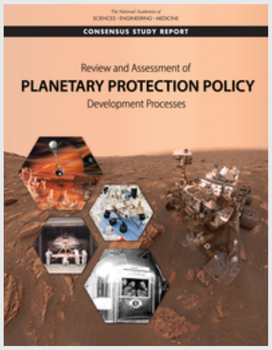

Review and Assessment of Planetary Protection Policy Development Processes

DETAILS

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CONTRIBUTORS

Committee on the Review of Planetary Protection Policy Development Processes; Space Studies Board; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

Review and Assessment of
PLANETARY PROTECTION POLICY
Development Processes

Committee on the Review of Planetary Protection Policy Development Processes

Space Studies Board

Division on Engineering and Physical Sciences

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Cover: Designed by Kimberly De Rose. *Background*: Curiosity rover during a global dust storm that enveloped Mars in 2018, courtesy of NASA Jet Propulsion Laboratory, Caltech, and Malin Space Science Systems. *Top:* Artist's conception of space probe landing on the surface of Titan with Saturn in the background, courtesy of NASA and artist Craig Attebery. *Center, right:* Curiosity rover during testing in a clean room, courtesy of NASA Jet Propulsion Laboratory and Caltech. *Center, left:* Preparing one of the Viking lander for dry-heat microbial reduction in a custom-built oven at the NASA Kennedy Space Center, courtesy of NASA. *Bottom:* Apollo 11 astronauts in NASA's mobile quarantine facility aboard the *U.S.S. Hornet* following their return to Earth in July 1969, courtesy of NASA.

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MIA BROWN, Research Associate
ANDREA REBHOLZ, Program Coordinator
DANIELLE MONTECALVO, Lloyd V. Berkner Space Policy Intern

[1] Member, National Academy of Engineering.
[2] Member, National Academy of Medicine.
[3] Member, National Academy of Sciences.

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---

[1] Member, National Academy of Sciences.
[2] Member, National Academy of Engineering.

Preface

Planetary protection is the practice of protecting solar system bodies (i.e., planets, moons, comets, and asteroids) from contamination by Earth life in order to preserve the opportunity for scientific studies at those destinations relating to the origins of life and/or prebiotic chemical evolution, and of protecting Earth's inhabitants and environment from harm that could be caused by possible extraterrestrial life forms. The 1967 United Nations "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Bodies" (the Outer Space Treaty [OST]) to which the United States and most other spacefaring nations are signatory, states in Article IX that all states parties to the treaty "shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination, and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." In addition, Article VI of the same treaty specifies that states parties "shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities."

Internationally, technical aspects of planetary protection are developed through deliberations by the Committee on Space Research (COSPAR), part of the International Council for Science (ICSU), which consults with the United Nations as required. The international consensus guidelines for planetary protection are developed through the deliberations of the COSPAR Panel on Planetary Protection, which are regularly undertaken on the basis of participants either reporting new scientific findings with policy implications (e.g., water being more abundant at a particular target than was previously recognized), and/or raising questions regarding specific concerns that may need to be to be addressed (e.g., new activities in space exploration that could affect policy compliance). The Panel develops recommendations that COSPAR may adopt for inclusion into the official COSPAR Planetary Protection Policy. Through this process, the COSPAR Planetary Protection Policy has evolved steadily and incrementally over the years since it was initially created. Spacefaring organizations such as NASA formulate and implement planetary protection policies and procedures for their space missions to be consistent with COSPAR Planetary Protection Policy.

In recent years there have been significant developments related to the exploration of planetary environments. There have been major advances in the state of scientific knowledge regarding the environments of solar system destinations thought to be capable of having harbored life or thought to be capable of currently harboring life. Scientific understanding has also evolved regarding the nature of life on Earth in environments that are thought to be analogous to some of those expected at solar system destinations. In addition, there have been advances in the technology available to reduce microbial populations on spacecraft and to measure various levels of biological cleanliness. Meanwhile, NASA's priorities have evolved in two directions: First, to place special emphasis on robotic exploration of the so-called Ocean Worlds (i.e., a subset of the moons of the giant planets and other bodies of the outer solar system known [or strongly suspected] to have liquid water beneath their icy surfaces), especially, but not limited to, Europa and Enceladus, moons of Jupiter and Saturn, respectively; and second, to planning for sample return missions classified as "restricted Earth return" (which have not been undertaken since Apollo) and the human exploration of Mars. A range of other nations and non-state actors also have expressed an intent to send spacecraft and humans to Mars in the coming years. Can planetary protection policy evolve to accommodate this changing landscape in order to remain effective in addressing the challenges posed by Article IX, and now also Article VI, of the OST?

In response to the evolving landscape against which planetary protection policies operate, NASA's Associate Administrator for the Science Mission Directorate, John M. Grunsfeld, requested in February 2016 that the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine carry out a study of the current process by which planetary protection policy is developed and recommend actions or options for NASA to consider in ensuring effective coordination on planetary protection (see Appendix A). Subsequent discussions between the SSB and Dr. Grunsfeld's successor, Thomas H. Zurbuchen, resulted in the formulation of a somewhat expanded statement of task for the requested study:

> The National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to carry out a study that will describe how international and national planetary protection policy has been formulated and adopted and identify associated lessons to inform future policy development. Specifically, the committee will assess the current state of planetary protection policy development, and the extent to which the current policy-making process is responsive to the present state of science, technology, and engineering, including biological science, as well as the exploration interests of state and non-state actors. The committee's review will lead to recommendations on how to assure the planetary protection policy process is supportive of future scientific and societal interests, as well as spaceflight missions.
>
> It is suggested that the committee organize its review around three themes:
>
> - Historical context and the current policy development process—including a working definition of planetary protection and its goals;
> - Key factors in the current policy development process; and
> - The future of the policy development process.
>
> ***Historical Context and the Current Policy Development Process—including a working definition of planetary protection and its goals***
>
> In addressing this theme, the committee should consider the following questions and formulate lessons learned where appropriate:
>
> - How has the planetary protection policy development process evolved over the course of lunar and planetary exploration? What approaches to planetary protection policy development were used in the Apollo and Viking eras of solar system exploration, and subsequent Mars exploration? What factors informed and drove those choices?
> - What worthwhile lessons can policymakers take from the history of planetary protection policy development in looking toward future exploration and sample return missions?
> - Who are the actors involved in the present-day planetary protection policy development process? What are the respective roles and responsibilities of international organizations, national organizations and national space agencies (including agencies' planetary protection officers), advisory committees, and others in the process?
> - What scientific, technical, philosophical, and/or ethical assumptions and values about the importance of avoiding forward contamination of extraterrestrial planetary environments are prioritized in the current planetary protection policy development process?
> - What scientific, technical, philosophical, and ethical assumptions and values about the importance of

protecting Earth and its environment ("backward contamination") are prioritized in the current planetary protection policy development process?

- How does the current process take into account new scientific and technical knowledge?
- How does the state of scientific understanding of planetary environments and their ability to harbor life inform the current planetary protection policy development process? What scientific knowledge or exploration interests are not taken into account?
- How does the current planetary protection policy development process balance interest in acquiring scientific knowledge of planetary environments to inform future scientific studies, exploration, and planetary protection policy choices with the interest in protecting those environments in the here-and-now?

Key Factors in the Current Policy Development Process

In addressing this theme, the committee should consider the following questions and formulate recommendations as appropriate:

- To what extent does the current process consider the interests of state and non-state actors in exploring planetary environments, including obligations under Article VI of the Outer Space Treaty?
- How does the current process reconcile uncertainties in knowledge, differences between scientific and other exploration interests, as well as potentially competing interests?
- What are the barriers, or challenges, that inhibit the process of effective planetary protection policy development?

The Future of the Policy Development Process

Looking at both historical and contemporary approaches to planetary protection policy development, the committee should make recommendations about the future of planetary protection policy process development in relation to these questions:

- How could the planetary protection policy development process be made more adaptable to the evolving landscape of knowledge about and myriad interests in planetary environments?
- How can a planetary protection regulatory environment in the U.S. government be established and evolve to keep pace with nongovernmental spacefaring entities?
- How does a future process evaluate the state of the art and what technologies are required to ensure compliance with planetary protection policy for future missions?
- What risk assessment and/or quality control principles should be applied to ensure that a future process takes into account our understanding of the capabilities of Earth organisms and the potential for extraterrestrial life to be encountered by planetary missions?

Furthermore, Dr. Zurbuchen requested that the portion of the statement of task's first theme concerning "a working definition of planetary protection and its goals" be addressed in an interim report.

In response to the requests from Drs. Grunsfeld and Zurbuchen, the SSB established the Committee on the Review of Planetary Protection Policy Development Processes, which held its first meeting in Washington, D.C., on March 7-9, 2017. The meeting was devoted to Dr. Zurbuchen's request for an interim report addressing the definition of planetary protection and its goals. The draft interim report was sent to eight external reviewers for comment on April 21 and delivered to NASA on June 7.

The committee held three additional meetings—in Washington, D.C.; Irvine, California; and Woods Hole, Massachusetts, on May 23-25, June 27-29, and August 8-10, respectively—and an initial draft of the complete report was assembled in the final months of 2017 and the first few months of 2018. A complete draft of this report was sent to external reviewers for comment on April 27. This report was revised in response to reviewer comments and submitted for final approval to the National Academies Report Review Committee on June 14 and approved for release on June 18, 2018.

The work of the committee was made easier thanks to important contributions made by the following individuals: William Ailor (The Aerospace Corporation), Gale Allen (NASA Headquarters), David Bearden (The

Aerospace Corporation), David Beaty (NASA Jet Propulsion Laboratory), Benjamin Berlin (Federal Aviation Administration), Linda Billings (National Institute of Aerospace), Charles Philip Brinkman (Federal Aviation Administration), Alicia Brown (Senate Committee on Commerce, Science, and Technology), Jonathan K. Charlton (Subcommittee on Space, House Committee on Science, Space, and Technology), Kelvin Coleman (Federal Aviation Administration), Catharine Conley (NASA Headquarters), Brian Cooke (Jet Propulsion Laboratory), Nicholas Cummings (Subcommittee on Space, Science, and Competitiveness, Senate Committee on Commerce, Science, and Technology), Rick Davis (NASA Headquarters), Mary Lynne Dittmar (Coalition for Deep Space Exploration), Meredith Drosback (SciLine), G. Ryan Faith (Subcommittee on Space, House Committee on Science, Space, and Technology), Kenneth Farley (California Institute of Technology), Barry Goldstein (NASA Jet Propulsion Laboratory), Tom Hammond (Subcommittee on Space, House Committee on Science, Space, and Technology), Ken Hodgkins (Department of State), Robert Hubbard III (Senate Committee on Commerce, Science, and Transportation), Margaret Kieffer (NASA Headquarters), Gerhard Kminek (European Space Agency), Jer-Chyi Liou (NASA Johnson Space Center), Eric Mahr (The Aerospace Corporation), Aarti Matthews (Space Exploration Technologies Corp.), Andrew Maynard (Arizona State University), Michael Meyer (NASA Headquarters), Vince Michaud (NASA Headquarters), Michael Mineiro (Subcommittee on Space, House Committee on Science, Space, and Technology), James Muncy (PoliSpace), George Nield (Federal Aviation Administration), Ryan Noble (Commercial Spaceflight Federation), Russell Norman (House Committee on Science, Space, and Technology), Bill Nye (The Planetary Society), Aaron Oosterle (PoliSpace), Scott Pace (National Space Council), J.D. Polk (NASA Headquarters), Betsy Pugel (NASA Headquarters), Benjamin Roberts (Moon Express), John Rummel (SETI Institute), Caryn Schenewerk (Space Exploration Technologies Corp.), Mitchell Sogin (Marine Biological Laboratory), Ellen Stofan (Smithsonian Institution), Anne Sweet (NASA Headquarters), Pamela Whitney (Subcommittee on Space, House Committee on Science, Space, and Technology), Paul Wooster (Space Exploration Technologies Corp.), A. Thomas Young (Lockheed Martin Corporation, retired), and Thomas Zurbuchen (NASA Headquarters).

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report: George Church (Harvard Medical School), Athena Coustenis (Paris Observatory), Robert Crippen (Thiokol Propulsion, retired), Lennard Fisk (University of Michigan), Steve Isakowitz (The Aerospace Corporation), Christopher Johnson (Secure World Foundation), Charles Kennel (University of California, San Diego), B. Gentry Lee (Jet Propulsion Laboratory), Jonathan Lunine (Cornell University), Dava Newman (Massachusetts Institute of Technology), Robie Samanta Roy (Lockheed Martin Corporation), and Gerhard Schwehm (European Space Agency, retired).

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Steven J. Battel (Battel Engineering, Inc.). He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Summary

Protecting Earth's environment and other solar system bodies from harmful contamination has been an important principle throughout the history of space exploration. For decades, the scientific, political, and economic conditions of space exploration converged in ways that contributed to effective development and implementation of planetary protection policies at national and international levels. Advances in scientific knowledge have, in general, permitted planetary protection requirements to be adapted or substantially simplified for certain solar system bodies (e.g., the Moon, Venus, and Mercury) so that only missions to those few bodies thought to be capable of harboring extinct or extant life, or processes relevant to prebiotic chemistry, needed to apply planetary protection measures beyond documentation. Whether or not this trend will continue as the exploration of Mars and the so-called Ocean Worlds of the outer solar system progresses remains to be seen.

Only a few spacefaring nations and international organizations have engaged in solar system exploration, with the United States being the largest player and a key international leader in the development of planetary protection policies and procedures. From an economic perspective, spacefaring nations accepted the costs of planetary protection measures in government-sponsored space exploration, and private-sector enterprises did not undertake missions that implicated planetary protection. During the Apollo era, the NASA budget peaked at about 4 percent of the federal budget, and space exploration was a national security priority. Consequently, cost did not pose limitations to prudent planetary protection requirements.

However, the future of space exploration will likely not see the same convergence of factors and will, instead, create serious challenges to the development and implementation of planetary protection policy. The most disruptive changes are associated with (1) sample return from, and human missions to, Mars and (2) missions to those bodies in the outer solar system possessing water oceans beneath their icy surfaces. In addition, by the mid-1970s, NASA lost its special national priority, and budgets have hovered around 0.5 percent of federal spending ever since. Space missions of ever-increasing complexity have to grapple with cost caps.

In response to a request from NASA, the National Academies of Sciences, Engineering, and Medicine established the Committee to Review the Planetary Protection Policy Development Processes to examine the history of planetary protection policy, assess the current policy development process, and recommend actions to improve the policy development process in the future.

Readers interested in the specific aspects of the report are directed to the following chapters or to the more extensive guide at the end of Chapter 1:

- Working definition of planetary protection and its goals—Chapter 1
- Historical context for planetary protection—Chapter 2
- Current policy development process—Chapter 3
- Challenges posed by future human and robotic missions to Mars—Chapters 4 and 5
- Challenges posed by private-sector activities in space—Chapter 6
- Future of the policy development process—Chapters 5 and 7

The committee concludes that the following fundamental elements of planetary protection policy remain relevant and vital:

- The Outer Space Treaty (OST), as the policy and legal foundation for both government-sponsored and nongovernment planetary missions;
- The role of the Committee on Space Research (COSPAR) in fostering international cooperation in the development of planetary protection guidelines;[1]
- The need for science-based decision making;
- The involvement of a wide-range of scientific communities; and
- U.S. leadership in planetary protection policy making.

However, the current planetary protection policy development process is inadequate to respond to progressively more complex solar system exploration missions, especially in an environment of significant programmatic constraints.

GENERAL ADVICE TO NASA CONCERNING PLANETARY PROTECTION

Today's planetary protection policies and policy development process have been forced to grapple with issues not seen since the Viking Mars landers and Apollo Moon landings. In addition, they are facing much greater challenges as NASA and other national and international space agencies move forward on the Mars Sample Return campaign, exploration of the icy moons of Jupiter and Saturn, and human landings on Mars. Shortcomings in adapting legacy planetary protection policy for modern-day life detection missions began with the Mars Science Laboratory project, and they have become even more apparent with recent difficulties with the Mars 2020 and Europa Clipper projects in negotiating formal, executable, and affordable requirements. Therefore, as a first step in preparing effectively for this new environment, the committee recommends that *NASA, under the direction of the Office of the Administrator, should develop a planetary protection strategic plan that clearly addresses the agency's approach for the following:*[2]

- *Managing planetary protection policy implementation,*
- *Securing relevant outside expert advice,*
- *Developing a long-range forecast of future solar system exploration missions having planetary protection implications,*
- *Setting planetary protection research and technology investment priorities, and*
- *Identifying the agency's strategy for dealing with major policy issues such as sample return and human missions to Mars and private-sector solar system exploration missions.*

[1] COSPAR is a scientific organization established by the International Council for Science (ICSU) in 1958 "to promote at an international level scientific research in space, with emphasis on the exchange of results, information and opinions, and to provide a forum, open to all scientists, for the discussion of problems that may affect scientific space research. The objectives of COSPAR are to be achieved through the organization of scientific assemblies, publications, or any other means." Although it is not formally associated with the United Natons (UN), COSPAR does organize scientific symposia on behalf of and provide information and advice to the UN Committee on the Peaceful Uses of Outer Space. For more about COSPAR, see https://cosparhq.cnes.fr.

[2] Recommendation 7.1 in Chapter 7, "A NASA Planetary Protection Strategic Plan."

As a key step in managing the future development of planetary protection policies, the committee *recommends that NASA assess the completeness of planetary protection policies and initiate a process to formally define the planetary protection requirements that are missing. NASA should ensure that all future headquarters' planetary protection requirements imposed on spaceflight missions follow NASA standard project management and systems engineering protocols for review, approval, and flow-down of requirements and, when disagreements occur, ensure that NASA's conflict-resolution process is followed. For future new situations, such as private-sector missions to other bodies or human exploration of Mars, the policies and their potential impacts should be evaluated and examined well in advance of a mission start*.[3]

In addition, all parts of NASA need to be aware of proposed changes to COSPAR policies, given the latter's role in maintaining the de facto, international consensus planetary protection policy. Therefore, the committee *recommends that NASA should ensure that in assessing changes to COSPAR planetary protection policies and requirements there is a process to engage the full breadth of NASA stakeholders, including the spaceflight mission and science communities. This process should be at least as disciplined as the process NASA uses to review, concur, and approve changes to its own policies*.[4]

ADVICE TO NASA CONCERNING THE OFFICE OF PLANETARY PROTECTION

In managing the execution of policy, NASA's Office of Planetary Protection (OPP) currently has several conflicting duties: formulating policy, implementing policy, and ensuring policy compliance. Concerns remain over whether new policy will be developed with an eye toward minimizing conflict of interest while also instituting proper oversight and review of the decisions of the OPP. Future policies need a clear conflict resolution path in the case where disagreements exist. The committee *recommends that NASA expeditiously complete the transition of the OPP to the Office of Safety and Mission Assurance (OSMA) and clarify the remaining issues concerning roles, responsibilities, resources, and locations of OPP functions. The chief of OSMA should complete the Science Mission Directorate's move toward instituting a formal method for imposing planetary protection requirements that are in accordance with standard NASA systems engineering practices*.[5] As part of the transition of the OPP to OSMA, *NASA should evaluate the European Space Agency process for planetary protection implementation and strongly consider incorporating the elements of that process that are effective and appropriate*.[6]

The development of planetary protection policy at NASA has benefited in the past from the input of an internal advisory committee; however, that process is no longer in use. The committee *recommends that NASA reestablish an independent advisory body and process to help guide formulation and implementation of planetary protection adequate to serve the best interests of the public, the NASA program, and the variety of new entrants that may become active in deep space operations in the years ahead. The advisory body and process should involve a formal Federal Advisory Committee Act committee and interagency coordination, as well as ad-hoc advisory committees, if and as circumstances dictate. This advisory apparatus should be situated and engage within NASA at a level commensurate with the broad cross-cutting scope of its purview and the potentially broad interests that the involved issues may engender.*[7]

Modern biology, specifically the ability to sequence the genomes of hundreds of thousands of organisms across the entire tree of life on Earth, offers a scientific pathway to the future for development of planetary protection policy. DNA sequencing techniques may be able to identify organisms that come from Earth-bound spacecraft assembly cleanrooms without the need to treat every microbe on a spacecraft as a potential compromising agent. The committee *recommends that NASA should engage the full range of relevant scientific disciplines in the formulation of its planetary protection policies. This requires that scientific leaders outside of the standard planetary*

[3] Recommendation 3.2 in Chapter 3, "Assessment of NASA Planetary Protection Policies."
[4] Recommendation 3.3 in Chapter 3, "Assessment of NASA Planetary Protection Policies."
[5] Recommendation 3.4 in Chapter 3, "The OPP's Move to OSMA."
[6] Recommendation 3.9 in Chapter 3, "Comparing the ESA and NASA Planetary Protection Policy Process."
[7] Recommendation 3.6 in Chapter 3, "An Independent Planetary Protection Advisory Committee."

protection community in NASA participate in revisions to NASA and COSPAR planetary protection policies and requirements.[8]

One important role for advisory groups would be to assist NASA in meeting critical planetary protection research and technology priorities by conducting a strategic assessment of the research underpinning the technology needs to implement planetary protection for likely future missions. Thus, the committee *recommends that NASA should adequately fund both the Office of Planetary Protection and the research necessary to determine appropriate requirements for planetary bodies and to enable state-of-the-art planetary protection techniques for monitoring and verifying compliance with these requirements. The appropriate investment in this area should be based on a strategic assessment of the scientific advances and technology needs to implement planetary protection for likely future missions*.[9]

The National Academies' Space Studies Board (SSB) has been providing strategic guidance to NASA's planetary protection activities for more than 50 years. In general, the National Academies' recommendations have been positively received and ultimately incorporated into COSPAR policy. However, *the SSB and NASA should pursue new mechanisms to anticipate emerging issues in planetary protection, respond more rapidly, and address new dimensions, such as private-sector missions and human exploration. Future decadal survey committees should give greater prominence to planetary protection issues and play a more proactive role in their identification and possible resolution*.[10]

ADVICE CONCERNING SAMPLE RETURN FROM AND HUMAN MISSIONS TO MARS

Although NASA and other entities are planning for robotic sample return and human missions to Mars in, respectively, the 2020s and 2030s, NASA does not currently have a policy for planetary protection for human exploration. Therefore, the committee *recommends that NASA develop an agency-wide strategic plan for managing the planetary protection policy development challenges that sample return and human missions to Mars are creating*.[11]

Furthermore, the current U.S. government process to oversee samples returned from Mars and elsewhere originates in the Apollo era and is out of date. Therefore, the committee *recommends that the Administration, most probably through the National Space Council, National Security Council (NSC), and the Office of Science and Technology Policy, should revisit NSC Memorandum 25 in light of NASA plans for Mars sample return missions and human-crewed missions to Mars and revise or replace its provisions for engaging relevant federal agencies in developing back-contamination protection policies*.[12]

Sample return and human missions to Mars also create additional planetary protection challenges in two areas: early consultations between mission planners on issues relating to sample containment and back contamination, and the development of an international consensus as to appropriate planetary protection procedures for such missions. These challenges are addressed by the following three recommendations:

- *NASA's process for developing planetary protection policy for sample return missions should include early consultation with mission developers and managers, mission and receiving facility science teams, and microbiologists and include providing a means to use the best available biological and technological knowledge about back contamination and containment*.[13]
- *NASA's process for developing a human Mars exploration policy should include examination of alternative planetary protection scenarios and should have access to the necessary research that informs these alternatives. It should also include plans to engage with other nations on the policy and legal implications of missions to Mars*.[14]

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[8] Recommendation 3.7 in Chapter 3, "Capturing Scientific Advances in the Development of Planetary Protection Policy.

[9] Recommendation 3.8 in Chapter 3, "Research and Technology Development for Planetary Protection."

[10] Recommendation 4.3 in Chapter 4, "Assessment of SSB Activities."

[11] Recommendation 3.5 in Chapter 3, "The OPP's Move to OSMA."

[12] Recommendation 4.1 in Chapter 4, "Executive Branch Coordination."

[13] Recommendation 3.1 in Chapter 3, "Lessons Learned from Mars 2020 Planetary Protection Implementation."

[14] Recommendation 5.1 in Chapter 5, "Future Studies Required to Develop the Next Human Exploration Policy."

- *The Department of State, informed by consultations with the appropriate experts and stakeholders, should embark on active international diplomacy to forge consensus on appropriate policies for planetary protection for a broad range of future missions to Mars. The goal should be to maintain and develop international consensus on how best to mutually and cooperatively meet all signatories' obligations under Articles IX and VI of the Outer Space Treaty. Such diplomacy should take into consideration, to the extent possible, the best available science as well as anticipate new missions in space.*[15]

ADVICE CONCERNING THE PRIVATE SECTOR

Another significant challenge to planetary protection is the absence to date of any significant voice for the burgeoning private sector in policy development process. As private-sector activities impinge on areas previously the exclusive domain of government-sponsored programs (e.g., missions to Mars), the applicability of planetary protection regulations is a key issue to be faced. One set of regulations for private-sector activities and another for those undertaken by governmental entities is likely cumbersome, open to ambiguity and abuse, and probably unworkable. Therefore, the committee *recommends that planetary protection policies and requirements for forward and back contamination should apply equally to both government-sponsored and private-sector missions to Mars*.[16]

If planetary protection policies operate in an even-handed manner, then the private sector needs an entrée to the policy-setting process. Therefore, the committee *recommends that NASA ensure that its policy-development processes, including new mechanisms (e.g., a revitalized external advisory committee focused on planetary protection) make appropriate efforts to take into account the views of the private sector in the development of planetary protection policy. NASA should support the efforts of COSPAR officials to increase private-sector participation in the COSPAR process on planetary protection*.[17]

A more basic issue concerning the development of private-sector space activities beyond low-Earth orbit is the so-called regulatory gap. That is, no regulatory agency within the U.S. government has authority to meet the OST obligation to "authorize and continually supervise" in-flight space exploration by nongovernmental entities. The committee *recommends that Congress address the regulatory gap by promulgating legislation that grants jurisdiction to an appropriate federal regulatory agency to authorize and supervise private-sector space activities that raise planetary protection issues. The legislation should also ensure that the authority granted be exercised in a way that is based on the most relevant scientific information and best practices on planetary protection*.[18]

THE FUTURE

One final issue in policy development has the potential to impact all future spacecraft missions, be they robotic or human or private sector or government sponsored. That is, For how long do planetary protection policies apply? As capabilities increase and knowledge of solar system environments grow, it is conceivable that there may be a lesser need for strict policies. Therefore, given the implications with respect to the OST, the committee *recommends that NASA and COSPAR should facilitate development of an international strategy for establishing periods of biological exploration. Such a strategy should ensure that individual nation-states are all using the same values. Specification of this period is vital to the calculations of probability of contaminating a potential habitat on another world*.[19]

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[15] Recommendation 4.2 in Chapter 4, "Department of State."
[16] Recommendation 6.1 in Chapter 6, "Private-Sector Space Activities and Planetary Protection."
[17] Recommendation 6.3 in Chapter 6, "Private-Sector Participation in the Development of Planetary Protection Policy."
[18] Recommendation 6.2 in Chapter 6, "Planetary Protection, the Private Sector, and the Regulatory Gap."
[19] Recommendation 3.10 in Chapter 3, "Defining a Period of Planetary Protection."

1

Introduction

From the beginning of the space age, scientific goals have powerfully shaped solar system exploration. Missions have been focused on research to understand the origin and evolution of solar system bodies and discover evidence of extant or relic life. Two seminal questions formulated by the original NASA astrobiology program definition in 1995 were Where did we come from? And Are we alone? Those profound questions have captivated the public and yielded congressional support for NASA's programs, including its orbiting, in situ, and sample return missions that have the best prospects of locating and detecting extinct or extant life in the solar systm.

Liquid water is necessary for all life as we know it, so finding present or past existence of water is critical in the search for extraterrestrial life. The science community accepts that Mars, at one time, had large amounts of liquid water on the surface. Much of the remaining water is locked into ice at or near the surface, and liquid water may still be present underground. Similarly, the so-called Ocean Worlds (i.e., a subset the icy bodies of the outer solar system)—especially Jupiter's Europa and Saturn's Enceladus—have abundant liquid water beneath surface ice shells. Saturn's Titan also has a deep subsurface liquid water ocean. Moreover, that ocean is potentially in contact with the moon's surface, which is itself a veritable laboratory for prebiotic chemistry with lakes and rivers of methane and ethane. In addition, Jupiter's Ganymede, and even Callisto, may have water deep under their icy surfaces.

NASA's next two major strategic science missions that have significance for both life detection and planetary protection are Mars 2020 (potentially the first phase of a sample return campaign) and the Europa Clipper. Other mission concepts for the exploration of the Ocean Worlds have been and are being studied.[1] As complicated as those science missions will prove to be, the character of solar system use and exploration is on the verge of a dramatic change.

Planning for Mars sample return brings much greater challenges to not only science and engineering but also planetary protection. Except for the return of lunar material during the Apollo program and the benign samples of a comet (Stardust mission), the solar wind (Genesis mission), and asteroids (Hayabusa 1, Hayabusa 2, and OSIRIS-REx mission), planetary protection policy has not had to address the complex issues associated with the return of samples of extraterrestrial material. Especially for sample return missions, the need to develop better and more complete planetary protection policies is becoming urgent, given the pressing timelines of mission planning

[1] These include, but are not limited to, the Titan Mare Explorer (http://www.astro.cornell.edu/academics/courses/astro2202/TiME_06497165.pdf), the Enceladus Habitability and Life Signature, Europa lander (https://europa.nasa.gov/resources/58/europa-lander-study-2016-report), and Dragonfly (http://dragonfly.jhuapl.edu).

and design. Human exploration of Mars will involve potential contamination challenges that planetary protection policy also has not needed to manage in the past.

The space agencies of other nations, including India and the European Space Agency (ESA), have sent orbiters to Mars, and others, such as the China and the United Arab Emirates, are preparing for similar missions for launch in the near future. Further, NASA is planning human missions to Mars in future decades. Exploration of Mars might also generate interest from private-sector entities that want to undertake their own missions or provide goods and services to NASA in activities related to Mars.[2] Very recently, one company, SpaceX, conducted its own private test launch of a new vehicle, the Falcon 9 Heavy, with a dummy payload that was propelled into an Earth-escape trajectory. While the Federal Aviation Administration did indeed approve the launch, only very recently—i.e., after the public release of the prepublication version of this report—has it been become clear that formal, but limited, consultations on the planetary protection implications of this test flight took place between NASA, the Federal Aviation Administration, and SpaceX.

While science continues to be a fundamental rationale for the robotic exploration of all parts of the solar system, other motivations are emerging in deep-space activities. Those drivers, some of which are mentioned above, may be characterized in the following three categories:

- Traditional government agencies, especially NASA, seek to pursue broader geopolitical and technological objectives embodied in human exploration missions to Mars;
- New governmental entrants seek to join the community of space-faring nations via robotic and perhaps human missions to the Moon and eventually to Mars; and
- Private-sector entities seek to both provide commercial transportation to the Moon and Mars and also leverage past scientific findings for commercial benefits, including lunar missions and asteroid mining.[3]

This future transformative context for solar system exploration has implications for planetary protection policy development and implementation. The involvement of more governments and, potentially, the private sector introduces new players, priorities, and opportunities for using and advancing science and technology. Efforts to establish a human presence on Mars also will profoundly affect the historical and internationally well-accepted objectives of avoiding harmful contamination of other planetary bodies.

Past planetary protection policies have exclusively applied to government-sponsored missions by a small number of countries because only governments undertook space exploration that required consideration of planetary protection. In the United States, NASA's requirements have sufficed for these missions. However, as noted above, both governments and the private sector are beginning to consider missions that could expand the nature and scales of activity. An arena that was formerly the exclusive purview of a few space-faring countries (notably the United States, Russia, Japan, and various European nations) is expanding. NASA, the federal government, and the international community do not yet have planetary protection policy development processes in place that are ready to respond to expansion in the number of actors and types of activities.

Furthermore, while past planetary protection policies have focused primarily on meeting international scientific objectives, some future missions can be expected to stimulate growing public interest, and even concerns. Increasingly promising prospects for searching for evidence of the origin and existence of life elsewhere in the solar system and the approaching reality of robotic and crewed collection of samples from Mars will increase public interest in how space missions will be prepared to meet the dual objectives of planetary protection (see the below section, "Interim Report").

This report addresses the implications of changes in the complexion of solar system exploration as they apply to the process of developing planetary protection policy. In particular, it responds to a request from NASA to examine the history of planetary protection policy, assess the current policy development process, and recom-

[2] See, for example, E. Musk, Making humans a multi-planetary species, *New Space* 5:46-61, 2017; and E. Musk, Making life multi-planetary, *New Space* 6:2-11, 2018.

[3] At least one private-sector entity is planning robotic and human missions to orbit and/or land on Mars. For details see, for example, E. Musk, Making humans a multi-planetary species, *New Space* 5:46-61, 2017; and E. Musk, Making life multi-planetary, *New Space* 6:2-11, 2018.

mend improvements to make the process more responsive to present and future needs. (See Preface for the full statement of task.)

SCOPE OF THIS STUDY

In response to NASA's request, the National Academies established the Committee to Review the Planetary Protection Policy Development Processes (hereinafter referred to as "the committee"), operating under auspices of the Space Studies Board. (See Appendix F for committee member biographies.) This report presents the results of the committee's reviews and deliberations. The committee considered planetary protection policy development from the perspective of all types of missions—including government-sponsored and private-sector efforts having either scientific or commercial objectives and utilizing either robotic or human-crewed spacecraft.

In its broadest sense, planetary protection policy addresses missions to and from all types of solar system bodies, including the Moon, planets, small bodies (such as comets and asteroids), and the satellites of other planets. Current policy places these targets into categories based on the type of mission, the likelihood that a body may be able to harbor life, and the probability that terrestrial organisms might survive on that body or that material returned to Earth might pose a risk to the terrestrial biosphere.

Based on existing knowledge and capabilities, only three objects create serious planetary protection concerns: Mars, Europa, and Enceladus. For Mars, there is very strong evidence of past abundant water on the surface, and measurements indicate a past habitable environment where life may have formed and could potentially survive today in some subsurface refugia. Massive amounts of near surface water ice have been verified at Mars. Missions that have examined Europa and Enceladus indicate the presence of internal liquid water in contact with a rocky core that, therefore, might support indigenous life forms.[4] Within this set of bodies, current and anticipated plans for private-sector activities only involve missions to Mars.[5] Because the Moon and most asteroids are, in general, considered of low priority for studies of life and/or prebiotic chemistry, those bodies pose few planetary protection challenges for government-sponsored or private-sector missions, and no planetary protection requirements are imposed beyond the preparation, review, and approval of brief documentation.

The committee's charge focused on the process by which planetary protection policy is formulated. The charge did not ask the committee to propose specific policies or to assess specific standards, procedures, or validation methods through which space missions execute planetary protection policies. However, the committee found it necessary to consider implementation when the policy development process impacts the translation of policies into implementation roles and responsibilities. The committee also examined specific examples of how implementation requirements have been levied when the cases help illuminate strengths or weaknesses of the policy development process. Further in response to its charge, the committee considered topics related to research and technology development in terms of how it might be needed to support policy development in the future.

INTERIM REPORT

NASA's charge to the committee included a request for an interim report that addressed the rationales for and goals of planetary protection and that suggested a working definition of planetary protection. NASA asked for the interim report to be completed shortly after the committee's first meeting, so the interim report focused

[4] There is evidence for liquid water oceans under the thick crusts of, for example, Jupiter's moons Ganymede and Callisto. However, these oceans are sandwiched between upper and lower layers of ice. Such a configuration is less interesting than that found at Europa and Enceladus from an astrobiological perspective because there is no contact between liquid water and the satellites silicate core. Saturn's Titan has hydrocarbon lakes, a complex "hydrological" cycle based on methane and ethane, so the greatest current planetary protection concern would be for compromising studies related to prebiotic organic chemistry. For more on the possibility of living systems based on liquid hydrocarbons see, for example, National Research Council, *The Limits of Organic Life in Planetary Systems*, The National Academies Press, Washington, D.C., 2007, pp. 69-78.

[5] A presentation by S.P. Worden to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe on April 25, 2018, indicated that the Breakthrough Foundation was in advanced discussions with NASA to initiate a project to send "chipsats" to Europa and/or Enceladus. For details, see http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_180812.

exclusively on planetary protection as it applied to robotic, scientific missions undertaken by the U.S. government. The committee delivered its interim report to NASA on June 7, 2017.[6] Consideration of broader aspects of planetary protection, including private-sector and human missions and implications for implementation roles and responsibilities, were deferred until this final report.

The interim report adopted the same two goals for planetary protection that NASA, international, and Space Studies Board documents have reflected for decades:

1. ***The control of forward contamination,*** defined by NASA as "the control of terrestrial microbial contamination associated with robotic space vehicles intended to land, orbit, flyby, or otherwise encounter extraterrestrial solar system bodies";[7] and
2. ***The control of back contamination,*** defined by NASA as "the control of contamination of the Earth and the Moon by extraterrestrial material collected and returned by robotic missions."[8]

The interim report then identified two related rationales for planetary protection, in priority order:

1. Preserve the integrity of Earth's biosphere; and
2. Protect the biological and environmental integrity of other solar system bodies for future science missions.[9]

As made clear in the interim report, the first rationale encompasses human safety because it is an integral component of the interdependent survival of human, animal, and plant species inhabiting planet Earth.

With respect to the development and implementation of planetary protection policy, the committee emphasizes that the fundamental goal of such policy is to enable, not inhibit, exploration and the search for life.

The interim report also discussed whether planetary protection might involve a third rationale focused on avoiding false results in searching for evidence for life in in situ or returned samples. After further discussion, the committee concluded that there is no need to identify a third rationale.

Avoiding false results in searching for evidence of life is important for the science investigations and the implementation of planetary protection policies. In principle, a false-negative might expose the terrestrial environment to possibly harmful organisms. A false-positive might inhibit distribution of safe samples for analysis by the broad scientific community. Over the longer term, false negative results could expose future exploration missions—including human missions—to overlooked hazards, while false positive results could unjustifiably curtail any immediate or future scientific activities.

The process to develop planetary protection policies has a legitimate interest in ensuring that space missions satisfy requirements, including contamination and cleanliness requirements, connected to the integrity of scientific investigations. Meeting such requirements minimizes the ambiguity of scientific measurements and their interpretation concerning examination of both in situ and returned samples of extraterrestrial matter. However, science mission teams, not those responsible for planetary protection policy, have always established the requirements for the integrity and quality of scientific investigations, subject to peer review, satisfaction of planetary protection directives, and management oversight. The appropriate use of peer review will ensure the validity of all scientific findings used to influence new planetary protection policies or practices from both government-sponsored and

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[6] National Academies of Sciences, Engineering, and Medicine (NASEM), *The Goals, Rationales, and Definition of Planetary Protection: Interim Report*, The National Academies Press, Washington, D.C., 2017.

[7] As will become clear later, neither Article IX of the Outer Space Treaty nor the consensus international planetary protection policy maintained by the Committee on Space Research (COSPAR) of the International Council for Science (ICSU) makes a distinction between robotic and human space flight.

[8] NASA, Planetary Protection Provisions for Robotic Extraterrestrial Missions, NASA Interim Directive 8020.109A, March 30, 2017.

[9] The interim report referred to protection of other solar system bodies "in their natural state." That language does not appear in prior COSPAR or NASA documents. In order to avoid implying that the committee intends to broaden planetary protection policy beyond issues regarding protecting scientific searches for evidence of life, the committee has removed the phrase from its statement of rationale 2 in this final report. Whether planetary protection policies expand beyond their traditional focus on biological/organic contamination has been raised in ethical discussions of planetary protection. See the section "Ethical Considerations" below.

private-sector missions. For this reason, the committee concludes, as it argued in the interim report,[10] that the two traditional rationales for planetary protection policy already address the need for planetary protection officers to ensure that space missions satisfy the requirements for the integrity of scientific investigations established by the science mission team.

Altogether, in the committee's judgment, the voice of the planetary protection office, shaped with appropriate expert consultation, is presumed to be authoritative, but not dispositive, on matters that derive directly from the two rationales for planetary protection identified above, and all the more so in matters pertaining to the safety and integrity of Earth's biosphere. However, the committee does not believe there are substantive arguments to augment these two rationales—that is, preserve the integrity of Earth's biosphere and protecting integrity of other solar system for future studies—with a third one focused on the integrity of the science investigations themselves.

Finding: The committee finds no reason to augment these two established rationales for planetary protection with a third one focused on the integrity of the science investigations themselves.

As part of the conflict resolution process (discussed in Chapter 3), matters of broader programmatic significance, including cost, risk, and overall program objectives as well as planetary protection, may be brought to bear for ultimate judgement and decision, at the level of an associate administrator or higher if needed. For example, a false-positive result concerning a sample return from Mars could compromise biological study of the returned material. This situation would not, by itself, constitute a hazard to Earth or Mars in planetary protection terms. The potentially compromised sample could remain in confinement on Earth, and the false-positive result could lead to restrictions on any future activities on Mars. Neither of these outcomes is good for space exploration, but the consequences of false positive results requires assessment by NASA officials responsible for the overall success and effectiveness of NASA science and exploration programs. False positives would likely have international repercussions because they would impact all missions to the relevant body (e.g., Mars), not just those launched by NASA.

The interim report's second task was to provide a working definition of planetary protection. Taking into consideration U.S. obligations under the Outer Space Treaty (OST) and current planetary protection approaches as developed by NASA and the Committee on Space Research (COSPAR) (see Chapters 2 and 3),[11] the committee adopted the following definition:

> Planetary protection involves at least three fundamental activities—policy formulation, policy implementation, and compliance and validation. It encompasses those goals, rationales, policies, processes, and substantive requirements that are intended to ensure that any interplanetary space mission does not compromise the target body for a current or future scientific investigation and does not pose an unacceptable risk to Earth (in the case, for example, of sample return missions).[12]

This definition encompasses a wide range of activities that contribute to effective policy. For example, implementation involves translating policy into planetary protection goals and requirements for specific missions, as well as validation of compliance with requirements. New scientific findings and technological advances inform both policy formulation and implementation about how to make the planetary protection actions more effective in future space exploration activities. Policy formulation occurs at both national and international levels, and in the case of internationally cooperative missions, all of these steps have international implications.

[10] NASEM, *The Goals, Rationales, and Definition of Planetary Protection: Interim Report*, The National Academies Press, Washington, D.C., 2017, pp. 8-10.

[11] COSPAR is a scientific organization established by the International Council for Science (ICSU) in 1958 "to promote at an international level scientific research in space, with emphasis on the exchange of results, information and opinions, and to provide a forum, open to all scientists, for the discussion of problems that may affect scientific space research. The objectives of COSPAR are to be achieved through the organization of scientific assemblies, publications, or any other means." Although it is not formally associated with the United Nations, COSPAR does organize scientific symposia on behalf of and provide information and advice to the UN Committee on the Peaceful Uses of Outer Space. For more about COSPAR see https://cosparhq.cnes.fr.

[12] NASEM, *The Goals, Rationales, and Definition of Planetary Protection: Interim Report*, The National Academies Press, Washington, D.C., 2017.

In both the interim report and in this final report, the committee defines planetary protection in terms of avoiding harmful biological and organic contamination. Other forms of contamination (e.g., with abiotic chemical, mechanical, or esthetic consequences) can also occur during planetary exploration missions. However, in this report, the committee focuses on effects that can interfere with searches for extraterrestrial life or the well-being of terrestrial life.

DEFINITION AND USE OF THE TERM "POLICY"

NASA's definition of policy refers to "the philosophies, fundamental values, and general direction of the Agency or Center [that] are used to determine present and future decisions." NASA adds that "because established policies are general in nature, they may need more specific requirements established in procedural requirements for full implementation."[13]

This definition works well in the context of planetary protection. The committee believes that NASA's planetary protection policy can be developed as a set of guiding principles that point to a course of action (a plan) that accomplishes goals that are clearly articulated. The policy is also required to establish clear responsibilities for leadership within the agency for formulating and executing that plan. "Policy" in this context is not the detailed implementation requirements or performance standards that are established for particular planetary exploration missions. Those detailed requirements and technical goals are most effective when they flow down from the policy (principles and guidelines) in a way that can be validated for compliance and effectiveness. More general requirements that describe how high-level policy will be executed and that reflect the application of broad scientific and technical knowledge to meet planetary protection goals do become an element of policy.

NASA has, to date, cited the COSPAR planetary protection policy as its principal guidance, although that policy is not binding on member states (or only insofar as the states adopt it). However, the United Nations (UN) Committee on the Peaceful Uses of Outer Space, of which the United States is a member, has endorsed COSPAR as the appropriate international authority for creating consensus planetary protection guidelines.[14]

The COSPAR policy goes beyond the definition of policy in the foregoing paragraph and includes substantial detail on requirements and goals for planetary exploration missions. Member states do have binding obligations under the OST, but the treaty's language does not address, in and of itself, an implementation policy (i.e., a course of action for specific space missions). Further, NASA has played a particularly influential role in the COSPAR process for determining, reviewing, and updating the COSPAR policy and has then used the COSPAR guidelines as justification, translating its own policy into implementing requirements and processes.

> **Finding:** Creating a more arms-length relationship within NASA between those responsible for the development of planetary protection policies and those responsible for implementing the requirements deriving from the policies would create a greater sense of equity and fairness.

ETHICAL ISSUES

In its deliberations, the committee recognized that ethical issues also permeate planetary protection endeavors. The origins of planetary protection in the 1950s reflect ethical thinking about forward and backward contamination at a time when the policies and international law that characterize this area today did not exist. The development of planetary protection processes, such as in COSPAR in the early 1960s, and legal obligations in the OST in 1967 created a complex mosaic of scientific, political, legal, and ethical issues.

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[13] NASA, NPR 1400.1G, NASA Directives and Charters Procedural Requirements.

[14] See paragraph 25 of UN Committee on the Peaceful Uses of Outer Space, "Space Science for Global Development: Report on the United Nations Office for Outer Space Affairs and Committee on Space Research Coordination Meeting in Support of the Preparations for UNISPACE+50," Vienna, Austria, May 22-23, 2017, and paragraph 332 of UN, "Report of the Committee on the Peaceful Uses of Outer Space, Sixtienth [sic] Session (7-17 June 2017)," General Assembly, Official Records, Seventy-second Session, Supplement No. 20, http://www.unoosa.org/res/oosadoc/data/documents/2017/aac_1052017crp/aac_1052017crp_25_0_html/AC105_2017_CRP25E.pdf and http://www.unoosa.org/oosa/en/ourwork/copuos/2017/index.html.

Planetary protection experts recognize that the changing nature of space exploration, including plans to send humans to Mars and the growth in private-sector space activities, presents ethical challenges as well as scientific, political, and legal ones. For example, a 2010 COSPAR Workshop on Ethical Considerations for Planetary Protection in Space Exploration at Princeton University considered whether existing policy adequately captured the range of ethical issues emerging with changes in space exploration goals, technologies, and participants.[15]

Among other things, the workshop participants recommended expanding planetary protection policy to address ethical concerns about contamination of planetary bodies "beyond biological and organic constituent contamination."[16] These concerns include the need to value and protect non-living extraterrestrial environments. The workshop participants acknowledged that expanding the scope of planetary protection ethics would require developing new policy processes, such as a separate COSPAR track "to provide guidance on requirements/best practices for protection of non-living/non-life-related aspects of outer space and celestial bodies."[17]

The Princeton workshop acknowledged that its recommendations required greater attention in COSPAR and beyond on the substantive scope and procedural needs of planetary protection ethics. The implications of actually finding extraterrestrial life would also require an expansion of planetary protection ethics. However, dialogue on expanding planetary protection ethics has not advanced sufficiently to permit the committee to make relevant findings and recommendations. Nor did the committee believe it had the mandate to study specifically the implications of an expanded ethical approach to planetary protection, especially given the many challenges to existing planetary protection policy objectives and processes. A number of these challenges (e.g., the likelihood of future human activities on Mars or the question of setting time horizons beyond which planetary protection requirements might be relaxed or removed) directly affect the core ethical concerns of planetary protection that have been present since the 1950s. Thus, the committee kept these ethical concerns in mind in analyzing planetary protection policy but did not explicitly create a set of findings and recommendations on these issues.

As the number of nations and non-state actors who potentially will be involved in the exploration of outer space in the future increases, there will need to be a generally accepted ethical basis for policy (such as a function played by the Universal Declaration of Human Rights) so that actors not subject to direct governmental authority have a sense of the goals of good policy. While science and technology are easily communicated across cultural and national boundaries, that is not necessarily the case with legal and ethical principles, and unrecognized intercultural differences can lead to serious misunderstandings. The broader the participation in space exploration becomes, the more such intercultural differences need to be understood. Closer to home, the biological research community has long been a leader in flagging ethical issues associated with research progress, the most recent having been CRISPR,[18] and would be attuned to working with similar issues in the space context. Periodic updates of ethical implications could be a way to convey norms to the international public and private space community as concerns arise; formal COSPAR policy would presumably follow. NASA, by convening the updates would have a new tool to extend its leadership in planetary protection policy.

HOW TO READ THIS REPORT

The committee recognizes that this report will likely be read by individuals with varying degrees of interest in and familiarity with the history and practice of planetary protection. Ideally, every reader will begin on page one and work their way through to the final page. For the more selective reader, the committee offers this guide on how best to read and make use of this report.

Readers interested in the following aspects of the study should consult the chapters indicated:

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[15] J. D. Rummel, M. S. Race, G. Horneck, and the Princeton Workshop Participants, Ethical considerations for planetary protection in space exploration: A workshop, *Astrobiology* 12(11):1017-1023, 2012.

[16] Ibid., p. 1020.

[17] Ibid.

[18] A genome editing technique that uses a CRISPR (clustered regularly interspaced short palindromic repeats) sequence of DNA and its associated protein to add or remove specific gene sequences to a cell.

- Working definition of planetary protection and its goals—Chapter 1 (section "Interim Report")
- Historical context—Chapter 2 (all sections)
- Current NASA policy development process—Chapter 3 (all sections)
- Policy development process beyond NASA—Chapter 4 (all sections)
- Challenges posed by future robotic missions to Mars—Chapter 3
- Challenges posed by human missions to Mars—Chapter 5
- Challenges posed by private-sector activities—Chapter 6 (all sections)
- Future of the policy development process—Chapter 5 (later sections, beginning with "Planetary Protection and Humans on Mars") and Chapter 7 (all sections)
- Example of the evolution of planetary protection policies—Appendix B

As the committee addressed each element of its charge, the following two overarching conclusions emerged:

- First, the historical underpinnings of planetary protection policy, including the OST as the foundation for policy development; COSPAR's role in fostering international cooperation on planetary protection guidelines; science-based decision making; and U.S. leadership in policy-making all remain vital.
- Second, some aspects of the current planetary protection policy development process, which has been built on a chain of incremental refinements to legacy approaches over a period of 50 years, are inadequate to respond to the implications of progressively more complex solar system exploration missions. Today's planetary protection policies have already been forced to grapple with issues not seen since the Apollo Moon landings in the 1960s and the Viking Mars landers in the 1970s, and they will face much greater challenges as efforts such as the Mars sample return campaign, exploration of the icy moons of Jupiter and Saturn, and human landings on Mars take place. And, as noted elsewhere, complex missions are taking place in an environment of programmatic constraints such as cost caps that did not generally exist in the Apollo era.

In the chapters that follow in this report, the committee identifies lessons learned from planetary protection policy development in the past and issues that need to be resolved to make future policies effective. These issues include the need for a comprehensive NASA planetary protection strategic plan that identifies relevant future missions that demand early planetary protection guidance; establishes planetary protection research and technology development investment priorities; creates a robust process for securing independent, expert, outside advice, and peer review; assesses legacy requirements and identifies opportunities for improvement based on new science; improves the clarity of the translation of policy into mission requirements; and engages the federal government and the international community in timely planetary protection policies for sample return and human missions to Mars.

The careful reader of this report will notice that some material appears in several different places in the report. Such repetition is unfortunate but necessary to provide the readers only interested in particular aspects of the planetary protection policy development process with a comprehensive discussion of specific topics (e.g., the intertwined roles of NASA, COSPAR, and the National Academies Space Studies Board in the development of planetary protection policies).[19]

[19] In 1988, the name of the Space Science Board (established in 1958) was changed to the Space Studies Board.

2

Historical Context

The planetary protection policy development process has evolved over decades of solar system exploration. National initiatives, such as the Apollo program and the Viking missions to Mars, were major influences early in the process of developing planetary protection policy, and a number of other national and international activities have influenced the process.[1] This chapter summarizes roles and impacts of key elements of this history.

PLANETARY PROTECTION BEFORE THE OUTER SPACE TREATY

The international community expressed concern that space exploration could potentially contaminate planetary bodies, jeopardizing their biological exploration and posing risks to Earth's biosphere, even before Sputnik began the spaceflight era. In 1956, the International Astronautical Federation (IAF) attempted to coordinate international efforts to prevent interplanetary contamination, and 2 years later the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS) made initial attempts to deal with interplanetary contamination and spacecraft sterilization. In 1957, the U.S. National Academy of Sciences (NAS) urged that lunar and planetary studies avoid interplanetary contamination and asked the International Council for Science (ICSU) to assist in evaluating the possibilities of such contamination and developing means to prevent it. In 1958, the ICSU established an ad hoc Committee on Contamination by Extraterrestrial Exploration (CETEX), which in turn recommended establishing a code of conduct for space missions and research. In accepting the CETEX recommendations, ICSU established the Committee on Space Research (COSPAR) to coordinate worldwide space research.[2]

These organizations of the international scientific community had an early focus on planetary protection, among other issues. In 1961, ICSU declared that all countries launching space experiments that could have an adverse effect on other scientific research should provide ICSU and COSPAR with the information necessary to evaluate the potential contamination.[3] In 1962, COSPAR organized a Consultative Group on Potentially Harmful

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[1] For a thorough discussion of the history of planetary protection through about 2011, see M. Meltzer, *When Biospheres Collide: A History of NASA's Planetary Protection Programs*, NASA SP-2011-4234, U.S. Government Printing Office, Washington, D.C., 2011.

[2] In 2017, COSPAR membership included 43 national member organizations—for example, the National Academies of Sciences, Engineering, and Medicine (NASEM) in the case of the United States—and 13 international scientific unions, and its various assemblies and topical meetings involve roughly 10,000 scientists from around the world.

[3] For more information on the role of COSPAR see, for example, https://cosparhq.cnes.fr/scientific-structure/ppp.

Effects of Space Experiments to help conduct these evaluations. These actions set the foundations for the key role COSPAR has played in the international development of planetary protection policies.

OUTER SPACE TREATY

With adoption of the Outer Space Treaty (OST)[4] in 1967, planetary protection became part of international law and, with U.S. ratification of the treaty, federal law. For the past 50 years, the OST has been the most important international legal instrument regarding activities in space. All spacefaring countries to date are parties to the OST and are, thus, bound under international law to comply with the treaty. In 2017, congressional testimony confirmed the OST's continuing importance to space activities.[5]

The OST contains many obligations on states parties, with the prohibition on the placement of nuclear weapons in space being one of the most important.[6] In terms of planetary protection, the key provisions are Article IX, which is specific to planetary protection, and Article VI, which requires states parties to authorize and continually supervise the space activities of nongovernmental entities under their respective jurisdictions. Together, Articles IX and VI mean that states parties are required to address planetary protection issues for space activities of both governmental space agencies, such as NASA, and nongovernmental actors, such as private-sector enterprises.

To date, private-sector space activities have not raised planetary protection concerns, and, thus, Article IX implementation by states parties has not specifically addressed the private sector. However, states parties have a clear obligation under Article VI of the OST to authorize and continually supervise the space activities of nongovernmental entities.[7] As this report discusses below,[8] potential private-sector missions to Mars raise planetary protection questions, which Articles VI and IX of the OST require states parties to address.

The planetary protection obligations of Article IX provide that states parties shall conduct space exploration "so as to avoid harmful contamination" of celestial bodies and to avoid "adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." Thus, Article IX imposes obligations to avoid forward and backward contamination and provides that states parties "shall adopt appropriate measures" to do so.

These planetary protection provisions reflect the general duty in Article IX that states parties conduct space activities "with due regard to the corresponding interests of all other States Parties to the Treaty." This due-regard obligation implements the principle in Article I of the OST that space "shall be free for exploration and use by all States," including "free access to all areas of celestial bodies."

The due-regard obligations on planetary protection do not impose specific requirements on space missions or the exploration of particular celestial bodies. What constitutes harmful contamination for one celestial body might not be relevant for another such body. Further, space exploration missions increase scientific knowledge about celestial bodies, permitting states parties to adapt their planetary protection approaches based on the best available science.[9] Article IX requires states parties to evaluate harmful forward and backward contamination and,

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[4] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, opened for signature January 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205 (hereinafter "Outer Space Treaty").

[5] See, for example, U.S. Senate Committee on Commerce, Science, and Transportation, "Reopening the American Frontier: Reducing Regulatory Barriers and Expanding American Free Enterprise in Space," hearing of the Subcommittee on Space, Science, and Competitiveness, April 26, 2017, https://www.commerce.senate.gov/public/index.cfm/2017/4/reopening-the-american-frontier-reducing-regulatory-barriers-and-expanding-american-free-enterprise-in-space.

[6] Outer Space Treaty, Article IV.

[7] In connection with proposed legislation in Congress, statements have been made asserting that the Outer Space Treaty does not directly apply to private-sector space activities (see, e.g., R. Kelly, *Nemitz v. United States,* A Case of First Impression: Appropriation, Private Property Rights and Space Law Before the Federal Courts of the United States, *Journal of Space Law* 30(2):297-309, 2004). These assertions fail to acknowledge that, under the Outer Space Treaty, the U.S. government is required to authorize and *continually* supervise the space activities of nongovernmental entities, including activities that raise planetary protection concerns under Article IX.

[8] See Chapter 5 of the report discussing private-sector space activities.

[9] For example, scientific study of material returned from the Moon produced the conclusion that it posed no health or environmental threats on Earth. Thus, lunar missions that return such material to Earth are no longer classified as restricted Earth return in, for example, NASA and COSPAR planetary protection policies.

where necessary, adopt measures that appropriately manage such. Thus, the OST requires states parties to have a process or processes to identify planetary protection, design appropriate measures to address these, and implement the measures in space missions.

Article IX reinforces this requirement by stating that, in their space activities, states parties (1) "shall be guided by the principle of co-operation and mutual assistance"; and (2) "shall undertake appropriate international consultations" when a state party "has reason to believe that an activity or experiment planned by it or its nationals in outer space . . . would cause potentially harmful interference with the activities of other states parties in the peaceful exploration and use of outer space."[10] Further, Article IX permits a state party to request consultations if it has reason to believe the space activities of another state party might "cause potentially harmful interference with activities in the peaceful exploration and use of outer space."[11]

Thus, when implementing their treaty obligations on planetary protection, states parties are required to consider the interests of other states parties in the exploration and use of space and consult with other states parties where these interests may be seriously affected.

For 50 years, states parties to the OST have implemented their Article IX obligations through planetary protection processes functioning at international and national levels. Internationally, states parties have used COSPAR to formulate consensus and science-based guidance on planetary protection objectives. Nationally, space agencies have developed their own planetary protection processes. Over time, the international and national planetary protection processes have influenced one another, reflecting Article IX's emphasis on international consultation and cooperation.

To be clear, *planetary protection guidance developed through COSPAR is not legally binding under the OST*. COSPAR has no authority to compel OST states parties to implement its recommendations. Nor does the OST require states parties to use COSPAR in fulfilling Article IX obligations. However, states parties have, for five decades, implemented Article IX by using COSPAR and following its planetary protection guidance. For its part, the United States has exhibited sustained leadership within COSPAR and demonstrated commitment to COSPAR's planetary protection guidance. Indeed, NASA requires that non-U.S. space agencies using NASA assets follow COSPAR guidance, thus actually enforcing the guidance that COSPAR produces. New spacefaring countries have also emphasized the importance of the COSPAR process and its recommendations to their efforts.[12]

Strong commitment to the COSPAR process and COSPAR guidance over 50 years helps explain why serious controversies about the meaning of, or compliance with, Article IX's planetary protection provisions have not arisen. For example, the OST does not define "harmful contamination," but states parties have so far not engaged in contentious debates about the meaning of this term. The area of planetary protection has not required international lawyers to apply the rules of treaty interpretation in response to problems among countries about what Article IX means.[13] Compared to interpretation and compliance problems experienced in other areas of international law, what has transpired under the OST's planetary protection provisions is impressive.

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[10] The inclusion of "its nationals" in this provision of Article IX underscores a state party's obligation in Article VI to authorize and *continually* supervise space activities of nongovernmental entities.

[11] The concept of "harmful interference" in Article IX is broader than "harmful contamination," with the expanded scope incorporating matters than do not involve planetary protection. The harmful interference concept in Article IX arose from concerns that some space activities, such as the early 1960s launching of millions of small copper wires into orbit by the United States to enhance radio communication capabilities (Project West Ford, see, e.g., C. Peebles, *High Frontier: The U.S. Air Force and the Military Space Program*, Air Force History and Museums Program, 1997), could interfere with different space activities of other countries. Recent legislative proposals in the United States seeking to enhance private-sector space activities, such as asteroid mining, have raised unprecedented interpretations concerning the meaning of "harmful interference" in Article IX. See, for example, J. Gabrynowicz, "Hearings on Exploring Our Solar System: The ASTEROID Act as a Key Step," testimony to the Subcommittee on Space of the Senate Committee on Science, Space, and Technology, September 10, 2014, https://science.house.gov/legislation/hearings/subcommittee-space-exploring-our-solar-system-asteroids-act-key-step.

[12] See, for example, Omran Sharaf, "Planetary Protection in Emirates Mars Mission," presentation to Legal Subcommittee, UN Committee on Peaceful Uses of Outer Space, Slides 17-18, March 2017, http://www.unoosa.org/documents/pdf/copuos/lsc/2017/tech-03.pdf.

[13] The international legal rules on treaty interpretation are found in the Vienna Convention on the Law of Treaties (1969). Although the United States is not a party to the Vienna Convention, it considers the convention's treaty interpretation rules to be binding on the U.S. government as customary international law.

The success, to date, of Article IX implementation has benefitted from important features of space exploration that have reduced the potential for controversy and conflict over implementation of the OST. These features include the following:

- A limited number of countries undertaking space missions that create planetary protection concerns;
- A predominant spacefaring nation, the United States, which supported planetary protection objectives through NASA and provided sustained leadership in COSPAR, as well as bilateral relations with other spacefaring countries;
- The focus on robotic planetary missions and the absence of human exploration activities after Apollo that limited the range of planetary protection concerns;
- The narrow focus on avoiding biological/organic contamination related to, among other things, the search for extraterrestrial life; and
- The absence of private-sector space activities that raise planetary protection concerns.

Changes in the nature of space exploration and use present challenges to planetary protection efforts. For example, private-sector missions to Mars would raise the issue of which agency of the U.S. government has the authority to regulate such missions, including for planetary protection compliance. Resolving where such authority resides cannot be ignored, because Article VI of the OST requires the United States to authorize and continually supervise the space activities on nongovernmental entities in the United States as well as U.S. government entities.[14] Sending humans to Mars will also raise serious questions about what "harmful contamination" in Article IX of the OST means.[15] Various concerns about the planetary protection policy processes in COSPAR and NASA regarding missions to Mars also raise questions related to the obligations in Article IX.

Although facing a potentially more challenging context, spacefaring nations remain bound under the OST's Article IX provisions on planetary protection. The nature of these obligations provides states parties with ample opportunity to adjust their international cooperation and national activities to address new planetary protection issues. In this context, U.S. leadership on planetary protection becomes even more important.

Finding: The OST provides the critical and effective international legal framework for countries to identify risks of forward and backward contamination, formulate risk management strategies, and implement those strategies in space missions. States parties to the OST have not experienced serious disagreements on the meaning of, or compliance with, the treaty's planetary protection provisions.

Finding: Planetary protection policies and requirements for forward and backward contamination apply equally to both government-sponsored and private-sector missions to Mars.

COMMITTEE ON SPACE RESEARCH

COSPAR is a scientific organization whose purpose is to "provide the world scientific community with the means whereby it may exploit the possibilities of satellites and space probes of all kinds for scientific purposes, and exchange the resulting data on a co-operative basis."[16] COSPAR promulgates guidelines from the international scientific community to assist national space agencies in developing their own policies and procedures.

NASA science and policy have, to date, provided the basis for practically all substantive COSPAR guidelines. For example, in 1963, on the basis of Space Studies Board (SSB)[17] studies and advice, NASA adopted planetary protection policies for the Moon, Mars, and Venus. COSPAR followed U.S. policy in 1964 and established an

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[14] The report analyzes the "regulatory gap" in U.S. law in Chapter 5.

[15] The report examines the planetary protection implications of human-crewed missions to Mars in Chapter 4 below.

[16] See, for example, A.W. Frutkin, *International Cooperation in Space*, Prentice-Hall, Englewood Cliffs, N.J., 1965, pp. 85-86.

[17] Prior to 1988, the Space Studies Board was known as the Space Science Board.

interim quantitative framework for developing planetary protection standards that set limits on the probabilities of carrying viable organisms aboard spacecraft to planetary bodies or producing accidental impacts.

In 1969, COSPAR replaced the interim framework adopted in 1964 with guidelines that prescribed limits on the probability that a planet would be contaminated during the so-called period of biological exploration.[18] Again, this decision reflected policies that NASA had recently adopted. Further following NASA's lead, in 1970, COSPAR issued a statement of policy specifically recommending that the "Jovian planets be treated with the same quarantine requirements (for flybys, orbiters or entry probes) as currently apply to Mars . . . until further information is available."[19] Clearly, NASA policy was the driving factor in the development of international cooperation and harmonized guidelines on planetary protection within COSPAR.

This pattern continued in more recent decades. In 1982, acting on the SSB's advice, NASA reviewed this quantitative policy and associated probabilistic approach to planetary protection requirements and implementation adopted in 1969 in light of new information obtained by planetary exploration and changes to, or uncertainties in, parameters used in the quantitative approach. On the basis of this review, NASA changed its policy and proposed that COSPAR adopt a new qualitative planetary protection policy. The new policy

- Established guidance for different combinations of target planet and mission type—i.e., orbiter, lander, etc. (see Table 2.1);
- Placed sample return missions in a separate category;
- Simplified documentation procedures; and
- Recommended implementing procedures (e.g., trajectory biasing, cleanroom assembly, spacecraft sterilization, etc.) if the planet–mission combination warranted such measures.

Similarly, NASA proposed the new planetary protection policy to COSPAR, and COSPAR adopted it in 1984 by amending its existing planetary protection guidelines by replacing "the basic probability of one in one thousand that a planet of biological interest will be contaminated shall be used as the guiding criterion during the period of biological exploration" with the mission/target categorization scheme outlined in Table 2.1.[20,21]

Again based on NASA input, COSPAR made the following changes to its planetary protection guidelines:

- In 1994, COSPAR amended the 1984 policy to include refinements of the Mars guidance.
- In 2002, COSPAR further refined these Mars recommendations and included guidance for the outer planets and icy moons and sample return missions.
- In 2008, COSPAR added explicit recommendations for individual target bodies and guidelines for human missions to Mars.
- In 2017, COSPAR updated the definition of Special Regions on Mars.

Finding: For five decades, the states parties to the OST have used COSPAR policy as part of complying with their planetary protection obligations under the treaty and, thus, have made COSPAR interdependent with their respective national rules, institutions, and processes on planetary protection.

Finding: All spacefaring nations, including new entrants to space exploration, have declared they will comply with COSPAR guidance on planetary protection. Such commitment highlights the importance of the COSPAR planetary policy development process to the behavior of spacefaring nations, including state party efforts to comply with their planetary policy obligations in the OST.

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[18] COSPAR, COSPAR Decision No. 16, *COSPAR Information Bulletin*, No. 50, pp. 15-16, 1969.
[19] COSPAR, COSPAR Decision No. 14, *COSPAR Information Bulletin*, No. 54, p. 12, 1970.
[20] COSPAR, COSPAR Internal Decision No. 7/84, Promulgated by COSPAR Letter 84/692-5.12.-G, July 18, 1984.
[21] See, also, D.L. DeVincenzi, P.D. Stabekis, and J. Barengoltz, Refinement of planetary protection policy for Mars missions, *Advances in Space Research* 18:314, 1994.

TABLE 2.1 Mission Type Categories as Specified in COSPAR's Planetary Protection Policy

Mission Category	Mission Type	Planetary Bodies	Planetary Protection Requirements (Illustrative Examples)
I	Any	Bodies not of direct interest for understanding the process of chemical evolution or the origin of life (e.g., undifferentiated, metamorphosed asteroids, and others [to be determined]).	None.
II	Any	Bodies of significant interest relative to the process of chemical evolution and origin of life, but only a remote chance that contamination could compromise future investigations (e.g., comets, carbonaceous chondrite asteroids, outer solar system planets, Venus, the Moon, icy bodies of the outer solar system [note 1] and others [to be determined]).	Brief documentation only (except for missions to the Moon, which also require an inventory of all organic compounds present in excess of 1 kg).
III	Flyby, orbiter (no direct contact)	Bodies of significant interest to the process of chemical evolution and/or origin of life and where scientific opinion provides a significant chance that contamination could compromise future investigations (e.g., Mars [note 2], Europa, Enceladus, and others [to be determined]).	Documentation on contamination control and organics inventory, plus trajectory biasing, cleanroom assembly, bioload reduction.
IV	Lander, probe (direct contact)	Bodies of significant interest to the process of chemical evolution and/or origin of life and where scientific opinion provides a significant chance that contamination could compromise future investigations. (e.g., Mars [note 3], Europa, Enceladus, and others [to be determined]).	Documentation (as for Category III) plus microbial reduction plan; Category III procedures plus partial sterilization and bioassay monitoring.
V (unrestricted)	Earth return after contact with another body	Earth-return missions from bodies deemed by scientific opinion to have no indigenous life forms (e.g., Venus, Moon, and others [to be determined]).	None except for requirements for category above for outbound phase.
V (restricted)	Earth return after contact with another body	Earth-return missions from bodies deemed by scientific opinion to be of significant interest to the process of chemical evolution and/or origin of life (Mars, Europa, and others [to be determined]).	Same as for Category IV plus sterile or contained returned hardware and continual monitoring of project activities.

Note 1 Missions to Ganymede, Titan, Triton, Pluto/Charon, and Kuiper belt objects greater than half the diameter of Pluto can be assigned to Category II if they demonstrate by analysis their "remote potential for contamination of the liquid water environments that may exist beneath their surfaces (a probability of introducing a single viable terrestrial organism of $<1 \times 10^{-4}$) addressing both the existence of such environments and the prospects of accessing them."

Note 2 Mars orbiters are required to meet an orbital lifetime requirement (20 or 50 years after launch with a probability $\geq$0.99 or 0.95, respectively. Lifetime requirements are not required if the orbiter meets a total bioburden level of $\leq$500,000 spores.

Note 3 Category IV missions to Mars are subdivided into IVa, IVb, and IVc. Category IVa missions—i.e., those not carrying instruments designed to investigate extant martian life—are restricted to a surface bioburden of $\leq$300,000 spores, and an average of $\leq$300 spores m^{-2}. Category IVb missions—i.e., those carrying instruments designed to investigate extant martian life—must meet Category IVa requirements plus: "the entire landed system is restricted to a surface bioburden of $\leq$30 spores [note 4] or to levels of bioburden reduction driven by the nature and sensitivity of the particular life-detection system"; or "the subsystems which are involved in the acquisition, delivery, and analysis of samples used for life detection must be sterilized to these levels, and a method of preventing recontamination of the sterilized subsystem and the containment of the material to be analyzed is in place." Category IVc missions—i.e., those accessing special regions on Mars, even if not carrying life detection instrument—must meet Category IVa requirements plus: "if the landing site is within the special region, the entire landed system is restricted to a surface bioburden level of $\leq$30 spores (note 4)"; or "if the special region is accessed through horizontal or vertical mobility, either the entire landed system is restricted to a surface bioburden level of $\leq$30 spores (note 4), or the subsystems which directly contact the special region shall be sterilized to these levels, and a method of preventing their recontamination prior to accessing the special region shall be provided."

Note 4 The 30 spore limit "takes into account the occurrence of hardy organisms with respect to the sterilization modality. This specification assumes attainment of Category IVa surface cleanliness, followed by at least a four order-of-magnitude reduction in viable organisms. Verification of bioburden level is based on pre-sterilization bioburden assessment and knowledge of reduction factor of the sterilization modality."

NOTE: The table also shows examples of the solar system bodies assigned to each category and the corresponding principal planetary protection requirements. Note that the table does not incorporate all of the nuances of current planetary protection policy for Category III and IV missions to Europa and Enceladus or Category V missions to Mars, Europa, Enceladus or small solar system bodies.
SOURCE: Data from G. Kminek, C. Conley, V. Hipkin, and H. Yano, "COSPAR Planetary Protection Policy," *Space Research Today*, No. 200, December 2017, pp. 12-24.

THE NATIONAL ACADEMIES AND PLANETARY PROTECTION

The National Academies have been intimately involved in the development of planetary protection policies since the late 1950s, and the SSB has been NASA's principal source of independent, multidisciplinary advice on planetary protection issues (see Figure 2.1).

The Early Years of the Space Age

On August 2, 1958, the NAS announced the establishment of the SSB in response to a joint request from the National Science Foundation (NSF), the National Advisory Committee for Aeronautics, and the Advanced Research Projects Agency. One of the tasks given to the SSB was to cooperate with ICSU and other international organizations on "the prevention of undesirable and unnecessary contamination of Moon and planet surfaces and atmospheres with alien particles of energy and matter introduced from Earth by space vehicles."[22] In the latter part of 1958, the SSB endorsed the activities and initial recommendations of CETEX and began the task of securing the support and cooperation of relevant federal agencies to implement contamination control protocols. SSB recommendations formed the basis of the NAS response to ICSU. At about the same time, the SSB established the East Coast group of the Panel on Extraterrestrial Life (EASTEX) as a forum for the discussion of issues concerning the detection of extraterrestrial life and the biological contamination of planetary environments. A parallel West Coast group (WESTEX), under the leadership of Joshua Lederberg, was subsequently established and concentrated its efforts on the requirements for spacecraft sterilization. WESTEX issued its first recommendations to NASA that "an immediate study program be initiated to determine sterilization requirements and to develop recommendations compatible with present design and assembly processes."[23]

Lederberg and his much more junior WESTEX colleague Carl Sagan "advocated that a high priority be placed on preventing planetary probes from carrying terrestrial contamination into space, and nearly as high a priority on the prevention of back contamination from sample return missions."[24] Both argued that these priorities be official SSB policy and that they be adopted by COSPAR. However, at least one member of WESTEX argued strongly that concerns about back contamination were overblown. In fact, it was argued that the risks associated with the introduction of extraterrestrial pathogens into the terrestrial environment were minor compared to the "potential benefits to mankind of unhampered traffic with the planets."[25]

The Lederberg-Sagan viewpoint prevailed, and the twin objectives of planetary protection—protecting extraterrestrial environments from biological contamination that might preclude future scientific activities and protecting Earth's environment and its inhabitants from potentially harmful extraterrestrial contamination—eventually became enshrined in SSB, NASA, and COSPAR policies.

The Middle Years of Planetary Protection

In the period between the early 1960s and the late 1980s, the SSB and its various committees drafted some dozen reports for NASA on various aspects of planetary protection policy. Many of the reports issued in this period were concerned with the estimation of key numerical parameters—particularly P_g, the probability of growth—appearing in the probabilistic equations providing the requirements flowing from planetary protection policies

[22] National Research Council (NRC), "National Academy of Sciences Establishes Space Science Board," press release, August 3, 1958.
[23] September 14, 1959.
[24] Meltzer, p. 35.
[25] Norman Horowitz letter to Joshua Lederberg, January 20, 1960, quoted in Meltzer, p. 36.

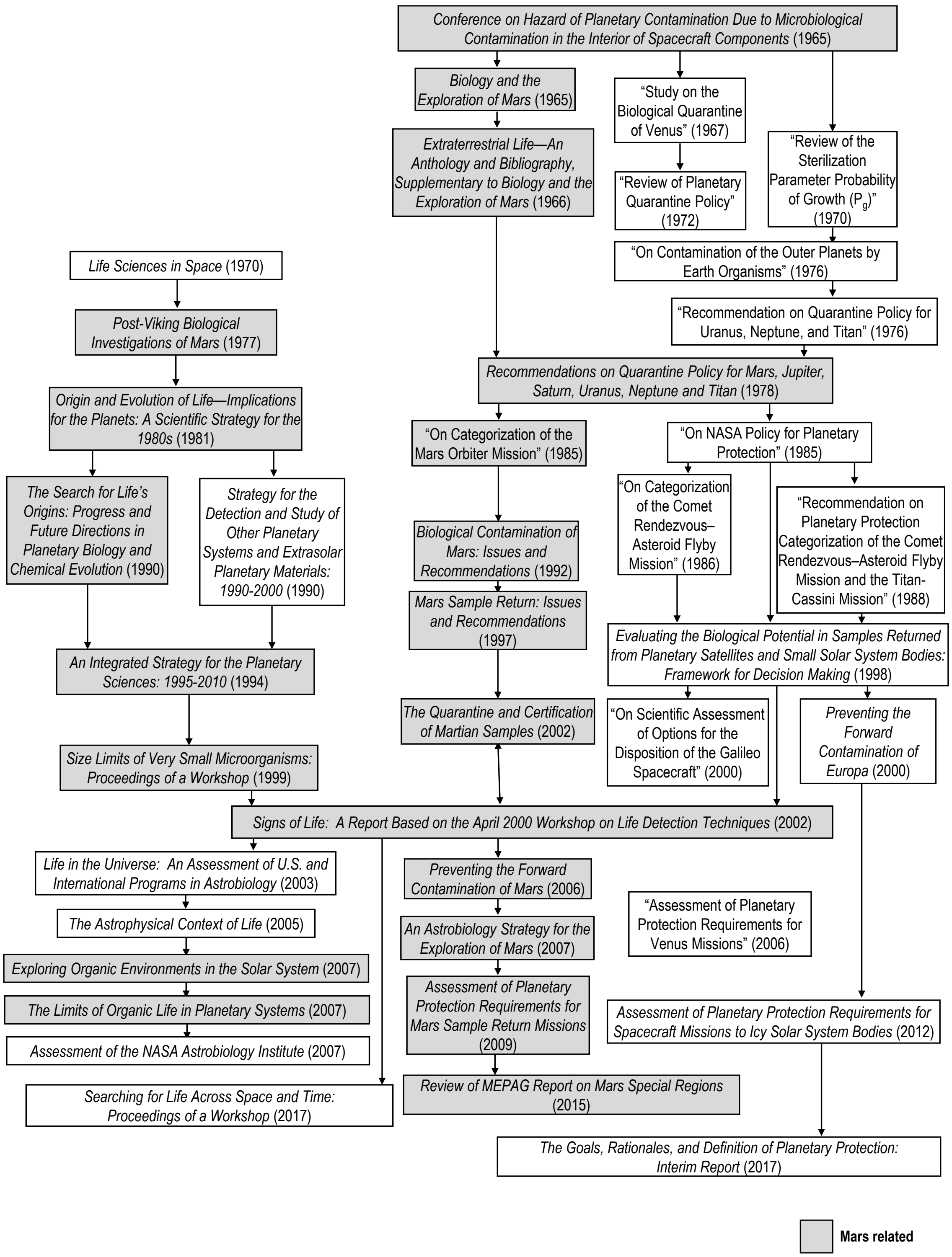

FIGURE 2.1 A graphical summary of all reports issued by the Space Studies Board (formerly the Space Science Board) in the general areas of exobiology, astrobiology, and planetary protection. SOURCE: National Academies of Sciences, Engineering, and Medicine, *Space Studies Board Annual Report 2016*, The National Academies Press, Washington, D.C., 2017.

in vogue during that period.[26,27,28] As NASA spacecraft ventured into new parts of the solar system and/or new information was received from ongoing missions, the SSB would propose new values for key numerical factors on the basis of the latest scientific understanding. Thus, the chronological listing of these reports (see Figure 2.1) reflects the penetration of NASA spacecraft beyond the Moon, to Mars and Venus, in support of the Mariner and Viking missions, and out into the outer solar system in preparation for the flights of Pioneers 10 and 11 and Voyagers 1 and 2.

SSB studies focusing on the estimation of numerical factors effectively ceased when the requirements flowing from contemporary planetary protection policies evolved from a quantitative to a qualitative standard based on target-body mission-type characteristics in 1984.[29] Thereafter, the focus of the SSB's planetary protection studies changed to providing advice to NASA on the appropriate characterization of specific missions. Only three such studies were conducted by the SSB in the 1980s: for the Mars Orbiter mission in 1985,[30] the Comet Rendezvous–Asteroid Flyby (CRAF) in 1986,[31] and CRAF and Cassini-Huygens in 1988,[32] reflecting the post-Viking slowdown in the pace of solar system exploration activities.

The SSB's Planetary Protection Activities in the Recent Past

The number of requests from NASA for input on planetary protection issues began to accelerate in the early 1990s and has continued unabated to the present time. In addition, the complexity of the requested study topics has followed a similar trajectory. The change in pace and scope can be attributed to the following five factors:

- The post-Viking doldrums were over. NASA's planetary science budget began to rise virtually monotonically.
- New, more numerous, smaller, and lower-cost missions began to appear as part of NASA's Discovery program adding a quantity of projects that had to fit planetary protection requirements into very tight cost caps.
- The nature of the missions planned became more complex. The era of flyby probes and simple orbiters was over. The new types of spacecraft—landers, rovers, and sample return missions—posed planetary protection challenges not previously addressed.
- Plans for missions to new planetary environments—asteroids, comets, the giant planets and their icy satellites—not covered by planetary protection guidelines, began to appear.
- International cooperation became more common. U.S.-provided payloads on foreign spacecraft and foreign instruments on NASA missions posed unique planetary protection issues.
- Planetary protection became more controversial. The implementation of requirements derived from long-standing planetary protection policies began to conflict, or appear to conflict, with the legitimate scientific aspirations of the scientific community.

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[26] C. Sagan and S. Coleman, Spacecraft sterilization standards and contamination of Mars, *Journal of Astronautics and Aeronautics* 3(5):22-27, 1965.

[27] C. Sagan and S. Coleman, "Decontamination Standards for Martian Exploration Programs," pp. 470-481 in NRC, *Biology and the Exploration of Mars*, National Academy Sciences, Washington, D.C., 1966.

[28] S. Schalkowski and R.C. Kline, Jr., "Analytical Basis for Planetary Quarantine," pp. 9-26 in *Planetary Quarantine* (L.B. Hall, ed.), Gordon and Breach, London, U.K., 1971.

[29] D.L. DeVincenzi, P.D. Stabekis, and J. Barengoltz, Refinement of planetary protection policy for Mars missions, *Advances in Space Research* 18:314, 1994.

[30] NRC, "On the Categorization of the Mars Orbiter Mission," letter from Harold Klein, Chair, Committee on Planetary Biology and Chemical Evolution, to Arnauld Nicogossian, Director, NASA Life Sciences Division, June 6, 1985.

[31] NRC, "On the Categorization of the Comet Rendezvous–Asteroid Flyby Mission," letter from Harold Klein, Chair, Committee on Planetary Biology and Chemical Evolution, to Arnauld Nicogossian, Director, NASA Life Sciences Division, May 16, 1986.

[32] NRC, "Recommendation on Planetary Protection Categorization of the Comet Rendezvous-Asteroid Flyby Mission and the Titan-Cassini Mission," letter from Harold Klein, Chair, Committee on Planetary Biology and Chemical Evolution, to John Rummel, Chief, NASA Planetary Quarantine Program, July 6, 1988.

The key planetary protection issues addressed by the SSB during the last couple of decades are as follows:

- Mars forward contamination,
- Mars sample return and backward contamination,
- Sample return for small solar system bodies, and
- Exploration of the icy bodies of the outer solar system.

The subsequent sections briefly describe the relevant issues addressed and the SSB's recommendations.

Mars Forward Contamination

In 1990, NASA commissioned the SSB to examine policy issues relating to the forward contamination of Mars in light of the most recent findings in the planetary and life sciences. The committee's report recommended that Viking-level bioload-reduction procedures—that is, a 10^{-5} reduction in the spacecraft's bioload beyond that achievable by standard cleaning techniques such as swabbing with alcohol—be used only on landed spacecraft carrying life detection experiments.[33] Swabbing or other cleaning techniques would suffice for all other landers. The report's recommendation was accepted by NASA and subsequently was incorporated into COSPAR policy: Specifically, Category IV missions (see Table 2.1) were divided into two subcategories—IVa (landers without life detection instruments) and IVb (landers with life detection instruments).

Issues relating to the forward contamination of Mars were revisited by the SSB more than a decade later when NASA requested that the 1992 report be updated in light of recent scientific advances and the introduction of the concept of Special Regions on Mars—that is, areas where terrestrial organisms might survive or where indigenous life might exist—by COSPAR. The SSB's 2006 report recommended that because then current understanding of the martian environment was insufficient to distinguish Special and Non-Special Regions, all of Mars should be treated as a Special Region until proven otherwise.[34]

One potential outcome of the SSB 2006 recommendation on Special Regions was that its implementation would effectively undo the relaxation of planetary protection policies for Mars landers initiated by the 1992 report. Another potential outcome was that NASA and COSPAR needed to define a Special Region more explicitly than was the case in 2005 to 2006. The latter option was taken and resulted in a series of additional activities on the part of NASA, COSPAR, and a recent joint study by the SSB and the European Science Foundation.[35] Details of the latter activities concerning Special Regions and their associated planetary protection concerns can be found in Appendix B. Spacecraft intending to enter Special Regions receive a mission categorization of IVc (see Table 2.1).

Mars Sample Return and Backward Contamination

As the exploration of Mars resumed in earnest in the latter half of the 1990s, planning began for executing the long-standing goal of returning samples collected on the surface of Mars to Earth for study. NASA commissioned the SSB to address the planetary protection implications of sample return in the context of the then-current scientific understanding of the prospects for indigenous life on Mars and its potential to cause harm to Earth's biosphere. A 1997 report addressing these issues recommended that any samples returned to Earth be strictly contained and that any release from containment be contingent on the results of a biohazard assessment.[36] The report's recommendations were accepted by NASA and subsequently were incorporated into COSPAR policy.

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[33] NRC, *Biological Contamination of Mars*, National Academy Press, Washington, D.C., 1992.

[34] NRC, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C., 2006.

[35] NASEM and the European Science Foundation, *Review of the MEPAG Report on Mars Special Regions*, The National Academies Press, Washington, D.C., 2015.

[36] NRC, *Mars Sample Return Issues and Recommendations*, National Academy Press, Washington, D.C., 1997.

Subsequently, the specifics of the biohazard assessment were addressed in a series of workshops sponsored by NASA.[37] The details of the containment facility within which the initial studies of martian samples would be conducted were the subject of a 2002 SSB report.[38] However, budgetary and technical issues precluded the launch of a Mars sample return mission in the early 2000s.

In 2008, as part of a developing trend to revisit policy recommendations on major planetary protection issues at least once per decade, NASA asked the SSB to revisit the 1997 sample return report. The resulting study, issued in 2009, gave a nuanced endorsement of the recommendations made a decade earlier.[39]

Sample Return for Small Solar System Bodies

Soon after the SSB's 1997 report on back contamination from Mars, NASA requested that a new SSB study be initiated to "extend current advice on Mars to other small solar system bodies."[40] The study committee assessed the potential for living entities to be present in samples returned to Earth from a variety of different small bodies, including satellites, comets, and asteroids. They also compared the potential risk of returning samples via spacecraft to that inherent in the natural influx of similar materials to Earth in the form of, for example, meteorites. By considering how its assessment of the biological potential of different bodies varied according to their respective environmental conditions, the committee devised a novel approach to gauging concerns about back contamination. Environmental factors—such as the presence of organic matter, liquid water, or sterilizing radiation—pertaining to a specific body can be assembled in a decision tree to determine whether or not samples returned from it be classified as restricted Earth return (i.e., subject to strict containment).[41] This approach was very well received, and it is now incorporated in both NASA and COSPAR policies.

Exploration of the Ocean Worlds of the Outer Solar System

The discovery in the mid-1990s of evidence that Jupiter's moon Europa harbors an ocean of liquid water beneath its icy surface prompted the formulation of plans for robotic missions to study this unique aquatic environment and also how it might be protected from contamination by those selfsame spacecraft. NASA requested that the SSB initiate a study on forward contamination issues as they related to Europa. The study committee was unable to reach consensus on a scheme to extend to Europa the qualitative planetary protection approach used for Mars missions. The committee's report recommended, with two dissenting opinions, that a quantitative approach be adopted for Europa.[42] The recommended approach was retrograde in that it represented a return to a methodology that had already been abandoned for other solar system bodies. Nevertheless, NASA accepted the committee's recommended approach, and it was subsequently incorporated into COSPAR policy. Indeed, the numerical methodology was subsequently extended to cover other icy solar system bodies.

In keeping with the policy of revisiting major planetary protection recommendations on a quasi-decennial timescale, NASA requested in 2011 that the SSB reassess the 2000 Europa report's recommended methodology and its applicability to the other icy satellites of the outer solar system. Such a revisit was appropriate because of increased scientific understanding of Europa and related bodies and by lingering concern that the quantitative approach now incorporated in NASA and COSPAR policy was both cumbersome and arbitrary. The study committee rapidly agreed that the existing approach was not scientifically defensible. In its place, the committee

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[37] See, for example, J.D. Rummel, M.S. Race, D.L. DeVincenzi, P.J. Schad, P.D. Stabekis, M. Viso, and S.E. Acevedo, eds., *A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth*, NASA/CP-20-02-211842, NASA Ames Research Center, Moffett Field, Calif., 2002, and references therein, https://planetaryprotection.nasa.gov/summary/DraftTestProtocol.

[38] NRC, *The Curation and Certification of Martian Samples*, The National Academies Press, Washington, D.C., 2002.

[39] NRC, *Assessment of Planetary Protection Requirements for Mars Sample Return Missions*, The National Academies Press, Washington, D.C., 2009.

[40] Letter to Claud Canizares, Chair, Space Studies Board, from Wesley T. Huntress, Jr., Associate Administrator for Space Science, NASA, May 5, 1997.

[41] NRC, *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making*, National Academy Press, Washington, D.C., 1998.

[42] NRC, *Preventing the Forward Contamination of Europa*, National Academy Press, Washington, D.C., 2000.

recommended that a decision-tree methodology should be adopted.[43] The suggested decision tree was conceptually similar to the one already incorporated in COSPAR policy for determining whether or not samples returned from small solar system bodies be categorized as restricted or unrestricted Earth return. Despite the simplicity of the decision-tree approach and its precedents in existing COSPAR policies, NASA and COSPAR did not adopt the methodology. NASA's failure to provide a formal, written response to the SSB's 2012 report precluded any definitive discussion of its perceived deficiencies.

NASA POLICY

Planetary Protection Policy Development Within NASA

NASA's involvement in planetary protection began in earnest soon after it was established. In response to the SSB's September 1959 recommendation to adhere to the ICSU policy and to sterilize U.S. space probes,[44] NASA issued an initial planetary protection guideline to all NASA field centers on October 15, 1959.[45]

At that time, scientific opinion about the Moon harboring extraterrestrial life was divided. If ice or water was beneath the lunar surface, then microorganisms, insulated by the material above, might exist there. On that chance, NASA Headquarters officials included lunar spacecraft under the terms of the 1959 directive.

First in line for application of the NASA sterilization policy were the robotic Ranger lunar hard-lander spacecraft. The first two Rangers (in 1961) were test vehicles, primarily designed to test the flight system, and as such were not sterilized.[46]

Sterilization was implemented beginning with Ranger 3. All components, including the lunar capsule subsystem components, were subjected to heating at 125°C for 24 hours. When Rangers 3, 4, and 5 each experienced a series of failures in 1962, NASA established a board of inquiry that found problems with the quality and reliability assurance program. Recommendations of the board, including abandoning heat sterilization, were implemented for the last four Ranger flights in 1964 and 1965, all of which were successful. Although subsequent robotic missions to the Moon in the Surveyor and Lunar Orbiter programs were not subject to heat sterilization, they did provide important information about sources and mechanisms of contamination. Microbial assays conducted at various stages during spacecraft assembly and transportation to the launch site revealed, for example, that shipping containers and spacecraft shrouds were important sources of microbial contamination.[47]

NASA established the Office of Planetary Quarantine in 1963.[48] In the same year, on the basis of extensive studies and the advice of the SSB, NASA adopted the following policy regarding the Moon, Mars, and Venus:

> Lunar spacecraft will reduce their microbial load to a "minimum" through the use of assembly and check out in clean rooms and the application of surface sterilants after final assembly and check out; Mars flights will have less than 10^{-4} probability of hitting the planet, while landers would be sterilized after complete assembly and check out, using appropriate procedures and sealed units that would not be open; Venus flights will have less than 10^{-2} probability of hitting the planet.[49]

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[43] NRC, *Assessment of Planetary Protection Requirements for Spacecraft Missions to the Icy Solar System Bodies*, The National Academies Press, Washington, D.C., 2012.

[44] NRC, "Space Probe Sterilization," letter from Hugh Odishaw, Executive Director, Space Science Board, to T. Keith Glennan, Administrator, NASA, and Roy Johnson, Director, Advance Research Projects Agency, September 14, 1959.

[45] Abe Silverstein, "Sterilization of Payloads," memorandum for director, Goddard Space Flight Center, October 15, 1959, folder 006696, "Sterilization/Decontamination," NASA Historical Reference Collection.

[46] However, as part of the test program, the Ranger 1 battery was exposed to the planned heat sterilization temperature profile with disastrous results. A week later, with the battery installed in the spacecraft, the battery erupted, spewing electrolyte all over the entire inside of the spacecraft. The temperature profile was modified and a new heat-treated battery was installed with similar results. Following that, there were no more attempts in the Ranger program to heat-sterilize batteries.

[47] M. Meltzer, *When Biospheres Collide: A History of NASA's Planetary Protection Programs*, NASA SP-2011-4234, U.S. Government Printing Office, Washington, D.C., 2011, p. 98.

[48] The office's name was changed to Planetary Protection in 1976.

[49] NASA, Unmanned Spacecraft Decontamination Policy, NMI-4-4-1, NASA, Washington, D.C., September 9, 1963, https://archive.org/stream/nasa_techdoc_19700073941/19700073941_djvu.txt.

Following the experience with the Rangers and in preparation for the Viking missions to Mars, NASA conducted a comprehensive research program to develop a dry-heat process that could effectively sterilize spacecraft systems. Additionally, the Viking project successfully executed a component selection and qualification process along with a comprehensive testing program to implement safely dry-heat system sterilization, and Viking subsequently landed on Mars in 1976.[50]

In 1982, NASA, acting on advice by the SSB, completed an effort to change planetary protection policy drastically. The current policy places substantive planetary protection controls only on missions to bodies where there is evidence of indigenous water or other unique chemistry that could support the evolution of life.[51] For the near-term future, this means only Mars, Europa, or Enceladus.

Institutional Developments Within NASA

Planetary protection responsibilities were located within various organizational niches within NASA throughout the period 1963 to 1991. However, in 1992 NASA created the Office of Planetary Protection (OPP) within what was then called the Solar System Exploration Division, and this arrangement effectively survived until 2018. However, unlike many of NASA's other scientific activities, planetary protection did not have an internal advisory process (equivalent to other standing committees of the NASA Advisory Council) until the late 1990s.

In 1997, the SSB recommended that NASA create an external advisory committee for planetary protection to integrate the latest scientific knowledge and to involve a broader set of federal agency and international stakeholders. The report noted the following:

> Although NASA is the lead agency on matters pertaining to the exploration of space and extraterrestrial bodies, other federal agencies, such as the U.S. Department of Agriculture, may have a regulatory interest in the return of samples from Mars or other solar system objects. To coordinate regulatory and other oversight responsibilities, NASA should establish a panel analogous to the Interagency Committee on Back Contamination that coordinated regulatory and oversight activities during the lunar sample-return missions. To be effective, planetary protection measures should be integrated into the engineering and design of any sample-return mission, and, for an oversight panel to be in a position to coordinate the implementation of planetary protection requirements, it should be established as soon as serious planning for a Mars sample-return mission has begun.[52]

After a NASA task force reiterated the need for this type of committee, the Planetary Protection Advisory Committee (PPAC) was formed in 2000 under the aegis of the NASA Advisory Council (NAC). The PPAC's membership included scientists, representatives from other federal agencies (e.g., Department of Agriculture, Department of Health and Human Services, Environmental Protection Agency, and Federal Aviation Administration), and international representatives (e.g., from the European Space Agency and the Japan Aerospace Exploration Agency). The committee did not include representatives from the commercial space industry, because at that time private-sector entities were not conducting space activities with planetary protection implications.

PPAC's charge was to advise the OPP, review proposed missions at an early stage, and assign a planetary protection category to them. The OPP then informed the mission team as to the necessary planetary protection requirements to be met. In 2006, the NAC was reorganized and the scientists then serving on the Council, including the chair of PPAC, were removed. The PPAC became a subcommittee under the NAC's Science Committee. This change caused concern among the PPAC members because, by being subordinated under a committee that focused on the science missions, the new planetary protection subcommittee lacked the level of independence necessary for effective planetary protection. During this period, neither the PPAC nor the Planetary Protection Subcommittee received the attention needed for renewing and refreshing the membership. This problem was particularly evident

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[50] The Viking experience is discussed in detail in Chapter 4.

[51] G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December 2017, pp. 12-24.

[52] NRC, *Mars Sample Return: Issues and Recommendations*, National Academy Press, Washington, D.C., 1997, p. 6.

in the reduced participation of federal agencies and other national space agencies. By 2016, the committee had become completely moribund, and it was formally disbanded in late 2017.

HISTORICAL CASE STUDIES

The Apollo Experience

When the Apollo program began, discussions on forward and backward contamination were already beginning to formalize at NASA and other organizations. In the late 1950s, the NAS, NSF, and the American Institute of Biological Sciences began discussions on spacecraft sterilization for forward contamination, while WESTEX was addressing how to protect the exploration of and preservation of planetary surfaces.[53]

The "National Security Action Memo (NSAM235): Large Scale Scientific or Technological Experiments with Possible Adverse Environmental Effects" was signed and went into effect on April 17, 1963. The policy required that

> The head of any agency that proposes to undertake a large-scale scientific or technological experiment that might have significant or protracted effects on the physical or biological environment will call such proposals to the attention of the Special Assistant to the President for Science and Technology. Notification of such experiments will be given sufficiently in advance that they may be modified, postponed, or cancelled, if such action is judged necessary in the national interest.[54]

NSAM No. 235 ensured that relevant agencies were following an approval process that would provide for the safety of the United States. The process generally includes the following three steps:[55]

1. The sponsoring agency notifies the Special Assistant to the President for Science and Technology with a "detailed evaluation of the importance of the particular experiment and the possible direct or indirect effects that might be associated with it";
2. The Special Assistant reviews the material provided by the sponsoring agency and makes a recommendation to the President; and
3. Based on the recommendation, if there is not enough information available to make a decision, then the Special Assistant may request additional studies be conducted from organizations such as the NAS, international scientific bodies, and intergovernmental organizations.

In parallel with the NSAM No. 235, the Interagency Committee on Back Contamination (ICBC) was created in 1967 to serve in an advising capacity with the mission to[56,57]

[53] B. Pugel. "Restricted by Whom? A Historical Review of Strategies and Organization for Restricted Earth Return of Samples from NASA Planetary Missions," presentation to the Committee on Planetary Protection Policy Development Processes, Space Studies Board, National Academy of Sciences, July 2017, Slide 29.

[54] J.F. Kennedy, "National Security Action Memoranda (NSAM 235): Large-Scale Scientific or Technological Experiments with Possible Adverse Environmental Effects," Papers of John F. Kennedy, Presidential Papers, National Security Files, Meetings and Memoranda, JFKNSF-340-023, John F. Kennedy Presidential Library and Museum, https://www.jfklibrary.org/Asset-Viewer/Archives/JFKNSF-340-023.aspx.

[55] J.F. Kennedy, "National Security Action Memoranda (NSAM 235): Large-Scale Scientific or Technological Experiments with Possible Adverse Environmental Effects," Papers of John F. Kennedy, Presidential Papers, National Security Files, Meetings and Memoranda, JFKNSF-340-023, John F. Kennedy Presidential Library and Museum, https://www.jfklibrary.org/Asset-Viewer/Archives/JFKNSF-340-023.aspx; B. Pugel, "Restricted by Whom? A Historical Review of Strategies and Organization for Restricted Earth Return of Samples from NASA Planetary Missions," presentation to the Committee on Planetary Protection Policy Development Processes, Space Studies Board, National Academy of Sciences, July 2017, Slide 14.

[56] NASA History Office, "The Lunar Quarantine Program," Chapter 1 in *Biomedical Results of Apollo*, Section V Quarantine, SP-368, https://history.nasa.gov/SP-368/s5ch1.htm.

[57] See, for example, J.R. Bagby, Jr., *Back Contamination: Lessons Learned During the Apollo Lunar Quarantine Program*, prepared for the Jet Propulsion Laboratory under Contract #560226, July 1, 1975.

- To protect the public's health, agriculture, and other living resources;
- To protect the integrity of the lunar samples and the scientific experiments; and
- To ensure that the operational aspects of the program were least compromised.

The ICBC was comprised of 12 members from six government agencies and other organizations, including the following: NASA (six members), Public Health Service (two members), Department of Agriculture (one member), Department of Commerce (one member), Department of the Interior (one member), and NAS (one member).[58]

The formalization of lunar quarantine protocols developed during the 1960s and began when the NAS advised NASA to create an interagency committee to handle the fast-paced emergence of interplanetary exploration in 1960. Five years later, the SSB had already convened the first meeting between government agencies on backward contamination, and NASA was establishing interagency liaison tools to facilitate the establishment of rules and procedures for back-contamination control. In 1966, the ICBC began meeting and 1 year later produced "MSCI 8030.1—Management Instruction: Assignment of Responsibility for Prevention of Contamination of Biosphere by Extraterrestrial Life."[59]

Planetary protection protocols distinguish between restricted and unrestricted Earth return. Restricted Earth return applied to Apollo missions 11 (1969), 12 (1969), and 14 (1971), where astronauts, laboratory team members, and other relevant staff were quarantined (see Figure 2.2). Although these missions occurred before Biosafety Levels (BSLs) were standardized,[60] the Lunar Receiving Facility treated them as BSL-3/BSL-4. Unrestricted Earth return occurred for all missions after Apollo 14. During the lunar quarantine process, out of the total mass of lunar samples returned by the Apollo missions, 25 percent were returned under quarantine protocols.[61]

After the completion of Apollo 11 and Apollo 12, the ICBC reviewed the quarantine procedures in January 1970. The primary concern was whether quarantine procedures be continued for crewmembers, while biological examination of the returned lunar samples would continue to assure integrity of the sample. The following month, the SSB advised that the quarantine policy continue to be followed. After the Apollo 14 mission in January 1971, lunar quarantine was discontinued.[62]

Early Soviet Mars Missions

The former Soviet Union conducted many unsuccessful Mars missions during the 1960s and 1970s. The missions of Mars 1 (1962) and Mars 2 and 3 (1971) are of particular interest to understanding the implementation of planetary protection policies. Soviet planetary protection protocols were believed to have largely differed from then-applicable U.S. procedure and included a combination of heat, radiation, and gaseous techniques, depending on the nature of the materials being sterilized.[63]

Mars 1 was a flyby mission, while Mars 2 and 3 were orbiter-lander combinations. The Mars 1 mission was set to take photographs of the martian surface and successfully collected data in interplanetary space while in transit but lost contact with the spacecraft prior to its Mars flyby. The lander portion of Mars 2 was equally unsuccessful, and it crashed onto the martian surface in late-November 2017. However, the lander of its twin, Mars 3 (see Figure 2.3), did succeed in landing on the Red Planet early the following month. Unfortunately, radio contact with the lander was lost 20 seconds after touchdown. According to Soviet scientists, life detection instruments were

[58] B. Pugel. "Restricted by Whom? A Historical Review of Strategies and Organization for Restricted Earth Return of Samples from NASA Planetary Missions," presentation to the Committee on Planetary Protection Policy Development Processes, Space Studies Board, National Academy of Sciences, July 2017, Slide 5.

[59] Ibid., Slide 13.

[60] BSLs are a set of precautions for containment of dangerous biological agents in enclosed laboratories. The levels range from 1 (least strenuous) to 4 (most demanding).

[61] B. Pugel. "Restricted by Whom? A Historical Review of Strategies and Organization for Restricted Earth Return of Samples from NASA Planetary Missions," presentation to the Committee on Planetary Protection Policy Development Processes, Space Studies Board, National Academy of Sciences, July 2017, Slide 9.

[62] Ibid., Slide 14.

[63] B.C. Murray, M.E. Davies, and P.K. Eckman, Planetary contamination II: Soviet and U.S. practices and policies, *Science* 155:1505-1511, 1967.

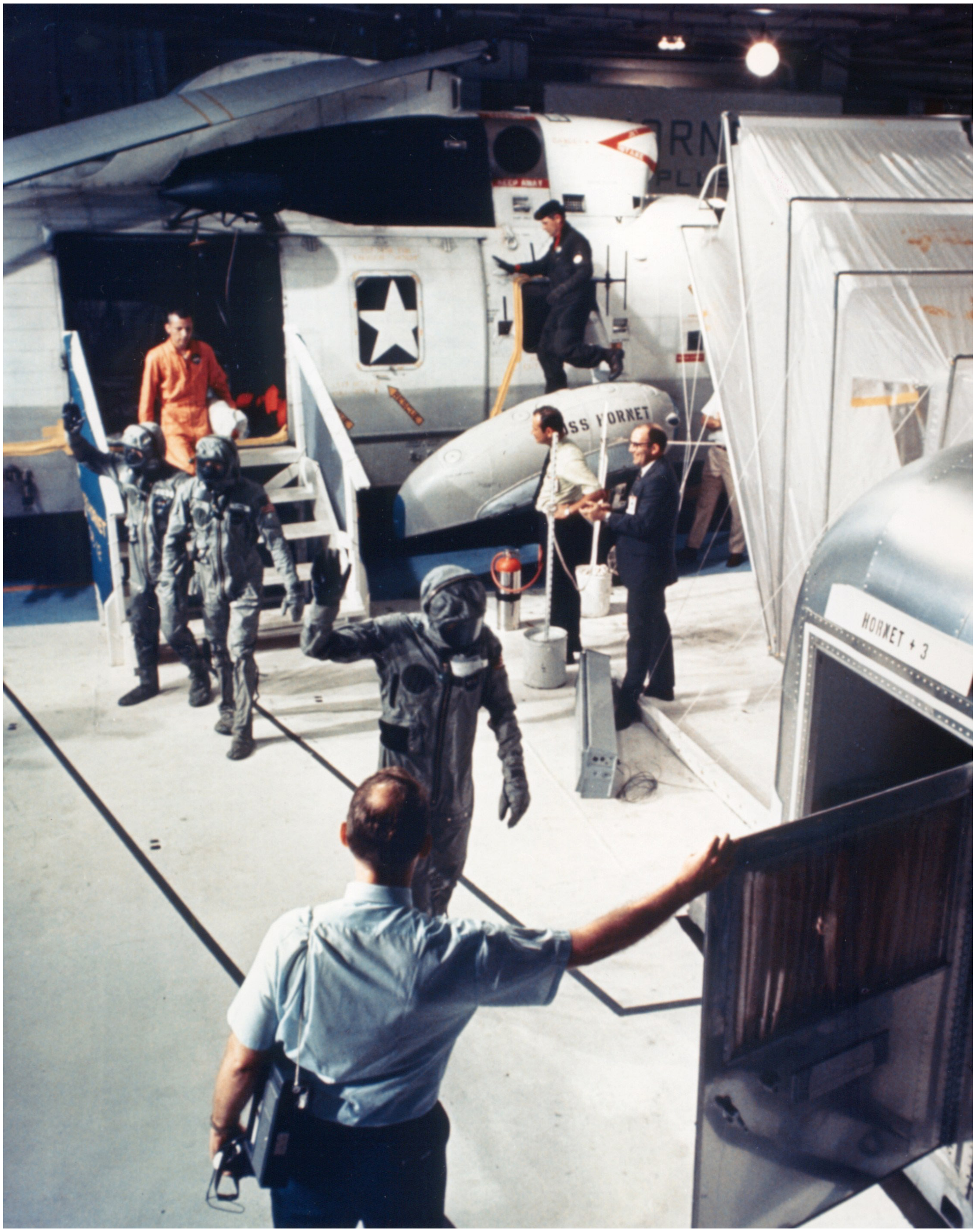

FIGURE 2.2 The Apollo 11 astronauts in their so-called Biological Isolation Garments—an aspect of the planetary protection procedures applied to the crew of the first lunar landing mission—transit from their recovery helicopter to the mobile quarantine facility aboard the USS Hornet in the Central Pacific in July 1969. SOURCE: Project Apollo Archive, Apollo Image Gallery, Apollo Splashdown and Post-Flight Photos, Image S69-40753, http://www.apolloarchive.com/apollo_gallery.html. Courtesy of NASA/Ed Hengeveld.

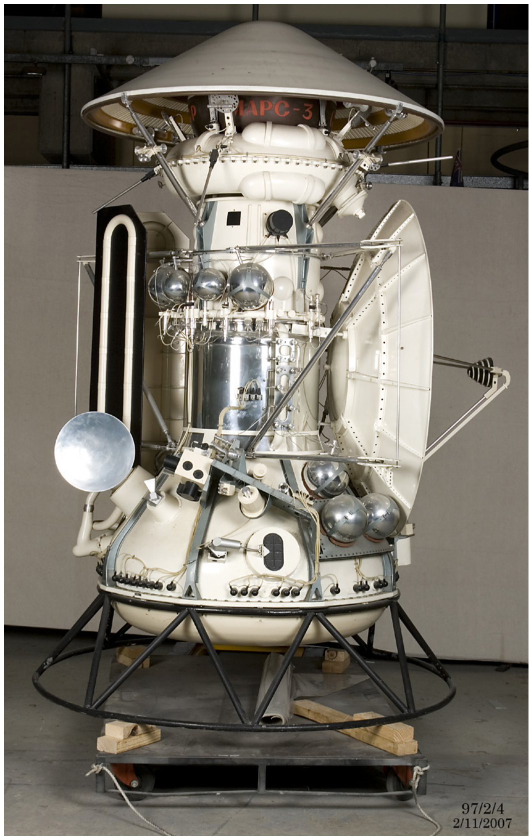

FIGURE 2.3 A full-scale model of the Mars 3 orbiter and lander. SOURCE: Collection: Museum of Applied Arts and Sciences. Photo: Nitsa Yioupros.

not included on the Mars 2 and 3 landers. The Mars 2 and 3 orbiters were somewhat more successful but returned little or no useful scientific data.[64]

Soviet sources claimed that the planetary protection protocols applied to the Mars 1, 2, and 3 missions were on par with then-applicable COSPAR standards, but evidential data were not made readily available at the time.[65,66] According to V.T. Vashkov, a member of the USSR space program, the methods used for sterilizing Mars 1, 2, and 3 primarily included a combination of the following:[67,68]

- A combination of heat or radiation sterilization of individual components depending on their nature;
- Assembly of sterile components in laminar-flow cleanrooms;

[64] A.S. Siddiqi, *Deep Space Chronicle: A Chronology of Deep Space and Planetary Probes 1958-2000*, NASA-SP-2002-4524, NASA, Washington, D.C., 2002, pp. 86-88.
[65] B.C. Murray, M.E. Davies, and P.K. Eckman, "Planetary contamination II: Soviet and U.S. practices and policies, *Science* 155:1507, 1967.
[66] L.B. Hall, ed., *Planetary Quarantine: Principles, Methods, and Problems*, Gordon and Breach, New York, 1971, p. 35.
[67] Memos from NASA Planetary Quarantine Officer Lawrence B. Hall Memo to Associate Administrator for Space Science and others, "Soviet Planetary Quarantine Sterilization of Mars 1 and 2," June 1, 1972, and "Analysis of the Planetary Quarantine Effort in the U.S.S.R.," no date.
[68] M. Meltzer, *When Biosphere's Collide: A History of NASA's Planetary Protection Programs*, NASA SP-2011-4234, 2011, pp. 65-66.

- Surface cleaning of the assembled spacecraft with hydrogen peroxide followed by ultraviolet irradiation; and
- Prior to launch, the entire spacecraft was exposed to "OB mixture"—a gas consisting of one part of ethylene oxide to 1.44 parts of methyl bromide—at 50°C for 6 hours.

To ensure that their planetary protection procedures were effective, bioassays were conducted on a model of the spacecraft using a "mopping" technique that is believed to be similar to the swabbing procedure NASA uses for Mars missions. The spacecraft was further protected in the confines of a plastic bag until it exited Earth's atmosphere.[69]

Besides the lack of hard information about the detailed implementation of prelaunch planetary protection protocols employed on early Soviet planetary missions, a postlaunch practice is worth mentioning. Tracking of early Soviet spacecraft clearly indicated that their interplanetary trajectories were not intentionally biased away from their intended destinations.[70] Rather, the Soviet practice was to deflect unwanted, Earth-escape and/or cruise stage away from the intended destination via a terminal manoeuver. Thus, a spacecraft failure prior to the terminal course correction left the target body open to contamination by uncleaned hardware.

The Viking Missions

NASA's Viking missions in the 1970s first explored the possibility that Mars might harbor, or once sustained, life.[71] By any standard, Viking stands out as one of the most ambitious and expensive robotic projects NASA has ever implemented. Launched in 1975, Viking's two orbiters and two landers carried out high-resolution, remote-sensing measurements at Mars, successfully executed soft landings, and conducted the first in situ life detection experiments on another solar system body.

The goals and objectives of the Viking project meant that both planetary protection and science integrity were concerns. NASA and COSPAR had previously discussed planetary protection in connection with Mars, but the Viking missions were the first time planetary protection measures were applied in connection with in situ, life detection experiments. The Viking project fully embraced planetary protection objectives and incorporated requirements established by NASA and guidance from COSPAR into the design of the spacecraft and the scientific instruments. One prime contractor built all the scientific instruments for Viking, which facilitated the effective implementation of planetary protection measures.

To meet planetary protection objectives, the Viking team developed new approaches, including the construction of a unique facility to sterilize spacecraft (see Figure 2.4) and use of a special metal-tape data recorder. Implementing planetary protection measures also affected the selection of components, the design of subsystems, and the choice of propellant for the spacecraft. Despite the demanding nature of the planetary protection requirements, implementation of the requirements remained "stable since day-one."[72]

Even though Viking's life detection experiments produced null or, at best, inconclusive results, the planetary protection program was a success. In today's dollars, Viking cost about $6.8 billion,[73] making it still the most expensive planetary science mission ever launched. Of that, about $4.4 billion can be attributed to the landers where the dominant share of the planetary protection effort was expended. An independent analysis by the Aerospace Corporation estimates that Viking spent about 10 percent of its lander budget on meeting planetary protection

[69] Ibid., p. 66.
[70] B.C. Murray, M.E. Davies, and P.K. Eckman, "Planetary contamination II: Soviet and U.S. practices and policies, *Science* 155:1507-1510, 1967.
[71] The Viking planetary protection narrative provided in this document is taken from the presentation to the committee by A.T. Young, who was the NASA Mission Director for the Viking Landers.
[72] T. Young, Lockheed Martin (retired), presentation to committee, May 24, 2017.
[73] See, for example, NASEM, *Powering Science: NASA's Large Strategic Science Missions*, The National Academies Press, Washington, D.C., 2017, p. 11.

FIGURE 2.4 One of the Viking landers sealed in its protective bioshell to prevent recontamination after dry baking in a specially constructed oven at 111.7°C for more than 30 hours. SOURCE: Courtesy of NASA. https://www.nasa.gov/centers/kennedy/about/history/50thgallery/1975-01-07.html.

requirements (~$400 million).[74] As noted above, Viking was defined and developed during the Mercury/Gemini/Apollo era when very expensive, so-called "flagship" missions were the norm. In addition, biology was less advanced in the 1970s, and whole spacecraft sterilization was a reasonable approach in light of existing knowledge.

The conditions that explain the Viking approach to planetary protection and that made Viking a success in planetary protection terms no longer exist. NASA space science projects routinely have budget constraints, require the use of heritage hardware developed for other programs, and have instruments built by many contractors all over the world. These factors often limit the flexibility in how a project may be able to implement planetary protection policies. In addition, microbiology has developed significantly since the 1970s, especially in the area of genomics. This new knowledge opens up possibilities for new approaches to planetary protection in connection with space exploration.

[74] D. Bearden and E. Mahr, "Cost of Planetary Protection Implementation," presentation to the committee, June 28, 2017, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_180771.pdf.

NASA Mars Missions: 1976 to 2001

After the Viking mission failed to produce convincing results from its life detection experiments, Mars projects went into a long hiatus. The Mars science community began to think in terms of the detection of "habitable environments" rather than life itself. At the same time, very expensive multi-billion dollar missions (e.g., Galileo, Cassini), which in NASA's reduced budget environment could only be launched once per decade, began to fall into disfavor and alternatives were sought.

Seventeen years after Viking, NASA launched Mars Observer (MO), an experiment in cost reduction as well as a return to basic science. This experiment failed in two ways. First, by the time all the necessary deep space modifications (thermal control, communications, propulsion, etc.) had been made to allow spacecraft designed for Earth orbit to operate at Mars, the cost was approaching that of a purpose-built mission. Second, MO failed to reach Mars, probably as the result of an explosion in the propulsion system.

Subsequent to MO, NASA entered the "faster-better-cheaper" era of missions for which there was a heavy emphasis in shortening development time and reducing development costs, all while encouraging innovative approaches to mission architecture. That period yielded some early notable successes (Mars Pathfinder and Mars Global Surveyor), but then some very spectacular and public failures in 1999 (Mars Climate Orbiter and Mars Polar Lander). An independent review found that the failures resulted from an indiscriminate application of the concept of faster-better-cheaper.[75]

After the twin failures, the Mars Exploration Program underwent a thorough restructuring that, among other actions, reinstituted the rigorous systems engineering that is required of complex space missions.[76]

Beagle 2

The European Space Agency's (ESA's) Mars Express mission was launched in 2003. It carried a small lander, Beagle 2, which was designed and built in the United Kingdom (see Figure 2.5). The primary goal of Beagle 2 was to search for evidence of past life within the martian soil using instruments designed to detect the following:

- Presence of water;
- Existence of minerals deposited in aqueous environments;
- Occurrence of residual organic or carbonaceous species;
- Complexity of organic structure; and
- Identification of isotope fractionation between organic and inorganic phases.

Beagle 2 was classified as a Category IVa mission (see Table 2.1) under COSPAR guidelines and was required to meet the bioburden levels of the hardware, at launch, and for exposed surfaces. Beagle 2 utilized a variety of bioload-reduction techniques tailored to the requirements of specific components. These methods included dry heating, alcohol wipes, exposure to hydrogen peroxide gas, and irradiation by gamma rays. In addition, the mission complied with all requisite clean room procedures, and bioload reduction was confirmed by microbiological analyses. Unfortunately, the mission was not a success, because all communications with the spacecraft were lost as it was scheduled to land on the martian surface.

NASA Mars Missions: 2001 to 2013

From the launch of Mars Odyssey in 2001 through that of the Mars Science Laboratory (MSL) Curiosity launched in 2011, NASA's Mars Exploration Program has been fully successful, with some missions operating

[75] T. Young, J. Arnold, T. Brackey, M. Carr, et al., *Mars Program Independent Assessment Team Report*, NASA, Washington, D.C., March 2000, https://ntrs.nasa.gov/search.jsp?R=20000032458.

[76] S. Hubbard, *Exploring Mars, Chronicles from a Decade of Discovery*, University of Arizona Press, Tucson, Ariz., 2012.

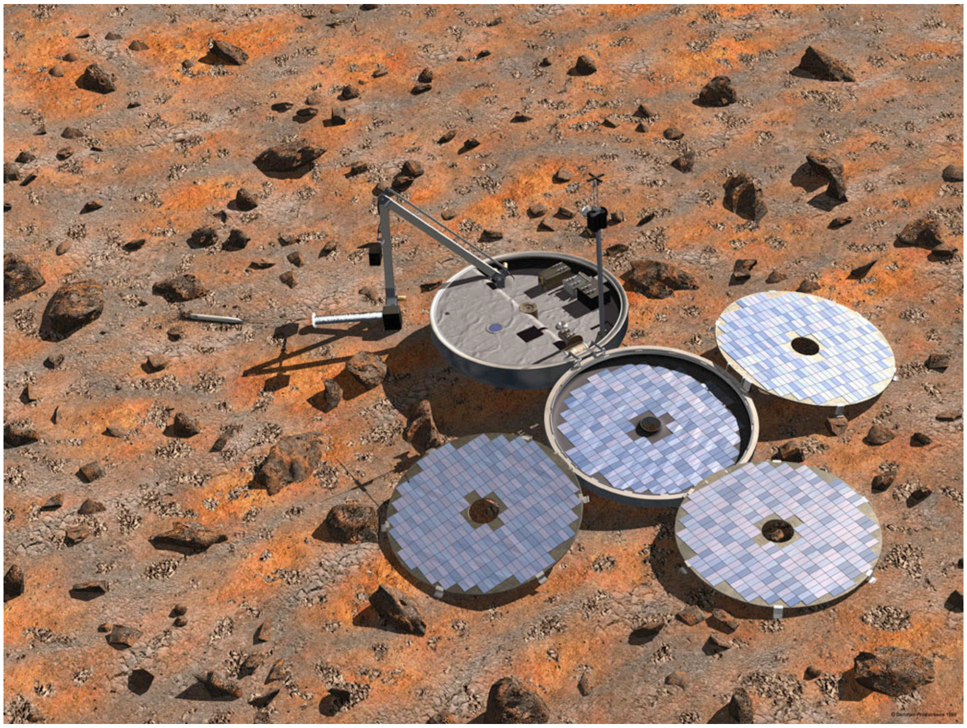

FIGURE 2.5 An artist's impression of how Beagle 2 should have unfolded itself to deploy its instrumented arm, solar panels, and main antenna once it had landed on Mars. It is believed that various petals did not fully deploy upon landing. SOURCE: European Space Agency, "Artist's Impression of Beagle 2 Lander," January 23, 2002, http://www.esa.int/spaceinimages/Images/2001/04/Artist_s_ impression_of_Beagle_2_lander. Courtesy of European Space Agency/Denman Productions.

many years past their prime mission.[77] During this period leading up to launch of MSL in 2011, planetary protection was always a requirement for project implementation. However, the requirements were relatively straightforward, because the missions were focused on planetary geology rather than on life detection. Consequently, Mars Pathfinder (launched in 1996) and the two Mars Exploration Rovers (MERs)—Spirit and Opportunity (launched in 2003)—were classified as IVa (see Table 2.1), because their primary missions did not include searches for evidence of extant life.

The pace and scientific focus of the missions prior to MSL was not accidental. Rather, there was a strategic approach to deploy an orbiter to characterize the planet, then a lander to examine ground truth in areas identified by the orbiters. The top-level scientific objective was to locate ancient habitable environments and then characterize the local geology. However, up through the 2004 twin MERs and 2008 Phoenix lander, there was no landed scientific payload that was specifically designed to test for complex organic compounds. Because Phoenix was targeted to test for water ice at the martian north pole, it was categorized IVc (see Table 2.1).[78] A bioshield "cocoon" surrounding the digging and sample acquisition arm was designed and implemented without substantial difficulty. Phoenix was a smaller class of mission (a so-called Mars Scout) with fewer instruments and objectives than a flagship mission like MSL.

[77] Missions during this period were Mars Odyssey (Orbiter), Mars Exploration Rovers Spirit and Opportunity (Landers), Mars Reconnaissance Orbiter (Orbiter), Phoenix (Lander), and MAVEN (Orbiter).

[78] Category IVc is for missions investigating regions that are likely to be able to support terrestrial organisms or where there is high potential for martian life, i.e., "Special Regions," see Appendix B. Category IVa is for spacecraft carrying instruments not designed to search for extant life.

The lack of instruments seeking complex organics was deliberately changed with the formulation of MSL. It was thought that by a launch originally scheduled for 2009, the progression of scientific knowledge would be sufficient that landed areas that might contain organics could be located. At the time of the level-1 science requirements definition, the Planetary Protection Officer (PPO) was engaged and asked to provide the mission categorization and the planetary protection requirements for the mission.

At the time of launch in 2011, MSL was 2 years late and $900 million over budget, and some notable planetary protection issues had erupted into the public sphere. Specifically, MSL carried a set of drill bits that were to be housed in a sterile box until landing on Mars and that would then be used to examine samples of rocks on Mars. However, the box was opened before launch to remove one of the bits to be installed in the drill. The bits were re-cleaned, but the protocol approved by the PPO for ensuring sterility of the drill bit system was broken. Consequently MSL's planetary protection categorization was downgraded from IVc to IVa, thus requiring that the landing site would not be likely to be able to harbor life (i.e., not a Special Region).

As a result of these issues, in 2013, the NASA Planetary Science Division commissioned a MSL lessons learned study.[79] Among other responsibilities, the study was to delve into the planetary protection practices and procedures. The report, which was presented to the Planetary Protection Subcommittee of NASA Advisory Council, says, in part, that "Planetary Protection, as a discipline, does not follow effective systems engineering and management practices,"[80] that the process of transmitting planetary protection requirements for MSL were not sufficiently clear, concise, and verifiable, and that various formal documents relating to planetary protection requirements for MSL had ambiguities.

The thrust of the lessons learned report's planetary protection conclusion was that even if prior, less structured approaches for issuing requirements had worked in the past, those approaches were no longer satisfactory for increasingly complex new missions. It would appear that as the instrumentation came ever closer to being able to detect the "fingerprints of life," standard practices of the PPO began to collide with the constraints of major mission implementation. Thus, as the committee will explain below, it is no surprise that Mars 2020, which would be the de facto start of a campaign to return samples from a body of astrobiological interest, would encounter even more difficult and contentious planetary protection issues.

Phobos-Grunt

The Russian space agency, Roscosmos, space mission,[81] Phobos-Grunt, attempted to explore the martian moon and return samples of Phobos to Earth for analysis. The Phobos spacecraft consisted of the Russian sample return package and a small Chinese Mars orbiter, Yinghuo-1. Also included was a small capsule, the Living Interplanetary Flight Experiment (LIFE), funded by the U.S.-based Planetary Society. The presence of an experiment provided by a private U.S. organization on a Russian spacecraft raised interesting questions as to the respective responsibilities of the United States and Russia under articles VI and IX of the OST.

The Phobos-Grunt mission was intended to return not only a sample from Phobos but also the terrestrial microorganisms confined in the LIFE capsule for the duration of the round trip. Phobos-Grunt was launched in November 2011 and was scheduled to arrive back to Earth in the summer of 2014 after 34 months in space. However, after being launched into Earth's orbit, the spacecraft failed to respond to commands from the ground. In January 2012, the spacecraft fell to Earth in an uncontrolled descent and crashed in the South Pacific Ocean.[82]

The Phobos-Grunt mission was one of the first complex missions involving planetary protection, due to its risk of both forward and backward contamination. According to one Russian scholar, "this [imposed] on us a huge responsibility and [involved] a thorough compliance with all requirements of planetary protection in both

[79] M. Saunders, "MSL Lessons Learned Study," presentation to Planetary Protection Subcommittee of the NASA Advisory Council, April 29, 2013, https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/MSL_LL_to_NAC.pdf.

[80] M. Saunders, "MSL Lessons Learned Study," presentation to Planetary Protection Subcommittee of the NASA Advisory Council, May 20, 2014, Finding 6, Slide 10, https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/MSL_LL_-_2.pdf.

[81] For more information about the State Space Corporation Roscosmos, the Russian space agency, see http://en.roscosmos.ru.

[82] D. Clery, Russia Explores New Phobos-Grunt Mission to Mars, *Science*, February 2, 2012, http://www.sciencemag.org/news/2012/02/russia-explores-new-phobos-grunt-mission-mars

major areas: the protection of Mars from terrestrial microorganisms (necessary for further studies of the planet) and protection of Earth from potential extraterrestrial contamination."[83] The LIFE capsule was a unique test to see if terrestrial life could survive exposure to the space environment during a round-trip between Earth and Mars.[84] However, the risks involving the LIFE capsule posed a threat to the contamination of Mars.

Because of the complexity of execution and involvement from international partners, the Phobos-Grunt mission had to pass a variety of planetary protection requirements. The design of the capsule involved multiple sealing techniques, including an outer titanium shield, an inner ceramic carrier that is easily sterilized, 30 polymer containers holding the microorganisms, and a polymer container holding a permafrost sample. There was an indium wire crushed for sealing the top and bottom units and three integral locking lugs that are safety wired in place to prevent the top from coming undone.[85] Overall, LIFE was designed as a passive experiment with no active control or actuators with placement inside the space volume between the aero shell heat shield and internal avionics.[86] Moreover, "LIFE aimed to be '*simple, compact, and rugged*,'" while "strictly following COSPAR planetary protection guidelines to responsibly reduce any possibility that this experiment could contaminate Mars with its life signature."[87]

This was a controversial case. In fact, the NASA and ESA planetary protection officers met with officials from Roscosmos and the Space Research Institute (IKI) of the Russian Academy of Sciences about Phobos-Grunt twice, prior to its launch. In addition, they reviewed the spacecraft's proposed trajectory and hardware reliability data. During the second meeting, the NASA and ESA officials signed a formal set of documents agreeing that Roscosmos's proposed approach—that is, treating Phobos-Grunt as if it were a restricted Earth return mission—was consistent with COSPAR guidelines.[88]

Non-NASA Sample Return Missions

As new national and international space agencies began to develop their own plans for planetary exploration missions, they were often able to build upon planetary protection policies and implementations used by prior U.S. and/or Soviet spacecraft. However, when plans called for undertaking activities not previously attempted, the new players, by necessity, became involved in the planetary protection policy development arena.

Following ESA's very successful Giotto flyby of the nucleus of Comet Halley in 1986, interest in both NASA and ESA turned to follow-on studies of comets. The NASA project was the CRAF mission, and ESA began consideration of a follow-on Comet Nucleus Sample Return (CNSR) mission.[89] While CRAF posed no significant planetary protection issues, CNSR did potentially. ESA began work needed to define and implement the requirements for such a mission. Legal issues such as the ownership of the samples returned by CNSR and questions relating to the landing site, if not located in the territory of a participating nation, had to be addressed.

Unfortunately, all of this preparatory work came to naught. In 1992, NASA cancelled CRAF due to budgetary constraints, and the following year, ESA abandoned the ambitious CNSR plans, opting instead to develop a CRAF-style project. ESA's multi-asteroid flyby and comet-rendezvous spacecraft, Rosetta, was launched in 2004, and it went on to conduct a highly successful mission to comet 67P/Cheryumov-Gerasimenko. Although Rosetta's Philae module completed the first soft-landing on a comet nucleus and ultimately hard-landed itself on September 30, 2016, it broke no new ground from a planetary protection perspective.

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[83] N.M. Khamidullina, Realization of the COSPAR Planetary Protection Policy in the Phobos-Grunt Mission, *Solar System Research* 46(7):498-501, 2012.

[84] D. Warmflash et al., "Living Interplanetary Flight Experiment (LIFE): An Experiment on the Survivability of Microorganisms During Interplanetary Transfer," presentation at the First International Conference on the Exploration of Phobos and Deimos, Moffett Field, Calif., November 5-7, 2007, http://www.lpi.usra.edu/lpi/contribution_docs/LPI-001377.pdf.

[85] Ibid.

[86] Ibid.

[87] R. Fraze, T. Svitek, B. Betts, and L. Friedman, "Phobos-LIFE: Preliminary Experiment Design," presentation at the First International Conference on the Exploration of Phobos and Deimos, NASA Ames Research Center, Moffett Field, Calif., November 5-7, 2007, LPI Contribution No. 1377, https://www.lpi.usra.edu/lpi/contribution_docs/LPI-001377.pdf.

[88] Protocol, Phobos-Grunt Technical Meeting, held in Moscow on November 6, 2009.

[89] G.H. Schwehm, Rosetta-comet nucleus sample return, *Advances in Space Research* 9:185-190, 1989.

The Japanese Hayabusa 1 mission is interesting from the planetary protection policy implementation perspective because it involved activities on the part of Japan, the United States, Australia, and COSPAR. Hayabusa 1, formerly known as MUSES-C (Mu Space Engineering Spacecraft-C), was developed by JAXA to return samples from a small near-Earth asteroid named 1998 SF36 (later given the formal designation of 25143 Itokawa) to Earth for further analysis. JAXA and the Japanese Institute for Space and Astronautical Science (ISAS) performed an assessment of the mission's planetary protection categorization, based on the framework presented in the SSB's 1998 report on sample returns from small solar system bodies, and concluded that Hayabusa 1 is a Category V, unrestricted Earth return mission.[90] Since NASA was providing communications and navigation support for the mission, ISAS requested that NASA's PPAC review the JAXA/ISAS findings. The PPAC reviewed the findings, evaluated the mission for the purpose of its categorization, and recommended that

> No special containment for samples returned from 1998 SF36 is required for the purposes of planetary protection, provided that subsequent information obtained prior to sample return remain consistent with the classification of that body as an undifferentiated metamorphosed asteroid. As such, we recommend that for NASA purposes, the mission be designated Planetary Protection Category V, "unrestricted Earth return."[91]

Because Hayabusa's samples were scheduled to return to Earth in the Woomera Prohibited Area in South Australia, ISAS and Environment Australia requested that COSPAR review the planetary protection aspects of the Hayabusa mission. Following presentations from ISAS and NASA on the deliberations of NASA's PPAC about the mission and its target body, and consideration with respect to the COSPAR policy, the workshop agreed to the following statement: "The COSPAR Workshop on Planetary Protection considered the categorization of the MUSES-C mission, and concurred with the recommendations of the NASA Planetary Protection Advisory Committee on the Muses-C mission, agreeing that its asteroid target (1998 SF36) meets the SSB classification for a body from which a Category V mission with 'unrestricted Earth-return' is warranted."[92]

The actions by PPAC and COSPAR led to Environment Australia issuing a one-page decision instrument that the action by the Japan's ISAS to return a sample from 1998 SF36 is "not controlled." Soon afterward, Biosecurity Australia issued a 38-page document for public comment on the action,[93] and after receiving comments, issued a 2-page policy memorandum permitting the sample return.

Hayabusa was launched on May 9, 2003, and after several near-death experiences, returned trace samples of 25143 Itokawa to Earth on June 13, 2010, 3 years later than originally planned.

NASA Missions to the Outer Planets

Pioneers 10 and 11 and Voyagers 1 and 2 were the first spacecraft to explore the outer planets, contributing valuable information and paving the way for subsequent, more detailed investigations. In particular, the Voyager spacecraft revealed intriguing information about Europa, suggesting that this moon of Jupiter might "have a thin crust (less than 18 miles or 30 kilometers thick) of water ice, possibly floating on a 30-mile-deep (50-kilometer-deep) ocean." The Voyager spacecraft provided evidence that "the most active surface of any moon seen in the Saturn system was that of Enceladus. The bright surface of this moon, marked by faults and valleys, showed evidence of tectonically induced change."[94]

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[90] NRC, *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making*, National Academy Press, Washington, D.C., 1998.

[91] Minutes of the NASA Planetary Protection Advisory Committee, March 19, 2002.

[92] Report of the Workshop on Planetary Protection, held under the auspices of the Committee on Space Research (COSPAR) and the International Astronomical Union (IAU) of the International Council for Science (ICSU) at Williamsburg, Virginia, April 2-4 2002. Report Prepared by the COSPAR Panel on Planetary Protection, John D. Rummel, Chair, COSPAR, Paris, 2002.

[93] Biosecurity Australia, "Quarantine Review of the MUSES-C Project: Surface Sample Returned from Asteroid 1998 SF36," Commonwealth Department of Agriculture, Fisheries and Forestry, Australia, July 2002, http://www.agriculture.gov.au/SiteCollectionDocuments/ba/memos/2002/animal/2002-35a.doc.

[94] NASA, Voyager to the Outer Planets and Into Interstellar Space, *NASA Facts*, JPL 400-1538, Jet Propulsion Laboratory, Pasadena, Calif., September 2013, https://www.jpl.nasa.gov/news/fact_sheets/voyager.pdf.

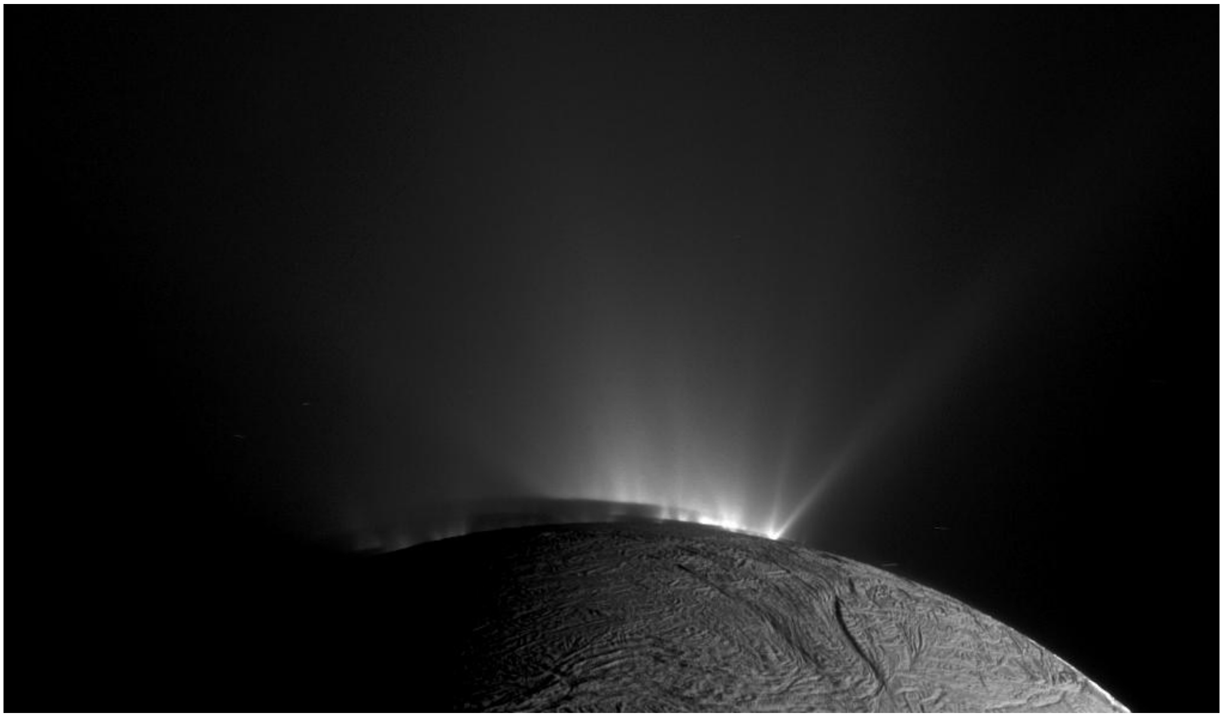

FIGURE 2.6 Plumes of salty ice grains emanating from the south polar region of Saturn's moon, Enceladus. The image was taken by the narrow-angle camera on NASA's Cassini spacecraft in 2010. SOURCE: NASA, "Encroaching Shadow," PIA17184, November 30, 2010, https://photojournal.jpl.nasa.gov. Courtesy of NASA/JPL-Caltech/Space Science Institute.

Following the Pioneers and Voyagers, NASA's Galileo mission was launched to Jupiter in October 1989 and arrived at Jupiter in December 1995. The spacecraft spent nearly 8 years collecting vast amounts of scientific data on the planet and its moons. The Galileo mission was classified as a Category II (see Table 2.1) mission for planetary protection purposes, requiring only documentation on probabilities of impact, contamination control procedures used during assembly, and disposition of all launched hardware at completion of the mission. Microbiological assays were not required. However, because of the Voyager discoveries, the Galileo planetary protection plan contained the following disposition requirement:

> In addition, the Project will supply data obtained bearing on the biological interest of the Jovian satellites to the Planetary Protection Officer in a timely manner. This information will be provided by letter before the end of mission and while the spacecraft is controllable. If the Planetary Protection Officer finds that a satellite requires protection beyond that called for in Category II requirements, the Project will negotiate options that will preclude an impact of that satellite by the Orbiter.[95]

One of the most significant discoveries from Galileo was the detection of the magnetic signature of a global ocean of salty water below the icy surface of Europa. The thickness of the ice crust is still a subject of scientific debate. As a result, on September 21, 2003, the Galileo spacecraft made a controlled entry into the atmosphere

[95] J. Barengoltz, "Project Galileo Planetary Protection Plan (draft)," NASA/JPL PD 625-14, March 28, 1984.

of Jupiter, thereby preventing any possibility of collision with and possible contamination of one of Jupiter's icy moons.[96]

The Cassini mission was launched in October 1997 and entered orbit around Saturn in July 2004. It spent 13 years studying the planet, its rings, moons, and magnetosphere. Like Galileo, the Cassini mission was classified as Category II (see Table 2.1) for planetary protection purposes, with the same disposition requirement proviso.

During close flybys of Saturn's Enceladus in January and February of 2005, NASA's Cassini spacecraft imaged plumes emanating from the moon's southern polar regions (see Figure 2.6).[97] After many flybys of Enceladus, including flying through the water plumes, three lines of evidence—that is, direct detection of salt-laced ice grains, a combination of gravity and topographic mapping, and oscillation in the moon's rotation state—led to the conclusion that Enceladus contains a salty, liquid ocean underneath the ice surface. Multiple lines of evidence, including measurements of electric fields and tidal distortions, led researchers to conclude that Titan also possesses a global ocean.

THEMES FROM FIVE DECADES OF PLANETARY PROTECTION POLICY DEVELOPMENT

Looking back over the history of planetary protection policy and practice, notable themes emerge. First, the emphasis to date has been almost entirely on science and the protection of scientific exploration. Policies have generally been based on well-established scientific understanding, and for forward contamination, they have been directed on preserving the ability to undertake future scientific studies of solar system bodies. Indeed, with the exception of the Apollo program in the 1960s and 1970s, the principal focus of solar system exploration has been on research carried out on or near other bodies, and so the focus of planetary protection has been on forward contamination rather than backward contamination. As a result, efforts have concentrated on avoiding biological and organic contamination as a requirement to support scientific searches for evidence of life and the origin of life beyond Earth.

A second important theme has been adjustment of planetary protection policies in response to growing scientific knowledge about solar system bodies. In the early 1960s, when no data about any solar system body's capacity to support terrestrial or indigenous life existed, all bodies were treated with caution. However, as researchers learned more about which bodies are likely or unlikely to support life, the number of bodies for which planetary protection remains an issue has been significantly reduced.

The international dimensions of planetary protection policy comprise a third theme. International cooperation and coordination have been integral components of the policy development process. The OST, which has been ratified by 105 countries, including all of the spacefaring nations, and signed by 25 more, has been a remarkably successful and non-contentious basis for international cooperation on planetary protection policies. Similarly, COSPAR has proved an effective forum for the development of international consensus on planetary protection guidance for science exploration missions.

Fourth, the United States has demonstrated sustained international leadership on planetary protection as part of space exploration activities. Scientific advice developed by the SSB, most of which has been incorporated, and policies designed by NASA have been the driving and determining factors in the formulation and implementation of COSPAR guidance on planetary protection. However, NASA has experienced difficulty in achieving an effective institutional design for planetary protection policy development, as evidenced by problems with the placement of the OPP within the agency and with the provision of external advice to the OPP (see Chapter 3).

Fifth, only a small number of countries have engaged in space exploration activities that have planetary protection implications. The limited number of spacefaring nations has contributed to the success of international cooperation under the OST and through COSPAR.

[96] See, for example, NRC, "Scientific Assessment of Options for the Disposal of the Galileo Spacecraft," letter from Claude Canizares, Chair, Space Studies Board, and John Wood, Chair, Committee on Planetary and Lunar Exploration, to John Rummel, Planetary Protection Officer, NASA, June 28, 2000.

[97] C.C. Porco, P. Helfenstein, P.C. Thomas, A.P. Ingersoll, J. Wisdom, R. West, G. Neukum, et al., Cassini observes the active South Pole of Enceladus, *Science* 311:1393-1401, 2006.

Sixth, during this historical period through the present day, private-sector enterprises have not conducted space activities that required the implementation of planetary protection measures. Companies have supplied components to government-sponsored missions, and planetary protection policies applied to the integration of these components into spacecraft. However, no company has undertaken space missions on its own that generated significant planetary protection issues.

Finally, since 1972, human space exploration by the leading government agencies has been limited to low Earth orbit. The space shuttle program and development of the International Space Station have not presented planetary protection issues.

As the next four chapters explain, changes in space exploration and the science informing planetary protection create challenges that are likely to transform how countries and international cooperation mechanisms approach planetary protection and develop policy for it.

3

Summary and Assessment of the Current Process

The committee's statement of task calls for an examination of the current policy development processes from both a national and international perspective, including a review of the major players and stakeholders and their respective roles and responsibilities. The charge also asks for an assessment of how the current process takes into account relevant new scientific knowledge and technical developments. In addition, the charge asks the committee to consider how the current process attends to balancing the immediate planetary protection needs with the need to gather scientific information to support future studies. This chapter addresses those elements of the charge.

In assessing the effectiveness of the current process, the committee considered a number of best practices—for example, broad stakeholder engagement and participation, clarity of roles and responsibilities, transparency, access to new scientific and technical knowledge, timeliness, and consistency—that are important for effective policy development and implementation. Notwithstanding the successes achieved over many years, whether the current process will continue to function as well in the future will depend on how well the processes of planetary protection policy development embrace these practices. The committee's recommendations are numbered according to the chapter and order in which they appear.

PLANETARY PROTECTION POLICY DEVELOPMENT PROCESS

Planetary protection policy development involves a process that flows between national and international policy formulation and national policy implementation. Figure 3.1 is a simplified depiction of these processes and their interaction, and it provides context for this chapter's more detailed analysis. Planetary protection policy development is grounded in the Outer Space Treaty (OST). As a state party to the treaty, the U.S. government has binding obligations under international law to comply with its planetary protection provisions, which are also federal law under the Constitution.

NASA policies satisfy this obligation for government-sponsored space activities. For private-sector space activities with planetary protection implications, a "regulatory gap" exists because Congress has not adopted legislation giving a federal agency jurisdiction over such activities (see Chapter 6).

NASA draws on scientific input from the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine, internal agency advisory groups, and consultants to the Office of Planetary Protection (OPP), to formulate policies to direct NASA activities that have planetary protection implications. This stage involves setting high-level objectives in NASA Policy Directives (NPDs) and requirements for specific types of

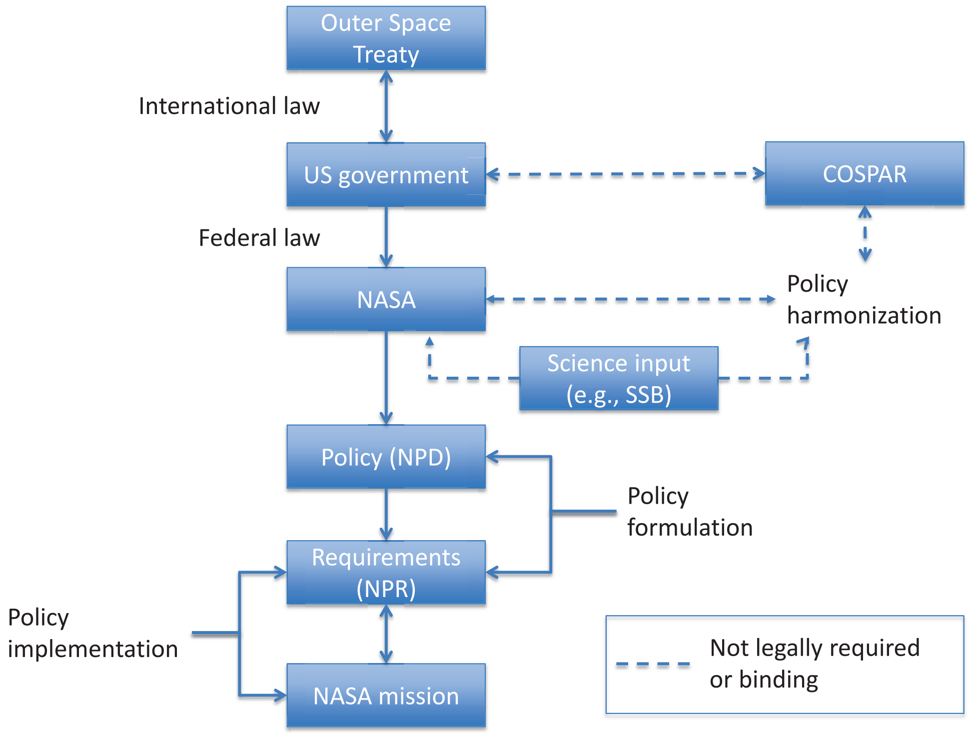

FIGURE 3.1 Notional diagram of relationships in major U.S. and international planetary protection policy development. NOTE: Acronyms defined in Appendix G.

missions in NASA Procedural Requirements (NPRs). In NASA, the NPDs and NPRs are coupled such that the two types of directives together represent the policy.

NASA policy formulation affects, and is informed by, efforts to forge international consensus on planetary protection policies. The U.S. government supports the Committee on Space Research (COSPAR) in order to help achieve international consensus on science-based planetary protection policies. As noted in Chapter 2, NASA science and policy positions have historically determined the guidance COSPAR has produced. The United Nations Committee on the Peaceful Uses of Outer Space, of which the United States is a member, has endorsed COSPAR as the appropriate international authority for creating consensus planetary protection guidelines.[1] However, the OST does not require the U.S. government to support COSPAR, participate in COSPAR, or adopt and implement COSPAR guidance. In this international harmonization step, nothing is incorporated in the NASA policy that does not have the agreement of NASA and the U.S. government.

In reality, the policy development process is not as simple as Figure 3.1 might suggest. Activities at one step can create a need for players lower in the process (e.g., in NASA) to revise or frame new policies to address issues that have not been addressed at higher levels in the flow (e.g., COSPAR), thereby acting as feedback loops. The discussion below will show that efforts to implement policies prescribed for controlling terrestrial contamination risks in the Mars 2020 mission's sample collection systems (the policy implementation phase) have led to a need for NASA to refine its policies (the policy formulation phase). Similarly, experience with the Europa Clipper mis-

[1] See paragraph 25 of United Nations Committee on the Peaceful Uses of Outer Space, "Space Science for Global Development: Report on the United Nations Office for Outer Space Affairs and Committee on Space Research coordination meeting in support of the preparations for UNISPACE+50," Vienna, Austria, May 22-23, 2017. And paragraph 332 of United Nations, "Report of the Committee on the Peaceful Uses of Outer Space, Sixtienth (*sic*) Session (7-17 June 2017)" General Assembly, Official Records, Seventy-second Session, Supplement No. 20., http://www.unoosa.org/res/oosadoc/data/documents/2017/aac_1052017crp/aac_1052017crp_25_0_html/AC105_2017_CRP25E.pdf and http://www.unoosa.org/oosa/en/ourwork/copuos/2017/index.html.

sion provides an example of how efforts to develop planetary protection raised issues that players in the policy harmonization process (e.g., NASA, COSPAR, and the scientific community) would have done well to have anticipated in order to permit timely development of policies and requirements for the mission.

NASA implements planetary protection policies and requirements in NASA-led missions by translating the NASA procedural requirements into the design of spacecraft and mission activities. The translation process sometimes involves negotiations between OPP and the science and engineering teams. Policy implementation includes verifying that space missions comply with the applicable requirements. Experience with individual missions often provides lessons that can be applied to subsequent policy formulation and harmonization actions.

CURRENT NASA PLANETARY PROTECTION POLICY DEVELOPMENT PROCESS

Overview of NASA Planetary Protection Policy Documents and Institutional Roles

NPDs establish NASA's objectives and instruct agency officials and staff about what they are required to do to achieve these objectives. NPRs guide how officials and staff implement policy directives in the context of specific missions. These two sets of documents, taken together, define NASA's policy. Occasionally, NASA issues a NASA Interim Directive (NID) that temporarily modifies policy directives or implementation requirements.[2] (See Figure 3.2 on the structure of NASA policy documents.)

Current NASA planetary protection policy is contained in:

- One NPD, revalidated in 2013, that establishes the high-level objectives and defines agency office roles and responsibilities for planetary protection; and
- One NID, adopted in 2017, that provides the implementation requirements for robotic missions.[3]

Both documents appear to be silent on whether a particular individual or office has the responsibility to *develop and maintain* NASA's planetary protection policies.[4]

To date, NASA has not developed procedural requirements for planetary protection concerning human missions to Mars, but the agency has issued a NASA Policy Instruction (NPI) that contains the policy guidelines for the development of an NPR for crewed planetary missions (see Chapter 5).

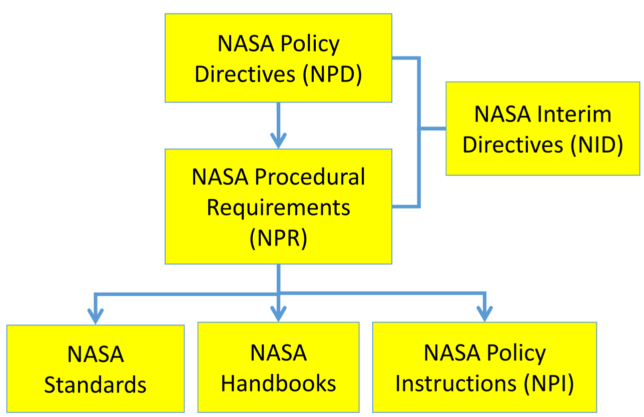

FIGURE 3.2 NASA documentation tree. SOURCE: Data from NASA, NASA Policy Directive 1400.1K (NPD 1400.1K), Documentation and Promulgation of Internal NASA Requirements and Charters, August 4, 2015, Figure 1.

[2] NIDs may replace NPDs or NPRs on a short-term basis (not to exceed 12 months) if an immediate change is warranted.

[3] These implementation requirements include the COSPAR guidelines contained in the COSPAR Planetary Protection Policy.

[4] In briefing the committee about NASA's expectations for this study, both the former NASA chief scientist and the acting NASA chief scientist noted that one concern was the extent to which a separation of responsibilities between policy formulation, policy implementation, and implementation verification was advisable.

BOX 3.1
Responsibilities of the NASA Planetary Protection Officer

As defined in various NASA documents, including NASA Policy Directive (NPD) 8020.7G[1] and NASA Interim Directive (NID) 8020.109,[2] the roles and responsibilities of NASA's planetary protection officer are as follows:

- Identifying project-specific planetary protection standards, procedures, and requirements to achieve planetary protection policy objectives.
- Independently evaluating the implementation of planetary protection provisions by spaceflight missions to determine whether:
  1. Necessary measures have been taken to meet NASA requirements and planetary protection policy objectives;
  2. The recommendations of relevant regulatory agencies with respect to planetary protection have been considered, and pertinent statutory requirements have been fulfilled;
  3. International obligations have been met and international implications have been considered in collaboration with the Office of the General Counsel and the Office of International and Interagency Relations.
- In coordination with safety and mission assurance organizations in the various NASA centers, maintaining oversight of program and project compliance with planetary protection provisions. This role includes participation in reviews, inspections, and evaluations of plans, facilities, equipment, personnel, procedures, and practices of NASA organizational elements and NASA contractors.
- Keeping the chief of the Office of Safety and Mission Assurance informed of risks to planetary protection policy objectives and recommending actions as necessary to ensure conformance with applicable standards, procedures, requirements, and guidelines.

[1] NASA, NASA Policy Directive (NPD) 8020.7G: Biological Contamination Control for Outbound and Inbound Planetary Spacecraft, effective date February 19, 1999, https://nodis3.gsfc.nasa.gov/lib_docs.cfm?range=8.

[2] NASA, NASA Interim Directive (NID) 8020.109: Planetary Protection Provisions for Robotic Extraterrestrial Missions Responsible Office: Science Mission Directorate, effective date March 30, 2017, https://nodis3.gsfc.nasa.gov/OPD/OPD_list.cfm.

Formally, NASA assigns most of the responsibilities for *administering* the agency's planetary protection policy to the planetary protection officer (PPO). (See Box 3.1 on the PPO's responsibilities.) Other NASA officials and staff have specific responsibilities for implementing planetary protection policy. On November 30, 2017, NASA transferred responsibility for overall administration of its planetary protection policy from the Associate Administrator of the Science Mission Directorate to the Chief of the Office of Safety and Mission Assurance (OSMA). The Associate Administrator for the Human Exploration and Operations Mission Directorate and the Associate Administrator for the Space Technology Mission Directorate are designated to ensure that the NPD on planetary protection is incorporated into human spaceflight missions.[5] The directors of NASA centers and their program/project managers are responsible for meeting the procedural requirements for planetary protection and for cooperating with the PPO's administration of NASA planetary protection activities. Finally, NASA has had a standing Planetary Protection Subcommittee (PPS) of the NASA Advisory Council's (NAC's) Science Committee to provide

[5] The administration's fiscal year 2019 budget proposal to Congress includes a proposal to move the Space Technology Mission Directorate under the Human Exploration and Operations Mission Directorate.

advice and support to the PPO, NASA administrators, and mission directorates on planetary protection issues. However, NASA reorganized the NAC in late 2017, and the subcommittee was eliminated.[6]

NASA's acting chief scientist explained to the committee that the decision to move the OPP from the Science Mission Directorate (SMD) to the OSMA would fit more effectively with OSMA's role as a *technical authority*, which focuses on verification, validation, and compliance concerning mission requirements, including safety, reliability, and quality assurance. This move makes the Chief of the OSMA responsible for making final decisions on planetary protection policy issues.

With the move to OSMA, NASA plans to divide the planetary protection functions into two roles:

1. The PPO for administering policy directives and procedural requirements; and
2. A new planetary protection research manager, responsible for performing gap analyses, identifying and coordinating planetary protection research, identifying new and emerging planetary protection risks and uncertainties associated with human exploration missions to Mars and other planetary bodies, coordinating with appropriate agency organizations to develop risk mitigation methodologies, and maintaining cognizance of international advances in the state of the art and adaptations to new technologies, materials, processes and risks.

Whether or not the planetary protection research manager would be located in SMD or somewhere else in NASA was not clear to the committee. SMD has a clear charter, an established process, and a proven record of managing the agency's space and Earth science programs. Given the close linkage between SMD's astrobiology and planetary science programs and planetary protection research needs, SMD would be the obvious choice as the home for NASA's planetary protection research program.

Current NASA Planetary Protection Policies

NASA's overarching policy document for planetary protection is applicable to all spaceflight missions, including human spaceflight.[7] This NPD explicitly incorporates its implementing requirements document,[8] and consequently, the requirements document is considered a part of the NASA planetary protection policy.

The 2017 NID sets forth NASA's biological and organic contamination control requirements applicable to robotic planetary flight programs and specifically addresses two topics. The first is the control of terrestrial microbial contamination associated with robotic space vehicles intended to land, orbit, flyby, or otherwise encounter extraterrestrial solar system bodies. The second is the control of contamination of Earth and the Moon by extraterrestrial material collected and returned by robotic missions. The NID also defines the following:

- Planetary protection categorization of missions;
- General mission requirements for NASA participation in non-NASA or non-U.S. missions;
- Detailed documentation and review requirements and their schedules;
- Process of monitoring and verification;
- Waivers and deviations; and
- Delegated responsibilities of the PPO.

The NID refers to a NASA handbook[9] that describes uniform microbiological assay procedures that are to be used to assess the degree of microbiological contamination of intramural environments where spacecraft hardware is assembled, tested, and launched and to assess the level of microbial contamination on spacecraft hardware.

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[6] See, for example, December 15, 2017, memorandum from Thomas Zurbuchen, associate administrator, Science Mission Directorate to the chairs of the various NASA planetary science analysis/assessment groups.
[7] NPD 8020.7G, *Biological Contamination Control for Outbound and Inbound Planetary Spacecraft, (Revalidated 05/17/13 w/change 1)*.
[8] NID 8020.109A, *Planetary Protection Provisions for Robotic Extraterrestrial Missions*.
[9] HDBK 6022, *NASA Standard Procedures for the Microbial Examination of Space Hardware*.

Overview of NASA's Process for Developing Planetary Protection Policy

Traditionally, NASA's development of new or modified planetary protection policy has involved action, first within NASA, and second through international cooperation within COSPAR. The interdependence between the NASA-level activity and COSPAR efforts is reflected in how COSPAR policy statements and implementation guidance mirror NASA's NPD and NID for planetary protection. As Chapter 2 described, NASA has been the lead actor in the development and revisions of COSPAR planetary protection guidance. This NASA leadership role has been driven by NASA's need for new or additional policies for missions that have not yet been fully considered by COSPAR. Under this pattern, changes in NASA and COSPAR policy occur synergistically, although COSPAR has no authority to compel NASA to change NASA's planetary protection policies. Chapter 4 describes how COSPAR operates, and the present subsection focuses on the NASA process for developing or modifying planetary protection policy.

NASA has a comprehensive process for creating new or revising existing NPDs and NPRs. Proposed changes typically emerge from the OPP, and, once a proposal has been formally drafted, any new or revised NPD, NPR, or NID is released to all affected NASA parties for review. The review involves extensive discussions on the proposal, including on implementation issues. NASA ensures that all questions and comments on the proposed change are addressed, and negotiations among affected NASA parties often produce revised proposals. All affected NASA parties are required to concur in changes that appear in a new or revised NPD, NPR, or NID. More recently, NASA has waited to update its planetary protection procedural requirements until the NPR comes up for renewal per NASA's directives policy.

The committee understands that this comprehensive process is used whenever changes to NPDs and NPRs on planetary protection are proposed. This approach ensures that changes to the operative policy and requirement mandates within NASA are fully vetted by affected stakeholders in the agency.

However, questions can arise if COSPAR adopts changes to its planetary protection guidance that have not been comprehensively reviewed and approved within NASA beforehand. Although NASA has been the driving force behind changes in COSPAR guidance to date, COSPAR—as an international forum—can produce proposals and adopt recommendations for changes to its planetary protection guidance that do not originate within NASA and that have not been comprehensively vetted by all relevant NASA stakeholders. In other words, changes to COSPAR guidance could be adopted with the concurrence of only a few NASA officials who may be concurrently participating in COSPAR's internal deliberative processes.

The adoption of new COSPAR guidance in these circumstances would not change any NPD, NPR, or NID, but NASA would then face conflict between its commitment to follow COSPAR guidance and its commitment to vet thoroughly within the agency any changes to NASA planetary protection directives and requirements. Rejection or revision of the new COSPAR guidance after internal NASA review would put the United States at odds with the international scientific consensus achieved in COSPAR and create potential problems for future policy harmonization efforts within COSPAR.

Often both the COSPAR policy and the NASA policy have been incomplete when it comes to new missions that are being proposed for the first time. That is the case for Mars 2020, which is the first stage of a possible Mars sample return campaign, and Europa Clipper, which is the first Category III (see Table 2.1) mission to an Ocean World. In cases such as these, the NASA PPO defines the missing policy requirements and provides them to SMD, its programs, and their new missions. This additional policy guidance and requirements were not available sufficiently early in the mission design process, and then it was provided to the mission teams by a variety of means including letters, email, and verbal directions. This process will be discussed further in the next sections.

LESSONS LEARNED FROM THE MARS 2020 MISSION

The most recent planetary science decadal survey designated the highest-priority strategic mission to be initiating the first phase of a Mars sample return campaign by developing what at the time was called the Mars Astrobiology Explorer and Cacher (MAX-C), an in situ science rover with sample caching capability.[10]

[10] National Research Council (NRC), *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011.

Returning samples from Mars has remained a priority for the planetary science community for roughly 50 years because such a mission has the best chance of determining whether life emerged elsewhere in the solar system. Answering the big question of "Are we alone?" means that this is the next logical step in planetary science exploration and provides most science return for the investment.

While some may argue for intensified in situ missions, sample return has continued to be the implementation approach of choice for at least four reasons:

- Samples can be analyzed by many laboratories rather than by a single rover.
- Investigations may be conducted by hundreds of researchers sharing samples rather than a single set of investigators operating remote experiments.
- Advanced instrumentation can be utilized that is too large or complex for in situ missions.
- Alternate measurement routes can be followed as new data emerges so that one can pursue the pathways of discovery.

As an example of the latter reason, the hundreds of kilograms of Moon rocks returned by the Apollo astronauts are still yielding new data and insights.[11,12]

Mars 2020 and Planetary Protection

After several years of study and cost reductions, the first step toward a Mars sample return campaign was approval of a rover with the MAX-C science and caching capabilities but now known as Mars 2020 (see Figure 3.3).[13] The mission presented several notable challenges for planetary protection.

First, because Mars 2020 will be the first phase of a sample return campaign, planetary protection regulations regarding restricted Earth return (see Table 2.1) become applicable. Thus, Mars 2020 becomes the first-ever mission to have to deal with samples returned from Mars and, therefore, moves NASA into a new planetary protection regime.

Second, when Mars 2020 received formal authority to proceed in 2013 (Key Decision Point A in Figure 3.4), the project was given a cost constraint of $2.1 billion (real-year dollars), including the cost of the launch vehicle. In part to meet the cost constraint, the project was required to maximize the use of hardware and software inherited from the Mars Science Laboratory (MSL) Curiosity mission. Moreover, NASA officials were unable to portray Mars 2020 as the first phase in a sample return campaign because the administration had not yet committed to the goal of returning samples from Mars. Indeed, NASA officials were enjoined from mentioning the possibility of returning samples from Mars to Earth prior to an August 28, 2017, presentation by NASA Associate Administrator Thomas Zurbuchen to the National Academies' planetary science decadal survey's midterm review committee.[14] The reality of a sample return campaign became even more apparent in April 2018, when NASA and the European Space Agency (ESA) signed a statement of intent to develop a joint Mars sample return plan under which each agency would have lead responsibilities for specific mission elements. The statement added that "this endeavor may be in concert with other international or commercial partners."[15]

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[11] See, for example, E.H. Hauri, T. Weinreich, A.E. Saal, M.C. Rutherford, and J.A. Van Orman, High pre-eruptive water contents preserved in lunar melt inclusions, *Science* 333:213-215, 2011.

[12] See, for example, F.M. McCubbin, B.L. Jolliffc, H. Nekvasil, P.K. Carpenter, R.A. Zeigler, A. Steele, S.M. Elardoa, and D.H. Lindsley, Fluorine and chlorine abundances in lunar apatite: Implications for heterogeneous distributions of magmatic volatiles in the lunar interior, *Geochimica et Cosmochimica Acta* 75:5073-5093, 2011.

[13] MAX-C was assessed by an independent cost and technical evaluation by the Aerospace Corporation as costing ~$3.5 billion in fiscal year (FY) 2015 dollars, which the planetary science decadal survey's steering committee rejected as being too expensive. The decadal survey committee set the not-to-exceed cost threshold at ~$2.5 billion in FY2015 dollars. For details, see NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011, pp. 268-271 and 340.

[14] See, for example, National Academies of Sciences, Engineering, and Medicine (NASEM), *Review of Progress Toward Implementing the Decadal Survey Vision and Voyages for Planetary Sciences*, The National Academies Press, Washington, D.C., 2018 (in preparation).

[15] Associate Administrator for Science Thomas Zurbuchen, NASA, and Director Human and Robotic Exploration Programmes David Parker, ESA, "Joint Statement of Intent between the National Aeronautics and Space Administration and the European Space Agency on Mars Sample Return," April 26, 2018, https://mepag.jpl.nasa.gov/announcements/2018-04-26%20NASA-ESA%20SOI%20(Signed).pdf.

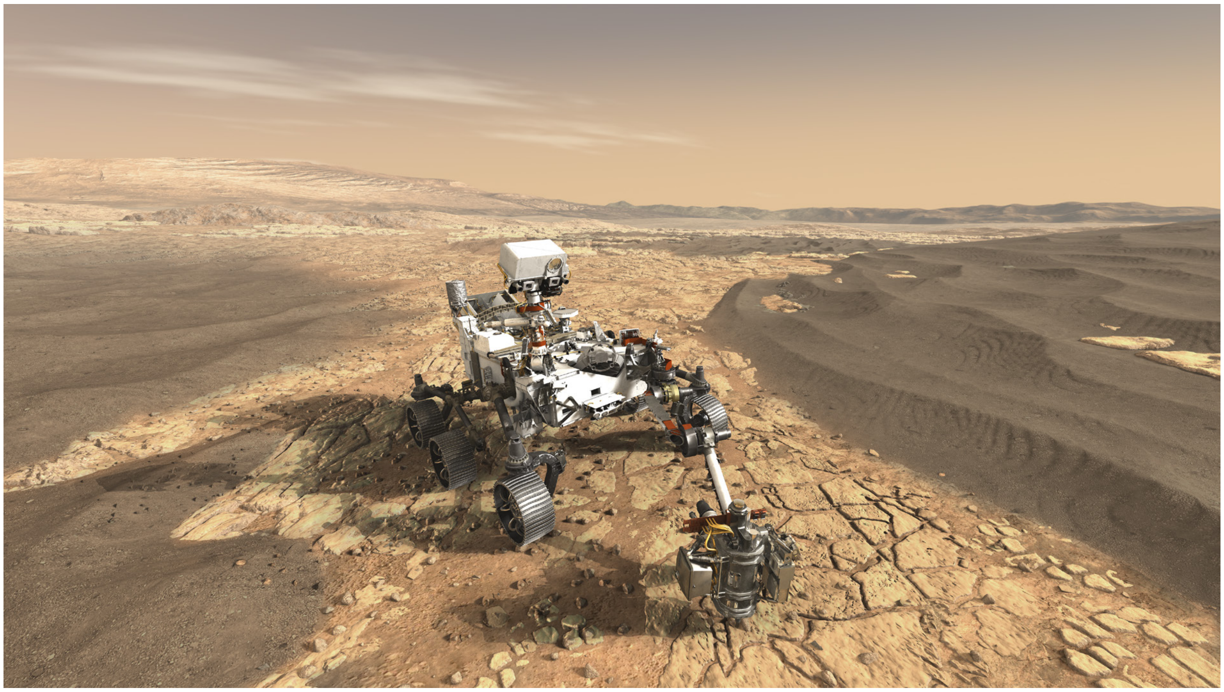

FIGURE 3.3 Artist rendition of NASA's Mars 2020 rover exploring the surface of Mars. SOURCE: NASA, "NASA's Mars 2020 Rover Artist's Concept #1," PIA21635, November 2017, https://photojournal.jpl.nasa.gov. Courtesy of NASA/JPL-Caltech.

Prior to the August 28 presentation,[16] Mars 2020 was officially a reflight of MSL with new science objectives, new instruments, and the ability to collect and cache samples that might or might not be collected and returned to Earth at a later time. As a result of this ambiguity, a conflict between the PPO and the mission implementation arose early in the Mars 2020 planning because MSL had not been subjected to the planetary protection requirements that the PPO believed would be needed for, what was in essence, the first phase of an officially unacknowledged sample return campaign.

Dry heat sterilization that had been used for Viking, for example, would likely damage Mars 2020 hardware irreparably or result in large amounts of organic outgassing. In addition, a new sampling and caching system for returnable samples was needed but had not yet been designed. While the project recognized from the start that planetary protection and scientific cleanliness would be a major issue, there emerged over a period of 3 years a fundamental disagreement between the project and the OPP both about level-1 requirements and about approaches in implementation. This 3-year period is outlined in Figure 3.4 and corresponds roughly to the time from authority to proceed in 2013 to the approval of the planetary protection plan in 2016.

The project took the position that planetary protection practices that worked for MSL would be acceptable for most hardware on Mars 2020 and that a systems approach would identify those specific parts that would require sterilization and that could be verified by appropriate modeling. The means of demonstrating the "sterility" of the parts requiring sterilization became a source of disagreement between the PPO and the project.

The in situ instruments, while not intended for life detection per se, would be sensitive to very small amounts of organic carbon, meaning they need to be very clean to avoid erroneous results produced by contamination on

[16] T. Zurbuchen, NASA, presentation to the committee August 28, 2017, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_181241.pdf.

the instruments. More challenging are the sample collection mechanism and canisters, which would be the first part of the Mars sample return campaign and thus be planetary protection Category V (restricted Earth return).

Several complex and contentious issues arose during the negotiations over planetary protection requirements and how they were to be applied to Mars 2020. Chief among those was tension between the goals of reducing potential contamination by viable organisms and total organic carbon. Meeting the two goals often proved mutually incompatible.

While the planetary protection community continues to hold Viking planetary protection procedures (i.e., sterilization by means of dry heat microbial reduction) as the gold standard, the cost constraint and required reuse of the MSL design effectively eliminated any full-spacecraft and most subsystem-level heat sterilization techniques. The cost for redesign of the spacecraft to withstand sterilization temperatures would have been prohibitive. Further, given the reuse of the MSL design, utilizing dry heat microbial reduction would have resulted in significant organic outgassing that would overwhelm the total organic carbon limits necessary to meet the mission's science objectives.

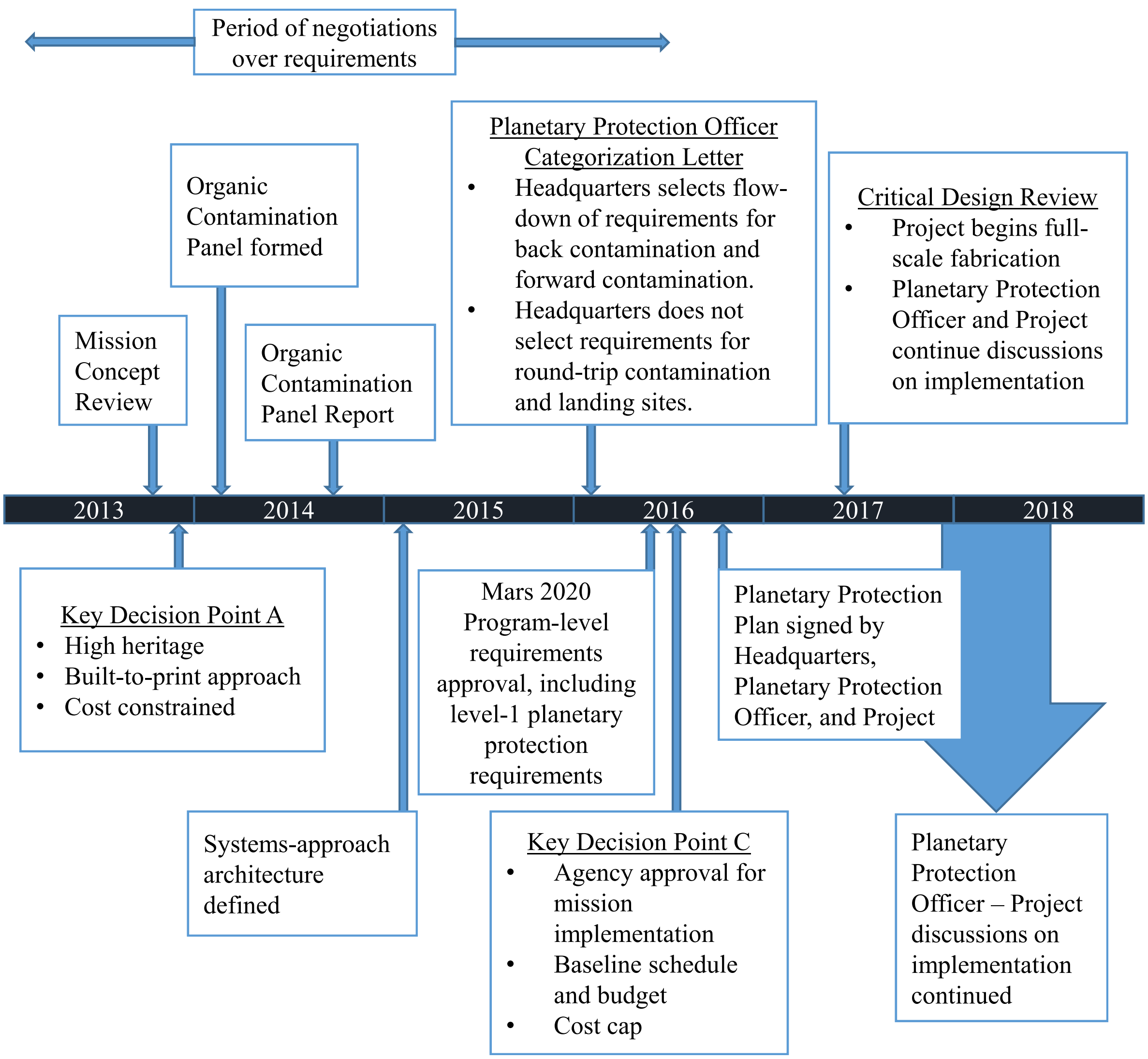

FIGURE 3.4 Timeline of major Mars 2020 development milestones and planetary protection events. SOURCE: Compiled by the committee from various NASA sources.

In addition, a "round trip" science integrity contamination requirement on the hardware cleanliness became an issue. The requirement's rationale, from a planetry perspective, was based on avoiding a "false positive" that might keep returned samples in containment permanently. Mars 2020 project officials objected to this rationale. As explained in the "Interim Report" section of Chapter 1, the committee concluded that there was no need for a separate round trip planetary protection requirement.

Finally, applying certain very prescriptive Viking era requirements (bake subsystem Z for X hours at temperature Y) into level-1[17] performance requirements that could require a new Mars 2020 design was a major hurdle.[18] Such standard prescriptions do not translate well as new missions emerge with differing designs and objectives, and thus more innovative approaches to planetary protection goals are needed. The planetary protection requirements for surface cleanliness could be satisfied by alternative techniques, provided that the project demonstrates the efficacy of the alternative method.

Mars 2020 Planetary Protection Issue Resolution

Deliberations among the science community, NASA officials, and Mars 2020 project managers determined that controlling total organic carbon would be the driving requirement for the hardware design and cleanliness. The science team concluded that the number of viable organisms could be reduced by selective heating of specific parts such as the sample collection tubes. Given the importance of organic contamination, NASA constituted an Organic Contamination Panel (OCP) of experts that provided guidance to the project.

The OCP recommended a total organic carbon (TOC) baseline limit of 10 ppb with a threshold (not to exceed) of 40 ppb. NASA officials and project managers accepted the recommendations of the OCP, and NASA's PPO endorsed these requirements. Organics were sorted into two categories to reflect the differing impact on science instrumentation and the relative importance of different sources of carbon.

With respect to round-trip cleanliness, both science and planetary protection objectives would benefit by minimizing the number of viable organisms in the sample tube, but a measurable (integer) value was needed as the level-1 requirement in order to determine specific allocations to the various potentially contaminating processes. Thus, the Mars 2020 team initially proposed a requirement of less than 10 culturable spores per sample. Following further discussions, a requirement of one viable organism per sample was proposed and eventually accepted by the OPP, and NASA headquarters officials established this limit as a level-1 requirement. However, the OPP still disagreed with the method by which the level of confidence in meeting that requirement was calculated, preferring to use a Viking era limit based on surface area of the sample tubes.[19]

In order to adapt the contamination control approach for Mars 2020 to produce an equivalent of Viking era post-sterilization cleanliness, the project instituted a systems engineering approach. By treating the sample contact hardware and associated instrumentation as elements of a much larger system with a total contamination budget, the project was able to vary the technique of sterilization and cleaning by functional element while still meeting the level-1 requirements. For example, while the sample collection tubes are baked at 350°C, other parts of the spacecraft and instruments were cleaned by alternative methods that were approved for MSL (e.g., treatment by chemicals, gasses, or lower temperature sterilization). According to the Mars 2020 project team's measurements and modeling described to the committee, the systems engineering approach will permit them to meet the limits

[17] The term "level-1" refers to NASA's highest-level mission performance requirements. Level-1 requirements are usually set by NASA headquarters to define the top-level objectives that a mission is required to meet to be successful. Level-2, and lower, requirements are derived (flow down) from level-1, and they provide increasing levels of implementation detail to assist engineers to ensure that their subsystems designs will ultimately support the level-1 requirements.

[18] Spaceflight mission engineers need high-level requirements—for example, "operate on Mars for one full year," that they can then "flow down" to specific requirements for subsystems, instruments, parts selection, and so on.

[19] While NASA resolved the dispute by approving the Mars 2020 team's proposed limit, this disagreement highlights the difference between the ESA approach and NASA. Chapter 3 explains that in ESA the project manager is given broad latitude to determine how top-level requirements flow down to translate into implementation requirements at spacecraft system and subsystem levels.

on viable microorganisms by more than a factor of 16,000 and to meet the limits on TOC with a margin of at least 37 percent.[20]

NASA conducted extensive reviews of the Mars 2020 project's approach to meet both planetary protection and returned sample contamination control requirements. The project conducted multiple independent peer reviews and subsystem reviews prior to critical design review and during Phase-C, and the Standing Review Board engaged at life cycle reviews and subsystem reviews. The NASA Headquarters Mars Program Office and SMD consulted additional experts at various points during development, including the Planetary Protection Subcommittee (PPS), the Returned Sample Science Board, an Independent Assessment Review, a Cache Cleanliness Science Study Team, and a Contamination Control and Planetary Protection Working Group.

Those reviews differed in content based on their particular focus and timing. However, according to the Mars 2020 program executive at NASA Headquarters, the review teams found the project team had a clear understanding of the technical challenges and had developed a credible approach that was compliant with requirements.[21] No showstoppers were identified, and each review group provided useful insights, which NASA took seriously.

As noted earlier, some time passed after the original decision to proceed with Mars 2020 in 2013 before these reviews were initiated. The project engaged with the PPS in November 2014 and in June and December 2015; the IAR met in March and October 2015, with a follow-up teleconference in January 2016; the CCSST did a quick-look in April 2016; the RSSB has had ongoing engagement since its inception; and the CCPPWG was initiated in summer 2016 with ongoing engagement with the project throughout 2017.

NASA's OPP objected to the project team's approach for three reasons:

- The new approach does not comply with the OPP's requirement for cleanliness of the sample hardware (equivalent to the Viking post-sterilization level);
- The systems approach cleanliness budget may not take into account all possible sources of contamination; and
- Modeling techniques such as computational fluid dynamics cannot be applied to organismal contaminants.

Nevertheless, NASA Headquarters approved this systems approach to contamination control. Although the long-running disagreement was eventually resolved by a NASA Headquarters decision, the committee found the failure to exercise a dispute resolution process sooner to be a troubling symptom of either a gap in NASA's policy or a breakdown in utilizing policies that were available. For the reasons indicated in the section "The OPP 's Move to the OSMA" later in this chapter, the committee expects that the move to OSMA will engender a cleaner, dispute-resolution process.

Lessons Learned from Mars 2020 Planetary Protection Implementation

The 3-year long (from about mid-2013 until mid-2016) and often contentious discussion between the Mars 2020 project team and the OPP suggests several lessons for any new policy development:

1. Early discussions and agreement between a given project team and PPOs, preferably at the mission definition stage, on the mission's planetary protection requirements and approach are of paramount importance. In particular, if a mission is moving into scientific or programmatic territory not fully developed (e.g., Mars sample return, humans to Mars or putative missions to the internal oceans of icy bodies) much dialogue and research is clearly warranted.
2. All planetary protection requirements imposed by NASA Headquarters need to reflect the agency's standard project management and systems engineering protocols.

[20] Mars 2020 project communication to committee. For an example of this new systems engineering process see I.G. Mikellides, A.D. Steltzner, B.K. Blakkolb, R.C. Matthews, K.A. Kipp, D.E. Bernard, M. Stricker, J.N. Benardini, P.S. Shah, and A. Robinson, The viscous fluid mechanical particle barrier for the prevention of sample containment on the Mars 2020 Mission, *Planetary and Space Science* 142:53-68, 2017.

[21] George Tehu, Mars 2020 program executive, NASA Headquarters, personal Communications to committee member G. Scott Hubbard, March 2, 3, and 16, 2018.

3. Implementation of planetary protection policies to specific missions need to embrace the principles of flexibility, adaptability, and openness to innovation:
   i. Current and future missions will be cost constrained or cost capped with all the attendant complications (e.g., reuse of heritage hardware, instruments from worldwide labs, distributed systems). Responsibility for dealing realistically with the inherent conflicts between cost constraints and rigorous planetary protection is best shared by decision makers who set the cost constraints, planetary protection officials, and mission managers.
   ii. Standardized or rote application of sterilization or contamination control mechanisms may not be feasible in a cost-capped, complex effort.
   iii. Project teams need to be able to devise implementation approaches to meet planetary protection requirements; defining implementation approaches is not an appropriate role for the OPP.
   iv. Project teams need to draw on the wealth of experience and expertise from the planetary protection community, via an independent advisory structure, to adequately formulate a reasonable and implementable mitigation strategy.
4. The process of setting requirements needs to include independent outside expert review.
5. Modeling techniques of contamination transport such as winds using computational fluid dynamics need to be further assessed by the OPP for ongoing application.
6. Existing planetary protection standards need to be reviewed and revised on a continuing basis to reflect modeling and testing results that improve detection sensitivity and mission compliance requirements within a peer-review framework that includes outside/foreign party participation (i.e., COSPAR, ESA, etc.).
7. Mechanisms for conflict resolution need to be understood, and utilized as early and often as necessary. The fact that the OPP has moved to OSMA, which has an established dispute resolution process, will help meet this need.

Finding: In connection with Mars sample return, planetary protection requirements for the sample containment, verification of containment, return vehicle, and sample receiving facility are not yet in place.

Recommendation 3.1: NASA's process for developing planetary protection policy for sample return missions should include early consultation with mission developers and managers, mission and receiving facility science teams, and microbiologists and include providing a means to use the best available biological and technological knowledge about back contamination and containment.

LESSONS LEARNED FROM THE EUROPA CLIPPER MISSION

The most recent planetary science decadal survey listed as its second highest priority a mission to Europa, the moon of Jupiter where the Galileo spacecraft identified the presence of a subsurface salty liquid water ocean, and thus a potential habitat for life.[22] In 2011, after a series of reviews, NASA concluded that a Europa mission, named Europa Clipper (see Figure 3.5), could be executed for approximately $2 billion to achieve the science objectives of examining the putative ocean under Europa's icy surface.

Europa Clipper and the Planetary Protection Process

Unlike Mars 2020, the Europa Clipper mission only requires an orbiter and will not involve any purposeful spacecraft contact with the icy moon. The Clipper mission is classified as planetary protection Category III (see Table 2.1), the key risk being the probability of accidental contact with Europa's ice crust. Clipper's orbits will take it very low (possibly as low as 25 km) above the icy surface, and that will increase the risk of a crash that could possibly contaminate a small part of the moon for future lander missions or, in the worst case, contaminate the

[22] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011.

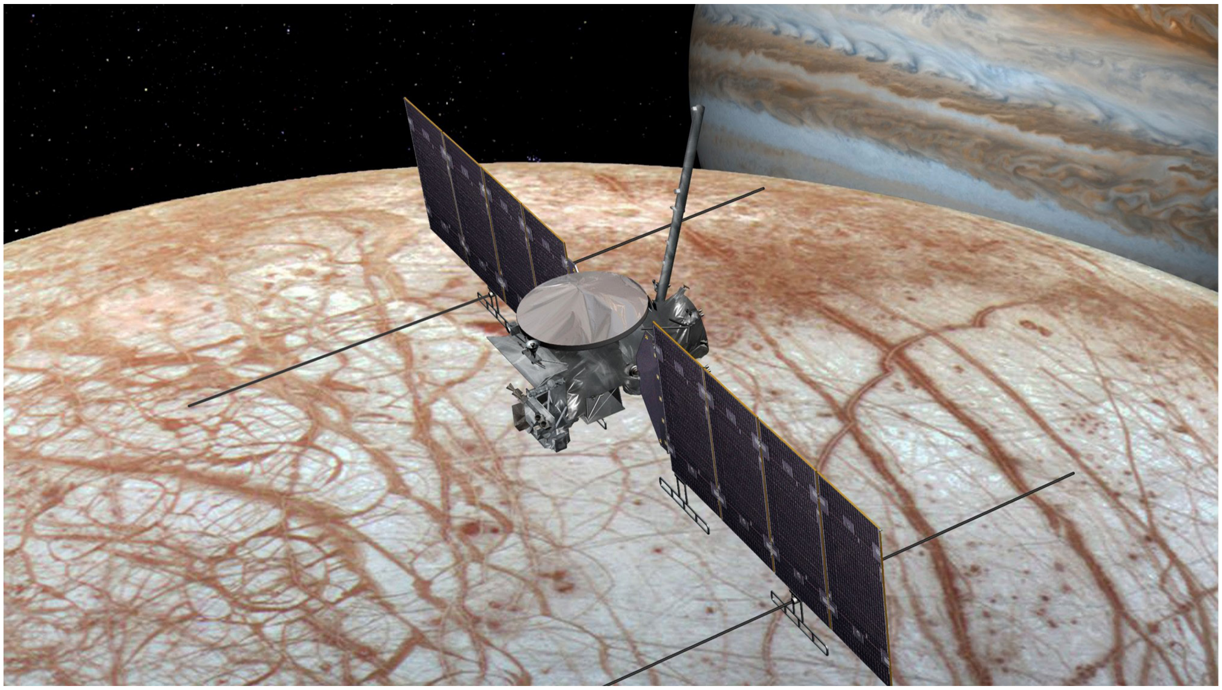

FIGURE 3.5 An artist's impression of NASA Europa Clipper spacecraft during one of its close flyby of Europa. SOURCE: NASA, "Europa Clipper Spacecraft (Artist's Concept)," 2016, PIA20025, https://photojournal.jpl.nasa.gov. Courtesy of NASA/JPL.

europan ocean. The project team has developed an approach to navigation, spacecraft propulsion, orbital dynamics, and risk mitigation that will ensure with a high degree of confidence that the spacecraft will not contact Europa.

As with other planetary exploration spacecraft, there is also an end-of-mission plan that calls for a planetary protection procedure to eliminate the potential for contaminants inside the spacecraft to touch Europa. In some cases, such as the Cassini (Saturn) or Galileo (Jupiter) orbiters, the spacecraft has been directed to dive into the planetary atmosphere, burning up as it does so. The currently planned end-of-mission plan for Europa Clipper is a disposal at the moon Callisto.[23] The outermost of Jupiter's four Galilean satellites, Callisto affords the energetically simplest solution (i.e., least demanding in terms of propulsion requirements) for disposal that satisfies the planetary protection requirements. Although Callisto likely has a liquid water ocean deep below its crust, there is no evidence that matter has been or is transferred between the ocean and the surface so that a spacecraft impact on the surface is not considered to be a forward contamination risk.

The icy body contamination requirement contained in NPR 8020.12D states the following: "The probability of inadvertent contamination of an ocean or other liquid water body must be less than 1×10^{-4} per mission."[24] The document defines icy body contamination as "the introduction of a single viable terrestrial microorganism into a liquid-water environment." The 10^{-4} criterion was suggested by the SSB in 2000,[25] but it can be traced back to rather arbitrary estimates made in the early 1960s.[26] In order to address the 10^{-4} requirement, the Europa Clipper

[23] T. Lamy, B.B. Buffington, S. Campagnolay, C. Scott, and M. Ozimek, "A Robust Mission Tour for NASA's Planned Europa Clipper Mission," 2018 Space Flight Mechanics Meeting, doi:10.2514/6.2018-0202, p. 6, https://www.researchgate.net/publication/322314079_A_Robust_Mission_Tour_for_NASA%27s_Planned_Europa_Clipper_Mission.

[24] Although NID 8020.109 is currently the approved directive, the Europa Clipper mission is subject to the previous version NPR 8020.12D per its level-1 requirements.

[25] NRC, *Preventing the Forward Contamination of Europa*, National Academy Press, Washington, D.C., 2000, pp. 2 and 22-23.

[26] See, for example, B. Sherwood, A. Ponce, and M. Waltemathe, "Forward Contamination of Oceans Worlds: A Stakeholder Conversation," conference paper IAC-17.A1.6.1x40187, 68th International Astronautical Congress, Adelaide, Australia, 2017.

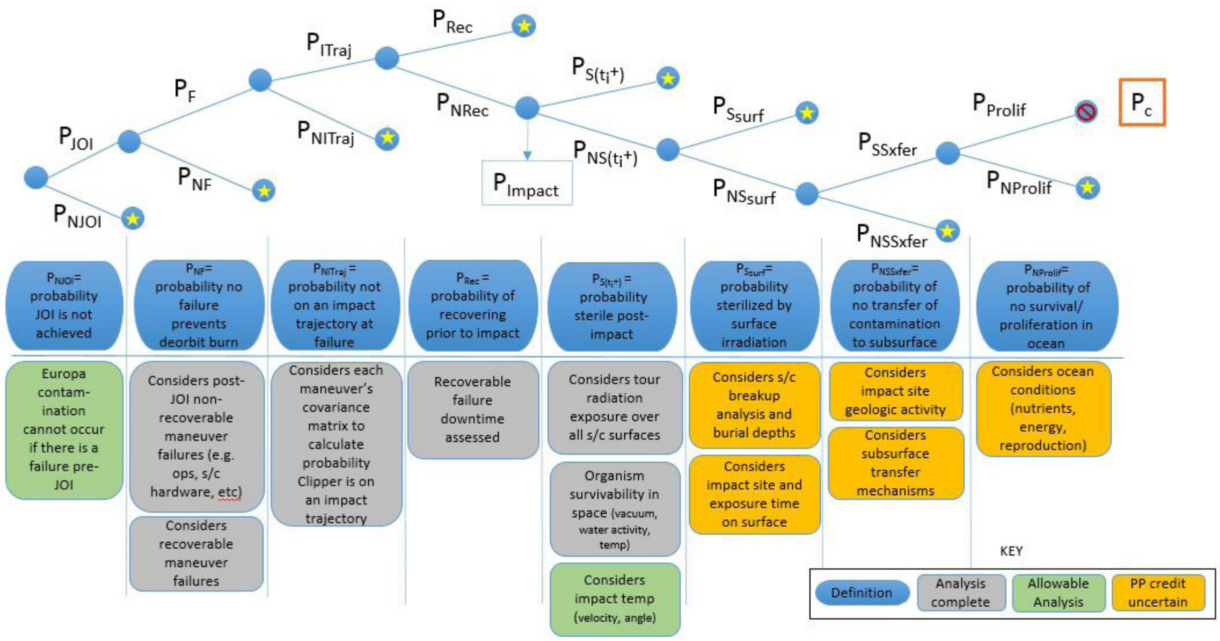

FIGURE 3.6 A schematic depiction of the Icy Bodies Planetary Protection Probabilistic Model used to calculate the probability of icy body contamination. SOURCE: Redrafted from an original provided by the Europa Clipper Project, NASA, Jet Propulsion Laboratory

project has developed a mathematical Icy Bodies Planetary Protection Probabilistic Model (IBPPPM) for calculating the probability of icy body contamination and deriving allowable initial bioburden (bioburden on the spacecraft at launch) such that the requirement is satisfied.[27] The IBPPPM has been designed to demonstrate compliance with regard to Europa, Ganymede, and Callisto. Some of the key questions the model answers are the following:

1. What is the probability (P_c) of icy body contamination?
2. What is the probability of impacting Europa, Ganymede, or Callisto?
3. What are feasible initial bioburden allocations (by bioregion)?
4. What regions of the flight system are driving P_c?
5. What groups or types of organism are driving P_c?
6. What environmental factors (e.g., ionizing radiation) have the most effect on P_c?
7. What are the effects of a given cleaning protocol on P_c?

This model has been provisionally accepted by the PPO. Figure 3.6 shows graphically how the model works, representing the Europa contamination event tree, and is intended to be an illustration that communicates the various events considered in the model. It is not intended for direct use in mathematical calculations.

In the committee's discussion with the Europa Clipper project staff about their approach, several issues emerged that are relevant to future policy development. These issues included the following:

1. NASA's NPR 8020.12D contains some of the parameters and their supporting rationale required for this model, and these are level-1 requirements imposed on the project. However, these level-1 requirements do not contain all of the essential parameters needed for the model. As a result, the project has been evaluating

[27] M. DiNicola, K. McCoy, C. Everline, K. Reinholtz, and E. Post, "A Mathematical Model for Assessing the Probability of Contaminating Europa," 978-1-5386-2014-4/18/, IEEE Aerospace Conference, 2018.

the scientific evidence for these additional parameters and has used their results to specify the missing parameters as part of the project's definition of level-2 requirements, a normal project function. Although the PPO tentatively approved the model, disagreements have remained over some of these assumptions and parameters, particularly regarding the levels and efficacy of jovian radiation belt exposure for sterilization of the spacecraft and the transport of viable microorganisms from Europa's surface to the ocean.

2. The PPO has directed the project to use specific values for these missing parameters without following standard NASA protocols for flowing level-1 requirements to the project. These parameters have been specified by letter, email, or verbally. Box 3.2 describes some of the most important parameters that have been imposed on the project by the PPO, the method of their imposition, their source, and an analysis of their validity.

It appears that a conflict resolution process has either been lacking or not implemented. That is, the PPO's and the project's current understanding of how planetary protection requirements are imposed has not included the ability to disagree with the PPO's specification of parameters.

These issues illuminate important lessons learned that are relevant to future planetary protection policy development and the need for an orderly process for developing and peer reviewing requirement details for missions for which there is no prior experience.

BOX 3.2
Planetary Protection Officer Imposed Parameters in the Icy Bodies Planetary Protection Probabilistic Model

1. The planetary protection officer (PPO) has defined the surface irradiation credit in the planetary protection categorization letter to be 0 days. That is to say, any viable organism that lands on the surface will remain viable forever because there is no allowed credit from the Jupiter, solar, or cosmic radiation that is bombarding the surface of Europa. During 2017, however, the PPO verbally stated that 3.5-days' worth of radiation credit will be allowed. This means that any viable organism that remains after 3.5 days will remain forever. The rationale provided to the project is that the spacecraft could land in a crack that leads directly to the subsurface ocean. However, the current best estimate for the age of the Europa surface is 20 to 180 million years old.
2. The PPO has defined the radiation sterilization threshold as 10 Mrad. This means that it takes a radiation dose of 10 Mrad to fully sterilize the spacecraft, independent of other lethality modalities. The PPO provided this parameter verbally in 2015, but this parameter is different than the one provided to the JUNO mission, another spacecraft currently orbiting Jupiter, which was only 7 Mrad. Regardless, an internal project assessment of current literature research suggests that 5.5 Mrad is adequate to fully sterilize the spacecraft.[1] While some extremophiles may exhibit stated hardiness, no such organisms have been found alive in Jet Propulsion Laboratory or Kennedy Space Center cleanrooms to date. Genetic inventory from both cleanrooms published to date shows that 5.5 MRad is sufficient for sterility of all detected organisms, most of which perish at much lower radiation thresholds.
3. The PPO specified that the probability of a single viable organism transferring from the Europa surface to the subsurface ocean and the subsequent proliferation of that organism to be one. Thus there is a 100 percent probability that any organism that lands on the surface will reach the ocean and that this organism will begin to multiply. There is no consideration for the type of organism; no consideration for the efficacy of surface-to-subsurface transfer mechanisms; and, as stated above, any organism that remains after 3.5 days has an infinite amount of time to make this transfer.

[1] M. Ruehle, Jet Propulsion Laboratory, "Planetary Protection for Europa Clipper," in preparation for publication, Pasadena, CA.

- *Lesson 1*. The absence of a complete set of planetary protection requirements can cause a major disruption to project development, particularly if these subsequently are imposed late in the project life cycle. Early definition of requirements is essential to effective project implementation.
- *Lesson 2*. The imposition of any requirements, including planetary protection requirements, on spaceflight missions needs to follow standard system engineering protocols to ensure that every appropriate requirement is properly understood, implemented, and can be adequately verified.
- *Lesson 3*. NASA's conflict resolution process is essential in executing spaceflight missions, and its use is required when disagreements between technical authorities and projects occur. This ensures that senior NASA management understands the risks, benefits, and consequences of decisions when accepting any particular position by either party.
- *Lesson 4*. The early establishment of requirements, including those for planetary protection, has been shown to minimize the risk and uncertainty of future design changes and thus increased cost for the missions. Future research into the important parameters for these missions, including reevaluating legacy requirements such as those from Viking, will likely reduce the cost of these missions while still meeting U.S. obligations under Article IX of the OST.

Future Ocean World Missions

There is a chance that the Clipper mission will be followed in the future by a lander and maybe even an ocean-exploring Europa submarine. The Jet Propulsion Laboratory is currently studying a Europa lander (see Figure 3.7),[28] and an initial mission concept was presented at a Mission Concept Review in June 2017. At the request of the NASA SMD, the Jet Propulsion Laboratory is now investigating additional options. If this and any other follow-on missions were to be implemented, the planetary protection requirements that apply to landing on a body potentially capable of supporting life will surely come into play. The formulation of planetary protection policies for such missions will need to be informed by new research. In particular the scientific question of whether

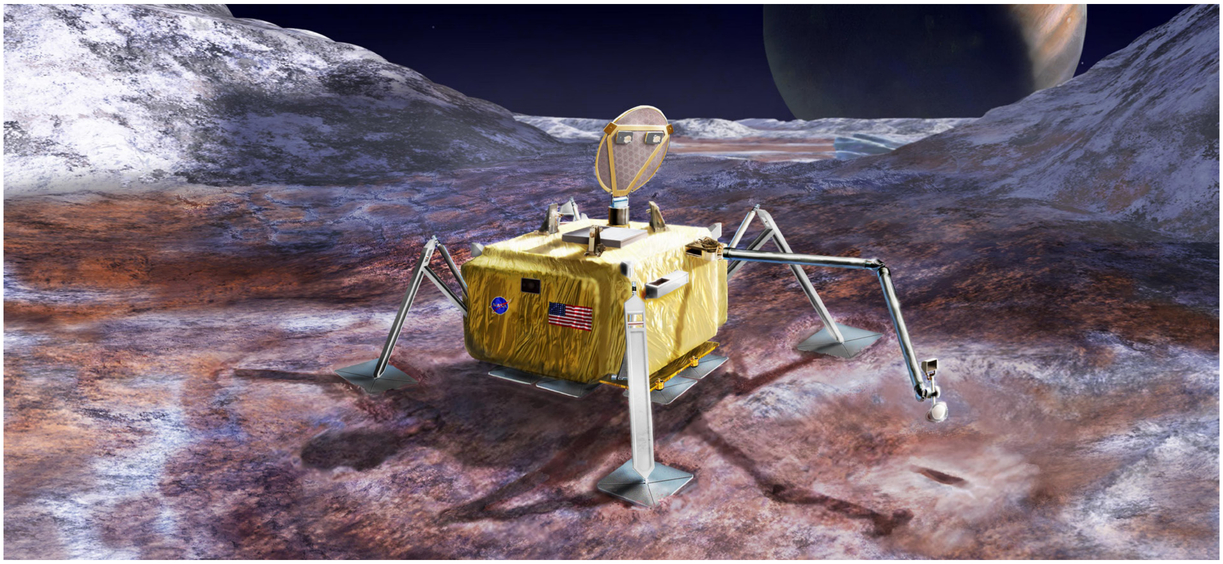

FIGURE 3.7 An artist's impression of a Europa lander. Such a mission is currently under study by NASA for launch in the mid-to-late 2020s. SOURCE: Courtesy of NASA.

[28] NASA, *Report of the Europa Lander Science Definition Team*, JPL D-97667, Jet Propulsion Laboratory, Pasadena, California, 2017, https://europa.nasa.gov/resources/58/europa-lander-study-2016-report.

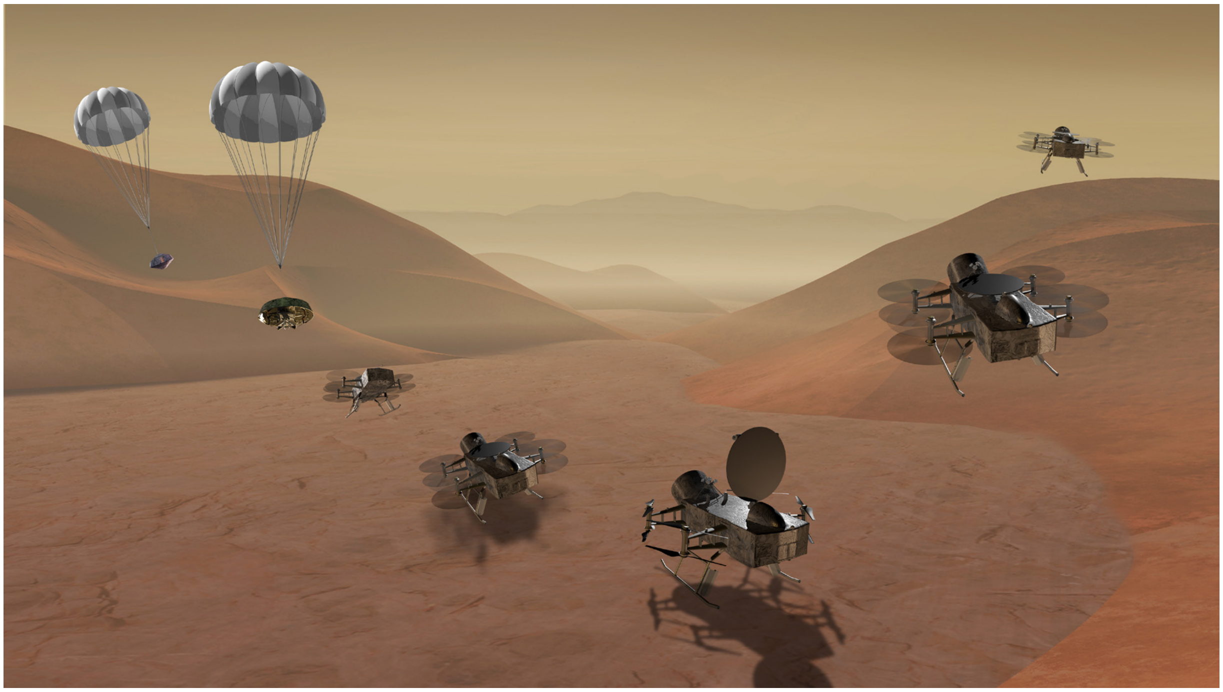

FIGURE 3.8 An artist's conception of Dragonfly, a rotorcraft lander designed to explore Titan. It is currently under study as one of two possible candidates for NASA's fourth New Frontiers mission for launch in the mid-2020s. SOURCE: Courtesy of Johns Hopkins University Applied Physics Laboratory/Steve Gribben.

a single organism, deposited on the surface, could contaminate Europa's entire ocean within a reasonable period of biological exploration needs to be revisited.

NASA recently selected two finalists for the next mission in its New Frontiers Program and two missions for further technology development. One of the former missions is Dragonfly (see Figure 3.8),[29] a rotorcraft lander designed to study Titan's habitability and methane cycle. One of the latter missions is the Enceladus Life Signatures and Habitability, a plume fly-through spacecraft, which will receive funds to develop cost-effective techniques that limit spacecraft contamination and thereby enable life detection measurements on cost-capped missions. Although not apparently directly related to planetary protection research, this technology funding will help enable future planetary protection measures. As with Europa Clipper, this will be a flyby mission and will not attempt to land on the surface of Enceladus. However, very similar issues to Europa Clipper will exist including the ones listed in Box 3.2.

ASSESSMENT OF NASA'S PLANETARY PROTECTION POLICY DEVELOPMENT PROCESS

Assessment of NASA Planetary Protection Policies

While NASA's formal policy documents define the authority of NASA officials, including the PPO for planetary protection, for establishing top-level (i.e., level-1) program requirements,[30] the committee did not find these

[29] For more about Dragonfly, see http://dragonfly.jhuapl.edu.

[30] Top-level requirements are labeled as level-1 requirements by the SMD and contained in an appendix to a mission's parent program plan.

documents to be either clear or explicit about how top-level requirements to deal with first-of-a-kind situations are to be developed or about how authority for establishing lower-level requirements is delegated from headquarters down to project officials. As described in the next section, the NPR policy requirements were insufficient, and new additional level-1 requirements for recent projects such as Mars 2020 and Europa Clipper were not adequately defined early in the projects' lifetimes. Consequently, there were situations in which the OPP needed to levy additional requirements intermittently during the project. In a more orderly project planning and development process, the committee would have expected that level-1 requirements would be sufficiently complete at the outset so that translation to level-2 and lower requirements would be easily traceable to the higher-level requirements very early in project formulation. Failure to do so represents a shortcoming in NASA's planetary protection policy development processes.

As an example of where the current policies fail to contain all the requirements that are necessary to implement planetary protection within a spaceflight mission, the current policy does not specify a period of biological exploration for the icy moons of the outer solar system.[31] Typically, the PPO issues a categorization letter that defines the planetary protection category for that mission. This letter may include additional requirements to be imposed on the project that are not contained in the NASA NPR.[32] In the case of Mars 2020 and Europa Clipper, the OPP also used other more informal methods for imposing these requirements (i.e., either verbally or via email, or, in extreme cases, by rejecting project-level planetary protection documents rather than providing specific guidance) for which there did not appear to be a solid scientific basis.

This ad hoc process raises an issue concerning how to impose previously undefined planetary protection policy and requirements. Ad hoc requirements can also create conflict between the OPP and the mission project team, particularly if the basis of the requirements are not mutually agreed. When a situation like this occurs, NASA has a standard conflict resolution process defined in NPD 1000.0 and NPR 7120.5 that can be used to resolve such disagreements. NASA's process expects that each requirement will have a scientific and/or engineering and/or policy basis that is understood by the relevant stakeholders. Furthermore, using letters, verbal direction, and non-approval are not in accordance with these policies or with good systems engineering practices. (See Appendix C for a description of NASA's policies on good program and project management and systems engineering practices.) As noted above for Mars 2020, this standard approach was only recently used to resolve differences between the OPP and the mission project team.

The committee learned that NASA SMD recently began instituting a more orderly process by establishing some planetary protection requirements as part of their normal definition of the top-level requirements for the mission. This more formal process is in accordance with NASA's requirements for project management and systems engineering. However as noted above, some planetary protection requirements were being imposed without adequate review and concurrence. The recent efforts in SMD to ensure a more systematic process are expected to continue with the transfer of the OPP to OSMA, however as the committee discusses below, the lack of an established advisory committee means that there is still no platform for independent expert review.

> **Finding:** Because NASA planetary protection policies have been incomplete with respect to unique aspects of new, first-of-a-kind missions, requirements for these spaceflight missions have not always been clearly defined at the beginning of a project or communicated to projects in accordance with NASA's standard protocols for imposing headquarters-level requirements.

> **Finding:** The NASA OPP and the mission project teams have not been following standard NASA spaceflight program and project management and systems engineering practices. In particular the OPP has been issuing level-1 requirements informally through letters, email, and verbal direction, and the project teams have

[31] An NRC 2012 report, *Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies* (The National Academies Press, Washington, D.C.), recommended 1,000 years.

[32] As an example, the Europa Clipper categorization letter, dated September 30, 2016, contains a requirement that the probability of transferring a viable organism from the surface of Europa to its sub ocean is 1, even though the current best estimate on the age of Europa's ice is millions of years.

accepted this practice even though this methodology is inconsistent with normal NASA practices. NASA officials delayed unnecessarily in taking advantage of NASA's established conflict resolution process.

Recommendation 3.2: NASA should assess the completeness of planetary protection policies and initiate a process to formally define the planetary protection requirements that are missing. NASA should ensure that all future headquarters planetary protection requirements imposed on spaceflight missions follow NASA standard project management and systems engineering protocols for review, approval, and flow-down of requirements and, when disagreements occur, ensure that NASA's conflict resolution process is followed. For future new situations such as private-sector missions to other bodies or human exploration of Mars, the policies and their potential impacts should be evaluated and examined well in advance of a mission start.

As noted in the section "Overview of NASA's Process for Developing Planetary Protection Policy" above, COSPAR can make a change to planetary protection guidance without the concurrence of relevant NASA stakeholders; something not done for other types of NASA internal policy and procedural directives. For example, the COSPAR Bureau approved changes in its planetary protection policy for Mars Special Regions (Appendix B) in March 2017.[33] These changes originated as a result of discussions held at a COSPAR planetary protection colloquium held in September 2015.[34] These changes had not been vetted by all affected NASA stakeholders. As examples, these changes modified COSPAR planetary protection guidance concerning human activities on Mars that had not been reviewed or concurred with by the NASA human spaceflight community.[35] Moreover, there is additional language on required analyses of Mars landing site ellipses that was not vetted by the NASA organizations responsible for assessing landing sites. Notably, only 26 people, with 2 people representing NASA and 2 the Jet Propulsion Laboratory, attended this colloquium at which the new language was suggested. This small number of participants hardly represents the breadth of international or U.S. stakeholders. Once approved internationally, affected organizations in NASA will find it difficult to disagree with the proposed NASA updates to its internal policies. However, it could be argued that changes in COSPAR planetary protection guidelines proposed in September 2015 could have been vetted by NASA and international stakeholders in the 18 months leading up the March 2017 meeting of the COSPAR Bureau. Furthermore, changes to COSPAR's policy with respect to Enceladus also were proposed during the same September 2015 colloquium and also were approved by the COSPAR Bureau at its meeting in March 2017.[36]

Finding: The COSPAR process can approve international guidance on planetary protection without such guidance being reviewed and agreed upon in advance by the range of NASA stakeholders that participate in making NASA policy on planetary protection.

Recommendation 3.3: NASA should ensure that in assessing changes to COSPAR planetary protection policies and requirements there is a process to engage the full breadth of NASA stakeholders, including the spaceflight mission and science communities. This process should be at least as disciplined as the process NASA uses to review, concur, and approve changes to its own policies.

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[33] G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December 2017, pp. 12-24.

[34] G. Kminek, V.J. Hipkin, A.M. Anesio, J. Barengoltz, P.J. Boston, B.C. Clark, et al. Meeting Report: COSPAR Panel on Planetary Protection Colloquium, Bern, Switzerland, September 2015, *Space Research Today*, No. 195, pp. 42-51.

[35] A reviewer informed the committee that "a representative of NASA human spaceflight" participated in the 2016 business meeting of COSPAR's Panel on Planetary Protection at which the report of the September 2015 colloquium was discussed and the recommendation to change the COSPAR policy was formulated.

[36] G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December 2017, pp. 12-24.

The OPP's Move to OSMA

Based on the information NASA provided the committee on its decision to move the OPP to OSMA from SMD, the committee believes this change is well founded and can improve how NASA manages planetary protection policy. Under the former arrangement in which the OPP resided in SMD, there was an inherent conflict of interest because the dispute resolution official was directly responsible for science missions as well as planetary protection. As a part of OSMA, the OPP can function more like a NASA technical authority, and disagreements between the OPP and flight projects on planetary protection issues can be resolved through formal OSMA conflict resolution procedures that have worked well in other areas within OSMA's purview.[37]

The OPP's move to OSMA could also help alleviate staffing challenges the OPP has faced in the past. The small size of the OPP (typically no more than two NASA civil servants plus occasional consultants and contractors) is inadequate for the new challenges planetary protection policy faces. As a part of OSMA, the OPP can take advantage of OSMA's practice of delegating verification activities to OSMA offices in NASA centers responsible for executing space missions. However, NASA has not completed the OPP's transition to OSMA, and a number of issues remain unclear. For example, NASA officials could not yet tell the committee where the OPP's research and technology function will be located in NASA and how it will operate.

Three pending developments will create a need for planetary protection policies that go beyond the demands of the past several decades:[38]

- A Mars sample return campaign and a mission to land and explore the ocean under the ice of Europa, both of which will include life detection objectives;
- Human spaceflight to Mars possibly in the late 2030s; and
- Potential Mars missions by space entrepreneurs, such as SpaceX.

Developing planetary protection policies that encompass these initiatives will require negotiations that cross international boundaries (possibly via COSPAR for international planetary protection policy), federal agency lines (e.g., with the Federal Aviation Administration for private-sector space missions and U.S. health and environmental agencies for sample returns), and multiple NASA directorates for human spaceflight and science. Such a breadth of responsibility may be better placed at the level of the NASA Administrator's office, perhaps through the NASA Chief Scientist, rather than in OSMA or in any individual mission directorate.

Finding: NASA has not finalized all issues related to transferring the OPP from SMD to OSMA or revised its policy directives, procedural requirements, and advisory structure to reflect this important change.

Recommendation 3.4: NASA should expeditiously complete the transition of the OPP to OSMA and clarify the remaining issues concerning roles, responsibilities, resources, and locations of OPP functions. The Chief of the Office of Safety and Mission Assurance should complete the Science Mission Directorate's move toward instituting a formal method for imposing planetary protection requirements that are in accordance with standard NASA systems engineering practices.

[37] The transfer of the PPO from SMD is consistent with a prior National Academies recommendation concerning Mars sample return: "There is a critical need for . . . the office of NASA's planetary protection officer to be formally situated within NASA in a way that will allow for the verification and certification of adherence to all planetary protection requirements. . . . Clear lines of accountability and authority at the appropriate levels with NASA should be established for . . . the planetary protection officer, in order to maintain accountability and avoid any conflict of interest with science and mission efforts." For more details, see, NRC, *Assessment of Planetary Protection Requirements for Mars Sample Return Missions*, The National Academies Press, Washington, D.C., 2009, p. 69.

[38] A fourth potential issue was raised by Lisa Pratt, NASA's new planetary protection officer during a presentation to the SSB's Committee on Astrobiology and Planetary Science on March 28, 2018. Dr. Pratt noted that CubeSats and other small spacecraft, whether flown singly or as adjuncts to traditional (large) missions, present new planetary protection concerns for ensuring that they are compliant with all necessary planetary protection requirements. Additional discussion of this topic is beyond the scope of the current study.

Recommendation 3.5: NASA should develop an agency-wide strategic plan for managing the planetary protection policy development challenges that sample return and human missions to Mars are creating.

An Independent Planetary Protection Advisory Committee

Throughout its history and across its missions, NASA has routinely solicited independent advice from formally constituted advisory bodies consisting of experts drawn from among national and international scientific and technical communities. The members of these advisory bodies are drawn, typically, from both within and outside of government, independent stakeholders, and representatives of other agencies with overlapping responsibilities, as well as, when appropriate, individuals with special expertise in space law, ethics, and public communication.

The OPP had long been advised by such a body encompassing all these components, owing to the breadth, potential impact, and likely broad public interest and concerns that planetary protection issues could engender. Over the past approximately two decades, this independent advisory apparatus operated originally as a Planetary Protection Advisory Committee (PPAC) of the NAC, and, more recently, as a subcommittee (PPS) of the NAC's Science Committee.[39] For a variety of reasons, the PPAC/PPS experienced occasional hiatuses in its authorization to meet or to appoint members. The PPS had not met for a year or more when, in late 2017, it was formally disbanded by NASA.

Agency officials have final authority in decision making, as well as final accountability for the outcomes of their decisions. Nonetheless, it has long been accepted that decision making is improved, both in the formulation of policies and the implementation of policies, if the issues are thoughtfully aired and analyzed by committed independent experts. Moreover, engaging independent experts drawn broadly from the involved communities, provides an effective mechanism to promote communication and understanding in both directions. And, ultimately, the scientific, technical, and space-industry communities will be more likely to accept and take ownership of decisions in which they—through representation—have a role in formulating and influencing final decisions.

In the past, at least post-Apollo, planetary protection has been centered mainly in the Science Mission Directorate and its predecessor organizations and focused on issues of forward contamination. In the few instances of returned-sample missions, the samples originated on bodies only remotely contemplated as having the possibility of deleteriously contaminating Earth.[40] Thus, for those missions, backward contamination did not loom as large as might be the case going forward. For many missions currently contemplated, the stakes of contamination are higher in all dimensions, not only involving forward contamination, primarily a scientific concern, but also including dimensions that have the potential to engender significant public concerns, even alarm, around the possibility bringing extraterrestrial organisms to Earth.

Additionally, the potential stakeholders within NASA encompass a much larger range than heretofore of NASA mission directorates. At the same time, the cast of actors in deep space may be expanding to including nongovernmental entities. These factors, the committee argues, suggests that a planetary protection advisory group might most effectively be constituted at a level of the agency having broad, cross-cutting purview—perhaps at the Administrator or Chief Scientist level within NASA.

Finding: The development and implementation of planetary protection policy at NASA has benefited in the past from a formally constituted independent advisory process and body. As this report is written, both the advisory body and process are in a state of suspension.

Recommendation 3.6: NASA should reestablish an independent and appropriate advisory body and process to help guide formulation and implementation of planetary protection adequate to serve the best interests of the public, the NASA program, and the variety of new entrants that may become active

[39] During the period 2012-2015, the PPS provided advice to NASA regarding the need to develop planetary protection requirements for human exploration missions, assess planetary protection lessons learned from the MSL mission, develop bioburden accounting software for future Mars sample return missions, and establish interactions between the OPP and OSMA.

[40] The Genesis mission collected samples of the solar wind and the Stardust mission collected particles from the tail of a comet.

in deep space operations in the years ahead. The advisory body and process should involve a formal Federal Advisory Committe Act committee and interagency coordination, as well as ad hoc advisory committees, if and as circumstances dictate. This advisory apparatus should be situated and engage within NASA at a level commensurate with the broad cross-cutting scope of its purview and the potentially broad interests that the involved issues may engender.

The roles of the advisory body include the following:

- Serve as a sounding board and source of input to assist in development of planetary protection requirements for new missions and U.S. input to the deliberations of COSPAR's Panel on Planetary Protection;
- Provide advice on opportunities, needs, and priorities for investments in planetary protection research and technology development; and
- Act as a peer review forum to facilitate the effectiveness of NASA's planetary protection activities.

Capturing Scientific Advances in the Development of Planetary Protection Policy

The science that underpins planetary protection policies has always involved some uncertainty and debate about the basis for estimates of likelihood of viable organisms on a spacecraft or on a solar system body. Many factors that influenced forward contamination mitigation strategies in the late 1950s and early 1960s, such as estimates of the allowable bioburden on or the probabilities of contamination of a spacecraft, used statistical estimates that were sometimes little more than educated guesses.[41,42,43] These approaches were adopted well before the genome era of microbiology.

With a relatively limited budget (see next section below), NASA's OPP has funded research to begin to apply new advances in biotechnology and approaches to bioload reduction to planetary protection procedures. Work on the former has led to acceptance of certain biochemical assay techniques on a case-by-case basis, namely ATP (adenosine triphosphate) and LAL (limulus amebocyte lysate) assays, as supplements to the so-called NASA Standard Assay.[44] Additionally, molecular techniques have been adapted to inventory the microbial burden in clean rooms and on spaceflight hardware[45] and used during spacecraft assembly campaigns and on the International Space Station.[46]

With respect to approaches to bioload reduction beyond the standard dry-heat, microbial reduction used for the Viking spacecraft, NASA has certified the use of hydrogen peroxide vapor as a means to sterilize exposed surfaces. However this technique does not impact organisms within enclosed volumes or encapsulated in other materials. Other techniques that have been used at the subsystem or component level by NASA and other space agencies include the following:[47]

- Autoclaving for tubing and cleanroom materials
- Gamma radiation for the sterilization of the parachute for the Beagle-2 Mars lander
- Low-temperature hydrogen peroxide plasma for the batteries and electronic assemblies of the Beagle-2 Mars lander

[41] C. Sagan and S. Coleman, Spacecraft sterilization standards and contamination of Mars, *Journal of Astronautics and Aeronautics* 3(5):22-27, 1965.

[42] C. Sagan and S. Coleman, "Decontamination Standards for Martian Exploration Programs," pp. 470-481 in NRC, *Biology and the Exploration of Mars*, National Academy of Sciences, Washington, D.C., 1966.

[43] S. Schalkowski and R.C. Kline, Jr., "Analytical Basis for Planetary Quarantine," pp. 9-26, in L.B. Hall (ed.), *Planetary Quarantine*, Gordon and Breach, London, U.K., 1971.

[44] See, for example, https://planetaryprotection.nasa.gov/requirements.

[45] M.T. La Duc, K. Venkateswaran, and C.A. Conley, A genetic inventory of spacecraft and associated surfaces, *Astrobiology* 14:15-23, 2014

[46] Lang et al., A microbial survey of the International Space Station (ISS), *PeerJ* 5:e4029; doi:10.7717/peerj.4029, 2017.

[47] See, for example, https://planetaryprotection.nasa.gov/requirements.

The communities now involved in modern biological sciences are exploding with more new discoveries—for example, about extremophiles, biofilms, prions, and genomics—that are likely to be relevant to planetary protection science. For example, genome sequencing of environmental samples (e.g., permafrost, sand, and feces) has made a dramatic change in how life is detected now on Earth.[48] Modern genomic analysis of extreme environments on Earth generates detailed lists of which particular bacterial species and which particular genes are necessary to thrive in the terrestrial environments that are the closest analogues to Mars or icy bodies, such as polar or desert desiccated environments or frozen oceans, etc. The organisms that thrive on human skin or the soles of shoes of spacecraft assembly technicians are not the same organisms found in Antarctic oceans, dry valleys, or in the stratosphere that are the closest analogues to the environments where Mars or icy satellite landers would explore. The organisms from spacecraft cleanrooms would not be predicted to grow and reproduce on Mars or icy bodies. Consequently, rather than treating every bacterial species as a potential growing pathogen for Mars and elsewhere, a more nuanced view about which microbes to avoid bringing to Mars or icy bodies might be to specify the particular microbes that are found in the particular Earth regions most like landing sites on Mars or icy bodies, and to survey spacecraft assembly rooms for those particular organisms.[49,50] If developments such as these prove feasible, they could have profound impacts on the way planetary protection is implemented in the future. For example, information about the abundances of microbes with known environmental tolerances might permit credit to be taken for environmental exposure, when implementing a probabilistic approach for missions to the outer planets.

The science of planetary protection will need to keep pace with the latest advances in biological science and technology.[51] However, the field is relatively narrow—a niche field—compared to the extraordinarily broad field of biology in which it resides. Based on data supplied to the committee by NASA's OPP, there are a few dozen very active participants in recent COSPAR planetary protection science meetings.[52] Meeting organizers have had mixed success at recruiting microbiologists to participate in meetings where new scientific findings are considered for their implications for planetary protection policy. For example, scientists affiliated with the NASA Astrobiology Institute, which have been active in studies relating to extremophile microbes on Earth and what sorts of biochemistry they use and on origin of life, have not been substantially represented in such meetings. Practical considerations—for example, availability of support for travel to COSPAR meetings, especially those outside the United States—are a major reason for the limited participation in planetary protection workshops and colloquia.

There are several reasons that planetary protection science has attracted only a small minority of scientists. First, until recent years with expanding ambitions for Mars missions and new plans for missions to the icy moons of Jupiter or Saturn, there have been few solar system exploration missions that would require little more than the most basic planetary protection procedures. Second, planetary protection is an operational activity that does not naturally attract scientists who are more interested in pushing the frontiers of their fields. There have also been difficulties in translating latest technologies from the bench into workable procedures that enable NASA to effectively render planetary protection requirements.

These factors may help explain the difficulty in engaging forefront researchers in translating new advances into planetary protection practice, but they do not reduce the need. Studies, workshops, and brainstorming sessions organized by NASA, other space agencies (e.g., ESA and JAXA), the SSB, and COSPAR to advise planetary protection policy makers need to reach out internationally to a sufficiently broad range of microbiologists (e.g., including molecular genomic scientists). Furthermore, astrobiologists who explore diverse types of life on Earth are best qualified to advise on which organisms are likely to grow on Mars or icy bodies and, thus, require surveillance on spacecraft and which do not require surveillance. While most attention to date has been directed

[48] For example, there are 4500 references in *PubMed* with keywords "metagenomic" and "environmental sample."

[49] See, for example, F. Abreu, A. Carolina, V. Araujo, P. Leão, K.T. Silva, F.M. Carvalho, O.L. Cunha, et al., Culture-independent characterization of novel psychrophilic magnetotactic cocci from Antarctic marine sediments, *Environmental Microbiology* 18:4426-4441, 2016.

[50] See, for example, Y.M. Shtarkman, Z.A. Koçer, R. Edgar, R.S. Veerapaneni, T. D'Elia P.F. Morris, and S.O. Rogers, Subglacial Lake Vostok (Antarctica) accretion ice contains a diverse set of sequences from aquatic, marine and sediment-inhabiting bacteria and eukarya, *PLoS One,* 2013, https://doi.org/10.1371/journal.pone.0067221.

[51] While biology is an important field for planetary protection, many other areas are also important. For example, recent research on recurring slope lineae on Mars illustrates the relevance of geology and hydrology to planetary protection science.

[52] See reports of recent colloquia organized by COSPAR's Panel on Planetary Protection at https://cosparhq.cnes.fr/content/pppreports.

toward studies of so-called terran life (i.e., life as we know it), it is not too soon to begin to begin to identify issues relevant to non-terran life, if it exists.[53] Exploration of the diversity or organisms, terran and non-terran would be an area of interest and assessment by the new planetary protection research manager and an appropriate role for the NASA Astrobiology Institute.

Finding: The field of planetary protection science fills a rather small sector of modern science, and it has not been able to engage a substantial number of scientists who have been leading in important areas of modern sciences. For example, while the field of biology has made enormous advances in recent years many of those advances that could be applicable to improving approaches to planetary protection have not yet been fully integrated into the development of planetary protection policy or translated into practical approaches to implement policies.

Recommendation 3.7: NASA should engage the full range of relevant scientific disciplines in the formulation of its planetary protection policies. This requires that scientific leaders outside of the standard planetary protection community in NASA participate in revisions to NASA and COSPAR planetary protection policies and requirements.

Research and Technology Development for Planetary Protection

As NASA transfers the OPP to OSMA, a new planetary protection research manager, working separately from the PPO, will provide strategic guidance on research and technology needs. This role, as described in the NASA Decision Memorandum, is to "focus on tools and techniques for the avoidance of organic-constituent and biological contamination in NASA's current and future human and robotic exploration missions."[54] The details of how the new research manager will coordinate with the mission directorates regarding planning and funding are still being developed at NASA.

The OPP's total budget has remained approximately constant at some $2 million to $2.5 million per year since 2006 (see Appendix D). Of the total, approximately one-half is devoted to principal investigator–initiated, peer-reviewed research awarded via the Planetary Protection Research program, a component of NASA's Research Opportunities in Space and Earth Sciences (ROSES) activity. The remainder funds directed research in support of specific programmatic needs, contractor support, and the day-to-day operations of the OPP.

NASA uses its annual ROSES solicitation to request proposals for planetary protection research. The objective of solicited research is to improve NASA's understanding of the potential for both forward and backward contamination, how to minimize it, and to set standards in these areas for spacecraft preparation and operating procedures. Improvements in technologies and methods for evaluating the potential for life in returned samples are also of interest. Many of these research areas derive directly from recent SSB recommendations on planetary protection. As a complement to the ROSES Exobiology program, the Planetary Protection Research program solicits research in laboratory simulations and Earth analogs of planetary environments, modeling planetary environmental conditions and transport processes, modern molecular analytical methods, and new or improved methods, technologies, and procedures for spacecraft sterilization.

During the last 10 years (2006 to 2017), NASA has only funded planetary protection research proposals submitted via ROSES in 7 of those years: 2006 (four funded), 2007 (six funded), 2008 (two funded), 2010 (one funded), 2011 (five funded), 2012 (one funded), and 2014 (four funded and three partially funded). See Appendix D for a list of funded projects. In 2015 it appears no proposals were selected. These proposals are generally funded at a level of $300,000 to $500,000 and can take up to 4 years to complete. Given the scope of issues facing planetary protection, such a modest investment would appear to be far less than optimal. However, even after leveraging

[53] For a more complete discussion of non-terran life see, for example, NRC, *The Limits of Organic Life in Planetary Systems*, The National Academies Press, Washington, D.C., 2007.

[54] Agency Program Management Council Decision Memorandum, "*Planetary Protection Authority Transition*," May 17, 2017, approved May 22, 2017.

research conducted under NASA's larger Astrobiology program, the limited Planetary Protection Research funding level noted above has been inadequate to support a critical-mass number projects in any planetary protection research area.

NASA has used the SSB to perform specialized studies, for specific scientific areas of planetary protection interest and organize topical workshops to explore a variety of planetary protection issues. Many of the recent reports from the SSB and NASA's advisory groups have included recommendations for research that is necessary to advance planetary protection's ability to understand and verify potential biological contamination. The 2012 report on icy solar system bodies contained eight specific research recommendations;[55] the 2015 Joint European Science Foundation/NAS Review of the Mars Exploration Program Analysis Group's (MEPAG's) Report on Special Regions had 17 specific recommendations;[56] and the MEPAG report, itself, had 14 recommendations.[57] Many of these recommendations have not yet been acted upon. Discussions with the NASA PPO suggest that funding has just not been available to support all of this recommended research. As a result of these shortcomings, the missions have been forced to conduct their own planetary protection research, construct their own models, and carry out their own analyses. Mars 2020 is but one example where the project used advanced computational methods to evaluate contamination. This budget-driven outcome has resulted in the project offices possibly being better informed on mission-specific planetary protection issues than the OPP itself.

As discussed in the previous section, the Planetary Protection Research program has been slow to take advantage of the recent significant advances in fields such as genomics. Research results have the potential to reduce the overall cost of planetary protection, and the committee believes that increasing research funding is a very good return on investment.

According to a presentation from the Aerospace Corporation,[58] the costs of planetary protection are about 10 percent of total mission costs. Then for a total budget for NASA exploration programs of a few billion dollars, the cost of planetary protection will be about a few hundred million dollars. NRC studies have recommended that at least 10 percent of a program cost be invested in advanced research and technology.[59] Thus, it could be argued that an agency budget for planetary protection research would be a few tens of millions of dollars.

Finding: NASA has not adequately funded the research necessary to advance approaches to implementing planetary protection protocols and verifying that those protocols satisfy NASA's increasingly complex planetary protection requirements. For an agency program of solar system exploration and planning for human exploration missions, costing several billion dollars per year, an investment in relevant planetary protection research and technology of less than one-tenth of one percent of that total seems inadequate.

Recommendation 3.8: NASA should adequately fund both the Office of Planetary Protection and the research necessary to determine appropriate requirements for planetary bodies and to enable state-of-the-art planetary protection techniques for monitoring and verifying compliance with these requirements. The appropriate investment in this area should be based on a strategic assessment of the scientific advances and technology needs to implement planetary protection for likely future missions.

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[55] NRC, *Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies*, The National Academies Press, Washington, D.C., 2012, pp. 55-58.

[56] NASEM and the European Science Foundation, *Review of the MEPAG Report on Mars Special Regions*, The National Academies Press, Washington, D.C., 2015, pp. 45-47.

[57] J.D. Rummel, D.W. Beaty, M.A. Jones, C. Bakermans, et al., A new analysis of Mars "Special Regions": Findings of the Second MEPAG Special Regions Science Analysis Group (SR-SAG2), *Astrobiology* 14:887-968, 2014.

[58] D. Bearden and E. Mahr, "Cost of Planetary Protection Implementation," presentation to the committee, June 28, 2017, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_180771.pdf.

[59] NRC, *An Enabling Foundation for NASA's Earth and Space Science Missions*, The National Academies Press, Washington, D.C., 2010.

Comparing the ESA and NASA Planetary Protection Policy Process

The committee's charge does not include an assessment of the ESA planetary protection policy development process, but it is helpful to consider whether aspects of the ESA process offer useful lessons for NASA. ESA's fundamental objectives for planetary protection, the vesting of authority for the policy at the top level of the agency, the policy's ties to compliance with the OST, and the linkage to COSPAR guidelines are all similar to NASA's. ESA's PPO resides in the Product Assurance and Safety (PA&S) Department, which is a technical authority, and thus the organizational arrangement is much like NASA's placement of its OPP in OSMA. That arrangement reduces organizational conflicts of interest at ESA by separating lines of responsibility for formulating policy, establishing requirements, and implementing requirements. ESA uses an independent Planetary Protection Working Group, with members from outside ESA selected for their specific expertise, to provide advice and recommendations to support the head of PA&S. This arrangement seems similar to NASA's Planetary Protection Advisory Subcommittee, although the latter has been disbanded.

There appears to be a notable difference in how NASA and ESA delegate execution of policy and requirements to individual flight missions. At ESA, individual mission project managers are responsible for identifying the planetary protection requirements specific to their projects and defining the planetary protection implementation and management approach for their missions. The extent of that delegation at NASA appears to fall short of that at ESA. Finally, ESA's PPO performs inspections and reviews to ensure compliance with planetary protection requirements, just as at NASA, but the project manager appears to have more discretion in implementing recommendations from the reviews than is the case at NASA.[60]

Finding: ESA's planetary protection process reduces organizational conflicts of interest by separating lines of responsibility for formulating policy, establishing requirements, and implementing requirements and by giving more authority to mission project managers to translate top-level requirements into implementation approaches.

Recommendation 3.9: NASA should evaluate the ESA process for planetary protection implementation and strongly consider incorporating the elements of that process that are effective and appropriate.

DEFINING A PERIOD OF PLANETARY PROTECTION

Defining the length of time over which a solar system body needs to be protected from contamination in order to permit unimpaired biological study—that is, the *period of biological exploration*—has been a difficult issue throughout the history of planetary protection policy. Several definitions of the term have been used. In the late 1960s, the period of biological exploration was set initially at 20 years, based on the optimistic assumption that in that time 100 flight missions to planets of biological interest would have been conducted successfully.[61] Another definition referred to the time required to establish whether or not a planet has indigenous life and, if so, to characterize it.[62] The 20-year time span was used again as the likely time required to answer the questions about life on a planet. During this period, unsterilized spacecraft would be prohibited from impacting a planetary body. This gave rise to the minimum orbital lifetime requirement. When it became obvious that the pace of exploration was far slower than originally imagined, the period of biological exploration was reevaluated on an individual-planet basis. For Mars, it became 50 years after the launch of a given spacecraft so that the end of the period moves forward indefinitely as long as spacecraft are headed to the Red Planet.

For the icy moons of Jupiter and Saturn, the timeframe is not clear. NASA's PPO promulgated requirements on NASA missions, including Europa Clipper, which established the time to be infinite. However, an infinite

[60] Examples of the separation of the roles of policy formulation and implementation/enforcement can be found in many U.S. governmental agencies. The U.S. Department of Agriculture, for example, sets meat and poultry-handling safety standards which are overseen and enforced by the Food Safety and Inspection Service.

[61] COSPAR, COSPAR Decision No. 16, *COSPAR Information Bulletin* No. 50, July 1968, pp. 15-16.

[62] NRC, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C., 2006.

period is not representative of the current scientific consensus. For example, the 2012 SSB report *Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies* recommended a period of 1,000 years.[63]

A period of biological exploration has important legal as well as scientific implications. It involves the OST's prohibition against national appropriation on a celestial body by means of claim, use, occupation, or any other means.[64] To prevent having a period of biological exploration being construed as appropriation, there would need to be, at the very least, a clear relationship between the length of a period of biological exploration and its scientific objectives, as well as identification of a definite date by which the period will end.[65]

Finding: As the exploration of the icy moons rises in priority and plans for piloted missions to Mars emerge, it is necessary to reevaluate and clarify the period of biological exploration.

Recommendation 3.10: Given the implications with respect to the Outer Space Treaty, NASA and COSPAR should facilitate development of an international strategy for establishing periods of biological exploration. Such a strategy should ensure that individual nation states are all using the same values. Specification of this period is vital to the calculations of probability of contaminating a potential habitat on another world.

[63] NRC, *Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies*, The National Academies Press, Washington, D.C., 2012.

[64] Outer Space Treaty, Article II.

[65] A resolution of appropriate period of biological exploration will have the effect of establishing sunset clauses for planetary protection at bodies where non-scientific missions may occur in the future.

4

Policy Development Process Beyond NASA

BROADER U.S. GOVERNMENT INVOLVEMENT IN PLANETARY PROTECTION POLICY DEVELOPMENT

Executive Branch Coordination

The National Aeronautics and Space Act of 1958 provided for the exchange of information and discoveries among federal agencies particularly to ensure "close cooperation among all interested agencies of the United States in order to avoid unnecessary duplication of effort, facilities and equipment."[1] Such cooperation arose in the 1960s, via the establishment of the Interagency Committee on Back Contamination (ICBC)[2] to provide advice regarding policy and procedures to prevent potential contamination from lunar samples returned during the Apollo program (see "The Apollo Experience," in Chapter 2). The ICBC membership included representatives from the Departments of Agriculture; Health, Education, and Welfare (in particular, the Public Health Service); and Interior, plus members from the National Academy of Sciences and NASA.[3] After playing an active role in overseeing the Lunar Receiving Laboratory and of the release of lunar samples, the ICBC was disbanded after the end of the Apollo program.

Building upon National Security Action Memorandum 235,[4] Presidential Directive-National Security Council (NSC) Memorandum 25 (NSC-25)[5] re-established and extended the formal process by which the U.S. government reviews and approves space activities that could potentially have large-scale adverse environmental effects on Earth. Although the 1977 directive applied mainly to the launch of nuclear power systems, it also provided a basis and process for assessing the risks of backward contamination from returned astronauts and extraterrestrial samples.

[1] T.A. Mahoney, N. Weiner, and L. Kollath, *Organizational Strategies for Protection Against Back Contamination*, Final Report of NASA Grant NGL 24-005-160.

[2] See, for example, J.R. Bagby, Jr., "Back Contamination: Lessons Learned During the Apollo Lunar Quarantine Program," prepared for the Jet Propulsion Laboratory under Contract #560226, July 1, 1975.

[3] B. Pugel. "Restricted by Whom? A Historical Review of Strategies and Organization for Restricted Earth Return of Samples from NASA Planetary Missions," presentation to the Committee on Planetary Protection Policy Development Processes, Space Studies Board, National Academy of Sciences, July 2017, Slide 5.

[4] See "The Apollo Experience" in Chapter 2.

[5] The White House, "Scientific or Technical Experiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space," Presidential Directive NSC-25, December 14, 1977. https://fas.org/irp/offdocs/pd/pd25.pdf.

Under NSC-25, any agency that proposes to undertake a scientific or technological experiment that could have serious terrestrial environmental consequences is first required to submit an environmental impact statement and seek approval from the director of the White House Office of Science and Technology Policy (OSTP). Prescribed consultations between the director of OSTP and the chair of the Council on Environmental Quality (CEQ) provide a means to secure interagency input to the decision-making process. The directive noted that although approval of a proposal rests entirely within the U.S. government, "the National Academy of Sciences and, where appropriate, international scientific bodies or intergovernmental organizations may be consulted in the case of those experiments that might have adverse effects beyond the United States."[6] This language provides an opportunity for consultation with, for example, the Space Studies Board (SSB) and Committee on Space Research (COSPAR) when considering planetary protection policies related to back contamination from returned samples and astronauts.

Although NSC-25 prescribes an interagency review process, it does not adequately capture the full range of federal agencies that, today, would have a legitimate role in reviewing planetary protection plans for returned astronauts and samples. Nor does the directive provide sufficiently clear guidance on how the interagency review process is to operate. An up-to-date approach that establishes an early, clear, and orderly process for formulating policy regarding the return of samples and humans from Mars is needed.

Finding: NSC-25 is out of date. Plans to send robotic sample return and human-crewed missions to Mars in the next few decades will, in all likelihood, create planetary protection challenges that current national processes on developing planetary protection policy are not well-equipped to handle.

Recommendation 4.1: The Administration, most probably through the National Space Council, National Security Council (NSC), and the Office of Science and Technology Policy, should revisit NSC Memorandum 25 in light of NASA plans for Mars sample return missions and human-crewed missions to Mars and revise or replace its provisions for engaging relevant federal agencies in developing back contamination protection policies.

Department of State

Responsibilities for space policy activities in the Department of State reside in the Office of Space and Advanced Technology (SAT) of the Bureau of Oceans and International Environmental and Scientific Affairs. The office coordinates interagency participation in development and implementation of international agreements relating to civil space programs. SAT also provides the U.S. representative to the United Nations (UN) Committee on the Peaceful Uses of Outer Space (COPUOS), and it stewards U.S. compliance with the Outer Space Treaty (OST), including those related to planetary protection.

As noted in Chapter 2, planetary protection policy, including implementation of the OST's provisions on planetary protection, has not, to date, created international disputes and disagreements that required sustained Department of State involvement. However, changes in space exploration activities, especially planned sample return and human missions to Mars, might create more diplomatic contexts in which spacefaring nations want to discuss planetary protection. Thus, planetary protection might become a more important issue for the Department of State's responsibilities for space policy activities.

Finding: The effectiveness of COSPAR's development of planetary protection policy guidelines and international compliance with the provisions of the OST has mitigated the need for significant interventions by the Department of State. However, the planned sample return and human missions to Mars will raise planetary protection issues that require more diplomatic attention.

[6] See Section 6 of The White House, "Scientific or Technical Experiments with Possible Large-Scale Adverse Environmental Effects and Launch of Nuclear Systems into Space," Presidential Directive NSC-25, December 14, 1977, https://fas.org/irp/offdocs/pd/pd25.pdf.

Recommendation 4.2: The Department of State, informed by consultations with the appropriate experts and stakeholders, should embark on active international diplomacy to forge consensus on appropriate policies for planetary protection for a broad range of future missions to Mars. The goal should be to maintain and develop international consensus on how best to mutually and cooperatively meet all signatories' obligations under Articles IX and VI of the Outer Space Treaty. Such diplomacy should take into consideration, to the extent possible, the best available science as well as anticipate new missions in space.

Department of Transportation

Within the Department of Transportation, the Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST) has licensing and regulatory responsibilities for all U.S. private-sector space launch and reentry activities. These regulatory roles consider compliance with international agreements, protection of public health and safety, and U.S. national security and foreign policy priorities. AST also works to foster the U.S. private-sector space transportation industry. The office's formal charter does not extend beyond activities connected with launch and reentry, and so it has no explicit authority to deal with planetary protection aspects of private-sector space missions. AST draws on advice from a formally established advisory committee—the Commercial Space Transportation Advisory Committee (COMSTAC)—that advises the FAA Administrator on matters of interest to AST.[7] COMSTAC members are senior experts from a wide range of stakeholder groups, including the aerospace industry, other industries having interests in space transportation (e.g., finance and insurance), academia, and space-related nongovernmental organizations.

The FAA's authority is unclear in two areas important for planetary protection policy. First, while the agency issues licenses for private-sector launches and spacecraft reentry, it has no authority to review or approve post-launch mission operations or activities around or on another planetary body.[8] Second, there is no explicit legislative or executive guidance about whether FAA's spacecraft reentry licensing authority extends to review or approval of plans to prevent back contamination from sample return missions. These two areas underscore the importance of addressing the, so-called "regulatory gap" discussed in Chapter 6.

Department of Commerce

The Office of Space Commerce, under the auspices of the Department of Commerce (DoC), oversees and leads the activities surrounding space commerce policy. The primary mission of the office is to serve as an advocate, resource, and voice for the U.S. commercial space industry within the Executive branch.[9] Within the DoC, the Office of Space Commerce partners with other offices including, but not limited to, the National Oceanic and Atmospheric Administration Commercial Remote Sensing Regulatory Affairs office that is responsible for licensing commercial remote sensing satellites, and the Bureau of Industry and Security that oversees the licensing and approvals for dual-use technology.

Currently, the role of the Office of Space Commerce is to coordinate all commercial space-related activities, programs, and initiatives, which primarily revolve around commercial remote sensing policy and regulations. These functions include supporting the activities of the U.S. commercial space sector through economic growth and advancement in technological development, coordinating and developing policies relevant to commercial

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[7] For more information about COMSTAC see, for example, https://www.faa.gov/about/office_org/headquarters_offices/ast/advisory_committee.

[8] The FAA did conduct a "Payload Review" for a company planning commercial lunar activities. However, the review was limited to "public health and safety, safety of property, U.S. national security or foreign policy interests, or international obligations of the United States." It was not an authorization to conduct on-orbit activities (see FAA, "Fact Sheet—Moon Express Payload Review Determination Share," August 3, 2016, https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20595). "'This is more symbolic than substantive,' says John Logsdon, a space policy specialist and professor emeritus at George Washington University" (R.E. Bichell, "Florida Company Gets One Bureaucratic Step Closer to Landing on the Moon," August 4, 2016, *NPR*, https://www.npr.org/sections/thetwo-way/2016/08/04/488730799/florida-company-gets-one-bureaucratic-step-closer-to-landing-on-the-moon).

[9] See National Oceanic and Atmospheric Administration, *Budget Estimates: Fiscal Year 2019*, 2018, http://www.corporateservices.noaa.gov/nbo/fy19_bluebook/FY19-NOAA-CJ.pdf#page=544.

space policy within the DoC and as representatives of U.S. commercial space interests in negotiations with foreign entities, and promoting U.S. commercial geospatial technologies within interagency working groups.[10]

On May 24, 2018, President Trump signed a memorandum implementing Space Policy Directive 2. This document directs the Secretary of Commerce to consolidate all responsibilities of the DoC with respect to the Department's regulation of commercial spaceflight activities within the Office of the Secretary and to develop a plan for an entity to administer the Department's regulation of commercial spaceflight activities.[11] This action is consistent with and partially preempts provisions of the American Space Commerce Free Enterprise Act (see the next section) that would make the Office of Space Commerce the leading entity for overseeing and approving commercial space activity, except for current launch licensing approvals conducted by the FAA AST and space communications licensing by the Federal Communications Commission.

Plans to reorganize the Office of Space Commerce have two major implications: expansion of office personnel and expertise; and a request for more funding. In the 2018-2022 DoC Strategic Plan, the Office of Space Commerce is expected to "expand commercial space activities."[12]

Congress

As noted above, Congress has assigned authority to review and approve private-sector space launches and reentries to the FAA. Congress also has accepted NASA's responsibilities for ensuring U.S. compliance with planetary protection provisions of the OST, for government-sponsored space missions. However until recently, there has been little legislative attention to planetary protection policy development or implementation.

Two recent legislative proposals suggest that new congressional interest in the subject is emerging and evolving. The proposed NASA Authorization Act of 2015 included a section that called for a National Academies "study to explore the planetary protection ramifications of potential future missions by astronauts such as to the lunar polar regions, near-Earth asteroids, the moons of Mars, and the surface of Mars."[13] The proposed study would examine prior work relevant to planetary protection for human missions, identify relevant remaining concerns, and recommend methodologies for assessing planetary protection concerns for human missions. The bill passed in the House of Representatives but not in the Senate.

In 2017, the American Space Commerce Free Enterprise Act was introduced in the House and approved by the Committee on Science, Space, and Technology.[14] The bill contains a number of provisions relevant to planetary protection. For example, in its section on compliance with the OST, the bill provided that the "federal government shall not presume all obligations of the United States under the OST are obligations to be imputed upon United States non-governmental entities."[15] This instruction generates questions about its implications for the obligation of the U.S. government to authorize and continuously supervise the nongovernmental space activities that involve planetary protection issues.

In addition, this bill proposes establishment of a Private Space Activity Advisory Committee, which would report to Congress, the President, and the Secretary of Commerce. The proposed committee is required to have at least three industry members and prohibits any Federal employee or official from participating. The eight duties assigned to the committee included the following:[16]

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[10] See NOAA, "Legal and Departmental Authorities of the Office of Space Commerce," Office of Space Commerce, http://www.space.commerce.gov/law/office-of-space-commercialization.

[11] For more information about Space Policy Directive 2, see D.J. Trump, "Streamlining Regulations on Commercial Use of Space," May 24, 2018, https://www.whitehouse.gov/presidential-actions/space-policy-directive-2-streamlining-regulations-commercial-use-space.

[12] See NOAA, "DOC Strategic Plan Prioritizes Space Commerce," Office of Space Commerce, February 13, 2018, http://www.space.commerce.gov/doc-strategic-plan-prioritizes-space-commerce.

[13] National Aeronautics and Space Administration Authorization Act of 2015, H.R. 810.

[14] For more information about the American Space Commerce Free Enterprise Act of 2017, H.R. 2809, see https://www.congress.gov/bill/115th-congress/house-bill/2809).

[15] H.R. 2809, §80103(c), Compliance with the Outer Space Treaty.

[16] H.R. 2809, §80109, Private Space Activity Advisory Committee.

- Identify any challenges the United States private sector is experiencing . . . with the authorization and supervision of the operation of space objects . . . with international obligations of the United States relevant to the private sector . . . and . . . with harmful interference to private sector activities in outer space.
- Review existing best practices for United States entities to avoid the harmful contamination of the Moon and other celestial bodies.
- Review existing best practices for United States entities to avoid adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter.

In April 2018, the House of Representatives passed the American Space Commerce Free Enterprise Act. But, at the time this report was written, the Senate had not acted on this or any related bill. Congressional action is still needed in order to facilitate development of planetary protection policy relating to private-sector space activities. At the present, no federal regulatory agency has the jurisdiction to authorize and continually supervise on-orbit activities undertaken by private-sector actors, including activities that could raise planetary protection issues. The committee discusses this problem in Chapter 5.

COSPAR PLANETARY PROTECTION PROCESS

Current COSPAR Planetary Protection Guidelines

The current COSPAR planetary protection policy states that

> The conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized. In addition, the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by a spacecraft returning from an interplanetary mission. Therefore, for certain space mission/target planet combinations, controls on contamination shall be imposed in accordance with issuances implementing this policy.[17]

The policy adopts the five mission-type-target-body categories and their range of requirements (see Table 2.1) from the NASA policy.

COSPAR guidelines are not legally binding on any state or national space agency, but spacefaring nations, including the United States, have taken them seriously and largely complied with them. For example, all missions of the European Space Agency (ESA) have complied with COSPAR guidelines. Japanese missions have also followed COSPAR guidelines. The same can be said for certain Russian missions, India's Mars orbiter mission, and the United Arab Emirates' Hope Mars orbiter mission, scheduled for launch in March 2020. In other cases, such as Russia's Phobos-Grunt, launched in 2011, compliance was controversial (see Chapter 2). Some in the science community and legal community asserted that this latter mission violated COSPAR guidelines and even Article IX of the OST itself. In the end, the mission failed to leave Earth's orbit, so the asserted violations did not lead to actual forward contamination risks.

In short, COSPAR has been a uniquely important forum through which common planetary protection standards have been adopted around the world, and a major organ through which the United States and all other spacefaring nations have historically chosen to meet their obligations under Article IX of the OST.

> **Finding:** COSPAR has been a crucial forum for furthering international cooperation with respect to planetary protection ever since its creation in 1958.

How COSPAR Works: Organization and Decision Making

COSPAR is a scientific organization established by the International Council for Science (ICSU) in 1958. Although it is not formally associated with the UN, COSPAR does organize scientific symposia on behalf of and

[17] G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December 2017, pp. 12-24.

provide information and advice to the UN's COPUOS. Formal COSPAR members are either national scientific institutions (e.g., National Academies of Sciences, Engineering, and Medicine in the United States) or international scientific unions (e.g., International Union of Biological Sciences). Any person may become a COSPAR associate "by attending a COSPAR biennial Assembly or a COSPAR event involving registration or by communicating his/her interest to the Secretariat."[18] The by-laws stipulate that an associate is expected to become a member of up to three of COSPAR's scientific discipline commissions. Such membership is not limited to scientists, and associates are allowed to participate in COSPAR's scientific commissions and can vote during the business meeting. COSPAR by-laws also allow for the honorific status of COSPAR Associated Supporter. This status is open to "any duly constituted legal entity or individuals. Such entities and persons wishing to become COSPAR Associated Supporters must request this status in writing to the President through the Secretariat and pay an adherence fee."[19] Lockheed Martin Corporation and Orbital ATK, for example, are among COSPAR's few private-sector Associated Supporters. In short, COSPAR has an open process in terms of membership and participation in policy decision making. Thus it more nearly resembles community-based ad hoc organizations (e.g., like NASA's informal analysis/assessment groups such as the Mars Exploration Program Analysis Group) rather than the formally organized NASA advisory entities such as the NASA Advisory Council.[20]

COSPAR is governed by a Council comprised of the president, representatives of national member institutions, the chairs of COSPAR's eight scientific commissions, and the chair of the Finance Committee. The COSPAR Bureau, which oversees day-to-day operations, is elected by the Council, is comprised of the president, two vice presidents, and six other members.

COSPAR policy and guidelines are established and amended through the process of resolutions. An amendment to existing planetary protection policy and guidelines can be considered if a COSPAR Associate, Bureau, or Council member brings the underlying issue to the attention of the chair of the Panel on Planetary Protection. If the issue is complex, the chair requests the convening of a COSPAR workshop or colloquium to review, discuss, and evaluate the merits of the issue and the associated proposal for an amendment. Proposals for amendments may be based on new discoveries, the results of new research, or recommendations to agencies by advisory bodies (internal or external). Proposals may also be based on the identification of new implementation strategies, the need for more detailed guidelines, and new challenges. After a discussion by participants, workshops may suggest wording for a proposed amendment and prepare a draft resolution to be presented to the COSPAR Panel on Planetary Protection during its business meeting at the next COSPAR Scientific Assembly. The participants present during the business meeting to discuss the proposed amendment to the planetary protection policy and, if no objections are raised, it is approved and passed on to the COSPAR Council, via the Bureau (Figure 4.1). With approval by the Council, the proposed amendment becomes part of formal COSPAR guidance on planetary protection.

Unlike most COSPAR panels, which serve as fora for discussion and advice to COSPAR on particular topics, the Panel on Planetary Protection can recommend international standards to guide compliance with the OST. In the past, the panel has had no formal membership except for a chair and vice chairs. Participation in panel meetings depended entirely on who chose to attend. COSPAR recently reconstituted the Panel on Planetary Protection to introduce a formality in its structure and processes to ensure that all space agency stakeholders affected by COSPAR planetary protection policy can participate in the formation of the policy.[21] The reconstituted panel is fully endorsed by the UN Committee on Peaceful Uses of Outer Space.

In the revised structure, the chair will be a recognized scientific leader who is not a national space agency official. One vice chair will be an expert in planetary protection, and a second vice chair will be designated by the UN Office of Outer Space Affairs. The remaining members of the panel will be nominated by national space agencies (and approved by COSPAR). The chairs of the COSPAR scientific commissions concerned with solar system studies (Scientific Commission B) and with space life sciences (Scientific Commission F), or their nominees, also

[18] COSPAR By-Laws, Section IX. Associates, https://cosparhq.cnes.fr/about/by-laws.

[19] COSPAR By-Laws, Section X. Associated Supporters, https://cosparhq.cnes.fr/about/by-laws.

[20] For more information about MEPAG and NASA's other analysis/assessment groups see, for example, https://www.lpi.usra.edu/analysis.

[21] J.D. Rummel and G. Kminek. "COSPAR's Planetary Protection Policy: Updating a Consensus Standard," IAC-17, E7,7-B3.8, 7, 68th International Astronautical Congress, Adelaide, Australia, September 25-29, 2017.

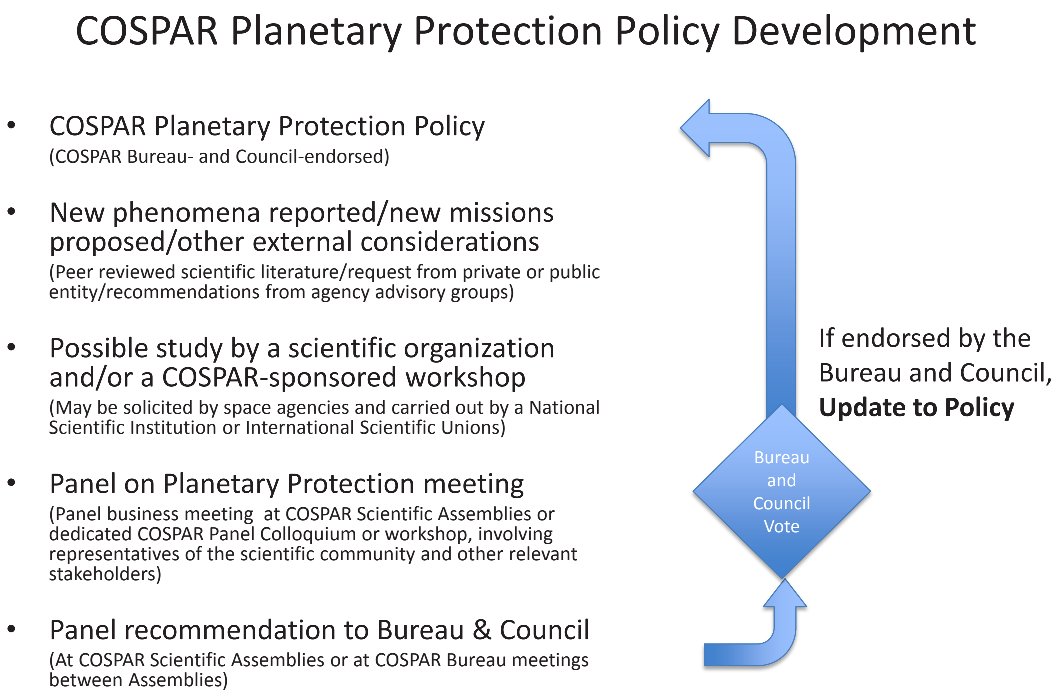

FIGURE 4.1 Process to adopt or update the COSPAR planetary protection policy. SOURCE: Adapted from G. Kminek and J. Rummel, "COSPAR's Planetary Protection Policy," *Space Research Today*, Number 193, August 2015, p. 8, Copyright 2015, with permission from Elsevier.

will be members. Panel meetings will be open to participation by all interested parties including representatives of COSPAR's national scientific institutions (e.g., the SSB in the case of the United States), scientific commissions, and international scientific unions. The restructuring effort was concluded successfully when the new terms of reference for the Panel on Planetary Protection were adopted by the Bureau and the Council in March 2017 and endorsed by COPUOS in June 2017.[22] The initial membership of the panel was approved by the COSPAR Bureau during its March 2018 meeting. Effective from COSPAR's July 2018 Scientific Assembly, the Panel on Planetary Protection will be chaired by Athena Coustenis (Paris Observatory) and its vice chairs will be Gerhard Kminek (ESA planetary protection officer) and Niklas Hedman (UN Office for Outer Space Affairs). In addition, the Bureau accepted the membership of eight panel members nominated by space agencies (see Table 4.1).

ASSESSMENT OF THE COSPAR PROCESS

Completeness of COSPAR Policies

As Chapter 2 noted, COSPAR's planetary protection policy has followed the development of U.S. policy as NASA has pursued missions not yet covered by the COSPAR policy. The current COSPAR policy is incomplete with respect to these missions as noted in the section "Assessment of NASA Planetary Protection Policies" in Chapter 3. As a consequence, the NASA Office of Planetary Protection has been required to define new planetary protection policy to cover the gaps in the current international policy. However, this U.S. leadership role may change in

[22] L.A. Fisk, "Planetary Protection: The COSPAR perspective," presentation to the committee on June 28, 2017, Slides 13-18, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_180773.pdf.

TABLE 4.1 Space Agency Representatives Recently Selected to Serve on COSPAR's Reconstituted Panel on Planetary Protection

Country	Space Agency	Appointed Representative	Biographical Material Source
China	China National Space Administration	Lei Li	https://www.researchgate.net/profile/Lei_Li167
France	National Centre for Space Studies (CNES)	Michel Viso	https://www.linkedin.com/in/michel-viso-a566051b
Germany	German Aerospace Center (DLR)	Petra Rettberg	http://www.dlr.de/me/en/DesktopDefault.aspx/tabid-1761/2381_read-7063
India	Indian Space Research Organisation	Seetha Somasundaram	http://vigyanprasar.gov.in/isw/drseetha_story.html
Italy	Italian Space Agency (ASI)	Eleonora Ammannito	https://www.linkedin.com/in/eleonora-ammannito-5120b615
Japan	Japan Aerospace Exploration Agency (JAXA) Institute of Space and Astronautical Science (ISAS)	Saku Tsuneta	https://www.nins.jp/public_information/pdf/06_Saku_Tsuneta.pdf
Russia	Space Research Institute (IKI)	Elena Deshevaya	https://www.energia.ru/ktt/en/monographer/deshevaya.html
United States	NASA	James L. Green	https://solarsystem.nasa.gov/people/740/james-green

NOTE: Additional agency representatives and members nominated by COSPAR's Scientific Commissions B and F will be added later.

the future as Europe and other nations pursue new missions that have not yet been accomplished. The European Science Foundation has initiated an international activity—Planetary Protection for Outer Solar System—to tackle the science, technology, and policy-making components of biological and organic contamination of the Ocean Worlds and small solar system bodies.[23] This 3-year long initiative is providing an international platform where science, industry, and policy makers will meet to exchange key information on the matter of planetary protection.

> **Finding:** The COSPAR policy has historically been incomplete with respect to missions to solar system bodies that have not yet been explored by any nation. These gaps in the current COSPAR policy need to be defined by the nation pursuing a new mission to a previously unexplored body, such as Europa, where the policy has not yet been fully documented. This role has historically been filled by the United States.

Breadth and Depth of Participation in Policy Development

As this report noted in Chapter 3, both NASA and COSPAR have not always been successful at recruiting a wide range of scientists to participate in meetings where new scientific findings are considered for their implications for planetary protection policy.

In addition to the need to expand scientific participation in COSPAR planetary protection colloquia and workshops, the level of participation in the meetings of COSPAR's Panel on Planetary Protection has been uneven in the past. The relatively limited participation has been a consequence of the informal manner in which the COSPAR

[23] For more details see, for example, the Planetary Protection of Outer Solar System website at http://pposs.org.

Panel on Planetary Protection has operated. The recent changes to the panel's structure and organization discussed above may help alleviate this problem.

The new panel structure calls for a U.S. representative from a federal agency that has responsibility for compliance with the OST. In nominating its representative for COSPAR's Panel on Planetary Protection, the U.S. government may wish to ensure that the nominee can represent the various components of the U.S. policy on planetary protection, including the treaty obligations of the government, the perspectives of the scientific community, human exploration organizations, and the interests of the private sector.

Finding: COSPAR's reorganization of its Panel on Planetary Protection will help ensure a more structured and formal process for COSPAR planetary protection policy deliberations; however a need remains to ensure that U.S. participation in panel deliberations is appropriately representative of all stakeholder perspectives.

Should COSPAR's Panel on Planetary Protection evolve still further and develop, for example, an even closer relationship with the United Nations? The committee understands that COSPAR and COPUOS have discussed this possibility and concluded that it was not appropriate at this time.[24] Nevertheless, if it proves to be advisable at some time in the future, a possible model for the evolution of COSPAR's Panel on Planetary Protection from a quasi ad hoc body to a more formal consensus-building body with designated national representatives is discussed in Appendix E. In particular, parallels can be drawn between the reorganization of COSPAR's Panel on Planetary Protection and the Inter-Agency Space Debris Coordination Committee.

ASSESSMENT OF SSB ACTIVITIES

The National Academies, and the SSB in particular, have been a significant, if not the dominant, source of scientific advice on planetary protection issues for the past 60 years. In fact, it is arguable that the current planetary protection policies of NASA and COSPAR are derived almost exclusively from input provided by the SSB. The leadership role played by the SSB is a reflection of the dominant role played by NASA in the robotic exploration of the solar system. When NASA initiates a spacecraft mission that will undertake activities not covered in existing policies, the agency frequently asks the SSB for planetary protection advice relevant to the new activity. The requested advice is incorporated in NASA policies and forwarded to COSPAR for possible inclusion in COSPAR policies. The SSB's role as the U.S. National Committee for COSPAR facilitates the adoption of National Academies' advice by COSPAR

The SSB's international leadership role in the provision of scientific advice on planetary protection is not automatically assured. It is contingent on three factors: first, NASA's leadership in space activities; second, NASA's request for scientific advice from the SSB; and third, the acceptance of that advice when received. Although there is no expectation on the part of the SSB that all recommendations will be accepted, the historical trend has been that the proffered advice has been well received. However, there are signs that all three factors may not apply into the indefinite future. New international players have their own space aspirations. Foreign space agencies have their own sources of scientific advice. The European Space Agency, for example, looks increasingly to the European Space Science Committee of European Science Foundation (ESF) for input on planetary protection issues. Moreover, NASA's less-than-positive reaction to the SSB's 2012 report on the icy bodies of the outer solar system and failure to initiate any follow-up activity, for example, has left the door open for others to fill the advisory gap for these astrobiologically important objects.

As noted above, the ESF's European Space Science Committee secured funding from the European Commission Horizon 2020 program to initiate the Planetary Protection for Outer Solar System (PPOSS) project.[25] The PPOSS consortium includes COSPAR, various European academic, commercial, and trade organizations and space agencies, plus international participants from the China Academy of Space Technology and the Japan Aerospace

[24] Private communication from COSPAR President Lennard J. Fisk to committee, May 2018.

[25] For more details see, for example, the Planetary Protection of Outer Solar System website at http://PPOSS.org. The Space Studies Board has observer status on the PPOSS steering group.

Exploration Agency. The initiation of PPOSS has caused the center of gravity for the development of planetary protection policies for the Ocean Worlds to shift from the United States to Europe and points eastward.

Other factors that have influenced the provision of planetary protection advice by the SSB include the following:

- The SSB is reactive in that it responds to requests for scientific advice and does not typically self-initiate planetary protection studies. As a result, issues addressed by the SSB in response to NASA requests are usually conducted in the context of existing planetary protection policies and do not typically address foundational issues associated with forward and backward contamination. One such foundational issue is the validity of the various probabilities and other numerical factors appearing in both NASA and COSPAR policies (e.g., acceptable spore counts following bioload reduction and 10^{-4} probability for contaminating an internal ocean of an icy body of astrobiological interest as detailed in Table 2.1).
- The planetary science decadal surveys are not appropriate vehicles for discussing the details of planetary protection policies and their implementation. Moreover, what discussion there is of specific planetary protection issues associated with recommended missions is unfocussed because it is scattered throughout a survey report. A proactive approach by future survey committees to identify future planetary protection issues and approaches to their resolution would be of benefit to mission planners, mission managers, and the scientific community.
- The effectiveness of the National Academies' activities depends upon the availability of relevant experts in academia, research institutes, and industry who can be called upon to provide their expertise. The limited size of the planetary protection community presents special difficulties when finding suitable experts to populate advisory committees. A typical committee consists of only two or three individuals with direct experience of the issue to be addressed, with the balance of the membership being drawn from experts in related disciplines such as planetary science, environmental microbiology, and aerospace engineering. This approach has not compromised the quality of the resulting advice, but it does prolong the completion of the study, with additional time being required to educate those committee members unfamiliar with basic planetary protection concepts.
- All the planetary protection reports drafted by the SSB have focused exclusively on the scientific and technical issues associated with robotic spacecraft missions sponsored by national and international space agencies. Thus, the SSB has been silent on the potentially contentious topics of planetary protection issues associated with private sector and human space activities.
- The National Academies are not typically able to provide advice on short timescales. The need to educate non-experts on basic planetary protection concepts (see above) only exacerbates lengthy response times.
- The National Academies respond to requests for scientific and technical input via a variety of established mechanisms. Best known are the formal reports issued by ad hoc committees. Most recent SSB advice to NASA on planetary protection topics has come via this mechanism. Short reports drafted by standing committees such as the Committee on Planetary Biology and Chemical Evolution,[26] Committee on Planetary and Lunar Exploration,[27] and Committee on the Origins and Evolution of Life[28] also once provided more timely advice to NASA. But changes in National Academies' policies precluded the ability of standing committees to draft such reports. The current Committee on Astrobiology and Planetary Science (CAPS), which is the successor to the aforementioned groups, has regained the ability to draft short reports, but only on topics related to the implementation of recommendations contained in the planetary science decadal survey. The current decadal survey mentions the need for advanced planetary protection technology

[26] See, for example, National Research Council (NRC), "On the Categorization of the Comet Rendezvous–Asteroid Flyby Mission," letter from Harold Klein, Chair, Committee on Planetary Biology and Chemical Evolution, to Arnauld Nicogossian, Director, NASA Life Sciences Division, May 16, 1986.

[27] See, for example, NRC, "Scientific Assessment of Options for the Disposal of the Galileo Spacecraft," letter from Claude Canizares, Chair, Space Studies Board, and John Wood, Chair, Committee on Planetary and Lunar Exploration, to John Rummel, Planetary Protection Officer, NASA, June 28, 2000.

[28] See, for example, "Assessment of Planetary Protection Requirements for Venus Missions," letter from Jack Szostak, Co-Chair, Committee on the Origins and Evolution of Life, to John Rummel, Planetary Protection Officer, NASA, February 8, 2006.

development.[29] However, the decadal survey contains no specific planetary protection recommendations. Therefore, is not clear if CAPS, as currently chartered, could respond to a request for a short report addressing a planetary protection issue.

- In addition to study reports, the National Academies also organizes a variety of convening events, including workshops, roundtables, and meetings of experts. None of the three permit the drafting of a report containing consensus conclusions and recommendations, but they provide a sponsor with a mechanism for the discussion of specific topics on a somewhat timelier basis than a study activity. Although the SSB has organized three meetings of experts for NASA's Office of Planetary Protection in recent years, the other two mechanisms have not been employed to address planetary protection issues. The roundtable activity, in which participants from government, industry, and academia discuss issues of mutual interest, may be particularly suitable to initiate a dialogue on planetary protection issues. However, as with a meeting of experts, when the National Academies convene a roundtable any meeting summary and/or conclusions are the product of the requesting agency or entity. Neither type of activity results in a National Academies reviewed or endorsed report. This critical difference has occasionally resulted in incorrect attribution of such activities as having made National Academies' recommendations when in fact they did not.

Despite any actual or perceived issues with the activities of the National Academies in the area of planetary protection, the House of Representatives' Committee on Appropriations recognized the work of the SSB in this area in the recently passed Commerce, Justice, Science, and Related Agencies Appropriations Bill for Fiscal Year 2019. The report accompanying the bill noted that "planetary protection requirements for each NASA mission and target body are determined based on scientific advice from the Space Studies Board (SSB) . . . and on NASA policy, which is guided by international technical standards established by the international Committee on Space Research." The committee further acknowledged the importance for "NASA and its academic and industry partners" to follow current planetary protection protocols in order to ensure that precautions are taken to further the future exploration of outer space.[30]

Finding: The SSB's international leadership role in planetary protection has been a reflection of the dominant U.S. role in the robotic exploration of the solar system and NASA's sustained interest in securing and using scientific advice from the SSB, but those factors are not necessarily guaranteed in the future. The SSB has been reactive to requests from NASA rather than proactive, constrained by the limited pool of planetary protection experts to serve on study committees, unable to provide advice on short time-scales, and focused on issues for robotic scientific missions.

Recommendation 4.3: The SSB and NASA should pursue new mechanisms to anticipate emerging issues in planetary protection, respond more rapidly, and address new dimensions such as private-sector missions and human exploration. Future decadal survey committee's should give greater prominence to planetary protection issues and play a more proactive role in their identification and possible resolution.

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[29] NRC, *Vision and Voyages for Planetary Science in the Decade 2013-2022*, The National Academies Press, Washington, D.C., 2011.

[30] U.S. House of Representatives, "Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2019," 115th Congress, p. 60, https://docs.house.gov/meetings/AP/AP00/20180517/108330/HRPT-115-HR.pdf.

5

Planetary Protection Challenges from the Human Exploration of Mars

CURRENT INTEREST IN HUMAN MISSIONS TO MARS

In addition to robotic missions to Mars, NASA has stated its intent to send humans to the Red Planet.[1] At least two private-sector enterprises, Lockheed Martin and Space Exploration Technologies (SpaceX), have also started developing plans for sending humans to Mars (see Table 5.1). Likely new international relationships, new non-government players, and a potentially potent new contamination source (i.e., humans) will, in the committee's view, affect the processes for planetary protection policy development.

PLANETARY PROTECTION AND HUMANS ON MARS

NASA planetary protection documents acknowledge that NASA does not have a policy for human exploration on the surface of Mars and mostly call for a significant number of tests and experiments before sending humans there.[2] Current Committee on Space Research (COSPAR) principles and guidelines for human missions to Mars (see Box 5.1) state that "the intent of this planetary protection policy is the same whether a mission to Mars is conducted robotically or with human explorers . . . even if specific implementation requirements must differ."[3] Implementing the current COSPAR principles and guidelines may be impossible in any practical manner for human missions. Living quarters and spacesuits are imperfect, and leaks will contaminate the immediate martian environment with biological and chemical matter from Earth. Furthermore, waste from human presence will present even bigger contamination challenges. Human presence on Mars would, thus, raise serious planetary protection challenges and questions not confronted before, including (but not limited to) what "harmful contamination" of Mars means in terms U.S. obligations under the Outer Space Treaty (OST).

The planetary protection challenges generated by human missions to Mars will require policy makers to adapt existing approaches and develop new strategies. For example, rather than thinking about forward contamination in terms of an entire body, assessing the effects of human presence on local and regional scales might be more

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[1] For a possible human Mars architecture see, for example, H. Price, J. Baker, and F. Naderi, A minimal architecture for human journeys to Mars, *New Space* 3:73-81, 2015.

[2] Planetary Protection Requirements for Human Extraterrestrial Missions NPI 8020.7 and NPD 8020.7G.

[3] G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December 2017, pp. 12-24.

TABLE 5.1 Private-Sector Interest in Human Missions to Mars

Company	Status
Lockheed Martin	In May 2016, Lockheed Martin unveiled their Mars Base Camp concept for humans orbiting Mars, perhaps as early as 2028. This effort would be part of a public-private effort that would take advantage of NASA's work as well as other sectors of the commercial space enterprise.[1]
SpaceX	In September 2016 and again in September 2017, SpaceX announced a plan for sending humans to the surface of Mars. The plan includes, as a demonstration, launching an unmanned vehicle to Mars in 2022.[2] The SpaceX announcement in 2017 replaced the Red Dragon concept in favor of a simpler landing system that uses propulsive landing to the surface of Mars. SpaceX has informed the committee that the company still plans to send robotic and human landers to the Mars surface.

[1] T. Cichan, S.A. Bailey, T. Antonelli, S.D. Jolly, R.P. Chambers, B. Clark, and S.J. Ramm, Mars base camp: An architecture for sending humans to Mars, *New Space* 5:203-217, 2017.
[2] E. Musk, Making humans a multi-planetary species, *New Space* 5:46-61, 2017; and E. Musk, Making life multi-planetary, *New Space* 6:2-11, 2018.

effective. Similarly, the NASA Human Exploration and Operations Mission Directorate (HEOMD) is studying and developing a so-called *exploration zone* approach that would define the locus of a human landing site, in situ resource areas, and scientific regions of interest (see Figure 5.1). These ideas heighten the need for policies that address planetary protection at varying spatial scales.

Adapted and new approaches will also create novel planetary protection and other policy challenges. For example, the establishment of an exploration zone or regions of interest on Mars by the United States would raise questions about whether such an act violated the OST's prohibition of national appropriation of part of a celestial body.[4] If a nation or a private-sector entity wishes to protect a limited region temporarily without exercising any claim of ownership, how can a planetary protection policy be developed for that purpose? International discussions can resolve such questions.[5]

In addition, human missions to Mars would also raise potential back contamination problems. NASA's Chief Medical Officer, J.D. Polk, told the committee that he was less worried about back contamination from Mars microbes than he was concerned about return of microorganisms carried by the crew from Earth to Mars and back.[6] If those organisms experienced mutation through prolonged exposure to the space environment during the mission, such microbes might pose a health risk to returning crew as well as the public on Earth. As with the first Apollo astronauts, NASA expects to quarantine the crew until proven safe from returned risks.[7] Appropriate experiments on radiation mutation of Earth microbes may be needed to establish new policy.

DEVELOPMENT PROCESS FOR A NEW PLANETARY PROTECTION POLICY

Except for the so-called Mars Special Regions, current planetary protection requirements treat the planet globally (i.e., as a single monolithic entity).[8] Given that Mars has approximately 80 distinct geological regions, such a blanket treatment may be unwarranted. It is reasonable to expect that the modification of planetary protection requirements to enable human exploration will have an impact on future science investigations, the magnitude of

[4] Outer Space Treaty, Article II.
[5] For example, the states parties to the agreement on the International Space Station agreed that the operation of the station did not constitute an appropriation of low-Earth orbit space even though the station has been using the same orbit path for approximately 20 years. See "Agreement Among the Government of Canada, Governments of the Member States of the European Space Agency, the Government of Japan, the Government of the Russian Federation, and the Government of the United States of America Concerning Cooperation On the Civil International Space Station," ftp://ftp.hq.nasa.gov/pub/pao/reports/1998/IGA.html.
[6] Personal communication from J.D. Polk to J.A. Alexander, July 28, 2017. See, for example, P.W. Taylor, Impact of space flight on bacterial virulence and antibiotic susceptibility, *Infection and Drug Resistance* 8:249-262, 2015.
[7] See "The Apollo Experience" in Chapter 2.
[8] See, for example, J.D. Rummel, D.W. Beaty, M.A. Jones, C. Bakermans, et al., A new analysis of Mars "Special Regions": Findings of the Second MEPAG Special Regions Science Analysis Group (SR-SAG2), *Astrobiology* 14:887-968, 2014.

BOX 5.1
COSPAR Principles and Guidelines for Human Missions to Mars

The intent of this planetary protection policy is the same whether a mission to Mars is conducted robotically or with human explorers. Accordingly, planetary protection goals should not be relaxed to accommodate a human mission to Mars. Rather, they become even more directly relevant to such missions—even if specific implementation requirements must differ. General principles include:

- Safeguarding the Earth from potential back contamination is the highest planetary protection priority in Mars exploration.
- The greater capability of human explorers can contribute to the astrobiological exploration of Mars only if human-associated contamination is controlled and understood.
- For a landed mission conducting surface operations, it will not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems.
- Crewmembers exploring Mars, or their support systems, will inevitably be exposed to martian materials.

In accordance with these principles, specific implementation guidelines for human missions to Mars include:

- Human missions will carry microbial populations that will vary in both kind and quantity, and it will not be practicable to specify all aspects of an allowable microbial population or potential contaminants at launch. Once any baseline conditions for launch are established and met, continued monitoring and evaluation of microbes carried by human missions will be required to address both forward and backward contamination concerns.
- A quarantine capability for both the entire crew and for individual crewmembers shall be provided during and after the mission, in case potential contact with a martian life form occurs.
- A comprehensive planetary protection protocol for human missions should be developed that encompasses both forward and backward contamination concerns, and addresses the combined human and robotic aspects of the mission, including subsurface exploration, sample handling, and the return of the samples and crew to Earth.
- Neither robotic systems nor human activities should contaminate Special Regions on Mars, as defined by this Committee on Space Research (COSPAR) policy.
- Any uncharacterized martian site should be evaluated by robotic precursors prior to crew access. Information may be obtained by either precursor robotic missions or a robotic component on a human mission.
- Any pristine samples or sampling components from any uncharacterized sites or Special Regions on Mars should be treated according to current planetary protection Category V, restricted Earth return, with the proper handling and testing protocols.
- An onboard crewmember should be given primary responsibility for the implementation of planetary protection provisions affecting the crew during the mission.
- Planetary protection requirements for initial human missions should be based on a conservative approach consistent with a lack of knowledge of martian environments and possible life, as well as the performance of human support systems in those environments. Planetary protection requirements for later missions should not be relaxed without scientific review, justification, and consensus.

SOURCE: G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December, 2017, pp. 19-20.

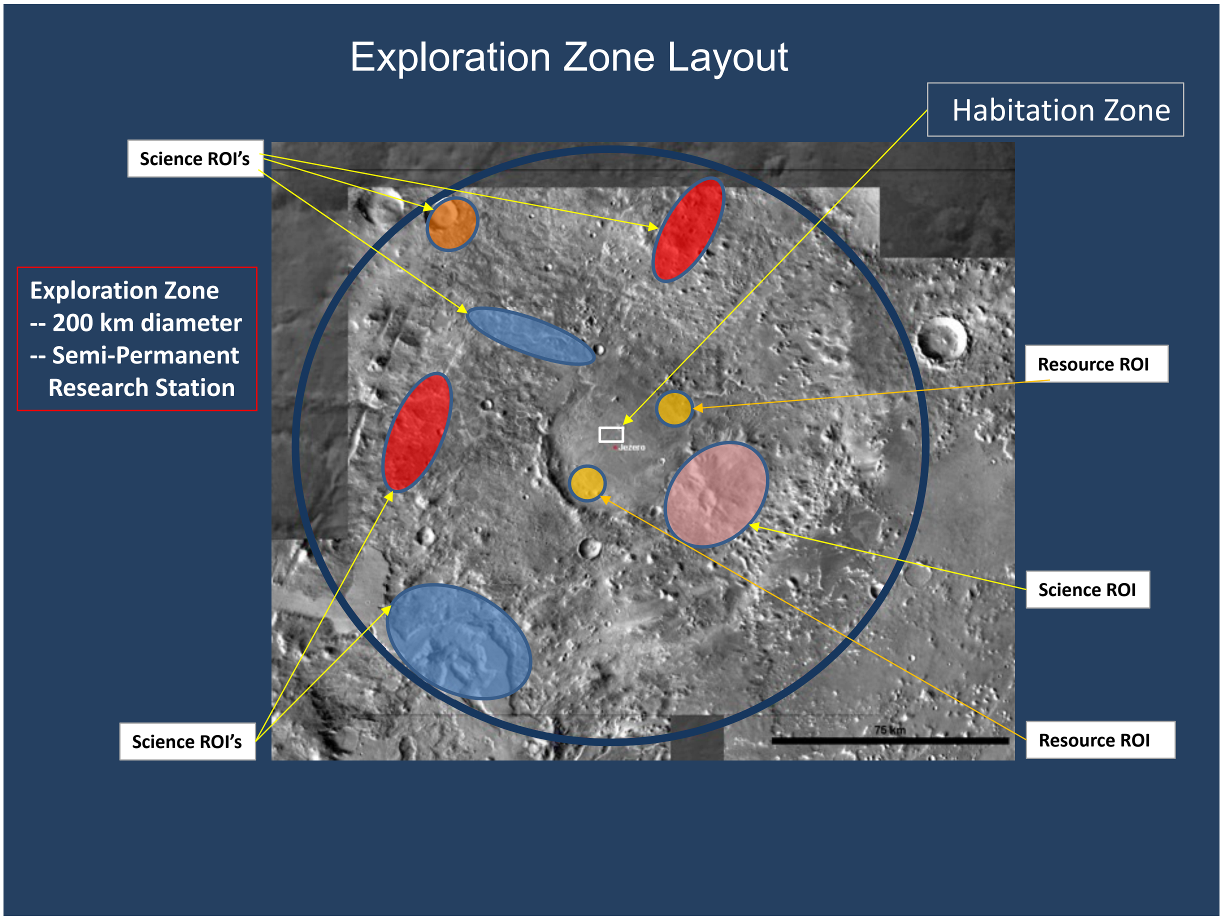

FIGURE 5.1 The notional layout of an exploration zone on Mars centered on a human landing site in Jezero crater (one of the landing sites under consideration for Mars 2020). Different regions of interest (ROIs) are designated for scientific study and resource utilization. Each ROI may have a different planetary protection categorization. SOURCE: Adapted R. Davis, presentation to the committee, May 23, 2017, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_180766.pdf. Courtesy of NASA.

which cannot be known at this time. However, existing planetary protection requirements imposed on the robotic science missions would become irrelevant only if future human missions exceed the current levels of contamination on a planet-wide basis. Therefore, *the processes for selecting a human exploration strategy and for developing planetary protection policy are inextricably linked*.

As NASA begins to develop a planetary protection policy that will encompass future human missions, policy makers will need to consider all the potential approaches for human missions. An illustrative list of these approaches might include the following:

1. Require human spaceflight missions to follow the same standards as robotic science missions (i.e., follow the current COSPAR guideline). If humans cannot meet the standards, they cannot go; implying that scientific investigation has greater importance than human exploration. This alternative is, of course, completely incompatible with plans for human presence on Mars.
2. Promulgate a policy that terminates or eliminates all forward biological contamination planetary protection requirements for all types of missions for Mars. This approach effectively assumes that the period of

protected biological exploration for Mars has ended. Science missions would still need to be cleaned based on the contamination control requirements imposed by the missions' science instruments.

3. Establish exploration zones (perhaps through an international process) where humans are allowed to explore based on scientific and engineering studies that establish zone extent and perhaps even duration (see Figure 5.1). Set requirements for human missions that are relaxed from current COSPAR standards based on realistic engineering considerations and the outcome of the research and technologies studies addressing specific items in Box 5.1 above. As noted in the discussion below of future studies, this alternative assumes exploration activities can protect large parts of Mars for scientific study and that contamination from the human habitats will not expand into these other regions of interest.
4. Delineate, via international agreement, areas of scientific interest that cannot be accessed by human missions. Ensure that these zones have sufficient buffers to protect the scientific endeavors from human contamination. The process will have to acknowledge that non-access is by mutual agreement to serve scientific research and is not intended to abrogate the OST's provisions.[9]

Alternative four is not in conflict with option three above, and some combination of three and four may be optimum. The process by which a new planetary protection policy for human exploration of Mars is developed will need to provide for international discussions of, and choices amongst, alternatives such as these.

FUTURE STUDIES REQUIRED TO DEVELOP THE NEXT HUMAN EXPLORATION POLICY

The feasibility and limitations of a policy that allows for protected science zones or unprotected human exploration zones depend on the extent to which contaminants can be transported across Mars. After many decades of intensive scientific Mars exploration, the only known truly global phenomena are dust storms. While some dust storms occur on a part of the planet every year, there are occasionally extreme events that cover the entire planet. Mars scientists have concluded, therefore, that the surface dust of Mars is "well-mixed."[10] It is conceivable that some release of contaminants might be (or might have been in the past) carried a significant distance by those dust storms. The committee hastens to add that the Mars atmosphere is very thin, mostly carbon dioxide with a pressure about that of Earth at an altitude of 30 km. Thus even at the highest velocities measured by landers (~130 km per hour) the force exerted is extremely small; about like a puff of your breath. Only because martian dust is extremely fine, like flour or talcum powder, can it be moved by such small forces. However, microorganisms are also tiny and have low mass so it is conceivable they might be blown by those forces as well.

There are several questions that require further research in order to provide a scientific basis on which to develop new policy. The following are examples:[11]

1. Because some releases of gases, dust, or other emissions from a human base are inevitable, how far would such contamination travel in the very thin atmosphere of Mars? Would it be diluted extensively and/or sterilized before reaching the science region of interest?
2. If a human habitat on Mars were to suffer a catastrophic blowout event and release microbes from the astronauts, how far would the contamination travel and what effect could it have on the science regions?

[9] Article I of the Outer Space Treaty ensures that "The exploration and use of outer space . . . shall be free for exploration and use by all States without discrimination of any kind"; Article II specifies that outer space "is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means"; and Article XII ensures that "[a]ll stations, installations, equipment and space vehicles on the moon and other celestial bodies shall be open to representatives of other States Parties to the Treaty on a basis of reciprocity." The U.S. negotiator for the OST explained at the time that this provision "does not confer, or imply the existence of any right or power to veto proposed visits to other countries' facilities on a celestial body" (see S. Hobe, B. Schmidt-Tedd, K.-U. Schrogl, and G.M. Goh, eds., *Cologne Commentary on Space Law*, Heymanns, Cologne, Germany, Volume 1, 2009. p. 10).

[10] H. Wang and M.I. Richardson, The origin, evolution, and trajectory of large dust storms on Mars during Mars years 24-30 (1999-2011), *Icarus* 251:112-127, 2015.

[11] A recent NASA-sponsored workshop (Dust in the Atmosphere of Mars and Its Impact on Human Exploration, June 13-15, 2017) addressed some of the same issues as those below, but the committee believes that a further consideration of such topics is warranted.

3. Using the current knowledge of Mars and modern biological expertise, is there credible evidence that any terrestrial microbes would survive in the harsh radiation and very dry oxidizing conditions on the surface of Mars?
4. To what extent might modern genomic techniques be applied to assessing contamination and possibly even eliminate the need for some contamination control requirements?

The committee believes that to formulate new policy, research is essential to develop advanced biological contamination measurement techniques and instrumentation. For example, DNA (deoxyribonuclic acid) sequencing to identify possible contaminants is not incompatible with options number 3 and 4 above and could be an enabling technology. However, the most important current contaminant requirement for the Mars 2020 mission is considered to be the total organic carbon burden, which may not be able to be addressed by genomic techniques. There are also capabilities such as highly sophisticated computational fluid dynamics analysis, the use of wind tunnels, and other ground-based simulations and experiments that could be carried out prior to any space-based project in order to bound the problem. The important point is that modern existing tools, knowledge, and facilities need to be used to assess the risks and, thereby, provide scientific information to inform policy decisions.

Finding: Although NASA is planning for human missions to Mars in the 2030s, NASA does not currently have an adequate planetary protection policy for human exploration and activities on Mars. In addition, neither NASA nor the Department of State have crafted strategies for productive international dialog on developing policy for planetary protection and for other issues, such as the relationship between exploration zones on Mars and the OST's prohibition on national appropriation of parts of celestial bodies, associated with human missions to Mars.

Recommendation 5.1: NASA's process for developing a human Mars exploration policy should include examination of alternative planetary protection scenarios and should have access to the necessary research that informs these alternatives. It should also include plans to engage with other nations on the policy and legal implications of missions to Mars.

6

The Private Sector and Planetary Protection Policy Development

PRIVATE-SECTOR SPACE ACTIVITIES AND PLANETARY PROTECTION

Private-sector enterprises have long been involved in space activities, such as launching and operating communication satellites.[1] Today, private-sector work with communications satellites and their associated distribution networks account for approximately 80 percent of the more than $375 billion global space economy (see Figure 6.1).[2] Traditional private-sector space activities, such as launching and operating communications satellites, do not generate planetary protection concerns. As noted in Chapter 3, this fact helps explain the lack of private-sector involvement in planetary protection policy development processes, such as those of the Committee on Space Research (COSPAR).

In addition, the committee noted the emergence of private-sector interest in new types of space activities, which fall within what is variously called "space entrepreneurship" and "new space." These new activities include delivering crew and cargo to the International Space Station, launching and operating remote sensing technologies, plans for asteroid mining, interest in space tourism, transport to the lunar surface, and missions to Mars. The only "new space" areas that implicate serious planetary protection concerns are missions to Mars.[3]

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[1] In the 2010 National Space Policy, "commercial space" activities involve "space goods, services, or activities provided by private sector enterprises that bear a reasonable portion of the investment risk and responsibility for the activity, operate in accordance with typical market-based incentives for controlling cost and optimizing return on investment, and have the legal capacity to offer these goods or services to existing or potential nongovernmental customers." Executive Office of the President, *National Space Policy of the United States of America*, June 28, 2010, p. 10. https://www.nasa.gov/sites/default/files/national_space_policy_6-28-10.pdf.

[2] The Space Foundation, The Space Report 2017, https://www.thespacereport.org/year/2017.

[3] Some "new space" activities, such as missions to the lunar surface, would have to satisfy procedural planetary protection requirements (e.g., documentation and inventory of organics), such as being assigned a category (e.g., Category II, mission to the Moon), but, once these procedural obligations are met, the activities would not have to comply with any substantive planetary protection requirements. Returning extraterrestrial materials to Earth may potentially cause planetary protection concerns. Samples returned from the Moon are classified as unrestricted Earth return. Current COSPAR policy for the return of samples from asteroids, comets, and other small solar system bodies requires determination as to whether a mission is classified as restricted or unrestricted Earth return. This determination "shall be undertaken with respect to the best multidisciplinary scientific advice, using the framework presented in the 1998 report of the US National Research Council's Space Studies Board entitled, *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making*." It is conceivable that the referenced framework could trigger a determination of restricted Earth return for certain organic- or water-rich small bodies. The martian moons, Phobos and Deimos, are currently a gray area with respect to their sample-return categorization. This uncertainty is currently being addressed by parallel studies sponsored by the Japan Aerospace Exploration Agency and by NASA and the European Space Agency.

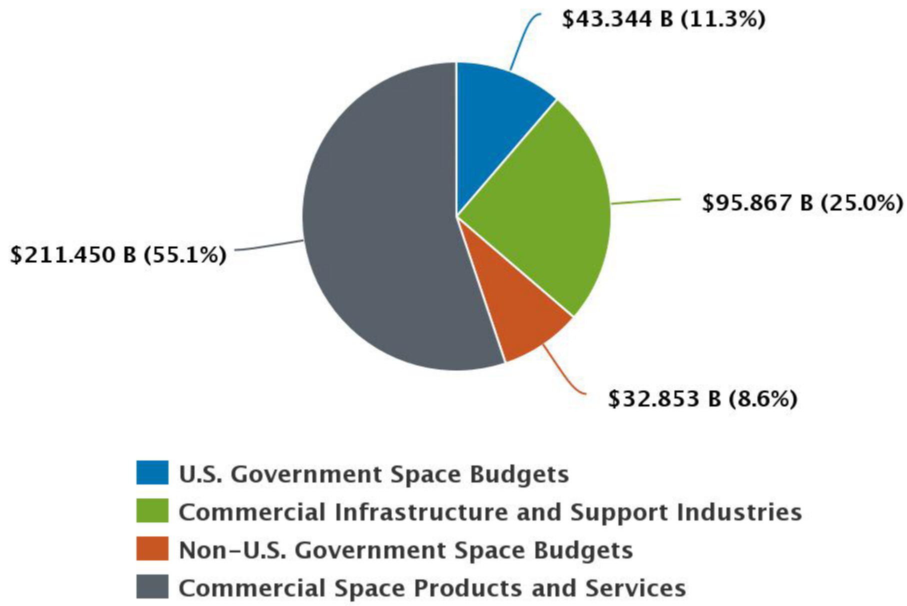

FIGURE 6.1 The gross make-up of the global space economy. SOURCE: Courtesy the Space Foundation.

Finding: Current planetary protection policy and requirements do not mandate significant actions beyond documentation and inventory of organic materials for the vast majority of ongoing and planned private-sector space activities.

In connection with missions to Mars, Chapter 5 noted that at least two major companies have expressed interest in and described plans to send their own robotic and/or human missions to Mars. The planetary protection challenges that robotic and human missions to Mars would create also arise with the development and execution of plans for private-sector missions to Mars.

Recommendation 6.1: Planetary protection policies and requirements for forward and back contamination should apply equally to both government-sponsored and private-sector missions to Mars.

The possibility of private-sector missions to Mars creates two planetary protection policy issues requiring attention by the policy development process: (1) the so-called "regulatory gap" in federal law; and (2) the participation of the private sector in the development of planetary protection policy.

PLANETARY PROTECTION, THE PRIVATE SECTOR, AND THE REGULATORY GAP

No federal regulatory agency has the jurisdiction to authorize and continually supervise on-orbit activities undertaken by private-sector entities, including activities that could raise planetary protection issues.[4] The com-

[4] See, for example, Subcommittee on Space of the Committee on Science, Space and Technology, U.S. House of Representatives, Hearings on Space Traffic Management: How to Prevent a Real Life "Gravity," May 9, 2014, https://science.house.gov/legislation/hearings/space-subcommittee-hearing-space-traffic-management-how-prevent-real-life; and Hearings on Exploring Our Solar System: The ASTEROIDS Act as a Key Step, September 10, 2014, https://science.house.gov/legislation/hearings/subcommittee-space-exploring-our-solar-system-asteroids-act-key-step.

mittee heard from numerous experts that this regulatory gap is a serious problem in U.S. space law.[5] Despite legislative and executive branch attention to this issue, Congress has not, to date, eliminated the regulatory gap.[6] Addressing this gap is a necessary prerequisite to the development and implementation of an effective planetary protection policy applicable to private-sector entities. As a current example of this concern, on February 6, 2018, SpaceX conducted a test launch of its new Falcon 9 Heavy vehicle in which the dummy payload (i.e., a used Tesla roadster) was boosted into a Mars-crossing orbit. Only after the initial release of this report was it revealed that formal, but limited, consultations on the launch's planetary protection implications took place between the Federal Aviation Administration (FAA), NASA, and SpaceX (Appendix H).[7]

In 2015, Congress required a report from the Office of Science and Technology Policy (OSTP) on how the United States could authorize and continually supervise private sector on-orbit activities to meet its Outer Space Treaty (OST) obligations.[8] OSTP proposed legislation under which Congress would authorize the Department of Transportation to grant authorizations for private-sector space missions. In exercising this authority, the Secretary of Transportation would be advised by "an interagency process in which designated agencies would review a proposed mission in relation to specified government interests, with only such conditions as necessary for fulfillment of those government interests."[9]

For private-sector space activities that raise planetary protection issues, such as robotic or human missions to Mars, the regulatory gap creates concerns under the OST. The treaty requires the United States to authorize and continuously supervise the space activities of nongovernmental entities,[10] including activities that create potential forward or backward contamination risks. This obligation also requires the United States to "adopt appropriate measures" for planetary protection purposes.[11] Thus, government and private space activities are required to meet equivalent standards and perform in equivalent ways under the treaty's planetary protection obligations. In addition to legal authority, the agency given this jurisdiction will require relevant technical and scientific expertise or access to such expertise.

NASA is not a regulatory agency and, therefore, cannot authorize and continually supervise private-sector space activities. However, NASA is where the federal government's expertise on planetary protection resides. Possible regulatory agencies, such as the Department of Commerce or the Department of Transportation, have the competency to regulate private-sector space activities. However, they do not have the necessary scientific and technical expertise to guide the development of regulations on planetary protection for the private sector. Any approach to eliminating the regulatory gap needs to ensure that the expertise NASA uses to address planetary protection informs the exercise of regulatory authority. One model for achieving this goal is the memorandum of

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[5] Other bodies of federal law that apply to private-sector space activities, such as export control regulations, do not address the regulatory gap with respect to planetary protection. Export control regulations have raised issues with, for example, private-sector launching and operation of satellites and remote sensing technologies. However, these space activities do not involve planetary protection concerns. For export control regulations, see International Traffic in Arms Regulations, 22 CFR Parts 120-130 (implemented by the Department of State), and Export Administration Regulations, 22 CFR Parts 730-774 (implemented by the Department of Commerce).

[6] The "regulatory gap" affects other private-sector space activities that do not necessarily implicate planetary protection, such as lunar missions and asteroid mining. In reviewing private-sector plans for lunar missions, the Federal Aviation Administration (FAA) tested the scope of its regulatory authority, leading it to conclude that the FAA might need additional authority to evaluate future missions in order to ensure the United States complies with the OST. See, for example, FAA, Fact Sheet—Moon Express Payload Review Determination, August 3, 2016, https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20595.

[7] I. Klotz, Launch of Tesla casts U.S. policy into new legal regime, *Aviation Week and Space Technology*, February 15, 2018, http://aviationweek.com/commercializing-space/launch-tesla-casts-us-policy-new-legal-regime.

[8] U.S. Commercial Space Launch Competitiveness Act, P.L. 114-90. (2015), Section 108.

[9] Executive Office of the President, Office of Science Technology Policy, Report submitted in fulfillment of a requirement contained in the U.S. Commercial Space Launch Competitiveness Act, April 4, 2016 ("Section 108 Report"), https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/csla_report_4-4-16_final.pdf.

[10] Outer Space Treaty, Article VI ("The activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty.").

[11] Outer Space Treaty, Article IX.

understanding NASA and the FAA entered to "avoid conflicting requirements and multiple sets of standards [and to] exchange knowledge and best practices" in the context of commercial transport of passengers to low Earth orbit.[12]

Although Congress has not yet enacted the necessary legislation, it could resolve the regulatory gap in different ways. It could empower a single agency to regulate private-sector space activities that raise planetary protection concerns. Congress could also adopt the approach recommended by the OSTP—provide a federal regulatory agency with authority over private-sector space missions, the exercise of which is informed by an interagency process.[13,14] Whatever approach Congress adopts to close the regulatory gap would benefit from the inclusion of mechanisms helping the private sector become familiar with expected authorization processes and associated timelines.

Finding: A regulatory gap exists in U.S. federal law and poses a problem for U.S. compliance with the OST's obligations on planetary protection with regard to private sector enterprises. The OST requires states parties, including the United States, to authorize and continually supervise nongovernmental entities, including private sector enterprises, for any space activity that implicates the treaty, including its planetary protection provisions.

Recommendation 6.2: Congress should address the regulatory gap by promulgating legislation that grants jurisdiction to an appropriate federal regulatory agency to authorize and supervise private-sector space activities that raise planetary protection issues. The legislation should also ensure that the authority granted be exercised in a way that is based upon the most relevant scientific information and best practices on planetary protection.

PRIVATE-SECTOR PARTICIPATION IN THE DEVELOPMENT OF PLANETARY PROTECTION POLICY

The need to fill the regulatory gap and apply planetary protection policy equally to government-sponsored and private-sector missions highlights issues related to the participation of the private-sector in making planetary protection policy. Historically, the private sector has not been involved in the development of planetary protection policy because the space activities pursued by companies have not generated concerns with forward or backward contamination. However, the interest of some private-sector enterprises in missions to Mars generates questions about private-sector participation in planetary policy development. The vibrancy and innovation associated with "new space" activities suggest that private-sector interest in missions to Mars might increase as NASA moves its Mars projects forward, and as the Falcon 9 Heavy launch on February 2018 has demonstrated, at least one private entity has the wherewithal to send an object to Mars.

On the one hand, the committee has identified only two companies that space exploration experts presently consider potentially serious players in missions to Mars. Even with these two companies, doubts exist whether they will be able to mount their own missions to Mars, as opposed to providing goods and services to government-sponsored missions. Creating new participation rights or mechanisms for the private sector in terms of planetary protection policy development on this basis could be perceived as granting special treatment for specific enterprises.

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[12] 2012 Memorandum of Understanding Between the Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) for Achievement of Mutual Goals in Human Space Transportation, https://www.nasa.gov/sites/default/files/files/NASA-FAAMOU_signed.pdf.

[13] In February 2018, the reestablished National Space Council recommended that the Department of Commerce take the lead in regulating private-sector space activities (See https://spacepolicyonline.com/news/second-national-space-council-meeting-focuses-on-regulatory-reform-china). In April 2018, the House of Representatives passed H.R. 2809, the American Space Commerce Free Enterprise Act, which designates the Department of Commerce as the federal agency responsible for the authorization and supervision of private-sector space activities called for in Article VI of the OST. However, H.R. 2809 retains the licensing roles of the FAA (for launch and reentry) and Federal Communications Commission (for space communications) will retain their traditional roles in licensing launch/reentry and space communications, respectively. For more information about H.R. 2809, see https://www.congress.gov/bill/115th-congress/house-bill/2809). To date, the Senate has not acted on this or any related bill.

[14] In late May 2018, President Trump signed Space Policy Directive 2 and thereby initiated a process to streamline regulations on the commercial use of space as recommended by the National Space Council in February 2018. For more details see https://www.whitehouse.gov/presidential-actions/space-policy-directive-2-streamlining-regulations-commercial-use-space.

On the other hand, the private sector already participates in making space policy. NASA directly engages with the private sector on various space issues, and companies can communicate with members of Congress on legislation, the White House on policy, and federal agencies on regulations affecting their space activities.[15]

At the international level, COSPAR has long been open to the participation of representatives from the private sector. COSPAR permits officials or staff from companies to attend its colloquia, workshops, symposia, assemblies, and policy-making deliberations. COSPAR allows industry representatives to have the same membership status as scientists. Despite its openness to commercial participation, not many companies have been involved in COSPAR activities on planetary protection. Few firms have taken out Associated Supporter status,[16] and few individuals working in the private sector appear within the ranks of COSPAR associates.[17] The lack of private-sector participation in COSPAR's planetary protection policy development primarily exists because, to date, companies have not pursued space activities that implicate planetary protection.[18]

This pattern might change if commercial interest in Mars increases in the coming years, but, at the moment, there is little evidence of such a change. COSPAR officials told the committee they would like to increase private-sector participation in COSPAR's planetary protection policy development processes. One option for COSPAR to expand such participation would be to partner with an organization having a larger level of private-sector participation, such as the International Astronautical Federation (IAF). Past joint COSPAR-IAF congresses have not been especially effective at promoting substantial cross-organizational interactions.[19] Another option is for COSPAR and other interested parties to sponsor special sessions on planetary protection issues at the annual IAF-organized International Astronautical Congress.[20] Nevertheless, with sufficient motivation by all the players, such a partnership might enhance how the COSPAR process reflects private-sector input on the science informing planetary protection policy and facilitate private-sector commitment to complying with planetary protection guidance from COSPAR.

> **Finding:** To date, planetary protection policy development at national and international levels has not involved significant participation from the private sector. The lack of private-sector participation creates potential challenges for policy development, because private-sector actors need to be able to understand and embrace appropriate planetary protection measures.

> **Recommendation 6.3: NASA should ensure that its policy-development processes, including new mechanisms (e.g., a revitalized external advisory committee focused on planetary protection), make appropriate efforts to take into account the views of the private sector in the development of planetary protection policy. NASA should support the efforts of COSPAR officials to increase private-sector participation in the COSPAR process on planetary protection.**

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[15] For example, commercial space groups are widely represented in the Commercial Space Transportation Advisory Committee (COMSTAC), which advises the FAA and other agencies on the development of regulatory standards for safe and competitive space flights. See "Department of Transportation" in Chapter 3. For more information about COMSTAC, see https://www.faa.gov/about/office_org/headquarters_offices/ast/advisory_committee.

[16] As of August 2017, there were two companies each from the United States. and China and five from Europe that are Associated Supporters. See COSPAR, https://cosparhq.cnes.fr/associated-supporters.

[17] The committee has been unable to confirm this with objective data because COSPAR does not collect data on the research or employment background of its associated members, who number in the thousands.

[18] Another reason could arise from the lack of interest scientists and engineers have for joint meetings. For example, the history of joint meetings between the International Astronautical Federation (which is rich in commercial engineers) and COSPAR (which is focused on the science of planetary protection) has been disappointing.

[19] Two such joint COSPAR-IAF meetings have taken place in recent decades: The first and second World Space Congresses took place in Washington, D.C., and Houston, Texas, in 1992 and 2002, respectively.

[20] One such special session, "New Challenger for Planetary Protection," is being organized at the 2018 IAC in Bremen, Germany.

7

A NASA Planetary Protection Strategic Plan

For more than 50 years, planetary protection policy has been guiding agencies and missions on requirements, practices, and procedures that satisfy the requirements of the Outer Space Treaty (OST). Changes in planetary protection implementation have occurred incrementally as experience accumulated and mission targets varied. The planetary protection tools of the Viking era are probably no longer affordable or even feasible for spacecraft now in development. They also may no longer be necessary if newly emerging biotechnologies can meet the sterility requirements for new missions such as Europa Clipper.

Now an unprecedented combination of highly complex future missions developed in the context of cost caps, new space actors, and a revolution in biological science suggest that it is time to review the historic approaches to formulating policies for assessing contamination risks and incorporate more recent and relevant scientific and technological information into new approaches. The mission challenges, including visiting regions where there may be evidence of past or present life and returning samples from those regions as well as putting humans on the surface with all the billions of biota carried by our species, are described in detail elsewhere in this report. New space actors who wish to operate via commercial missions are also noted. Rather than respond to this very challenging and potentially extremely rewarding situation by again invoking the planetary protection concepts and tools from the past, the space exploration community has an opportunity to plan in advance to meet oncoming needs and capitalize on new scientific discoveries.

Earlier chapters in this report have discussed how key NASA documents define the agency's top-level policy planetary protection goals and major roles and responsibilities for implementation of the policy. However, in assessing NASA's policy development processes, the committee did not find a clear articulation of who in the agency is responsible for policy formulation or whether policy formulation and implementation are intended to be separate, independent responsibilities. Furthermore, NASA's top-level documents do not present a related strategy for planning, budgeting, and setting priorities for the planetary protection program or performance metrics for the program. Such considerations have a direct impact on NASA's ability to execute policy and, equally importantly, to ensure that the policy can evolve as needed in the future. All of these issues are appropriate items for a planetary protection strategic plan.

Finding: The issues raised in the committee's assessment of NASA's planetary protection policy development processes comprise appropriate topics for a planetary protection strategic plan, but NASA currently lacks such a plan.

Recommendation 7.1: NASA, under the direction of the Office of the Administrator, should develop a planetary protection strategic plan that clearly addresses the agency's approach for

- **Managing planetary protection policy implementation,**
- **Securing relevant outside expert advice,**
- **Developing a long-range forecast of future solar system exploration missions having planetary protection implications,**
- **Setting planetary protection research and technology investment priorities, and**
- **Identifying the agency's strategy for dealing with major policy issues such as sample return, human missions to Mars, and private-sector involvement in solar system exploration missions.**

The sections below elaborate on each of these topics and relate them to recommendations stemming from the committee's assessments in earlier chapters. Having a plan that addresses these issues will not, by itself, resolve the issues or solve the problems that the committee has identified, but developing a comprehensive plan is an important step in that direction.

MANAGING PLANETARY PROTECTION POLICY IMPLEMENTATION

Three of the committee's recommendations are relevant to issues associated with the managing the implementation of planetary protection policy:

- *Recommendation 3.2* called attention to the need for NASA to assess the completeness of planetary protection requirements for future missions and to identify requirements early in a mission's design and development lifetime. It also recommended that NASA adhere to established project management and systems engineering protocols when planetary protection requirements are levied on projects rather than to depend on informal mechanisms and to utilize established conflict resolution processes.
- *Recommendation 3.3* noted the need to ensure that all relevant stakeholders are engaged as new or modified planetary protection policies are considered.
- *Recommendation 3.4* emphasized the need to clearly define institutional roles, responsibilities, and resources for planetary protection activities that have been recently assigned to the Office of Safety and Mission Assurance.

A planetary protection strategic plan could provide a basis for how NASA intends to act on each of these recommendations. Specifically, such a plan would address the following elements:

- Relative roles and responsibilities in NASA for planetary protection policy formulation, implementation, and compliance validation;
- Plans for conducting a thorough review of the completeness of current policies and requirements, especially with respect to potential new issues associated with future missions;
- Reaffirmation of established processes for defining and communicating requirements, especially level-2 and lower level requirements;
- Use of NASA standard project management and systems engineering protocols in developing planetary protection requirements and delegating implementation responsibilities;
- Management and mitigation of risk in a cost-capped program environment;
- Participation by all agency stakeholders in policy changes and requirements development;
- Institutional roles and responsibilities for planetary protection research and technology development; and
- Resource needs (workforce and budget) to conduct planetary protection responsibilities effectively.

SECURING RELEVANT OUTSIDE EXPERT ADVICE

Two of the committee's recommendations are relevant to issues associated with securing relevant outside advice:

- *Recommendation 3.6* called for the reestablishment of an independent planetary protection advisory committee. The recommendation's parent section (see "An Independent Planetary Protection Advisory Committee" in Chapter 3) outlines the reasons that NASA needs to have access to independent outside expert advice and notes that the former Planetary Protection Subcommittee of the NASA Advisory Council's Science Committee no longer exists. Such a committee, if reestablished, could provide both policy and technical advice and facilitate NASA's interactions with other federal agencies and other stakeholders, including scientists and the private sector.
- *Recommendation 3.7* urged NASA to broaden its sources of scientific input to include all relevant scientific disciplines.

The roles of the advisory body could include the following:

- Serve as a sounding board and source of input to assist in the development of planetary protection requirements for new missions and U.S. input to Committee on Space Research (COSPAR) Panel on Planetary Protection deliberations,
- Provide advice on opportunities, needs, and priorities for investments in planetary protection research and technology development, and
- Act as a peer-review forum to facilitate the effectiveness of NASA's planetary protection activities.

PLANNING FOR FUTURE SOLAR SYSTEM EXPLORATION MISSIONS HAVING PLANETARY PROTECTION IMPLICATIONS

Chapter 3 discussed the committee's concerns over the adequacy of investments in research on new scientific and technological tools to make planetary protection activities more effective, reduce uncertainties, and facilitate timely improvements to planetary protection policies. Recommendation 3.8 called for a strategic assessment of technology needs and opportunities for future missions. The analysis in Chapter 3 regarding experience with planetary protection activities in two highly relevant missions—Mars 2020 and Europa Clipper—emphasized the importance of identifying key planetary protection issues and requirements very early in a mission's design and development cycle. Only by means of such early engagement, can planetary protection officials and project teams have the time to make informed tradeoffs between often competing demands of requirements to satisfy planetary protection objectives and mission cost and technical constraints.

A long-range forecast of likely future missions that will have implications for planetary protection is an essential element of a planetary protection strategic plan. The forecast would become a tool for the following:

- Advisory bodies as they assist NASA in setting priorities for research and technology investments; and
- NASA planetary protection officials as they look ahead well in advance at likely future missions and begin to consider planetary protection guidelines and requirements that mission planners will need to understand and incorporate into their planning.

DEVELOPING A STRATEGY FOR SAMPLE RETURN FROM AND HUMAN MISSIONS TO MARS

Preparations for new missions to Mars are opening a new era of solar system exploration that will have profound planetary protection implications. Mars 2020 will begin a multi-mission program to return samples from Mars to Earth and, thereby, introduce the first serious back contamination considerations since the Apollo program. Plans for human missions to Mars in the foreseeable future pose entirely new considerations for how to meet international planetary protection obligations. The committee has noted in Chapters 3 and 5 that planetary protection policies to deal with these new events are significantly incomplete. Recommendation 3.5 called for an agency-wide strategic plan for managing planetary protection responsibilities for the new Mars missions.

The committee calls attention to several important aspects of the Mars planetary protection policy. First, the policy will need to address requirements for sample containment, verification of containment, and receiving facilities for returned samples and their return vehicle. Recommendation 3.1 emphasizes that this policy will need to draw on input from a broad range of experts, including mission and facility development teams and scientists from across the spectrum of biology and biotechnology. The current U.S. government-wide policy for dealing with space experiments that might have effects potentially harmful on Earth is a Presidential Directive (NSC-25) that dates back to 1977. Because this policy concerns all relevant federal agencies, any revision will need to come from outside NASA. Nevertheless, NASA is the best agency to stimulate discussion within the government leading to appropriate revisions that the committee recommends (Recommendation 4.2).

One of the most important elements of a human Mars exploration strategy will be consideration of whether and how to partition the planet so that human activities and robotic scientific investigations can coexist in a manner that protects scientific research from harmful contamination and reflects the intent of articles of the OST. Recommendation 5.1 suggests that NASA efforts to draft a Mars strategy include analysis of alternative scenarios for facilitating simultaneous human and robotic activities on Mars and to engage other nations in these studies. Recommendation 4.2 acknowledges that such international discussions will need leadership from the Department of State, with expert assistance from NASA.

Each of the issues regarding a planetary protection strategy for Mars exploration will require significant effort. The committee concludes that an overall NASA planetary protection strategic plan is an appropriate platform for organizing the effort and creating a plan for the job.

DEVELOPING A STRATEGY FOR PRIVATE-SECTOR SOLAR SYSTEM EXPLORATION MISSIONS

In Chapter 6 the committee discusses the planetary protection policy implications from growing private-sector missions to solar system bodies, especially Mars, and the committee offers two recommendations. First, the OST requires that states parties bear responsibility for ensuring that private-sector missions as well as government-sponsored missions comply with planetary protection provisions of the treaty. Therefore, Recommendation 6.2 calls on Congress to address the gap in current federal regulations that currently fail to assign authority for monitoring private-sector compliance with planetary protection requirements. As the home of U.S. government expertise in planetary protection, NASA is best able to assist in identifying the issues to be addressed by a legislative solution.

Second, the committee has noted that development of planetary protection policy has been largely a scientific effort throughout the history of solar system exploration. On an international level, COSPAR has provided a successful mechanism for developing international, science-based agreement and cooperation on planetary protection for more than 50 years. Recommendation 6.1 indicates that future planetary protection guidelines apply equally well to government-sponsored and private-sector missions. This is especially true if policies are developed in a way that ensures that private-sector concerns are understood as policy evolves. COSPAR officials told the committee that the organization is well aware that private-sector entities comprise a new stakeholder in planetary protection policy development. In Recommendation 6.3, the committee encourages NASA to exercise opportunities to promote private-sector participation in development of planetary protection policy, both within NASA and in COSPAR.

CONCLUDING THOUGHTS

At the dawn of the space age, visionary proponents of solar system exploration imagined a time when one could answer questions about whether life ever existed on other solar system bodies and about how life originated on Earth. That time has come as sophisticated life detection instruments are being prepared to study the surface of Mars, return samples of the planet to Earth, and send human explorers for first-hand studies of the planet and as missions to explore Jupiter's icy moon Europa and its interior ocean begin development. Soundly framed and executed planetary protection policies will play a critical role in ensuring that these efforts will be able to deliver unambiguous answers and to preserve opportunities for continued scientific studies and exploration. Such policies will need to be consonant with new dimensions of solar system exploration—for example, including new advances and capabilities in biotechnology, realistic budgets, the entry of new international and private-sector players, and eventual human presence on other bodies—that go beyond past experience and demand proactive attention. NASA has played a pivotal leadership role on behalf of the United States in developing successful planetary protection policies for more than five decades, and the committee's recommendations are intended to help sustain that success in the future.

A

Letter Requesting This Study

National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

Reply to Attn of: Science Mission Directorate

FEB 29 2016

Dr. David Spergel
Chair, Space Studies Board
National Research Council
500 5th Street, NW
Washington, DC 20001

Dear Dr. Spergel:

We live in an incredible time of space and Earth Science discovery. In recent years there have been significant developments related to the exploration of planetary environments, and solar system destinations thought to be capable of having harbored life or thought to be capable of currently harboring life. NASA's Cassini mission revealed a global ocean lies beneath the icy crust of Saturn's moon Enceladus, and NASA's Galileo probe discovered a body of liquid water locked inside the icy shell of Jupiter's moon Europa. Further, the Mars 2020 mission will look for signs of past life, collect samples for possible future return to Earth, and will demonstrate technology for future human exploration of Mars.

The 1967 United Nations Outer Space Treaty (OST) to which the U.S. is signatory, states that all States Parties to the treaty "shall conduct exploration so as to avoid their harmful contamination, and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter," and "shall bear international responsibility for national activities in outer space, whether such activities are carried on by governmental agencies or by non-governmental entities." Today, a range of other nations and non-state actors have expressed an intent to send spacecraft and humans to Mars in the coming years.

The technical guidelines for planetary protection are developed through the Committee on Space Research (COSPAR) Panel on Planetary Protection. Through this process, planetary protection policy has evolved steadily over the years, and spacefaring organizations such as NASA formulate and implement planetary protection policies and procedures for their missions to be consistent with COSPAR Planetary Protection Policy. While the Space Studies Board (SSB) advice has always been directed to NASA, the recommendations have almost always been considered by COSPAR, and many have been adopted internationally. In order to remain effective, planetary protection policy must account for the evolving landscape and challenges presented by the OST.

As NASA implements plans for future missions, this is a good time for a study of the current process by which planetary protection policy is developed and to recommend actions for NASA to consider in ensuring effective coordination on planetary protection. I would like to suggest that the SSB conduct a study of these issues and develop a report that presents its findings and recommendations. To strongly affect the implementation of planetary protection for NASA missions currently in formulation, we would need to receive the results of the study by the end of 2017. The scope and focus of such a study are described in the enclosed Statement of Task. I would like to request that the SSB submit a plan for such a study and a report on its findings.

Once the agreement with the National Research Council on the scope and cost for the proposed study has been achieved, the NASA Contracting Officer will issue a task order for implementation. Mr. David Pierce will be the technical point of contact for this effort and may be reached at (202) 358-3808 or david.l.pierce@nasa.gov.

Sincerely,

John M. Grunsfeld
Associate Administrator for
Science Mission Directorate

cc: Office of the Chief Scientist/E. Stofan

- A.Kaminski

Science Mission Directorate/G.Yoder

- C. Conley
- J. Green
- D. Holland
- D. Pierce
- B. Pugel
- G. Robinson

STATEMENT OF TASK

Review of Planetary Protection Policy Development Processes

February 2016

Background and Scope

Planetary protection is the practice of protecting solar system bodies (i.e., planets, moons, comets, and asteroids) from contamination by Earth life in order to preserve the scientific integrity of studies at those destinations relating to the origins of life and/or prebiotic chemical evolution and protecting Earth's inhabitants and environment from harm that could be caused by possible extraterrestrial life forms. The 1967 United Nations "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Bodies" (the Outer Space Treaty – OST) to which the U.S. and most other spacefaring nations are signatory, states in Article IX that all States Parties to the treaty "shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination, and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." In addition, Article VI of the same treaty specifies that States Parties "shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities."

The technical guidelines for planetary protection are developed through the deliberations of the Committee on Space Research (COSPAR) Panel on Planetary Protection, which are regularly undertaken on the basis of participants either reporting new scientific findings with policy implications (e.g., water being more abundant at a particular target than was previously recognized) and/or raising questions regarding specific concerns that may need to be to be addressed (e.g., new activities in space exploration that could affect policy compliance). The Panel develops recommendations that the COSPAR Bureau may adopt for inclusion into the official COSPAR Planetary Protection Policy. Through this process, the COSPAR Planetary Protection Policy has evolved steadily and incrementally over the years since it was initially created. Spacefaring organizations such as NASA formulate and implement planetary protection policies and procedures for their space missions to be consistent with COSPAR Planetary Protection Policy.

In recent years there have been significant developments related to the exploration of planetary environments. There have been major advances in the state of scientific knowledge regarding the environments of solar system destinations thought to be capable of having harbored life or thought to be capable of currently harboring life. Scientific understanding has also evolved regarding the nature of life on Earth in environments that are thought to be analogous to some of those expected at solar system destinations. In addition, there have been advances in the technology available to reduce microbial populations on spacecraft and to measure various levels of biological cleanliness.

Meanwhile, NASA's priorities have evolved to include special emphasis on robotic exploration of the moons of Jupiter and Saturn that are now known to have liquid water oceans, especially, but not limited to, Europa and Enceladus, as well as Restricted Earth Return missions (that have not been undertaken since Apollo) and human exploration of Mars. A range of other nations and nonstate actors also have expressed an intent to send spacecraft and humans to Mars in the coming years. Planetary protection policy must account for this evolving landscape in order to remain effective in addressing the challenges posed by Article IX, and now also Article VI, of the OST.

It is proposed here to have the Space Studies Board (SSB) of the National Academies of Science, Engineering, and Medicine carry out a study of the current process by which planetary protection policy is developed and recommend actions or options for NASA to consider in ensuring effective US Government coordination on planetary protection. In recent years, the SSB has provided recommendations to NASA on planetary protection requirements for spacecraft missions to Venus, Mars, and the icy satellites of the giant planets. In addition, the SSB has provided recommendations on the planetary protection requirements for spacecraft designed to collect and return to Earth samples from the Earth's Moon for the Apollo Program, and more recently Venus, Mars, and a variety of small solar system bodies such as moons, comets, and asteroids. Recently, the SSB and the European Science Foundation conducted a joint review of a NASA Mars Exploration Program Analysis Group's report on Mars Special Regions: i.e., zones where terrestrial life might proliferate, and thus require visiting spacecraft to return to Viking-era stringency in planetary protection constraints. While the SSB advice has always been directed to NASA, the recommendations have almost always been considered by COSPAR, and many have been adopted internationally; the proposed study may have similar impacts.

Statement of Task

The SSB of the National Academies of Sciences, Engineering, and Medicine will appoint an *ad hoc* committee to carry out a study that will describe how international and national planetary protection policy has been formulated and adopted and identify associated lessons to inform future policy development. Specifically, the committee will assess the current state of planetary protection policy development and the extent to which the current policy-making process is responsive to the present state of science, technology, and engineering, including biological science, as well as the exploration interests of state and nonstate actors. The committee's review will lead to recommendations on how to assure the planetary protection policy process is supportive of future scientific and societal interests, and as well as spaceflight missions.

The committee should consider the following questions in carrying out its review:

- How has the planetary protection policy development process evolved over the course of lunar and planetary exploration? What approaches to planetary protection policy development were used in the Apollo and Viking eras of solar system exploration and subsequent Mars exploration? What factors informed and drove those choices?

- What worthwhile lessons can policymakers take from the history of planetary protection policy development in looking toward future exploration and sample return missions?
- Who are the actors involved in the present-day planetary protection policy development process? What are the respective roles and responsibilities of international organizations, national organizations, and national space agencies (including agencies' planetary protection officers), advisory committees, and others in the process?
- How does the current process take into account new scientific and technical knowledge?
- To what extent does the current process consider the interests of state and nonstate actors in exploring planetary environments, including obligations under Article VI of the OST?
- How does the current process reconcile uncertainties in knowledge, differences between scientific and other exploration interests, as well as potentially competing interests?
- What are the barriers, or challenges, that inhibit the process of effective planetary protection policy development?
- What scientific, technical, philosophical, and/or ethical assumptions and values about the importance of avoiding forward contamination of extraterrestrial planetary environments are prioritized in the current planetary protection policy development process?
- What scientific, technical, philosophical, and ethical assumptions and values about the importance of protecting Earth and its environment ("backward contamination") are prioritized in the current planetary protection policy development process?
- How does the state of scientific understanding of planetary environments and their ability to harbor life inform the current planetary protection policy development process? What scientific knowledge or exploration interests are not taken into account?
- How does the current planetary protection policy development process balance interest in acquiring scientific knowledge of planetary environments to inform future scientific studies, exploration, and planetary protection policy choices with the interest in protecting those environments in the here-and-now?

Looking at both historical and contemporary approaches to planetary protection policy development, the committee should make recommendations about the future of planetary protection policy process development in relation to these questions:

- How could the planetary protection policy development process be made more adaptable to the evolving landscape of knowledge about and myriad interests in planetary environments?
- How can the regulatory environment in the U.S. Government evolve to keep pace with non-governmental spacefaring entities?

- How does a future process evaluate the state of the art and what technologies are required to ensure compliance with planetary protection policy for future missions?
- What risk assessment and/or quality control principles should be applied to ensure that a future process takes into account our understanding of the capabilities of Earth organisms and the potential for extraterrestrial life to be encountered by planetary missions?

Schedule

A peer reviewed and approved report shall be delivered to NASA on or before December 31, 2017.

B

Mars Special Regions: A Case Study in the Evolution of Planetary Protection Policies

The concept of so-called Special Regions on Mars—that is, any region "interpreted to have a high potential for the existence of extant martian life forms" or regions where the conditions permit the proliferation of organisms introduced from Earth[1]—presents an interesting case study in the evolution of planetary protection policies and associated requirements. This appendix presents a chronological discussion of this evolution with particular emphasis on the role played by the National Academies and its committees.[2]

LATE 1990s/EARLY 2000s

Observations conducted by NASA's Mars Global Surveyor in the late-1990s and early-2000s led to the discovery of transient activity in martian gullies suggesting that liquid water may have flown on the surface of Mars in recent times.[3] This discovery (see Figure B.1, step 2) had an important impact on planetary protection, demonstrating that some regions may be more suitable to life than others.[4]

2002-2003

In April 2002, the Committee on Space Research (COSPAR) and the International Astronomical Union convened a workshop in Williamsburg, Virginia, to discuss planetary protection policies.[5] The workshop (Figure. B.1, step 3) resulted in a revision of COSPAR's policies (Figure B.1, steps 4-7) and, in particular, established a new mission category—Category IVc—for spacecraft accessing a Special Region on Mars.[6] COSPAR defined a Special

[1] G. Kminek, C. Conley, V. Hipkin, and H. Yano, "COSPAR Planetary Protection Policy," *Space Research Today*, No. 200, December 2017, p. 18.

[2] Material in this appendix has been extracted and adapted from the report National Academies of Sciences, Engineering, and Medicine and European Science Foundation, *Review of the MEPAG Report on Mars Special Regions*, The National Academies Press, Washington, D.C., 2015

[3] M.C. Malin and K.S. Edgett, Evidence for recent groundwater seepage and surface runoff on Mars, *Science*, 288, pp. 2330-2335, 2000.

[4] M. Meltzer, *When Biospheres Collide: A History of NASA's Planetary Protection Programs*, NASA SP-2011-4234, U.S. Government Printing Office, Washington, D.C., 2011, pp. 381-383.

[5] J.D. Rummel, "Report of the Workshop on Planetary Protection Held Under the Auspices of the Committee on Space Research and the International Astronomical Union of the International Council for Science at Williamsburg, Virginia, USA on 2-4 April 2002," COSPAR, Paris, 2002.

[6] COSPAR, Planetary Protection Policy, *COSPAR Information Bulletin*, No. 156., pp. 67-74, 2003.

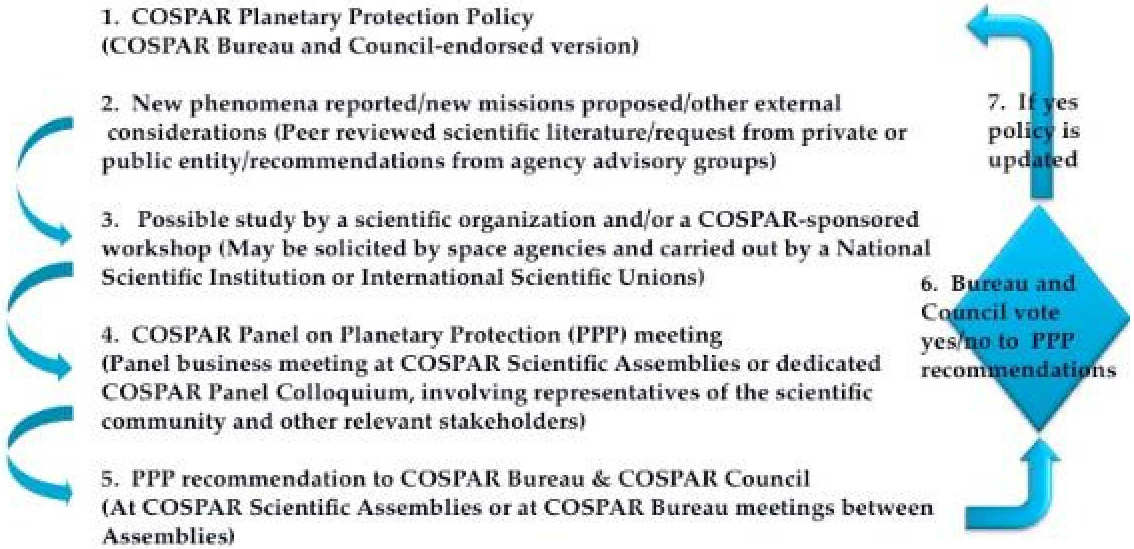

FIGURE B.1 The seven notional steps in the process by which planetary protection policies are set and subject to periodic revision. SOURCE: Adapted from G. Kminek and J. Rummel, "COSPAR's Planetary Protection Policy," *Space Research Today*, Number 193, August 2015, p. 8, Copyright 2015, with permission from Elsevier.

Region as a zone "within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant martian life forms. Given the current understanding, this is to apply to regions where liquid water is present or may occur. Specific examples include, but are not limited to: subsurface access in an area and to a depth where the presence of liquid water is probable, penetrations into the polar caps, [and] areas of hydrothermal activity."[7]

2005-2006

In 2005, NASA adopted COSPAR's concept of a Special Region within its planetary protection policy. In addition, NASA requested the National Research Council (NRC) to conduct (Figure B.1, step 3) a study to assess the body of policies, requirements, and techniques designed to protect Mars from Earth-originating organisms that could interfere with and compromise scientific investigations.[8] The resulting NRC report, *Preventing the Forward Contamination of Mars*, concluded that there were insufficient data to distinguish between Special Regions on Mars and regions that are not special.[9] The committee proposed a new classification system, which would replace COSPAR's Categories IVa through IVc, with Category IVn for Non-Special Regions and Category IVs for Special Regions.[10] In addition, the NRC committee commented: "Until measurements are made that permit distinguishing confidently between regions that are special on Mars and those that are not, NASA should treat all direct-contact missions (i.e., all Category IV missions) as Category IVs missions."[11] In other words, the NRC recommended that all of Mars be considered a Special Region until additional observational data with better resolution can be obtained.

[7] COSPAR, Planetary Protection Policy, *COSPAR Information Bulletin* No. 156, p. 71, 2003.
[8] National Research Council (NRC), *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C. 2006, p. 1.
[9] NRC, *Preventing the Forward Contamination of Mars*, The National Academies Press, Washington, D.C. 2006.
[10] Ibid.
[11] Ibid, pp. 118-119.

If implemented, this recommendation required that all Mars landers be subjected to the most stringent—so-called Viking-level—bioload reduction procedures.

2006

The programmatic consequences of subjecting all Mars landers to Viking-level bioload reduction led NASA to request that NASA's Mars Exploration Program Analysis Group (MEPAG) charter a so-called Science Analysis Group (SAG) to look at Special Regions (Figure B.1, step 3). In particular, the MEPAG group—SR-SAG—was asked "to develop a quantitative clarification of the definition of 'special region' that can be used to distinguish between regions that are 'special' and 'non-special'" and to undertake "a preliminary analysis of specific environments that should be considered "special" and "non-special."[12] The SR-SAG found that COSPAR's definition of Special Regions needed additional clarification; specifically, the uses of the words propagate and likely, which can have different meanings and interpretations.[13] The SR-SAG also constrained physical variables that could be used to define a Special Region, such as the following: how long they exist (about 100 years), the maximum depth of penetration by a spacecraft (about 5 m into the crust), and the lower limit for the survival of terrestrial life in terms of temperature (–15°C or –20°C including margin) and water activity (0.62 or 0.5 including margin).[14] The SR-SAG report concluded by proposing a new definition of Special Region that retained the original COSPAR definition and added to it a set a clarifications and implementation guidelines.[15]

2007-2010

In 2007, COSPAR held a Mars Special Regions Colloquium, with the goal of reviewing the conclusions and recommendations contained in both the 2006 NRC and MEPAG reports and devising a consolidated definition of Special Regions (Figure B.1, step 4).[16] The report of the COSPAR Colloquium disagrees with the NRC 2006 report by stating that there is sufficient data to distinguish between Special and Non-Special Regions and it differs from SR-SAG report by reducing the lower temperature limit for the survival of terrestrial life from –20°C to –25°C.[17] The colloquium report also recommended that the definition of a Special Region and the list of terrains classified as Special be reviewed every 2 years.[18] COSPAR subsequently adopted (Figure B.1, steps 4-7) the recommendations of the colloquium report and planetary protection policy was updated (Figure B.1, step 1).

2014

Following the recommendation of the COSPAR colloquium to review the standards every 2 years, MEPAG empaneled a new science analysis group (SR-SAG2) in the latter part of 2014 to revisit (Figure B.1, steps 2-3) the concept of Special Regions on Mars in light of the latest scientific findings.

The resulting SR-SAG2 report provided a comprehensive distillation of the current understanding of the limits of terrestrial life and relevant martian conditions and presented an analytical approach for considering Special Regions using current and future improvements in knowledge. The SR-SAG2 report also determined that the lower limit for temperature should be –18°C and water activity (a_w) above 0.60 and updated the list of features on Mars that should be classified as Special, Non-Special, and Uncertain regions.[19] In reference to human missions,

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[12] D. Beaty, K. Buxbaum, M. Meyer, N. Barlow, W. Boynton, B. Clark, J. Deming, et al., Findings of the Mars Special Regions Science Analysis Group, *Astrobiology* 6:677-732, 2006.

[13] Ibid., p. 684.

[14] Ibid., pp. 684-691.

[15] Ibid., p. 719.

[16] Ibid. pp. 677-732.

[17] G. Kminek, J.D. Rummel, C.S. Cockell, R. Atlas, N. Barlow, D. Beaty, W. Boynton, M. Carr, et al., Report of the COSPAR Mars Special Regions Colloquium, *Advances in Space Research* 46:826, 2010.

[18] Ibid.

[19] J.D. Rummel, D.W. Beaty, M.A. Jones, C. Bakermans, N.G. Barlow, P.J. Boston, V.F. Chevrier, et al., A new analysis of Mars "Special Regions": Findings of the Second MEPAG Special Regions Science Analysis Group (SR-SAG2), *Astrobiology* 14:894-898, 2014.

the SR-SAG2 found that although these locations would be preferable for potential in situ resources, human missions should not contaminate Special Regions, and precautions should be taken to avoid converting Non-Special Regions to Special Regions.[20]

2014-2015

In October 2014, following the completion of the SR-SAG2 report—but prior to its formal publication in the November 2014 issue of the journal *Astrobiology*—NASA's asked (Figure B.1, step 3) the National Academies "to review the conclusions and recommendations contained in the SR-SAG2 report and assess their consistency with current understanding of both the martian environment and the physical and chemical limits for the survival and propagation of microbial and other life on Earth." Since the European Space Agency (ESA) had already requested the European Science Foundation (ESF) conduct a very similar review of the SR-SAG2 report, the National Academies and ESF established a joint committee to address the needs of both space agencies.

The joint committee discussed findings of the SR-SAG2 report in light of additional information from scientific publications not addressed by the MEPAG group and new knowledge obtained by ongoing space missions, field studies, and laboratory experiments. The joint committee focused on the survivability of life forms singularly versus in communities and SR-SAG2's approach to defining geographical areas as Special Regions. The major conclusions of the joint committee were as follows:

- The authors of the SR-SAG2 report were commended for their comprehensive review of the issues associated with Special Regions and the factors used to define them.
- The environmental parameters used to define Special Regions are appropriate.
- The reported detection of methane in the martian atmosphere, may indicate biogenic activity, and if confirmed, that may demand that the methane source region be designated as a Special Region.
- The identification of Mars Special Regions is problematic for several two reasons. First, detailed knowledge of the physical and chemical conditions of the surface and sub-surface of Mars at various scales is lacking, particularly the microscale. Second, current understanding of the ability of life to propagate is limited. It is not known if one, ten, or one million cells from a single species are required for propagation in an extraterrestrial environment or if replication in alien conditions is only possible in the context of diverse microbial communities.
- Supported the current practice of reassessing the concept of a Special Region and its definition every 2 years.
- Suggested that some of the specific terrains identified as Special Regions in both the COSPAR policy and in the SR-SAG2 report are best regarded as "Uncertain Regions" until proven otherwise.[21,22]

2015

The reports of SR-SAG2 and joint National Academies-ESF review committee were formally presented at an international workshop, organized by COSPAR's Panel on Planetary Protection, and held in Bern, Switzerland, on September 22-24, 2015. Each group had a half day to present their conclusions and recommendations. An additional half day was devoted to additional discussion of both reports and to reaching consensus on proposed revisions to COSPAR's policies concerning Mars Special Regions.

[20] Ibid.

[21] National Academies of Sciences, Engineering, and Medicine and the European Science Foundation, *Review of the MEPAG Report on Mars Special Regions*, The National Academies Press, Washington, D.C., 2015.

[22] See, also, P. Rettberg,A. Anesio, V.R. Baker, J.A. Baross, S.L. Cady, E. Detsis, C.M. Foreman, et al., Planetary protection and Mars Special Regions—A suggestion for updating the definition, *Astrobiology* 16:119-125, 2016.

2016

Recommendations from the Bern Workshop were forwarded to the COSPAR Panel on Planetary Protection for presentation, discussion, and final approval (Figure B.1, steps 4-7) at the July 2016 COSPAR Scientific Assembly in Istanbul.[23] Unfortunately, political unrest in Turkey caused the assembly's cancellation and subsequent deliberations by the Panel on Planetary Protection (Figure B.1, step 5) were conducted remotely. Since the scheduled meetings of COSPAR's leadership groups (Figure B.1, step 6) in Istanbul could not take place, subsequent discussion and approval (Figure B.1, step 7) of the Panel on Planetary Protection recommendations concerning Mars Special Regions were deferred until the next meeting of the COSPAR Bureau, scheduled for March 2017.

2017

The COSPAR Bureau approved (Figure B.1, step 7) the Panel on Planetary Protection's recommendations concerning the policy updates at its March 2017 meeting.[24] However, the pace of scientific results concerning Mars continued unabated. Of particular note was the publication in the latter part of the year of new results concerning so called recurring slope lineae (RSL) by Colin Dundas and colleagues (Figure B.1, step 2). RSL are dark features found on canyon and crater wall which appear to extend downslope, darken and then fade on a seasonal cycle. Dundas and colleagues' analysis indicated that "the terminal slopes of [RSL] match the stopping angle for granular flows of cohesionless sand in active martian aeolian dunes."[25] In other words, RSL may have a lot more to do with flowing sand than with running water.

At about the same time, the former chairs of NASA's by then-defunct internal planetary protection and planetary sciences advisory committees initiated a dialogue on issues of common interest relating to Mars Special Regions (Figure B.1, step 3). The first result of this dialogue was the convening of a workshop in Washington, D.C., to discuss the consequences of creating an artificial special region if a spacecraft equipped with a radioisotope power system crashes on Mars.[26] Planning is under way for a second workshop, to be held in 2018, on the exploration of Special Regions.

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[23] G. Kminek, V.J. Hipkin, A.M. Anesio, J. Barengoltz, P.J. Boston, B.C. Clark, et al. Meeting Report: COSPAR Panel on Planetary Protection Colloquium, Bern, Switzerland, September 2015, *Space Research Today*, No. 195, pp. 42-51.

[24] G. Kminek, C. Conley, V. Hipkin, and H. Yano, COSPAR Planetary Protection Policy, *Space Research Today*, No. 200, December 2017, pp. 12-24.

[25] C.M. Dundas, A.E. McEwen, M. Chojnacki, M.P. Milazzo, S. Byrne, J.N. McElwaine, and A. Urso, Granular flows at recurring slope lineae on Mars indicate a limited role for liquid water, *Nature Geosciences* 10:903-908, 2017.

[26] Personal communication from Clive Neal to committee staff, December 12, 2017.

C

NASA's Standard Program and Project Management and Systems Engineering Practices

To successfully implement spaceflight programs and projects, NASA focuses on mission success across a challenging portfolio of high-risk and complex endeavors, many of which are executed over long periods of time. NASA has established a comprehensive set of directives (NASA Policy Directives [NPD]s, NASA Procedural Requirements [NPRs], etc.) that sets forth how these programs and projects are to be implemented. The highest level document, NPD 1000.0, *NASA Governance and Strategic Management Handbook*, sets forth the governance framework through which the agency manages its missions and executes its responsibilities. This governance model, which balances different perspectives from different elements of the organization, is fundamental to NASA's system of checks and balances. The cornerstone of this organizational structure is the separation of programmatic and institutional authorities.

> Programmatic authority resides within the mission directorates and their respective programs and projects. Institutional authority encompasses all organizations and authorities not in programmatic authority. This includes the Mission Support Directorate and Mission Support Offices at Headquarters and associated organizations at the field centers; other mission support organizations; center directors; and the technical authorities, who are individuals with specifically delegated authority in Engineering, Safety and Mission Assurance, and Health and Medical. The Engineering, Safety and Mission Assurance, and Health and Medical organizations are a unique segment of the institutional authority. They support programs and projects in two ways:
>
> - They provide technical personnel and support and oversee the technical work of personnel who provide the technical expertise to accomplish the program or project mission.
> - They provide Technical Authorities, who independently oversee programs and projects. These individuals have a formally delegated technical authority role traceable to the Administrator and are funded independent of programs and projects.[1]

NPR 7120.5, *NASA Space Flight Program and Project Management Requirements*, establishes the requirements by which NASA formulates and implements spaceflight programs and projects, consistent with the governance model described above, and it establishes a standard of uniformity for the process. It defines program and project life cycles; management oversight and approval; approving and maintaining program and project plans,

[1] Material in this appendix is derived from NASA documents NPD 1000.0, NPR 7120.5, and NPR 7123.1.

baselines, and commitments; roles and responsibilities; technical authority; and the process for handling dissenting opinions.

NPR 7123.1, *NASA Systems Engineering Processes and Requirements*, establishes the requirements on the implementing organization for performing systems engineering.

> Systems engineering at NASA requires the application of a systematic, disciplined engineering approach that is quantifiable, recursive, iterative, and repeatable for the development, operation, maintenance, and disposal of systems integrated into a whole throughout the life cycle of a project or program. The emphasis of systems engineering is on safely achieving stakeholder functional, physical, and operational performance requirements in the intended use environments over the system's planned life within cost and schedule constraints. This document complements the administration, management, and review of all programs and projects, as specified in NPR 7120.5.[2]

Two processes defined in these NPRs are particularly important to understand the committee's assessment of NASA's planetary protection policy development: (1) requirement development and flow down and (2) handling dissenting opinions.

1. There are many different types of requirements, starting at the headquarters level, where stakeholder expectations are captured flowing down both the programmatic and institutional (including technical authority) chains into the project and down through the project's work breakdown structure. However regardless of the source, all requirements are expected to:
    - Be individually clear, correct, and feasible,
    - Not be stated as *how* to satisfy the requirement,
    - Be implementable,
    - Have only one interpretation of meaning,
    - Have one actor-verb-object requirement, and
    - Be able to be validated at the level of the system structure at which they are stated.

    Also when requirements are presented in pairs or as a set, they are required to have:
    - Have no redundancy,
    - Be consistent with terms used,
    - Not conflict with one another, and
    - Form a set of "design-to" requirements.
2. "To support mission success, NASA teams need to have full and open discussions, with all facts made available to support understanding and objective assessment of issues to make the best possible decisions. Diverse views are to be fostered and respected in an environment of integrity and trust with no suppression or retribution. To support these goals, NASA has established a uniform, recognized, and accepted process for resolving serious dissent and has formalized it in policy. This is the *dissenting opinion* process, which further empowers team members to provide their best input to decision makers on important issues and clearly defines the roles and responsibilities of both sides when there is a dissent. A dissenting opinion expresses a view that a decision or action, in the dissenter's judgment, needs to be changed for the good of NASA and requests a review by higher-level management. In this context, 'for the good of NASA' is to be read broadly to cover NASA, mission success, safety, the individual project, and the program."[3]

[2] Material in this appendix is derived from NASA documents NPD 1000.0, NPR 7120.5, and NPR 7123.1.
[3] Material in this appendix is derived from NASA documents NPD 1000.0, NPR 7120.5, and NPR 7123.1.

D

NASA's Planetary Protection Research Program

NASA's annual Research Opportunities in Earth and Planetary Sciences (ROSES) solicitation for research proposals describes the scope of the Planetary Protection Research program as follows:[1]

> Planetary protection involves preventing biological contamination on both outbound and sample return missions to other planetary bodies. Numerous areas of research in astrobiology/exobiology are improving our understanding of the potential for survival of Earth microbes in extraterrestrial environments, relevant to preventing contamination of other bodies by organisms carried on spacecraft. Research is required to improve NASA's understanding of the potential for both forward and backward contamination, how to minimize it, and to set standards in these areas for spacecraft preparation and operating procedures. Improvements in technologies and methods for evaluating the potential for life in returned samples are also of interest. Many of these research areas derive directly from recent National Research Council (NRC) recommendations on planetary protection for solar system exploration missions (see http://planetaryprotection.nasa.gov/documents/ for online reports and a list of publications).
>
> As a complement to the Exobiology program (see program element C.5), the Planetary Protection Research (PPR) program solicits research in the following areas:
>
> - Characterize the limits of life in laboratory simulations of planetary environments or in appropriate Earth analogs. Of particular interest are studies on the potential and dynamics of organism survival and reproduction in conditions present on the surface or subsurface of Mars (e.g., gullies and ice-rich environments), or on Europa and other icy satellites—potentially in the presence of a heat source brought from Earth.
> - Model planetary environmental conditions and transport processes that could permit mobilization of spacecraft-associated contaminants to locations in which Earth organisms might thrive, for example Mars Special Regions or the subsurface of icy bodies, such as Europa and other outer planet satellites.
> - Develop or adapt modern molecular analytical methods to rapidly detect, classify, and/or enumerate the widest possible spectrum of Earth microbes carried by spacecraft (on surfaces and/or in bulk materials, especially at low densities) before, during, and after assembly and launch processing. Of particular interest are methods capable of identifying microbes with high potential for surviving spacecraft flight or planetary environmental conditions (e.g., anaerobes, psychrophiles, radiation-resistant organisms).

[1] NASA Solicitation and Proposal Integrated Review and Evaluation System, Research Opportunities in Space and Earth Sciences 2018, Solicitation NNH18ZDA001N-PPR, "Planetary Protection Research," released February 14, 2018, https://nspires.nasaprs.com/external/solicitations/summary!init.do?solId={3C61CFE1-591A-1683-ED8A-047843D6F167}&path=open, Appendix C.15.

- Identify and provide proof-of-concept on new or improved methods, technologies, and procedures for spacecraft sterilization that are compatible with spacecraft materials and assemblies.

Projects funded via this program in the period 2005-2014 are shown in Table D.1.

TABLE D.1 Projects Funded via NASA's Research Opportunities in Space and Earth Sciences (ROSES) Planetary Protection Research Program During the Period 2005-2014

ROSES Year	Proposals Received	Proposals Funded	PPO Research Funding* (dollars in thousands)	PPO Total Funding* (dollars in thousands)	Principal Investigator	Title of Proposal
2005	Unknown	1			John Moore, Colorado School of Mines	Development of self-sustaining, high temperature synthesis combustion for contingency sterilization of a sample return mission
2006	22	4	$910	$2000	William Hug, Photon Systems, Inc.	Deep ultraviolet instrument for instant bioload classification
					Adrian Ponce, Jet Propulsion Laboratory	Evaluating the probability of growth for Earth microorganisms in special regions on Mars
					Kasthuri Venkateswaran, Jet Propulsion Laboratory	Microbial characterization of the Phoenix spacecraft and its payload facility
					Jaroslava Wilcox, Jet Propulsion Laboratory	Qualification of low-energy e-beam irradiation for sterilization of s/c surfaces
2007	13	6	$790	$2000	Mark Anderson, Jet Propulsion Laboratory	Spore detection and sterilization using meta-stable helium
					William Hug, Photon Systems, Inc.	Non-contact spacecraft surface bioload assay sensor
					Christopher McKay, NASA Ames Research Center	Raman ultraviolet fluorescence for planetary protection bioburden monitoring
					Lisa Monaco, NASA Marshall Space Flight Center/Jacobs Sverdrup	Development of a microarray-based instrument for detection of Earth microbes
					Andrew Schuerger, University of Florida	Biotoxicity of Mars soils: Compatibility of terrestrial microorganisms to simulated conditions of special regions on Mars
					J. Anthony Spry, Jet Propulsion Laboratory	Molecular methods for characterization of embedded bioburden

continued

TABLE D.1 Continued

ROSES Year	Proposals Received	Proposals Funded	PPO Research Funding* (dollars in thousands)	PPO Total Funding* (dollars in thousands)	Principal Investigator	Title of Proposal
2008	5	2	$1000	$2500	Richard Greenberg, University of Arizona	Permeability and transport through Europa's icy crust
					David Summers, NASA Ames Research Center	Microbial contamination detection at very low levels by ^{125}I radiolabeling
2009	Unknown	0	$1300	$2500		
2010	4	1	$1200	$2700	Shirley Chung, Jet Propulsion Laboratory	Cleaning to sterility using CO_2 composite spray
2011	19	5	$1200	$2600	Fei Chen, Jet Propulsion Laboratory	Laser-induced plasma shockwave cleaning for planetary protection
					Patrick Hogue, Johns Hopkins University	Advanced microbial census and sterilization research for planetary protection
					Andrew Schuerger, University of Florida	Metabolism, growth, and genomic responses of Serratia liquefaciens under simulated martian conditions
					Parag Vaishampayan, Jet Propulsion Laboratory	Metagenomics approach to predict functional capabilities of microbes in clean room facilities
					Dale Winebrenner, University of Washington	Ultraviolet susceptibilities of microbes in water ice to address forward contamination on Mars and other icy worlds
2012	21	1	$1400	$2600	Eric Suh, California Institute of Technology	Assessment of the effects of vapor phase hydrogen peroxide treatments on future spacecraft electronics materials
2013	Not solicited	0	$1600	$2500		
2014	19	4 and 3 partially funded	$1700	$2400	Daniel Austin	Microorganism survivability in high velocity impacts
					Fei Chen, Brigham Young University	Life at low water activity with salts relevant to Mars and icy satellites
					Vincent Chevrier, University of Arkansas	Potential growth and survival of sulfate reducing bacteria on the martian surface
					Wayne Schubert, Jet Propulsion Laboratory	Dry heat inactivation of embedded spores
					Adam Abate, University of California, San Francisco	PCR-activated cell sorting-based molecular detection of spores and other microbial communities (partial funding)

TABLE D.1 Continued

ROSES Year	Proposals Received	Proposals Funded	PPO Research Funding* (dollars in thousands)	PPO Total Funding* (dollars in thousands)	Principal Investigator	Title of Proposal
					Stephanie Smith, University of Idaho	Evaluating microbial hardiness and archiving of isolates from NASA's next generation lander (partial funding)
					Kasthuri Venkateswaran, Jet Propulsion Laboratory	Germination-induced molecular detection of spores and other heat-tolerant microbial communities (partial funding)
2015	Unknown	0	$1700	$25040		
2016	Not solicited	0	Unknown	Unknown		
2017	Unknown	Not yet selected	Unknown	Unknown		

NOTE: All information, except those in columns indicated by *, was compiled from the relevant ROSES databases "NASA Solicitation and Proposal Integrated Review and Evaluation System" (https://nspires.nasaprs.com/external/index.do). Items in columns with an * were derived from information supplied to the committee by NASA's Planetary Protection Officer (Catharine Conley, "Day-to-day Operations of the Planetary Protection Office: Past, Present, and Future," presentation, May 23, 2017, Slide 26, http://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_180763.pdf). PPO, planetary protection officer.

E

Orbital Debris Mitigation Guidelines: A Model for International Collaboration and Consensus Building

Bilateral and multilateral dialogues in outer space exploration can be considered critical stepping-stones for building technical and legal consensus measures among spacefaring nations. These channels of communication also develop formal structures such as international organizations. It is instructive to follow the evolution of discussions concerning the development of guidelines for the mitigation of space debris because they offer parallels with the development of the Committee on Space Research's (COSPAR's) planetary protection policies.[1] Moreover, the current international regime governing space debris mitigation offers lessons as to how COSPAR's planetary protection policies might develop in the future.

In creating an effective international regulatory structure for space exploration, the United States has continually supported the development of these international forums to develop effective technical and policy consensus standards. One primary example of this is the development of a set of international orbital debris mitigation guidelines.

Concern for the impact that space debris can have on the utilization and exploration of outer space derives from the increased number of antisatellite tests conducted in the 1960s[2] that would impact the national security of the United States. From a civil space perspective, NASA scientist Donald Kessler proposed in the late 1970s a dilemma where the collision of objects in space would create a congested low Earth orbit and make outer space not an explorable environment and unusable.[3] The Department of Defense and NASA therefore became two of the largest stakeholders invested in addressing the orbital debris issue.

Scientific and technical research ensued, but the creation of a policy framework for addressing orbital debris did not arise until the late 1980s. Technical and scientific consensus occurs first at the national level through an interagency process. The first mention of space debris in U.S. national space policy was from 1988, under President Reagan, which stated that "all space sectors will seek to minimize the creation of space debris."[4]

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[1] Terms of Reference and further information can found online. https://cosparhq.cnes.fr/scientific-structure/ppp.

[2] See the *Crosslink* issue on "Understanding Space Debris: Causes, Mitigations, and Issues," Fall 2015, http://aerospace.wpengine.netdna-cdn.com/wp-content/uploads/crosslink/Crosslink_Fall_2015.pdf, p. 5.

[3] Later known as the Kessler Syndrome or Kessler Effect. See M. La Vone, "The Kessler Syndrome: 10 Interesting and Disturbing Facts," *Space Safety Magazine*, September 15, 2014, http://www.spacesafetymagazine.com/space-debris/kessler-syndrome.

[4] Presidential Directive on National Space Policy, February 11, 1988, https://www.hq.nasa.gov/office/pao/History/policy88.html.

In 1989, the *Report on Orbital Debris* by the Interagency Group (Space) first showed the need for close coordination and consensus of orbital debris activities.[5] Priorities and initiatives under U.S. guidance fell into four categories:[6]

- Preliminary research to define the debris environment more precisely;
- Ways to reduce data management limitations;
- Adaptation of several operational procedures to limit growth in the debris population; and
- Design philosophies for future missions and spacecraft that address orbital debris considerations.

It is important to note the difference between regulatory and non-regulatory agencies. Regulatory agencies such as the Federal Aviation Administration (FAA) and the Federal Communications Commission (FCC) are responsible for collecting the comments and input of the private sector who have also adapted their own policies for addressing orbital debris.[7]

The interagency process falls in to place when other agencies (who are not the main stakeholders) are in some way involved. The two major agency stakeholders created internal policies for addressing orbital debris. The Department of Defense included orbital debris in their 1987 policy that sought to "minimize the impact of space debris on its military operations."[8] NASA adapted an internal policy—NASA Management Instruction 1700.8—Policy for Limiting Orbital Debris Generation that would "employ design and operations practices that limit the generation of orbital debris consistent with mission requirements and cost effectiveness and requires each program or project to conduct an assessment demonstrating compliance."[9]

Both the 1989 and the 1995 interagency reports on debris emphasized the importance of international collaboration in order to find an effective solution for addressing orbital debris. It was recommended that the "continuing U.S. participation in the international dialogue on debris should continue to be governed by consideration of U.S. commercial, scientific, civil operational, and national security interests."[10]

The interagency working groups for orbital debris are prime examples of how technical consensus standards are effective mechanisms for creating both internal agency and national policies. The development of technical standards on the national level is a key first step in bringing orbital debris standards into the international forums.

> To promote consistency in policy and practice, the U.S. should develop and maintain a common approach for achieving U.S. policy and program objectives in formal international organizations such as United Nations for a and in informal, technical, government agency-level multilateral groups such as the IADC.[11]

While the United States was formalizing their regulatory approach to orbital debris, other nations were individually going through the same process. The United States took the lead on these international discussions through bilateral and multilateral mechanisms, which created the platform for international dialogue for orbital debris. These high-level discussions between space agencies from the United States, the Russian Federation, Japan, and the European Space Agency led to an informal multilateral organization called the Inter-Agency Space Debris Coordination Committee (IADC) in 1993.[12]

The IADC is an international governmental forum for "the worldwide coordination of activities related to the issues of man-made and natural debris in space" with the purpose to "exchange information on space debris research

[5] *Report on Orbital Debris by the Interagency Group (Space) for the National Security Council*, Washington, D.C., February 1989, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19900003319.pdf.

[6] Ibid., p. 17.

[7] See FCC Amendments for orbital debris at https://www.fcc.gov/document/mitigration-orbital-debris.

[8] Office of Science and Technology Policy (OSTP), *Interagency Report on Orbital Debris,* Executive Office of the President, Washington, D.C., November 1995, p. 27. https://www.iadc-online.org/References/Docu/IAR_95_Document.pdf.

[9] OSTP, *Interagency Report*, p. 27; and NASA, *NASA Safety Standard: Guidelines and Assessment Procedures for Limiting Orbital Debris*, NSS 1740.14, August 1995, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19960020946.pdf.

[10] OSTP, *Interagency Report*, 1995, p. 43.

[11] OSTP, *Interagency Report*, 1995, p. 44.

[12] OSTP, *Interagency Report*, 1995, pp. 43-44.

activities between member space agencies, to facilitate opportunities for cooperation in space debris research, to review the progress of ongoing cooperative activities, and to identify debris mitigation options."[13] Comprised of national space agencies, the organization is represented by delegates who have the high-level decision-making authority.

In order for international technical consensus to come into fruition, there are many steps that need to take place. First, for spacefaring nations, a technical consensus is reached at the national level. Second, international dialogue through bilateral, multilateral, or through the development of international and interagency committees develops. Third, the topic of interest is formally introduced as an item to be discussed at the UN Committee on the Peaceful Uses of Outer Space (COPUOS). Fourth, mitigation guidelines through technical consensus is reached by member states and organizations at the subcommittee and committee level at COPUOS. Fifth, the guidelines are adopted by the UN General Assembly.

In the case of international debris dialogues to formally move forward as an international entity, many steps needed to take place. The process began when the United States began cooperating with other nations in orbital debris initiatives and expanded cooperation with other agencies through the formulation of the IADC. The United States, alongside many other nations, needed to have orbital debris formally considered as an item of discussion at the next Science and Technical Subcommittee (STSC) at COPUOS. What the STSC considered were items that included "scientific research relating to space debris, including relevant studies, mathematical modelling and other analytical work on the characterization of the space debris environment,"[14] which was ultimately a result of the work of the IADC. Discussions over the next 5 years led the adoption of a technical report by the subcommittee and the distribution of the report to other UN entities including the Legal Subcommittee of COPUOS, UNISPACE III, and other international organizations.[15] In 2007, the next step occurred when a set of voluntary orbital debris mitigation guidelines were adopted in the subcommittee and then adopted in the full COPUOS committee. The voluntary guidelines adopted at COPUOS was then forwarded to the UN General Assembly and adopted under resolution 62/217 on December 22, 2007.[16]

[13] https://www.iadc-online.org/index.cgi?item=home.

[14] United Nations, *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*, Office for Outer Space Affairs, 2010, http://www.unoosa.org/pdf/publications/st_space_49E.pdf, p. iii.

[15] United Nations, *Report of the Scientific and Technical Subcommittee on its thirty-seventh session, held in Vienna from 7 to 18 February 2000*, A/AC.105/736, 2000, http://www.unoosa.org/oosa/oosadoc/data/documents/2000/aac.105/aac.105736_0.html.

[16] United Nations, *International Cooperation in the Peaceful Uses of Outer Space*, A/RES/62/217, Office for Outer Space Affairs, 2007, http://www.unoosa.org/oosa/oosadoc/data/resolutions/2007/general_assembly_62nd_session/ares62217.html.

F

Biographies of Committee Members and Staff

MEMBERS

JOSEPH K. ALEXANDER, *Chair*, is a consultant in science and technology policy at Alexander Space Policy Consultants. He was a senior program officer with the Space Studies Board (SSB) of the National Academies of Sciences, Engineering, and Medicine from 2005 until 2013, and he served as SSB director from 1998 until November 2005. Prior to joining the National Academies, he was deputy assistant administrator for science in the Environmental Protection Agency's (EPA's) Office of Research and Development where he coordinated a broad spectrum of environmental science and led strategic planning. From 1993 to 1994, he was associate director of space sciences at the NASA Goddard Space Flight Center and served concurrently as acting chief of the Laboratory for Extraterrestrial Physics. From 1987 until 1993, he was assistant associate administrator at NASA's Office of Space Science and Applications where he coordinated planning and provided oversight of all scientific research programs. He also served from 1992 to 1993 as acting director of life sciences. Prior positions have included deputy NASA chief scientist, senior policy analyst at the White House Office of Science and Technology Policy, and research scientist at the Goddard Space Flight Center. His book, *Science Advice to NASA: Conflict, Consensus, Partnership, Leadership*, was published in 2017. His research interests were in radio astronomy and space physics. He has a B.A. and M.A. in physics from the College of William and Mary.

JOHN R. CASANI is a consultant who is retired from the Jet Propulsion Laboratory. He is a recipient of several NASA awards, including the Distinguished Service Medal. He received the American Institute of Aeronautics and Astronautics (AIAA) Space System Award, the von Karman Lectureship, the National Space Club Astronauts Engineer Award, the American Astronautical Society's Space Flight Award, and the Smithsonian National Air and Space Museum's Lifetime Achievement Award. He held senior project positions on many of the Mariner missions to Mars and Venus and in 1970 became project manager of Mariner 6 and 7. Later, Dr. Casani would project-manage NASA's Voyager mission to the outer planets, Galileo mission to Jupiter, and Cassini mission to Saturn, as well as the proposed Jupiter Icy Moons Orbiter mission. He is a member of the National Academy of Engineering (NAE) and an honorary member of the AIAA. Dr. Casani holds a B.S. in electrical engineering and an honorary D.Sc. from the University of Pennsylvania, Philadelphia, and an honorary degree in aerospace engineering from the University of Rome, Italy.

LEROY CHIAO is co-founder and CEO of One Orbit, LLC. He is a former NASA astronaut and International Space Station (ISS) commander. He works in business, consulting, executive coaching and space education. He is a professional international speaker, and as co-founder and the CEO of OneOrbit, provides keynotes and training to companies and schools. Dr. Chiao also holds appointments at Rice University and the Baylor College of Medicine and is an advisor to the Houston Association for Space and Science Education. He has worked in both government and commercial space programs, and has held leadership positions in commercial ventures and NASA. Dr. Chiao left NASA following a 15-year career with the agency. A veteran of four space missions, he most recently served as commander and NASA science officer of Expedition 10 aboard the ISS. He has logged more than 229 days in space—more than 36 hours of which were spent in extra-vehicular activity (EVA). He has served on the White House appointed Review of U.S. Human Spaceflight Plans Committee, and currently serves on the Human Exploration and Operations Committee of the NASA Advisory Council. As a space station commander and space shuttle mission specialist, Dr. Chiao was also a certified co-pilot of the Russian Soyuz spacecraft. He is an expert in all facets of U.S. and Russian EVA hardware and operations and is EVA certified in U.S. and Russian spacesuits, tools, and training programs. He was the first American to visit China's Astronaut Research and Training Center. Dr. Chiao is a fellow of the Explorers Club, and a member of the International Academy of Astronautics and the Committee of 100. He studied chemical engineering, earning a B.S. from the University of California, Berkeley, and an M.S. and Ph.D. at the University of California, Santa Barbara.

DAVID P. FIDLER is the James Louis Calamaras Professor of Law at the Indiana University Maurer School of Law and an adjunct senior fellow for cybersecurity at the Council of Foreign Relations. Professor Fidler works on international law and global governance across many policy areas, including cyberspace, global health, trade and investment, environmental protection, weapons of mass destruction, terrorism, and national/international security. His current research focuses on various aspects of national and international cybersecurity, including policy efforts to establish deterrence in cybersecurity policies. He is the recipient of a Fulbright New Century Scholar Award. He earned his J.D. from Harvard Law School.

JOANNE I. GABRYNOWICZ is a professor emerita of space law at the University of Mississippi and editor-in-chief emerita at the *Journal of Space Law*. She is a visiting professor at the Beijing Institute of Technology School of Law. Dr. Gabrynowicz advises the U.S. government and the United Nations on space law. Dr. Gabrynowicz has taught space law for 30 years. She taught at the University of North Dakota and the University of Mississippi. She is a guest lecturer at universities around the world and the author of numerous articles. Dr. Gabrynowicz is the recipient of a number of awards in the field, including Women in Aerospace's Outstanding International Award and the International Institute of Space Law's Lifetime Achievement award. Prior to her academic career, Dr. Gabrynowicz was the managing attorney of a New York City law firm. She is a member of the American Bar Association Forum on Aviation and Space Law and a director of the International Institute of Space Law. She earned her J.D. from the Benjamin N. Cardozo School of Law of Yeshiva University.

G. SCOTT HUBBARD is an adjunct professor in the Department of Aeronautics and Astronautics at Stanford University, the director emeritus of the Stanford Center of Excellence for Commercial Space Transportation, and the editor-in-chief of the peer-reviewed journal *New Space*. He has been engaged in space-related research as well as program, project, and executive management for more than 40 years including 20 years with NASA—culminating as director of NASA's Ames Research Center. At Stanford, his research interests include the study of both human and robotic exploration of space with a particular focus on technology and missions for planetary exploration, especially Mars. Examples include novel hybrid propulsion for applications such as a Mars Ascent Vehicle and drilling techniques for a future Mars sample return mission. He served as NASA's first Mars program director and successfully restructured the entire Mars program in the wake of mission failures. His award-winning book entitled, *Exploring Mars: Chronicles from a Decade of Discovery*, describes his work on NASA's Mars Program. He previously served as the sole NASA representative on the Columbia Accident Investigation Board and directed the impact testing that established the definitive physical cause of the accident. He was the founder of NASA's Astrobiology Institute, conceived the Mars Pathfinder mission with its airbag landing, and was the manager for NASA's highly successful Lunar Prospector Mission. Prior to joining NASA, he was a staff scientist at the Lawrence Berkeley National Laboratory and directed a high-tech start-up company. He has received eight NASA medals, including NASA's highest award, the Distinguished Service Medal. He currently chairs the SpaceX Commercial Crew Safety Advisory Panel and serves on the NASA Advisory Council as an at-large member. He has received several honorary doctorates and earned his B.A. in physics and astronomy at Vanderbilt University.

EUGENE H. LEVY is the Andrew Hays Buchanan Professor of Astrophysics in the Department of Physics and Astronomy at Rice University. Dr. Levy's research interests focus on theoretical cosmic physics, with an emphasis on elucidating mechanisms and processes that underlie physical phenomena in planetary and astrophysical systems. His research also includes the generation and influences of magnetic fields in natural bodies, including Earth, Sun, and planets, the theory of cosmic rays, and the theory of physical processes associated with the formation of the solar system, stars, and other planetary systems. Prior to joining Rice University, Dr. Levy served in various capacities at the University of Arizona, including as dean of the College of Science, head of the Planetary Science Department, director of the Lunar and Planetary Laboratory, and professor of Planetary Science. He has won multiple awards including the Alexander von Humboldt-Stiftung Senior Scientist Award by the Federal Republic of Germany, the Martin Luther King, Jr. Distinguished Leadership Award through the University of Arizona, and the NASA Distinguished Public Service Medal. Dr. Levy received his Ph.D. in physics from the University of Chicago.

NORINE E. NOONAN is professor emirata of biological science at the University of South Florida (USF) at St. Petersburg. Her research includes science and technology policy in the government sector, specifically with regard to space science. Dr. Noonan has more than 30 years of experience serving in both the public and academic sector as the vice chancellor for Academic Affairs at USF-St. Petersburg, dean in the School of Sciences and Math at the College of Charleston, and the branch chief of the Science and Space office at the Office of Management and Budget. Her professional activities have included membership on six National Science Foundation (NSF) advisory committees, two of which she chaired. She has also served as an expert reviewer for EPSCoR and INBRE programs in two states. In October 2005, she received the NASA Public Service Medal, the highest civilian honor the agency can bestow. Dr. Noonan received her Ph.D. in cell biology and biochemistry from Princeton University.

KENNETH OLDEN is retired from the EPA. He is an environmental risk assessor who was director of the National Center for Environmental Assessment and Human Health Risk Assessment Research Program at the EPA. Prior to that, he was the founding dean of a new School of Public Health on the Hunter College campus of the City University of New York. He also served as director of the National Institute of Environmental Health Sciences and the Nation Toxicology Program in the Department of Health and Human Services. In 1977, he became the first African-American to be awarded tenure and the rank of independent investigator at the National Institutes of Health. He held several positions at the Howard University Cancer Center, including director, professor, and chairman of the Department of Oncology. Dr. Olden has received numerous awards including the Presidential Distinguished Executive Rank Award from President William J. Clinton, the Presidential Meritorious Executive Rank Award, the Calver Award, the Sedgwick Medal, and the Julius B. Richmond Award. Dr. Olden received a Ph.D. in cell biology and biochemistry from Temple University. He is a member of the National Academy of Medicine (NAM).

FRANCOIS RAULIN is professor emeritus at Université Paris Est-Créteil and continues his research at the Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA). His scientific fields of interest are related to planetology, exo/astrobiology, and planetary protection. He is particularly interested in the organic chemistry of extraterrestrial environments, which he studies using a combination of laboratory experiments, theoretical modeling, and data analysis. He was a research fellow in Carl Sagan's laboratory at Cornell University, an assistant professor at Université Paris Val de Marne, and a CNRS/NSF postdoctoral fellow at Cyril Ponnamperuma's Laboratory of Chemical Evolution at the University of Maryland. He later became full professor at University Paris 12, director of LISA, and director of the federation of CNRS laboratories in exobiology. He has been and continues to be involved in multiple spacecraft missions and has been a co-investigator of CIRS of multiple instruments on Cassini-Huygens and Rosetta. He is currently the deputy team leader for the MOMA instrument on ExoMars

2020. His awards include the European Space Agency (ESA) award for outstanding contribution to the Huygens probe, NASA Group Achievement Award, ISSOL Fellow Award, and Chevalier de la Légion d'Honneur. He is a past-president of the French Society of Exobiology, a former chair of ESA's Planetary Protection Working Group, and a former member of ESA's Human Spaceflight and Exploration Science Advisory Committee. He received his Doctorat d'Etat from the Université Paris 6.

GARY RUVKUN is a professor of genetics at Harvard Medical School and Massachusetts General Hospital in Boston. Dr. Ruvkun's laboratory identified the first microRNA that is conserved across animal phylogeny including humans. He has also explored how bacterial attacks on animals are surveilled and countermeasures are deployed. Using comparative genomics, Dr. Ruvkun's laboratory has been exploring the few hundred genes that are universal to all known life on Earth, inherited from a common ancestor over the past 3-4 billion years. Meteoritic exchange between Earth and Mars may have inoculated both planets with related ancestral organisms, allowing the sophisticated DNA technology of genomics to be marshalled to the detection of life on Mars. To this end, Dr. Ruvkun is collaborating on a NASA MATISSE project to engineer a DNA sequencing instrument that will be deployed to other planets to search for life that is ancestrally related to life on Earth. He is a member of the National Academy of Sciences (NAS) and the NAM. His honors and awards include the Albert Lasker Award for Basic Medical Research, the Dan David Prize for Aging research, the Wolf Prize, the Gruber Prize, and the Breakthrough Prize in Life Sciences. Dr. Ruvkun has a Ph.D. in biophysics from Harvard University.

MARK P. SAUNDERS is an independent consultant. Since retiring from NASA, he has been consulting to various NASA offices providing program/project management and systems engineering expertise. This has included support to the Office of Chief Engineer, the Office of Independent Program and Cost Evaluation, the Mars Program, and the Science Office for Mission Assessments. He has participated in the rewriting of NASA's policy on program/project management; advised and supported the agency's independent program/project review process; and has supported the review of various programs and projects. At NASA Headquarters, he served as director of the independent program assessment office, where he was responsible for enabling the independent review of the agency's programs and projects at life-cycle milestones to ensure the highest probability of mission success. At NASA's Langley Research Center (LaRC), he was initially the deputy director and then the director, Space Access and Exploration Program Office and had the responsibility for planning, directing and coordinating the center's research, technology, and flight programs for advanced aerospace transportation and human/robotic exploration systems. Prior to this he was the manager of Exploration Programs and led all LaRC space exploration research and development activities supporting the agency's Aerospace Technology, Human Exploration, and Development of Space and Space Science Enterprises. At the office of space science he served as program manager for the Discovery Program, and at the Space Station Freedom program operations he served as special assistant to the deputy director. He received the Presidential Meritorious Rank Award, Outstanding Performance awards, and multiple NASA Outstanding Leadership Medals. He earned his B.A. at the Georgia Institute of Technology in industrial engineering.

BETH A. SIMMONS is the Andrea Mitchell University Professor of Law and Political Science in the Department of Political Science at the University of Pennsylvania. Her area of expertise is primarily in international relations, international law, and international political economy, with her most current research interests including the ways in which international institutions shape and are shaped by domestic political system, and global performance assessments as informal governance mechanisms in international affairs. Prior to joining the University of Pennsylvania, Dr. Simmons was a professor of international affairs at Harvard University, director of Harvard's Weatherhead Center for International Affairs, and president of the International Studies Association. She is a member of the NAS. Dr. Simmons received the American Political Science Association's Woodrow Wilson Award for best book published in the United States on government, politics, or international affairs for two of her books: *Who Adjusts? Domestic Sources of Foreign Economic Policy During the Interwar Years* and *Mobilizing for Human Rights: International Law in Domestic Politics*. She received her Ph.D. in government from Harvard University.

PERICLES D. STABEKIS is an independent consultant. He is retired from his position as program manager and aerospace consultant with the SETI Institute. His seminal contributions are in planetary protection. He has supported the NASA planetary protection program as principal investigator, program manager, and consultant. He has worked with all the NASA planetary protection officers, lending his expertise to the development and definition of planetary protection policy and requirements for outbound and inbound planetary missions; providing advice to international partners on requirements and methods of implementation; contributing to strategic planning and programmatic development; helping to guide NASA efforts in planetary protection-related new technology development; and monitoring planetary protection–related activities of ongoing flight projects. In his 46-year career, Mr. Stabekis worked for Exotech Systems, GE, Lockheed Martin, Windermere, Northrop Grumman, and Genex Systems. He contributed to, and managed contracts supporting NASA's Exobiology, Astrobiology, and Life Sciences programs. He was the Lockheed flight program manager of the NASA Life Sciences' flagship shuttle missions SLS-1 and SLS-2, as well as IML-1 and IML-2. He is a recognized expert in the field, and has authored and co-authored a number of technical and policy papers. He has received numerous awards throughout his career, including the NASA Public Service Medal, SLS-2 Group Achievement Award, and SLS-1 Group Achievement Award. He received his M.S. in aerospace engineering from Howard University.

ANDREW STEELE is a senior staff scientist at the Geophysical Laboratory of the Carnegie Institution for Science. Prior to this he was a National Research Council postdoctoral scientist at NASA Johnson Space Center and a visiting research fellow at Oxford University. At Carnegie, he has worked on the question of life detection in the solar system with an emphasis on Mars. Among his research achievements are the discovery of discrete carbonaceous phases on Mars and the Moon, helping to advance the understanding of volatile cycling on Earth, the Moon, meteorites and comets, developing a robust strategy for life detection on solar system bodies, and involvement in the testing and data reduction of planetary mission data from Stardust, Apollo, Curiosity, and Rosetta missions. He has a background in the use of biological, chemical, and geological instrumentation to address the science questions he pursues in particular the search for life elsewhere. He has also played a role in the science definition of the Mars 2020 rover mission, coinvestigator on the rover's SHERLOC instrument, and an active member of the two committees seeking to define the conditions for the safe and clean return of samples by Mars 2020 and beyond. He has served on many committees on Mars exploration for MEPAG, chairing the Astrobiology Field Laboratory mission concept team, and the NASA advisory council as a member of the Planetary Protection Subcommittee. He received his Ph.D. in microbiology from the University of Portsmouth.

STAFF

DAVID H. SMITH joined the SSB as a senior staff officer in 1991. He has been and is the study director for a variety of National Academies' activities in the general areas of astrobiology, planetary science, and planetary protection. He also organizes the SSB's Lloyd V. Berkner Space Policy Internships and the joint SSB–Chinese Academy of Sciences Forum for New Leaders in Space Science. He received a B.Sc. in mathematical physics from the University of Liverpool in 1976, achieved the honors standard in Part III of the Mathematics Tripos at the University of Cambridge in 1977, and a D.Phil. in theoretical astrophysics from Sussex University in 1981. Following a postdoctoral fellowship at Queen Mary College University of London, he held the position of associate editor and, later, technical editor of *Sky and Telescope*. Immediately prior to joining the staff of the SSB, Dr. Smith was a Knight Science Journalism Fellow at the Massachusetts Institute of Technology.

MIA BROWN joined the SSB as a research associate in 2016. She comes to SSB with experience in both the civil and military space sectors and has primarily focused on policies surrounding U.S. space programs in the international sector. Some of these organizations include NASA's Office of International and Interagency Relations, Arianespace, the United Nations Office for Disarmament Affairs (Austria), and the U.S. Department of State. From 2014 to 2015, Mia was the managing editor of the *International Affairs Review*. She received her M.A. in international space policy from the Space Policy Institute at the Elliott School of International Affairs at George

Washington University. Prior to entering the Space Policy Institute, Mia received her M.A. in historical studies from the University of Maryland, Baltimore County, where she concentrated in the history of science, technology, and medicine and defended a thesis on the development of the 1967 Outer Space Treaty.

ANDREA REBHOLZ joined the Aeronautics and Space Engineering Board as a program coordinator in January 2009. She began her career at the National Academies in October 2005 as a senior program assistant for the NAM (formerly the Institute of Medicine) Forum on Drug Discovery, Development, and Translation. Prior to the National Academies, she worked in the communications department of a D.C.-based think tank. Ms. Rebholz has a B.A. in integrative studies—event management from George Mason University's New Century College and earned the certified meeting professional designation in 2012. She has more than 15 years of experience in event planning, project administration, and editing.

DANIELLE MONTECALVO was a Lloyd V. Berkner Space Policy Intern at the SSB during the summer of 2017. In 2018, Ms. Montecalvo interned at the Office of International and Interagency Relations at NASA Headquarters, where she worked on space policy initiatives and public outreach projects. She graduated from American University in Washington, D.C., in May 2018 with a B.A. in international studies and physics. In fall 2018, she will begin her service as a secondary education English teacher as a Peace Corps Volunteer in Madagascar. Ms. Montecalvo is passionate about STEM education and engaging women in science, and she plans to incorporate science and math into the classroom during her service abroad. Her academic research focuses on the importance of how collegiate-level physics and other STEM courses can play a critical role in enhancing scientific literacy and shape overall attitudes toward space policy, particularly within the millennial population.

G

Acronyms

AST	Office of Commercial Space Transportation
ATP	adenosine triphosphate
BSL	Biosafety Level; Biohazard Safety Level
CAPS	Committee on Astrobiology and Planetary Science
CEQ	Council on Environmental Quality
CETEX	Committee on Contamination by Extraterrestrial Exploration
CNSR	Comet Nucleus Sample Return
COMSTAC	Commercial Space Transportation Advisory Committee
COPUOS	Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research
CRAF	Comet Rendezvous–Asteroid Flyby
CRISPR	clustered regularly interspaced short palindromic repeats
DNA	deoxyribonucleic acid
DoC	Department of Commerce
EASTEX	East Coast Panel on Extraterrestrial Life
ESA	European Space Agency
ESF	European Science Foundation
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
HEOMD	Human Exploration and Operations Mission Directorate
IADC	Inter-Agency Space Debris Coordination Committee
IAF	International Astronautical Federation

ICBC	Interagency Committee on Back Contamination
ICSU	International Council for Science
IKI	Space Research Institute
ISAS	Institute for Space and Astronautical Science
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LAL	limulus amebocyte lysate
LIFE	Living Interplanetary Flight Experiment
MAX-C	Mars Astrobiology Explorer and Cacher
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
MO	Mars Observer
MSL	Mars Science Laboratory
MUSES-C	Mu Space Engineering Spacecraft-C
NAC	NASA Advisory Council
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NID	NASA Interim Directive
NPD	NASA Policy Directive
NPI	NASA Policy Instruction
NPR	NASA Procedural Requirement
NRC	National Research Council
NSAM	National Security Action Memoranda
OCT	Organic Contamination Team
OPP	Office of Planetary Protection
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
OSMA	Office of Safety and Mission Assurance (NASA)
OST	Outer Space Treaty
OSTP	Office of Science and Technology Policy
P_c	probability of contamination
PPAC	Planetary Protection Advisory Committee
PPO	planetary protection officer
PPOSS	Planetary Protection for Outer Solar System
PPS	Planetary Protection Subcommittee
ROI	region of interest
ROSES	Research Opportunities in Space and Earth Sciences
RSL	recurring slope lineae
SAG	Science Analysis Group
SAT	Office of Space and Advanced Technology
SMD	Science Mission Directorate
SR	Special Regions

SSB	Space Science Board (1958-1988), Space Studies Board (1988 to date)
STSC	Science and Technical Subcommittee
TOC	total organic carbon
UN	United Nations
WESTEX	West Coast Panel on Extraterrestrial Life

H

Interagency Deliberations Concerning Initial Launch of the Falcon 9 Heavy

Very late in the production of this report, following its formal approval and public release of the prepublication version of this report by the National Academies of Sciences, Engineering, and Medicine, previously undisclosed information was brought to the committee's attention concerning consultations between the Federal Aviation Administration (FAA), NASA, and SpaceX on the planetary protection implications of the test flight of the Falcon 9 Heavy launched on February 6, 2018. The paragraphs below were drafted by Dr. Betsy Pugel of NASA's Office of Planetary Protection—with concurrence from SpaceX; the FAA; and NASA's Launch Services Program, Office of Safety and Mission Assurance, and Office of International and Interagency Relations—and are presented below unedited.

> In August of 2017, NASA responded to the Federal Aviation Administration's (FAA) interagency license review process regarding the Space Exploration Technologies (SpaceX) demonstration launch of the Falcon Heavy from Launch Complex 39A at Kennedy Space Center. At that juncture, the payload and trajectory were only generally defined with no direct reference to a Mars-targeted orbit.
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> On December 1, 2017, SpaceX founder Elon Musk posted the following information on twitter regarding the aforementioned demonstration launch, "Payload will be my midnight cherry Tesla roadster playing Space Oddity. Destination is Mars orbit. Will be in deep space for a billion years or so if it doesn't blow up on ascent." Given the interest by NASA and the broader scientific community about the integrity of celestial bodies where contamination could compromise future science investigations, NASA queried both the FAA and SpaceX regarding the new information. NASA raised the potential for planetary protection implications associated with Mars as a potential target body to the FAA and SpaceX, and requested more information on how SpaceX planned to address planetary protection for the Roadster purported to be headed to a Mars orbit. SpaceX clarified that the Falcon Heavy mission did not include a flyby, orbiter, or lander for a target body, which is consistent with the launch license issued by the FAA for this mission. A spacecraft not encountering another planetary body is not subject to NASA or COSPAR planetary protection policy.
>
> Using limited trajectory information provided from SpaceX to NASA via the FAA, NASA conducted limited long-term propagations of Tesla Roadster trajectories, primarily to assess immediate potential risks to NASA's scientific assets. Those trajectories could not be rendered into standard probability of impact calculations to assess longer-term risks to scientific assets beyond the immediate launch window. Consequently, NASA formally responded back to the FAA on January 22, 2018, that although NASA was not in a position to confirm the probability of an impact on Mars, NASA noted that SpaceX's information implied a consistency with international guidelines on planetary protection. The FAA issued the launch license for this mission on February 2, 2018.

We have previously seen that there is value in conducting standard longer-term propagations of the probability of impact of a spacecraft or launch vehicle hardware, including zero velocity returns of hardware. One example is the return of the Apollo 12 Saturn S-IVB third stage (COSPAR Object Identifier J002E3). Launched in 1971, in 2002 it was thought to be a new asteroid, J002E3. It was confirmed to be the Apollo 12 third stage and is now known to be in a 40 year cycle between heliocentric and geocentric orbit. This object could eventually reenter the Earth's atmosphere and represented a known example of why long-term propagations on the order of several decades are conducted in assessing probability of impact for target bodies of biological interest, such as Mars.