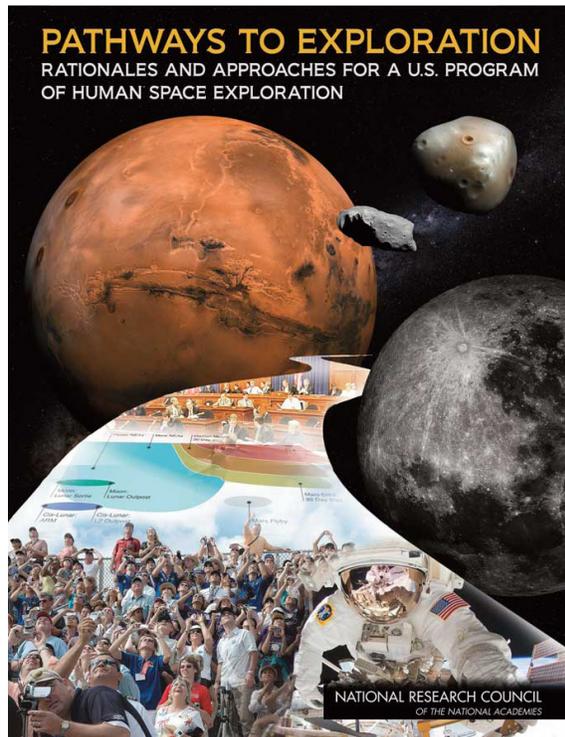


Pathways to Exploration—Rationales and Approaches for a U.S. Program of Human Space Exploration

Aeronautics and Space Engineering Board & Space Studies Board · Division on Engineering & Physical Sciences
Committee on National Statistics · Division of Behavioral and Social Sciences and Education · June 2014

The United States has publicly funded its human spaceflight program on a continuous basis for more than a half-century. Yet, a national consensus on the long-term future of human spaceflight beyond the nation's commitment to the International Space Station remains elusive. The NASA Authorization Act of 2010 tasked the National Academies to review “the goals, core capabilities, and direction of human space flight.” To address this charge the Academies formed a committee of experts to examine rationales, identify enduring questions, consider public input, and review potential pathways for human space exploration. *Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration* presents the committee's conclusions, including major recommendations—indicated by bold text below—for a sustainable U.S. human spaceflight program over the next several decades.



Enduring Questions

Enduring questions are those that serve as motivators of aspiration, scientific endeavors, debate, and critical thinking in the realm of human spaceflight. They are intended not only to stand the test of time but also to continue to drive work forward in the face of technological, societal, and economic constraints. The committee asserts that the enduring questions motivating human spaceflight are:

How far from Earth can humans go?

What can humans discover and achieve when we get there?

Rationales for Human Spaceflight and the Public Interest

All of the arguments the committee heard supporting human spaceflight have been used in various forms and combinations to justify the program for many years. These rationales divide into a set of pragmatic rationales and a set of aspirational rationales.

Pragmatic Rationales:

Economic benefits — While it is clear that the NASA human spaceflight program has stimulated economic activity and has advanced development of new products and technologies, it is impossible to develop a reliable comparison of the returns from spaceflight versus other government R&D investments.

National security — An active U.S. human spaceflight program gives the United States a stronger voice in an international code of conduct for space, enhances U.S. soft power, and supports collaborations with other nations. However, the direct contribution of human spaceflight to national security has been and is likely to remain limited.

National stature and international relations — Being a leader in human space exploration enhances international stature and national pride. International cooperation on human spaceflight projects has important geopolitical benefits.

Inspiration of students and citizens — The challenge and excitement of space missions can serve as an

inspiration for students and citizens to engage with science and engineering, although it is difficult to measure this impact.

Scientific discovery — The relative benefits of robotic versus human efforts in space science are constantly shifting as a result of changes in technology, cost, and risk. The current capabilities of robotic planetary explorers cannot match the flexibility of humans to function in complex environments.

Aspirational Rationales:

Human survival — It is not yet possible to say whether off-Earth settlements could eventually be developed that would outlive human presence on Earth and lengthen the survival of our species.

Shared destiny and aspiration to explore — Some say it is human destiny to continue to explore space. While not all share this view, for those who do, it is an important reason to engage in human spaceflight.

The committee concluded that no single rationale alone seems to justify the value of pursuing human spaceflight. Yet, the aspirational rationales, when supplemented by the practical benefits associated with the pragmatic rationales, do, in the committee's judgment, argue for a continuation of the nation's human spaceflight program, provided that the pathways and decision rules recommended in this report are adopted. Public opinion about space has been generally favorable over the past 50 years, but much of the public is inattentive to space exploration and spending on space exploration is not a high priority for most of the public.

Horizon Goal

The technical analysis completed for this report—discussed fully in Chapter 4 of the report—shows clearly that for the foreseeable future, the only feasible destinations for human exploration are the Moon, asteroids, Mars, and the moons of Mars. Among this small set of plausible goals, the most distant and difficult is a landing by human beings on the surface of Mars. Thus the horizon goal for human space exploration is Mars. All long-range space programs, by all potential partners, converge on this goal.

Policy Challenges

A program of human space exploration beyond low Earth orbit (LEO) that satisfies the pathway principles defined below is not sustainable with a budget that increases only enough to keep pace with inflation. The current program to develop launch vehicles and spacecraft for flight beyond LEO cannot provide the flight frequency required to maintain competence and safety, does not possess the “stepping-stone” architecture that allows the public to see the connection between the horizon goal and near-term accomplishments, and may discourage potential international partners.

International Collaboration

International collaboration has become an integral part of the space policy of essentially all nations participating in space around the world. It is evident that U.S. near-term goals for human exploration are not aligned with the goals of the nation's traditional international partners which look toward human operations on the lunar surface. It is also evident that given the rapid development of China's capabilities in space, it is in the best interests of the United States to be open to China's inclusion in future international partnerships. In particular, current federal law preventing NASA from participating in bilateral activities with the Chinese serves only to hinder U.S. ability to bring China into its sphere of international partnerships. Given the scale of a human mission to Mars, contributions by international partners would have to be of unprecedented magnitude to defray a significant portion of the cost.

Recommendations for a Pathways Approach

Having completed assembly of the International Space Station, the nation must now decide whether to embark on human space exploration beyond LEO in a sustained and sustainable fashion. Having considered past and current space policy, explored the international setting, articulated the enduring questions and rationales, and identified public and stakeholder opinions, the committee draws on all this information to ask a fundamental question: What type of human spaceflight program would be responsive to these factors? This committee argues that it is a sustainable human exploration program beyond LEO.

The committee has concluded that the best way to ensure a stable, sustainable human spaceflight program that pursues the rationales and enduring questions is to develop a program through the rigorous application of a set of Pathway Principles.

NASA should adopt the following Pathway Principles:

I. Commit to designing, maintaining, and pursuing the execution of an exploration pathway beyond low Earth orbit toward a clear horizon goal that addresses the “enduring questions” for human spaceflight.

II. Engage international space agencies early in the design and development of the pathway on the basis of their ability and willingness to contribute.

III. Define steps on the pathway that foster sustainability and maintain progress on achieving the pathway's long-term goal of reaching the horizon destination.

IV. Seek continuously to engage new partners that can solve technical or programmatic impediments to progress.

V. Create a risk-mitigation plan to sustain the selected pathway when unforeseen technical or budgetary

problems arise. Such a plan should include points at which decisions are made to move to a less ambitious pathway (referred to as an “off-ramp”) or to stand down the program.

VI. Establish exploration pathway characteristics that maximize the overall scientific, cultural, economic, political, and inspirational benefits without sacrificing progress toward the long-term goal, namely:

- 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 to develop confidence in NASA’s ability 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

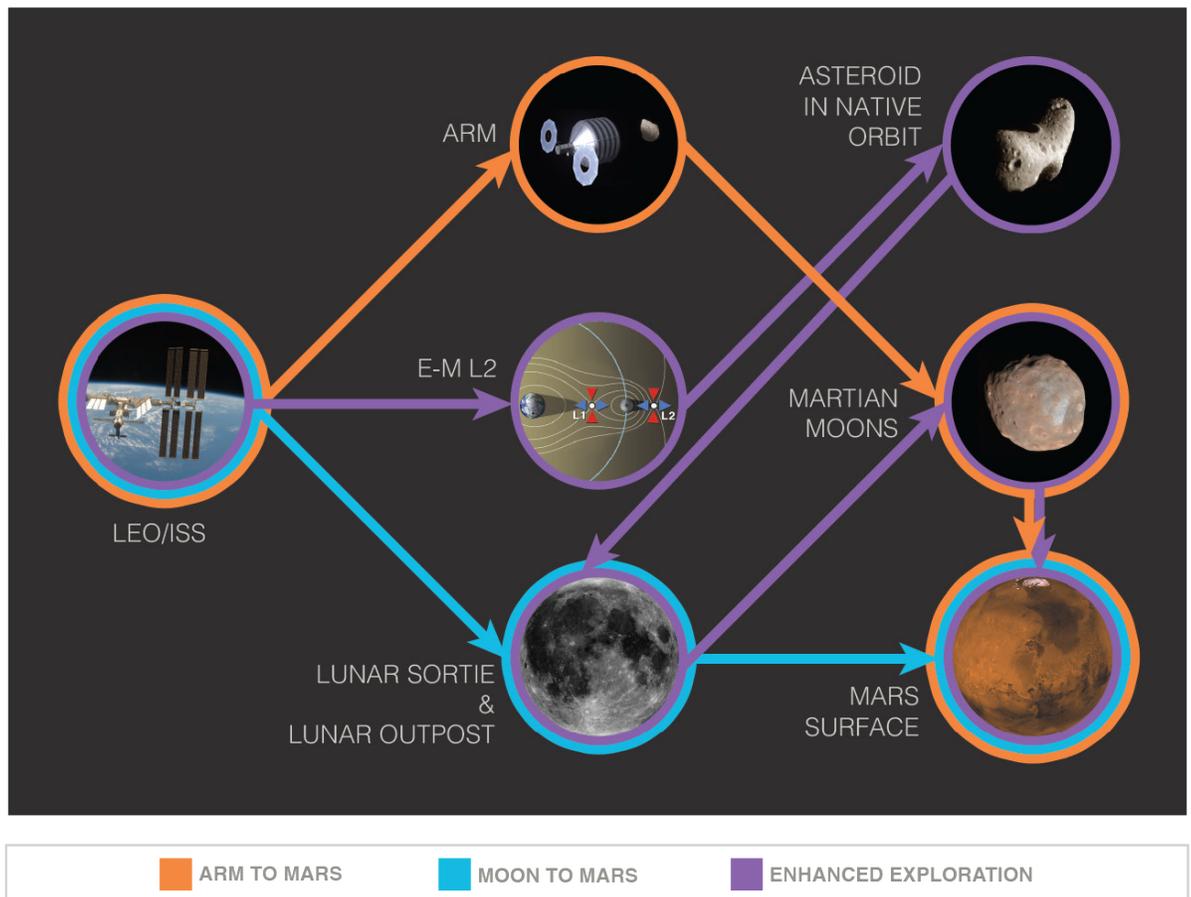
of critical technical capability, proficiency of operators, and effective use of infrastructure.

Whereas the overall pathway scope and cost are defined by application of the pathway principles, once a program is on a pathway, technical, cost, or schedule problems that arise should be addressed by the administration, NASA, and Congress by applying the following decision rules:

- A. If the appropriated funding level and 5-year budget projection do not permit execution of a pathway within the established schedule, do not start down that pathway.
- B. If a budget profile does not permit the chosen pathway, even if NASA is well along on it, 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 in such a way that continued budget increases are required for the pathway’s sustainable execution; rather, the increase in funds should be applied to rapid retirement of important technology risks or to an increase in operational tempo in pursuit of the pathway’s previously defined technical and exploration goals.
- D. Given that limitations on funding will require difficult choices in the development of major new technologies and capabilities, give high priority to choices that solve

Representative Pathways to Mars

See the full report for a detailed description of these Pathways.



important technological shortcomings, that reduce overall program cost, that allow an acceleration of the schedule, or that reduce developmental or operational risk.

E. If there are human spaceflight program elements, infrastructure, or organizations that are no longer contributing to progress along the pathway, the human spaceflight program should divest itself of them as soon as possible.

Recommendations for Implementing a Sustainable Program

No matter which pathway is ultimately selected, the successful implementation of any plan developed in concert with pathways and decision rules will rest upon several other conditions. Together with the highest-priority recommendation of the pathways approach and decision rules, the committee offers the following prioritized recommendations as being those most critical to the development and implementation of a sustainable human space exploration program. Below is a summary of the committee's recommendations to NASA:

1. Commit to design, maintain, and pursue the extension of human presence beyond low Earth orbit (LEO). Commit NASA's human spaceflight asset base, both physical and human, to this effort, while redirecting, consolidating, and eliminating human spaceflight resources as needed.

2. Maintain long-term focus on Mars as the horizon goal for human space exploration.

3. Establish and implement the pathways approach so as to maximize the overall scientific, cultural, economic, political, and inspirational benefits of individual

milestones and to conduct meaningful work at each step along the pathway without sacrificing progress toward long-term goals.

4. Vigorously pursue opportunities for international and commercial collaboration in order to leverage financial resources and capabilities of other nations and commercial entities. International collaboration would be open to the inclusion of China and potentially other emerging space powers in addition to traditional international partners. Specifically, future collaborations in major new endeavors should seek to incorporate:

a. A level of overall cost-sharing that is appropriate to the true partnerships that will be necessary to pursue pathways beyond LEO.

b. Shared decision-making with partners, including a detailed analysis, in concert with international partners, of the implications for human exploration of continuing the International Space Station beyond 2024.

5. Engage in planning that includes mission requirements and a systems architecture that target funded high-priority technology development, most critically entry, descent, and landing for Mars; advanced in-space power and propulsion; and radiation safety.

The committee also concludes that if the resulting plan is not appropriately financed, it will not succeed. Nor can it succeed without a sustained commitment on the part of those who govern the nation—a commitment that does not change direction with succeeding electoral cycles. Those branches of government responsible for NASA's funding and guidance are therefore critical enablers of the nation's investment and achievements in human spaceflight.

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See the full report for a listing of the membership of the Technical Panel and the Public and Stakeholder Opinions Panel.

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