Affordable Exploration of Mars: Recommendations from a Community Workshop

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There is a growing opinion that within two decades initial human missions to Mars are affordable under plausible budget scenarios, with sustained international participation, and --- especially --- without requiring those first missions to achieve a burdensome number of goals. In response to this view, a group of experts from the Mars exploration stakeholder communities attended the "Affording Mars" workshop at George Washington University in December 2013. Participants reviewed scenarios for proposed affordable and sustainable human and robotic exploration of Mars, the role of the International Space Station as the essential early step toward humans to Mars, possible "bridge" or "transition" missions in the 2020s, key capabilities required for affordable initial missions, international partnerships, and usable definitions of affordability and sustainability. We report here the findings, observations, and recommendations that were agreed to at that workshop. In the context of affordable early missions to

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Mars, we also discuss the recent report of the National Research Council on human space flight and a pair of recent scenarios that appear to promise reduced costs.

"By the mid-2030s, I believe we can send humans to orbit Mars and return them safely to Earth. And a landing on Mars will follow." --- President Barack Obama, April 15, 2010

I. Introduction: Achieving an Affordable and Sustainable Path to Mars for Human Explorers

Human exploration of Mars has been identified for decades as one of the most compelling goals for human space flight in the post-Apollo era and has been for some years the highest-priority long-term goal for NASA. Over the past several years, significant experience in long-duration human space operation has been gained using the International Space Station (ISS). More recently, design concepts have been presented by groups inside and outside space agencies that build upon this experience to enable far less-costly approaches than have been previously considered possible.

Moreover, there is continuing strong public interest in humans exploring Mars. As demonstrated in the recent Mars Generation Survey, Americans overwhelmingly support human and robotic Mars exploration. Among the findings of this scientific national poll were that 71 percent of Americans believe we will land humans on Mars by 2033 and 75 percent believe that NASA's budget should be doubled to one percent of the U.S. federal budget to fund initiatives including a human mission to Mars. Complete results of the poll can be found at http://www.exploremars.org/wp-content/uploads/2013/03/Mars-Generation-Survey-full-report-March-7-2013.pdf

II. The Affording Mars Workshop

In response to this broad support for human Mars exploration, the first *Affording Mars Workshop* was planned to assess what is necessary to make initial missions feasible, sustainable, and affordable. Hosted jointly by Explore Mars, Inc. and the American Astronautical Society, the invitation-only workshop was held on December 3-5, 2013 at George Washington University. This three-day workshop began with overviews of current scenarios for human missions to Mars, the future plans for capability development on ISS, the case for scientific robotic exploration of Mars, and opportunities for international partnerships. Breakout sessions addressed topics such as "What is affordability?" and how it can be incorporated into mission planning, including prioritization of capabilities and technologies. Other breakout sessions dealt with precursor missions, current scenarios for human Mars exploration, and building on ISS experience in the management of complex programs. Workshop participants and other documents can be found at http://www.exploremars.org/ .

Approximately sixty individuals participated in the workshop. These participants came mainly from NASA, industry, and academia and were intended to be representative of the broad community of stakeholders in human space flight. The results of the workshop, including the findings and recommendations, have been presented to NASA leadership, Congress, and at professional conferences.

Although the workshop discussed Mars scenarios extensively, the goal was not to evaluate them in depth, a goal intended for a follow-on workshop in autumn, 2014. Instead, the workshop primarily addressed the many hindrances to sustained human exploration programs. These include issues such as current loss of technological capability, shrinking budgets, lack of planned compelling missions, and the need for sustained political commitment over multiple U.S. administrations. Output of the meeting was a set of near-term recommendations that support human spaceflight beyond low-Earth orbit (beyond ISS) to enable humans on Mars in the 2030s. See Figure 1 for examples considered at the workshop of notional concepts for human exploration. A selected bibliography of recent papers and presentations used at the workshop is at the close of this report.

A. Workshop: Structure, Findings, and Observations

A few ground rules and assumptions were adopted by the planning team to allow the workshop participants to focus on a manageable number of major issues.

- SLS and Orion will be available during the time periods considered by the workshop.
- The International Space Station will play a critical role in preparing to travel beyond LEO.
- Robotic missions will enable human missions to Mars.
- There are emerging scenarios and capabilities that will influence mission architecture and planning over the next two decades.

This paper summarizes the observations from three topical breakout sessions:

1. The ISS and the path to Mars: The critical coming decade
2. Affordability and sustainability: what does it mean and what are its implications within guidelines established at the start of the workshop?

3. Notional sequence(s) of cost-achievable missions for the 2020s to 2030s, including capability objectives at each stage and opportunities for coordinated robotic partnerships

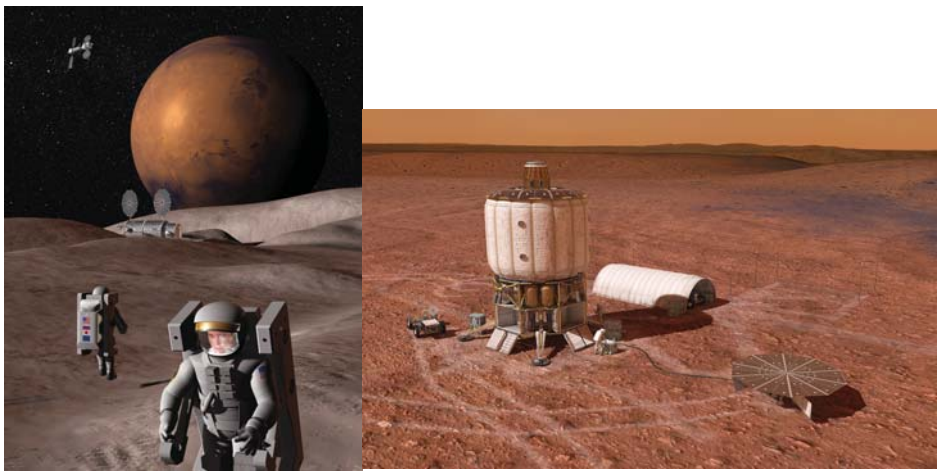

Figure 1. Conceptual martian moon (left) and surface (right) exploration of the type discussed at the workshop. [Courtesy: Lockheed Martin (left); Boeing Corporation (right)]

B. Workshop Principles of Agreement

The workshop participants agreed on a handful of top-level principles intended to guide decision-makers:

- Mars should be the overarching goal of human space flight over the next two to three decades, consistent with U.S. space policy.
- Identifying and solving key technical gaps over the next several years will be important in making the human exploration of Mars feasible by the 2030s. Between now and then, human exploration of deep space must be prioritized in a manner that advances the objective of human exploration of Mars starting in the 2030s. Alternative major goals for human space flight will be costly diversions.
- Taking advantage of ISS, especially including international partnerships, is essential for human missions beyond LEO and, especially, to Mars.
- Continuation of robotic precursor missions to Mars throughout the 2020s is essential. The robotic Mars exploration science strategies of NASA and ESA should be coordinated with humans-to-Mars efforts while preserving their primary science objectives.
- International and industrial partnerships, efficiency, consistency of purpose, and policy/budget stability are the required elements to allow a two-decade-long humans-to-Mars (H2M) effort to succeed.

C. Breakout Session Findings and Recommendations

Breakout Session #1: The International Space Station (ISS) as a Platform to Advance Exploration

ISS is playing a pivotal role in support of future missions beyond LEO. The following is a summary of the numerous roles for ISS as a platform for exploration beyond LEO, including H2M.

- Long-duration human exposure to microgravity by a wide range of crew members to develop a statistical database to understand how to reduce risk.
- Fundamental physiology research supporting long-duration missions.
- Platform for long-duration testing and exposing hardware to a space environment such as life-support systems to demonstrate reliability and reduce logistics supply chain.
- Demonstration platform for mission operations concepts relevant to Mars missions, such as in-space telerobotic control of robotic systems, contingency and exploration-class EVA suits and capabilities.
- Using ISS as a platform for testing multi-vehicle proximity operations such as rendezvous and docking relevant for assembling very large spacecraft stacks.
- Using ISS to assess Mars mission capability gaps.

➢ *Recommendation 1*: Review current ISS logistics demands and processes to determine those areas that could be modified to more closely mimic initial Mars missions.

- *Recommendation 2:* Perform an analysis elaborating which tasks are most effectively and efficiently performed on ISS versus a hypothetical cis-lunar facility to provide a basis for comparison.

Reflections on commercial activity in LEO: An affordable human exploration program will be augmented by the transition of government-led activity in low-Earth orbit to non-government organizations. This will include commercial launch and delivery capabilities for crew and cargo in support of ISS operations and expanded utilization and funding support from other U.S. government research organizations as well as academic, commercial, and international research entities. Continuing NASA's efforts to enable a LEO-focused research and utilization constituency/community and an operational framework could eventually free NASA's ISS operational resources to be directly applied to exploration-related missions or activities beyond LEO.

The ISS program and NASA must engage key stakeholders, including Congress, the public, and potential users in defining its role as the initial "stepping stone" to Mars.

- *Recommendation 3:* ISS program is encouraged to continue to work with technology communities to assess how ISS could be used to support the development and demonstration of relevant exploration capabilities.

This breakout session included extended discussion of an interim or transition step in the 2020s between human spaceflight in LEO and human missions to Mars. One option discussed is a modest, short-lived human-tended facility in the vicinity of the Moon to serve as a transition from ISS to the long-duration habitat necessary for Mars missions[10]. [Other options for interim missions (e.g., lunar exploration, asteroids, etc.) were covered in Session 3.] Illustrations of proposed designs for two such facilities are shown in Figure 2.

Such a facility could be important during the early 2020s in advance of initial missions to Mars to demonstrate crew operations in a deep-space environment. The workshop group discussed a number of concepts for such a "bridge" facility. Although no specific concept was favored by the participants, there was consensus agreement on its importance and potential capabilities. Such a facility could

- Continue the international partnerships developed on ISS
- Demonstrate both human and untended/autonomous systems-level operations in deep-space
- Develop capabilities for deep-space operations that must be less dependent on Earth
- Temporarily sustain operations that demonstrate progress toward missions to Mars
- Provide an opportunity to extend commercial crew and cargo programs beyond LEO to circumlunar space
- Establish a potential assembly site for large Mars-bound spacecraft that cannot be launched on a single SLS flight (See the scenarios discussed in Section IID)

- *Recommendation 4:* The ISS program should

  - Define objectives and conceptual designs for this "bridge" facility, including the options for using hardware supplied by international partners
  - Evaluate the objectives that must be satisfied, and determine the most efficient and effective way of achieving them: via ISS, a habitation facility on orbit in the lunar vicinity, or other option.

[10] Human operations from the Earth-Moon L1 or L2 location has been extensively assessed for more than half a century since Arthur C. Clarke's *A Fall of Moondust* in 1961. These venues are attractive sites for lunar surface exploration and a number of scenarios use them as rendezvous, staging, and departure locations for missions to Mars (see Section IID).

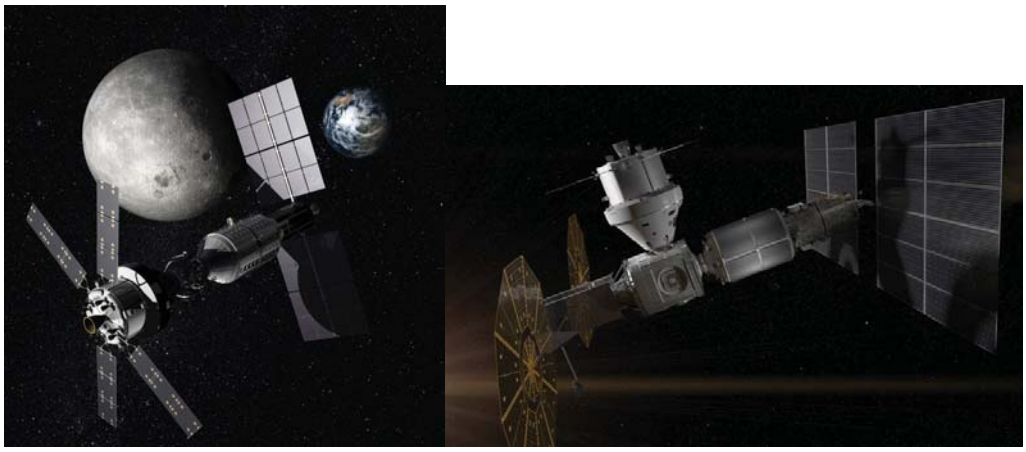

Figure 2: Deep-space habitation facilities for the 2020s using ISS-based designs and components. (Courtesy: Lockheed Martin (left image), The Boeing Corporation (right image))

Breakout Session #2: Affordability and Sustainability of Human Mars Exploration

Considerable discussion at the workshop was devoted to the definition of "affordable" in the context of human missions to Mars, especially the initial ones. In a breakout session devoted to this topic the following definition was adopted for the purposes of the workshop: *A strategy that enables success within a budget and timeframe justified by the importance of mission goals.* That is, an "affordable" mission is that which political leaders were willing to support. In effect, this definition recommends adding a political Level 0 requirement to planning architectures for Mars exploration: in effect, the workshop participants recommended that human space flight architectures are fundamentally incomplete without an analysis of whether they are likely to be funded by the political leaders. In addition, "sustainable" in the context of the workshop was used politically and financially, in contrast to engineering sustainability. That is, there was general agreement that engineering solutions can be found to sustain human Mars missions and the greatest challenge facing a successful program is political commitment and sustainability. As with affordability, political sustainability must be included as a Level 0 requirement.

Discussion around these definitions led to the workshop conclusion that successful human exploration beyond LEO will likely require incremental mission planning and execution; international, governmental, and private sector partnerships; policy/mission consistency; openness to developments that could potentially foster new and efficient program advancement; and political commitment for sustained support for agreed-upon priorities for space exploration. Examples of how this may be achieved include

- Incremental Approach: An incremental approach will be required to achieve human travel to Mars within constrained budgets. The incremental approach allows for modest elements of the overall plan to be assessed and budgeted. These elements can also be offered for bid to private or international partners.
- Avoid Single-Use Hardware: Architectural elements, including point designs that support multiple customers and multiple goals are highly desirable because it spreads fixed cost bases and avoids repeated non-recurring engineering costs.
- Space agency budgets should at least keep pace with a realistic measure of inflation. Currently NASA's budget is inadequate to support its programs. Current flat budgets are not realistic and result in reduced buying power over time. Modest increases above inflation will be necessary to achieve adequate support of this and other NASA priorities.
- Alternate Models: Alternate acquisition and development methods should be considered to enable efficiency, such as creating a hybrid contracting approach, and employing other innovative management approaches. These could include streamlined government oversight and Skunk Works/Phantom Works-like structures.

Establishing a well-thought-out, widely vetted, and compelling plan for the initial human missions to Mars with a regular cadence of achievements is the highest priority for the national space agencies. Sustainability and affordability of this plan can be achieved. To do so it is also important that the space community and policymakers agree on and construct a strategy that incorporates the following suggested principles:

- All human space exploration and related robotic activities must be prioritized and conducted with the requirement that a human landing on Mars is the overarching and eventual goal for human space flight. Deviation from this will lead to delays from which it will be difficult to recover.
- Continuity and stability of programs and budgets: budgetary and policy consistency are essential. As such, the space communities need to design programs/missions that lend themselves to budgetary stability and take an incremental approach to constructing a program. Budgetary increases for inflation must also be included *as a minimum*, so that NASA and our international partners' buying power can be maintained for the duration of this long-term program.
- Full use should be made of current relevant capabilities such as the ISS, robotic precursor missions to Mars, and the technology development programs of NASA, industry, and international partners.
- Robotic and human precursor missions will be necessary and must clearly advance capabilities required for crewed missions to the surface of Mars.
- Provide a clear return for stakeholders by developing missions and capabilities in concert with national and international partners. Development of partnerships among industry, academia, other government agencies, and multiple agency directorates will allow leveraging of resources and talent.
- Establish ambitious dates for compelling near-term milestones to enable efficient use of resources and expedited management, while protecting sufficient flexibility to adjust for developments of capabilities, new discoveries, and changing political environments. Example milestones over the coming decade include

    - Successful demonstration of SLS and Orion
    - A Mars "free-return" mission using SLS and Orion
    - Sustained robotic science-driven exploration coordinated with human space flight goals
    - Regular progress on relevant technology capabilities developed on ISS
    - Deployment of a transitional deep-space facility in the early 2020s

  Consistent and continuous communication is essential, including

    - Assuring that stakeholders (political leaders, policy makers) are fully informed of progress, program goals, and the criticality of stable budgets.
    - Developing a coalition of advocates from industry, government, academia, human space flight, and science communities who share a common interest.
    - Clearly and regularly communicating to the public the achievements and benefits of the program.

Breakout Session #3: Notional Sequence of Missions Leading to Humans on Mars

The third breakout session of the workshop concentrated on potential mission sequences for achieving a human mission to Mars. This set of precursor missions, along with the first human landing mission, can be thought of as an end-to-end campaign, and the different options for achieving that campaign are options. The purpose of the third breakout session was to begin the process of assessing these options.

It became clear at the start of the breakout session that a top-level set of accomplishments and requirements must be established and generally agreed-upon by stakeholders. While it was beyond the scope of a three-day workshop to define such requirements, the following list was used to guide the discussions:

- Human Mission to Mars by the 2030s
- Incremental Approach: Near-Term and Regular Accomplishments
- Realistic Budgets
- International Program
- Public and Stakeholder Engagement
- Sustainable Approach
- Clear Science Objectives

➢ *Recommendation 5:* Development and vetting of a set of highest-level requirements must be undertaken now for initial human Mars missions in the 2030s to guide investments over the coming decade.

This breakout session focused on developing a list of potential precursor missions that could be used leading up to a human landing mission. The participants purposefully decided to "cast a wide net" so that most relevant mission concepts would be considered. The resulting list of potential missions is long and is naturally tied to

particular Mars mission architectures. The discussion emphasized the progressive extension of capabilities along the pathways. For example, the proposed NASA Asteroid Redirect Mission (ARM) demonstrates longer crew durations outside the Van Allen belts, tests Orion systems, and uses solar electric propulsion (SEP) to move the large mass of the asteroid into a Distant Retrograde Orbit (DRO).

Assessing mission options is just beginning and will be the purpose of our follow-on workshop in autumn, 2014, although there are several clear findings from the breakout session:

- Interactions between the NASA Human Exploration and Operations and Science Mission Directorates participants were highly beneficial. Each group brought strengths that complemented the other.
- International cooperation brings program stability, although also includes challenges.
- There appear to be no technical "showstoppers" for a human Mars mission, although several technical challenges remain to be addressed. The most common examples expressed at the workshop were entry, descent, and landing techniques and radiation protection.
- There are also several emerging technology opportunities. A frequently mentioned example was solar electric propulsion.

➢ *Recommendation 6*: Detailed assessment of mission options is a priority effort that will require dedicated resources and sufficient analysis time. This activity is proposed to take advantage of the Global Exploration Roadmap (GER) and associated activities, although with more detailed engineering analysis.

D. Relevant Assessments Published Subsequent to the Workshop

Three studies relevant to the workshop's recommendations were completed and published after our workshop concluded: The National Research Council's *Pathways to Exploration*[1] (hereafter *Pathways*), Addendum #2 to NASA's Design Reference Architecture 5.0[2] (hereafter DRA 5.0-2), and the Boeing/Roscosmos scenario for human Mars exploration[3] (hereafter BR). It is beyond the scope of this paper to discuss these three works in depth. Here we summarize a selection of their results that are most directly relevant to our workshop recommendations discussed in previous sections.

The NRC's *Pathways* report presents an extensive, detailed assessment of approaches for human exploration of Mars over the next few decades. Relevant to our workshop, the committee that authored this report emphasize that at least modest increases in NASA's budget appear to be required for sustained human missions beyond LEO (cf., Sections 1.6 and 4.4). Findings and recommendations in *Pathways* that are generally the same as those identified via our workshop include

- Mars is the most compelling long-range goal for human space flight and NASA's investments and operations toward this goal should not be compromised by diversions and unrelated goals
- International participation is important and, perhaps, essential for human exploration beyond LEO
- NASA and partners should concentrate in the very near term on a small, essential handful of technology priorities
- NASA's human exploration of Mars should proceed via a series of "stepping stones" of increasing complexity, capability, and visibility
- A risk-mitigation plan should be adopted by NASA to prepare for unexpected developments

The *Pathways* study makes it clear that a specific architecture was not being advocated for NASA and its international partners. However, characteristics of a attractive architectures were recommended, which was generally similar to the deliverables of our workshop, although the *Pathways* study had much greater depth. That said, the architecture assessed in greatest detail by the *Pathways* committee (i.e., "Enhanced Exploration," somewhat similar to the very ambitious NASA DRA 5.0) served as an instructional contrast with a pair of similar architectures produced at about the same time by BR and DRA 5.0-2 (cf., Section 3.3 by C. R. Mercer, S. R. Oleson, and B. G. Drake). Notably, the latter two studies included candidate initial Mars scenarios that appear to be substantially more affordable than the *Pathways* "Enhanced Exploration" mainly due to some of the characteristics also identified by our workshop: (1) fewer early goals, specifically landing humans on the martian surface, and (2) use of existing or near-future technologies, specifically storable in-space propellants and solar-electric propulsion.

III. Conclusion

Affordability and sustainability will require dedicated effort. Careful coordination among stakeholders, NASA, industry/commercial, and potential international partners will be required. The human space flight stakeholders must initiate sustainable programs that will clearly advance the goal of initial missions to Mars by the mid-2030s. A logical, affordable architecture with a campaign of mission "stepping stones" and elements

must be developed. Management efficiencies and flexibility must be incorporated based on lessons learned from ISS, commercial programs, and other past NASA programs, as well as from DOD and industry. Above all, political and budgetary stability is essential over two decades. Accomplishing the goal will require a policy and budget commitment over multiple U.S. Congressional and Presidential elections as has been done for other major undertakings in history. Sending humans to Mars is far less an issue of cost than it is of commitment.

Human and robotic exploration of space is critical to national prosperity, security, scientific and technological progress, and leadership, as well as demonstration of cultural leadership. With clearly defined exploration goals, we have a chance to maintain and further our intellectual and technological capabilities and leadership. Our national stakeholders expect U.S. leadership. Furthermore, our international partners are awaiting NASA leadership in international space exploration. These expectations and the ability to build on our heritage and past investments are not timeless and must be exploited before the opportunity slips away. The international space community is widely recognized by the public for filling these needs and this community is prepared to write the next chapter in the exploration of space: Humans to Mars!

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