze-drying processes currently used to produce shelf stable products reduce the nutrient content, and degradation continues through storage at ambient conditions. The nutritional content of 109 flight food items is currently being measured soon after processing, after one year, and after three years of ambient temperature storage to determine whether they meet the nutritional requirements as specified by the nutrition standards and as determined through the Nutrition Status Assessment (https://lsda.jsc.nasa.gov/scripts/experiment/exper.aspx?exp_index=1343). Studies of the stability of food nutrients will identify vitamins and amino acids at risk for degradation in the space food supply, and characterize degradation profiles of the unstable nutrients.

Preliminary shelf life findings have indicated that the current food system is inadequate for long duration missions. A study investigating the effect of the ingredient formulation, the type of processing and packaging, and storage conditions has determined that no single solution will extend the nutrition and acceptability of the food system for longer duration missions. Hurdle approaches combining optimized formulation, packaging, processing, and storage solutions must be investigated. Methods to maintain food system acceptability and nutrition over long duration missions, including implementation of a bio-regenerative pick and eat salad crop supplemental system, are also under investigation.

Reducing the flight resources required for the food system is a major goal due to the significant ratios of rocket size to mass of cargo delivered during an exploration mission. Nutrient dense foods must be developed to reduce the food and packaging mass and volume overhead. Food packaging materials must be developed that are compatible with novel processing technologies, minimize the mass and volume, and provide an adequate oxygen and moisture barrier to maintain the required shelf lives. These studies must provide solutions that overcome resource challenges during extended periods of food storage (i.e., 18 months for ISS, up to 5 years for a long duration mission having pre-positioned food) without compromising nutrition and acceptability.

Conclusion

The biomedical risks inherent in space exploration beyond low-Earth orbit, and in particular those of future human expeditions to Mars, are the primary focus of the research and technology development efforts of NASA's Human Research Program. This work is ongoing and, with the possibility of such missions within the next decade, assumes great relevance to NASA's exploration goals. Efforts to date have quantified the risks to be encountered and have developed meaningful preventive and recuperative capabilities to protect and enhance the capabilities of astronauts participating in those missions. These efforts will continue, with a more applicable and operational focus in response to more well-defined exploration mission requirements. It is the goal of the Human Research Program to reduce the greatest human risks of space exploration missions to maximize astronaut safety, health and performance on what will certainly be the most complex, challenging, expensive and dangerous missions ever undertaken by human explorers.

Long Pole 9: Sustainability

The Long Pole

A sustainable enterprise is able to continue indefinitely until a deliberate decision is made to terminate it. The ultimate basis of sustainability is value – benefit – to stakeholders. Value whose creation and delivery is built into the enterprise design and is then actually experienced by stakeholders, not simply asserted: value that is commensurate with the cost to produce it and value to stakeholders that have sufficient collective leverage to influence outcomes.

Sustainability was judged to be a long pole, a critical capability, because it is an essential attribute of Mars exploration that is both enabled by and results in value to the nation. It will enable Mars exploration to continue after the first several human missions unlike Apollo, which was never designed to be sustainable. It will defeat the “been there, done that” cliché that pervades modern culture and is a threat to sustained Mars exploration and its value to the nation.

Sustainability must be deliberately built in to the enterprise design. It will not just happen. It is often confused with affordability. If the enterprise were affordable surely it would be sustainable. Not so. An enterprise that is sustainable is by definition affordable but an enterprise that is affordable is not by definition sustainable.

Statement of Achievability

Sustainability is achievable. Both portent and guidepost to its achievability is the attention that it has received in high level NASA and stakeholder policies and studies such as:

- NASA Human Exploration and Operations Mission Directorate's Sustainable Exploration Internal Principles (2016);
- National Academies' Pathways to Exploration Report (2014):²¹ “.. recommendations to enable a sustainable U.S. human spaceflight program;”
- Bi-partisan NASA Authorization Act of 2010 human space exploration Long Term Goal²²: “.. to expand permanent human presence beyond low-Earth orbit ...” and to achieve Key Objectives in doing so. A Goal ratified and expanded by the 2015 Pioneering Space National Summit.

Significant contributions to sustainability can be made by embracing proven best practices in stakeholder engagement from other domains and by undertaking changes in NASA's philosophy of human space flight and management structure, changes that respond to opportunities for improvement and to the evolving external environment.

Primary Challenge to Closing the Long Pole:

The primary challenge to closing the sustainability long pole is creating a critical mass and broad portfolio of international partner and in-space economic private sector stakeholders for the human exploration of Mars. A challenge that will require sustained leadership and vision to surmount. A challenge that will require developing and pursuing an architecture that engages international partner and in-space economic private sector stakeholders, even if the architecture involves intermediate destinations or new business models to do so. The first step is a shared vision.

This needs to be solved because these stakeholders are a critical component of sustainability.

Secondary Challenges to Closing the Long Pole:

Secondary challenges to closing the sustainability Long Pole are:

1. Development and deployment of a narrative, a proven best practice of the themed attraction industry to engage stakeholders;
2. Undertaking changes in NASA's philosophy of human space flight and management structure, changes that respond to opportunities for improvement and to the evolving external environment.

²¹National Academies' Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration Report (2014) [<https://www.nap.edu/catalog/18801/pathways-to-exploration-rationales-and-approaches-for-a-us-program>]; ISBN: 978-0-309-30507-5

²²NASA Authorization Act of 2010 [https://www.nasa.gov/pdf/649377main_PL_111-267.pdf]

Narrative, as used in the themed attraction industry to engage stakeholders, is an enterprise organizing principle:

- Narrative shapes the enterprise...shapes and connects the dots. Strategy is narrative;
- Narrative messages enterprise intent, value, and values;
- Narrative engages enterprise stakeholders:
 - ◆ Acknowledges their experiences and beliefs;
 - ◆ Highlights their aspirations, accomplishments, and struggles;

Because narrative drives all three – shaping, messaging, engagement – narrative promotes enterprise coherence and efficacy. In a system engineering sense, narrative is the Level 0 requirement to be deconstructed and flowed down to drive all other requirements.

Narrative is based on value to the nation and opportunity, and it evolves as they do. NASA human space exploration's narrative today should be shaped by:

- The NASA Authorization Act of 2010's mandated long-term goal of NASA human spaceflight to "expand permanent human presence beyond low-Earth orbit;"
- The National Academies' "Pathways to Exploration" Report;
- HEOMD's Sustainable Exploration Internal Principles.

To illustrate the concept, a case can be made that the narrative for NASA human space exploration has evolved to the present as shown in this figure.

Narrative Evolves with Value and Opportunity .. for example:



An arc from the past into the future

Deployment of the narrative should include an enduring strategic engagement campaign developed by relevant professionals making use of best practices from previous such campaigns in other domains.

Changes in NASA's philosophy of human space flight and management structure, changes responding to opportunities for improvement and to the evolving external environment, should include:

- NASA moves from directing to orchestrating in mindset and management process;
- Efficient acquisition methods;
- Improved insight/oversight models;
- Acceptance of appropriate risk;
- Transparent funding processes and priorities.

Time to Close the Long Pole: At least 5 years

Closing the Long Pole Requires Access To (at a minimum):

Closure of the sustainability Long Pole requires access to any intermediate destination of importance to international partner and in-space economic private sector stakeholders. Potential intermediate destinations need to be used as a mechanism to build an ever-increasing base of international partner and in-space economic private sector stakeholders for sustained Mars exploration founded on mutual value. Intermediate destinations include:

- Earth Surface
- International Space Station
- Any Earth orbit
- High-Earth Orbit/Cislunar
- Lunar surface
- Asteroids
- Martian System

Current Strategies to Close the Long Pole and Minimum Success Criteria

NASA is currently undertaking a number of activities and approaches to close the sustainability Long Pole:

- Human Exploration and Operations Mission Directorate's (HEOMD) Sustainable Exploration Internal Principles;
- International Space Station partnerships;
- Global Exploration Roadmap;
- Commercial Crew and Cargo Program;
- Collaboration for Commercial Space Capabilities Program;
- NextSTEP Program.

Additional strategies will be required to address the Challenges to closing the sustainability Long Pole identified here.

The minimum success criteria adequate to close the sustainability Long Pole is international partner and in-space economic private sector stakeholders adequate for indefinite sustainability.

Closing this long pole has commonality with any other long pole that involves technology, systems, capabilities, etc. that could potentially be provided by an international partner or in-space economic private sector stakeholder. Of special note is the logistics dimension of the Aggregation/Refueling/Resupply long pole because of its strong potential to do so.

APPENDICES

Planetary Protection Considerations For Affordable, Achievable and Sustainable Human Missions

An important aim of the AM IV workshop was to consider common elements of different human architectures, and to identify priority near-term actions and investments necessary to ensure achievability in the timescale of about two decades. Now that the main 'long poles' have been identified and examined more closely, it is appropriate to focus on Planetary Protection and associated space policy and regulatory requirements because they represent challenges to different phases of mission plans. A brief overview of planetary protection was presented at the workshop so that sub-groups were informed about current and future implications upon mission architecture and implementation. Integrating planetary protection in the early planning phases will be important to encourage cross-cutting deliberations and planning, and avoid costly re-designs of major systems in later mission phases. It is possible that incrementally improved, integrated and pre-tested systems will also avoid the need for major advances in many systems and substantially reduce overall costs of Mars missions while effectively addressing planetary protection needs. Below is a brief overview of relevant studies, workshops and documents related to planetary protection and human missions to extraterrestrial locations.

Historically, formal discussion of round-trip Mars missions trace to the late 1990s when NASA began considering possible Mars sample return missions and associated needs for biocontainment, handling and test protocols upon return to Earth.²³ Additional workshops and policy deliberations were undertaken by both NASA and various international experts between 2000-2005²⁴ to consider the implications of planetary protection policy for human missions to Mars. Ultimately, these led to updated international policy for human missions beyond Earth orbit, the first such guidelines since the Apollo era.^{25,26} The COSPAR PP Principles & Guidelines for Human Missions, which still provide the current framework for future human mission planning, are based on four overall principles and eight operating guidelines, as summarized in Table 1.

NASA's overall framework for long duration human missions acknowledges that PP requirements will impact missions in many ways.²⁷ While a planetary protection policy is in place for human missions to the Moon and other celestial bodies (COSPAR 2008), it is clear that defined protocols, technologies, and operational details must still be developed to address both robotic and human aspects of mission planning. Moreover, PP information and policies must be integrated early in mission planning to take advantage of synergies and cross-cutting efforts in many development activities.

Already, many aspects of human mission planning are known to involve forward and backward contamination considerations, including: chemical pollutants detection and measurement; biological monitoring, and microbial identification; equipment decontamination, sterilization and reuse; sample containment and handling; advanced life support systems (ALS), including closed-loop recycling capabilities and waste handling & disposal; Extravehicular Activities (EVA) and equipment, including suits & associated life support and ingress/egress concerns; subsurface drilling equipment and operations; ISRU systems; laboratory-habitat separation; quarantine capabilities; and possible robotic teleoperations for pre-cursor sampling and characterization. Fortunately, because missions to bodies like the Moon and asteroids are not constrained by planetary protection considerations, they can provide useful testbeds for technology and operations development that feed-forward to human missions on Mars surface.

In order to move from current qualitative PP guidelines to detailed quantitative requirements, the PP Subcommittee (PPS) of the NASA Advisory Committee (NAC) adopted NPI 8020.7²⁸ outlining an incremental process as a path forward towards future development of NASA Procedural Requirement (NPR) for Human Missions. A key part of this path forward included convening a Workshop on Planetary Protection Knowledge Gaps for Extraterrestrial Missions, which analyzed and identified key knowledge gaps in three areas important to planetary protection: (1) microbes and human health; (2) technology and operations for contamination mitigation and control, and (3) understanding natural dispersal/survival of microbes under martian conditions.²⁹ The workshop participants identified over two dozen specific R&TD topics that must be addressed before comprehensive PP requirements can be formulated. A subsequent COSPAR international workshop³⁰ built upon the NASA Workshop findings, prioritized the R&TD gaps that were identified, and assessed different locations and mission prospects as possible test-beds to address gaps and study the effectiveness of planetary protection practices (i.e., Earth analogues & simulations; ISS, lunar & cislunar; Mars, Phobos/Deimos). The COSPAR report is currently in preparation and should be available in mid-2017.

For more background information on Planetary Protection, including links to diverse NASA and COSPAR reports, refer to the Documents section of the NASA Planetary Protection Website: <https://planetaryprotection.nasa.gov>

²³NASA, 2002. A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth. (J.D. Rummel et al. (eds.), NASA/CP-2002-211842, Washington DC Available: <https://planetaryprotection.nasa.gov/summary/DraftTestProtocol>

²⁴Among the noteworthy early human workshop reports on planetary protection are:

NASA 2005, PP Issues in the Human Exploration of Mars, NASA/CP-2005-213461 (workshop held 2001) Available at: <https://planetaryprotection.nasa.gov/documents>

NRC, 2002. Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Surface of Mars. NRC, Space Studies Board. <http://www.nap.edu/catalog/10360.html>

MEPAG, 2005. Report of the MEPAG Mars Human Precursor Science Steering Group: An analysis of the Precursor Measurements of Mars Needed to Reduce the risk of the First Human Missions to Mars (D.W. Beatty et al., JPL Doc. I.D. CL#05-0381 (2005). <https://planetaryprotection.nasa.gov/documents>

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²⁵COSPAR Principles and Guidelines for Human Missions to Mars, page A-5 in: COSPAR Planetary Protection Policy: <https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf>

²⁶Conley, C.A. & J.D. Rummel, 2008. Planetary protection for humans in space: Mars and the Moon. *Acta Astronautica* 63, 1025-1030

²⁷NASA, 2012. Mars Design Reference Architecture 5 (DRA), Addendum 2.0, Section 13, Planetary Protection, pages 78-84. Available: <https://planetaryprotection.nasa.gov/documents>

²⁸ NASA Planetary Protection Procedural Requirements Document for Human Extraterrestrial Missions (NPI 8020.7). See *Introductory Material* Section on: NPI 8020.7 and Path to Requirements, by B. Siegel on <https://planetaryprotection.nasa.gov/humanworkshop2015/>

²⁹ NASA Workshop on Planetary Protection Knowledge Gaps for Human Extraterrestrial Missions, 2015. (Rpt. published 2016): <<http://hdl.handle.net/2060/20160012793>>

³⁰ COSPAR Workshop on Refining Planetary Protection Requirements for Human Missions, 2016. (publication expected in mid-2017)

Workshop Participants

TABLE 1: COSPAR Planetary Protection Principles and Guidelines for Human Missions

[Summarized from: <https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf> (page A-5)]

PP PRINCIPLES for Human Missions

- ★ Safeguarding the Earth from potential back contamination is the highest planetary protection priority in Mars exploration.
- ★ The greater capability of human explorers can contribute to the astrobiological exploration of Mars only if human-associated contamination is controlled and understood.
- ★ For a landed mission conducting surface operations, it will not be possible for all human associated processes and mission operations to be conducted within entirely closed systems.
- ★ Crewmembers exploring Mars, or their support systems, will inevitably be exposed to martian materials.

PP IMPLEMENTATION GUIDELINES for Human Missions:

- ★ **Continuous monitoring and evaluation** of terrestrial microbes will be needed to address forward and backward contamination concerns
- ★ A **quarantine capability** (for individuals & entire crew) is needed during and after the mission
- ★ There is a need to develop comprehensive planetary protection **protocols for combined human and robotic aspects of missions**
- ★ **Neither robotic systems nor human activities should contaminate “Special Regions”** (water/ices)
- ★ **Uncharacterized sites** should be **evaluated by robotic precursors** prior to crew access
- ★ **Pristine samples** or sampling components from uncharacterized sites or Special Regions should be **treated as planetary protection Category V, Restricted Earth Return**
- ★ An **onboard crewmember** should be designated as **responsible** for implementing planetary protection measures during the mission
- ★ **Planetary protection requirements** will be **based on conservative approach** and not relaxed without scientific review, justification, and consensus

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