HUMANS ORBITING MARS

A Critical Step Toward The Red Planet
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This workshop, titled Humans Orbiting Mars, brought together key leaders from NASA’s science, technology, and human spaceflight directorates, individuals from major industry partners, leading scientists, policy-makers, and congressional staff.

The workshop provided a broad-based, expert synthesis of the technical, programmatic, and policy issues necessary to create a sustainable program of human Mars exploration, focusing on the potential of an orbital mission to Mars in 2033 as a critical step to safely landing humans on the surface shortly thereafter.

At the conclusion of the workshop, the major findings were captured by the participants in the following statements:

- The plan presented at the workshop for a long-term humans-to-Mars program that constrains costs by minimizing new developments was credible.
- This plan includes, as an essential element, separating the human trip to the surface of Mars into two pieces. The critical initial element is a human mission to orbit Mars in 2033.
- An orbital mission will enable scientific exploration of Mars and its moons while developing essential experience in human travel from Earth to the Mars system.
- Such a program would fit within a budget that grows with inflation after NASA ends its lead role in the International Space Station.
- Landing humans on Mars can affordably and logically follow later in the 2030s.
- There will be both scientific and public support for this orbit-first approach.
- Pursuing this orbit-first approach will establish a framework for involving the private sector and international partners, and will create a unified Mars science and exploration community.

This report synthesizes the workshop’s presentations and discussion. The sense of the workshop was that the human exploration of Mars is affordable, that much of the necessary technology is under development, and that lessons learned from the robotic Mars Exploration Program can be applied in order to build a consistent, politically stable program that spans decades.

The workshop—and by extension this report—is meant to inform the conversation among relevant stakeholders and the public about the future of human spaceflight at NASA. The concept plan presented by the JPL study team serves as a starting point—an existence proof—that a program of human exploration of Mars is affordable and executable. It is up to NASA and its partners to articulate the actual strategy that a broad coalition can come together and support.
The future of the human spaceflight program is a critical issue facing NASA today. After the cancellation of the Moon-focused Constellation program, the U.S. Congress, anticipating the retirement of the space shuttle, directed NASA to create the heavy-lift Space Launch System (SLS) rocket and to continue development of the Orion crew capsule. The combined system will provide NASA with the capability to send humans beyond low-Earth orbit for the first time since the 1960s. The questions NASA faces are: “To where?” and, “Is it affordable?”

Reports by two blue-ribbon committees examined these questions during the Obama administration: the 2009 report by the Review of U.S. Human Spaceflight Plans Committee and the 2014 report by the Committee on Human Spaceflight. Though written during significantly different periods in NASA’s human spaceflight program, both reports state that the surface of Mars is the ultimate goal for human exploration. Both propose several exploration programs NASA could pursue to achieve this goal, though it was in the purview of neither to endorse a specific path. Both emphasize that increased budgets for human spaceflight are needed for NASA to be successful in this endeavor, emphasizing that flat budgets do not enable any proposed program of human exploration.

The Obama administration’s stated policy for human spaceflight is “by 2025, [to] begin crewed missions beyond the moon, including sending humans to an asteroid,” and “by the mid-2030s, send humans to orbit Mars and return them safely to Earth.” NASA has announced several Orion test flights and proposed an astronaut-asteroidal boulder rendezvous in cis-lunar space in the early 2020s in an attempt to meet these goals. However, NASA has yet to specify how it plans to sustain a long-term human spaceflight program beyond the eventual end of the International Space Station (ISS), or to achieve the president’s goal to get humans to Mars orbit by the 2030s. NASA has promoted its Evolvable Mars campaign to demonstrate their commitment to exploring the Red Planet, and while this is an important development, no human missions are yet planned to Mars or even beyond the Moon. Much of the hardware needed to sustain human life in deep space re-
mains in early stages of development. The proposed asteroid rendezvous mission remains controversial.

For decades, The Planetary Society has argued that Mars should be the ultimate goal of human exploration. To that end, the Society believes that NASA should develop a sustainable, affordable, and executable human exploration program leading to Mars, and should do so soon. This program’s success will depend on NASA articulating a clear strategy to engage a coalition of political, industrial, scientific, international, and public entities that will provide the long-term stability needed to land humans on the Red Planet and return them safely to Earth.

1.1 - HUMANS ORBITING MARS WORKSHOP

As a step in engaging such a coalition, The Planetary Society convened a workshop in Washington, D.C. from March 30 to April 1, 2015. The workshop was co-chaired by Planetary Society board members Scott Hubbard, the first “Mars Czar” at NASA and former director of NASA’s Ames Research Center, and John Logsdon, preeminent space historian and founder of the Space Policy Institute at George Washington University.

This workshop, titled Humans Orbiting Mars, brought together key leaders from NASA’s science, technology, and human spaceflight directorates, individuals from major industry partners, leading scientists, policy-makers, and congressional staff. This independent workshop was funded exclusively by the members of The Planetary Society.

The workshop provided a broad-based, expert synthesis of the technical, programmatic, and policy issues necessary to create a sustainable program of human Mars exploration, focusing on the potential of an orbital mission to Mars in 2033 as a critical step to safely landing humans on the surface shortly thereafter.

The workshop did not attempt to address the overarching question of why we should send humans to Mars, as this topic has been widely discussed in other venues and identified as the “Horizon Goal” by the National Academies. Mars is widely promoted as the ultimate goal of human spaceflight, including by Congress, NASA, and the White House itself.

1.2 - RESULTS OF THE WORKSHOP

At the conclusion of the Humans Orbiting Mars workshop, the results of the event were captured by the participants in the following statements:

- The plan presented at the workshop for a long-term humans-to-Mars program that constrains costs by minimizing new developments was credible.
- This plan includes, as an essential element, separating the human trip to the surface of Mars into two pieces. The critical initial element is a human mission to orbit Mars in 2033.
- An orbital mission will enable scientific exploration of...
Mars and its moons while developing essential experience in human travel from Earth to the Mars system.

- Such a program would fit within a budget that grows with inflation after NASA ends its lead role in the International Space Station.
- Landing humans on Mars can affordably and logically follow later in the 2030s.
- There will be both scientific and public support for this orbit-first approach.
- Pursuing this orbit-first approach will establish a framework for involving the private sector and international partners, and will create a unified Mars science and exploration community.

The sense of the workshop was that the human exploration of Mars is affordable and achievable within a time horizon of interest to major stakeholders, that much of the necessary technology either exists or is under development today, and that lessons learned from the robotic Mars Exploration Program can be applied in order to build a consistent, politically stable program that spans decades. The components of an affordable humans-to-Mars program are here, now. NASA should define a strategic plan to Mars that engages a broad community, and then execute it.

This report synthesizes the workshop’s presentations and discussion. The goal of this report is to inform a conversation among relevant stakeholders and the attentive public in the hopes of forming a coherent community supporting a sustainable program of human spaceflight that leads to Mars. Following the authors of the 2014 report Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration, we define stakeholders as those who may reasonably be expected to have an interest in NASA’s programs and the ability to exert some influence over its direction. We define the attentive public in the manner of the Pathways report as well: they are members of the public who are both very interested in and well informed about space-related issues.

12 - To see how individual workshop presentations and panel discussions map to specific sections in this report, please consult Appendix B.
13 - Committee on Human Spaceflight, Pathways to Exploration. Table 3-6: Stakeholders Included in the Survey. Examples of stakeholders include: for-profit companies that interact directly or indirectly with NASA (e.g., contractors and aerospace firms); scientists and engineers in relevant fields; top scientists and engineers in non-space fields that may influence national science and technology policy; deans and heads of academic departments that could reasonably be expected to have some students with an interest in space; top experts and researchers working in fields related to national security/defense who can reasonably be expected to have an interest in space issues; space writers, science journalists, and bloggers; planetarium and public observatory directors; officers and board members of space advocacy groups.
The history of humanity’s effort to reach Mars is defined by a disconnect between ambition and budget.

Mars is a dream deferred, remaining ever distant as NASA’s human spaceflight program centered around the space shuttle and then the International Space Station (ISS) in the decades following Apollo.

Given the significant political, financial, and technological changes that have occurred since the last visit to the Moon, a number of axioms were proposed that should be acknowledged in planning any realistic strategy to get humans to Mars:

1. A “Kennedy Moment” (i.e., an enduring political commitment reflected in a high budget priority for NASA) will not come again.¹

2. Any proposed program architecture must fit within projected NASA human spaceflight budgets (allowing only for inflation) before there can be a discussion of increases.

3. We cannot afford to hit “reset” again. We should expect to use the Space Launch System heavy-lift rocket and Orion crew capsule capabilities currently being developed.

4. Past cost estimates of Mars missions developed from 1989 – 1998 (e.g., the $500 billion number from the Space Exploration Initiative’s “90-day Study”) have been demonstrated to be either incorrect or no longer relevant.

¹ One could argue that there have been several attempts to replicate the “moment” aspect of the Kennedy Moment (e.g., George H.W. Bush’s Space Exploration Initiative or George W. Bush’s Vision for Space Exploration) but none of these moments have followed up with the requisite financial commitments needed to enable the visions presented. In this report, we define the “Kennedy Moment” to be the announcement and the financial commitment by Congress and the White House through the 1960s.

5. Ongoing independent cost estimates are required in order to establish credibility and drive realistic budgeting.

6. A well-articulated strategy and baseline architecture (beyond the next five years) is needed to engage stakeholders. The interest horizon of stakeholders is the decade of the 2030s.

7. Establishing a U.S.-led humans-to-Mars architecture will allow international and commercial partners to identify clear areas for contribution.

8. In order to fund any executable human exploration program, NASA must end its large financial commitment to operating the International Space Station by the late 2020s.

Given these axioms, the following guiding principles were proposed.

### 2.1 - THE 4 CS: CLARITY, COALITION, CONVERGENCE, & COMMERCE

#### 2.1.1. Clarity of Purpose and Budget

Clarity begins with NASA’s mission statement. A statement like “Explore Deep Space” could provide the principal motivation from which most critical robotic science missions and the human exploration of Mars could be derived.

Along with a straightforward goal, there should be a clear understanding of who is ultimately in charge. This individual would be the strongest advocate for the program inside and outside the agency, imbued with enough power to have clear control over the details of the program and able to act effectively when confronted with programmatic challenges. The value of this role has been demonstrated in the robotic Mars Exploration Program at NASA.

The costs and justifications of the program must be clear to NASA, to the White House, to Congress, and ultimately to the American people and international partners. Independent estimates to provide clarity as to costs are required. In order to maintain political and public support, projected costs must be accurate, reliable, and carefully tracked over time.

#### 2.1.2. COALITION, CONVERGENCE: MULTIPLE COMMUNITIES

For much of NASA’s history, its robotic science and human spaceflight programs have operated as almost separate entities competing for resources. In order for the United States to send humans to Mars, the space science community and the human spaceflight community must work together. Fortunately, in recent years, collaboration has been improving between the two directorates within NASA.

The following actions were recommended at the Humans Orbiting Mars workshop for each community in order to build trust and collaboration for a humans-to-Mars project in the coming decades:

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<td><strong>Seek areas of intersection in human and robotic spaceflight</strong></td>
<td><strong>Provide scientific support to enable the goals of the human space program.</strong></td>
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<td><strong>Support community and NASA leadership in establishing a collaborative (or even interdependent) program.</strong></td>
<td><strong>Continue to support future opportunities for technology demonstrations relevant to the human space program.</strong></td>
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<td><strong>Design to a realistic (constrained) budget.</strong></td>
<td><strong>Limit new hardware development to only those systems that are critically needed.</strong></td>
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<td><strong>Maintain a working program plan with specific missions and dates, but keep flexibility to change the plan as implementation evolves.</strong></td>
<td><strong>Make decisions on the basis of cost and technology requirements.</strong></td>
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<tr>
<td><strong>Limit new hardware development to only those systems that are critically needed.</strong></td>
<td><strong>Employ early, independent cost and technical assessments.</strong></td>
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<tr>
<td><strong>Make decisions on the basis of cost and technology requirements.</strong></td>
<td><strong>Involve the scientific community from the earliest stages of mission planning.</strong></td>
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3. The Human Exploration and Operations Mission Directorate (HEOMD) and the Science Mission Directorate (SMD) now have representatives/ liaisons based in each other’s offices at NASA Headquarters, for example.
ARE MULTI-DECADE PROJECTS VIABLE?

Multi-decade projects are the norm in human spaceflight. The space shuttle, from the commitment by President Nixon until its retirement in 2011, was a nearly 40-year program. The International Space Station program has lasted over 20 years (and longer if one includes previous planning work done for Space Station Freedom). A program that takes 18 years to reach Mars orbit and 24 years to reach the Martian surface is possible if a proper coalition of support is developed.

The Space Launch System (SLS) and Orion crew capsule, while controversial in their conception and development, are programs whose success depends on their regular use. Cancelling either program at this point would have far-ranging negative consequences, not only forcing NASA to significantly restructure its workforce and redefine its goals at a number of major centers but also disrupting the existing political support system for the nation’s space program. Alternatively, utilizing SLS and Orion in a way that maximizes stability could provide the deep political support and programmatic capability needed to pursue a program of human Mars exploration over multiple decades. This, of course, assumes that both SLS and Orion are affordable at a use rate adequate for programmatic safety and public engagement.

NASA’s robotic Mars Exploration Program is a model for programmatic consistency. Its structure was set in motion in 2000 – 2001 and the program’s goals have remained the same for 15 years, through two presidential administrations, and four NASA administrators. The robotic Mars program’s budget has averaged $700 million per year (in 2014 dollars) and produced eight highly successful missions in that timeframe.1 This continuity was possible because the Mars Exploration Program:

- Created clear roles of accountability and authority beginning with the new position of Mars Program Director at NASA headquarters.
- Established a highly coordinated implementation team operating under the principles of Program System Engineering.
- Developed and executed a comprehensive strategy.
- Planned and operated within a stable budget throughout its first decade.
- Actively engaged academia, the National Academies, NASA’s advisory structure, the White House’s Office of Management and Budget, the Office of Science and Technology Policy, relevant congressional committees, and public organizations like The Planetary Society.

Any coordinated effort to send humans to Mars should look to the robotic program to provide a model for executing a consistent, sustainable program.

To enable a successful collaborative environment between science and human exploration, the nation, its elected leaders, and NASA must converge on a long-term strategic framework. An articulated long-term strategy helps all participants understand the institutional commitment behind the goal. Directorates may be hesitant to share power or resources if the humans-to-Mars program is seen as transitory or subject to the whims of a new NASA Administrator, Congress, or president. Putting in the time and effort to create a detailed strategy will demonstrate the agency’s commitment to the program.

This strategic framework is also critical for the effective engagement of international partners, who will be needed for any major human spaceflight program. A strategic framework allows international partners—traditional and new—to identify areas in which they wish to contribute.

The Pathways report suggests that an orbit-first humans-to-Mars strategy could provide the core for a broad coalition of supporters. The report featured a survey of stakeholders regarding what the next goal should be in the human spaceflight program. A mission to Mars orbit to explore the Martian moons received the strongest level of support.4

Ultimately only NASA can develop the framework within which these disparate coalitions—science, exploration, international partners, commercial enterprises—can find common interest. And it is the convergence of these interests that can provide support for the program at critical times during its development.

2.1.3 - COMMERCE: A TRAILING EDGE OF ECONOMIC DEVELOPMENT IN SPACE

Sustaining a Mars exploration program is not possible without engaging both the “new” and “old” commercial space sectors. Major industry partners are already deeply involved in the development of SLS and Orion, and a number of new space companies have shown significant advancement in just the past few years. NASA’s new approach to fixed-price commercial services contracts has led to new launch systems capable of successfully resupplying the ISS and competing in the global launch market. NASA’s Commercial Crew program is advancing to provide the first private transportation of U.S. astronauts to the ISS in 2017.

A strategic framework for Mars exploration provides a means for the active, eager, and capable U.S. space industry to define its role within the program. The services-based contracting model for Mars (like the successful Commercial Orbital Transportation Services for the ISS) could potentially provide significant cost savings for cargo and human launches. Perhaps more importantly, broad engagement with the space industry would strengthen the coalition of support necessary to maintain a multi-decade program to send humans to Mars.

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4. Committee on Human Spaceflight, Pathways to Exploration. Table 3.1.3. Goals for NASA’s Human Spaceflight Program Over the Next 20 Years. 66 percent of the respondents strongly or somewhat favored “Conduct orbital missions to Mars to teleoperate robots on the surface.”
NASA has not publicly discussed the costs required to pursue its Evolvable Mars campaign, possibly due to the open nature of the program.¹

But without an honest, independent assessment of cost, it is difficult for supporters—in Congress, the Office of Management and Budget, external groups, or industry—to advocate for the resources necessary for the effort to be successful.

Affordability of the project, particularly within the annual appropriations process, should be taken into account for any long-term humans to Mars architecture. That means planning for constrained funding and accepting that an Apollo-era budget priority for NASA is unlikely to occur again.

It also means countering the widespread misperception that Mars is fundamentally unaffordable. The cost estimates in various Mars architecture concepts have consistently decreased over the years, though statements to the contrary are frequently made in public debates about the viability of Mars exploration.²

3.1 - THE KENNEDY MOMENT WILL NOT HAPPEN AGAIN

The Apollo program was a product of the Cold War. Responding to the Soviet launch of the Sputnik satellite in 1957 and the orbital flight of Yuri Gagarin in 1961, the Kennedy administration and Congress provided the necessary funding to support an aggressive space development program tasked with landing a man on the Moon by the end of the decade. Despite tepid public support, NASA’s budget increased fourfold over the course of a few years, ultimately peaking at four percent of total federal spending and 19 percent of non-defense discretionary spending (Figure 1 - next page).


This level of spending was not sustainable. Significant decreases began under the Johnson administration prior to the first Moon landing in 1969. But it was President Richard Nixon who fundamentally demoted NASA's funding priority within the U.S. government.\(^3\)

Nixon shifted NASA from a national security priority to a domestic agency that competed with other domestic agencies for limited, discretionary federal resources.\(^4\) Every subsequent presidential administration has adopted this viewpoint. In this context, NASA's budget has not thrived.

NASA currently receives approximately 0.5 percent of all U.S. government expenditures.\(^5\) With this level of funding, a path to Mars can appear difficult. The Pathways report evaluated multiple plans for human spaceflight, as shown in Figure 2, and found that none of them were fiscally possible without, at minimum, allowing budgets to grow with inflation. Even with inflationary growth, the human Mars missions that used NASA's latest architecture concepts\(^6\) were only possible, in budget terms, of getting to Mars in the 2040s.\(^7\)

An affordable path forward is possible: one example is suggested in Section 4 of this report. However, it is important first to address existing misconceptions regarding the cost of reaching Mars.

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\(^3\) “We must think of [space activities] as part of a continuing process... and not as a series of separate leaps, each requiring a massive concentration of energy. Space expenditures must take their proper place within a rigorous system of national priorities... What we do in space from here on in must become a normal and regular part of our national life and must therefore be planned in conjunction with all of the other undertakings which are important to us.” Nixon, Richard. “Statement About the Future of the United States Space Program.” March 7, 1970. http://www.presidency.ucsb.edu/ws/?pid=2903. Online by Gerhard Peters and John T. Woolley, The American Presidency Project.


\(^7\) Committee on Human Spaceflight, Pathways to Exploration. Section 4.7.5: Operationally Viable Scenarios. Note that the Committee considered two dates for extended ISS operations: 2020 and 2028. Current NASA policy is to operate the ISS to at least 2024. For the purposes of this report, references to the budget and timeline conclusions from the Pathways report are for the scenarios in which the ISS extended to 2028.
3.2 - THE 90-DAY STUDY AND THE MYTH THAT MARS IS UNAFFORDABLE

The first NASA study conducted for a human mission to Mars took place in 1962, but since no missions even remotely similar in scope had ever been undertaken, no cost estimates were attempted. NASA presented plans for a human Mars mission to President Nixon in 1969 which proposed preliminary steps such as developing a reusable shuttle, constructing a large Earth-orbiting space station, and establishing a permanent lunar base. The cost of implementing such a plan would have required NASA’s budget to return to its Apollo peak for at least a decade. The Nixon White House rejected nearly all the elements of the plan save for the shuttle concept.

In 1989—the 20th anniversary of the Apollo 11 Moon landing—the George H.W. Bush administration proposed its Space Exploration Initiative (SEI), which was intended to rejuvenate the nation’s space program with an ambitious exploratory agenda resulting in human missions to the Red Planet by the start of the 21st century. NASA’s ensuing report (known as the 90-Day Study) estimated the cost of this endeavor to be around $480 – $540 billion ($920 billion – $1.03 trillion in 2014 dollars). This cost proved to be politically untenable, and Congress subsequently rejected funding for SEI.

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The cost estimates from the 90-Day Study that undermined the SEI were misleading for a number of reasons. They extended through a 30-year time span, an unusually large amount of time for government accounting, and assumed funding for a broad range of programs beyond the Mars initiative, including:

- Operating all existing programs, including the space shuttle
- Constructing an Earth-orbiting space station
- Creating a permanent Moon base
- Executing Mars missions to establish and populate multiple surface facilities over a 20-year period
- Establishing funding reserves greater than 55 percent of total mission cost

The costs of the Mars campaign alone totaled roughly $240 billion ($460 billion in 2014 dollars) spread over 15 years. This was a significant price tag but substantially less than the costs of all the programs assumed by the SEI.

Beginning in 1993, NASA produced a series of new Mars Architecture Studies for a human exploration mission. The proposed program differed from the 90-Day Study’s program in that it involved Mars exploration only, included a single crewed mission, and introduced new concepts such as in-situ resource utilization. The cost estimating process also benefited from better models, leading to higher fidelity estimates. The 1993 architecture costs were estimated at $120 billion—
half the cost of the Space Exploration Initiative’s proposed Mars architecture and one-fifth of the overall costs set forth in the 90-Day Study.

NASA produced another series of Design Reference Studies in 1997 – 1998, which focused on organizational and management innovations and assumed the inclusion of international partners. An inter-center group at NASA estimated costs for eight separate approaches to carrying out a human Mars program. Each approach involved two cargo missions and one crewed mission to Mars. With approximately 15 percent added as budget reserves, the studies found that the costs for every approach were less than $20 billion ($30 billion in 2014 dollars).

The decline in cost estimates for human missions to Mars, as seen in Figure 3, is attributable to several factors: 1) the earlier mission architectures involved far more ambitious programs over a much longer time period; 2) better cost estimating methodology allowed for lower reserve estimates in the later architectures; and 3) NASA’s management practices improved. Other significant factors in the reduced estimates are the addition of commercial and international partners and the incorporation of new technologies.8

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A study group from the Jet Propulsion Laboratory (JPL) in Pasadena, California provided the feature presentation at the Humans Orbiting Mars workshop: a minimal exploration architecture that would allow humans to orbit Mars by 2033 and land on the surface by 2039, as seen in Figure 4.

Intermediate missions to validate hardware in cis-lunar space would occur during the 2020s.¹

The study group pursued a minimal architecture by embracing existing programs and limiting new hardware development, thus avoiding a common source of budget overruns and schedule delays. The JPL study was done as input to the overall NASA planning process.

The concept architecture proposed a series of missions that would increase in complexity as the program developed. Each mission builds on the experience gained from previous missions and leaves a legacy for those that come after.

The architecture relies on the Block II version of the Space Launch System (SLS) heavy-lift rocket, the Orion crew capsule, 100 kWe solar electric propulsion (SEP) tugs, and a long-duration crew habitation module. Notably, only the habitat module and chemical transfer stages would be brand new—all other hardware is currently in various stages of development.

4.1 - THE MOON AS A PROVING GROUND FOR MARS

Missions don’t exist in isolation. Getting humans to Mars by the 2030s will require new hardware and space-based operations that must be demonstrated closer to Earth. Cis-lunar space is seen as the logical region for these activities. NASA itself refers to this large volume of space around the Moon as a “proving ground” for future human expeditions. Interim missions in cis-lunar space provide an opportunity for ongoing engagement of the public and other stakeholders throughout the 2020s. It also provides an opportunity to return to the Moon, a major achievement under any program of human exploration and a means by which to broaden the base of support for a mission to Mars.

JPL’s study team proposed the following series of missions to take place in the 2020s:

2020: Flight test of a 50 kWe Solar Electric Propulsion (SEP) system in interplanetary space with crewed docking operations in cis-lunar space. This could be achieved via the Asteroid Redirect Mission (ARM) or a dedicated technology demonstration mission without an asteroid.

2025 & 2027: Astronauts perform long-duration stays in a Deep Space Habitat (DSH) in cis-lunar space.

2026: Robotic technology demonstration at Mars to validate the use of Supersonic Retro-Propulsion (SRP) for entry, descent, and landing.

Humans would briefly return to the surface of the Moon in 2035 within the context of an end-to-end test of the Mars lander system and a simulation of Mars surface operations.

Figure 5 highlights additional types of intermediate missions being discussed for cis-lunar space.

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NASA’s Evolvable Mars Campaign states that the Moon will be an important area for human exploration in the 2020s (see Figure 6), though there are no missions explicitly planned beyond the crewed docking demonstration with the ARM in 2025. There remains skepticism within the science community and elsewhere as to the efficiency of portions of NASA’s plan.1

1 “Maneuvering a large test mass is not necessary to provide a valid in-space test of a new SEP stage. We therefore find that a SEP mission will contribute more directly to the goal of sending humans to Mars if the mission is focused entirely on development and validation of the SEP stage.” NASA Advisory Council, Finding: Asteroid Redirect Mission and Solar Electric Propulsion. April 9 – 10, 2015. http://www.nasa.gov/sites/default/files/atoms/files/april9-10_finalrecom-tagged.pdf
For example, the capabilities and experience NASA says it will develop during the ARM—including crew operations beyond low-Earth orbit; deep space guidance navigation and control; solar electric propulsion (SEP); and exploration capabilities outside the spacecraft—can be accomplished without the effort and risk associated with retrieving part of an asteroid.

The workshop discussions reflected wide agreement on the need for intermediate steps and on cis-lunar space as the logical region for them. However, until there is a well-defined, long-term strategy to get to Mars, the debate about the value of current cis-lunar missions will likely continue.

4.2 - MARS ORBIT AS A CRITICAL STEP TOWARD LANDING

Apollos 8 and 10 orbited the Moon before Apollo 11 landed. Mariner spacecraft orbited Mars before Vikings I and II landed. The JPL study architecture discussed at the workshop calls for humans to orbit Mars first and then land in the following mission. An orbit-only mission would maintain a focus on the critical systems and techniques needed to sustain humans during their voyage to Mars and back. It also advantageously spreads out the risk and cost associated with developing the hardware for landing.

A mission to Mars orbit also provides significant scientific and human-exploration opportunities for studies of the moons of Mars: Phobos and Deimos. The benefits of both of these
targets were discussed at the workshop, though Phobos as the primary target was the focus of the workshop and of the JPL study team’s plan.

In the mission scenario presented by the JPL team, as seen in Figure 7, two SLS launches pre-position cargo in the Mars system. Two chemical transfer stages, delivered to Mars via a solar electric propulsion tug, await the arrival of the crew in high Mars orbit: one to take the crew to and from Phobos and one to return the crew to Earth. A solar electric propulsion tug places a Phobos habitat, derived from the Deep Space Habitat, on the Martian moon. Notably, the tugs can deliver this cargo to Mars orbit outside the standard launch windows that open every 26 months.

After these preparations, two more SLS Block II launches to Earth orbit put the remaining mission components in place: a crewed Orion capsule and exploration upper stage; a Deep Space Habitation module; and a chemical Mars-orbit insertion stage. The crew docks with the habitation module and re-ignites the exploration upper stage to begin the long voyage to Mars.

### MARS ORBIT/PHOBOS MISSION SUMMARY

**Precursor to Mars landing mission**

**Validates method for getting to Mars orbit and back**

**Uses Solar Electric Propulsion (SEP) tugs to pre-position assets in the Mars system prior to crew arrival**

~2 ½ year round trip with a crew of four, including ~300 days at Phobos

**HARDWARE**

- 4 SLSs, Block II
- 2 100 kW Electric Propulsion tugs
- 1 Phobos Transfer stage (to get crewed Orion from high Mars orbit to Phobos and then back to high orbit)
- 1 Trans-Earth Injection stage (for returning crew to Earth)
- 1 Mars Orbit Insertion stage
- 1 Deep Space Habitat
- 1 Phobos Habitat (common design with Deep Space Habitat)
- 1 Orion crew capsule

**TECHNOLOGY DEVELOPMENT REQUIRED:**

- SLS Block II
- Exploration Upper Stage with docking and engine restart capability
- 100 kW Electric Propulsion tug
- Phobos/Deep Space Habitat
- In-space Chemical Propulsion Stages (Phobos/Deimos Transfer Stage)
The crew enters high Mars orbit and docks with the Phobos transfer stage. Leaving the Deep Space Habitat behind, the crew descends to Phobos, meets up with their prepositioned Phobos habitat, and makes history with a 300-day stay on the Martian moon (see Figure 8).

The crew reuses the Phobos transfer stage to return to high Mars orbit in their Orion capsule. There they meet up with their Deep Space Habitat and the Earth return stage. They return to Earth, ultimately splashing down in Orion.

As noted throughout this report, workshop participants highlighted the necessity of including international and commercial partners, though the JPL study team did not explicitly discuss such participation in detail.
4.3 - BOOTS ON THE GROUND

4.3.1 - A SHORT-STAY MISSION IN 2039

Based on the experience gained from the Phobos mission, NASA could confidently pursue a more ambitious mission to land astronauts on Mars by the end of the 2030s. The JPL study team explored a short stay mission on Mars (24 days) as the next logical step.

This mission would use the now-validated approach for getting crew to the vicinity of Mars and back to Earth. The difficult task of landing would be the prime focus.

A total of six SLS Block II launches would be needed, as seen in Figure 9. As in the first orbital mission, two SLS Block II launches would place cargo in Mars orbit in advance. There would be two solar electric propulsion tugs: one to place the Earth-return stage in high Mars orbit, and the second carrying a habitat resupply module and a transfer stage needed to return from low to high Mars orbit.

Two years before the crew launch, NASA would use two SLS Block II launches to pre-position the crew lander in high Mars orbit. The lander is a 12-meter spacecraft that includes a Mars ascent vehicle, providing an abort-to-orbit capability if the landing attempt goes awry. The lander is mated with an Exploration Upper Stage in Earth orbit, which then sends it along to be aerocaptured in high Mars orbit, where it will await the arrival of the crew.

As in the first mission, NASA would then use two SLS Block II launches to place a crewed Orion and Exploration Upper Stage in Earth orbit, which would dock with a Deep Space Habitat and a chemical Mars-orbit insertion stage.

The crew arrives in Mars orbit in the same fashion as in the 2033 mission. Two members of the crew enter the landing vehicle and become the first people in history to set foot on the Red Planet. After a stay of 24 days, they launch to low Mars orbit and dock with the pre-positioned chemical transfer stage. This transfer stage lifts them back up to high Mars orbit, where they are reunited with their fellow crew members. The Trans-Earth Injection (TEI) stage takes them home.

4.3.2 - TOWARD A PERMANENT HUMAN PRESENCE

As envisioned by the JPL study team, NASA would attempt its first long-duration stay on Mars in 2043, choosing a site that would become a permanent base. Over time, infrastructure could be built up at this location, which would see a regular crew rotation to sustain a continuous human presence. Under this scenario:

- NASA would send a new crew to Mars every four years.
- The SLS launch rate would be one launch every six months.
- NASA would send two cargo landers with each crewed mission.
- NASA would build up infrastructure on Mars to provide power, in-situ resource utilization, food production, and habitable volume.
- The Mars program would evolve to put in place a reusable transportation architecture between Earth and Mars with an increased flight rate.
- With the eventual acquisition of a water source on Mars, NASA could achieve a permanent presence with an Antarctica-type population.
HUMANS ORBITING MARS: A CRITICAL STEP TOWARD THE RED PLANET

MARS SHORT-STAY MISSION SUMMARY

Cargo and crew travel to Mars using methods from the 2033 mission

Additional launches needed to position the landing vehicle in high Mars orbit to await crew arrival

A crew of two lands on Mars using supersonic retro-propulsion (no parachutes)

Return of the crew to high Mars orbit is achieved via a two-step ascent using the Mars ascent vehicle and an additional chemical booster stage

HARDWARE

- 6 SLSs Block II
- 2 100 kWe Solar Electric Propulsion Tugs
- 1 Exploration Upper Stage
- 1 Trans-Earth Injection stage
- 1 Mars Orbit Insertion stage
- 2 Deep Space Habitats
- 1 Orion crew capsule
- 1 Mars Ascent Vehicle
- 1 Mars ascent vehicle boost stage
- 1 Mars lander (23 tons useful landed payload)

TECHNOLOGY DEVELOPMENT REQUIRED:

- Mars Ascent Vehicle
- Mars lander with supersonic retro-propulsion
4.4 - THE SCIENTIFIC POTENTIAL OF MARS ORBIT AND PHOBOS

There is a large community of Mars scientists that could serve as a cornerstone of support within any coalition for the human exploration of the Red Planet. But workshop participants emphasized that this support is not a given. Many in the scientific community feel that science is treated as an afterthought in human exploration missions. They worry that science budgets often compete with (and lose to) human missions.

To build support within the scientific community, it is important that any plans for human exploration to Mars involve the scientific community and incorporate their goals during early stages of development. The scientific community has defined its top priority scientific goals for Mars. It is also important that programmatic costs are managed so as not to threaten science missions within NASA, as discussed in section 2.1.2.

Having astronauts in Mars orbit will provide significant opportunities for science. But, as workshop participants noted, NASA should focus the science objectives of a human mission to areas best served by humans (such as sample collection on Phobos) and not in areas where robotic assets have proven capable (like remote sensing and reconnaissance of the Martian surface from orbit). The workshop participants focused on two activities that would benefit from a human presence: the tele-operation of robotic assets on the Martian surface and extensive sampling and exploration of Phobos.

4.4.1 -TELE-OPERATION OF ROBOTIC SURFACE ASSETS

A major limitation to the effectiveness of current robotic assets on the surface of Mars is the time delay—due to the round-trip travel time for signals between Earth and Mars. Communications from Earth require, on average, 20 minutes. As a result, robotic assets are not operated in real time. Teams of scientists and engineers must construct sequences of commands that are uploaded before the day begins on Mars. These sequences require significant discussion, planning, and validation before they can be sent to ground assets on the Red Planet.

By contrast, the two-way communication time from Phobos to Mars is just 40 milliseconds. Real-time control of robotic vehicles on the Martian surface could increase the number of command cycles per sol and reduce “restricted sols”—catch-up periods during which the science team stands down in order to synchronize schedules to the Martian day. These restricted sols can have significant impacts on operations. NASA’s Mars Science Laboratory Curiosity team considers just 43 percent of all sols as unconstrained planning cycles.

It will be necessary to evaluate complexities introduced by real-time operation of robotic assets by astronauts in orbit. An additional consideration for study is the likely need for one or more telecommunications orbiters to relay information to a rover on the surface.

The scientific potential of tele-operations will depend on the instrument suites of the rovers on the ground and on the locations of their landing sites. These rovers also must be designed, built, launched, and safely landed on the Martian surface. Funding for these types of rovers are not included in the cost assessments of any human exploration plan for Mars.

The scientific value of rovers on the Red Planet is clear. Adding more time for truly interactive exploration and enabling more serendipity could potentially increase scientific return.

4.4.2 -PHOBOS

Scientific knowledge of the Martian moons contains significant gaps, including the fundamental question of their origins: are Phobos and Deimos captured asteroids as their spectral characteristics suggest? Or are they from Mars itself, either accreting at the same time as Mars or forming from the ejecta of a major impact event (which could explain their orbits)? Answering any of these questions would be scientifically important. If Phobos is a captured asteroid, it may represent a class of as-yet unexplored solar system bodies. Understanding the capture process, as recorded in the details of Phobos’ surface and interior composition, could be important to understanding other enigmatic classes of small bodies, such the Trojan asteroids. If the moons are from Mars, they would provide important insights regarding the formation and ancient history of the Red Planet.

Astronauts on Phobos would have the same advantages over robotic exploration as they would on the surface of Mars: quick decision-making, serendipity, and mobility. This is not to discount the challenges astronauts would face while maneuvering on the surface. The dimensions of Phobos are only 27 km x 22 km x 18 km, resulting in a very low but not insignificant gravity field. Established extra-vehicular activity (EVA) techniques will not work in this environment. New techniques would need to be developed and validated.

4.4.3 -SAMPLES RETURNED FROM MARS AND PHOBOS

The major questions regarding Phobos’ origin can be answered by sampling its surface. Samples would provide insights into its age, composition, and origin as well as the history of activity in the Martian system.

Phobos also presents an interesting opportunity for Martian sample collection. Meteorites collide with Mars regularly, and...
ejecta from some of the larger impacts are thrown into Martian orbit. Phobos inevitably passes through these debris fields, accumulating on its surface a broad sampling of materials from the Red Planet. Current estimates place the bulk concentration of Martian ejecta on Phobos as approximately 250 parts per million, concentrated in the upper meter of that moon’s regolith. This material would be difficult for a robot to excavate but relatively straightforward for an astronaut.

Martian meteorites found on Earth are usually dense, crystalline, volcanic rocks. But the story of Martian habitability is best told by weak sedimentary rocks, the types of rocks layered by or altered by water. Phobos is likely covered with debris accelerated to significantly lower velocities than the Martian meteorites that found their way to Earth, and this debris is likely to include sedimentary materials (such materials are destroyed by the high-energy impacts necessary to eject Earth-bound meteorites). Phobos’ surface is therefore highly interesting from a scientific perspective, offering, in effect, the opportunity for a dual sample return mission.

The highest priority for the Mars science community is a carefully curated sample return from the planet itself. The possibility of merging these goals with human missions to Mars has previously been discussed. For example, astronauts in Mars orbit could retrieve samples that have been robotically collected from the surface and launched into Mars orbit. This approach would effectively replace the robotic part of the proposed three-mission robotic sample-return campaign (the Mars 2020 rover can be considered part one of this robotic effort). Given that a robotic campaign could return samples by the end of the 2020s, it was noted at the workshop that it would be unfortunate if the return of the first Mars samples were delayed by relying on humans in orbit in 2033, though it is an interesting backup option to consider.

4.5 - COST

The large cost estimates associated with human missions to Mars have bedeviled NASA for decades. As discussed in Section 3, much of the problem is due to outdated mission architectures and estimation methods. Affordability is possible, but it depends on the design of the architecture to mitigate both the total and the year-to-year development costs.

In 2014, an independent assessment of NASA’s current human exploration architectures was performed for the Pathways report by the Aerospace Corporation. This team analyzed a variety of future scenarios for human spaceflight and found that if the ISS is extended to 2028, no Mars landing could happen any earlier than the mid-to-late 2040s, even with a budget growing to match inflation.

To properly compare their concept architecture to those referenced in the Pathways report, the JPL study team asked the Aerospace Corporation to apply the same cost analysis to their orbit-first scenario. The Aerospace assessment used the same people, the same methods, the same models, and the same assumptions used in the Pathways report.

The Aerospace team examined two scenarios: one in which NASA’s International Space Station program continues until 2028 (Figure 11), and one in which NASA’s primary role in the ISS ends by 2024 (Figure 10), which is current policy. In both scenarios, the JPL concept generally fits within a NASA human spaceflight budget that grows only with inflation, though it is considerably better under the “ISS commitment ends in 2024” scenario.

7 Committee on Human Spaceflight, Pathways to Exploration. Section 4.2.7: Affordability.
8 Committee on Human Spaceflight, Pathways to Exploration. Section 4.2.7.2: Pathway Cost Range Methodology.

Notably, this cost analysis does not assume any international contributions or potential savings provided by commercial partners. As NASA defines its overall strategy and both types of partners are integrated into the long-term plan, a more realistic budget will need to be developed and analyzed by an independent entity.

This first-order analysis demonstrates that an orbit-first mission can get humans to Mars over a decade sooner than any plan analyzed in the Pathways report while plausibly fitting within a budget for human spaceflight that increases only with inflation. The addition of international and commercial partners would likely improve the financial sustainability of this project.
NASA’s human spaceflight program has existed for over 50 years, even though it has generally lacked majority public support.

Throughout the 1960s, the majority of the public did not consider that project Apollo was “worth the cost,” yet President Kennedy’s challenge was met. The space shuttle program lasted four decades, and the ISS remains in orbit despite relatively low public priority for space-related issues. Human spaceflight is clearly possible and sustainable without overwhelming public demand, though it does benefit greatly from the support a small but attentive segment of the public that remains very interested in and well informed about space issues.

Recent polls show that fewer than 40 percent of Americans would support the exploration of Mars by humans (see Figure 12). History demonstrates that this need not, and does not, preclude ambitious programs of human exploration. However, this sobering fact is a reminder that the space program is constrained by a lack of a strong public demand for increased resources. It is all the more important, then, to define an affordable, sustainable program.

Though space exploration is not the top priority for most Americans, the 36 percent of the public that does support the human exploration of Mars is a significant asset, particularly...
when there is no organized opposition to the program. Atten-
tion to Mars exploration has increased in recent years on a
number of fronts, from the outpouring of interest during the
landings of NASA’s Mars Pathfinder, Spirit, Opportunity, and
Curiosity rovers to the public fascination with the (admittedly
outlandish) one-way concept promoted by Mars One and to
the high visibility of the first uncrewed test of the Orion crew
capsule—presented by NASA as a step on their “Journey to
Mars.”

The workshop discussed how these examples provide a clear
narrative of exploration by which to engage the public. By
maintaining a focus on the overall goal of humans on the sur-
face of Mars, the narrative can incorporate a variety of mile-
stones demonstrating success along the way, including a Pho-
bos mission before landing.

To sustain the public’s important role in the coalition of sup-
port for Mars, particularly among the portion of the public that
is attentive to space issues, exploration milestones must occur
frequently and be clearly associated with the ultimate goal of
humans on the Red Planet. The public as a whole is generally
not interested in hardware for Mars exploration; its interest
lies much more in the science return and the overall human
adventure.

A mission to Mars orbit would send humans farther into space
than we have been at any point in history. For the majority of
people alive today, who did not witness the Apollo landings,
it would represent the first time humans ventured more than
a few hundred miles beyond Earth’s surface. It would be the
most exciting, audacious, and ambitious mission ever attempt-
ed by NASA. A Mars orbital mission easily fits into a larger
narrative of Mars exploration, with boots on the ground being
the clear next step.

Pathfinder mission. (Source: Roger Launius. “Panel Discussion: Can an Early Orbital/Phobos Mission be Exciting to the Public?” Presented at the Humans
Orbiting Mars workshop, Washington, D.C., April 1, 2015)
SPOTLIGHT: FUTURE LEADERS IN SPACE

Some of the astronauts who will travel to Phobos in 2033 are in middle school now, but the individuals who will lead the science and technical teams for the mission are already contributing to our space program. Workshop co-chair John Logsdon convened the following panel to explore how future leaders in space feel about the human exploration of Mars.

Ashley Chandler Karp  
*Propulsion Engineer, Jet Propulsion Laboratory*

Karp works on the Mars 2020 rover and on a future Mars Sample Return mission concept, concentrating on launching the samples from the surface to Mars orbit. Her work focuses on using resources gathered at Mars to power a rocket. She is also the Principal Investigator for JPL’s hybrid propulsion test facility. She received her PhD from Stanford University in 2012.

For the Humans Orbiting Mars workshop, Karp conducted an informal survey of 116 of her colleagues representing over 30 countries. When asked if they thought a mission to Mars was possible by 2033, 74 (64 percent) of them responded yes. When asked, “What could be done right now to enable you to make your desired contribution?” 33 responded “precursor or technology demonstration missions,” 32 said “increased funding,” and 9 said “better STEM education.”

Sirisha Bandla  
*Associate Director, Commercial Spaceflight Federation (CSF)*

Bandla works on various policies with the aim to promote the commercial space industry and make commercial human spaceflight a reality. Before joining CSF, she worked as an aerospace engineer designing components for advanced aircraft at L-3 Communications.

“It’s no longer the NASA space program. It’s the U.S. space program. With partnerships between public and private organizations, the engagement is growing. Our next steps include the commercialization of low-Earth orbit, with NASA handing off access to LEO to private enterprise. Companies are already looking to the Moon for future commercial exploration. Will this hand-off allow NASA to start aiming for Mars?”

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Anne Caraccio  
*Chemical Engineer, Kennedy Space Center*

Caraccio works on the Mars Atmosphere and Regolith COllector/PrOcessor for Lander Operations (Marco Polo) project, which is focused on converting the Martian atmosphere into useful commodities like fuel and water. She was a crewmember of the 2014 HI-SEAS 2 Mission, where she lived in an isolated Mars-like habitat with an international crew. She is a PhD student in the Department of Chemical and Biomedical Engineering at the University of South Florida.

“Resource reutilization is one of the major technology brackets that will allow for continued human exploration into deep space. All of these exceptional technologies being developed for power, vehicle fuel and life support systems from Mars resources will break thresholds for a more sustainable life on our home planet. We must embrace the efforts of all scientists and engineers in the world to reach these critical requirements so that we can, together, combine and collaborate our science, rather than compete it, in order to travel into deep space.”

Julieynn Wong  
*3D4MD*

Wong is a Harvard-educated physician, researcher, innovator, educator, pilot, and journalist. She conducted medical research at Harvard Medical School, Massachusetts Institute of Technology, NASA Goddard Space Flight Center, NASA Ames Research Center, NASA Johnson Space Center, and the Mars Desert Research Station. She created 3D4MD, a platform that includes 3D4Mars, a digital library of 3D printable medical supplies to support healthcare on Mars missions.

“The dream of going to Mars has encouraged many people to go into space exploration, space sciences, and related fields. It’s the natural next step for human space exploration. But these things we’re researching aren’t just for space exploration. It helps many aspects of life here on Earth. There are thousands of people working with this motivation to go to Mars. It inspires today’s young innovators and it keeps them going. It’s their mission, their vision, and their goal to see a humans-to-Mars project all the way through.”

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International partnerships are important for any major undertaking in space. While participating nations contribute technical expertise and monetary support, collaboration in space helps to strengthen international relationships on Earth. The International Space Station provides the best case study of these benefits. And organizations like the International Space Exploration Coordination Group\(^1\) is an avenue by which exploration goals can be aligned among international partners.

However, without a clear strategy for reaching Mars, defining the relationships and contributions from international partners will be difficult. As the world’s largest space agency, NASA’s commitment to a long-term, well-defined strategy for exploring the Red Planet would create the framework necessary to engage the international community.

In a similar vein, the commercial space sector also depends on a clear strategy from NASA to define its role in the human exploration of Mars. Companies like SpaceX, Orbital ATK, and Boeing are working under services-based contracts to send cargo and crew to the ISS, and similar roles are possible in support of sending humans to Mars. But again, NASA must define its Mars strategy in adequate detail in order for the commercial sector to determine its role in the next phase of human spaceflight, particularly as NASA’s involvement in ISS draws to a close.

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CONCLUSION

A sustainable, executable, and affordable path to the human exploration of Mars includes an orbital mission at Mars as a critical step.

An orbital mission (particularly one that lands on Phobos) provides ample opportunities to advance our scientific understanding of Mars and its moons, test our technological capabilities, and engage the public with an unprecedented adventure in space exploration. Humans would travel farther, stay longer, and assume more risk than at any other point in NASA’s history.

The JPL study group’s plan demonstrates that such an approach is both plausible and monetarily preferable. The plan uses programs and hardware already being developed or under study. It reduces reliance on brand-new, untested technologies. It involves multiple missions to cis-lunar space to develop capabilities and provides public benchmarks to demonstrate progress toward the goal.

This plan once again demonstrates that the human spaceflight budget needs to grow, at minimum, with inflation. But just as importantly it demonstrates that a mission within a reasonable time span is possible without politically unfeasible increases to NASA’s overall budget. No new “Kennedy moments” are needed.

A sustainable strategy depends on a coalition of stakeholders invested in the program’s success. The path to the Red Planet through the cis-lunar space and Phobos provides an opportunity to engage a significant number of groups: scientists, technologists, supporters of lunar exploration, major industry invested in existing programs, NASA itself, and wide swaths of the public. History has demonstrated the power of coalitions in maintaining decades-long human spaceflight programs. Getting humans to Mars will be no different.

Humans will not reach the Red Planet using the exact architecture discussed above. At this early stage it is impossible for any plan to anticipate all the future technological, political, and engineering advances yet to come. But work can be done to define and articulate a flexible, executable strategy, and NASA is the organization to lead the way.

Once a flexible strategy is defined and pursued, it will provide an external metric by which to prioritize current technology investments, a framework to engage commercial and international partners, and a crucial benchmark by which the public and their representatives in government can measure progress.

NASA has an opportunity to lead the world to Mars. But the work must begin now.
### Appendix A. The Humans Orbiting Mars Workshop Agenda

#### Day 1 - Getting on With It! The Urgent Need for an Affordable Pathway to Mars

<table>
<thead>
<tr>
<th>TIME</th>
<th>TITLE</th>
<th>SPEAKER</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00AM – 9:15</td>
<td>Welcome and Opening Remarks</td>
<td>Bill Nye, The Planetary Society</td>
</tr>
<tr>
<td>9:15 – 10:00</td>
<td>Building Consensus on a Long Term, Cost Constrained, Executable Humans to Mars Program</td>
<td>Scott Hubbard, Stanford University</td>
</tr>
<tr>
<td>10:00 – 10:30</td>
<td>Why the Kennedy Moment Won’t Come Again</td>
<td>John Logsdon, George Washington University</td>
</tr>
<tr>
<td>10:30 – 11:00</td>
<td>Discarding Historical Baggage: The 90-Day Study Myth and Other Misconceptions</td>
<td>Joe Hamaker, Galorath Inc.</td>
</tr>
<tr>
<td>11:00 – 11:15</td>
<td>Break</td>
<td>-</td>
</tr>
<tr>
<td>11:15 – 11:45</td>
<td>Science Community Support for Humans in Mars Orbit and at Phobos</td>
<td>Steve Squyres, Cornell University</td>
</tr>
<tr>
<td>11:45 – 12:00PM</td>
<td>Discussion</td>
<td>Scott Hubbard, Cornell University</td>
</tr>
<tr>
<td>12:00 – 12:45</td>
<td>Working Lunch</td>
<td>All</td>
</tr>
</tbody>
</table>

#### Day 2 - Getting Humans to Mars Starting Now

<table>
<thead>
<tr>
<th>TIME</th>
<th>TITLE</th>
<th>SPEAKER</th>
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</thead>
<tbody>
<tr>
<td>12:45PM – 2:15</td>
<td>Humans to Mars: Thoughts Toward an Executable Program – Fitting Together Puzzle Pieces and Building Blocks</td>
<td>Firouz Naderi, Hoppy Price, John Baker, Jet Propulsion Laboratory; Terry Radcliffe &amp; Russell Persinger, The Aerospace Corporation</td>
</tr>
<tr>
<td>2:15 – 3:00</td>
<td>The Affording Mars Community Workshops: Consensus Architecture and Next Steps</td>
<td>Chris Carberry, Explore Mars, Inc.; Harley Thronson, NASA Goddard Space Flight Center &amp; American Astronautical Society</td>
</tr>
<tr>
<td>3:00 – 3:15</td>
<td>Discussion</td>
<td>-</td>
</tr>
<tr>
<td>3:15 – 3:30</td>
<td>Break</td>
<td>-</td>
</tr>
</tbody>
</table>
## APPENDICES

### APPENDIX A. THE HUMANS ORBITING MARS WORKSHOP AGENDA [CONT]

#### Day 1 - The Shape of a Unifying Program

<table>
<thead>
<tr>
<th>TIME</th>
<th>TITLE</th>
<th>SPEAKER</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:30PM – 4:30</td>
<td>Panel Discussion: How an Orbital/Phobos Mission Can Unite The Science and Human Exploration Communities</td>
<td>Chair: Jim Bell, Arizona State University with Ken Bowersox; Rick Davis, NASA Headquarters; Laurie Leshin, Worcester Polytechnic Institute; and Scott Murchie, Johns Hopkins University Applied Physics Laboratory.</td>
</tr>
<tr>
<td>4:30 – 5:30</td>
<td>Panel Discussion: Steps towards the Martian Moons between 2021 – 2033</td>
<td>Chair: Josh Hopkins, Lockheed Martin with Dan Britt, University of Central Florida; Michele Gates, NASA HQ; and Steve Stich, NASA Johnson Space Center.</td>
</tr>
<tr>
<td>5:30</td>
<td>Adjourn</td>
<td></td>
</tr>
<tr>
<td>5:30 – 6:30</td>
<td>Reception</td>
<td></td>
</tr>
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</table>

#### Day 2 - Selling the Program: Building Advocacy

<table>
<thead>
<tr>
<th>TIME</th>
<th>TITLE</th>
<th>SPEAKER</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:00AM – 10:00</td>
<td>Panel: Can an Early Orbital/Phobos Mission be Exciting to the Public?</td>
<td>Chair: Casey Dreier, The Planetary Society with Roger Launius, National Air and Space Museum; Alan Ladwig, Space Development Ventures; Bill Nye, The Planetary Society; and Lauren Worley, NASA HQ.</td>
</tr>
<tr>
<td>10:00 – 11:00</td>
<td>Panel: The New Space Generation and Mars</td>
<td>Chair: John Logsdon with Sirisha Bandla, Commercial Spaceflight Federation; Anne Caraccio, HI-SEAS Mission 2 Crew Member; Ashley Chandler Karp, Jet Propulsion Laboratory; and Julielynn Wong, 3D4MD.</td>
</tr>
<tr>
<td>11:00 – 11:20</td>
<td>A Space Community Assessment</td>
<td>Elliot Pulham, Space Foundation</td>
</tr>
<tr>
<td>11:20 – 12:30PM</td>
<td>Discussion, consensus, adjourn</td>
<td>Scott Hubbard</td>
</tr>
</tbody>
</table>
APPENDICES

APPENDIX B. MAPPING OF WORKSHOP PRESENTATIONS TO REPORT SECTIONS

The introduction and the conclusion represent The Planetary Society’s viewpoints. We make no claim that these two sections reflect the views of all the participants of the workshop, though the “sense of the workshop” items were presented, discussed, altered, and generally agreed to by the participants. Individual experiences may differ.

Sections 2 - 6 of this report reflect the content of the presentations, panel discussions, and audience discussion during the workshop. Since the structure of the report differs from that of the workshop’s agenda, we present a mapping between the two below.

Section 2: A Strategic Approach

Section 3: Affording Mars
- Carberry, Chris and Harley Thronson. Building a Community Consensus: Summaries of The Affording and Sustaining Mars Workshops.
- Hamaker, Joseph and Humboldt C. Mandell. Human Mars Missions Are Affordable (And We Can Prove It).
- Logsdon, John M. Why the Kennedy Moment Won’t Come Again.

Section 4: An Affordable, Sustainable Humans-to-Mars Program
- Bell, James F. How an Orbital/Phobos Mission Can United the Science & Human Exploration Communities. Panel discussion with Ken Bowersox; Rick Davis, NASA Headquarters; Laurie Leshin, Worcester Polytechnic Institute; and Scott Murchie, Johns Hopkins University Applied Physics Laboratory.
- Price, Hoppy; Baker, John; Firouz Naderi; Terry Radcliffe; and Russell Persinger. Humans to Mars, Thoughts Toward an Executable Program, Fitting Together the Puzzle Pieces & Building Blocks.
- Squyres, Steve. Science by Humans in Mars Orbit and at Phobos.

Section 5: Public Engagement and Orbiting First
- Dreier, Casey. Can an Early Orbital/Phobos Mission be Exciting to the Public? Panel discussion with Roger Launius, National Air and Space Museum; Alan Ladwig, Space Development Ventures; Bill Nye, The Planetary Society; and Lauren Worley, NASA HQ.
- Logsdon, John. The New Space Generation and Mars. Panel discussion with Sirisha Bandla, Commercial Spaceflight Federation; Anne Caraccio, HI-SEAS Mission 2 Crew Member; Ashley Chandler Karp, Jet Propulsion Laboratory; and Julielynn Wong, 3D4MD.

Section 6: Commercial and International Partners
- Logsdon, John. The New Space Generation and Mars. Panel discussion with Sirisha Bandla, Commercial Spaceflight Federation; Anne Caraccio, HI-SEAS Mission 2 Crew Member; Ashley Chandler Karp, Jet Propulsion Laboratory; and Julielynn Wong, 3D4MD.
- Pullum, Elliot H. Humans Orbiting Mars: A Space Community Assessment
APPENDIX C. WHICH MOON TO EXPLORE?

The majority of the discussion at the workshop assumed Phobos as the destination for human exploration in Mars orbit. But the surface of Phobos is rougher than that of Deimos, making it harder to find a safe, level landing site. Phobos is also much farther inside the Mars gravity well than Deimos, so a spacecraft would need a larger velocity to return from Phobos orbit. Phobos is bigger and a lot closer to Mars, which means that the moon has higher gravity and larger Mars tidal effects, which will complicate orbital maneuvers.

The eclipse periods—when Mars is between the moons and the Sun—cover less of Deimos’ orbit, meaning there will be more daylight hours on the smaller moon. Deimos’ higher orbit also means that operations from the moon would have greater line-of-sight capabilities, meaning that telecommunication opportunities would be more frequent than from Phobos.

The workshop emphasized the importance of involving the scientific community from an early stage. Both programmatic and scientific needs must be addressed early on in order to pursue a clear path to Mars. The question remains about which moon is a better choice—one that the scientific community is well positioned to answer.

APPENDIX D. LOAs (LIST OF ACRONYMS)

- ARM – Asteroid Retrieval Mission
- CCP – Commercial Crew Program
- COTS – Commercial Orbital Transportation Services
- DRA-5 – Design Reference Architecture 5
- DSH – Deep Space Habitat
- DSN – Deep Space Network
- EDL – Entry, descent, and landing
- EUS – Exploration Upper Stage
- EVA – Extra-vehicular activity
- FY – Fiscal year
- HEOMD – Human Exploration and Operations Mission Directorate
- HEO – High-Earth orbit
- HI SEAS – Hawai’i Space Exploration Analog and Simulation
- HMO – High-Mars orbit
- HSF – Human space flight
- ISECG – International Space Exploration Coordination Group
- ISRU – In situ resource utilization
- ISS – International Space Station
- JPL – Jet Propulsion Laboratory
- kWe – kilowatt electric
- LEO – Low-Earth orbit
- LMO – Low-Mars orbit
- MAV – Mars Ascent Vehicle
- MAVEN – Mars Atmosphere and Volatile EvolutioN
- MEP – Mars Exploration Program
- MOI – Mars orbit insertion
- NASA – National Aeronautics and Space Administration
- NRC – National Research Council
- OMB – Office of Management and Budget
- PTS – Phobos Transfer Stage
- SEI – Space Exploration Initiative
- SEP – Solar electric propulsion
- SLS – Space Launch System
- SMD – Science Mission Directorate
- SRP – Supersonic Retro-propulsion
- STEM – Science, technology, engineering, and mathematics
- TEI – Trans-Earth injection
- TMI – Trans-Mars injection
APPENDIX E. EXTERNAL REFERENCES


**APPENDIX F. IMAGE ATTIBUTIONS**

Cover: collage of artwork by Ron Miller and a mosaic of 102 Viking orbiter images of Mars. NASA / JPL / USGS

Pages 6 & 7: Mars Science Laboratory Mast Camera (Mastcam): NASA / JPL-Caltech / MSSS

Pages 8 & 9: Mars Science Laboratory Mast Camera (Mastcam): NASA / JPL-Caltech / MSSS

Page 12: Artwork by Ron Miller

Page 16: Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (HiRISE): NASA / JPL-Caltech / UA

Page 22: Artwork by Don Durda

Page 27: Artwork by Ron Miller

Page 30: Artwork by Ron Miller
ACKNOWLEDGEMENTS

The members of The Planetary Society provided the financial support that enabled the Humans Orbiting Mars workshop and its subsequent report. We are grateful for the more than 45,000 members from around the world that keep the Society an independent organization. They are living proof that people care deeply about the past, present, and future of space exploration.

We wish to thank the presenters, panelists, and guests who attended the workshop. They provided the hard work, probing questions, and careful thinking behind much of what is reflected in this report.

We also thank the individuals who graciously provided feedback on various drafts of this report: Jim Bell, Roger Launius, John Baker, Jason Davis, Laura Delgado López, and Dwayne Day. Karl Stull applied expert copy-editing to the final draft of this text. Despite their best efforts, it’s always possible that errors or omissions may have made it into this report. If they are to be found, they are the responsibility of the authors and the authors alone.

We are grateful to Ron Miller (http://www.black-cat-studios.com) and Dr. Dan Durda (https://www.boulder.swri.edu/~durda/paintings.html) for contributing their artwork to the report.