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

Report of the

Second Mars Affordability and Sustainability Workshop

October 14 – 16, 2014
The Keck Institute for Space Studies
The California Institute of Technology
Hosted by the NASA Jet Propulsion Laboratory

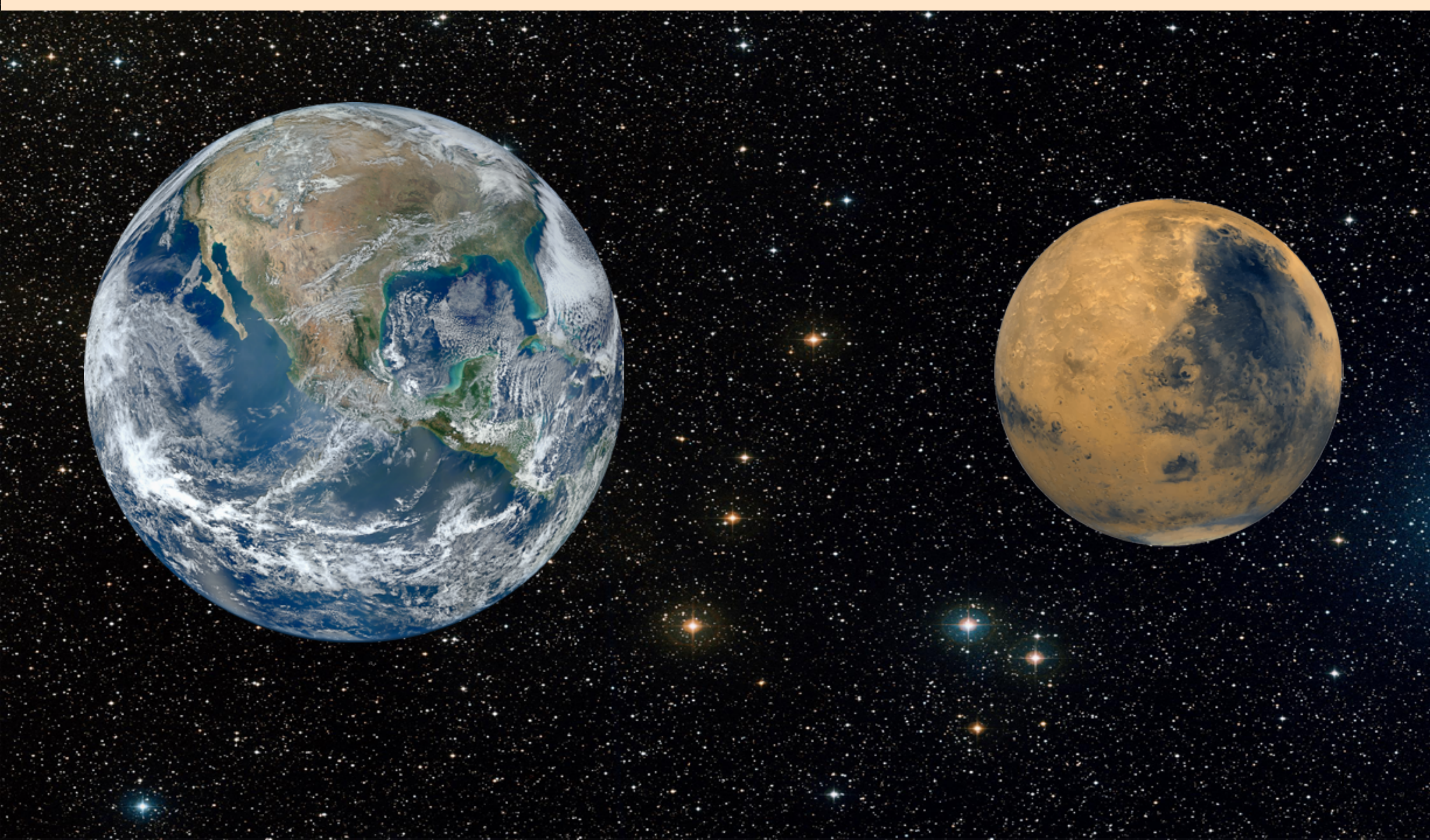
Organized by *Explore Mars, Inc.* and the *American Astronautical Society*

Chris Carberry (Explore Mars, Inc.),
Harley Thronson (American Astronautical Society & NASA GSFC),
& Richard Zucker (Explore Mars, Inc.)
Senior Editors

Joe Cassady (Aerojet Rocketdyne), Kevin Foley (Boeing), Jim Garvin (NASA GSFC),
Josh Hopkins (Lockheed Martin), & Sam Scimemi (NASA HQ)
Breakout Session Chairs and Associate Editors

OVERVIEW

To continue building community consensus on the future of human space exploration, the Second Mars Affordability and Sustainability Workshop (AM II) was hosted by the Jet Propulsion Laboratory (JPL) and held at the Keck Institute for Space Studies (KISS) conference building on the Caltech campus in Pasadena, CA, October 14 – 15, 2014. Approximately 60 invited professionals from the industrial and commercial sectors, academia, NASA, and the Canadian Space Agency participated in the workshop. These individuals were chosen to be representative of the breadth of interests in astronaut and robotic Mars exploration. AM II continued the work that began with the first Affording Mars Workshop (AM I) in 2013. AM II conducted side-by-side comparisons of potential Mars mission architectures and strategies, discussed potential science goals associated with architectures for human missions to Mars, and examined how to design and advance a humans-to-Mars program that is fiscally and politically sustainable. The output of the workshop consists of observations, findings, and recommendations intended to guide space agency leadership and national policymakers.



SUMMARY WORKSHOP FINDINGS & OBSERVATIONS

- An international human mission to the surface of Mars in the 2030s is recommended, although such a mission will require sufficient and stable long-term funding, as well as a critical series of risk-reduction activities in the 2020s. A key example is a long-duration crew habitation system in cis-lunar space that transitions from the essential facility, ISS, to the systems necessary for human Mars exploration. [*Sections II and IV*]

- Initial human missions to the surface of Mars should include elements necessary for eventual establishment of sustainable surface outposts broadly analogous to the initial phases of science-guided Antarctic exploration on Earth. Our workshop did not endorse one-way missions to Mars, where the humans on the first mission are settlers. AM II concluded that significant public support and inspiration derives from the national pride of having astronauts from participating countries return to Earth to be celebrated. [*Section II*]

- The workshop concluded that a robotic sample return mission may be required to learn how to protect against forward and backward contamination before humans land on Mars. [*Sections II and III*]

- Human-enabled science exploration of Mars should be a major element of any human space flight architecture. One potentially advantageous precursor activity is an all-robotic sample return to demonstrate high-mass entry, descent, and landing capabilities scalable to human-scale landers. [*Sections II and III*]

- Human missions to Mars orbit or the martian moons may be essential for risk reduction as immediate precursors to surface missions, which ultimately are the priority goal for human space flight. [*Section II*]

- Workshop subject matter experts in Mars geology and astrobiology with experience with high-latency telepresence (HLT; long light-travel time: e.g., MSL Curiosity, the twin Mars Exploration Rovers) assessed advantages of low-latency telepresence (LLT; short light-travel time). Quantitative studies of scientific benefits of LLT operations made possible by astronauts in proximity to surface robots would be required to adequately compare LLT versus HLT operations. As such studies are presently unavailable, they were not a factor in developing the findings on telerobotic exploration of Mars. Future work in this area is recommended. [*Section III*]

- Space agencies should more fully engage the broad community of partners in the definition of human exploration architectures and should employ the effective processes exemplified by the Global Exploration Roadmap. [*Sections II and IV*]

- The scientific goals for lunar exploration are compelling (i.e., see the 2011 NRC Planetary Decadal Survey and 2007 Scientific Context for Exploration of the Moon). However, the technical capabilities required for human lunar surface operations are of limited applicability to human Mars exploration. [*Section II*]

- NASA and its partners must further develop new management processes and efficiencies, as well as acceptance of reasonable risk. [*Section IV and the report from the AM I workshop*]

- Space agencies, along with their academic and industrial partners and national policymakers, must continue to develop together and effectively communicate the motivation and quantifiable goals for the future of human space exploration. The "story" of human space exploration must be comprehensive and coherent with each activity on the way to the surface of Mars readily understandable by the general public. [*Section II*]

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I. Background, Goals, and Structure

Planning for the second in a continuing series of Affording Mars workshops (AM II) began shortly after AM I concluded in December 2013. These workshops, organized jointly by Explore Mars, Inc. and the American Astronautical Society, bring together stakeholders from industry and commerce, academia, government, and the space communities and are intended to be representative experts in their respective fields.

AM I, which was held in Washington, D.C., concentrated on industry and government policies and practices that limit cost and schedule savings for initial human missions to Mars. [More information about AM I and its deliverables may be found at http://www.exploremars.org/affording-human-exploration-of-mars]. Building upon the findings and recommendations from this first workshop, AM II focused on 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, especially to Mars. In addition, a team of experienced Mars scientists was included in a breakout session that was specifically designed to initiate a new assessment of the role of human-enabled science exploration of Mars within the context of current and proposed future HSF architectures.

Workshop Goals

- Continue to build community consensus on the viability of human missions to Mars.
- Assess minimum path ("lean") architectures on the basis of both affordability and sustainability for initial missions by the mid-2030s.
- Initiate discussions as to the priority of science activities to be carried out by human explorers to Mars within the framework of affordable Mars architectures and "stepping stones": how major science goals affect architectures and vice versa.
- Review major programmatic and policy factors that enable affordable and sustainable Mars exploration.
- Identify meaningful, affordable activities that are necessary to carry out in the near term in order to advance key capabilities and technologies.

Workshop Deliverables from Representatives of the Stakeholder Communities

- Observations and commentary on the affordability and sustainability of Mars architectures and strategies presented at the workshop.
- Initial considerations about priority science goals enabled by human presence in the vicinity of Mars.
- Findings and recommendations on viable common features and capabilities of different architectures, priority near-term actions and investments for space agencies and industrial partners, future design and architecture studies, international participation, etc.
- Professional outreach and engagement strategy: follow-on workshops, conference presentations, briefings to NASA, the legislative branch, and other key constituents in human space flight.

Workshop Ground Rules and Guidelines

- The highest priorities for human space flight are successful initial missions to Mars by the mid-2030s.
- International partnerships 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.
- Technology development ends about a half-decade before the human mission(s) it enables. That is, there is an imperative to invest in the near term in priority technologies and capabilities.
- The Space Launch System (SLS) and Orion will be available during the periods considered here.
- Space agency budgets are likely to be flat, perhaps growing only for inflation, for at least the next few years. Budget growth above inflation will be necessary to achieve the goal of initial human missions to Mars by the mid-2030s.

Workshop Definition of Affordability: *An affordable mission is an activity that people are willing to pay for. A Level 0 requirement for Mars human exploration architectures is identification of the sustained source of funding.*

Key Questions/Issues to Be Discussed at the Workshop: Architectures, Scenarios, and Strategies

About a half-dozen teams were invited to present and discuss in detail their Mars exploration architectures and strategies. The titles of these presentations and the presenter are given in Appendix I.

To permit comparison among the presentations, each team was asked to include in their presentations responses to several key questions, where appropriate. Example questions included:

- What are the highest-level (Level 0) requirements adopted in the architecture/strategy?
- What are the highest-priority technology capabilities required to enable the architecture/strategy, and in what order should they be developed?
- What are the major milestones or "stepping stones" in the architecture/strategy and what purposes do they serve [e.g., demonstration of long-duration Environmental Control and Life Support Systems (ECLSS), long-duration operations without resupply]?
- Without necessarily discussing costs, what characteristics of the architecture/strategy are key to making it affordable?
- What aspects of the architecture/strategy make it sustainable from (1) programmatic or policy, (2) cost or budget, and (3) engineering and/or technology perspectives?
- What elements of the architecture/strategy are the most- and least-developed?

The workshop was constructed around three breakout sessions, which discussed their findings and recommendations in plenary session:

- Breakout 1: Comparing and contrasting the architectures and strategies: strengths, challenges, key milestones and architectural elements in common, investment and design priorities, etc.
- Breakout 2: Science enabled and enhanced by humans in the vicinity of Mars.
- Breakout 3: Sustainability: the international context, programmatic priorities, characteristics that promote sustainability and affordability, comparing/contrasting NASA strategy with the recent National Research Council (NRC) report on the future of human space flight, priority next steps, priority investments, recommended community activities, etc.

II. Breakout Session One: Humans-to-Mars Architectures: Side-by-Side Comparison and Review

Co-Chairs: Joe Cassady (Aerojet Rocketdyne) and Josh Hopkins (Lockheed Martin)

The AM II workshop opened with a series of presentations by NASA and the industrial participants and academic institutions, which provided a starting point and context for the more detailed discussions during this breakout session. The charter given to this session was to evaluate (based on material presented by several stakeholders) the various architectures and strategies, and attempt to answer the following questions:

1. Why are we sending human crews to Mars and what is the most attractive type of initial mission?
2. What are common elements, goals, milestones, and key technologies among the presentations?
3. What constraints will mission planners, architects, and others have to contend with?
4. What should the priority activities be over the coming decade?
5. Are lunar surface operations with astronauts a requirement in advance of human missions to Mars?

Question 1: Why and How Are We Going?

This question is important because the reasons for going to Mars should determine implementation, mission design and capabilities, and costs. The motivation for human missions to Mars has been developed extensively elsewhere, most recently by the National Research Council's Committee on Human Spaceflight Report, Pathways to Exploration. This breakout session discussed several reasons for human exploration of Mars, including eventual settlement, the potential for scientific discovery not readily possible without astronauts, multiple benefits made possible by peaceful international cooperation on major space missions – where ISS is an outstanding example – and an innate desire to explore. However, participants made a number of relevant observations.

The consensus of this breakout session was that human missions should eventually land astronauts on the surface. Missions that remain in orbit and/or on the surface of the martian moons were insufficient to achieve goals that have been identified over the years. Initial missions that do not land should be the priority goal if the technical or budget constraints are too great, as the cost of landing may be as much as ~1/3 of the total mission cost. The breakout session consensus was that initial missions to Mars orbit or moons would be challenged to justify the risk and time of astronauts if they are limited, for example, to operation from orbit of telerobotic science rovers on the Mars surface.[1] That is, *astronauts on the surface is a far more worthy mission objective on the basis of, as one example, scientific return*.

If, however, astronauts land, a key point of discussion was how many missions should there be and what is their nature. Three broad options were considered by our breakout session:

(1) an "Apollo-style" mission or series of missions to a handful of locations which will cease when major science questions have been answered. [**NB**: from the standpoint of current Mars science goals, such missions would easily achieve all of the objectives outlined in our second breakout session];

(2) a small, sustained human surface presence analogous to an Antarctic outpost and visited by astronauts on a rotating, non-permanent basis; and

(3) colonization or settlement of Mars. (While there are other options that do not require surface visits, the workshop consensus was that the goal should be humans to the surface rather than limited to Mars orbit.)

[1]The issue of telerobotics from orbit was also considered within the science Breakout Session 2.

After extensive discussion, the breakout session consensus did not favor the "Apollo-style" approach. The amount of resources necessary to carry out such a Mars exploration strategy would almost certainly demand (from taxpayers, government, and other stakeholders) a more ambitious program.

Since the workshop's overarching goal was assessing affordable approaches to Mars exploration, a "colonization" approach from the start, which would require a far more extensive infrastructure (agriculture, waste management, planetary protection, long-term habitation, in situ resource utilization (ISRU), etc.) was not considered viable. *Therefore, early Mars efforts should focus on developing an outpost that could be visited and utilized several times over many years on a regular basis with a cadence to be developed as part of future in-depth design studies.*

Management approaches and risk posture will play a large role on the ultimate cost of the mission, as summarized in the report from AM I. While not a technical subject per se, both will have a large impact on derivation of mission requirements (e.g., What systems can be less redundant? Do we maintain full contingency consumables for all abort scenarios?).

Breakout Session 1 Consensus: Why and How Are We Going?

- The goal should be to land humans on the martian surface, unless precluded by, for example, cost or lack of technical readiness. Telerobotic operations from orbit were considered a capability insufficient to achieve compelling goals.
- Landed human missions could be analogous to the manner in which Antarctica has been explored scientifically, with early missions laying the groundwork for future sustained missions or later settlement.
- The motivation for Mars exploration is the response to the human desire for exploring new frontiers and national benefits of collaboration.

Question 2: What are common elements, goals, milestones, and key technologies among the presentations?

This topic responds to the "compare and contrast" workshop goal with respect to the presented architectures and strategies. However, the presentations varied significantly in level of detail, emphasis, ground rules, and so on. Therefore, the results in Item 1 guided the discussion of this question. Although there are likely lower-cost or "leaner" architectures for Mars exploration than adopted for Item 1, the consensus was that these would not generally enable capability and infrastructure on Mars. Therefore, the session sought the lowest-cost architecture consistent with the goal eventually of a sustained outpost on Mars, which humans would continue to visit and expand. Discussion on a variety of topics produced the following:

Breakout Session 1 Consensus: Common Elements, Milestones, and Key Technologies

- Solar electric propulsion (SEP) should be an element of the mission architecture, likely as part of a pre-emplacement strategy with chemical propulsion for crew transportation. A minority view was expressed that an all-chemical architecture may be superior, if aerocapture is feasible. This is discussed in more depth below.
- Conjunction-class missions appear to be preferable to opposition-class missions, as the former offers much more time in the vicinity of Mars along with lower total Δv and entry velocities.
- An SLS-class heavy lift vehicle is required.
- The cargo necessary for Mars surface operations and return to Earth should travel separately from crew: that is, a "split mission." Such a mission allows some elements to be transported using slower, but more efficient methods and spaces out the launch rate more evenly.
- A "heavy" robotic Mars sample return should be considered as a way to advance human missions in collaboration with the science community. That is, the capability to land a much greater mass than is currently possible is critical to a human landing. This very significant sample return would be of great scientific, advance our understanding of surface toxicity, and help assess planetary protection concerns.
- Although it is too early for community agreement on a complete architecture for human Mars exploration, such agreement should be sought and is both possible and essential. In addition, although costs cannot be reliably calculated at this stage, analogies for cost (e.g., mass, complexity, number of "inventions") should be identified to allow comparison among different scenarios.

No consensus was reached on these topics:

- The merit of human missions to Phobos and/or Deimos.
- The value of initial missions to Mars orbit, unless necessitated by budgetary and other constraints (e.g., planetary protection, insufficient time to develop key technologies).
- Including or excluding nuclear propulsion in initial missions and, consequently, the importance of investment in this technology.

Question 3: What Are Constraints to the Initial Human Mars Missions?

To answer this question, the participants began by discussing the definition of a constraint. While sufficient, sustained funding was agreed to be the most limiting factor, it was agreed that assumption about the available budget would be treated in the workshop as a ground rule so that progress could be made on other important issues. We took as a given that agencies will be dealing with a "flat" or "flat with inflation" budget scenario at least for the next several years. Therefore, it was agreed as follows:

Constraints are engineering- , management-, or manufacturing-related pacing challenges that will need to be resolved in any successful plan.

Many topics were then considered, although they were ultimately distilled to four:

Non-budget constraints to initial human Mars missions:

- Based on information presented by NASA, production, processing, and launch capabilities leads to a maximum sustained two SLS flights per year with an occasional "surge" to three flights per year. As most Mars mission scenarios require launching a mass equivalent to a total of several SLS payloads, this constraint may mean that human Mars missions are not able to be launched at consecutive 26-month "windows."
- SLS flight rate is no more than one per year in the next decade (i.e., through ~2025).
- Initial human missions to Mars by the 2030s within expected budgets will require changes to current management and risk posture.
- Crew size of not less than three astronauts.

Question 4: What should the priority activities be over the coming decade?

The focus of this discussion was on missions to be conducted in the coming decade. However, in order to achieve those missions, recommendations were also sought on what must to be initiated within the next year, the next three years, and the next five years.

In addition to NASA's Asteroid Retrieval Mission (ARM), and fully utilizing the ISS, the highest-priority near-term "stepping stone" should be a long-duration, crew-tended habitat near the Moon with an exact location to be determined via trade studies and participation by partners. Such a facility would serve as a demonstration site and transition from ISS to a deep space habitation system for an initial Mars mission. The NASA Human Exploration and Operations Mission Directorate (HEOMD) solicited designs and technology capabilities for a habitation system dubbed the Exploration Augmentation Module (EAM) that is broadly similar to that identified as desirable by both Affording Mars workshops.

Breakout Session 1 Consensus: What should be completed within the next ten years (2015-2025) to support initial Mars exploration?

- Fully utilize the capabilities of the ISS.
- An affordable, crew-tended habitat in the vicinity of the Moon intended to be a prototype Mars transfer habitat. This should include international participation.
- Flying astronauts beyond low Earth orbit at least once per year beginning with EM-2. This means the SLS Block 1B should be implemented by the EM-2 flight. This does not exclude crewed missions on other vehicles, for example to ISS.
- Taking advantage of the opportunities for human exploration to support meaningful science missions in the 2020s using co-manifest capability on SLS Block1B.
- Although there are other viable mission concepts that could demonstrate high-power SEP, the ARM mission is a useful step toward demonstrating SEP for Mars missions.

Policymakers should be regularly provided with a broad range of examples of demonstrated progress. Evidence of progress is more likely to encourage a willingness to provide additional funding even if the final scenario or the ideal budget agreement has not been finalized.

Minority Report: Solar Electric Propulsion (SEP) versus All-Chemical Propulsion

A few participants raised issues with the majority opinion of using SEP for prepositioning cargo. Two participants stated that there would be no cost savings attributable to SEP. If so, the development of SEP would expend funding that could be used for building and operating flights to Mars sooner. Both participants advocated mission architectures that use aerocapture and/or direct entry (i.e., without first entering Mars orbit) to eliminate the Δv required for Mars orbit insertion. Using aerocapture, the spacecraft dips into the Martian atmosphere deeply enough to sufficiently reduce the relative velocity between the spacecraft and Mars to allow the spacecraft to enter Mars orbit. Over the years, numerous studies on aerocapture were carried out for both robotic and human missions, although has never been adopted. Robotic missions (e.g., Phoenix, Curiosity) have used direct entry to the martian surface, although with masses much less than would be used for astronauts. Aerocapture for human-scale missions requires either large-diameter rigid heat shields and/or ballute-type decelerators.

To help resolve issues raised in response to Question 4, a more rigorous study comparing SEP-based Mars architecture vs. chemical+aerocapture architecture should be conducted where costing should not be based on simple mass-based relationships. Given that the primary advantage of SEP is to increase the ratio of mass delivered to Mars versus payload launch mass, this breakout session expects:

SEP may be more attractive if:

- Launch vehicle (SLS) flight rate and, thus, launch mass are limited
- Heavy Mars landing (~ 15 metric tons or greater) entry, descent, and landing is feasible
- SEP is affordable, particularly if power levels are evolvable from commercially relevant systems of roughly 25 kW

Chemical+aerocapture may be more attractive if:

- Aerocapture or direct entry is feasible
- Higher launch mass to LEO per year is available
- Lower-cost launch is available
- Mars mission-class SEP would be expensive or dissimilar to other users
- EDL technology does not permit heavier landings that would benefit from high mass enabled by SEP.

Recommendations on Next Actions

As noted above, the workshop participants welcome the recent solicitation for designs and technologies relevant to a long-duration space habitation system and SEP.

In addition, AM II supports the prioritization of NASA and partner investments that is based upon Mars architectures that have been critically reviewed and vetted by a broad community of stakeholders.

Within one year NASA should:

- Issue broad area solicitations to include international partners to develop engineering architectures for initial human missions to Mars. Such architectures should be of sufficient depth and breadth (i.e., comparable to a NASA Phase A study) that:
    - Approximate costs can be estimated and compared
    - Potential partners can identify their role(s)
    - Priority technology capabilities are identified and incorporated into NASA funding priorities
    - Major "next steps" and precursors are identified.
- Increase integration of science goals into human exploration planning at NASA HQ and, presumably, at partnering institutions.
- Perform detailed assessment of programmatic and management approaches that will reduce costs relative to traditional "business as usual."

  Note: *The architectures studied should not be limited solely to the findings and recommendations in this report.*

Within three years NASA should:

Continue development of critical systems identified in the architectures described immediately above, which may include (as examples):

- EDL systems relevant to Mars for greater than ~15 metric tons
- Promising in-space propulsion systems, including advanced chemical, nuclear thermal propulsion
- Essential capabilities necessary for long-duration habitation in free space

Within five years NASA should:

- For those activities started within the three-year period, demonstrate sufficient progress to permit (1) downselection of the Mars architecture and (2) development of the long-duration free-space habitation system for deployment before the mid-2020s.

Question 5: Are lunar surface operations with astronauts a requirement in advance of human missions to Mars?

As recognized by multiple reviews and working groups, the Moon is an exciting target for scientific exploration. Moreover, many space agencies other than NASA have identified the lunar surface as a high-priority future target for human space flight.

It was the near-unanimous conclusion of the workshop that human operations on the lunar surface, including landing, mobility, power, and environmental control and life support systems (ECLSS), are not required in advance of initial human Mars missions. Moreover, resources and effort spent on human lunar surface operations will be a diversion from development of capabilities for Mars exploration. However, human lunar surface activities may be desirable to achieve scientific or exploration goals unrelated to Mars or for maintaining international partnerships or domestic political support.

Proposed topics for an Affording Mars III workshop include:

- Continuing broad community participation in Mars exploration architectures, scenarios, and strategies, especially as it involves younger generations.
- Continuing integration of the Mars science community with human architecture designs.
- The role of non-US partners in the Mars architecture, a relevant topic in light of the recent statement by ESA Director General, Jean-Jacques Dordain that the US should “lead the global exploration of space…” [7th AAS Wernher von Braun Symposium].
- Stakeholder review of progress on key exploration capabilities such as EDL, nuclear surface power, ISRU, low-latency telerobotics, solar surface power, and closed-loop life support.
- Implementing new management practices to reduce cost.
- Communication and public outreach.

III. Breakout Session Two: Science Enabled and Enhanced by Humans in the Vicinity of Mars

Co-Chairs: James B. Garvin (NASA) and Chris Carberry (Explore Mars, Inc.)

This breakout session assessed how humans on the martian surface or in orbit, including on Phobos or Deimos, could enable priority science goals. This session took advantage of participating in the workshop with the assessment of candidate architectures (Breakout Session 1). This was an initial assessment, with further development of science activities within the context of human missions to benefit significantly from continuing close collaboration in the development of human architectures.

This session considered first the role of astronauts in the scientific exploration of the planet.

A. Top-Level Benefits of Human Missions to the Surface:

1. The use of human flight systems (e.g., much larger returned sample mass to Earth) will bring enhanced capability for science.
2. Humans in the vicinity of Mars substantially improves operability of assets for science (e.g., low-latency telerobotic operation).
3. Increased human interactions with the environment and materials, especially direct
4. contact, dramatically increases science return (e.g., selection of disparate samples in a complex environment).
5. More time for analysis always improves the results (e.g., 30-day opposition-class missions versus 500-day conjunction-class mission), especially time devoted to in situ fieldwork.

   NOTE: This breakout session assessed these benefits in the context of different architectures (Table 1). The only relative rating in our assessment that does not display significant difference is the comparison of the 30-day astronaut surface stay with precursor robotic mission versus a 500-day astronaut surface stay with teleoperation.

B. Top-Level Benefits of Human Missions Limited to Mars Orbit and/or Martian moons

1. A human landing on Phobos or Deimos would be valuable to small-body science, but would be of minimal value to the science of Mars itself.
2. Teleoperation of assets on the surface of Mars from either high Mars orbit (areosynchronous) or from the surface of either Phobos or Deimos may be a feature of a human mission to the martian system. However, this would be insufficient to serve as a science justification alone for a human mission. That is, we did not identify compelling advantages over the operation of such assets from Earth.

   NOTE: One of the likely scientific goals in Mars exploration is investigation of the COSPAR Special Regions for extant life. This could include teleoperation of sterile rovers, which would require in-depth consideration of forward planetary protection issues.

C. Significance of Robotic Sample Return Prior to Human Visitation

1. Robotic Mars sample return (MSR) is an essential precursor to landing humans and returning them to Earth. Robotic sample return is crucial to addressing risks to crew health, back-contamination of Earth, and the affordability of protective systems.

   Note: The Mars architecture breakout session (#1) discussed the advantages of a high-mass (i.e., "heavy") robotic sample return utilizing test versions of human-scale landing and ascent vehicles. Such a mission would enable very ambitious science exploration.

D. Quantitative Assessment of the Science Value Added by a Crewed Mission

Our breakout session undertook an assessment of the science "added value" when astronauts are on-site in comparison with a purely robotic mission of a broadly similar architecture. Our results are presented in Table 1, where we recognize that our assessment was preliminary and must be developed further as a result of in-depth involvement of the science community and Mars architecture teams. We believe that our process at the workshop serves as a model for how such involvement should precede.

Table 1 only considered improvements in the value or nature of the science investigation, not improvements in operability (e.g., rate of return of science results), which is summarized in Table 2. For example, low-latency telerobotics (i.e., telepresence) from Mars orbit was assessed to not yield science investigations substantially different from telerobotics from Earth and, thus, would give a poor increase in science value in Table 1. As another example, on Phobos organic material on the moon could be studied, which is a very desirable goal. However, Mars surface and climate science would not be greatly enhanced above that which could be undertaken with a robotic program operated from Earth.

As part of its discussion, this session observed that humans in the vicinity of Mars improves operability of assets for science, which would be a watershed capability due to human cognition

Based on the discussion that produced Table 1, if telepresence is available for Mars exploration, what paradigm shifts are needed to fully take advantage of the decrease in latency?

- For teleoperating/telepresence to improve efficiency, high autonomy for the astronaut/robot team is required.
  - This likely means that some tasks (e.g., with a known and well-defined aim, such as acquiring a sample or drilling) can be accomplished far more quickly than robotic.
  - Higher-level tasks that require very broad and deep expertise (i.e., a full fieldwork campaign) will likely still require assistance from extensive expertise on Earth, as is required today.

- Autonomy could also be achieved via advancements in artificial intelligence and more trust in the spacecraft.

- If humans are teleoperating from the surface of Mars (versus in orbit), then, in addition to more sustained contact and lower latency, they could repair the robot and switch out sensors, etc. This would greatly expand the robot's value.

Table 1: Science Value Added by a Human Mission versus a Robotic Mission for Different Architectures

Mission Architectures ➔ / Planetary Decead 2013-2023 Science Goals ↓	Mars Flyby (i.e. Droppping something off)	Science in Orbit	Science from aerosync Orbit (Telespace to Mars Surface)	Humans on the Phobos Surface (without Mars Comm Network	Humans on the Mars Surface (30days; 10s km) NOT Assuming Precursor Mission	Humans on the Mars Surface (30days; 10s km) + Assuming Precursor Robotic Fieldwork	Humans Tele-operating on Mars Surface (limited EVA, 500days)	Humans on Mars Surface (500days; 100s km) NOT Assuming Precursor Mission	Humans on Mars Surface (500days; 100s km) Assuming Precursor Mission
Crosscutting: Building New Worlds	P	P	P	F	P	P	P	P	P
Crosscutting: Planetary Habitatas	P	P	P	F	G	VG	E	VG/E	E
Crosscutting: Workings of a Solar Sytem	P	P	P	P	P	P	P	P	P
Mars: Determine if Life Ever Arose on Mars	P	P	P	F	G	VG	E	VG/E	E
Mars: Understand the Processes and History of Climate	P	P	P	P	G	VG	VG/E	E	E
Mars: Determine the Evolution of the Surface and Interior	P	P	P	P	G	VG	VG/E	E	E
Small Bodies: Decipher the Record in the Primitive Bodies of Epochs and Processes not Obtainable Elsewhere	P	P	P	G	P	P	P	P	P
Small Bodies: Understand the Role of Primitive Bodies as Build-ing Blocks for PLanets and Life	P	P	P	G	P	P	P	P	P
Notes				Mars Metorites Organics on Phobos			Would Not Contaminate Study Areas (at the time of the mission and futre studies		Precursor Could do Science Before Con-tamination by humnas

- **Possible scores P/F/G/VG/E = Poor/ Fair/ Good/ Very Good/ Excellent**

Summary of Table 1: The Value Added by Humans on Site

(1) A round-trip human mission can return samples with greater total mass than all-robotic missions.

(2) Human missions to Mars require and allow greater infrastructure. Consequently, such missions can include a larger number of more complex scientific analysis tools. An obvious example includes greater mass and higher-power systems relative to purely robotic approaches.

(3) If humans are in the loop, either being on site or via telepresence, there will be an increase in cognition and a decrease in latency, which should achieve more, and faster and more adeptly.

(4) If humans are in the loop, there will be an increase in dexterity and adaptability to carry out more complex activities, yielding a better diversity of observations, work, and samples collected.

(5) Astronauts can leave behind or begin to build a network, which will be of intrinsic value to human flight systems and their mass-carrying capacity.

(6) Use of Phobos as an initial site for human exploration is a science convenience and benefit to small body science goals, but is not a good science objective for Mars itself.

Additional Observations about Value-Added Science via Human Presence on Site

More time for analysis always improves the science results (e.g., 30 days versus 500 days), especially time conducting in situ fieldwork. However, this time does not always require human presence on site. That is, robotic precursors operated from Earth or in the Mars vicinity can contribute towards fieldwork and site characterization for science. Moreover, except perhaps for life sciences studies, human time will be more expensive than robot time for science. That said, our breakout session made a number of additional preliminary observations relevant to astronauts on site to carry out science studies:

- Any 30-day human surface mission requires a robotic precursor mission for intensive site characterization and optimization

- About seven EVAs is not enough for careful sample selection and acquisition. We note that some participants disagreed. They did not believe full site characterization was required, but did assume a 1 m-scale geologic map of the region and some detailed reconnaissance is required in advance, as currently achievable with NASA Mars Exploration program assets.

- Five hundred days with a human crew on the surface for some portion of the time would significantly enable diversity in field study sites and samples: Additional advantages in human time versus robotic precursor mission are that human time allows for samples to be collected and then changed out later, and also allows for returning to sites.

- None of the Mars surface science objectives require humans for accomplishment.

- For telepresence, latency is much less to the surface of Mars compared to communication from Earth and contact will still be discontinuous and limited unless there is a full communication network in place (i.e., orbital network of comsats).

- Involving these moons (versus a free-orbiting spacecraft, such as areosynchronous) may add complexity to the mission.

- For humans at Mars, these moons could provide some protection for humans from galactic cosmic rays with up to 35% additional shielding while on the surface of the moon.

- Main contribution by humans on the martian moons towards Mars science would be access to possible Mars meteorites (on Phobos/Deimos) and all that comes with taking humans into the Mars vicinity: larger infrastructure, ability to pick up a sample capsule from orbit, etc.

Findings:

- Robotic sample return is necessary due to the risk of back-contamination of Earth, confidence in the flight systems, and the imperative of affordability.
- The use of human flight systems will bring enhanced capability for science.
- Humans in the vicinity of Mars improves operability of assets for science.
- Increased human interactions with the environment and materials, especially direct contact, dramatically increases science return.
- Use of Phobos is of benefit to small-body science, although not a good science objective for Mars.

Other Issues for Future Assessment:

- The role of ISS to carry out Mars-related science:
    1. Available closed system for human operations, perhaps relying on ISRU demonstrations.
    2. Evaluate telepresence for Mars-related science.
    3. Human life sciences for long-stays in deep space/on Mars.
- As part of heavy-lift development and testing, it might be essential to conduct a flight before initial human missions by landing a large robotic system on Mars, perhaps an all-in-one sample return.
    1. This possibility should be assessed within the Mars science community.
- What goals must be or can only be achieved before the first human mission(s) (e.g., human life sciences studies)?
- The strategy for identifying in situ resources is currently not a high priority within NASA's Science Mission Directorate (SMD) for science. Could HEOMD or others support state-of-the-art remote sensing for identification of resources? Otherwise such assays will not be conducted within the SMD program of reference.

E. Additional Capability to Conduct Science on the Basis of Having a Human Mission

Our breakout session also undertook an assessment of additional capabilities to carry out science when astronauts are on-site and partners with robotic systems. Our results are presented in Table 2, where we recognize that our assessment was preliminary and must be developed further as a result of in-depth involvement of the science community and Mars architecture teams. We believe that our process at the workshop serves as a model for how such involvement should precede.

While Table 1 only considered improvements in the value or nature of the science investigation, Table 2 considered improvements in operability (e.g., rate of return of science results).

Table 2: Additional Capability to Conduct Science on the Basis of Having a Human Mission

Mission Architectures ➔	Mars Flyby	Science from Aerosync Orbit (telepresence to Mars surface)	Humans on Phobos Surface (w/o assuming Mars comm network)	Humans on Mars Surface (30days; 10s km), NOT Assuming Precursor Mission	Humans on Mars Surface (30days; 10s km), assuming precursor robotic fieldwork	Humans Teleoperating on Mars Surface (limited EVA, 500days)	Humans on Mars Surface (500days, 100s km) NOT Assuming Precursor Mission	Humans on Mars Surface (500days, 100s km) Assuming Precursor Mission
Increase in Science access through addition of humans (vs robotics)	FR	FR+, IO	FR+, IO	FR+, IO+	FR+, IO+	FR+, IO+	FR+, IO++	FR+, IO++
Aiding Mars Sample Return	R	R, C-	R, C, M	R, C	R, C	R, C+	R, C+	R, C+

Key

- **FR** Getting mass a "free ride" to the Mars vicinity
- **FR+:** Getting a "free ride" to the Mars vicinity along with increased power, mass, complexity, etc. than would be likely for a robotics mission
- **IO:** Higher "operability" of surface assets possible due to decreased latency, higher dexterity, etc.; allowing us to achieve maximal science objectives
- **IO+:** Even higher "operability", due to having multiple advantages
- **IO++:** highest increase in operability (i.e., enables direct contact between human and science)
- **R:** retrieval of samples acquired via a precursor mission is possible
- **C:** enables collection (perhaps remotely) during mission
- **C-:** requires additional mission element (e.g., Mars ascent vehicle) to retrieve during-mission collection
- **C+:** enables sample selection and collection during mission, with diversity and careful consideration of samples
- **M:** Improved access to Mars meteorites

NEXT STEPS – The Science Breakout Session at AM II was an excellent start of a partnership between the Mars science community and the development of architectures for human exploration.

- There are many open issues as to how science can make humans to Mars affordable. One essential element is the requirement for a robotic sample return in advance of the initial human surface mission, which will allow improved assessment of surface conditions of the planet.

- The science goals/objectives vs. human mission architecture matrix is a key first step for identifying science opportunities and priorities.

- Revisitation of the 2008 Human Exploration of Mars Scientific Analysis Group (HEM-SAG) activities, as chartered by NASA Headquarters and the Mars Exploration Program Analysis Group (MEPAG), may be necessary in the context of "affordable" architectures.

- More work is needed in consideration of how low-latency telepresence at Mars with humans nearby, but not on the surface, may achieve high-priority science.

- Mars-related science at ISS deserves consideration by the community over the next 5+ years, which could include telepresence, life sciences etc.

- A follow-up meeting in 2015 would be advantageous.

The assessment of the breakout session attendees, all of whom are subject matter experts in Mars geology and astrobiology, was based upon current best practices, as published in the peer-reviewed scientific literature. Such practices only include experience with high-latency telepresence (HLT), as is the mode of science operation today on the MSL Curiosity rover on Mars, and which was demonstrated via the twin Mars Exploration Rovers (Spirit and Opportunity). Additional quantitative studies of the future scientific benefits of new operational modes involving low-latency telepresence (LLT) implemented with human explorers in close proximity to Mars surface robotic assets with rapid control-authority (i.e, humans in Mars orbit) would be required to adequately compare and contrast human surface science operations from those involving LLT and HLT. Such studies are not presently available and hence were not a factor in the development of the findings of the SBS at AM-II. Future work in this area is recommended, perhaps involving control experiments in surface geology and astrobiology using LLT from the International Space Station (ISS) to robotic assets at well-accepted Mars analogue sites on Earth, with metrics for scientific performance.

IV. Breakout Session Three: Affordability and Sustainability

Co-Chairs: Sam Scimemi (NASA) and Kevin Foley (Boeing)

This involved a structured discussion focused on identifying the characteristics and elements of sustainable objectives for human missions to Mars. This session was organized into three discussion topics: (1) NASA Sustainability Principles versus Principles of the NRC Report on the Future of Human Space Flight (http://www.nap.edu/openbook.php?record_id=18801); (2) Capability development versus pathway architecture; and (3) A vision for sustainability.

The first discussion topic focused on comparing and contrasting the NASA and NRC principles related to the development of a plan to send humans to Mars. [See our table comparing these principles in Appendix II.] Significant items of note that resulted from the discussion include:

- NRC principles address a broad vision of planning by identifying the need for broadly based scientific, cultural, economic, political, and inspirational benefits.
- NRC principles, and as a whole, its report, was directed at influencing congressional policy makers.
- NASA principles appear to be more internally focused on agency culture and processes.
- There is no distinction of the level of importance among either the NASA or the NRC principles.
- The NRC report creates an opportunity for the community to come together on crafting a consensus.
- The NRC principle on selecting a pathway is consistent with development of capabilities, as these will eventually have to be demonstrated along the path to Mars.
- Areas of agreement between NASA and NRC principles:
    - Multi-use or flexible architectural elements
    - Use of infrastructure instead of "throw away" elements
    - Cost/benefit analysis should be considered in making those choices
    - From industry perspective, the need to have a sustainable program so that industry can make investments: ISS crew and cargo were noted as examples, with the ISS being the stable program
    - Leveraging commercial systems redefines the intent by establishing common systems between industry and government needs
    - Commercial industry capabilities should follow government investments
    - Need to show incremental progress that engages the various stakeholders

The second discussion topic focused on NASA's strategy of capability development versus pathway architectures as adopted by the NRC in its report. It was the breakout session consensus that the objective of defining a pathway was to tell a story in public outreach, rather than define each mission or program. Given that Mars is the horizon goal, without delving precisely into what will be carried out at Mars, there are only a handful of "stepping stones" that can be considered as precursors to Mars. Once other constraints are factored in such as budget, technology development progress, mission execution activities, development of international partnerships and the like, the options for Mars pathways become even more limited.

This session concluded that it is possible to define a pathway to Mars with incremental demonstration of capabilities along the way without having to know and defend a long-term, total budget. Any such budget or cost would be highly unreliable, as there are many long-term factors that are speculative, such as advancing technology, improvements in acquisition approaches, relative roles of government and private industry, and international contributions. The priority goal is to identify the most widely agreed-upon early milestones and investments that demonstrate increasing capabilities for exploration beyond LEO.

The story underlying Mars exploration should be told in a professional and cohesive manner in which all stakeholders participate. For example, the Mars robotic "follow the water" campaign was widely vetted by the Mars science and engineering communities with the help of professional storytellers. It is vital that the storyteller has a good story to tell and that there be complementarity among telling the story and the implementation of the plan and stakeholders: industry, government, academia, and robotic and human spaceflight.

This breakout session's third and final discussion topic was an attempt to define what is sustainable. The session discussed many characteristics of what we perceived to be sustainable:

- Accepted Timeframe to achieve national, or international, horizon goal
- Cadence (frequency and timing) of returning value to stakeholders
- Proactively engaging stakeholders and communicating on a regular basis
- Promising less and giving/delivering more
- Achieving human space flight community consensus (implementation and communication)
- Executing the plan to reinforce confidence that the program is proceeding as planned and returning value as expected, which establishes trust history within and external to the HSF stakeholder community
- Policy consistency within the stakeholder leadership across multiple administrations and budget cycles
- Satisfies national interest/goal…of exploring, discovering, and extending a permanent human presence further into the solar system

Two elements of sustainability were emphasized: (1) the criticality of focus on initial Mars missions and (2) the cadence of missions subsequent to these early flights. Another element vital to the vision of a sustainable goal is for the goal to be enduring and transcendental against our traditional constraints of policy, budget and stakeholder changes.

A possible Level 0 requirement for sustainability was offered for consideration to the larger community: *Continuous positive return of value to stakeholders in an affordable manner driving investment over an extended time frame.*

APPENDIX I
Architecture and Scenario Presentations

"Considerations for a "minimum path" architecture," Bret Drake (NASA JSC)
"Steps to Mars," Josh Hopkins (Lockheed Martin)
"Modular Mars Architecture," Matthew Duggan (Boeing)
"Mars Vicinity Exploration Architecture," Joe Cassady (Aerojet Rocketdyne)
"SpaceX and Mars Exploration," Paul Wooster (SpaceX)
"Key Steps Leading to an Affordable Mars Mission," Jean-Marc Salotti (ENSC)
"Human Exploration Beyond LEO: International Scenarios," Jonathan Battat (MIT)

APPENDIX II

Principles of Sustainability: NASA and NRC Report

NASA Principles for Sustainability

Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth;

Exploration enables science and science enables exploration;

Application of high Technology Readiness Level (TRL) technologies for near term missions, while focusing sustained investments on technologies and capabilities to address challenges of future missions;

Near-term mission opportunities with a defined cadence of compelling human and robotic missions providing for an incremental buildup of capabilities for more complex missions over time;

Opportunities for U.S. commercial business to further enhance the experience and business base learned from the ISS logistics and crew market;

Multi-use, evolvable space infrastructure;

Substantial international and commercial participation, leveraging current International Space Station partnerships.

NRC Pathway Principles

1. Commit to design, maintain, and pursue the execution of an exploration pathway beyond low Earth orbit toward a clear horizon goal that addresses the "enduring questions" for human spaceflight.
2. Engage international space agencies early in design and development of the pathway on the basis of their ability and willingness to contribute.
3. Define steps on the pathway that foster sustainability and maintain progress on achieving the pathway's long-term goal of reaching the horizon destination.
4. Seek continuously to engage new partners that can solve technical and/or programmatic impediments to pathway progress.
5. Create a risk mitigation plan to sustain the selected pathway when unforeseen technical or budgetary problems arise. Such a plan should also include points at which decisions are made to move to a less ambitious pathway ("off-ramp," as defined below) or stand down the program.
6. Establish exploration pathway characteristics that maximize the overall scientific, cultural, economic, political, and inspirational benefits without sacrificing progress toward the long-term goal, these characteristics being:

a. The horizon and intermediate destinations have profound scientific, cultural, economic, inspirational, or geopolitical benefits that justify public investment;
b. The sequence of missions and destinations permits stakeholders, including taxpayers, to see progress and develop confidence in NASA being able to execute the pathway;
c. The pathway is characterized by logical feed-forward of technical capabilities;
d. The pathway minimizes the use of dead-end mission elements that do not contribute to later destinations on the pathway;
e. The pathway is affordable without incurring unacceptable development risk;
f. The pathway supports, in the context of available budget, an operational tempo that ensures retention of critical technical capability, proficiency of operators, and effective utilization of infrastructure.

Operational Decision Rules:

A. If the appropriated funding level and projected 5-year budget projection do not permit execution of a pathway within the established schedule, then do not start down that pathway.
B. If a budget profile does not permit the chosen pathway, even if NASA is well down it, then take an "off-ramp."
C. If the U.S. human spaceflight program receives an unexpected increase in budget for human spaceflight, NASA, the administration, and Congress should not redefine the pathway such that continued budget increases would be required for the pathway's sustainable execution, but rather the increase in funds should be applied to retire rapidly significant technology risks or increase operational tempo in pursuit of the pathway's predefined technical and exploration goals.
D. Given that limitations on funding will require difficult choices in the development of major new technologies and capabilities, give priority to those that solve significant existing technological shortcomings, reduce overall program cost, allow for an acceleration of the schedule, and/or reduce developmental or operational risk.
E. If there are human spaceflight program elements, infrastructure, and organizations that no longer contribute to progress along the pathway, the human spaceflight program should divest itself of them as soon as possible.

APPENDIX III
Workshop Planning Team and Participants

Chris Carberry (Explore Mars, Inc.) & Harley Thronson (NASA GSFC)
Co-Chairs

John Baker (JPL)
Joseph Cassady (Aerojet Rocketdyne)
Doug Cooke (Cooke Concepts and Solutions)
Kevin Foley (Boeing)
Paul Fulford (MDA)
Scott Hubbard (Stanford)
Kathy Laurini (NASA JSC)
Michael Raftery (retired)
Sam Scimemi (NASA HQ)
Charles Whetsel (JPL)

Layout & Design by M. Wade Holler (Explore Mars Inc.)

Second Affording Mars Workshop

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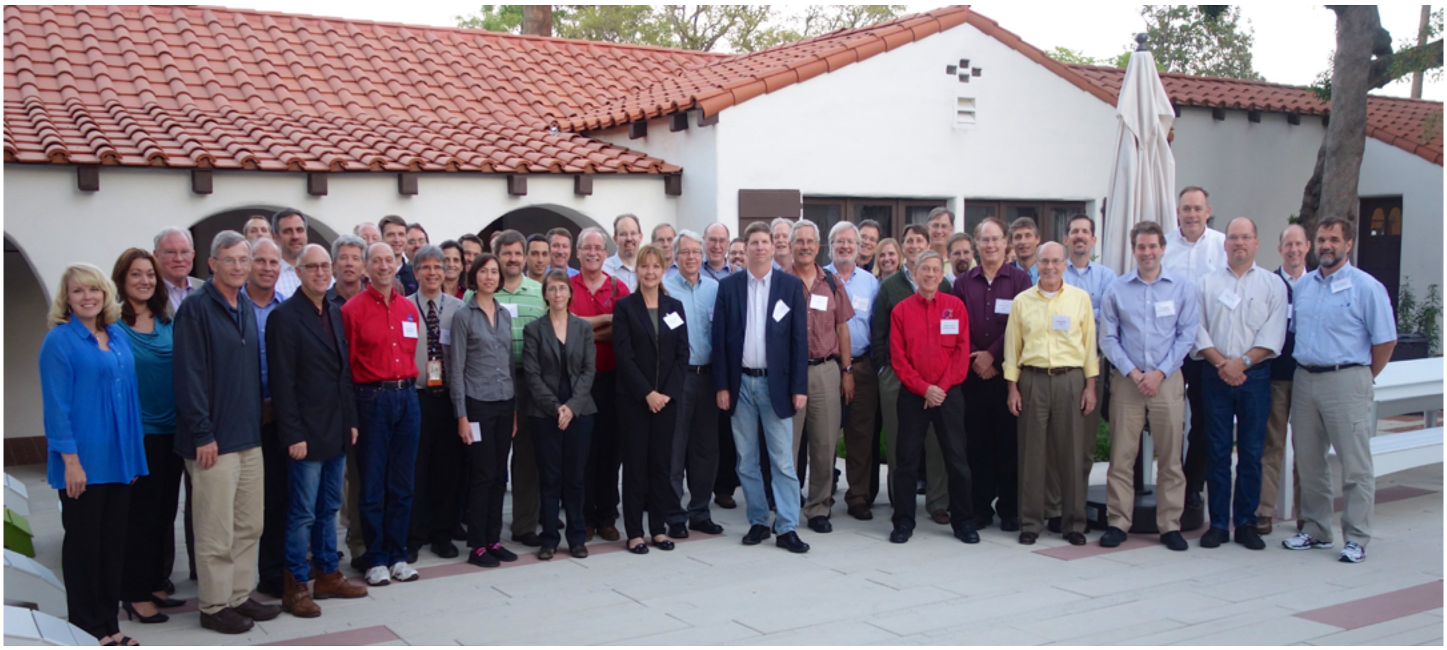
Last	First	Affiliation
Allwood	Abby	JPL
Baker	John	JPL
Barbier	Louis	NASA Headquarters OCS
Bass	Deborah	JPL
Battat	Jonathan	MIT
Beaty	David	JPL
Brown	Chad	NASA Kennedy Space Center
Carberry	Chris	Explore Mars, Inc
Cassady	Joseph	Aerojet Rocketdyne
Clark	Ian	JPL
Conley	Cassie	NASA Headquarters
Cooper	Darby	Boeing
Craig	Doug	NASA Headquarters
Craig	Mark	SAIC
Deininger	Bill	Ball Aerospace
Dienega	Serina	JPL
Drake	Bret	NASA Johnson Space Center
Duggan	Matt	Boeing
Dumbacher	Dan	Purdue
Edwards	Ashley	NASA HQ HEOMD
Ehlmann	Bethany	JPL
Foley	Kevin	Boeing
Ford	Ken	IHMC
Fulford	Paul	MDA
Garvin	Jim	NASA Goddard Space Flight Center
Gates	Michele	NASA Headquarters
Gonthier	Yves	Canadian Space Agency
Griffin	Brand	NASA Marshall Space Flight Center
Guidi	John	NASA Headquarters
Hitt	David	NASA Marshall Space Flight Center

Last	First	Affiliation
Hopkins	Josh	Lockheed Martin
Jermstad	Wayne	NASA Johnson Space Center
Joosten	Kent	NASA Johnson Space Center
Levack	Daniel	Aerojet Rocketdyne
Krezel	Jonathan	NASA HQ HEOMD
Maliga	Kate	Aerojet Rocketdyne
Martin	Tom	Aerojet Rocketdyne
McCleese	Dan	JPL
Meyer	Michael	NASA Headquarters
Post	Kevin	Boeing
Persinger	Randy	Aerospace
Pugel	Betsy	NASA Headquarters
Reuther	James	NASA HQ STMD
Robinson	Kimberly	NASA Marshall Space Flight Center
Rominger	Kent	ATK
Salotti	Jean-Marc	ENSC
Sauvageau	Donald	ATK
Scimemi	Sam	NASA Headquarters
Smith	Marshall	NASA Headquarters
Smitherman	David	NASA Marshall Space Flight Center
Thronson	Harley	NASA Goddard Space Flight Center
Troutman	Pat	NASA Langley Research Center
Ward	Brenda	NASA Johnson Space Center
Westhelle	Carlos	NASA Johnson Space Center
Whetsel	Charles	JPL
Whitmeyer	Tom	NASA Headquarters
Wilcox	Brian	JPL
Wooster	Paul	SpaceX
Zurek	Richard	JPL

Report of the

Second Mars Affordability and Sustainability Workshop



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Harley Thronson (American Astronautical Society & NASA GSFC),
& Richard Zucker (Explore Mars, Inc.)
Senior Editors

Joe Cassady (Aerojet Rocketdyne), Kevin Foley (Boeing), Jim Garvin (NASA GSFC),
Josh Hopkins (Lockheed Martin), & Sam Scimemi (NASA HQ)
Breakout Session Chairs and Associate Editors