

A Path to Planetary Protection Requirements for Human Exploration: A Literature Review and Systems Engineering Approach



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Abstract

As systems, technologies, and plans for the human exploration of Mars and other destinations beyond low Earth orbit begin to coalesce, it is imperative that frequent and early consideration is given to how planetary protection practices and policy will be upheld. While the development of formal planetary protection requirements for future human space systems and operations may still be a few years from fruition, guidance to appropriately influence mission and system design will be needed soon to avoid costly design and operational changes. The path to constructing such requirements is a journey that espouses key systems engineering practices of understanding shared goals, objectives and concerns, identifying key stakeholders, and iterating a draft requirement set to gain community consensus. This paper traces through each of these practices, beginning with a literature review of nearly three decades of publications addressing planetary protection concerns with respect to human exploration. Key goals, objectives and concerns, particularly with respect to notional requirements, required studies and research, and technology development needs have been compiled and categorized to provide a current ‘state of knowledge’. This information, combined with the identification of key stakeholders in upholding planetary protection concerns for human missions, has yielded a draft requirement set that might feed future iteration among space system designers, exploration scientists, and the mission operations community. Combining the information collected with a proposed forward path will hopefully yield a mutually agreeable set of timely, verifiable, and practical requirements for human space exploration that will uphold international commitment to planetary protection.

Keywords: *planetary protection, human spaceflight requirements, human space exploration, human space operations, systems engineering, literature review*

The Premise for Planetary Protection

It was the science fiction writing of authors such as Camille Flammarion and H.G. Wells in the late 1800’s, well before the space age, which stirred a perspective that perhaps life is not unique to Earth [1]. As both science and technology evolved over the following century, the possibilities of both encountering life beyond Earth and bringing life from Earth to other celestial bodies became a real possibility. With rapid advances in aerospace after World War II and the looming conquest of space, the International Astronautical Federation met in Rome in 1956 to discuss lunar and planetary contamination and built the framework for the International Institute of Space Law [2]. That same year, the United Nations Committee on

the Peaceful Uses of Outer Space (UNCOPUOS) began discussion of how contamination and sterilization would be dealt with in future space missions beyond Earth [2]. In the following two years, the U.S. National Academy of Sciences (NAS) urged the International Council of Scientific Unions (ICSU) to assist in evaluating the possibilities of extraterrestrial contamination and needed mitigating measures leading to the establishment of the Committee on Contamination by Extraterrestrial Exploration (CETEX) [2]. In 1958, this committee gave way to the Committee on Space Research or COSPAR, which still operates to this day and oversees aspects of interplanetary exploration including the practice of planetary protection. Planetary protection is the all-encompassing practice of controlling and mitigating biological cross-contamination between the Earth and celestial objects across the solar system. Not only is the implementation of planetary protection a sound engineering and scientific process, it is also an international commitment accepted by the 102 countries ratifying the United Nations Treaties and Principles on Outer Space, commonly known as the Outer Space Treaty, in which Article IX 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 and, where necessary, shall adopt appropriate measures for this purpose...”[3]

NASA and its international partners have vowed to uphold planetary protection practices and have documented processes and requirements for engineers to implement during the design and development of new interplanetary spacecraft. As we increase our scientific knowledge of terrestrial microorganisms, we continue to learn of the robustness of life and ability to survive the most extreme of environments; deep-sea thermal vents, subsurface, and even in high radiation environments. As planetary protection policy is updated to reflect this latest knowledge, NASA’s requirements also evolve to provide the latest guidance to those architecting future missions deep into the cosmos. Ensuring the biological cleanliness of spacecraft will enable effective science investigations into the potential of life beyond Earth. Similarly, we must guarantee appropriate containment measures for returned sample material to protect Earth’s inhabitants from potentially harmful forms of life found beyond our planet.

Planetary Protection & Human Exploration

For a brief period in history, the practice of planetary protection focused on the additional complexity of exploring with human crews. During the first three of NASA's Apollo missions to reach the lunar surface (Apollo 11, 12, and 14), the practice of planetary quarantine was enacted to minimize the potential for exposing returned extraterrestrial biological matter to Earth's inhabitants. While a general scientific consensus existed that the probability for life on the lunar surface was minimal, the consequences of any such risk was deemed severe enough to enact a quarantine program until the risk could be quantified as negligible. Since the close of the Apollo program, human exploration activities have been conducted solely in low Earth orbit; a region of no planetary protection concern. As such, no requirements currently exist for upholding planetary protection measures in extraterrestrial human exploration. Over the past few decades, however, there has been intermittent consideration into how planetary protection during human missions would be upheld. While robotic missions can address mitigation of biological contamination through extensive cleaning, sterilization, and containment operations, human exploration brings complex environmental systems, life support equipment, and open-loop systems; all of which make cleaning and sterilization practices infinitely more challenging. In fact the presence of human explorers by its very nature means a significant microbiological population will be present throughout the mission that cannot be cleaned or sterilized. Over the course of the past couple of decades, much thought has been given to planetary protection for the human exploration paradigm through community workshops, conferences, and published literature. In particular, four significant workshops and publications were conducted and produced between 2001 and 2005:

- Workshop on Planetary Protection Issues in the Human Exploration of Mars at Pingree Park in Fort Collins, Colorado in 2001,
- Safe on Mars Report published in 2002 by the National Research Council to detail precursor measurements necessary to support human operations on the Martian surface,
- Life Support and Habitation and Planetary Protection Workshop held at the Center for Advanced Space Studies in Houston, Texas in 2005, and

- ESA (European Space Agency) & NASA collaborative workshop on Planetary Protection and Human System Research and Technology held in Noordwijk, The Netherlands in 2005.

While several other workshops and publications have been held or produced over the past several decades, the aforementioned gatherings significantly increased the discussion and focus on planetary protection and human exploration. This was likely related to the increased focus on NASA's since cancelled Constellation program charged with sending humans back to the Moon and on to Mars. Collectively, the knowledge gained from workshops and publications such as these can serve as a springboard for collecting new knowledge and insight into tackling the complex issue of planetary protection and human spaceflight.

Planetary Protection Issues in the Human Exploration of Mars - Pingree Park Workshop

In June of 2001, approximately 30 individuals from NASA centers, academia, and private industry gathered at the Pingree Park Mountain Campus of Colorado State University to discuss planetary protection issues in the human exploration of Mars. This 2.5 day workshop was convened to examine the effects of human exploration on the scientific study of Mars and to address the question, "can human exploration of the Martian surface be done effectively and without harmful contamination?" [4] More specifically, the participants were divided into three working groups respectively addressing protecting Mars and Mars samples from contamination, protecting the health of human crews, and protecting Earth from potentially harmful Mars contamination. Following detailed investigation into these three primary areas of focus, the workshop membership was reconvened into two parallel sessions both focused on overall human exploration operations. The discussion from this workshop resulted in a series of 12 conclusions or general recommendations, 6 areas of further needed research, and 4 recommended topics for future workshops. In summary, the conclusion was drawn that indeed human exploration of the Martian surface is possible without harmful contamination, although not without incurring risk to both scientific return and crew safety. It should be the goal of future mission and system design to mitigate these risks through careful study of such areas as: understanding the nature of Martian dust distribution and transport,

identifying the division of roles between human and robotic explorers and how they can be operated in a complimentary manner, and mitigating spacesuit contamination so as to avoid confounding the search for life beyond Earth. Much of the content within the final report of this workshop has set a baseline from which future planetary protection requirements for human exploration can be crafted and needed studies can be planned.

National Research Council *Safe on Mars* Report

In 2002, the National Research Council published its report titled, *Safe on Mars: Precursor Measurements Necessary to Support Human Operation on the Martian Surface*. This report was sponsored by the National Academy of Science and NASA to investigate “issues which are directly relevant to managing environmental, chemical, and biological risks to humans operating on Mars while recognizing that a major objective of such human missions will certainly be to search for (possibly hazardous) life on Mars” [5]. With this charter, the Committee on Precursor Measurements Necessary to Support Human Operation on the Martian Surface conducted three multi-day public meetings to collect information from experts in related fields [5]. The scope of the investigation went well beyond planetary protection concerns in attempting to identify the wide range of hazards and associated risks likely encountered by the first human visitors to Mars including those of a chemical and physical nature. An entire section of findings relating to “potential hazards of the biological environment” acknowledges the significant unknowns of Mars biology, if it exists, and provides the recommendation of establishing Zones of Minimum Biological Risk (ZMBR) through precursor measurements of organic carbon (see Figure 1 on following page). This recommendation does not address specific detection thresholds for organic carbon measurements or whether such measurements could conclude the presence of Martian life, but rather lays out an operational paradigm for assessing the biological risk in future human exploration of Mars. The report also suggests the added benefit of conducting Mars sample return, particularly if conducted from a region to be explored further by human explorers, to identify the likelihood of biological risk. Unlike other reports and workshops focusing on planetary protection and the human exploration of Mars, this report exclusively focuses on the aspects of crew health and safety while touching on backward contamination concerns. The mitigation of forward contamination is not addressed by the *Safe on Mars* report.

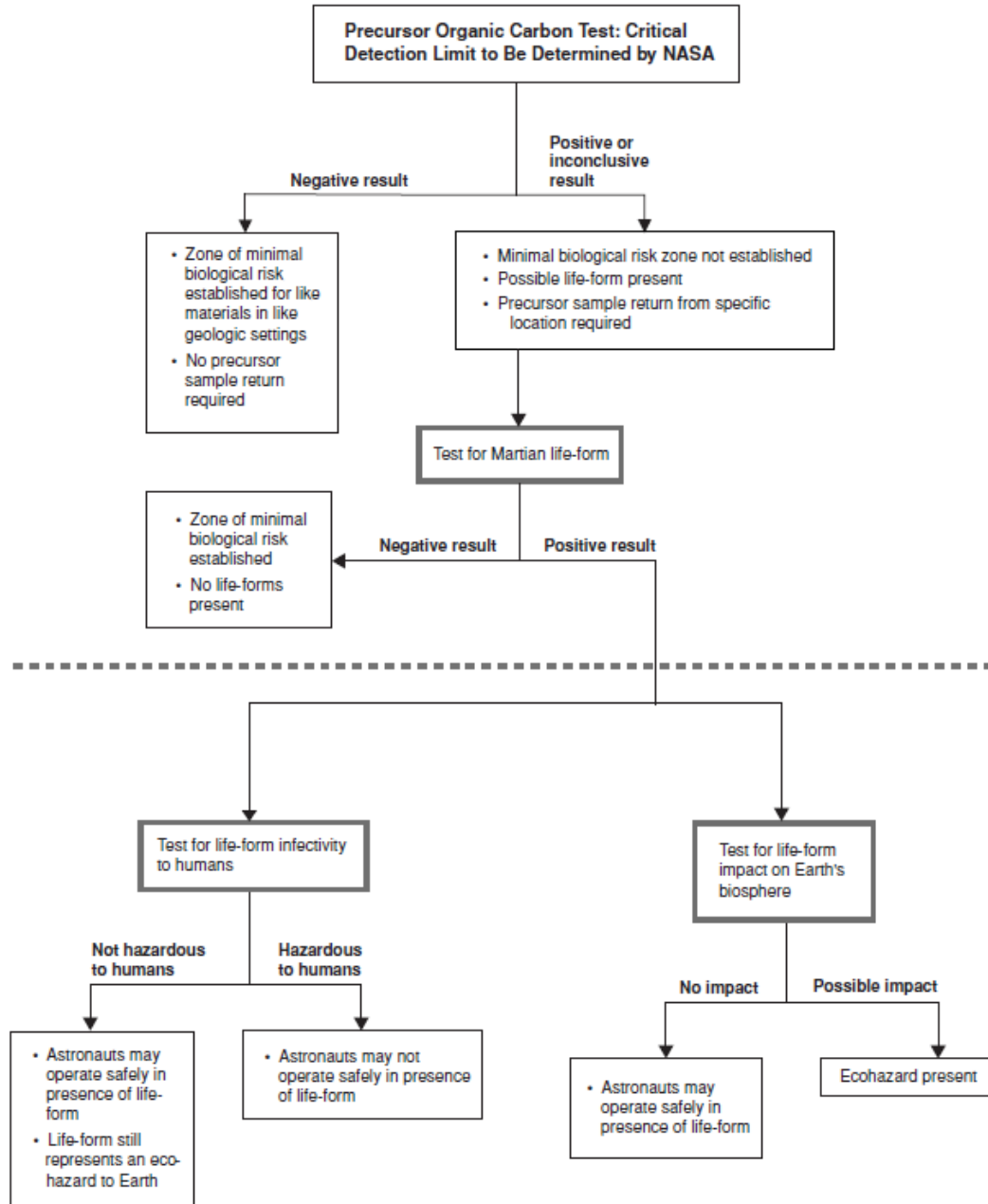


Figure 1 Mars biology testing protocol as identified by the National Research Council [5].

Life Support and Habitation and Planetary Protection Workshop

In April 2005 a three-day workshop convened in Houston, Texas, with the primary objective to “facilitate the development of planetary protection guidelines for future human Mars exploration missions and to identify the potential effects of these guidelines on the design and selection of related human life support, extravehicular activity and monitoring and control systems” [6]. The workshop pulled together expertise from NASA, private industry

and academia to review the relationship between planetary protection measures and advanced life support (ALS), advanced extravehicular activity (AEVA), and advanced environmental monitoring and control (AEMC) development programs. A series of plenary sessions and parallel group sessions initiated analysis of planetary protection requirements that are needed, methods of reducing risk in system development prior to full planetary protection policy development, and research areas and technology gaps to improve system capabilities in order to meet planetary protection needs [6]. Similar to the Pingree Park workshop, the three key tenets of avoiding forward contamination of Mars, protecting crew from harmful contamination associated with potential Martian life, and controlling backward contamination remained paramount throughout the workshop. In addition to these tenets were the following five top-level workshop objectives [6]:

- 1) Initiate communication, understanding, and a working relationship between the ALS, AEVA, AEMC and PP [planetary protection] communities regarding the effect of PP policy development and implementation requirements for future human missions.
- 2) Define top-level PP concerns and issues associated with both forward and back contamination, and determine their likely effects on ALS, AEVA and AEMC hardware and operations for the first human mission to Mars.
- 3) Identify PP requirements that will be needed to guide future technology development for ALS, AEVA and AEMC systems in advance of the first human mission.
- 4) Examine management approaches that may be used to reduce the risk of developing ALS, AEVA and AEMC systems prior to full definition of PP policies.
- 5) Identify important research areas and identify any gaps in science or technology capability that will help guide the development of technologies and approaches for ALS, AEVA, and AEMC consistent with PP concerns regarding both forward and back contamination.

In conducting the workshop, each main system area (ALS, AEVA, and AEMC) compiled a list of recommendations as well as some of the developmental needs and challenges that lay ahead. While the workshop concluded that a strong need exists to establish requirements for planetary protection during human missions, it also suggested that it was currently impractical to provide quantitative guidelines. This workshop in many ways serves as a

model for a future workshop called for in the recently released NASA Policy Instruction (NPI) 8020.7 *NASA Policy on Planetary Protection Requirements for Human Extraterrestrial Missions*. While NPI 8020.7 is discussed in detail later in this report, the document was constructed with the expectation that our state of knowledge has advanced sufficiently to necessitate a point of departure in the development of quantitative requirements once clear studies are identified and actively funded.

Mars Planetary Protection Joint ESA/NASA Workshop

Considered the third workshop in a series focused on planetary protection and human missions to Mars, starting with the Pingree Park workshop, the Mars Planetary Protection and Human System Research and Technology Joint ESA/NASA Workshop was held in May of 2005 in Noordwijk, The Netherlands [7]. This workshop considered the results of both the Planetary Protection Issues in the Human Exploration of Mars Workshop (Pingree Park) and the Life Support and Habitation and Planetary Protection Workshop to establish baseline considerations for further investigation. Advanced life support systems (ALS), extravehicular activities (EVA), and operations and support (OPS) served as the three main areas of focus during the workshop, from which future research development needs and specific precursor mission information were collected. In obtaining general considerations and recommendations, four primary ‘starting positions’ were given [7]:

- 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.
- It will not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems.
- Crewmembers exploring Mars will inevitably be exposed to Martian materials.

These very starting positions became the founding principles for the COSPAR *Principles and Guidelines for Human Missions to Mars* which currently constitutes internationally accepted

planetary protection policy for human missions. Throughout the workshop, each main focus group was asked to address the four following specific questions [7]:

1. What is the overall approach to contamination control?
2. What is the approach to waste & consumables management?
3. What are the off-nominal events that could potentially lead to contamination of Mars or the terrestrial biosphere?
4. What are the research and development activities required to cope with planetary protection requirements?

Answering these questions provided the workshop's findings as categorized into five areas: policy, special regions, operations and crew, waste management, and research and development. The first three of these areas led to the planetary protection guidelines now reflected in COSPAR policy while the remaining sections focused on notional waste management requirements and technology development needs. As with the preceding Life Support and Habitation and Planetary Protection Workshop, much of the results from this workshop's efforts will directly feed the next point of departure on the path to developing planetary protection requirements for human exploration.

As these workshops and publications have indicated, there are numerous challenges in upholding planetary protection policy while pushing further into the cosmos with humankind. Throughout the discussions cultivated in the early 2000's, there appeared to be a sense of urgency to give early consideration to potential restrictions on engineering and mission design in order to avoid the high costs of addressing policy restrictions after hardware had been designed, built, and readied for flight. Since the 2000's, this urgency has seemingly faded with the cancellation of the Constellation program and NASA re-focusing its efforts on building evolving capabilities to enable human exploration of asteroids, the Moon, and eventually Mars. Unfortunately, the need to address potential planetary protection requirements early in design has not diminished and renewed focus on the subject is warranted as NASA's path to the red planet is becoming further defined.

NASA's Relevant Human Exploration Plans

Human missions to Mars have been considered for well over 50 years with some of NASA's most recent plans evolving from mission architecture work started in the mid-2000's. NASA's Design Reference Architecture (DRA) 5.0 is perhaps the most thorough operational concept for conducting a human Mars mission and considers a progressive approach utilizing Earth-based analog testing, the International Space Station (ISS), and the Moon to eventually culminate in manned exploration of the Mars surface [8]. Specifically, DRA 5.0 investigates the requisite mission cadence leading up to and during a Mars surface campaign with detailed focus on exploration goals and objectives, transportation systems, surface systems, assessment of key architectural elements, and key challenges faced in such exploration. While DRA 5.0 provides an intensive look into the operational concept of a manned Mars mission, it was constructed under the assumption of a sustained exploration program. With the cancellation of NASA's Constellation Program in 2010, it became apparent that a robust exploration policy would require a flexible approach where different missions and capabilities could be exercised on an evolutionary path that showed human Mars exploration as an ultimate future goal as capabilities and technologies mature. Currently, this approach is captured through NASA's Evolvable Mars Campaign which suggests an exploration approach considering three phases of exploration operations: Earth reliant (low Earth orbit exploration), proving ground (lunar distant retrograde operations), and Mars ready (Mars and vicinity operations) (see Figure 2) [9].



Figure 2 NASA's Evolvable Mars Campaign phases of operation [9].

The evolutionary path of the Evolvable Mars Campaign suggests the presence of multiple opportunities to test and evaluate approaches to planetary protection for human missions. While DRA 5.0 assumes the implementation of some level of planetary protection requirements, it does not clearly denote a path to gradual incorporation and evaluation of planetary protection practices. A combination of the Evolvable Mars Campaign with DRA 5.0 provides an integrated approach to human Mars exploration with a multitude of opportunities to iteratively develop planetary protection requirements. Among those opportunities are the execution of the proposed Asteroid Redirect Mission (ARM) which suggests the identification and redirection of a small asteroid (or removal of a boulder from an asteroid surface) to a lunar distant retrograde orbit for study and sample retrieval by a human crew [10].

While planetary protection measures for the ARM mission are highly dependent upon the targeted asteroid, the implementation of requirements intended for more restrictive destinations, such as Mars, could yield valuable technology developments and operational lessons learned. Similarly, a return to the lunar surface, likely in partnership with the international community and emerging private space industry, would provide additional opportunities to exercise planetary protection technologies and operations in a lower-risk environment than the Mars surface. Some pathways of the Evolvable Mars Campaign could also involve manned exploration of the Mars' moon Phobos which is expected to contain significant amounts of Mars material [11]. While the extent of planetary protection measures for the exploration of Phobos is currently under review, such a destination may provide an optimal trial run of requirements for human missions prior to reaching the Mars surface.

As NASA's plans for pushing humankind deeper into the solar system continue to evolve, the agency is increasingly interested in ensuring exploration is sustained and a permanent independence from Earth is established [12]. Such a 'pioneering' approach would necessitate the ability to continually evolve planetary protection requirements while upholding the safety of the crew and Earth.

Private Space Industry & Planetary Protection Requirements

NASA is not considered a regulatory agency [13]. Unlike the Department of Transportation (DOT) or Federal Aviation Administration (FAA), NASA does not impose guidelines and regulations upon the public or private sector unless such an entity is specifically contracted to provide a service or product to the Agency. However, the UN Outer Space Treaty indicates a member state's responsibility for non-governmental activities in space and that such activities are subject to the same policies and guidance as governmental activities. Article VI of the Treaty states:

“States Parties to the Treaty 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, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty. 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.” [3]

With Article IX of the Outer Space Treaty calling for planetary protection measures, many of the newly emerging private space companies are in need of appropriate guidance to ensure proper implementation of planetary protection. While the FAA is performing most of the regulatory function for U.S. based commercial space activities, it is currently not clear how planetary protection practices might be regulated on the private sector side [14]. Emerging companies such as Deep Space Industries, Planetary Resources, and Shackleton Energy propose space mining activities; obtaining water and other resources from the Moon and asteroids. The Golden Spike Company promises private expeditions to the Moon while ambitious Mars exploration is called for by the private Mars One and Inspiration Mars teams. Even one of the most successful private space companies in recent times, SpaceX, has hinted at a Mars sample return mission concept called ‘Red Dragon’ [15]. The detail to which these companies and their concepts have considered planetary protection policy is unknown and unable to be verified in the absence of a regulatory authority.

While the question of how planetary protection regulation will be implemented for the emerging private space industry remains unanswered, it is clear that this industry represents a new stakeholder in the planetary protection requirement development process. As NASA progresses in the development of such requirements, consideration should be given as to what level of requirements may be applied to the regulation of this emerging industry. By including private space stakeholders in the requirement formulation process, it may be possible to create requirements that are implementable for an emerging industry and easily verified by a future regulatory authority.

NASA's Policy Instruction on Planetary Protection for Human Missions

On May 28, 2014, NASA Policy Instruction (NPI) 8020.7 was released. This document, titled *NASA Policy on Planetary Protection Requirements for Human Extraterrestrial Missions*, was created to address an action given by the Planetary Protection Subcommittee of the NASA Advisory Council (NAC) to create a set of planetary protection requirements for human missions. Typically, such requirements are held in a NASA Procedural Requirements (NPR) document and are issued such that all relevant NASA programs and projects must adhere to the requirements throughout mission development and execution. Currently, NPR 8020.12 *Planetary Protection Provisions for Robotic Extraterrestrial Missions*, is NASA's primary planetary protection requirements document, but is not implementable for human missions. The complexity of upholding planetary protection policy throughout human missions dictates the need to increase the scientific and technological knowledge base before effective, verifiable requirements can be created. The recently released NPI was meant to serve as a roadmap for the requirements development process as well as to raise programmatic awareness of the internationally accepted COSPAR *Principles and Guidelines for Human Missions to Mars*, which is included in Appendix A. These COSPAR guidelines lay the framework for future requirements and can serve to provide preliminary guidance to those developing human spaceflight mission architectures and hardware.

While the NPI acknowledges the process to develop procedural requirements for human spaceflight missions may take a few years, it provides insight into needed areas of study and

a forward path. While suggesting that further community input may be needed to refine the areas of study, the NPI lists three primary areas of study [16]:

- 1) Developing capabilities to comprehensively monitor the microbial communities associated with human systems and evaluate changes over time;
- 2) Developing technologies for minimizing/mitigating contamination release, including but not limited to closed-loop systems; cleaning/re-cleaning capabilities; support systems that minimize contact of humans with the environment of Mars and other solar system destinations;
- 3) Understanding environmental processes on Mars and other solar system destinations that would contribute to transport and sterilization of organisms released by human activity.

While gathering the appropriate knowledge to inform future requirements is crucial, it only serves as one step in the process outlined by the NPI. Two activities led by an ad-hoc team are meant to precede conducting needed studies; completion of a literature review to identify completed studies relevant to future requirements, and seeking input from a broad community to inform requirement development. These two activities serve to gather information and create a basis of knowledge from which appropriate studies may be conducted and verifiable requirements can be drafted. The NPI suggests that the knowledge gained through these activities will feed a 5-step process which includes: presentation of a list of required studies to NASA management, funding the needed studies starting no later than Fiscal Year 2016, conducting the studies in-parallel with developing requirements, integrating funding for meeting planetary protection requirements into the budget for human mission systems development, and developing and formalizing a NPR for human missions. Throughout this process, the ad-hoc NPI team coordinating the compilation of needed studies will also monitor progression through each of the aforementioned steps and guiding the eventual development of requirements to be documented in a NPR.

Planetary Protection & Human Exploration Literature Review

Among the first key steps to formulating effective requirements is acquiring an understanding of the current state of knowledge regarding planetary protection and human exploration. Conducting such an activity allows one to gain better insight into the goals and objectives for upholding planetary protection policy as viewed from a broad base of stakeholders. For the purpose of identifying needed areas of study to ensure the development of effective, verifiable requirements, such a literature review also helps to mitigate repeating previously conducted research or allows further refinement of ongoing investigation.

Literature Review Approach

The initial approach taken for conducting the NPI literature review was to collect and categorize existing information relevant to planetary protection and human exploration. As mentioned in the section on planetary protection and human exploration, several key workshops and reports provided the primary foundation from which to begin amassing knowledge. These reports and an informal literature review conducted by Richard Heidmann in July, 2003, titled *Impact of Planetary Protection Requirements on the Manned Mars Mission Design: A Quick Literature Survey* served as a point of departure for the in-depth literature review. Bibliographies and references from each of these reports and Heidmann's review were used to compile an ever-growing list of documents relevant to human exploration and planetary protection. Combined with extensive online searching using NASA's Technical Reports Server (NTRS) and Google Scholar, a total of 108 potential sources of relevant information were identified. It should be noted that these sources are not intended to be a complete listing of relevant literature, but are representative of a database of knowledge that is continually growing. Several additional reports have been published since the initial compilation of relevant literature (completed in late March, 2014) and it is known that numerous documents of similar relevance to the topic of planetary protection and human missions have yet to be captured.

As the literature was identified, it was categorized in accordance with the suggested study areas mentioned in NPI 8020.7. To assist in the categorization, the three study areas of the

NPI were paraphrased and refined to create a total of three main categories and six sub-categories used to organize all identified literature (see Figure 3).

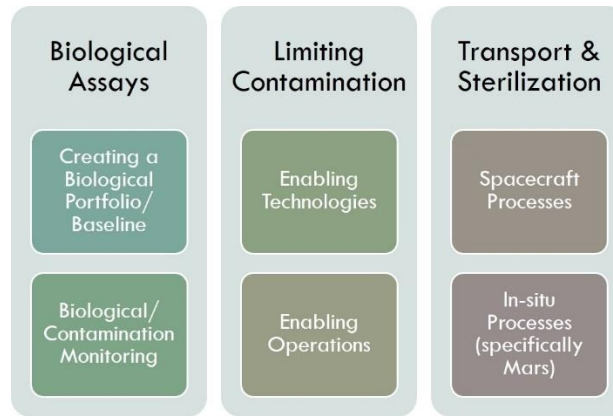


Figure 3 Literature categorization: primary categories and sub-categories.

The purpose behind such subdivision was to aid in referring back to key documentation when identifying needed areas of further study and in drafting potential requirements. It was noted that the first NPI study area to develop “...capabilities to comprehensively monitor the microbial communities associated with human systems and evaluate changes over time” could be summarized as the ability to both initially quantify and continuously monitor the biological burden (or ‘bioburden’) associated with human spaceflight [16]. Assuming a difference in the capability to initially quantify a spacecraft’s bioburden versus being able to continuously monitor changes to that bioburden led to the creation of the two sub-categories. Similarly, the second NPI study area of “developing technologies for minimizing/mitigating contamination release...” was sub-divided into the categories of technologies and operations as both can serve to mitigate contamination but are distinctly different approaches [16]. Lastly, the final NPI study area of “understanding environmental processes on Mars and other solar system destinations that would contribute to transport and sterilization of organisms released by human activity” was refined into the categories of processes related to the spacecraft and processes related solely to the Martian environment [16].

With the categorization paradigm in-place, each piece of literature that was identified was then reviewed and notated as fitting one or more of the aforementioned categories. This was recorded in a Microsoft Excel spreadsheet along with the title of the document, authors,

publication date, a brief description of the literature’s content, and a link to the document or document’s source for future reference (see Figure 4). If a particular document was seen as predominately addressing one of the study area sub-categories, the associated cell in the spreadsheet was annotated with a green ‘X’. The complete spreadsheet of documentation identified and categorized during the literature review can be viewed in Appendix B.

Title	Primary Author	Date	Overview Description	Bio Assays		Limiting		Environment	
				Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface
COSPAR Planetary Protection Policy, 20 Oct 2002, as amended 24 Mar 2011	COSPAR	2011	The official source of COSPAR Planetary Protection Policy applicable to robotic and human missions including general principles specifically relevant to mission planning and implementation as well as operating guidelines.				X		
Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface	National Research Council	2002	Investigates the hazards and associated risks likely encountered by the first human visitors to Mars. Recommends precursor measurements, if any, to be made prior to the first human mission. While investigates back contamination, does not address forward contamination.				X		
Planetary Protection Issues in the Human Exploration of Mars	Criswell, M.E., Race, M.S., Rummel, J. D., Baker, A.	2005	Frequently referred to as the "Pingree Park Report", this paper summarizes the results of five main working groups focusing on protecting against forward and back contamination while also protecting astronaut health. The result of the workshop was a detailed listing of recommendations including needed areas of future research. MUST READ!				X		
Life Support and Habitation and Planetary Protection Workshop Final Report	Fisher, J.W., Hogan, J.A., Joshi, J.A., et. al.	2006	Final report documenting the potential influence of Planetary Protection policies on activities in the Advanced Life Support (ALS), Advanced Extravehicular Activity (AEVA), and Advanced Environmental Monitoring and Control (AEMC) communities. MUST READ!	X	X	X	X	X	X

Figure 4 Partial screenshot of planetary protection literature review spreadsheet.

As the literature review progressed, it became apparent that additional categories beyond those identified in the NPI could be used to classify documentation. Specifically, some literature dealt strictly with the societal, public outreach, and policy aspects of planetary protection and future human missions. While certainly relevant to the translation of planetary protection policy to future requirements, such categorization was considered to be beyond the scope of this first attempt at a literature review. Future iteration of the literature review may consider the addition of such a policy and outreach category.

Re-vectoring the Literature Review Process

As relevant literature was reviewed and categorized, it became apparent that key information contained within the publications would not be easily retrievable without having to review the original documentation in its entirety. As the review was conducted, three types of information relevant to future requirements development became apparent. Some literature

identified suggested policies, restrictions, and guidelines which could serve as a springboard for the development of future requirements. Such information was parsed into a separate document; listing notional requirements for further review and development. Similarly, many publications called for needed areas of research and investigation as well as development of new technologies. This information was respectively captured in separate documents which listed the suggested studies and technology developments. As might be expected from the extensive collection of literature, repetition of notional requirements, needed studies, and needed technologies was observed. To address such cases of repetition, a system of cross referencing was established in each document where each publication calling for a particular requirement, study, or technology was annotated with a footnote at the end of a given bullet or sentence (see Figure 5).

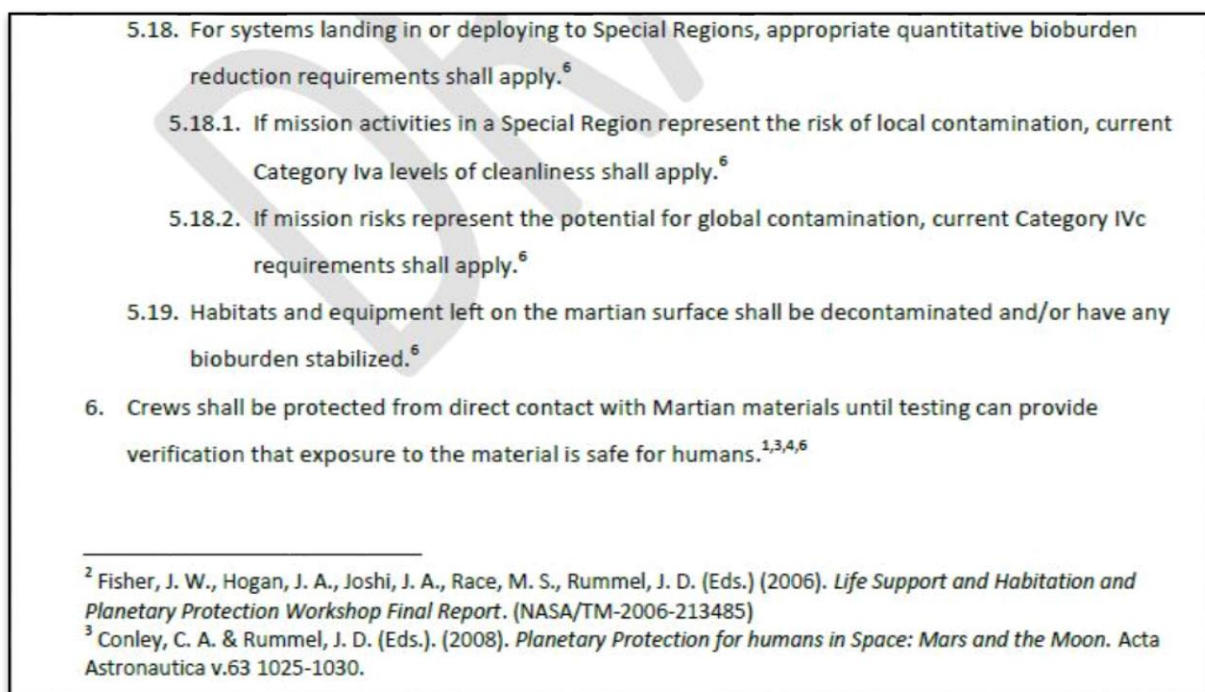


Figure 5 Screenshot of notional requirements listing showing footnote references.

Collectively, a total of 41 notional requirements, 33 suggested studies, and 28 needed technology developments were identified from the literature reviewed. Due to the extensive collection of literature (108 documents total), not all literature had been reviewed, categorized, parsed, and cross-referenced at the time of completing the initial literature

review. However, sufficient repetition was observed in the set of parsed notional requirements, studies, and technologies to suggest that little new information in these areas would be obtained. Future iteration of the literature review may be completed prior to developing the first draft of a NPR, in which the complete set of literature may be reviewed, categorized, parsed, and cross-referenced.

Notional Requirements

In reviewing literature relevant to planetary protection and human exploration, certain statements could be perceived as forming the building blocks of a future requirement set. Declarations that certain human systems should avoid or prevent venting to the Mars environment or that consideration must be given to monitoring the microbial population or microbiome of a spacecraft are indicative of future operational and functional requirements. While not written in standard systems engineering parlance and likely not specific or verifiable, such notional requirements provide valuable insight into the concerns and considerations of representative stakeholders in the future system design. In order to more easily navigate through the collection of notional requirements, each draft requirement was categorized as either a general/administrative requirement or a requirement addressing forward contamination, crew health, or backward contamination. Within each requirement category, related requirements were grouped as parent/child requirements to provide sufficient traceability and refinement. Of the listing of 41 notional requirements, three primary parent requirements were identified:

- 5.0 Forward contamination of Mars from terrestrially-associated microbial contaminants shall be minimized.
- 6.0 Crews shall be protected from direct contact with Martian materials until testing can provide verification that exposure to the material is safe for humans.
- 7.0 Back contamination from Mars to Earth shall be minimized and its prevention considered highest priority.

It should be noted that the numbering of these notional requirements indicate that requirements 1.0 through 4.0 are reserved for ‘general/administrative’ requirements. Such a numbering convention was used to easily reference these notional requirements and show the parent/child relationship between requirements. It is also interesting to note that these three primary parent requirements relate closely to the main foci of the key planetary protection reports and workshops referenced in the section on planetary protection and human exploration. It should be further noted that some of the notional requirements are repetitive while others are excessively lengthy and may benefit from further division into parent and child requirements. Future iteration is certainly required. In capturing these notional requirements during the literature review, it was decided to keep as much of the original text from the referring documentation as possible to show traceability back to the original concern expressed by the author(s) of the source document. As these requirements are reviewed further, it is expected that they will be re-organized, split and combined as needed to gradually move more closely to an effective and implementable requirement set. Throughout the material reviewed the three core tenets of mitigating forward contamination, safeguarding the crew from Martian material, and preventing backward contamination were consistently identified. The complete listing of notional requirements identified can be found in Appendix C.

Notional Studies

In addition to recording notional requirements from the reviewed literature, a listing of potential areas for future study and investigation became apparent. Some documentation would list open questions or unaddressed concerns with respect to the future human exploration of space and planetary protection. These ‘calls for study’ would reference a need of new or refined knowledge before operational decisions or requirements could be derived. For example, the 2008 report by Conley and Rummel titled *Planetary Protection for Humans in Space: Mars and the Moon* called for the evaluation of basic tests to monitor a crew’s medical condition and understand their responses to pathogens and adventitious microbes (microbes not native to the human microbiome) [17]. The driving need for such a study is to have the ability to apply a testing regimen to crews to determine if an off-nominal medical condition is due to terrestrial or extraterrestrial microbes. Before one can conclusively

identify an appropriate testing regimen, it is likely that several regimens will need to be developed and evaluated before a specific testing requirement can be derived.

As such potential future studies were identified from the collected literature, they were captured in a bulleted list and placed into one of the same six sub-categories used to categorize the literature. This allowed traceability to the study areas identified in the NPI. Each proposed study also had a ‘need statement’ following it to provide context for why a particular study was being suggested. It should be noted that these need statements were written from the perspective of the author of the literature review and not necessarily the author of the source document. As with the listing of notional requirements, each study was cross-referenced via a footnote to its corresponding source material. It is anticipated that this listing of suggested studies will be reviewed by a collection of internal and external stakeholders through a workshop as called for in the NPI prior to conducting studies. This process will allow for the prioritization of studies and mutual understanding of what knowledge currently exists in each of the study categories before resources are committed. The full listing of notional studies is documented in Appendix D.

Notional Technology Developments

Closely tied to the listing of needed studies were suggestions of technology developments which would enhance the ability to uphold planetary protection policy for future human missions. Numerous documents would call for either new technology development activities or a continued investment in developing a particular technology. As such technology references were identified, they were categorized based on general system functionality and documented in a brief, bulleted list. The compiled listing includes 7 areas of system functionality including: environmental control and life support, biological quantification, biological monitoring, extravehicular activities/space suits, Mars environment characterization, waste management systems, and robotic systems. An eighth category includes technologies which didn’t clearly fall in any of the aforementioned areas of system functionality. Examples of some of the technology needs identified include: closure of the spacecraft’s Environmental Control and Life Support (ECLS) system, Mars environment particle transport models, active monitoring systems to detect ‘unknown’ biology in a

pressurized environment, and robotic systems capable of in-situ sterilization/re-cleaning. As the listing of needed technology developments was constructed, NASA was undergoing revision of its technology development roadmaps, allowing preliminary results from the literature review to be considered in its roadmaps. The complete listing of needed technology developments coming from the literature review are contained in Appendix E.

Summary of Literature Review Findings

As identified by the NPI, the original goal of the planetary protection and human exploration literature review was to identify completed studies and investigations of relevance to aid in developing future requirements. It was assumed that gathering the published historical knowledge would provide a solid basis from which requirement development could occur. While conducting the review did indeed gather valuable insight into notional requirements, suggested areas of study and needed technology developments, it did not paint a clear picture of conclusive study results that would enable the creation of verifiable requirements. Instead, the literature review provided a summarization of key concerns and data that may need additional study before an appropriate requirement can be drafted. Similarly, the review highlights some requirements which may not require in-depth study at this time, given that much of the affected hardware and system design is very much conceptual and does not necessarily benefit from a verifiable requirement at this stage of development. As indicated by the NPI, the literature review is one step in a multi-step process which is set to also include a workshop to collect the current state of knowledge from NASA personnel, academia, international partners, and private industry. Combining the historical knowledge and key concerns from the literature review with the latest findings in current research at a workshop should yield a set of draft requirements with clearly defined studies to render such requirements complete.

The literature review provided several key findings valuable for the formulation or refinement of studies and draft requirements. Of the 108 documents identified, approximately 58% were categorized, with 12 key documents contributing to the initial parsed listing of notional requirements, studies, and technologies. This was not an exhaustive review of all identified literature due to the effort involved and lack of supporting personnel required to

review, categorize and interpret all documentation. However, it is the opinion of the author that the literature which was thoroughly reviewed did support the identification of re-occurring themes likely to be reinforced by an additional review. Among these themes was the observance that most of the planetary protection focus for future human missions has been on mitigating contamination through operations and/or technology. In all, nearly one third of the literature reviewed and categorized addressed the use of operations or technological advancements to aid in reducing either forward or backward contamination or both. The least amount of focus was given to Mars environmental processes and its effect on planetary protection concerns. This is expected as is known of the Mars surface environment, although it is anticipated that the state of knowledge in this area is rapidly increasing with the presence of new robotic spacecraft such as the Mars Science Laboratory. Much of the documentation reviewed addressed multiple categories rather than focusing on any one particular area. This likely also led to the conclusion that much broad thought has been given to the topic of planetary protection and human missions, but little depth has been achieved in researching specific concerns. Following this literature review with a community workshop to gather the latest state of knowledge and better define in-depth studies will ensure progress towards the development of a verifiable requirement set. Combining this effort with thoughtful iteration of the literature review will ensure that the latest basis of knowledge is available to inform the requirements development process. Such knowledge serves as a foundation for effective, verifiable requirements to shape future mission and system design.

A Systems Engineering Approach to Requirement Development

Most engineering projects are first created from continuing analysis of operational needs or through an innovative product development [18]. In the area of planetary protection, the need – avoiding harmful cross-contamination of biospheres – has clearly evolved from years of increasingly complex exploration operations and now serves as a key factor throughout robotic exploration system design. Requirements which flow down from this need must be clear and verifiable, yet do not force the design to only high-cost, long lead solutions. As in all aspects of systems engineering, a balance must be sought. To see how such a balance might be achieved for developing planetary protection requirements for human exploration systems, we can trace through a portion of the systems engineering process with close

consideration of the notional requirements, studies, and technologies identified in the literature review.

Identifying the Need, Goals & Objectives for Planetary Protection Requirements

Common to the practice of systems engineering and efficient design is the need to understand a future system's purpose. Such a "call for development" is usually captured through a system's statement of needs, goals and objectives. Larson, Kirkpatrick, Sellers, Thomas, and Verma define a system need as a driving singular statement that relates to a problem to be solved but not its solution [19]. Goals and objectives provide further resolution into the framework under which a system will operate and eventually give way to operational requirements.

The need, goals and objectives for upholding planetary protection policy for human spaceflight have been indirectly documented, although are not consistently considered from a systems engineering perspective. The overarching need to uphold planetary protection practices is as stated in Article IX of the UN Outer Space Treaty. The treaty states the need for planetary protection is to "...conduct exploration of them [the Moon and other celestial bodies] so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter..." [3]. Avoiding harmful contamination of celestial bodies and adverse changes to the Earth is the cornerstone of planetary protection practice and drives many operational decisions, technology investments and the development of applicable requirements.

One can distinctly separate this stated need for planetary protection into three distinct goals related to future requirements for human missions: mitigating forward contamination, preventing backward contamination, and ensuring the health & safety of the crew when exposed to extraterrestrial material. These three main goals are repeatedly stated in planetary protection literature and given particular focus and attention in the Pingree Park Report. It may be arguable that preventing backward contamination and ensuring crew health and safety are intrinsically tied together as most all future human exploration concepts call for the crew's return to Earth. While these goals are not overly specific and measurable, they do

provide further focus to the underlying need to avoid harmful contamination to celestial bodies and protect the Earth from adverse changes. Additionally, these goals point to categorizing future operational and functional requirements into three main areas: forward contamination, backward contamination, and maintaining crew health.

The main goals for planetary protection are given further resolution through the COSPAR *Principles and Guidelines for Human Missions to Mars* which might be considered draft objectives for implementing planetary protection requirements during human missions. This document outlines four general principles and eight guidelines for future missions which collectively address aspects of mitigating forward contamination, preventing backward contamination, and upholding crew health and safety. While this COSPAR document may not consist of concise, specific, measurable, and time-bound objectives, they do provide a starting point for decomposing requirements for human missions. Examples of some of the COSPAR guidelines include: the need for continued monitoring and evaluation of microbes carried by human missions, avoidance of the contamination of ‘special regions’ on Mars where microbial life could flourish, and assurance that a crewmember be given primary responsibility for upholding planetary protection practices throughout the mission. The COSPAR *Principles and Guidelines for Human Missions to Mars* are included in NPI 8020.7, *NASA Policy on Planetary Protection Requirements for Human Extraterrestrial Missions* located in Appendix A. The decomposition from a need statement in Article IX of the UN Outer Space Treaty to the objectives stated in the COSPAR *Principles and Guidelines for Human Missions to Mars*, show the main framework under which operational and functional requirements should be made traceable (see Figure 6 on following page).

Need for Planetary Protection

- Avoidance of harmful contamination of celestial bodies and adverse changes to Earth's environment.

Planetary Protection Goals for Human Spaceflight

- Mitigate forward contamination
- Prevent backward contamination
- Preserve crew health & safety

Planetary Protection Objectives for Human Spaceflight

- Provide continuous monitoring & evaluation of microbes carried by human missions
- Provide a quarantine capability for both the entire crew and individual crew members
- Develop a comprehensive planetary protection protocol for human missions
- Avoid contamination of "special regions" on Mars
- Characterize martian exploration sites with robotic precursors prior to human exploration
- Treat samples or sampling components from Mars "special regions" or uncharacterized sites as restricted Earth return material
- Assign a crewmember with primary responsibility for upholding planetary protection practices
- Planetary protection requirements should be conservative and not relaxed without scientific review, justification, and consensus

Figure 6 Paraphrased need statement, goals, and objectives to guide requirement development.

As the need statement, goals, and objectives for planetary protection give way to requirements, it becomes critical to gather community insight into each of these foundational components from both the internal NASA community as well as academia, international partners, private industry, and other external parties.

Planetary Protection Stakeholder Identification

As studies and investigations are designed to ensure an effective requirement set is being drafted, it is important to accurately identify the stakeholder community. Project stakeholders are defined by NASA's Systems Engineering Handbook as "the organization or individual who has requested the product(s) and those who are affected by or are in some way accountable for the products outcome" [20]. Such stakeholders reside both within the NASA community or are directly affected by the implementation of planetary protection policy (internal/active) or may experience the effects of planetary protection implementation but do not have a direct role in relevant system or mission design (external/passive). Identifying

such stakeholders in the planetary protection requirement development process, and encouraging their participation, helps to ensure adherence to appropriate goals and objectives while verifying the studies needed to create effective requirements (see Figure 7).

Internal/Active Stakeholders for Planetary Protection Requirement Development

- EVA/Spacesuit Development Community
- Environmental Control and Life Support Systems (ECLS) Development Community
- Human Mission Architecture Development Teams
- Robotic Systems Development
- Scientific Community (Astrobiology & Geology)
- Crew Office
- Spaceflight Medical Community
- Spacecraft Operations Community
- Human Factors Design Community
- In-situ Resource Utilization Development Community

External/Passive Stakeholders for Planetary Protection Requirement Development

- NASA International Partners
- Commercial/Private Space Industry
- Congress
- United Nations
- COSPAR
- Center for Disease Control

Figure 7 Active and passive stakeholders for planetary protection requirement development.

Throughout the requirement development process, it is important to keep such stakeholders engaged as the requirements are iterated. Ultimately, effective requirements are not only verifiable but can be validated as meeting the intent of the stated need, goals and objectives of the design. Keeping both active and passive stakeholders engaged throughout the process enables a nearly constant process of validation as the requirements and the systems they are applied to are continually developed. As stated by Kossiakoff and Sweet, “analysis must include interaction with the prospective users of the system, to gain a first-hand understanding of their needs and constraints...” [18]. It is this stakeholder interaction that will be cultivated through the NPI workshop and following requirement development activities.

Requirement Formulation & Decomposition

With the foundation of a need for planetary protection, resulting goals and objectives, and a historical knowledge base from an extensive literature review, we can begin the requirement formulation process with appropriate stakeholder representation. While we understand the drivers for exercising planetary protection policy, we need to also understand the goals and objectives of the requirement set itself, and thereby the resultant NPR, in order to identify when the requirements can be rendered complete. The need for an NPR is simple – both the Mars mission design and hardware development community are in need of a set of requirements to ensure their operational concepts and system designs will conform appropriately to planetary protection policy. A primary goal of developing such an NPR should be to ensure that requirements are in place prior to significant development occurring on future human missions to Mars. Having an initial set of requirements within the next few years that address forward and backward contamination in addition to crew health and safety should serve as a driving objective.

While these parameters may shape what is needed for a requirement set, it doesn't clearly identify the appropriate level of detail to expect from the NPR. As most NASA NPR's are mission-level requirements intended to translate policy into programmatic or project requirements, they should avoid being overly decomposed to the point of being attributable to the component or part level of a system. Identifying this appropriate balance can only come from appropriate stakeholder engagement to ensure sufficient guidance is being given to the relevant communities without driving detailed design solutions. It can be expected that a completed set of planetary protection requirements will consist mainly of mission and operational level requirements with some functional performance requirements providing a greater level of insight into acceptable, measurable levels of contamination and containment.

To build a complete requirement set, some consideration must be given to operational use cases (e.g., scenarios driving implementation of planetary protection practices), system interactions, and functional decomposition (e.g., which systems will perform requisite planetary protection functions). As with nearly all systems engineering processes, a high degree of iteration is also required in the requirements development process as the use cases,

system interactions, and functional assignments are likely to change in the early stages of concept development.

Planetary Protection Use Cases

A use case, or operational scenario is meant to “identify interactions needed among the system of interest, its reference elements, and its active stakeholders” [19]. While planetary protection itself is not considered a traditional engineering system, upholding the associated policy and soon-to-be requirements is dependent upon a complex series of interactions that occur with many systems. On a holistic level, aspects of planetary protection must be considered any time there is an interaction between a spacecraft, robotic element, and/or crewmember and an extraterrestrial environment. Such interactions cut across a multitude of systems associated with the human exploration of Mars and if we are to consider the existence of a complete ‘Mars exploration system’, planetary protection would serve as the basis of many interface requirements with the Martian surface. System venting and waste management, heat rejection (which may induce localized ‘special regions’ habitable for microbial growth), trajectory control, and transportation of contamination are some examples of interactions that may occur between Mars exploration systems and the Mars environment (see Figure 8 on following page). Each one of these interactions could set the foundation for an operational use case where planetary protection requirements may be exercised. To illustrate how tracing through an operational use case may assist the requirement development process, we can consider the scenario of a crewmember performing an extravehicular activity (EVA).

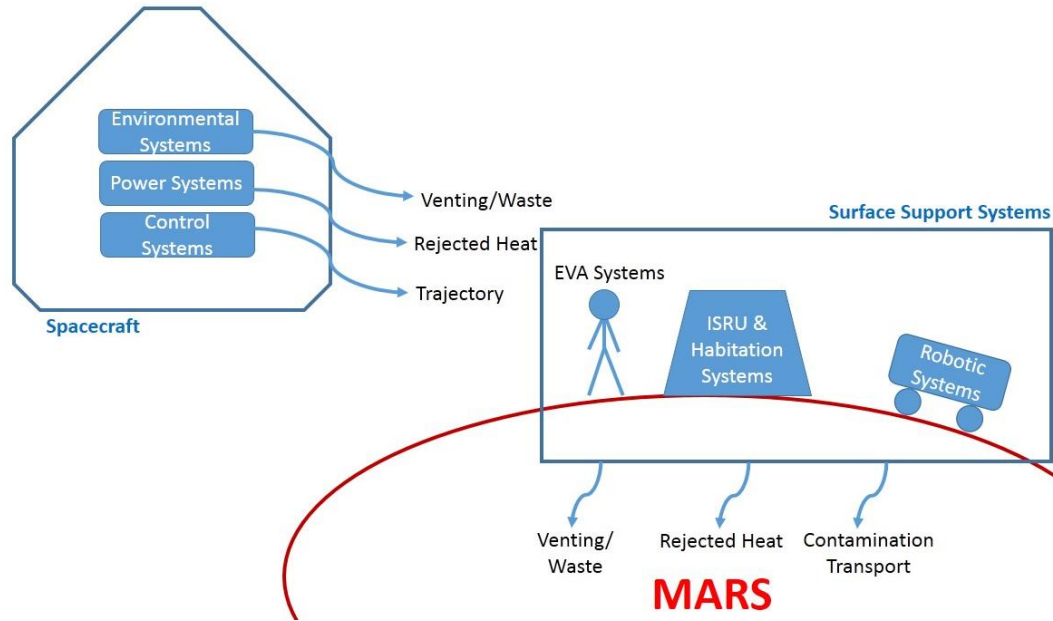


Figure 8 Overview of planetary protection interactions with the Mars environment.

In general, performing a spacewalk or EVA consists of three main operational activities: crewmember egress (of the spacecraft or habitat), conducting the EVA, and crewmember ingress. Each of these activities then holds a series of distinct actions which may have planetary protection implications (see Figure 9).

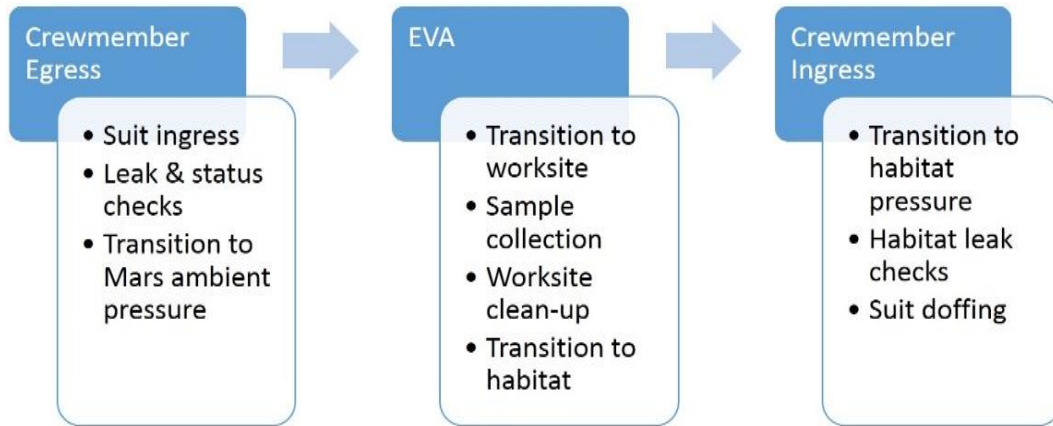


Figure 9 Example of an operational use case for EVA.

As we investigate such an operational use case for EVA, we see that interaction with the Mars environment is likely to first occur during the transition to Mars ambient pressure upon crewmember egress and may extend as far as suit doffing if dust is adhering to the spacesuit.

Further investigation of the activities identified in the EVA use case can lead to additional use cases and assist greatly in the next step of functional decomposition. If we investigate each operation associated with the crewmember ingress activity, we can build another detailed set of use cases and identify the related functions (see Figure 10). This process of continual decomposition allows us to clearly identify functions and subfunctions which need to be fulfilled and eventually assigned to systems, subsystems, and components. As this process unfolds we can begin to identify where functional requirements are needed and the studies we might need to conduct in order to appropriately inform those requirements and ensure compliance.

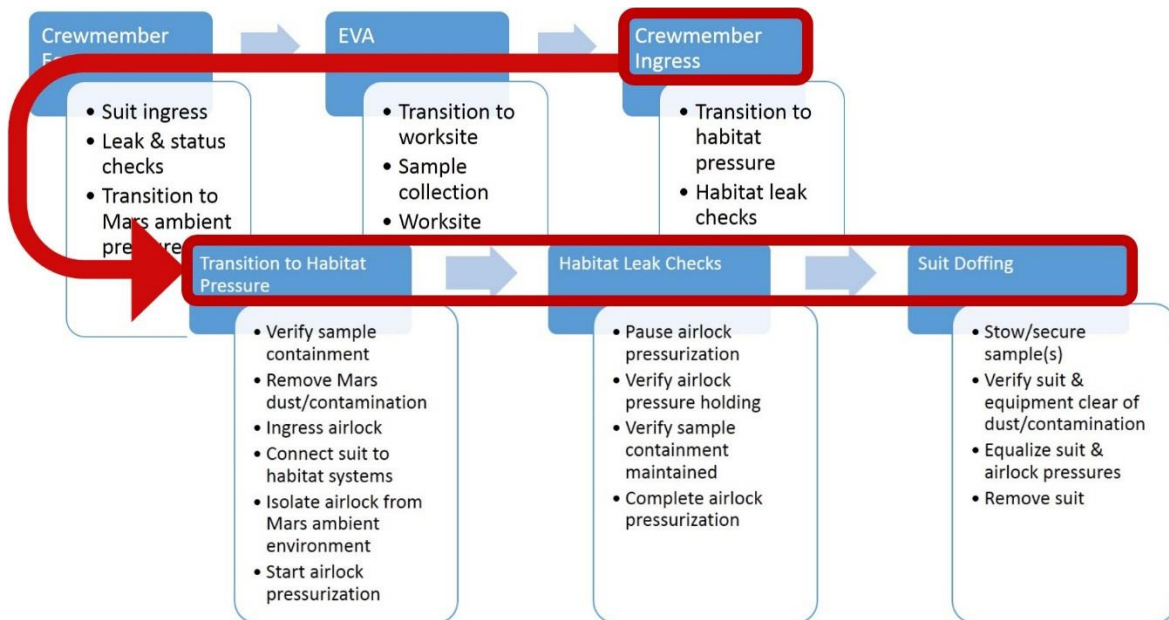


Figure 10 Decomposition of crewmember ingress activity into additional use cases.

Functional Decomposition

A functional architecture is described by Buede as defining what a system must do through the transformation of inputs into outputs using control information and mechanisms [21]. Ideally, at the early stages of concept design, this type of decomposition should avoid identifying a particular hardware solution, but will certainly allow some design solutions to come into focus through the observation of needed inputs, controls and outputs associated with a given function. The operational interactions and sequence of events identified in our

earlier use case analysis can help us identify key system functions. In many instances, these functions correlate directly to one action in an operational use case. Using the EVA use case shown previously, we can identify at least seven distinct operational activities or subfunctions that may interact with the Mars environment and be of planetary protection concern: transitioning to Mars ambient pressure, transitioning to the worksite, sample collection, worksite clean-up, transitioning to the habitat, transitioning to habitat pressure, and potentially suit doffing. When we further decompose the crewmember ingress activity in the EVA use case, three core subfunctions are identified: transitioning to habitat pressure, performing habitat leak checks, and doffing of the space suit. Taking a closer look at just one of those subfunctions – transition to habitat pressure – we begin to see potential functional inputs, outputs and controls based upon the defined high-level use case (see Figure 11).

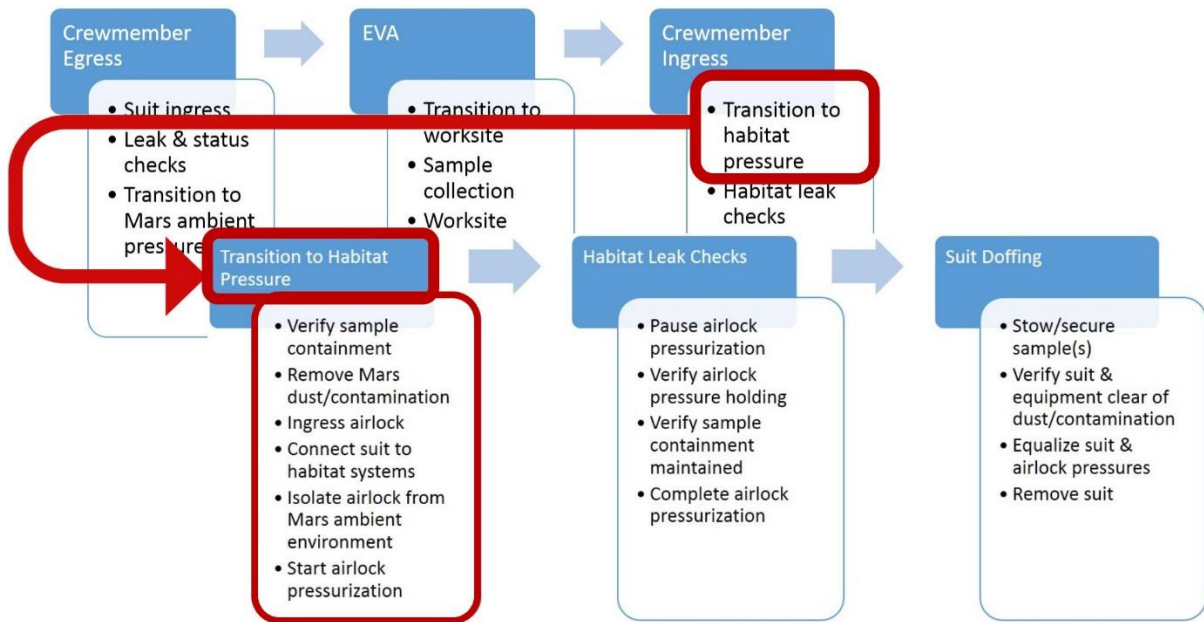


Figure 11 Transition to habitat pressure function and associated use case.

We can also review how we've progressed through the functional decomposition exercise through a high-level functional flow block diagram which depicts the relationship of the transition to habitat pressure to the overall EVA function on a Mars mission (see Figure 12 on following page).

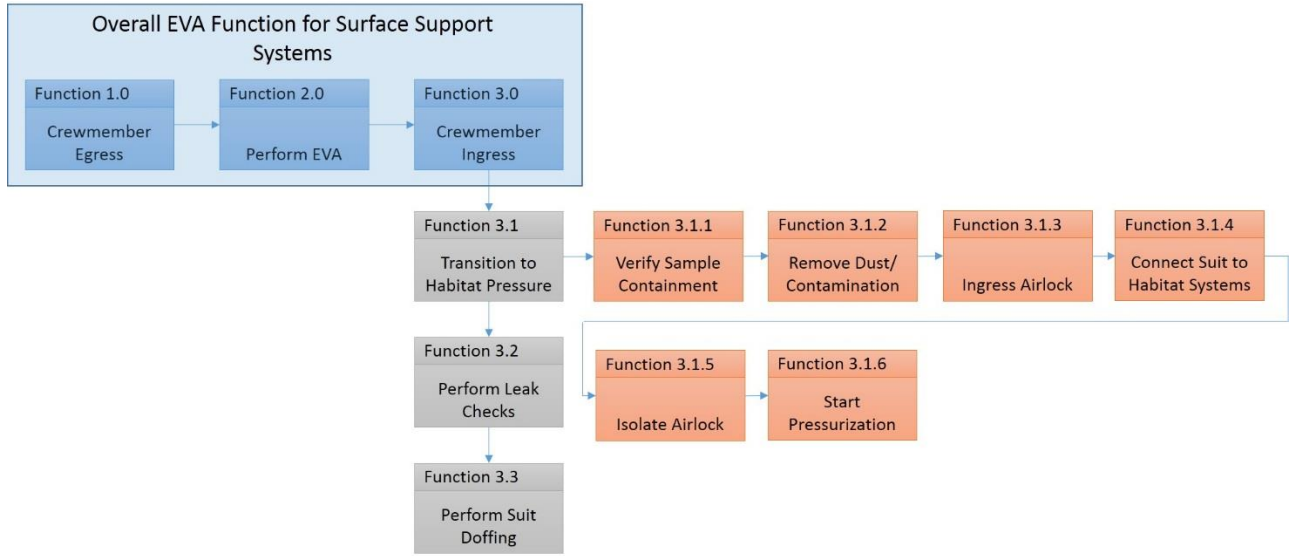


Figure 12 High-level functional flow block diagram for EVA function.

We can deduce from such an exercise in functional decomposition that the transition to habitat pressure subfunction receives samples, suited crewmembers, pressurizing gas, and dirt/contamination from the Mars environment while maintaining containment of samples and providing a pressurized and clean environment. This depicts a transition from input elements to different or maintained output elements while utilizing a system of mechanisms (space suit, airlock system, and sample containment system) and adhering to a set of controls (procedures, limits, and maintenance) (see Figure 13).

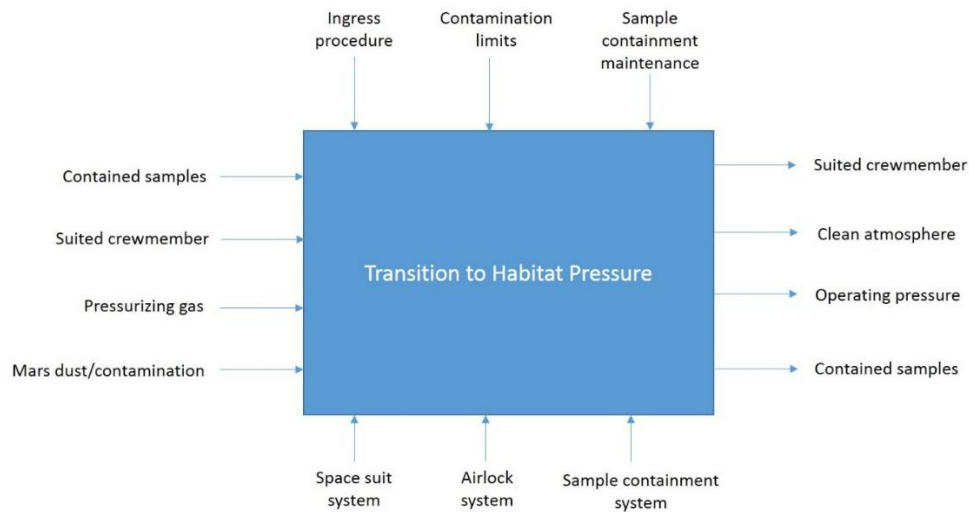


Figure 13 High-level context diagram of transition to habitat pressure subfunction

While a context diagram may depict the inputs, outputs, controls, and mechanisms interacting with a particular function, it falls short in showing how those interactions relate. Constructing an IDEF0 diagram, often used in systems engineering to show the flow of inputs and outputs across a series of functions, provides even greater resolution into the associated interactions with the transition to habitat pressure subfunction (see Figure 14). Collectively, such tools for visualizing functional decomposition can aid one in identifying the interactions and interfaces between functions, subfunctions, and the systems which perform them. Understanding such relationships aids in ensuring that requirements are traceable to a given function and prevents the formulation of unnecessary or poorly defined requirements. Given the complexities of translating planetary protection policy into requirements, tracing through such an exercise may prove valuable to adequately understand when certain functions provide the opportunity to interact with the Martian environment.

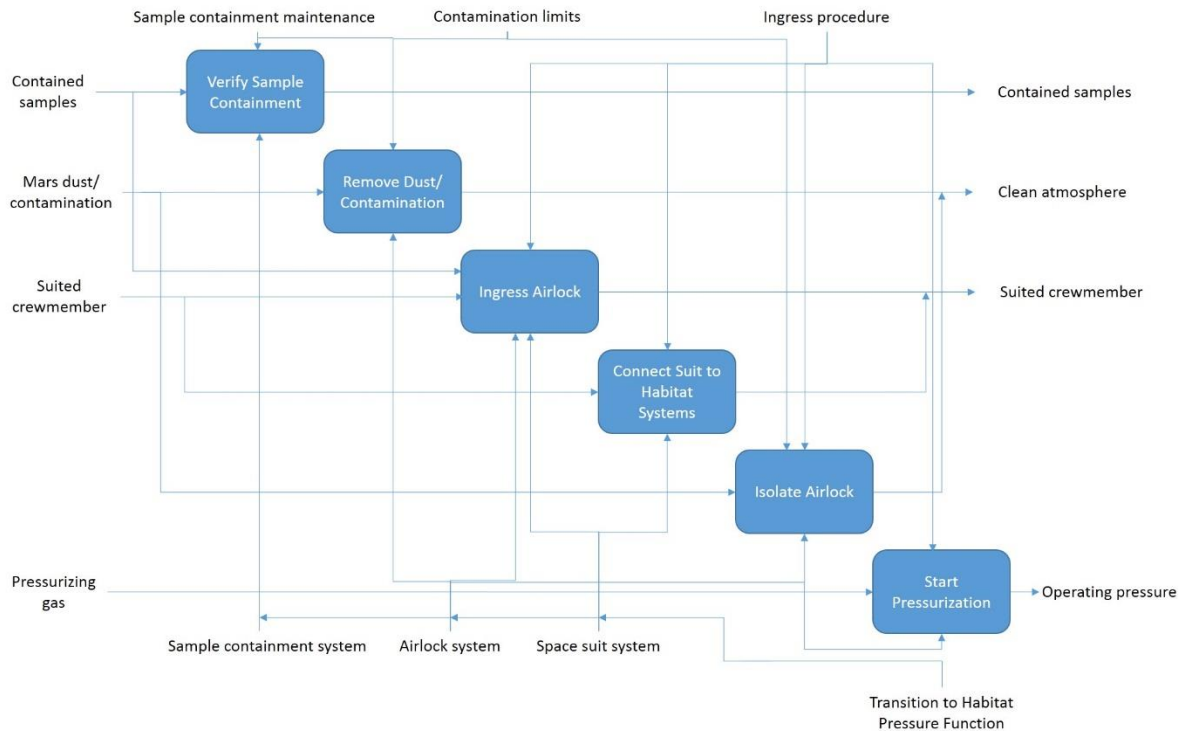


Figure 14 IDEF0 diagram of the transition to habitat pressure subfunction.

This exercise in functional decomposition stresses that planetary protection concerns are highly integrated throughout the execution of the transition to habitat pressure subfunction. A crewmember returning from EVA may have Martian dust on their suit and equipment and,

for a science-based EVA, is likely returning with samples. Mitigating the transfer of dust back into the habitat and preserving the containment of any samples are both paramount to preventing backward contamination. Various solutions provide for such mitigation efforts and the functional decomposition demonstrates that the space suit system, airlock system, and sample containment system all play a role in assuring an output of a suited crewmember with a clean atmosphere and contained samples. As planetary protection requirements are derived, we must ensure that these systems and their interfaces with the external Mars environment are addressed. Of similar interest is noting that a control in this process is the presence of contamination limits. The question of how much contamination is allowable should not be missed and brings us back to the relationship of notional requirements to needed studies and technology developments as we uncovered in the literature review.

Comparison with Literature Review Findings

The process of tracing through operational use cases and investigating functional decomposition can only go so deep without an initial requirement set. Knowledge gained from the literature review, and hopefully built upon in a future workshop, can be paired with such exercises to help refine a draft set of requirements and clearly indicate the studies and technologies that must advance to enable effective planetary protection measures for human exploration. In reviewing the notional requirement set for the EVA use case and specifically the subfunction of transitioning back to habitat pressure, we notice 13 notional requirements from the literature review that could be applicable. These requirements, obtained from Appendix C, include:

- 2.0 Planetary protection considerations shall be included in all aspects of human mission design and execution including; planning, training, operational protocols, and mission execution.
- 3.0 Spacecraft materials selected for design shall facilitate decontamination (e.g., withstand chemical disinfectants, heat treatment, etc.) as practicable.
- 4.0 Human missions shall assume that Martian life exists and is hazardous until proven otherwise.

6.0 Crews shall be protected from direct contact with Martian materials until testing can provide verification that exposure to the material is safe for humans.

7.0 Back contamination from Mars to Earth shall be minimized and its prevention considered highest priority.

7.1. Space suits used for the surface exploration of Mars shall not enter the return/ascent vehicle.

7.2. EVA tools used for the surface exploration of Mars shall not enter the return/ascent vehicle.

7.3. Samples returned by the crew from uncontrolled or otherwise untested areas of Mars shall be considered as potentially hazardous until proven otherwise through a series of tests.

7.5. Situations, technologies, or operations shall be avoided that would cause crew, support systems, hardware, or returning spacecraft to be exposed to Martian dusts, materials or microbes in ways that would allow them to return to Earth in an uncontained manner.

7.6. Any pristine or sampling components from any uncharacterized sites or special regions shall be treated according to current Category V planetary protection measures with restricted Earth return.

7.6.1. The returning spacecraft shall not be contaminated by Martian dust particles that are not sterilized or sealed within a suitable container.

7.6.2. Sealing surfaces of sample containers shall ensure that no particle 0.2 microns (micrometers) in size or larger can escape [based on smallest conceivable organism].

7.6.3. Samples returned from the Mars surface shall maintain their seal when subjected to TBD [to-be-determined] stresses.

We might then allocate these requirements to the mechanisms identified in the functional decomposition (see Table 1).

Table 1 Allocation of notional requirements to transition to habitat pressure subfunction.

Functional Decomposition Mechanism	Applicable Notional Requirements
Space Suit System	2.0, 3.0, 4.0, 6.0, 7.0, 7.1, 7.2, 7.5
Airlock System	2.0, 3.0, 4.0, 6.0, 7.0, 7.5
Sample Containment System	2.0, 3.0, 4.0, 6.0, 7.0, 7.3, 7.5, 7.6, 7.6.1, 7.6.2, 7.6.3

Through this requirement allocation exercise, we see that several notional requirements are indeed cross-cutting operational requirements (i.e., requirements 2.0, 3.0, 4.0, 6.0, & 7.5) while others are more uniquely applicable to one system/mechanism. This exercise sheds light on how some of these notional requirements may be modified to better inform future design efforts. For example, we might suggest requirement 4.0 serve as a parent for requirement 6.0 which could be re-structured and combined with requirement 7.5 as follows:

4.0 Human missions shall assume that Martian life exists and is hazardous until proven otherwise.

4.1. Exposure to uncontained Martian material shall be avoided until testing can provide verification that the material is non-hazardous [former Requirements 6.0 & 7.5].

Even with the aforementioned example of restructuring, the requirements remain vague and raise unanswered questions, such as:

1. How does one prove Martian life exists?
2. If Martian life is found, what testing is needed to prove it is non-hazardous?
3. What degree of certainty is needed in proving Martian life is non-hazardous?
4. How is material containment measured?

5. Is there an amount of uncontained material that is “tolerable”?

Identifying these questions leads us to compare such open questions and the decomposition of the EVA transition to habitat pressure subfunction to the notional studies obtained from the literature review. In reviewing the listing of notional studies, a total of nine studies could provide results which will help further answer the aforementioned questions and further refine the notional requirement set. While the full listing of studies are listed in Appendix D, those deemed applicable to this exercise are paraphrased in Table 2 and related to associated questions, notional requirements, and the appropriate controls and/or mechanisms identified in the decomposition of the EVA transition to habitat pressure subfunction.

Table 2 Relation of studies to questions, requirements, and decomposition of transition to habitat pressure subfunction.

Notional Study	Relevant Question(s) Addressed	Applicable Notional Requirement(s)	Associated Functional Control and/or Mechanism
B1 – Develop allowable contamination listing	Questions 3 & 5	6.0, 7.0, 7.5, 7.6.1	Contamination limits, sample containment system, sample containment maintenance
B4 – Classify signatures of life	Question 1	4.0, 6.0, 7.0, 7.3	Contamination limits, sample containment system, sample containment maintenance
B5 – Tests to monitor crew condition	Question 2	6.0, 7.0, 7.3	Ingress procedure
C6 – Investigate sample containment	Question 4	3.0, 6.0, 7.0, 7.3, 7.5, 7.6, 7.6.1, 7.6.2, 7.6.3	Sample containment maintenance, sample containment system
O7 – Develop operational methods for cleaning	Question 5	2.0, 3.0, 7.0, 7.5	Ingress procedure, space suit system, airlock system
O10 – Develop training program	Questions 2 & 4	2.0, 7.5	Ingress procedure
O11 – Identify human factors considerations	Questions 2 & 4	2.0, 7.1, 7.2, 7.5	Ingress procedure, space suit system, airlock system

Notional Study	Relevant Question(s) Addressed	Applicable Notional Requirement(s)	Associated Functional Control and/or Mechanism
Notional Study	Relevant Question(s) Addressed	Applicable Notional Requirement(s)	Associated Functional Control and/or Mechanism
E4 – Characterize Martian dust	Questions 1, 4, & 5	3.0, 4.0, 6.0, 7.0, 7.5, 7.6.1, 7.6.2	Contamination limits, sample containment system, sample containment maintenance
E5 – Experiments challenging Earth organisms	Questions 2, 3, & 4	4.0, 7.3	Contamination limits, sample containment system, sample containment maintenance

We can see from Table 2 that several studies will certainly assist in answering the questions derived from the notional requirement set as well as help define the operating regime of the systems (mechanisms) and controls identified through the functional decomposition. One may even be able to conclude from this exercise that some studies may be of even greater value in defining requirements such as developing a listing of allowable contamination (Study E1), investigating methods of sample containment (Study C6), and characterizing Martian dust (Study E4). As the notional requirement set is iterated, such effort may help in prioritizing which study investments should occur sooner in the development cycle.

Lastly, our listing of notional technology developments, listed in Appendix E, also relates to our operational use cases and functional decomposition. In fact, 10 technology development efforts hold close relation to inputs, outputs, and mechanisms identified in our EVA transition to habitat pressure functional assessment (see Table 3 on following page).

Table 3 Notional technology developments mapped to functional inputs, outputs, and mechanisms for transition to habitat pressure subfunction.

Notional Technology Development	Related Functional Input(s)	Related Functional Output(s)	Related Functional Mechanism(s)
ECLS-3: ECLSS Active Sterilization	Pressurizing gas, Mars dust/contamination	Clean atmosphere, Operating pressure	Airlock system
Quant-2: Rapid Cleanliness Assays	Contained samples, Mars dust/contamination	Contained samples, Clean atmosphere	Airlock system, Sample containment system
Monit-1: Microbial Burden Analysis	Contained samples, Mars dust/contamination	Contained samples, Clean atmosphere	Airlock system, Sample containment system
Monit-6: Biological Active Monitoring	Pressurizing gas, Mars dust/contamination	Clean atmosphere, Operating pressure	Airlock system
EVA-1: Dustlocks & Suitports	Suited crewmember, Mars dust/contamination	Unsuited crewmember, Clean atmosphere	Space suit system, Airlock system
Mars-1: DREAMS Development	Mars dust/contamination	N/A	N/A
Robo-2: Contained Sample Analysis	Contained samples	Contained samples	Sample containment system
Other-2: In-Situ Sterilization	Mars dust/contamination	Clean atmosphere	Airlock system, Space suit system
Other-3: Sample Sealing	Contained samples	Contained samples	Sample containment system
Other-5: Entry Assured Containment	Contained samples	Contained samples	Sample containment system

We see from this analysis that several technology developments may help ensure we successfully perform the EVA function of transitioning back to habitat pressure upon ingress. During that process, sample containment must be maintained which is dependent upon the containment technologies (Robo-2, Other-3, and Other-5) as well as some of the analysis, analyzing, and monitoring technologies (Quant-2 and Monit-1) to assure us that containment has not been breached. We can also extrapolate this exercise to observe the relation of some of these notional technology developments to the notional requirement set as we had done for

the studies relating to the EVA transition to habitat pressure subfunction (see Table 4).

Table 4 Notional technology developments and applicability to notional requirements.

Notional Technology Development	Applicable Notional Requirements
ECLS-3: ECLSS Active Sterilization	6.0, 7.0, 7.5, 7.6.1
Quant-2: Rapid Cleanliness Assays	3.0, 7.0, 7.3, 7.6.1, 7.6.2, 7.6.3
Monit-1: Microbial Burden Analysis	4.0, 6.0, 7.0, 7.3, 7.6.1, 7.6.2, 7.6.3
Monit-6: Biological Active Monitoring	4.0, 6.0, 7.0, 7.3, 7.6.1, 7.6.2, 7.6.3
EVA-1: Dustlocks & Suitports	2.0, 3.0, 4.0, 6.0, 7.0, 7.1, 7.2, 7.5
Mars-1: DREAMS Development	4.0, 6.0, 7.3, 7.5, 7.6
Robo-2: Contained Sample Analysis	7.0, 7.3, 7.5, 7.6.2, 7.6.3
Other-2: In-Situ Sterilization	3.0, 7.0, 7.6.1
Other-3: Sample Sealing	6.0, 7.0, 7.5, 7.6, 7.6.1, 7.6.2, 7.6.3
Other-5: Entry Assured Containment	2.0, 3.0, 4.0, 6.0, 7.3, 7.5, 7.6, 7.6.1, 7.6.2, 7.6.3

This is a process which can be utilized to show the series of interrelationships between the literature review products and the operational use cases and associated functional decompositions.

The Role of Iteration

The goal of achieving a balanced design, in which the seemingly competing factors of cost, schedule, and system performance lie in equilibrium, and can only be achieved through effective use of iteration. As we increase our knowledge related to planetary protection and future human exploration we will gain better insight into what constitutes effective, implementable requirements. This continual increase of knowledge has begun with the initial literature review and will be augmented through the upcoming workshop called for in the NPI and resulting studies and investigations (see Figure 15 on following page). The stakeholder community engaged in this process should continue to review and modify the notional requirement set as knowledge is gained until the community can conclude that an effective requirement set has been created.



Figure 15 Iterative knowledge building to feed requirements.

As planetary protection policy is updated to reflect the latest scientific knowledge, so should the requirement set be updated. Given a level of configuration control is needed as an affected system progresses through its development cycle, the associated stakeholder community must also give consideration as to the cost and schedule impacts of increasingly later changes to requirements. As the systems developed for future human exploration beyond low Earth orbit continue to mature, the level of associated iteration must decrease so as to avoid exorbitant cost and schedule impacts.

An Alternative Requirement Development Approach

While this paper has laid out a detailed process by which to build, develop, and iterate a set of planetary protection requirements for future human exploration missions, there are certainly alternate approaches that might be utilized with a similar degree of success. The process of decomposing planetary protection policy guidelines, constructing detailed use cases, functionally decomposing each use case, and updating notional requirements, studies, and technology needs to inform a developing system architecture is lengthy and tedious. While the level of effort may result in a more complete product with a full understanding of the interrelationships between policy, requirements and the affected systems, it comes at the cost of taking significant time and effort and being less adaptable to frequent updates in knowledge. An alternative, simpler approach could be taken by omitting all but the most generalized use cases and certainly all of the functional decomposition activities. Such an approach might entail simply taking the notional requirements coming from the literature review, complete with their inadequacies, and soliciting stakeholder input for review and iteration. This ‘brute force’ approach promises to be faster, allowing more time for iterations and adapting to updated knowledge, but at the risk of being contentious, missing unknown

relationships between requirements and affected systems, and not showing complete traceability. A summarization of the benefits and drawbacks to both a detailed systematic approach and brute force method are highlighted in Table 5. Ultimately the success of either approach is highly dependent upon proper identification of the stakeholders supplying input to the process and resulting requirement set.

Table 5 Comparison of requirement development approaches.

Detailed Systematic Approach		Brute Force Approach	
Pros	Cons	Pros	Cons
Ensures requirements are well-informed & based on latest knowledge.	Will take significant time and effort.	Likely faster process.	Highly contentious as ‘first cut’ requirements will be less than desirable to the majority.
Allows for extensive consensus-building among stakeholders.	Less room for iteration due to time to complete a full cycle.	Faster process allows more time for iteration.	Not as likely to uncover ‘unknowns’.
Shows clear traceability from policy driven Needs, Goals & Objectives.	Less adaptable to late-breaking updates in knowledge.	Adaptable to late-breaking updates in knowledge.	Fully dependent upon iteration.
Shows relationship between requirement development, informative studies, and developing technologies.			Lack of traceability with requirements.

Conclusion

We lay witness to the complexities of translating internationally accepted policy into an implementable requirement set which cuts across a multitude of yet-designed human exploration systems. What further complicates this effort is the presence of a diverse and incomplete basis of knowledge requiring further study and investigation before effective, verifiable requirements can be drafted. While consideration of planetary protection policy for human missions to Mars and other solar system destinations is not new, it has reached a critical point where pontification must turn to action in order to adequately inform the

engineering and scientific communities investigating future exploration architectures. Having compiled a literary basis of knowledge is the first step in this process, but converting this knowledge to actionable requirements takes new consideration of studies and appropriate implementation of system engineering practices.

In reviewing the notional requirements, studies, and technologies resulting from the literature review and comparing them to operational use cases and resulting functional decomposition, we begin to see a relationship emerge. Requirements ultimately are to be validated and verified. The validation comes from a comparison to the underlying need, goals and objectives of planetary protection policy, while the verification ensures the requirement can be effectively met. In order to construct a requirement that can be verified, one must ensure that the requirement can be measured. In effect, we observe that requirements tell us what should be verified, studies will enable us to identify the performance parameters we are to verify to, and developed technologies will enable the verification in addition to providing hardware that can meet the requirements. This interrelationship became evident throughout the literature review and should be considered as the notional requirement set is iterated and matured.

While considering the relationship between requirements, needed studies, and technology developments, a process of defining operational use cases and translating them to a functional architecture can be followed to ensure the development of a verifiable set of requirements (see Figure 16).

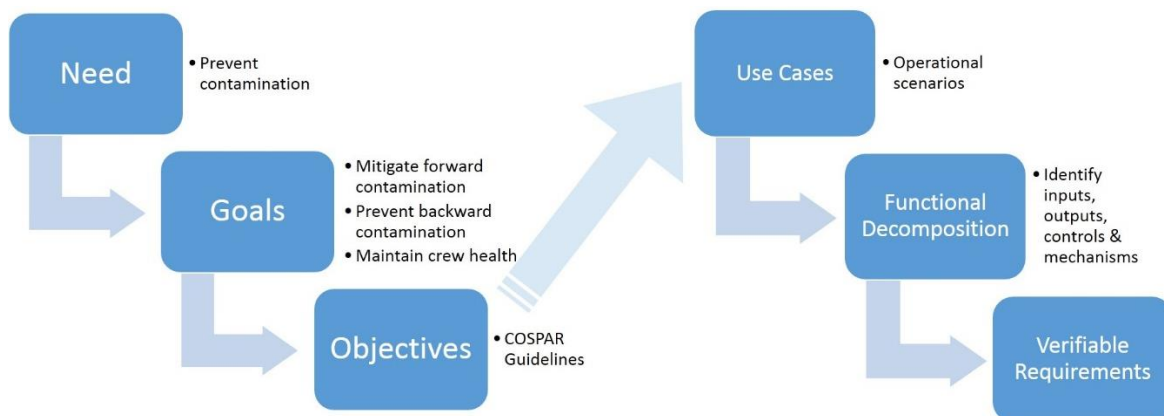


Figure 16 Overview of decomposition activities leading to verifiable requirements.

In practice, such an effort would benefit from the application of model-based systems engineering tools to effectively show the complex interrelationships between human exploration systems and their planetary protection requirements. Additionally, perhaps the most significant tools to effective requirements development are the proper identification of critical stakeholders and dedicated use of iteration. While both the proper stakeholder identification and iteration are evident in this detailed systematic approach, they become ever more critical if an alternative ‘brute force’ approach is applied to develop requirements on a shorter time scale. Given NASA’s continual pressure to apply current design and technologies to future mission goals in an effort to reduce operational costs, an appropriate balance between detailed system engineering rigor and rapid iteration must be sought. It is suggested that to effectively develop planetary protection requirements for future human missions, a combination of the two approaches is utilized. Such a combined approach may entail rapid iteration of a notional requirement set with key stakeholders while avoiding the effort involved in exercising detailed functional decomposition. Once the stakeholder community reaches consensus on a set of requirements, detailed systems engineering practices may be exercised in parallel with early system concept development to help guide detailed development of the functional architecture. While additional knowledge is being gathered and future informative studies and investigations are being designed, rapid iteration of a draft requirement set could be implemented with consideration of the literature review results. As the associated studies are completed and questions to better scope the notional requirements are answered, more complete systems engineering rigor should be applied with detailed use case and functional architecture analysis.

Future manned missions to Mars and beyond are currently in the incipient stages of concept development. It is during this early stage of mission and system design where the benefits of proper requirements development can be most effectively realized. And effective requirements will enable NASA to uphold its planetary protection obligation throughout its responsible scientific exploration to the red planet and beyond.

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Appendix A – NASA Policy Instruction 8020.7

NASA Policy Instruction NASA Policy on Planetary Protection Requirements for Human Extraterrestrial Missions

**NPI 8020.7
NPD 8020.7G**

1. Background

In May 2012, the Planetary Protection Subcommittee of the NASA Advisory Council (NAC) Science Committee formulated a recommendation that NASA Procedural Requirements (NPR) be developed for planetary protection on human missions under NASA Policy Directive (NPD) 8020.7, "Biological Contamination Control for Outbound and Inbound Planetary Spacecraft," as a parallel document to NPR 8020.12, "Planetary Protection Provisions for Robotic Extraterrestrial Missions." This recommendation was endorsed by the full NAC and forwarded to the Administrator in November 2012, and was agreed upon by the NASA Administrator in a letter dated March 8, 2013.

There is presently insufficient scientific and technological knowledge to establish detailed requirements and specifications to enable NASA to incorporate planetary protection into the development of crewed spacecraft and missions. Thus, this NASA Policy Instruction (NPI) establishes policy guidelines and describes the approach for obtaining the scientific information and developing the technologies and procedures over the next few years that are needed to draft an NPR for crewed planetary missions.

2. History

Even before Neil Armstrong's boot first touched the Moon, NASA has been concerned with the protection of Earth and its inhabitants from extraterrestrial life forms returned from inbound spacecraft. In order to protect against possible disease or other health issues incurred upon Earth's inhabitants, procedures were created to prevent such back contamination. Each of the early Apollo astronauts endured 21 days of quarantine upon their return to Earth, as determined by the Interagency Committee on Back-Contamination based on the fact that most terrestrial disease agents were capable of invading a host and causing evident disease symptoms within 21 days after exposure of the host. In addition to protecting against back-contamination, NASA is also dedicated to the preservation of any native extraterrestrial life forms and maintaining the scientific purity of the celestial bodies to which NASA travels. Contamination by biological material from Earth could make it impossible to determine if life was present before humans visited.

Since the end of the Apollo era, robotic missions have served as humankind's emissary to other solar system bodies, including the Sun, planets and small solar system objects. As an example, launched November 2011, the Mars Science Laboratory's (MSL) Curiosity rover was designed to assess whether Mars ever had a habitable environment, able to support small life forms called microbes. Planetary protection requirements called for the entire MSL flight system to launch with no more than 500,000 bacterial spores. This was accomplished mainly through the careful maintenance of clean room protocols, periodic cleaning of spacecraft surfaces with alcohol wipes, and dry heat treatment of some spacecraft parts.

Space exploration is now conducted by the space agencies of nations around the globe. The International Council for Science, a nongovernmental organization, established the Committee on Space Research (COSPAR) in 1958 as an interdisciplinary scientific body concerned with the progress on an international scale of all kinds of scientific investigations carried out with space vehicles, rockets and balloons.

The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, which established the basic legal framework of international space law, entered into force in 1967. Article IX of this treaty provides in relevant part, that:

“States Parties to the Treaty shall pursue studies of outer space, . . . , and conduct exploration of them so as to avoid their harmful contamination [“forward contamination”] and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter [“back contamination”] and, where necessary, shall adopt appropriate measures for this purpose.”

COSPAR established the first planetary protection guidelines for robotic missions in 2002. While not legally binding, COSPAR's Planetary Protection Policy is:

“for the reference of spacefaring nations, both as an international standard on procedures to avoid organic-constituent and biological contamination in space exploration, and to provide accepted guidelines in this area to guide compliance with [Article IX of the 1967 Outer Space Treaty] and other relevant international agreements.”

In March 2011, amendments to the COSPAR Planetary Protection Policy were approved by the Bureau and Council, World Space Council to include Principles and Guidelines for Human Missions to Mars (see Attachment A).

As NASA, in collaboration with our international partners, prepares to return humans beyond low-Earth orbit to explore the solar system and search for signs of life beyond Earth, it is critical that NASA guidelines be developed for crewed missions. A key NASA international partner, the European Space Agency (ESA) adheres to COSPAR Planetary Protection Policy for both crewed and robotic missions, as expressed in ESA/C(2007)112.

3. Policy Guidance

NASA adheres to the COSPAR guidelines. NPD 8020.7G (Biological Contamination Control for Outbound and Inbound Planetary Spacecraft [expires February 19, 2018]), quoting the COSPAR policy statement, requires Agency compliance with COSPAR policy regarding biological contamination control for outbound and inbound planetary spacecraft, covering all space flight missions¹ which may intentionally or unintentionally carry Earth organisms and organic constituents to the planets or other solar system bodies, including spacecraft which are intended to return to Earth and/or its biosphere from extraterrestrial targets of exploration. All missions in which NASA will participate are required to adhere to NPD 8020.7G and to be consistent with the COSPAR policy and guidelines for human missions (Attachment A).

4. Studies

Detailed studies must be conducted in order to obtain information critical to developing planetary protection requirements for human spaceflight missions. NASA will gather community input to determine the topics that should be studied; for example:

- 1) Developing capabilities to comprehensively monitor the microbial communities associated with human systems and evaluate changes over time;
- 2) Developing technologies for minimizing/mitigating contamination release, including but not limited to closed-loop systems; cleaning/re-cleaning capabilities; support systems that minimize contact of humans with the environment of Mars and other solar system destinations;
- 3) Understanding environmental processes on Mars and other solar system destinations that would contribute to transport and sterilization of organisms released by human activity.

5. Path Forward

NASA shall utilize the following roadmap to develop the necessary understanding of the scientific and technological basis to take sufficient steps to ensure planetary protection and then to develop an NPR setting forth requirements for planetary protection and carry out the NPR's mandates.

1. Present the required studies report to senior management for approval and commitment of funding, through a Memorandum of Understanding or other documentation.
2. Include sufficient funding for approved planetary protection studies as part of the NASA budget development process, leading to approval of funding for these studies no later than Fiscal Year 2016.
3. Conduct studies and develop planetary protection requirements.

¹ Emphasis added; in the title of the NPD, "planetary spacecraft" covers both robotic and human missions.

4. Integrate funding for planetary protection requirements into the ongoing budgets of all developing human missions that will come in contact with another celestial body.
5. Develop and formalize NPR for Planetary Protection for Crewed Missions.

In response to the Planetary Protection Subcommittee's recommendation, a cross-disciplinary *ad hoc* team was established that developed this NPI and is responsible for:

- Conducting a literature review to identify completed studies and investigations relevant to the development of verifiable planetary protection requirements for human missions;
- Seeking input from scientific and space operations community through a variety of sources, including, a workshop;
- Oversight of the recommended studies and following through on their completion to the development of specific requirements;
- Developing a draft NPR for planetary protection for human spaceflight that includes these specific requirements for mission development and follow the necessary NASA coordination and approval processes to baseline the NPR;
- Coordinating with relevant mission management teams within NASA, to ensure understanding of the requirements in order to achieve compliance.

The team is led by the Human Exploration and Operations Mission Directorate, with the Planetary Protection Officer serving as a technical advisor. Other participants include representatives from the following organizations: Science Mission Directorate, Space Technology Mission Directorate, Office of the General Counsel, Office of the Chief Scientist, Office of the Chief Medical Officer, and Office of International and Interagency Relations. Other organizations may be added as appropriate.

6. References

Attachment A: COSPAR Policy and Guidelines for Human Missions

Attachment B: Letter from NAC Planetary Protection Subcommittee Chair to
NAC Science Committee Chair

Attachment A: COSPAR Policy and Guidelines for Human Missions**COSPAR PLANETARY PROTECTION POLICY**

(20 October 2002; As Amended to 24 March 2011)

*APPROVED BY THE BUREAU AND COUNCIL, WORLD SPACE COUNCIL, HOUSTON,
TEXAS, USA*

(Prepared by the COSPAR/IAU Workshop on Planetary Protection, 4/02, with updates
10/02; 1/08, 4/09, 12/09, 3/11)

PREAMBLE

Noting that COSPAR has concerned itself with questions of biological contamination and spaceflight since its very inception, and

noting that Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (also known as the UN Space Treaty of 1967) states that:

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, and where necessary, shall adopt appropriate measures for this purpose. (UN 1967)

therefore, COSPAR maintains and promulgates this planetary protection policy for the reference of spacefaring nations, both as an international standard on procedures to avoid organic-constituent and biological contamination in space exploration, and to provide accepted guidelines in this area to guide compliance with the wording of this UN Space Treaty and other relevant international agreements.

...

APPENDIX: IMPLEMENTATION GUIDELINES AND CATEGORY SPECIFICATIONS FOR INDIVIDUAL TARGET BODIES

...

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 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.

Attachment B: Letter from NAC Planetary Protection Subcommittee Chair to NAC Science Committee Chair

November 20, 2012

TO: Wesley T. Huntress, Chair, NAC Science Committee**FROM:** Eugene H. Levy, Chair, Planetary Protection Subcommittee**RE:** Background to the PPS/Science Committee Recommendation through the NASA Advisory Council that NASA institute a Procedural Requirements Document on planetary protection for human exploration missions.

NASA Policy Document 8020.7G on “Biological Contamination Control for Outbound and Inbound Planetary Spacecraft” (hereinafter “NPD”) defines NASA’s Planetary Protection Policy to “cover all space flight missions” and designates the Associate Administrator for the Science Mission Directorate (SMD), as the official responsible for overall implementation of NASA's planetary protection policy, with the Planetary Protection Officer as the SMD AA's designee.

The NPD tasks the Associate Administrator for the Human Exploration and Operations Mission Directorate (HEOMD, by reference to the AA for Space Operations Mission Directorate and to the AA for Exploration Systems Mission Directorate) to ensure that applicable standards and procedures are established under the policy, in coordination with the Planetary Protection Officer, and that the consequent requirements in “detailed subordinate implementing documents are incorporated into human space flight missions.”

The Planetary Protection Subcommittee notes that the US/NASA adheres to international agreements under which COSPAR establishes common standards for planetary protection in the conduct of space missions. COSPAR has established and published planetary protection standards for human space missions. Currently, however, NASA has not established the required “subordinate implementing documents” for human missions. The Planetary Protection Subcommittee has submitted a recommendation that the requisite implementing documents be established, in accordance with NASA policy and COSPAR guidelines.

Establishing a formal requirements document is important to do now, in order to address misconceptions regarding NASA's planetary protection policy. For example, the recent report of the National Research Council (*Space Technology Roadmaps...*, 2012) stated erroneously (on pg. 225):

Similarly, it was observed that NASA planetary protection policies are limited to robotic missions. Until those policies are updated to provide guidance on human exploration, in compliance with recent COSPAR planetary protection policies, it would be premature to invest in new technologies relevant to planetary safety in TA07. [Emphasis added.]

in fact, COSPAR planetary protection policies have been updated to provide such guidance on human exploration, but the absence of a NASA Requirements Document obscures that fact, with manifest consequences as illustrated here.

Consequences of No Action on This Recommendation

1. Failing to implement the mandated Planetary Requirements Document will continue to promulgate an apparently widespread misperception that planetary protection requirements only apply to robotic mission. In the absence of such a document, ongoing efforts to develop technologies intended for the eventual human exploration of Mars is likely to follow pathways that are not compliant with planetary protection requirements for human missions to Mars, which would represent wasted effort and resources.
2. In the absence of this requirements document, NASA will be out of compliance with its own policy mandate as it plans the prominent flagship missions of human exploration, and out of step with international agreements to which the U.S. is a party. Planetary protection requirements constitute an international commitment of longstanding, having both crucial scientific implications and addressing matters of potential significant and broad-scale public concern. Planetary protection, especially as pertains to Mars exploration and the prospect of back contamination, whether the vector is a rock or a person, is not unlikely to become a matter of significant public concern at such time as human exploration of Mars might become an imminent reality. In the meantime, the development of support systems for human exploration is anticipated to focus on technologies that are generalizable along a path connecting precursor missions to eventual Mars-ready human-support systems. Failure to incorporate planetary protection standards at an early time would likely jeopardize this desirable technology-evolution path, and compromise the effective utilization of development resources. Altogether, lack of clearly defined and implemented standards for planetary back-contamination protection will reduce NASA's ability to retire the certain risks, and weaken the Agency's ability to respond to important drivers of Mars exploration from both scientific and public interest perspectives.

Background

In 2008, on the basis of advice from the U.S. Space Studies Board and information gathered by several NASA-sponsored and international workshops, guidelines on planetary protection requirements for human missions to Mars were formally approved by the Committee on Space Research (COSPAR) of the International Council for Science. COSPAR advises the UN Committee on the Peaceful Uses of Outer Space on scientific aspects of compliance with Article IX of the 1967 Outer Space Treaty (OST), as an international consensus standard. The United States is a party to the Outer Space Treaty. NASA policy (NPD 8020.7 and NPR 8020.12) requires compliance with COSPAR provisions on planetary protection, referencing OST Article IX.

NASA planetary protection policy applies equally to human and robotic missions, and specifies compliance with COSPAR guidelines on planetary protection; however, NASA currently has no NPR document providing requirements for human missions. The Planetary Protection Subcommittee of the NAC Science Committee has recommended that an NPR document be established now to support planning efforts for human deep space exploration missions, to be updated as planning progresses and as new information and policy revisions dictate.

Specifically, the PPS recommends that NASA adopt the current COSPAR guidelines for Mars into a new NPR document to ensure that the NASA policy of requiring compliance with COSPAR policy is made explicit for near-term human mission planners. (A draft of the NPR document has been prepared by the NASA Planetary Protection Office).

It is recognized that, as knowledge evolves, revisions to the NPR document may be called for. At an appropriate time, the National Research Council's Aeronautics and Space Engineering Board and the Space Studies Board, in cooperation with the European Science Foundation, should prepare a joint report to refine planetary protection requirements for human missions to Mars and other exploration targets. This would build on the prior Aeronautics and Space Engineering Board-Space Studies Board (ASEB-SSB) National Research Council (NRC) *Safe on Mars* report (which was prepared jointly by the Aerospace Engineering Board and the Space Studies Board, 2002) to inform future NASA policy, incorporating subsequent scientific, technological, and other developments.

Recent History

NASA has been developing guidelines on planetary protection requirements for human missions to Mars for over a decade. In 2001, a workshop on *Planetary protection issues in the human exploration of Mars* was held at Pingree Park, Colorado, to consider in detail the concerns for planetary protection that would be raised by the human exploration of Mars. In 2002, the ASEB and the SSB of the U.S. National Research Council published the *Safe on Mars* report (with Rick Hauck as Chair), that contained a number of recommendations regarding steps necessary to ensure the health of astronauts during Mars exploration. A second NASA-sponsored workshop was held in early 2005 at the Lunar and Planetary Institute in Houston, Texas to consider additional issues in *Life support, Habitation, and Planetary Protection* co-sponsored by SMD Planetary Protection and ESMD Advanced Life Support and Extravehicular Activities. The objective of these activities was to assess the potential for ensuring both protection of the Mars environment and preservation of astronaut health and the environment of the Earth after return, by identifying concerns and developing guidelines for planetary protection on human missions to Mars.

Results of these three efforts were considered at an international workshop held at ESA-ESTEC in mid-2005, co-sponsored by NASA and ESA. That workshop developed guidelines for review by the agencies and planetary exploration communities. The refined guidelines were subsequently communicated to COSPAR, and accepted at the biannual assembly in 2008 as part of COSPAR's policy by the Panel on Planetary Protection and the COSPAR Bureau and Council.

Appendix B - Planetary Protection and Human Exploration Literature Review

KEY:												
Green text = Document read/categorized		Yellow text = Document read/not categorized										
Red text = Document identified but unable to obtain												
ID	Title	Primary Author	Date	Overview Description	Bio Assays		Limiting		Environment		Location	Detailed Notes
					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface		
1	COSPAR Planetary Protection Policy, 20 Oct 2002, as amended 24 Mar 2011	COSPAR	2011	The official source of COSPAR Planetary Protection Policy applicable to robotic and human missions including general principles specifically relevant to mission planning and implementation as well as operating guidelines.				X			http://science.nasa.gov/media/medialibrary/2012/05/04/COSPAR_Planetary_Protection_Policy_v3-24-11.pdf	The policy provides the general, high-level framework for a requirements set (level 0 concerns), specifically with respect to operations.
2	Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface	National Research Council	2002	Investigates the hazards and associated risks likely encountered by the first human visitors to Mars. Recommends precursor measurements, if any, to be made prior to the first human mission. While investigates back contamination, does not address forward contamination.				X			http://www.nap.edu/openbook.php?record_id=10360&page=1	Chapter 5 lists potential hazards of the biological environment. Document provides good listing of potential investigations, but few of PP relevance in sections other than Ch. 5. Chapter 5 suggests establishing zones of minimal biological risk for exploration and taking organic measurements in-situ for establishing the zones. This could be considered a suggested requirement.
3	Planetary Protection Issues in the Human Exploration of Mars	Criswell, M.E., Race, M.S., Rummel, J. D., Baker, A.	2005	Frequently referred to as the "Pingree Park Report", this paper summarizes the results of five main working groups focusing on protecting against forward and back contamination while also protecting astronaut health. The result of the workshop was a detailed listing of recommendations including needed areas of future research. MUST READ!				X			http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050245096_2005249425.pdf	This is a very detailed report which can serve as a basis for future workshops. There is extensive focus on operations and listings of further areas of study/technology development. Much of the content may be leveraged for draft requirements.
4	Life Support and Habitation and Planetary Protection Workshop Final Report	Fisher, J.W., Hogan, J.A., Joshi, J.A., et. al.	2006	Final report documenting the potential influence of Planetary Protection policies on activities in the Advanced Life Support (ALS), Advanced Extravehicular Activity (AEVA), and Advanced Environmental Monitoring and Control (AEMC) communities. MUST READ!	X	X	X	X	X	X	http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060026298_2006228311.pdf	Each community was asked to define top-level planetary protection concerns associated with forward and back contamination and the effects on their hardware. Additionally, each team identified PP requirements that are needed, methods of reducing risk in system development prior to full PP policy development, and identifying important research areas and technology gaps to better system ability to meet PP needs.
5	The Need for Integrating Planetary Protection Science and Technology Into Mars and Lunar Human Exploration Planning	Conley, C. & Race, M. S.	2007	Points to 5 workshops/references that address Planetary Protection related R&D needs. Essentially a high-level (abstract) literature review.		X	X	X	X		http://www.jpi.usra.edu/meetings/7thmars2007/pdf/3172.pdf	A total of six targeted planetary protection areas of investigation are identified, including: life support systems, environmental monitoring, sample collection protocols, cross-contamination investigations, waste disposal, and spacesuit/hardware cleaning & repair.
6	Planetary Protection and Human Mars Exploration: Precursor and Analogue Studies	Rummel, J. D.	2005	Call for exercising planetary protection technologies and operations in a lunar and/or Earth analog environment. A provided table outlines recommendations for future human Mars missions.			X	X		X	http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-05-A1.7.06	A pre-Constellation document suggesting the use of the lunar and Earth analog environments to evaluate; habitats, EVA systems, exploration tools & ISRU and robotic precursor operations. Suggests investigating contamination of lunar environment from Apollo and the effectiveness of planetary protection requirements through Earth analogs. The provided Table could be utilized as a draft requirement set for human missions.
7	Progressive Protocol for Planetary Protection During Joint Human and Robotic Exploration of Mars	Sherwood, Brent	2004	Explores the paradox of needing human exploration to investigate viable Mars environments while such environments may easily be contaminated by human exploration. Lays out a progressive exploration plan that hinges on the axiom (to be proven) that Mars dust is naturally sterile and biologically inert and extensively leverages the use of human and robotic systems working together.				X		X	http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-04-IAA.3.7.2.10	Further investigates 8 issues that lead to the dilemma of using humans to explore Mars' microbiological past and 4 scenarios that could affect how exploration would be conducted. The paper goes further to suggest a zonation approach to characterize distinct environmental zones on Mars and their ability to harbor/sterilize life and then progressively explore these zones; "clearing" them incrementally for human exploration.
8	Planetary Protection Technologies at the Jet Propulsion Laboratory	Basic, C., Kern, R., Rohatgi, N., Koukol, R., et. al.	2000	Status report of technologies and methodologies used at JPL to determine biological cleanliness (assay methods) and provide cleaning and sterilization. Also provides insight into JPL PP approaches.	X	X	X				http://arc.aiaa.org/doi/pdf/10.2514/6.2000-5303	Investigates 4 main areas of PP technology development: bioburden reduction, validation (determining decontamination effectiveness), archiving the biological history of spacecraft, and providing maintenance (minimizing cross/re-contamination). Due to the desire to increase the speed of bioburden assessment & cleaning for spacecraft assembly, some of these approaches may warrant investigation for human mission bioburden quantification & monitoring.
9	Planetary Protection Considerations for Future Human Missions to Mars	Race, Margaret	2004	Brief, high-level paper outlining the top planetary protection issues and risks for future human Mars exploration. Focus on site classification, infrastructure/base operations, and R&D needs to pave the way for human exploration.			X	X			http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-04-IAA.3.7.2.06	Paper is very-high level and touches on similar key concerns represented in other papers; considering operational zones, careful site planning, human and robotic interaction, and R&D in venting, filtration, and detection and monitoring systems.
10	Advanced Planetary Protection Technologies for the Proposed Future Mission Set	Spry, James A.	2013	A thorough overview of planetary protection concerns including regulatory framework, current constraints and consideration for future missions. Focus is given to the applicability of new monitoring technologies.	X	X	X				http://arc.aiaa.org/doi/pdf/10.2514/6.2013-3347	Paper obtained from author. New technologies of particular interest to planetary protection are addressed in section VI, specifically DNA sequencing for microbial identification and use of vapor hydrogen peroxide sterilization techniques.

ID	Title	Primary Author	Date	Overview Description	Bio Assays		Limiting		Environment		Location	Detailed Notes
					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface		
11	What Should We Know, and When Can We Know It? Planetary Protection Precursors (Lunar and Elsewhere) to Human Mars Exploration	Rummel, J. D.	2004	Call for the use of a lunar exploration program to conduct chemical and microbiological studies on the impact of terrestrial contamination (both from Apollo and future missions). Stresses the need for robotic precursor missions to address PP concerns.				X			http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-04-G.6.05	A pre-Constellation document suggesting the use of the lunar environment to evaluate the effects of terrestrial contamination. Also calls for the development of a reliable field-capability to distinguish potential martian life-forms from Earth-originated contamination. Summarizes results of Pingree Park conference and provides a high-level PP exploration roadmap assuming a lunar campaign.
12	Planetary Protection as a Crosscutting Consideration in Human Missions and Technologies Beyond Low Earth Orbit	Race, M.S., Rummel, J. D., Conley, C. A., & Stabekis, P. D.	2011	Discusses planetary protection policy in the context of human missions beyond low Earth orbit with particular attention on key research studies and concerns as well as technology development needs.	X	X	X			X	http://arc.aiaa.org/doi/abs/10.2514/6.2011-5093	A good overview summary of needed studies and technologies for implementing planetary protection for human missions. Provides direct reference to COSPAR policy regarding human missions and makes a call for integrating with the development community and use of the lunar environment for testing PP protocols. Paper obtained from author. MUST READ.
13	Planetary Protection and Humans on Mars: NASA/ESA Workshop Results	Race, Margaret, et. al.	2008	Summarization of the 2005 Joint NASA/ESA workshop on planetary protection for human missions. Includes recommended requirements, studies, and needed technologies for human missions. MUST READ!	X	X	X	X	X	X	http://elib.dlr.de/57548/	Link is to abstract only - full document acquired as pdf. This summary includes actual presentations in the appendix. Overall the document seems to differ only slightly from the previous workshops (Pingree Park & Life Support & Habitation) in content. Suggested read so as to ensure future workshops progress the agenda of PP & HSF.
14	IAA Protecting the Environment of Celestial Bodies: IAA Report 2010	Hofmann, Rettberg, Williams	2010								http://iaaweb.org/iaa/Scientific%20Activity/Study%20Groups/SG%20Commission%205/sg56/sg56finaldraftreport.pdf	
15	ISECG (International Space Exploration Coordinating Group) Global Exploration Roadmap 2013	ISECG	2013	International roadmap identifying goals, long-range human exploration strategy, and suggested coordination of preparatory activities as shared by participating countries.							http://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/GER_2013.pdf	While the search for life is identified as a primary goal and repeated mention of the role of robotic precursor missions, no direct mention of planetary protection is made. The suggestion of human-assisted sample return is made without focus on PP concerns.
16	Strategy Knowledge Gap Summary Table	NASA	2013	A summarizing table of key knowledge gaps (research areas) for Moon, Mars, NEO, Mars vicinity, and Lunar vicinity exploration.	X					X	http://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/SKGs-Summary-Table-Final-for-Posting.pdf	The table identifies 2 key knowledge gaps regarding PP; forward and back contamination with respect to Mars exploration. There are several other knowledge gaps that may be of interest to the PP community, such as environmental modeling, dust characterization, etc.
17	The Global Exploration Strategy: The Framework for Coordination	ISECG	2007	Provides the strategy for global coordination in space exploration. No direct references to planetary protection.							http://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/Global-Exploration-Strategy-framework-for-coordination.pdf	While no direct mention of planetary protection, the framework does identify the globally shared goal of understanding the origins of life. Also makes mention of the need to coordinate international legal agreements, perhaps through this forum. Frequent mention of the interest in subsurface drilling for life detection activities.
18	Planetary Protection for Humans in Space: Mars and the Moon	Conley, C. & Rummel, J.	2008	An overview of Planetary Protection concerns for human exploration and some considerations for implementation in terms of operational constraints and guidelines and the suggestion of testbeds for PP technology development (Moon & Earth analogs).				X			http://www.sciencedirect.com/science/article/pii/S0094576508001240	A high-level PP overview based on workshop results up to the publication's date (2008). Re-iteration of some key operational constraints (i.e., robotic investigation preceding human exploration), needed technologies (closed-loop ECLS). No significant "new knowledge/approaches" compared to other publications.
19	Impact of Planetary Protection Requirements on the Manned Mars Mission Design: A Quick Literature Survey	Heidman, Richard	2003	Provides a high-level summary of open areas for development/investigation with respect to PP for human missions. Key areas addressed: technical fields needing development, biological monitoring, decontamination/sterilization, ECLS, EVA, ISRU and subsurface drilling.	X	X	X	X			Obtained internally via Andy Spry/JPL	
20	Using Artificial Life to Assess the Typicality of Terrestrial Life: Implications for Human Mission Planetary Protection	Lupisella, Mark	2001	An abstract that calls upon the use of artificial life in a large number of open-ended simulations with a minimal set of life defining characteristics to determine if terrestrial life is representative of life in general.	X						http://ntrs.nasa.gov/search.jsp?R=20010029454&terms=planetary+protection+human&q=N%3D0%26Ntk%3DTitle%26Ntt%3Dplanetary%2520protection%2520human%26Ntx%3Dmode%2520matchall	No indications of an actual study taking place or complete paper on the topic - need to check with author. The goal is to use artificial life to assess the extent to which terrestrial life is representative of biological phenomena in general.
21	Planetary Protection Issues and Human Exploration of Mars	DeVincenzi, D. L.	1991	Abstract summarizing proceedings of a workshop (full report is Item#30 in this survey). States workshop ground-rules adopted and a PP strategy for precursor missions.				X			http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920004437_1992004437.pdf	States that precursor information should precede human missions, returned samples should initially be considered hazardous, deposition of Earth microbes on Mars is inevitable with human missions, and human missions are unlikely until Mars materials are deemed non-hazardous. Suggests the strategy that all Mars orbiters will have Observer-like PP controls and all landers will have Viking-like controls and that all sample return missions will have hardware sterilization, bioshield, fail-safe sample sealing, broken surface contact chain, and Earth containment and quarantine analysis.
22	Planetary Protection Issues in Advance of Human Exploration of Mars	McKay, C.P. & Davis, W.L.	1989	Paper considers the planetary quarantine issues associated with establishing a human base on Mars and the role precursor missions can play in contributing to the database required for decisions regarding planetary protection.				X		X	http://www.sciencedirect.com/science/article/pii/0273117789902305#	Compares the planetary protection challenges of human exploration to Mars to the measures employed for lunar exploration during Apollo. Paper is a high-level overview of the issues posed by human missions and the information required from robotic precursor missions.

ID	Title	Primary Author	Date	Overview Description	Bio Assays		Limiting		Environment		Location	Detailed Notes
					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface		
23	Planetary Protection for Human Exploration of Mars	Conley, C. & Rummel, J.	2010	High-level introduction of planetary protection implementation guidelines for human missions as gathered by consensus over the course of a series of international workshops (~2003-2009).				X			http://www.sciencedirect.com/science/article/pii/S0094576509004317	Only touches high-level notional requirements stemming from international workshops. Focus is more on common assumptions regarding planetary protection policy for human missions. Most requirements suggested are operational in nature.
24	Planetary Protection for Life Support and Habitation Systems	Barta, D.J. & Hogan, J.A.	2010	Abstract only - did not have full document. States that planetary protection will impose requirements that have yet to be considered by those developing life support and habitation technologies.			X	X				Does not contain substantive input/details other than listing that operations, processes, and functions will be affected by the imposition of planetary protection requirements. It does suggest that compliance with such requirements may drive the development of new capabilities.
25	Rapid Biochemical Analysis on the International Space Station (ISS): Preparing for Human Exploration of the Moon and Mars	Maule, J., et. al.	2009	Abstract detailing the Lab-on-a-Chip Application Development Portable Test System (LOCAD-PTS) used to conduct 55 tests on the ISS to identify endotoxins using a Limulus Amebocyte Lysate (LAL) assay. LOCAD-PTS is hand-held and produces assay results in less than 20 minutes compared to the typical 3-5 days.	X	X					http://ntrs.nasa.gov/search.jsp?R=20090008540&hterms=Planetary+Protection+Human+Exploration&q=Nm%3D17%7CCollection%7CNACA%7C%7C123%7CCollection%7CNASA%2520STI%26Ntx%3Dmode%2520match%26Ntk%3DAll%26N%3D0%26No%3D10%26Ntt%3DPlanetary%2520Protection%2520for%2520Human%2520Exploration	The LOCAD-PTS uses cartridges and a pipette with several clean/sterilized swabbing kits. The LAL assay triggers generation of a yellow colored dye (p-nitroaniline) which is then measured to provide an LED reading that ranges from 0.05 Endotoxin Units (EU/ml) to 5 EU/ml.
26	In Situ Biological Contamination Studies of the Moon: Implications for Future Planetary Protection and Life Detection Missions	Glavin, D.P., Dworkin, J.P., Lupisella, M., Kmínek, G. & Rummel, J.D.	2010	Suggests in situ investigations on the lunar surface to assess contamination from the Apollo missions which may serve as a contamination baseline for future human missions.	X			X			http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/2010036597_2010034233.pdf	The paper is very much lunar focused and contains some interesting insight into Apollo sterilization methodologies. Its general premise is to "ground truth" data for Mars sample return and help define planetary protection requirements for human missions using the moon as a precursor.
27	Teleoperation from Mars Orbit: A proposal for Human Exploration	Landis, G.	2005								http://ntrs.nasa.gov/search.jsp?R=20050203988&hterms=Planetary+Protection+Human+Exploration&q=Nm%3D17%7CCollection%7CNACA%7C%7C123%7CCollection%7CNASA%2520STI%26Ntx%3Dmode%2520match%26Ntk%3DAll%26N%3D0%26No%3D10%26Ntt%3DPlanetary%2520Protection%2520for%2520Human%2520Exploration	Have abstract only.
28	Influence of Planetary Protection Guidelines on Waste Management Operations	Hogan, J., et. al.	2005	An abstract for what appears to be the conference leading to the Life Support and Habitation and Planetary Protection Workshop Final Report. States the concern that wastes left on Mars are a reservoir of live/dead organisms which can confound exobiology research if not controlled and/or properly contained.				X	X		http://ntrs.nasa.gov/search.jsp?R=20050157855&hterms=Planetary+Protection+Human+Exploration&q=Nm%3D17%7CCollection%7CNACA%7C%7C123%7CCollection%7CNASA%2520STI%26Ntx%3Dmode%2520match%26Ntk%3DAll%26N%3D0%26No%3D10%26Ntt%3DPlanetary%2520Protection%2520for%2520Human%2520Exploration	Appears to be an abstract for the Life Support and Habitation and Planetary Protection Workshop (see final report referenced earlier in this literature survey).
29	Critical Issues in Connection with Human Missions to Mars: Protection of and from the Martian Environment.	Horneck, G.	2004								http://ntrs.nasa.gov/search.jsp?R=20040103023&hterms=Planetary+Protection+Human+Exploration&q=Nm%3D17%7CCollection%7CNACA%7C%7C123%7CCollection%7CNASA%2520STI%26Ntx%3Dmode%2520match%26Ntk%3DAll%26N%3D0%26No%3D10%26Ntt%3DPlanetary%2520Protection%2520for%2520Human%2520Exploration	Have abstract only.
30	Planetary Protection Issues and Future Mars Missions	DeVincenzi, D. L., et. al.	1991	Results from a 1990 workshop listing recommended interim guidelines for planetary protection requirements for the Space Exploration Initiative (SEI) human missions to Mars in addition to providing an extensive literature listing in the bibliography.				X		X	http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19940029027_1994029027.pdf	Appears to be the first significant "workshop" on the human exploration of Mars and planetary protection. The summary recommendations (p. 36) and following bibliography provide a wealth of information regarding potential requirements, studies, and needed technologies.
31	Planetary Protection Issues Related to Human Missions to Mars	Debus, A. & Arnould J.	2008								http://www.sciencedirect.com/science/article/pii/S0273117707010290	"Free" article for download unavailable.
32	Synergistic Approach of Asteroid Exploitation and Planetary Protection	Sanchez, J.P. & McInnes, C.R.	2012								http://strathprints.strath.ac.uk/36476/1/Sanchez_JP_McInnes_CR_Pure_Synergistic_approach_to_asteroid_exploitation_and_planetary_protection_Nov_2011.pdf	
33	Scientific Field Training for Human Planetary Exploration	Lim, D.S.S., et. al.	2010	Paper outlines suggested approach for future crew training utilizing four Learning Design Principles (LDPs) focusing predominately on the use of field science exercises as a training tool.				X			http://www.sciencedirect.com/science/article/pii/S00320631000070X	No direct mention of planetary protection, however describes an effective training paradigm that could be applied to train a crew member designated with planetary protection/astrobiology responsibilities.
34	Reducing Biological Contamination by a Space Suited Astronaut: Laboratory and Field Test Results from Aouda. X	Groemer, Gernot, et. al.	2011								http://www.sciencedirect.com/science/article/pii/S0094576510003061	"Free" article for download unavailable.
35	Space Microbiology: Planetary Protection, Burden, Diversity and Significance of Spacecraft Associated Microbes	Bruckner, J. et. al.	2009								http://www.sciencedirect.com/science/article/pii/B9780123739445002935	"Free" article for download unavailable.
36	Don't Leave Home Without It: Planetary Protection for Robotic and Human Missions	Conley, C. & Billings, L.	2008	Provides a historical introduction into planetary protection policy and its current evolution towards measures for human missions including some high-level constraints that should be considered for human missions.				X			http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4526252	Re-identifies some very high-level notional requirements to be considered for human missions.
37	Impact of Planetary Protection on Environmental Characterization and Hazards Mitigation Technologies	Race, M. S.	2008	An overview of planetary protection policies with discussion of the implications for hardware design of environmental monitoring and control technologies. Posed as key risks and proposed (high-level) solutions as well as drafted requirements and R&D needs.	X	X	X	X	X	X	http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4526253	Excellent paper detailing high-level policy, considerations for forward and back contamination as well as astronaut protection, and detailed tables listing biohazard risks and solutions associated with each of the contamination concerns. The overall recommendations in Section 7 categorize potential requirements and recommendations for future research & technology development.

ID	Title	Primary Author	Date	Overview Description	Bio Assays		Limiting		Environment		Location	Detailed Notes
					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface		
38	Techniques for Estimation of Biological Contamination on Insulators Using Image Analysis	Dernfalk, A. D. & Gubanski, S. M.	2004	An overview of a digital image analysis technique to characterize biological contamination. This technique, however, is demonstrated on biological growth (fungal) on electrical insulators and likely not applicable.	X						http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1364336	Largely not applicable to spaceflight except for gross biological contamination (visable growth).
39	Technical Challenges in Meeting the Next Decade's Planetary Protection Requirements	Rummel, J. D.	2005	This paper takes a strategic look at future NASA missions (primarily beyond Mars and robotic) and the needed technologies to better implement planetary protection measures.			X				http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1559318	Table 1 in this publication provides a very extensive listing of required technology developments for planetary protection. While they are single-bullet listings and focused on future robotic missions (primarily icy moons), many are also relevant to human spaceflight missions.
40	Tools for Assessing Planetary Protection Implementation Strategies	Kastner, J., Beaudet, R. A., et. al.	2007	Outlines the development of software tools (and specifically the Planetary Protection Cost and Risk Analysis Tool - PaCRAT) at JPL for identifying the PP approach best suited to the mission architecture. Although this is written in context of robotic missions, a similar tool(s) for human missions may be useful.	X				X		http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4161297	Covers the development of the PaCRAT PP analysis tool which is meant to identify the most cost effective PP approaches to support a given mission architecture. It is built off of 3 tools: Contamination Likelihood Assessment (CoLA), Contamination Reduction Cost Estimation Tool (CoRCET), and the Contamination and Validation (CAVA) task. PaCRAT is envisioned as modular and still under development.
41	Plasma Decontamination of Space Equipment Using Cold Atmospheric Plasmas	Thomas, H. M., Shimizu, S., et. al.	2012	Indicates the German Space Agency (via DLR) is conducting a study investigating cold atmospheric plasma (CAP) as an alternative spacecraft decontamination strategy to the current "Viking" dry heat sterilization standard.			X				http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6384102	Results of the study are not included in this abstract, but it suggests that sterilization can occur in seconds/minutes and may be able to conform to odd shapes & surfaces. The surface materials subjected to treatment are analyzed for etching and deposition.
42	Robotic Sensor Agents: A New Generation of Intelligent Agents for Complex Environment Monitoring	Petriu, E. M., Whalen, T.E., et. al.	2004	Provides an introduction to intelligent, autonomous Robotic Sensor Agents (RSAs) for conducting complex environmental monitoring as developed at the University of Ottawa.				X	X		http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1337913	This paper is strongly focused on autonomous and semi-autonomous robotic assets for assessing a surrounding environment. While not directly relevant to planetary protection, such technology could be a platform for future robotic missions.
43	Microbioengineering: Microbe Capture and Detection	Powers, L., Lloyd, C., et. al.	2001	States that a microbe capture technology exists to detect very low levels (~20 cells/sq cm) of infectious bacteria within minutes using a handheld prototype detector and microbe capture chips.	X	X					http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1019739	Details are vague as no specific technology is identified in this abstract. It claims the technology is "based on molecular recognition and pathogenesis using iron acquisition and eukaryotic receptor adhesion strategies...using a pattern recognition algorithm for pathogen identification".
44	Planetary Protection Technologies: Technical Challenges for Mars Exploration	Buxbaum, K. L.	2005	Investigates some of the potential planetary technologies that may be most advantageous to upcoming robotic exploration missions. Four major areas are investigated; prelaunch/operations technologies, launched hardware, sample handling systems, and further research required to inform future technologies.	X	X	X		X		http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1559320	While written in the context of robotic spaceflight, several of the areas of technological interest may be applicable to human spaceflight. There is particular focus on the areas of forward contamination control with respect to cleaning & sterilization and to performing microbiological assays. Many of the sterilization activities are not applicable to human missions other than tools and robotic scouting equipment.
45	Surviving the Limits to Life at the Surface of Mars	Clark, Benton C.	1998	A detailed report addressing both knowns and unknowns of the Mars surface environment and how it affects the prospect for extant life on Mars or in martian material.					X		http://onlinelibrary.wiley.com/doi/10.1029/98JE02081/pdf	Very little that may be applied to future requirements, but good, highly technical summary of the challenges faced for microbial survivability on the Mars surface and the prospects of those challenges being overcome by biota.
46	Habitability of the Phoenix Landing Site	Stoker, Carol R., Zent, Aaron, et. al.	2010								http://onlinelibrary.wiley.com/doi/10.1029/98JE02081/pdf	
47	Humans and Robots Collaborating in the Search for Life Beyond Earth	Allen, Carl, McKay, David	2001	A call for the need to use robotics for further astrobiological exploration and their role with human exploration. Articulates the biological risk in the search for life and the mitigation that robotics affords.			X				http://arc.aiaa.org/doi/pdf/10.2514/6.2001-4772	A very high-level document with focus on major exploration destinations (Moon, Mars, Europa and the atmospheres of extra solar planets) and the role of robotics in site characterization and sample preparation.
48	Destruction of Chemical and Biological Warfare Agents using a Steam-Plasma	Farrar, L. Haack, D., et. al.	1999	Study that investigates the use of a steam-plasma with hydroxyl radicals and ultraviolet radiation to kill simulated biological and chemical agents.			X				http://arc.aiaa.org/doi/pdf/10.2514/6.1999-3540	Technology is more applicable to spacecraft and robotic sterilization. Unlikely the methods & technology is applicable to human spaceflight unless an approach is taken to sterilize surface regions before/after human exploration. Relies heavily on use of water.
49	Biological Burden Estimation of Mars Probes and Capsules and a Method of Burden Control	Botan, E., Gautraud, J. A., et. al.	1966								http://arc.aiaa.org/doi/pdf/10.2514/6.1966-2054	
50	Human Support for Mars Exploration: Issues and Approaches	Gross, Anthony R., Harper, Lynn D., et. al.	1992								http://ntrs.nasa.gov/search.jsp?R=19930028080	Need to attempt access via Library/NTRS.
51	Expanding Options for Implementing Planetary Protection During Human Space Exploration and Robotic Precursor Mission	Conley, C., et. al.	2013	Interim report prepared for the International Academy of Astronautics to address areas of further research and technology development for planetary protection with respect to human missions & robotic precursors and the plan to study them.			X	X				A high-level study plan for how additional research areas and needs for planetary protection technology development will be identified. Provides an overview of COSPAR human mission guidelines, technology areas of interest, and the forward process for conducting studies & collecting information.
52	Overview of Current Capabilities and Research and Technology Developments for Planetary Protection	Frick, Andreas, Mogul, Rakesh, et. al.										
53	Technologies for Outer Planet Missions: A Companion to the Outer Planet Assessment Group (OPAG) Strategic Exploration White Paper	Beauchamp, Patricia	2009	Paper is focused on technology needs for exploration of the outer planets and their moons. Planetary protection needs are one of the technology areas listed.			X				http://www.psi.edu/sites/default/files/imported/about/staff/sykes/sbag/roadmap/OPAG_Tech.pdf	Section 3.4 focuses on planetary protection technologies for outer planet exploration. The section does not delve into much detail beyond that PP considerations should be made early and elimination of re-contamination should be investigated.

ID	Title	Primary Author	Date	Overview Description	Bio Assays		Limiting		Environment		Location	Detailed Notes	
					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface			
54	Assessment of Planetary Protection and Contamination Control Technologies for Future Planetary Science Missions	Conley, C., Stabekis, P., et. al.	2012	An assessment of upcoming robotic missions and supporting planetary protection technologies provided as an update from an earlier 2005 assessment.	X	X	X		X	X		No focus on human missions, but some of the technologies and assay approaches are relevant to human spaceflight.	
55	When Biospheres Collide: A History of NASA's Planetary Protection Programs	Meltzer, Michael	2011								Obtained from NASA History Office		
56	In-Space Sterilization for Safe Early Demonstration of Control of Back Contamination	Clark, Benton C.	2003	This paper calls for a demonstration of in-space sterilization methodologies to assess their effectiveness in controlling back contamination.			X	X	X		http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-03-Q.3.b.02	Paper explores the concern of back-contamination assuming assured sample containment has already occurred. Written from the perspective of Mars sample return, many of the suggestions could be applicable to human missions and treatment of science samples gathered by future crews. The author calls for an in-space demonstration and suggests close investigation of dry heat and ionizing (radiation) methods in-situ.	
57	Astrobiological Exploration and Human Missions: First Steps	Rummel, J. D.	2006	Short paper on the use of the moon and Earth analogs as a testbed for astrobiological exploration with human crews.				X			http://arc.aiaa.org/doi/pdf/10.2514/6.IAC-06-A1.6.08	Paper is fairly generalized and high-level. One interesting suggestion is to measure lunar contamination from Apollo to gauge microbial survivability.	
58	The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities	Hoffman, S. J., Ed.	2001								http://ston.jsc.nasa.gov/collections/TRS/techrep/TP-2001-209371.pdf		
59	Human Exploration of Mars Design Reference Architecture 5.0	Drake, B. G.	2009	Outlines the mission design for a human Mars mission, largely based on the Constellation architecture (Ares V & Orion). One slide references planetary protection concerns (slide 28).				X			http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090012109_2009010520.pdf	Provides a good overview of the human Mars exploration concept. Key architectural areas of concern to PP will be use of ISRU, robotic/human interaction in assessment of 'special regions', extensive use of composite materials (outgas concerns?), surface nuclear power, and in-situ science characterization.	
60	Mars Design Reference Architecture 5.0 Study Executive Summary	Drake, B. G.	2008	Deeper mission design details than the Human Exploration of Mars Design Reference Architecture 5.0 document, but with little reference to planetary protection.	N/A							http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090010571_2009009101.pdf	Increased detail over previous document regarding mission design, system sizing, trades between nuclear and solar power systems, etc. Of little import to planetary protection at this level.
61	Human Exploration of Mars DRA 5.0 Addendum	Drake, B. G.	2009								http://www.nasa.gov/pdf/373667mainNASA-SP-2009-566-ADD.pdf		
62	Human Exploration of Mars DRA 5.0 Addendum #2	Drake, B. G. & Watts, K. D.	2009								http://www.nasa.gov/sites/default/files/files/NASA-SP-2009-566-ADD2.pdf		
63	A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth	Rummel, J. D., et. al.	2002								http://planetaryprotection.nasa.gov/file_download/10/MSRDraftTestProtocol.pdf		
64	Mars Science Goals, Objectives, Investigations, and Priorities: 2010	Johnson, J. R.	2010								http://mepag.jpl.nasa.gov/reports/MEPAG_Goals_Document_2010_v17.pdf		
65	An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars	Beatty, David W., et. al.	2005								http://mepag.jpl.nasa.gov/reports/MHP_SSG_(06-02-05).pdf		
66	Science Priorities Related to the Organic Contamination of Martian Landers	Mahaffy, P. & Beatty, David W., et. al.	2004								http://mepag.jpl.nasa.gov/reports/OCSSG_final_report_Nov_2004.pdf		
67	Planning for the Scientific Exploration of Mars by Humans	Garvin, James B. & Levine, Joel S., et. al.	2008										
68	Findings of the Mars Special Regions Science Analysis Group	MEPAG SR-SAG	2006								http://mepag.jpl.nasa.gov/reports/ast_2006_6_677.pdf		
69	Astrobiology and the Human Exploration of Mars	Levine, J.S., Garvin, J. B., et. al.	2010	Summarizes the key areas of astrobiological investigation as identified per Mars DRA 5.0 and the NRC "An Astrobiology Strategy for the Exploration of Mars" reports.	N/A							http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100021174_2010022994.pdf	While providing a succinct listing of astrobiology objectives and rationale for human exploration of Mars, little light is shed on potential studies, requirements, or necessary technologies.
70	Joint ESA/NASA Workshop on Planetary Protection & Human System Research and Technology	Kminek, G., Rummel, J. D., & Race, M. S.	2007	Full report of the joint ESA/NASA workshop held in May 2005 at ESA/ESTEC in Noordwijk detailing notional planetary protection implementation guidelines with respect to ALS and EVA systems, including the identification of potential contaminants, contamination pathways, and potential off-nominal events.	X	X	X	X	X	X	http://planetaryprotection.nasa.gov/file_download/56/ESA_NASA_PP_HumansMars2007.pdf	Similar in findings and context to the Life Support and Habitation and Planetary Protection Workshop Final Report (Item #4) and should be considered a complimentary text. Details extensive recommendations in the areas of policy, special regions, operations and crew, waste management, and research and development.	
71	Human Spaceflight Architecture Team (HAT) Destination Operations Team (DOT) FY2013 Final Report	HAT	2013	Document provides an overview of a Mars surface exploration Concept of Operations based on DRA 5.0 architecture. Planetary protection concerns are raised, but little novel recommendations given.				X			Provided by Mars DOT team via Mark Lupisella (no known link)	ConOps generally ascribes to the "zoned" exploration approach, with regions being 'cleared' for human exploration using robotics. Raises the concern of "special region" sample collection with deep drilling (a key objective). Outline of destination ConOps begins slide 74 with key planetary protection findings on slide 139.	
72	Biological Contamination Studies of Lunar Landing Sites: Implications for Future Planetary Protection and Life Detection on the Moon and Mars	Glavin, D. P., et. al.	2004								http://astrobiology.gsfc.nasa.gov/analytical/PDF/Glavinetal2004.pdf		
73	A New Era in Bioastronomy, Proceedings of a Conference held on the Kohala Coast, Hawaii	Treiman, A.H.	2000	Review Link provided 1st to determine if paper may be relevant.							http://adsabs.harvard.edu/full/2000ASPC...213...23M	Reference Bioastronomy '99, Aug. 2-6, 1999, ASP Conference Series 213, 303.	

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					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface		
74	Life on the Edge: Amazing Creatures Thriving in Extreme Environments	Gross, M.	2001								http://books.google.com/books?hl=en&lr=&id=tOiecnXl3eoC&oi=fnd&pg=PR9&dq=Life+on+the+Edge:+Amazing+Creatures+Thriving+in+Extreme+Environments&ots=6S6G4sl4w&sig=EUg_LeWi-3beo1XX1u_rty26C-M/#v=onepage&q=Life%20on%20the%20Edge%3A%20Amazing%20Creatures%20Thriving%20in%20Extreme%20Environments&f=false	e-book available for purchase.
75	Preventing the Forward Contamination of Mars	NRC	2005								www.nap.edu	
76	The Quarantine and Certification of Martian Samples	NRC	2002								www.nap.edu	
77	Biological Contamination of Mars: Issues and Recommendations	NRC	1992								www.nap.edu	
78	Mars Sample Return: Issues and Recommendations	NRC	1997								www.nap.edu	
79	Planning for Mars Sample Return: Design and Implementation Considerations for Handling and Testing Returned Samples	Race, M.S., and Rummel, J.D.	2003								http://papers.sae.org/2003-01-2672/	
80	Planetary Exploration in the Time of Astrobiology: Protecting Against Biological Contamination	Rummel, J.D.	2001	A great introductory read to the history of planetary protection and its chief concerns of protecting against (and minimizing) forward and back contamination. MUST READ.							http://www.pnas.org/content/98/5/2128.full.pdf+html	Contains a listing of open questions regarding returned sample analysis and testing which may also be applicable to human missions. Otherwise, serves as a great historical introduction into "what is planetary protection?".
81	Manned Mars Missions and Planetary Quarantine Considerations	Sharp, J.C.	1986	A quick review of the history of planetary protection, specifically the policy in place prior to COSPAR's categorization approach which utilized a "probability of terrestrial growth" approach. The author states that there are two approaches to human missions; 1) assure 100% containment through technology, 2) accept analytical approaches to enact "best effort".	X						http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19870008333_1987008333.pdf	Good historical background on what led to current COSPAR policy and the differences in implementation between the US & Soviet Union. There's the recurring theme that more needs to be known about the Mars environment and specifically the nature and distribution of Mars soil. A handful of potential study areas were identified and are similar to calls for other studies in other literature.
82	A Brief History of Organic Contamination Monitoring of Lunar Sample Handling	Allton, J. H.	1998	An overview of the potential sources of organic contamination identified in Apollo samples and a review of the contamination control process utilized with Apollo lunar samples.			X	X			http://www.lpi.usra.edu/meetings/LPSC98/pdf/1857.pdf	Provides some additional resources for evaluating (modeling) Apollo contamination of lunar samples. Also states that non-organic flexible sealing materials (and sample bags) are a technology need.
83	Reference Materials Consulted for HAT Destination Operations Team FY13 Mars Long-Stay Surface Mission POD ConOps Analyses	HAT	2013	A listing of references used in the HAT Mars Destination Operations Team Concept of Operations analysis.							List obtained via e-mail from Bette Siegel.	Have added most (not all) documents that appear to be applicable to this literature survey. Could warrant further review if time allows.
84	COSPAR Workshop on Developing a Responsible Environmental Regime for Celestial Bodies	Ehrenfreund, P., Hertzfeld, H., & Howells, K.	2013								http://www.gwu.edu/~spi/assets/docs/PEX_WorkshopReport_ES_March14_Web%20(1).pdf	
85	Toward a Global Space Exploration Program: A Stepping Stone Approach	COSPAR	2010								http://www.gwu.edu/~spi/A%20stepping%20stone%20approach%202011%20.pdf	
86	Field Analysis of Microbial Contamination Using Three Molecular Methods in Parallel	Morris, H., Stimpson, E., Schenk, A., Kish, A., et. al.	2010	A brief validation of contamination cleaning techniques on a Mars rover mock-up using 3 different assay methods. All assays indicate a significant reduction in contamination after rover cleaning.	X	X	X				http://www.ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100021062_2010020420.pdf	A field analysis conducted during the Arctic Mars Analogue Svalbard Expedition (AMASE) 2009 comparing adenosine-triphosphate (ATP), Limulus Amebocyte Lyosate (LAL), and primer-based polymerase chain reaction (PCR) assay methods. All methods demonstrated effective in-field cleaning, but little detail is given on the cleaning protocols enacted.
87	Design Tools for Cost Effective Implementation of Planetary Protection Requirements	Hamlin, L., et. al.	2006	General call for the need of cost analysis and planning tools that allow iteration of mission architecture and planetary protection requirements.							http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/40173/1/05-3851.pdf	Repeatedly states the need to improve upon considering planetary protection concerns early in system design. Suggests the use of cost analysis tools such as CoRCET (Contamination Reduction Cost Estimation Tool), being developed by JPL. Focus dominates on unmanned missions, but such tools could eventually be applicable to human spaceflight.
88	Microbial Monitoring of Spacecraft and Associated Environments	La Duc, M. T., et. al.	2004								http://link.springer.com/article/10.1007/s00248-003-1012-0#	"Free" article for download unavailable.
89	Thermal Resistance of Naturally Occurring Airborne Bacterial Spores	Puleo, J. R., et. al.	1978								http://aem.asm.org/content/36/3/473.full.pdf	
90	Method for Collecting Naturally Airborne Bacterial Spores for Determining their Thermal Resistance	Puleo, J. R., et. al.	1975								http://aem.asm.org/content/30/5/786.full.pdf	
91	Planetary Protection Issues in the Human Exploration of Mars (SAE Paper 2003-01-2523)	Race, M. S., Criswell, M. E., & Rummel, J. D.	2003	A summarization of the findings of the Pingree Park report (Item #3) in an abridged format. Excellent overview of the top concerns for human exploration with respect to PP as collected through a multi-day workshop. MUST READ!				X			www.sae.com - ICES Paper 2003-01-2523	Full paper provided by J. Rummel. An excellent (and suggested) alternative to reading the full Pingree Park report as it summarizes the key findings and details.
92	Biosafety in Microbiological and Biomedical Laboratories	CDC	1999								http://stacks.cdc.gov/view/cdc/5564/	
93	Microbiological Profiles of the Viking Spacecraft	Puleo, J. R., et. al.	1977								http://aem.asm.org/content/33/2/379.full.pdf	

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					Quantification	Monitoring	Technologies	Operations	Spacecraft	Surface		
94	<i>Mars Sample Handling Protocol Workshop Series, Workshop 4 Final Report</i>	Race, M. S., DeVincenzi, D. L., Rummel, J. D., & Acevedo, S. E.	2002								http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20060022638_2006007611.pdf	
95	<i>A Method for Assessing the Level of Microbial Contamination in Surgical Materials</i>	Keall, A.	1973	Short paper on a contamination analysis method especially useful for cellulosic materials. Method utilizes a small plastic pouch with a "rinsing agent" that is then massaged before extraction of the agent for analysis.	X	X					http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2672.1973.tb04070.x/pdf	Likely a method of minimal use to planetary protection. Perhaps beneficial in measuring contamination of soft good materials?
96	<i>Planetary Protection and Contamination Control Technologies for Future Space Science Missions</i>	Belz, A., et. al.	2005								http://solarsystem.nasa.gov/docs/D-31974%20Technology%20Report%20PP-CC-final-8-2005.pdf	
97	<i>Microbial Contamination of Spacecraft</i>	Pierson, D. L.	2001	Brief summary of assessing microbiological contamination of shuttle, Mir, and initial measurements from ISS. Some key findings include increases in the microbial population as the mission duration increases and little change to slight decreases in the fungal contamination with increases in mission duration.	X						http://gravitationalandspacebiology.org/index.php/journal/article/viewFile/261/260	Results are not as in-depth as "Survey of Environmental Biocontamination On Board the International Space Station", but slightly more insight into collection methods and historical analysis on Mir & shuttle. Predominate focus of this paper is with respect to crew health.
98	<i>Isolation and Characterization of Bacteria Capable of Tolerating the Extreme Conditions of Clean Room Environments</i>	LaDuc, M. T., Dekas, A., Osman, S., et. al.	2007								http://aem.asm.org/content/73/8/2600.full.pdf	
99	<i>Microbial Diversity and Its Relationship to Planetary Protection</i>	Crawford, R. L.	2005								http://aem.asm.org/content/71/8/4163.full.pdf+html	
100	<i>Preliminary Analysis of Spacesuit Contamination Vectors during a simulated crewed Mars Surface Expedition</i>	Groemer, G., Sattler, B., & Luger, U.	2011	Short paper on analysis of simulated forward and back contamination on a space suit simulator during the 2011 Rio Tinto analog mission. Results are still pending, but claims the analysis methods are robust for field work.		X		X	X		http://meetings.copernicus.org/epsc-dps2011/abstracts/EPSC-DPS2011-325.pdf	A simulator space suit (Aouda.X) was 'doped' with simulated microspherule contamination as was some soil sample target areas. Contamination was measured before and after EVA activities and identified most contamination remained on the hands and legs and <1% of the original particles remained on the simulated suit.
101	<i>Planetary Protection, Sample Return Missions and Mars Exploration: History, Status, and Future Needs</i>	DeVincenzi, D. L., Race, M. S., & Klein, H. P.	1998	Review of the major issues surrounding planetary protection for a Mars Sample Return (MSR) mission, including an in-depth historical review of planetary protection policy.			X				http://salegos-scar.montana.edu/docs/Planetary%20Protection/JofGeophyResVol103(E12).pdf	Applicable to human missions with respect to sample containment and return to Earth. Presumably, these concerns (studies, requirements & technologies) will be driven by an MSR mission prior to a human mission.
102	<i>Planetary Rover Developments Supporting Mars Exploration, Sample Return and Future Human-Robotic Colonization</i>	Schenker, P. S., Huntsberger, T. L., Pirjanian, P., et. al.	2003								http://www-robotics.jpl.nasa.gov/publications/Terrance_Huntsberger/Huntsberger_SpaceRobotics.pdf	
103	<i>Survey of Environmental Biocontamination On Board the International Space Station</i>	Novikova, N., De Boever, P., Poddubko, S., et. al.	2006	Excellent summary of biological contamination on the ISS. Results from over 500 samples taken over 6 years of surfaces, air, and water in an effort to characterize ISS contamination.	X	X			X		http://www.researchgate.net/publication/7405234_Survey_of_environmental_biocontamination_on_board_the_International_Space_Station/file/9cfd511271e02de1e.pdf	Paper references reports on MIR citing similar contamination results. Summarizing conclusion that surface and water contamination is more abundant than air. All samples were analyzed on the ground and the paper calls for better on-board/in-situ measurement capabilities.
104	<i>Rapid Inactivation of Seven Bacillus spp. Under Simulated Mars UV Irradiation</i>	Schuerger, A. C., Richards, J. T., Newcombe, D. A., et. al.	2006								http://diyhpl.us/~bryan/papers2/diybio/mars_analogue_papers/Schuerger_2006_icaros_B%20subtilis%20on%20Mars.pdf	
105	<i>Assessment of Planetary Protection Requirements for Mars Sample Return Missions</i>	NRC	2009								Obtainable from National Academies Space Studies Board Compilation of Reports (1958-2011)	
106	<i>Preparing for the Human Exploration of Mars: Health Care and Planetary Protection Requirements and Practices</i>	Rummel, J. D., & Conley, C. A.	2012	Paper suggests the need for effective monitoring of astronaut health during a mission in addition to the state of microbial populations within the spacecraft and ability to quantify any detrimental health effects experienced by the crew.	X	X		X			http://planetaryprotection.nasa.gov/file_download/64/Rummel_Conley_2012_IAC_A1.pdf	Paper suggests the close-coupling of monitoring astronaut health and planetary protection in addition to drawing attention to high-level planetary protection requirements as outlined by COSPAR. No significantly specific or new information in this area other than to call attention to the interrelationship of health monitoring & PP.
107	<i>On Mars: Exploration of the Red Planet</i>	Ezell, E. C., & Ezell, L. N.	1984								http://www.hq.nasa.gov/office/pao/History/SP-4212/contents.html	
108	<i>The Planetary Quarantine Program: Origins and Achievements</i>	Phillips, C. R.	1974								http://history.nasa.gov/SP-4902/sp4902.htm	

Appendix C – Planetary Protection Notional Requirements

Developing Planetary Protection Requirements for Human Spaceflight

- The following notional requirements are as obtained from an in-depth literature survey with sources identified. They are divided into four levels of planetary protection: 1) General/administrative requirements, 2) Requirements for protecting from forward contamination, 2) Requirements for the protection of astronaut health, and 3) Requirements protecting from back contamination. The later three areas were identified as the cornerstones of planetary protection with respect to human spaceflight per Criswell, et. al., 2005.
- Note some requirements list “TBD” measurements as the standards by which such a requirement would ascribe to are, as of now, currently undeveloped.

Drafted Requirements:

1. At least one crew member shall be adequately trained and responsible for planetary protection compliance during the course of the mission.^{2,5,6}
2. Planetary protection considerations shall be included in all aspects of human mission design and execution including; planning, training, operational protocols, and mission execution.⁵
3. Spacecraft materials selected for design shall facilitate decontamination (e.g., withstand chemical disinfectants, heat treatment, etc.) as practicable.²
4. Human missions shall assume that Martian life exists and is hazardous until proven otherwise.⁶
5. Forward contamination of Mars from terrestrially-associated microbial contaminants shall be minimized.¹
 - 5.1. Human missions shall not affect or otherwise contaminate “special regions” of Mars.⁶
 - 5.2. Landing sites shall be selected such that nominal and off-nominal operations shall have a low (TBD*) probability of allowing microbial or organic contamination to enter Mars special regions.³ *Note 10^{-4} probability is being used for introducing an Earth microbe to a liquid water body on any icy moon.⁴
 - 5.3. Microbial populations and organic and inorganic inventories of spacecraft contents and materials shall be identified prior to launch and maintained/monitored throughout the mission.^{2,3,4,5,6}
 - 5.4. Waste material left on the Mars surface shall be contained and/or sterilized to TBD levels.^{3,6}
 - 5.5. Spacecraft waste collected during transit to Mars shall be jettisoned as practicable.²

¹ Baker, A., Criswell, M.E., Race, M.S., Rummel, J.D. (Eds.). (2005). *Planetary Protection Issues in the Human Exploration of Mars*. (NASA/CP-2005-213461)

- 5.6. Spacecraft waste jettisoned during transit shall not pose a threat of contamination to Mars or other planetary bodies capable of hosting life.²
- 5.7. Spacecraft vehicle gases vented overboard shall pass through a filter [HEPA].^{2,6}
- 5.8. External off-gassing of spacecraft materials shall be quantified.²
- 5.9. Sub-surface access shall only be conducted using equipment sterilized to TBD.²
- 5.10. A clear TBD separation between the operator and drilling/sub-surface equipment shall be maintained.²
- 5.11. Any planned biological experiments shall exhibit TBD levels of containment.²
- 5.12. Use of local water (including ice) resources shall not be contaminated from terrestrial sources.²
- 5.13. Exploration of special regions, including access to subsurface ice or water, shall be restricted to sterilized clean equipment.³
- 5.14. Robotics shall be utilized to scout and survey intended EVA worksite locations and potential science way-points prior to human intervention.^{2,5,6}
- 5.15. Disposal of uncontained solids or fluids from spacecraft, rovers and habitats shall not be permitted.^{2,6}
- 5.16. Care shall be taken to avoid the creation of hybrid microenvironments where microbes from both Earth and Mars could mix.⁶
- 5.17. Pre-launch cleanroom assembly shall be required of all systems regardless of planned landing site.⁶
- 5.18. For systems landing in or deploying to Special Regions, appropriate quantitative bioburden reduction requirements shall apply.⁶
 - 5.18.1. If mission activities in a Special Region represent the risk of local contamination, current Category Iva levels of cleanliness shall apply.⁶
 - 5.18.2. If mission risks represent the potential for global contamination, current Category IVc requirements shall apply.⁶
- 5.19. Habitats and equipment left on the martian surface shall be decontaminated and/or have any bioburden stabilized.⁶

² Fisher, J. W., Hogan, J. A., Joshi, J. A., Race, M. S., Rummel, J. D. (Eds.) (2006). *Life Support and Habitation and Planetary Protection Workshop Final Report*. (NASA/TM-2006-213485)

³ Conley, C. A. & Rummel, J. D. (Eds.). (2008). *Planetary Protection for humans in Space: Mars and the Moon*. *Acta Astronautica* v.63 1025-1030.

6. Crews shall be protected from direct contact with Martian materials until testing can provide verification that exposure to the material is safe for humans.^{1,3,4,6}
 - 6.1. "Safe Zones" of operation shall be established that are demonstrated to be safe for human exploration.^{5,6}
 - 6.2. A quarantine capability for both the entire crew and for individual crewmembers shall be provided during the mission in the event of uncontrolled contact with a Martian life-form.^{2,3,4,5,6}
7. Back contamination from Mars to Earth shall be minimized and its prevention considered highest priority.^{1,6}
 - 7.1. Space suits used for the surface exploration of Mars shall not enter the return/ascent vehicle.²
 - 7.2. EVA tools used for the surface exploration of Mars shall not enter the return/ascent vehicle.²
 - 7.3. Samples returned by the crew from uncontrolled or otherwise untested areas of Mars shall be considered as potentially hazardous until proven otherwise through a series of tests.^{2,8}
 - 7.4. A quarantine capability and appropriate medical testing shall be provided to the crew after the completion of the mission.^{3,4,5,6}
 - 7.5. Situations, technologies, or operations shall be avoided that would cause crew, support systems, hardware, or returning spacecraft to be exposed to Martian dusts, materials or microbes in ways that would allow them to return to Earth in an uncontained manner.⁶
 - 7.6. Any pristine or sampling components from any uncharacterized sites or special regions shall be treated according to current Category V planetary protection measures with restricted Earth return.⁶
 - 7.6.1. The returning spacecraft shall not be contaminated by Martian dust particles that are not sterilized or sealed within a suitable container.⁷
 - 7.6.2. Sealing surfaces of sample containers shall ensure that no particle 0.2 microns (micrometers) in size or larger can escape [based on smallest conceivable organism].⁷
 - 7.6.3. Samples returned from the Mars surface shall maintain their seal when subjected to TBD stresses.⁷
 - 7.7. Any sterilization methodologies utilized shall be performed under dry and oxygen-free conditions to minimize damage to geochemically delicate specimens.⁷

⁴ Conley, C. A. & Billings, L. (Eds.). (2008). *Don't Leave Home Without It: Planetary Protection for Robotic and Human Missions*.

⁵ Conley, C. A., & Rummel, J. D. (Eds.). (2010). *Planetary Protection for Human Exploration of Mars*. *Acta Astronautica*, v. 66, p. 792-797.

7.8. Samples returned from the Martian surface shall be handled robotically until questions of possible indigenous life and biohazard can be answered.⁸

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⁶ Race, M. S. (Ed.). (2008). *Impact of Planetary Protection on Environmental Characterization and Hazards Mitigation Technologies*.

⁷ Clark, B. C. (Ed.). (2003). *In-Space Sterilization for Safe Early Demonstration of Control of Back Contamination*. IAC-03-Q.3..b.02

⁸ Allen, C. A., & McKay, D.S. (Eds.). (2001). *Humans and Robots Collaborating in the Search for Life Beyond Earth*. AIAA Paper 2001-4772.

Appendix D – Planetary Protection Notional Studies

Notional Planetary Protection/Technology Studies to Inform Human Spaceflight Requirements

Per the conductance of an in-depth literature survey, the following areas of suggested study were identified. The study areas are categorized by three major areas of investigation and six sub areas. Major areas of investigation include biological assays, limiting contamination, and environmental awareness. Those categories are subdivided into biological/bioburden quantification, biota monitoring, technology developments, operational developments, spacecraft environments, and mars surface & subsurface environments respectively. Each notional area of study is paired with a 'need statement' which attempts to capture the driving need for the study. No prioritization has been made with this listing and literature that calls for the study has been referenced.

Biological Assays Study Area:

Biological/Bioburden Quantification:

- Study B1: Develop a contaminant ranking/allowable concentration listing (similar to SMAC – Spacecraft Maximum Allowable Concentrations) to categorize contaminants in accordance to their risk to planetary protection and science investigation. *Need:* Must have the capability to identify the risks posed by different contaminant 'classes' on PP & science.¹
- Study B2: Develop a definition of the term "biosignature" and individual limits for the release of each identified biosignature. *Need:* An agreement by the scientific community needs to be reached to define what is meant by "biosignatures" (e.g., are all volatile organics considered biosignatures?) and what limits will be imposed upon biosignature contaminants.¹
- Study B3: Conduct extremophile research to quantify the microbial hitchhikers that may accompany a deep space mission. *Need:* It is known that there are some microorganisms that are capable of surviving and even thriving in extreme environments. A better understanding of such organisms may yield a list of organisms that should be guarded against in the spacecraft clean rooms associated with future missions.⁵
- Study B4: Develop a catalog of all known possible signatures of life. *Need:* 'Life' can be found in many different forms and conditions. Constructing a catalog of what is considered life will aid in conducting assays for identifying potential martian life and/or characterizing forward contamination.⁸

Biological/biota Monitoring:

Study B5: Evaluation of basic tests to monitor the crew's medical condition and understand their responses to pathogens or adventitious microbes. *Need:* The ability to have a testing regime to determine the crew's susceptibility to pathogenic microbes is considered an important part of crew health monitoring.²

Limiting Contamination Study Area:

Technology-focused Studies for Limiting Contamination:

Study C1: Quantify the level of biological and chemical material released from current concept space suits (Z-1 & Z-2) over the course of nominal traverse operations (predicted). *Need:* Identify an average contamination rate (rate of biological release) from spacesuit operations that could then be used to model surface contamination. The EVA community recommends human space suit chamber tests to determine biological and chemical signature characterizations generated by current suit system venting and leakage using sample tracer elements or markers.¹

Study C2: Identify the potential physical (chemical or biological) impacts that identified spacesuit and ALS leakage constituents would have in regard towards planetary protection forward contamination concerns. *Need:* In order to identify appropriate contamination limits the potential effects on science processes of known contaminants should be identified, studied, and documented.¹

Study C3: Perform analyses of mission scenarios using various Advanced Life Support (ALS) technology suites to comply with predicted requirements. If the calculated costs of plausible solutions are deemed excessive, seek further verification or reexamination of PP and scientific requirements. *Need:* ALS development costs will be highly affected by PP requirements. The ability to analyze various scenarios (nominal and contingency) will enable quick iteration of requirements that are achievable without excessive cost.^{1,5}

Study C4: Develop a level of cleanliness/sterilization required for subsurface/drilling equipment. *Need:* Since sub-surface access is a key objective in future Mars exploration and specifically astrobiology, standards of cleanliness need to be created for all sub-surface exploration equipment.¹

- Study C5:** Identify the impact of planetary protection requirements on the design and operations of ISRU systems. *Need:* In-situ Resource Utilization equipment will likely play a critical role in reducing needed mass to support human missions. A key component of ISRU is the ability to produce water or its constituent gases from a water supply which would likely require strict adherence to planetary protection requirements. This study would identify an appropriate balance between PP requirements and system design.⁵
- Study C6:** Investigate methods of scientific sample containment and in-situ sample canister sterilization to 'break the chain' of contact with the Mars surface (suggested investigation includes a 'dress rehearsal/test'). *Need:* Back-contamination is one of the most significant of planetary protection concerns. This study applies to both robotic missions and human missions and it is suggested that evaluation include use of polymerase chain reaction (PCR) or UV-fluorescent tagged amino acid assays to detect any tell-tale DNA or protein products from terrestrial organisms that are in the sample container.⁷

Operations-focused Studies for Limiting Contamination:

- Study O1:** Define specific surface task activities for EVA that would require the implementation of appropriate planetary protection measures. *Need:* Certain surface activities will dictate different levels of planetary protection (e.g., drilling). The Mars Destination Operations Team (DOT) Operations Concept (dated 11/7/2013) sheds some light on potential surface activities.¹
- Study O2:** Identify the level of microbial spore density and chemical/organic constituents allowable for EVA surface operations. *Need:* Assuming forward contamination is inevitable from EVA activities; establish a baseline for the level of contamination that is acceptable.¹
- Study O3:** Develop acceptable separation limits between sub-surface exploration activities and human operations. *Need:* Since human operations will inevitable create some level of forward contamination, a safe operating perimeter needs to be established between human operations and sub-surface activities to mitigate contamination and confounding results.¹
- Study O4:** Develop an interface/boundary definition between surface and sub-surface environments. *Need:* The zone between surface and sub-surface material is in need of definition (i.e.,

where does it begin, how extensive is it, and where does it end?) with the understanding that this boundary is likely different based upon differences in the Mars environment.¹

- Study O5: Develop a formal zoning classification system for identifying zones of biological, scientific, contamination and operational importance. *Need:* Using a 'zonation' approach will protect more sensitive regions from contamination in addition to keeping the crew safe from potential biological dangers.^{1,3,5}
- Study O6: Develop a policy/approach for the jettison of waste material in deep space and in vicinity of planetary bodies. *Need:* Active and passive jettison of spacecraft waste has potential PP impacts unless a policy is enacted regulating it.¹
- Study O7: Develop operational measures for cleaning. *Need:* Build upon existing hygiene procedures (such as Hazard Analysis and Critical Control Point (HACCP) analyses).¹
- Study O8: Develop a listing of contingency events and associated fault tolerance relative to planetary protection. *Need:* Ability to identify contingencies that pose a risk to planetary protection and categorize the acceptance of those risks.¹
- Study O9: Develop a waste material disposal plan that identifies the required probability of containment failure, duration of containment, characteristics of disposed material (e.g., sterile), and effect of container location and subsurface depth. *Need:* To develop a waste disposal strategy and required technologies, reasonable containment requirements should be identified.¹
- Study O10: Develop a training program/approach for future exploration crews. *Need:* It has been suggested that at least one crewmember on future missions be trained and responsible for compliance of planetary protection guidelines, likely requiring a formal training regimen.¹
- Study O11: Identify human factors considerations with relation to planetary protection and how they might be addressed (e.g., consequences of fatigue and implementing planetary protection protocol). *Need:* Although broad statements have been made that "human factors will need to be considered" for planetary protection, further investigation into what factors are of specific concern, has not been done.^{3,5}

Spacecraft & Mars Surface Environmental Study Area:

Spacecraft Environment/Induced Environment Studies:

- Study S1: Quantify the effects of flash sterilization (e.g., atmospheric re-entry) on microbial survival. *Need:* Identify both a minimal heating level and duration that provides TBD probability of sterilization.¹
- Study S2: Quantify the effects of spacecraft venting (nominal & contingency) on contaminate dispersion on Mars. *Need:* Develop a model/approach to quantifying contaminate release from spacecraft vents and a listing of types of expected contaminants.¹
- Study S3: Quantify the level of contamination associated with the Apollo landings through in-situ measurement. *Need:* To gain an understanding of microbiological survivability in a high-radiation lunar environment.⁶
- Study S4: Identify, based on known parameters, potential human landing sites and exploration zones with a low (TBD) probability of allowing mission-associated microbial or organic contamination to enter a Mars special region. *Need:* Landing sites will likely yield higher amounts of contamination which could be transported to nearby features/zones. Identifying landing sites where the effects of contamination may be minimized will help mitigate forward contamination.²

Mars Surface/Subsurface Environmental Studies:

- Study E1: Quantify the sterilization effects of Mars orbit/upper atmosphere UV radiation. *Need:* Identify exposure criteria to provide a TBD level of sterilization (specifying the D value).¹
- Study E2: Quantify the sterilization effects of Mars surface UV radiation, thermal environment, and pressure. *Need:* Identify exposure criteria to provide a TBD level of sterilization (specifying the D value).¹
- Study E3: Quantify the effects of wind dispersion of forward contamination on the surface of Mars through modeling. *Need:* Develop an understanding of how Mars wind might transport &

¹ Fisher, J. W., Hogan, J. A., Joshi, J. A., Race, M. S., Rummel, J. D. (Eds.) (2006). *Life Support and Habitation and Planetary Protection Workshop Final Report*. (NASA/TM-2006-213485)

dilute forward contamination so it can be modeled to identify appropriate exploration zones.^{1,2,5}

- Study E4:** Characterize the properties of Martian dust. *Need:* Develop an understanding of the dust's potential for back contamination, general nuisance properties, and in-situ sterilization capabilities (if any).¹
- Study E5:** Develop experiments that challenge Earth organisms with simulated Mars environmental conditions. *Need:* In an effort to quantify the effects of Martian dust and its inevitable ingestion into a Mars habitat, studies should investigate the effects of the Mars environment on Earth organisms.^{1,4,5}
- Study E6:** Identify probable biological targets in the Martian environment by looking at what types of organisms would be likely to exist and survive in the Martian environment, based on terrestrial studies. *Need:* In an attempt to hone and design the capability of identifying extraterrestrial life, we should create a solid understanding of what biological forms could currently survive in a Martian environment as we know it.^{1,4,5}
- Study E7:** Quantify the characteristics of a Mars 'special region'. Current verbal definitions state "any region on Mars that may reach both a minimum temperature of -25°C and a water activity of 0.5". *Need:* In order to prevent unsterilized activity occurring in a Mars special region, such regions and/or conditions need to be defined.²

² Conley, C. A. & Rummel, J. D. (Eds.). (2008). *Planetary Protection for humans in Space: Mars and the Moon*. *Acta Astronautica* v.63 1025-1030.

³ Conley, C. A., & Rummel, J. D. (Eds.). (2010). *Planetary Protection for Human Exploration of Mars*. *Acta Astronautica*, v. 66, p. 792-797.

⁴ Rummel, J. D. (Ed.). (2005). *Technical Challenges in Meeting the Next Decade's Planetary Protection Requirements*.

⁵ Race, M. S. (Ed.). (2008). *Impact of Planetary Protection on Environmental Characterization and Hazards Mitigation Technologies*.

⁶ Rummel, J. D. (Ed.). (2006). *Astrobiological Exploration and Human Missions: First Steps*. IAC-06-A1.6.8

⁷ Clark, B. C. (Ed.). (2003). *In-Space Sterilization for Safe Early Demonstration of Control of Back Contamination*. IAC-03-Q.3.b.02

⁸ Allen, C. A., & McKay, D.S. (Eds.). (2001). *Humans and Robots Collaborating in the Search for Life Beyond Earth*. AIAA Paper 2001-4772.

Appendix E – Planetary Protection Notional Technology Developments

Planetary Protection Technology Development Needs

What follows is a listing of technology development areas of interest for Planetary Protection. Some of these areas have development already underway, others do not. The areas have been identified via an in-depth literature survey and are categorized loosely by similar technology. Reference documentation is listed, no prioritization is implied at this stage of review.

Environmental Control & Life Support:

- ECLS-1: Non-venting life support systems.¹
- ECLS-2: Closure of the Environmental Control and Life Support System (ECLSS) will likely enhance compliance with planetary protection and science requirements.^{1,2,7}
- ECLS-3: Active sterilization technologies embedded in ECLSS.^{1,7}
- ECLS-4: Systems that minimize gravity-settled materials from becoming airborne after lift-off.¹

Biological Quantification:

- Quant-1: Spacecraft cleaning to sterility (to the extent possible for human missions and robotic assets).^{6,7}
- Quant-2: Assays for rapid assessment of cleanliness (also adaptable to monitoring) – cultivable, non-cultivable, molecular.⁶
- Quant-3: Particle transport models (also applicable to Mars Environment Characterization).^{6,7}
- Quant-4: Orbital debris analysis code.⁶
- Quant-5: Aseptic spacecraft assembly systems.⁶

Biological Monitoring:

- Monit-1: More accurate (to TBD level/accuracy) microbial burden analysis that identifies viruses, prions, and eukaryotic cells in addition to bacterial spores.¹

¹ Fisher, J. W., Hogan, J. A., Joshi, J. A., Race, M. S., Rummel, J. D. (Eds.) (2006). *Life Support and Habitation and Planetary Protection Workshop Final Report*. (NASA/TM-2006-213485)

- Monit-2:** Ensure forward contaminate monitoring capability be equal to or better than the current *Category IVa* specification.¹
- Monit-3:** Active monitoring systems that detect markers/organisms of terrestrial origin due to human-associated activities.^{1,2}
- Monit-4:** Ion mobility spectroscopy for microorganism identification.¹
- Monit-5:** Bioluminescent Bioreported Integrated Circuits (BBICS) which consists of small biochips which contain stabilized microorganisms that have been altered to emit light in the presence of certain chemicals.¹
- Monit-6:** Active monitoring systems with the ability to detect 'unknown' biology within a pressurized environment.⁷

Extravehicular Activities/Space Suits:

- EVA-1:** Dustlocks & suit ports to minimize Mars back contamination.¹

Mars Environment Characterization:

- Mars-1:** Development of the Dust characterization, Risk assessment and Environment Analyzer on Martian Surface (DREAMS) instrument by ASI is supposed to help characterize Mars landing site environments.³

Waste-Management Systems:

- Waste-1:** Spacecraft waste-jettison technologies.¹
- Waste-2:** Methods/approaches for retaining waste materials on the Mars surface without risk of forward contamination (e.g., passive physical containment, active destruction, and/or in-situ sterilization using Mars material).^{1,7}

² Conley, C. A. & Rummel, J. D. (Eds.). (2008). *Planetary Protection for humans in Space: Mars and the Moon*. *Acta Astronautica* v.63 1025-1030.

³ International Space Exploration Coordination Group (ISECG). (2013). *The Global Exploration Roadmap*.

Robotic Systems:

Robo-1: Re-cleanable/sterilizable robots, capable of being sterilized in-situ after re-contact with a "dirty" environment (e.g., contact with human explorers).^{2,5,7}

Robo-2: Systems for analysis of contained samples.^{6,8}

Other

Other-1: Facilities for transfer of collected samples under appropriate contamination control (suggested to operate at better than Biosafety Level 4).^{2,4,7}

Other-2: In-situ sterilization systems.^{6,7}

Other-3: Sample container sealing systems.^{6,7}

Other-4: Lightweight biobarriers.⁶

Other-5: Assured containment for Earth entry.⁶

Other-6: Meteoroid protection of spacecraft.⁶

Other-7: Quarantine systems and/or operational approaches for crew, samples, and associated equipment being returned to Earth.⁷

⁴ Conley, C. A., & Billings, L. (Eds.). (2008). *Don't Leave Home Without It: Planetary Protection for Robotic and Human Missions*.

⁵ Conley, C. A., & Rummel, J. D. (Eds.). (2010). *Planetary Protection for Human Exploration of Mars*. *Acta Astronautica*, v. 66, p. 792-797.

⁶ Rummel, J. D. (Ed.). (2005). *Technical Challenges in Meeting the Next Decade's Planetary Protection Requirements*.

⁷ Race, M. S. (Ed.). (2008). *Impact of Planetary Protection on Environmental Characterization and Hazards Mitigation Technologies*.

⁸ Allen, C. A., & McKay, D.S. (Eds.). (2001). *Humans and Robots Collaborating in the Search for Life Beyond Earth*. AIAA Paper 2001-4772.