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<th>Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration</th>
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<td>Committee on Human Spaceflight; Aeronautics and Space Engineering Board; Space Studies Board; Division on Engineering and Physical Sciences; Committee on National Statistics; Division of Behavioral and Social Sciences and Education; National Research Council</td>
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Summary

The United States has publicly funded its human spaceflight program continuously for more than a half-century. Today, the United States is the major partner in a massive orbital facility, the International Space Station (ISS), that is a model for how U.S. leadership can engage nations through soft power and that is becoming the focal point for the first tentative steps in commercial cargo and crewed orbital spaceflights. Yet, a national consensus on the long-term future of human spaceflight beyond our commitment to the ISS remains elusive.

The task for the Committee on Human Spaceflight originated in the National Aeronautics and Space Administration [NASA] Authorization Act of 2010, which required that the National Academies perform a human-spaceflight study that would review “the goals, core capabilities, and direction of human space flight.” The explicit examination of rationales, along with the identification of enduring questions set the task apart from numerous similar studies performed over the preceding several decades, as did the requirement that the committee bring broad public and stakeholder input into its considerations. The complex mix of historical achievement and uncertain future made the task faced by the committee extraordinarily challenging and multidimensional. Nevertheless, the committee has come to agree on a set of major conclusions and recommendations, which are summarized here.

ENDURING QUESTIONS

Enduring questions are questions that serve as motivators of aspiration, scientific endeavors, debate, and critical thinking in the realm of human spaceflight. The questions endure in that any answers available today are at best provisional and will change as more exploration is done. Enduring questions provide motivations that are immune to external forces and policy shifts. 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. Enduring questions are clear and intrinsically connect to broadly shared human experience. On the basis of the analysis reported in Chapter 2, the committee asserts that the enduring questions motivating human spaceflight are these:

- 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 the arguments that the committee heard in support of human spaceflight have been used in various forms and combinations to justify the program for many years. In the committee’s view, these rationales can be divided into two sets. Pragmatic rationales involve economic benefits, contributions to national security, contributions to national stature and international relations, inspiration for students and citizens to further their science and engineering education, and contributions to science. Aspirational rationales involve the eventual survival of the human species (through off-Earth settlement) and shared human destiny and the aspiration to explore. In reviewing the rationales, the committee concluded as follows:

• Economic matters. There is no widely accepted, robust quantitative methodology to support comparative assessments of the returns on investment in federal R&D programs in different economic sectors and fields of research. Nevertheless, it is clear that the NASA human spaceflight program, like other government R&D programs, has stimulated economic activity and has advanced development of new products and technologies that have had or may in the future generate significant economic impacts. It is impossible, however, to develop a reliable comparison of the returns on spaceflight versus other government R&D investment.

• Security. Space-based assets and programs are an important element of national security, but the direct contribution of human spaceflight in this realm has been and is likely to remain limited. 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; thus, it contributes to our national interests, including security.

• National stature and international relations. Being a leader in human space exploration enhances international stature and national pride. Because the work is complex and expensive, it can benefit from international cooperative efforts. Such cooperation has important geopolitical benefits.

• Education and inspiration. The United States needs scientists and engineers and a public that has a strong understanding of science. 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. The path to becoming a scientist or engineer requires much more than the initial inspiration. Many who work in space fields, however, report the importance of such inspiration, although it is difficult to separate the contributions of human and robotic spaceflight.

• 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, such as Curiosity and Cassini, are such that although they can go farther, go sooner, and be much less expensive than human missions to the same locations, they cannot match the flexibility of humans to function in complex environments, to improvise, and to respond quickly to new discoveries. Such constraints may change some day.

• Human survival. It is not possible to say whether human off-Earth settlements could eventually be developed that would outlive human presence on Earth and lengthen the survival of our species. That question can be answered only by pushing the human frontier in space.

• Shared destiny and aspiration to explore. The urge to explore and to reach challenging goals is a common human characteristic. Space is today a major physical frontier for such exploration and aspiration. Some say that 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.

As discussed in Chapter 2, the pragmatic rationales have never seemed adequate by themselves, perhaps because the benefits that they argue for are not unique to human spaceflight. Those that are—the aspirational rationales related to the human destiny to explore and the survival of the human species—are also the rationales most tied to the enduring questions. Whereas the committee concluded from its review and assessment that no single rationale alone seems to justify the costs and risks of pursuing human spaceflight, the aspirational rationales, when
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supplemented by the practical benefits associated with the pragmatic rationales, do, in the committee’s judgment, argue for a continuation of our nation’s human spaceflight program, provided that the pathways and decision rules recommended by the committee are adopted (see below).

The level of public interest in space exploration is modest relative to interest in other public-policy issues such as economic issues, education, and medical or scientific discoveries. 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 does not have high priority for most of the public.

HORIZON GOAL

The technical analysis completed for this study 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 that small set of plausible goals for human space exploration, the most distant and difficult is a landing by human beings on the surface of Mars; it would require overcoming unprecedented technical risk, fiscal risk, and programmatic challenges. Thus, the “horizon goal” for human space exploration is Mars. All long-range space programs, by all potential partners, for human space exploration converge on that 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. As shown in Chapter 4, 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.

Because policy goals do not lead to sustainable programs unless they also reflect or change programmatic, technical, and budgetary realities, the committee notes that those who are formulating policy goals will need to keep the following factors in mind:

- Any defensible calculation of tangible, quantifiable benefits—spinoff technologies, attraction of talent to scientific careers, scientific knowledge, and so on—is unlikely ever to demonstrate a positive economic return on the massive investments required by human spaceflight.
- The arguments that triggered the Apollo investments—national defense and prestige—seem to have especially limited public salience in today’s post-Cold War America.
- Although the public is mostly positive about NASA and its spaceflight programs, increased spending on spaceflight has low priority for most Americans. However, although most Americans do not follow the issue closely, those who pay more attention are more supportive of space exploration.

INTERNATIONAL COLLABORATION

International collaboration has become an integral part of the space policy of essentially all nations that participate in space activities around the world. Most countries now rarely initiate and carry out substantial space projects without some foreign participation. The reasons for collaboration are multiple, but countries, including the United States, cooperate principally when they benefit from it.

It is evident that near-term U.S. goals for human exploration are not aligned with those of our traditional international partners. Although most major spacefaring nations and agencies are looking toward the Moon, specifically the lunar surface, U.S. plans are focused on redirection of an asteroid into a retrograde lunar orbit where astronauts

\[1\] Although there is no strictly defined distinction between human spaceflight and human space exploration, the committee takes the latter to mean spaceflight beyond low Earth orbit, in which the goal is to have humans venture into the cosmos to discover new things.
would conduct operations with it. 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 its inclusion in future international partnerships. In particular, current federal law that prevents 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 and substantially reduces the potential international capability that might be pooled to reach Mars. Also, given the scale of the endeavor of a mission to Mars, contributions by international partners would have to be of unprecedented magnitude to defray a significant portion of the cost. This assessment follows from the detailed discussion in Chapter 4 of what is required for human missions to Mars.

RECOMMENDATIONS FOR A PATHWAYS APPROACH

NASA and its international and commercial partners have developed an infrastructure in LEO that is approaching maturity—that is, assembly of the ISS is essentially complete. 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 drew on all this information to ask a fundamental question: What type of human spaceflight program would be responsive to these factors? The committee argues that it is a program in which humans operate beyond LEO on a regular basis—a sustainable human exploration program beyond LEO.

A sustainable program of human deep-space exploration requires an ultimate horizon goal that provides a long-term focus that is less likely to be disrupted by major technological failures and accidents along the way or by the vagaries of the political process and the economic scene. There is a consensus in national space policy, international coordination groups, and the public imagination for Mars as a major goal for human space exploration. NASA can sustain a human space-exploration program that pursues the horizon goal of a surface landing on Mars with meaningful milestones and simultaneously reasserts U.S. leadership in space while allowing ample opportunity for substantial international collaboration—but only if the program has elements that are built in a logical sequence and if it can fund a frequency of flights sufficiently high to ensure the maintenance of proficiency among ground personnel, mission controllers, and flight crews. In the pursuit of that goal, NASA needs to engage in the type of mission planning and related technology development that address mission requirements and integration and develop high-priority capabilities, such as entry, descent, and landing for Mars; radiation safety; and advanced in-space propulsion and power. Progress in human exploration beyond LEO will be measured in decades with costs measured in hundreds of billions of dollars and significant risk to human life.

In addition, the committee has concluded that the best way to ensure a stable, sustainable human-spaceflight program that pursues the rationales and enduring questions that the committee has identified is to develop a program through the rigorous application of a set of pathway principles. The committee’s highest-priority recommendation is as follows:

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.

The pathway principles will need to be supported by a set of operational decision rules as NASA, the administration, and Congress face inevitable programmatic challenges along a selected pathway. The decision rules that the committee has developed provide operational guidance that can be applied when major technical, cost, and schedule issues arise as NASA progresses along a pathway. Because many decisions will have to be made before any program of record is approved and initiated, the decision rules have been designed to provide the framework for a sustainable program through the lifetime of the selected pathway. They are designed to allow a program to stay within the constraints that are accepted and developed when the pathway principles are applied. The committee recommends that,

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.²

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 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.

² The committee recognizes that budget projections are unreliable, but they are also indispensable. One way to make such projections more robust would be for NASA to conduct sensitivity analysis and evaluate plans against a range of possible 5-year budget projections that may vary by 10 percent or more. The analysis and evaluation might be undertaken as part of the risk-mitigation plan.
RECOMMENDATIONS FOR IMPLEMENTING A SUSTAINABLE PROGRAM

The committee was not charged to recommend and has not recommended any particular pathway or set of destination targets. The recommended pathways approach combines a strategic framework with practical guidance that is designed to stabilize human space exploration and to encourage political and programmatic coherence over time.

If the United States is to have a human space-exploration program, it must be worthy of the considerable cost to the nation and great risk of life. The committee has found no single practical rationale that is uniquely compelling to justify such investment and risk. Rather, human space exploration must be undertaken for inspirational and aspirational reasons that appeal to a broad array of U.S. citizens and policy-makers and that identify and align the United States with technical achievement and sophistication while demonstrating its capability to lead or work within an international coalition for peaceful purposes. Given the expense of any human spaceflight program and the substantial risk to the crews involved, it is the committee’s view that the only pathways that fit those criteria are ones that ultimately place humans on other worlds.

Although the committee’s recommendation to adopt a pathways approach is made without prejudice as to which particular pathway might be followed, it was clear to the committee from its independent analysis of several pathways that a return to extended surface operations on the Moon would make substantial contributions to a strategy ultimately aimed at landing people on Mars and would probably provide a broad array of opportunities for international and commercial cooperation. No matter which pathway is selected, the successful implementation of any plan developed in concert with a pathways approach and decision rules will rest on several other conditions. In addition to its highest-priority recommendation of the pathways approach and decision rules, the committee offers the following priority-ordered recommendations as being the ones that are most critical to the development and implementation of a sustainable human space-exploration program.

NASA should

1. Commit to design, maintain, and pursue the extension of human presence beyond low Earth orbit (LEO). This step should include
   a. Committing NASA’s human spaceflight asset base, both physical and human, to this effort.
   b. Redirecting human spaceflight resources as needed to include improving program-management efficiency (including establishing and managing to appropriate levels of risk), eliminating obsolete facilities, and consolidating remaining infrastructure where possible.
2. Maintain long-term focus on Mars as the horizon goal for human space exploration, addressing the enduring questions for human spaceflight: How far from Earth can humans go? What can humans do and achieve when we get there?
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
   a. Entry, descent, and landing for Mars.
   b. Advanced in-space propulsion and power.
   c. Radiation safety.
SUMMARY

In this report the committee has provided guidance on how a pathways approach might be successfully pursued and the likely costs of the pathways if things go well. However, 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—executive and legislative—responsible for NASA’s funding and guidance are therefore critical enablers of the nation’s investment and achievements in human spaceflight, commissioning and financing plans and then ensuring that the leadership, personnel, governance, and resources are in place at NASA and in other federally funded laboratories and facilities to advance it.