Pathways to Exploration:

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

Providing findings, rationale, prioritized recommendations, and decision rules that could enable and guide future planning for U.S. human space exploration.

"The United States has publicly funded its human spaceflight program on a continuous basis for more than a half-century. Today the U.S. is the major partner in a massive orbital facility—the International Space Station—that is both a model for how U.S. leadership can engage [other] nations… and is becoming the focal point for the first tentative steps in commercial cargo and crewed orbital spaceflights.

And yet, a national consensus on the long-term future of human spaceflight beyond our commitment to the ISS remains elusive….The complex mix of historic achievement and uncertain future made the task faced by this committee extraordinarily challenging and multi-dimensional."

Mitchell E. Daniels, Jr.
Jonathan I. Lunine

Co-chairs. Committee on Human Spaceflight

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Embargo: June 4, 2014 – 11am Eastern

THE COMMITTEE ON HUMAN SPACEFLIGHT

- The study was requested by Congress in the 2010 NASA Authorization Act.
- The committee addressed a multi-part, multi-disciplinary task statement shown below.
- The committee met six times between December 2012 and January 2014.
- Technical and Public and Stakeholder Opinions Panels each held four meetings.
- Committee members made site visits to JSC, KSC and MSFC—the key NASA human spaceflight centers.
- A call to the public to submit white papers addressing the role of human spaceflight and its suggested future was made in July 2013.
- The committee opened the study to a broad stage of public input in October 2013 via Twitter #HumansInSpace.
- The Public and Stakeholders Opinions Panel conducted a survey of key stakeholders.
- Representatives of past and current NASA and foreign programs, experts from academia and industry, all provided briefings to the panels and the committee.

STRUCTURE:

- Technical, engineering and affordability aspects of human space exploration

- Public and stakeholder input to understand motivations, goals and possible evolution of human spaceflight

http://www.nationalacademies.org/humanspaceflight

COMMITTEE:

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Linda A. Williams, Wyle Aerospace Group

THE STATEMENT OF TASK I:

In accordance with Section 204 of the NASA Authorization Act 2010, the National Research Council (NRC) will appoint an ad hoc committee to undertake a study to review the long-term goals, core capabilities, and direction of the U.S. human spaceflight program and make recommendations to enable a sustainable U.S. human spaceflight program.

The committee will:

1. **Consider the goals for the human spaceflight** program as set forth in (a) the National Aeronautics and Space Act of 1958, (b) the National Aeronautics and Space Administration Authorization Acts of 2005, 2008, and 2010, and (c) the National Space Policy of the United States (2010), and any existing statement of space policy issued by the president of the United States.

2. **Solicit broadly-based, but directed, public and stakeholder input** to understand better the motivations, goals, and possible evolution of human spaceflight--that is, the foundations of a rationale for a compelling and sustainable U.S. human spaceflight program--and to characterize its value to the public and other stakeholders.

3. **Describe the expected value and value proposition** of NASA's human spaceflight activities in the context of national goals--including the needs of government, industry, the economy, and the public good--and in the context of the priorities and programs of current and potential international partners in the spaceflight program.

4. **Identify a set of high-priority enduring questions** that describe the rationale for and value of human exploration in a national and international context. The questions should motivate a sustainable direction for the long-term exploration of space by humans. The enduring questions may include scientific, engineering, economic, cultural, and social science questions to be addressed by human space exploration and questions on improving the overall human condition.

THE STATEMENT OF TASK II:

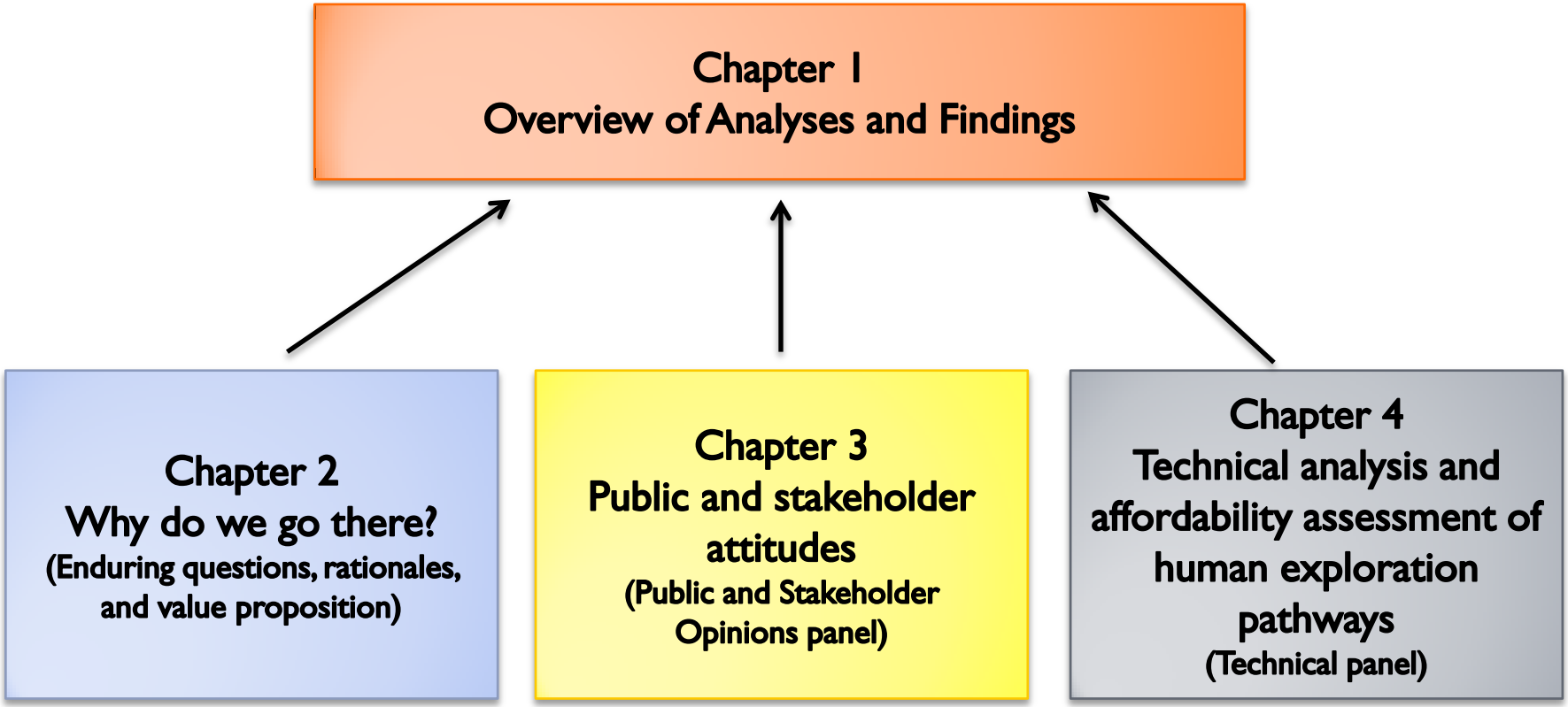
5. **Consider prior studies** examining human space exploration, and NASA's work with international partners, to understand possible exploration pathways (including key technical pursuits and destinations) and the appropriate balance between the "technology push" and "requirements pull". Consideration should include the analysis completed by NASA's Human Exploration Framework Team, NASA's Human Spaceflight Architecture Team, the Review of U.S. Human Spaceflight Plans (Augustine Commission), previous NRC reports, and relevant reports identified by the committee.

6. Examine the relationship of **national goals** to foundational capabilities, robotic activities, technologies, and missions authorized by the NASA Authorization Act of 2010 by assessing them with respect to the set of enduring questions.

7. **Provide findings, rationale, prioritized recommendations, and decision rules that could enable and guide future planning for U.S. human space exploration**. The recommendations will describe a high-level strategic approach to ensuring the sustainable pursuit of national goals enabled by human space exploration, answering enduring questions, and delivering value to the nation over the fiscal year (FY) period of FY2014 through FY2023, while considering the program's likely evolution in 2015-2030.

REPORT STRUCTURE:

The report is organized in a hierarchical fashion



THE BOTTOM LINE:

- If the United States is to have a human space exploration program, then it must be worthy of the considerable cost to the nation and great risk of life.

- Whereas the committee concluded from its review and assessment that no single rationale alone seems to justify the value of pursuing human spaceflight, 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 our nation's human spaceflight program, provided that the pathways and decision rules recommended in this report are adopted .

- Given the expense of any human spaceflight program and the significant risk to the crews involved, in the committee's view the only pathways that fit these criteria are those that ultimately place humans on other worlds.

FINDINGS I:
ESSENTIAL CORNERSTONES

The rationales for human spaceflight are a mix of the aspirational and the pragmatic.

- The primary rationale for the Apollo program was to demonstrate in an unambiguous but peaceful way the technological supremacy of the United States over the Soviet Union by beating the Russians to the Moon.

- The rationale for Apollo took place not only against a backdrop of cold-war potential for nuclear war but also in the midst of an existential conflict between two fundamentally different economic systems, a conflict that is now over.

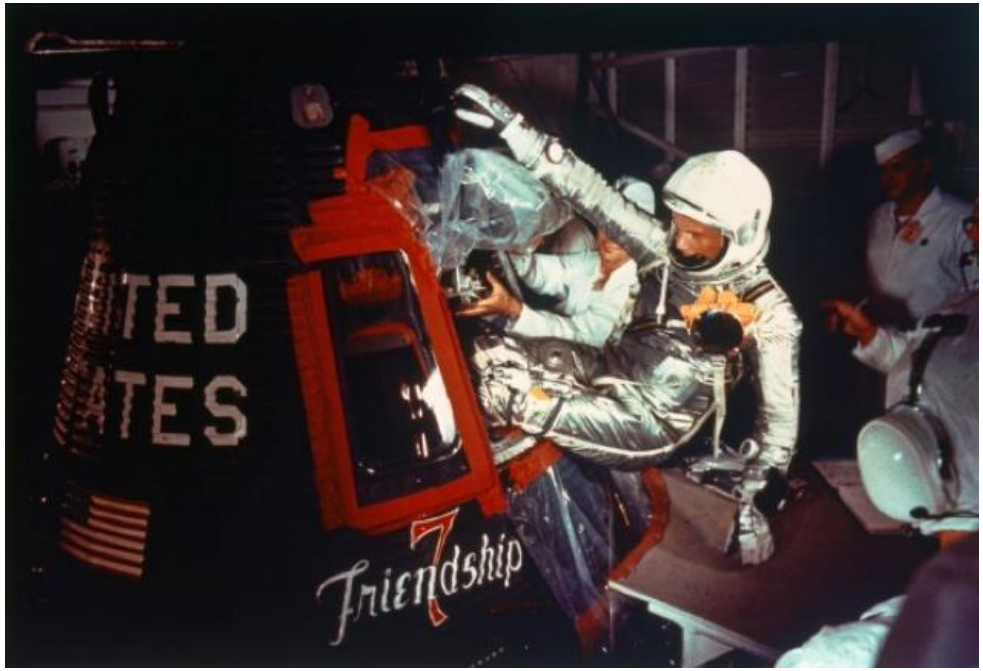
- Quantification of the value of human spaceflight to the nation today, in terms of economic return or increased quality of life, is difficult.

- This does not mean that there are no benefits: As W.B. Cameron wrote "not everything that can be counted counts, and not everything that counts can be counted."

FINDINGS II:
ESSENTIAL CORNERSTONES

The level of public interest in space exploration is modest relative to other public policy issues.

- 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.



FINDINGS III:
ESSENTIAL CORNERSTONES

The horizon goal for human space exploration is Mars.

- There is a small set of plausible goals for human space exploration in the foreseeable future, the most distant and difficult of which is a landing by human beings on the surface of Mars. All long-range space programs, by all potential partners, for human space exploration converge on this goal.

FINDINGS IV:
ESSENTIAL CORNERSTONES

A program of human space exploration beyond Low Earth Orbit that satisfies the "pathway principles" is not sustainable with a human spaceflight budget that increases only enough to keep pace with inflation.

- The current program to develop launch vehicles and spacecraft for flight beyond LEO cannot be sustained with constant buying power over time, in that it
  - 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.

- The committee proposes a *pathways approach* that requires the U.S. to settle on a definite pathway to the horizon goal and adhere to certain principles and decision rules to get there.

INTERNATIONAL COLLABORATION:

It is evident that U.S. near-term goals for human exploration are not aligned with those of our traditional international partners.

- While most major spacefaring nations and agencies are looking toward the Moon and specifically the lunar surface, U.S. plans are focused on redirection of an asteroid into a retrograde lunar orbit where astronauts would conduct operations with it.
- Although the United States is not expected to blindly follow the desires of other nations in shaping its own exploration program, there are a number of advantages to the United States being a more active player in lunar surface operations.
- Given the rapid development of China's capabilities in space, it is in the best interests of the U.S. to be open to future international partnerships.
- 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.

ENDURING QUESTIONS:

- Enduring questions are those that serve as motivators of aspiration, scientific endeavors, debate, and critical thinking in the realm of human spaceflight.

- Enduring questions are intended to not only stand the test of time, but also to continue to drive work forward in the face of technological, societal, and economic constraints.

The enduring questions motivating human spaceflight are:

- *How far from Earth can humans go? and,*
- *What can humans discover and achieve when we get there?*

RATIONALES:

*No **single** rationale alone seems to justify the value of pursuing human spaceflight.*

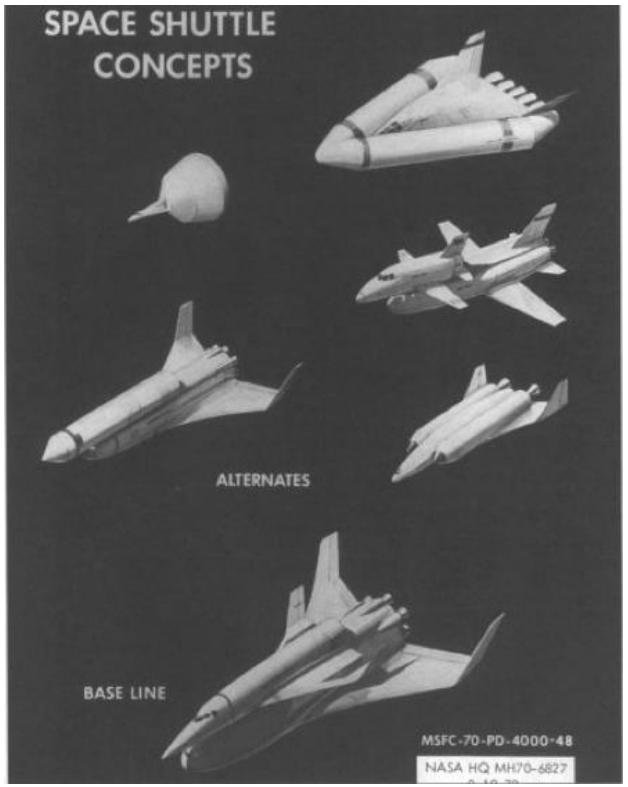
- The Pragmatic
  - **Economic**—The NASA human spaceflight program has stimulated economic activity and has advanced development of new products and technologies that have had or may in the future generate significant economic impacts. It is impossible, however, to develop a reliable comparison of the returns from spaceflight versus other government R&D investments.
  - **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.
  - **Education and inspiration**—Space missions can serve as an inspiration for students and citizens to engage with science and engineering, although the path to becoming a scientist or engineer requires much more than the initial inspiration.
  - **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 Aspirational
  - **Human survival**—Whether human off-Earth settlements could eventually be developed that would outlive human presence on Earth and lengthen the survival of our species is a question that can only be settled by pushing the human frontier in space.
  - **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.

VALUES AND VALUE PROPOSITIONS:

In business, a value proposition is a statement of the benefits or experiences being delivered by an organization to recipients, together with the price or description of the resources expended for them.

- The committee was tasked with "describing the expected value and value proposition of NASA's human spaceflight activities in the context of national goals."

- Chapter 2 presents a novel and very detailed analysis of how value propositions might be developed for the publically funded U.S. space program by looking at how stakeholders (both narrowly and very broadly defined) derive benefits from the program and, additionally, what opportunities would no longer be available were human spaceflight to be discontinued.



PUBLIC AND STAKEHOLDER OPINIONS:

- Summary of Public Opinion Findings
  - The level of public interest in space exploration is modest relative to other public policy issues. At any given time, a relatively small proportion of the U.S. public pays close attention to this issue, and an even smaller proportion feels well informed about it.
  - Space exploration fares relatively poorly among the public compared to other spending priorities. No particular rationale for space exploration appears to consistently attract support from a clear majority of the public.
  - These trends—generally positive views of space exploration and human spaceflight but low support in terms of funding and low levels of public engagement—have held true over the past few decades.

- Summary of Stakeholder Findings
  - For space exploration in general, "expanding knowledge and scientific understanding" emerged as the rationale that was shared by the overwhelming majority of the respondents. However, when restricted to human spaceflight, no single rationale garnered agreement from a majority of the respondents.
  - Support for human spaceflight goes up with involvement in work related to human space exploration. Lowest support among the non-space scientists and highest among the advocates and popularizers.

A STRATEGIC APPROACH TO A SUSTAINABLE PROGRAM OF HUMAN SPACEFLIGHT:

- If the nation deems continuity in human spaceflight to be a desirable national objective, it must decide *now* on whether to pursue a sustainable program of human space exploration, and on the nature of such a program.
  - ISS is essentially complete and has a finite lifetime
  - Without a commitment to human space exploration beyond LEO, U.S. human spaceflight will begin to wind down in the early 2020's as preparations for the closeout of ISS begin.
- A sustainable program of human deep space exploration must have an ultimate, "horizon" goal that provides a long-term focus less likely to be disrupted by major technological failures and accidents along the way and the vagaries of the political process and economic scene.
  - Mars is the horizon goal of human space exploration
- Given the magnitude of the technical and physiological challenges, should the nation decide to embark on a human exploration program whose horizon goal is Mars, NASA would need to begin to focus right away on the high-priority research and technology investments that would develop the capabilities required for human surface exploration of Mars. The most challenging of these will be
  - Entry, descent, and landing for Mars;
  - In-space propulsion and power; and
  - Radiation safety (radiation health effects and amelioration)

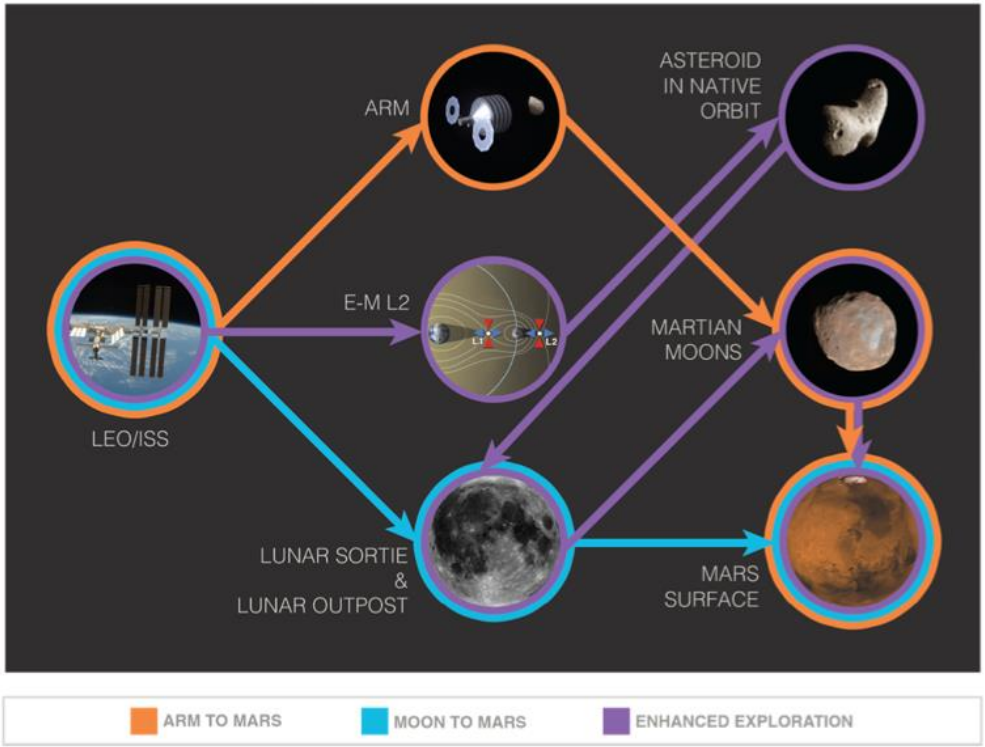
PATHWAYS APPROACH I:

- Stepping stones: Between LEO and the martian surface are regions of space with stepping stone destinations that are reachable with foreseeable advances in the state of the art of key capabilities. These include:
  - Cislunar space, which encompasses missions to the Earth-Moon L2 point, lunar orbit, and the lunar surface (both lunar sorties with relatively short stays and lunar outposts with extended stays);
  - Near-Earth asteroids (NEAs) in their native orbits; and
  - Mars, which encompasses a Mars flyby mission as well as missions to the moons of Mars, Mars orbit, and the surface of Mars.
- The committee does not recommend either a capabilities-based or flexible-path approach, approaches where no specific sequence of destinations is specified.
- Instead, *the committee recommends a **"pathways approach"** to human space exploration*: a specific sequence of intermediate accomplishments and destinations normally of increasing difficulty and complexity leading to an ultimate (horizon) goal with technology feed-forward from one mission to subsequent missions.

PATHWAYS APPROACH II:

- NASA can sustain a human space exploration program with meaningful milestones that simultaneously reasserts U.S. leadership in space while allowing ample opportunity for substantial international collaboration when that program
  - Has elements that are built in a logical sequence, and
  - Can fund a frequency of flights sufficiently high to ensure retention of critical technical capability, proficiency of operators, and effective utilization of infrastructure.

- However, a NASA human spaceflight budget that increases with inflation does not permit a viable pathway to Mars. The program will require increasing the budget by more than the rate of inflation.



HIGHEST PRIORITY RECOMMENDATION I:

PATHWAY PRINCIPLES

The cost, scope, and challenges of human spaceflight beyond LEO demand that a set of carefully thought-out principles be applied before any pathway is initiated. Progress toward deep space destinations will be measured on time scales of decades, with costs measured in hundreds of billions of dollars and significant risk to human life.

The following Pathway Principles are intended to be used to help establish a sustainable long-term course:

HIGHEST PRIORITY RECOMMENDATION II:
PATHWAY PRINCIPLES

NASA should adopt the following Pathway Principles:

I Commit to design, maintain, and pursue the execution of an exploration pathway beyond low Earth orbit toward a clear horizon goal that addresses the "enduring questions" for human spaceflight.

II Engage international space agencies early in 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 and/or programmatic impediments to pathway progress.

V Create a risk mitigation plan to sustain the selected pathway when unforeseen technical or budgetary problems arise. Such a plan should also include points at which decisions are made to move to a less ambitious pathway or 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, these characteristics being:

HIGHEST PRIORITY RECOMMENDATION III:
PATHWAY PRINCIPLES

NASA should adopt the following Pathway Principles (contd.):

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

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

HIGHEST PRIORITY RECOMMENDATION IV:

DECISION RULES

Whereas the overall pathway scope and cost are defined by applying the Pathway Principles, once on a pathway, if and when technical, cost, or schedule problems arise, they should be addressed by the administration, NASA, and Congress by applying the following Decision Rules:

A. If the appropriated funding level and projected 5-year budget projection do not permit execution of a pathway within the established schedule, then do not start down that pathway.

B. If a budget profile does not permit the chosen pathway, even if NASA is well down it, then take an "off-ramp".

C. If the U.S. human spaceflight program receives an unexpected increase in budget for human spaceflight, NASA, the administration, and Congress should not redefine the pathway such that continued budget increases would be required for the pathway's sustainable execution, but rather the increase in funds should be applied to retire rapidly significant technology risks or increase operational tempo in pursuit of the pathway's predefined technical and exploration goals.

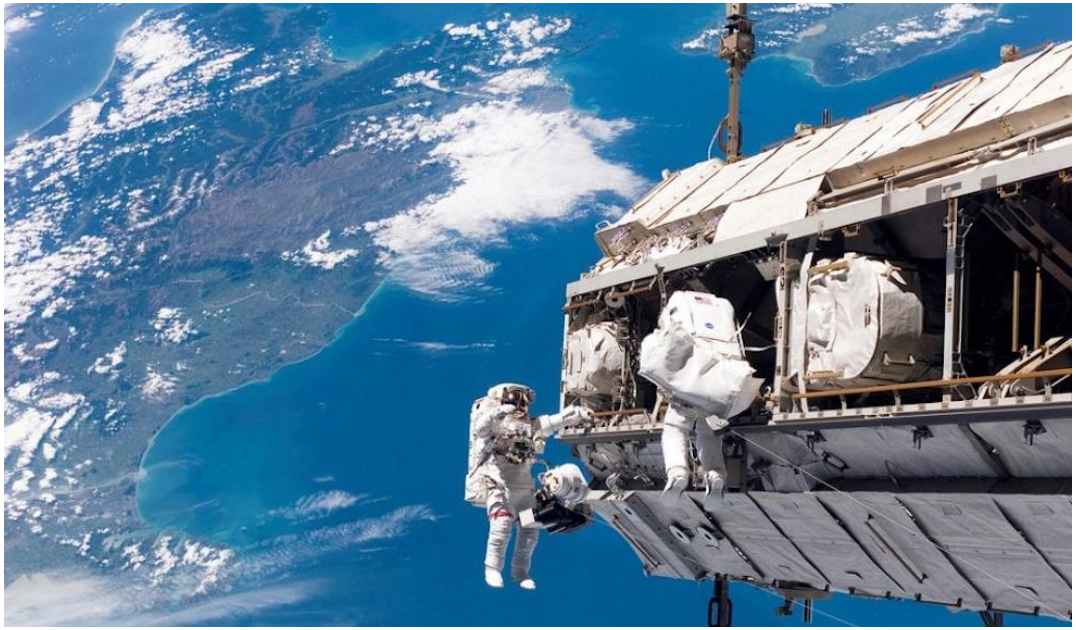
D. Given that limitations on funding will require difficult choices in the development of major new technologies and capabilities, give priority to those that solve significant existing technological shortcomings, reduce overall program cost, allow for an acceleration of the schedule, and/or reduce developmental or operational risk.

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

A SUSTAINABLE HUMAN SPACEFLIGHT PROGRAM I:

Human space exploration requires a long-term commitment by the nation that undertakes it. Therefore, the committee has concluded:

- National leadership and a sustained consensus on the vision and goals are essential to the success of a human space exploration program that extends beyond LEO. Frequent changes in the goals for U.S. human space exploration waste resources and impede progress. The instability of goals for the U.S. program in human spaceflight beyond LEO threatens our nation's appeal and suitability as an international partner.



A SUSTAINABLE HUMAN SPACEFLIGHT PROGRAM II:

There has not been a committed, passionate minority large and influential enough to maintain momentum for the kind of dramatic progress predicted by many at the time of Apollo. This problem adds to the difficulties—frequent redirection, mismatch of mission and resources, political micromanagement—afflicting the U.S. human spaceflight program after Apollo. The committee concludes:

- Simply setting a policy goal is not sufficient for a sustainable human spaceflight program, because policy goals do not change programmatic, technical, and budgetary realities. Those who are formulating policy goals 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 to ever demonstrate a positive 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 is a low priority for most Americans. At the same time, most Americans do not follow the issue closely, and those who pay more attention are more supportive of space exploration.

A SUSTAINABLE HUMAN SPACEFLIGHT PROGRAM III:

With most projections forecasting growing national debt in the decades ahead, there is at least as great a chance that human spaceflight budgets will be below the recent flat trend line as markedly above it. Nevertheless, the committee has concluded:

- Should the United States decide that the intangible benefits of human spaceflight still lift its rationale well into the range that justifies major, new, and enduring public investments in human spaceflight, it will need to craft a long-term strategy that will be robust in the face of technical and fiscal challenges.

Together with the highest priority recommendation to adopt the pathways approach, the Committee offers the following prioritized recommendations as being those most critical to the development and implementation of a sustainable human space exploration program. The committee recommends:

A SUSTAINABLE HUMAN SPACEFLIGHT PROGRAM IV:

PRIORITIZED RECOMMENDATIONS

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, and
   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 space flight: How far from Earth can humans go? and What can humans do and achieve when we get there?

3. Establish and implement the pathway 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.

A SUSTAINABLE HUMAN SPACEFLIGHT PROGRAM V:
PRIORITIZED RECOMMENDATIONS

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, as well as traditional International Partners. Specifically, future collaborations on major new endeavors should seek to incorporate:
    a. A level of overall cost sharing appropriate to the true partnerships that will be necessary to pursue pathways beyond LEO.
    b. Shared decision making with partners. This should include 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 targeting funded high-priority technology development, most critically:
    a. Entry, descent, and landing for Mars,
    b. Advanced in-space propulsion and power, and
    c. Radiation safety.

A SUSTAINABLE HUMAN SPACEFLIGHT PROGRAM VI:
PRIORITIZED RECOMMENDATIONS

None of these steps can replace the element of sustained commitment on the part of those who govern the nation, without which neither Apollo nor its successor programs would have occurred.

Hard as the above choices may appear, they probably are less difficult or alien to conventional political decision makers than the recognition that human spaceflight—among the longest of long-term endeavors—cannot be successful if held hostage to traditional short-term decision-making and budgetary processes.

CONCLUDING REMARKS:

Americans have continued to fly into space not so much because the public strongly wants it to be so, but because the counterfactual—space exploration dominated by the vehicles and astronauts of other nations—seems unthinkable after 50 years of U.S. leadership in space.

In reviving a U.S. human exploration program capable of answering the enduring questions about humanity's destiny beyond our tiny blue planet, we will need to grapple with the attitudinal and fiscal realities of the nation today while staying true to a small but crucial set of fundamental principles for the conduct of exploration of the endless frontier.