Planetary Protection and Contamination Control Technologies for Future Space Science Missions

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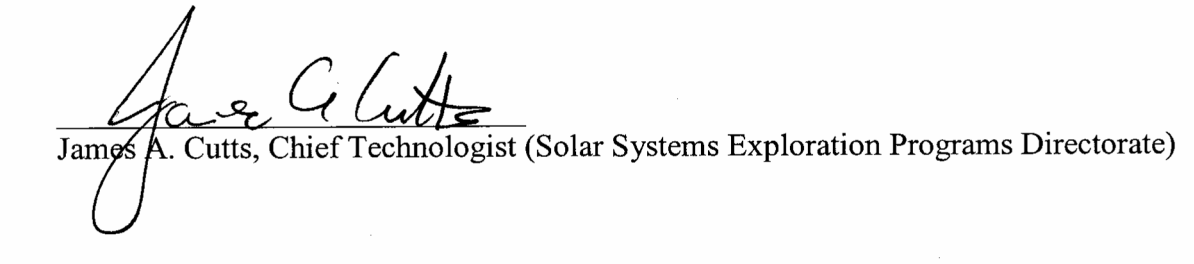
Approved



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Note: Cost Assessment information ("Analysis of Historical Funding Data" and "Projections of Funding Requirements for Solar System Exploration Missions") is contained in the NASA internal document JPL-D-31975.

Executive Summary

A review of technology needs in Planetary Protection and science contamination control was conducted at the Jet Propulsion Laboratory. This review was led by a Steering Committee consisting of project management and key mission analysts. The assessment team began by integrating the historical data on satisfying Planetary Protection requirements and then analyzed the design needs for future planned missions. The group then developed a framework to address the scope of issues in order to identify and prioritize outstanding technology needs. During this process, the assessment team determined that contamination control issues, driven by science rather than policy, were closely related to those of Planetary Protection and that both sets of goals would be more effectively addressed jointly rather than taken individually.

Using this framework, the group was able to develop lists of required capabilities and articulate specific technology goals for planned missions to Mars and beyond for the next decade, using the Design Reference Mission Set in use by NASA strategic planning groups. This framework included anticipated, though yet unformalized, requirements in both science instrumentation as well as Planetary Protection. From there, the assessment team developed roadmaps synchronizing the technology development to address these requirements with mission planning schedules. These roadmaps are tied to mission milestones and while they call for attention to a number of specific technologies, the roadmaps also suggest that satisfaction of these requirements is a key top-level requirement, to be integrated with mission architecture at an early phase.

This report addresses technology needs in three general areas: Forward protection, back protection for sample return missions, and systems analysis. The back protection studies do not include the landing site selection, nor the returned sample handling tasks. This report summarizes the major needs in each of these three target areas and makes associated recommendations. Some of these recommendations include:

- Coordination of Planetary Protection requirements with science requirements for contamination control
- Integration of Planetary Protection and contamination control requirements with other top-level requirements, to be addressed at the mission architecture level
- Development of Planetary Protection implementation procedures and technologies to targets of astrobiological interest in the Outer Planets
- Development of modeling expertise in spore and organic contaminant adhesion, contaminant transport, and planetary surfaces and subsurfaces
- Focus of microbial diversity research on environments and organisms relevant to missions currently in the planning stages
- Development of a scheme to organize sterilization and validation techniques in order to minimize redundancies and maximize investment returns
- Synchronization of Planetary Protection technology development and NASA approval (when required) with project milestones

1.0 Study Overview

1.1 Introduction

A study was conducted on behalf of the National Aeronautics and Space Administration (NASA) by the Jet Propulsion Laboratory (JPL) to assess the status of Planetary Protection and contamination control technologies to enable and/or enhance next decade (2010 – 2020) NASA Space Science missions. In conjunction with this analysis, an additional study objective was to define a roadmap for developing advanced technologies having a major impact on future missions. The study was sponsored by the Solar System Exploration Division of NASA.

James Cutts led a Steering Committee composed of project management and mission analysis experts; this group, listed in Table 1.1-1 below, held a series of three meetings. All group members are JPL employees, with the exception of Pericles Stabekis from NASA Headquarters. James Cutts and Andrea Belz were responsible for the assembly and production of this report. Additional contributions were provided by Don Hunter, Roger Kern, and Laura Newlin.

Table 1.1-1. Members of the Steering Committee

	Name	Title
1	James Cutts, Chair	Chief Technologist, Solar System Exploration Programs Office
2	Andrea Belz, Lead Author	JPL Consultant to Solar System Exploration Programs Office
3	David Beaty	Mars Program Science Manager*
4	Jack Barengoltz	Planetary Protection Engineer
5	Patricia Beauchamp	Life Detection Science and Technology Program
6	Karen Buxbaum	Mars Program Planetary Protection Manager*
7	Robert Gershman	Planetary Protection System Engineer
8	Charles Kohlhase	Mission Design Systems Engineering
9	Elizabeth Kolawa	Technology for Extreme Environments
10	Robert Koukol	Planetary Protection Engineer
11	Brian Muirhead	JPL Chief Engineer*
12	Frank Palluconi	MSL Project Scientist
13	Craig Peterson	Mission Impact Analysis
14	Pericles Stabekis	NASA Consultant to Planetary Protection Office
15	Rich Terrile	JIMO Project Scientist

* New position assumed during course of study

The specific objectives of the study were as follows:

- Determine the impact of recent and projected policy changes on various missions.
- Assess the capabilities of current State of Practice Planetary Protection and contamination control technologies and their potential for future improvement.
- Understand the mission needs in both science and engineering and determine the impact of technology development in Planetary Protection and contamination control.
- Formulate technology development plans to fill any gaps remaining between development programs and mission needs.

1.2 Recent Science Developments

Recent years have witnessed a dramatic increase in our understanding of the possibility of finding life on other bodies in the solar system. In 1998, Galileo's measurements of Europa determined the presence of a liquid ocean under an icy crust. While both the ice and the ocean remain poorly understood, subsequent measurements have confirmed their presence and have sparked a number of models regarding the accessibility of the ocean to the surface.

A number of Mars missions in the late 1990's and early 2000's also revealed that the surface of Mars was likely host to water in some form. While the complete hydrogeologic history is still unclear, the presence of liquid water has been seen in features ranging from km-wide canyons to microscopic mineral deposits.

A final set of discoveries prompting a better understanding of contamination risk is the dramatic expansion of our knowledge about extremophilic organisms. Indeed, it is now widely accepted that various organisms have evolved metabolic pathways to exploit almost every electrochemical niche known in nature, as well as the physical demands of desiccation, radiation, and heat. For this reason, environments previously seen as hostile are now known to serve as possible hosts to select organisms.

Taken jointly, the presence of liquid water on Europa, the history of water on Mars, and the improved understanding of extremophilia have led NASA to revisit the Planetary Protection requirements currently imposed in mission planning.

1.3 Related NASA Activities

The Committee on Space Research (COSPAR) of the International Council of Scientific Unions has developed a scheme of mission categories and associated Planetary Protection requirements. Specific mission requirements are determined by the NASA Planetary Protection Office (PPO), and the Space Studies Board (SSB) of the National Resource Council. These general requirements are currently implemented by *NASA Procedures and Guidelines NPG* 8020.12C, released in April, 2005.

This newest release incorporates changes suggested by COSPAR in October of 2002, based on the new science understanding of Mars and Europa, discussed above. Contamination issues for Europa have already been studied by the SSB Task Group on the Forward Contamination of Europa (Esposito et al., 2000) to provide appropriate guidance on mission planning. These changes introduced new categories for these targets, among the most interesting for potential missions. The categorization scheme is given in Appendix A.

Concurrently with this study, the SSB Working Group on Forward Contamination of Mars, chaired by Chris Chyba, has been charged by the NASA Planetary Protection Office to perform the following tasks: 1) assess and recommend levels of cleanliness and sterilization required to prevent the forward contamination of Mars by future spacecraft missions (orbiters, atmospheric missions, landers, penetrators, and drills), given current understanding of the Mars environment and of terrestrial microorganisms in extreme environments; 2) review methods used to achieve

and measure the appropriate level of cleanliness and sterilization for Mars spacecraft and recommend alternatives in light of recent advancements in science and technology; and 3) identify scientific investigations that should be accomplished to reduce the uncertainty in the above assessments.

There is also a NASA Planetary Protection Advisory Committee, reporting directly to the NASA Associate Administrator for Space Science. The Planetary Protection Advisory Committee (PPAC) was established in February 2001 to advise the NASA Administrator on programs, policies, plans, and other matters pertinent to the Agency's responsibilities for biological Planetary Protection. This group met in Pasadena in January, 2004, and was informed of the planning activities described in this document. Previous communication between PPAC and NASA suggested that Planetary Protection technology development required immediate attention due to the potentially long technology lead times and the rapidly changing understanding of extremophilia. The group also intends to address the establishment of appropriate bioburden standards, as well the assessment and control of bioburden.

The Solar System Exploration Directorate undertook this planning task because although the Directorate identified Planetary Protection as a priority in its roadmap of May, 2003, it did not include the effects of the revised COSPAR policies. This planning activity is designed to support other NASA committees to provide guidance in better integrating mission needs and technology development goals.

2.0 Planetary Protection and Mission Planning

2.1 Viking

As the first extraterrestrial biological exploration took shape in the 1950's in the form of the Viking project, the international community, represented by COSPAR, established a set of guidelines resulting in 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). Consistent with these goals, NASA then established the first set of guidelines, namely 8020.12/12A, defining planetary protection as: "The avoidance of contaminating the biosphere of a planet with terrestrial life forms so that the ecology of a planet is maintained in its pristine state during the period of scientific investigation."

The Viking project represented the first successful landing on Mars and largely still serves as the standard for current mission planning. In the early 1990s, NASA hired the Bionetics Corporation, which was responsible for carrying out some of the Planetary Protection work (then called "planetary quarantine") for Viking, to document the Viking Planetary Protection experience. This was performed in large part by conducting interviews with the participant team members. The Bionetics report includes the following general observations:

Planetary Protection was taken very seriously by top management at NASA, who implemented the details of meeting these requirements at all levels and throughout all disciplines. An advisory group was formed to guide the associated probability risk analyses and sterilization procedures. This group began to hold regular meetings with the Viking team members two years before the Viking project began in 1969 and met regularly through the launches in 1975.

While sterilization-tolerant parts and materials were carefully procured, some adhesives, lubricants, and other sealants did not maintain their integrity under terminal sterilization. For that reason, one conclusion of the Viking experience was that systems engineering to meet Planetary Protection requirements needed to be implemented earlier in the design process. Final measured bioburden levels were estimated to be on the order of 300 spores/m^2 (Puleo et al., 1977).

Science requirements imposed stricter contamination control requirements on the Viking Lander Biology Instrument (VLBI) than the simple planetary quarantine rules. As a result, satisfaction of the Planetary Protection requirements did not pose additional problems for the VLBI. On the other hand, the gas chromatograph mass spectrometer (GCMS) used to detect organic molecules demanded full organic contamination control in addition to heat tolerance. These joint design requirements posed significant challenges and may have led to partially compromised (though still successful) performance by the GCMS.

It is difficult to estimate the scale of the Planetary Protection investments in Viking in dollars since so much of it was integrally embodied in the design of the mission. It should suffice to say that there was a substantial investment in approaches to accomplishing the Planetary Protection goals and the overall cost of the mission was significantly impacted by the need of Planetary Protection and organic contamination control.

2.2 From Viking to the Present

The Viking experiments found no conclusive evidence of life on the surface of Mars. Moreover, no organic materials could be detected in the soils. As a result, interest in the biological exploration of Mars waned and there was a long hiatus in both orbital and landed missions to the planets. This situation changed in 1996, not as the result of spacecraft measurements, but as a consequence of the analysis of a meteorite, designated ALH84001, found in Allan Hills, Antarctica and identified as having come from Mars. The rock contained some remarkable features not previously seen in meteorites and identified by some scientists as fossil life forms.

The discovery of ALH84001 occurred contemporaneously with the development of the Mars Pathfinder lander mission and the Mars Global Surveyor (MGS) orbiter mission. Although these missions initially had primarily geological objectives, the ALH84001 analysis stimulated new interest in life on Mars and led ultimately to the development of an aggressive program of surface exploration of Mars, including Mars Sample Return. It quickly became clear that an effective Planetary Protection program to deal with both forward contamination of Mars by Earth sourced organisms and back contamination would be needed.

For the last six years, there has once again been significant funding for implementing Planetary Protection requirements, as detailed in document D-31975 (NASA internal). Investment areas include forward protection, back protection, and various microbiology activities.

2.3 Planetary Protection State of Practice

A detailed description of NASA's implementation of Planetary Protection requirements for relevant missions appears in Appendix C. In general, the basis for the State of Practice in Planetary Protection was established by the methods proven for Viking and applied in the missions implemented in the last decade. Additional techniques used in the Mars Odyssey (launched in 2001) and in the Mars Exploration Rover (launched in 2003) have supplemented this list. In Europe, a rigorous Planetary Protection program was also implemented for the Beagle mission.

A number of advanced technologies are under development by NASA and are planned for use in the Mars Reconnaissance Orbiter (MRO) in 2005, the Mars Phoenix Scout mission in 2007, the Mars Science Laboratory (MSL) in 2009, and in subsequent missions. In order to be put into practice on missions, some Planetary Protection technologies must not only reach Technology Readiness Level 6 from the perspective of the program and project using them, but they must also be validated (approved) for use by NASA.

In general, the State of Practice for forward protection may be organized into cleaning, sterilization, validation, and recontamination prevention. For cleaning, alcohol wipes are used extensively by spacecraft engineers. The approved sterilization protocol is dry heat microbial reduction (DHMR); limitations to this process will be discussed extensively in this report. Hydrogen peroxide vapor sterilization has been used extensively by the European Space Agency but has not yet been approved by NASA; progress on this task will also be described below.

Post-launch techniques, such as partial bioreduction by atmospheric entry at the planet, are under study and will be used for the MRO.

Validation is currently conducted with a microbial assay requiring 72 hours to mature, according to *NASA Procedures and Guidelines NPG* 8020.12B. This assay is biased toward organisms predisposed to grow in the NASA-approved culture medium. Recontamination prevention is achieved by conducting assembly in a clean room during assembly, test, and launch operations (ATLO) and through the use of high-efficiency particle arrestor (HEPA) filters for missions to Mars.

These techniques are summarized below in Table 2.3-1.

Table 2.3-1. State of Practice of Forward Protection Techniques

Process	State of Practice	Mission Application
Cleaning	Standard protocol (varies in effectiveness with materials)	All
Sterilization	DHMR is currently the only NASA-approved technique	All with sterilization requirements
	Hydrogen peroxide not approved yet by NASA	Not used by NASA missions; used by ESA missions (Beagle 2 and Mars 96)
	Partial bioreduction by atmospheric entry (not fully standardized yet by NASA)	Employed for MRO
Validation	Currently approved protocol requires 72 hours to assay	All with bioburden reduction requirements
Recontamination prevention	Assembly in clean room	All
	Use of HEPA filters	As needed for Mars missions
	Biobarriers	As needed

Table 2.3-2 and 2.3-3 describe Planetary Protection guidelines for forward protection for selected past orbiter and landed missions, respectively.

Table 2.3-2. Forward Protection for Past Orbiters

	MGS	MCO	Odyssey	Galileo
Status	In orbit	Failed	In orbit	Ended
PP Categorization	**III**	**III**	**III**	**II**
PP Implementation Assembly	Class 100K	Class 100K	Class 100K	Class 100K
Probability of impact analysis	Yes	Yes	Yes	Yes
Option to raise orbit	Yes	N/A	Yes	No
Alternative solution employed	N/A	N/A	N/A	Disposal at Jupiter

Table 2.3-3. Forward Protection for Past Lander Missions

	Viking	Pathfinder	MPL	MER	Beagle 2
Description	2 soft landers	1 airbag rover	1 soft lander/ 2 probes	2 airbag rovers	1 airbag lander
Status					
Landing	Success	Success	Fail	Success	Fail
Prime mission	Complete	Complete	NA	Complete	NA
Extended mission	Complete	Complete	NA	In progress	NA
Mass of landed elements	576 kg	800 kg	512 kg/3.6kg	1000 kg	50 kg
Science					
Life detection	Yes	None	None	None	No
Organics investigations	Yes	No	No	No	Yes
PP Categorization	**IVb***	**IVa**	**IVa**	**IVa**	**IVa**
Responsibility for implementation	JPL/Langley	JPL	JPL/ Contractor	JPL	ESA/Open University
PP and CC Implementation					
Cleaning					
Clean Room Assembly	100K	100K	100K	100K	10K
Cleaning by wipes (not to sterility)	Yes	Yes	Yes	Yes	Yes
Sterilization					
Hydrogen Peroxide	No	No	No	No	Some
Gamma Radiation	No	No	No	No	Some
DHMR: Components	Yes	Some	Some	Many	Some
DHMR: System level terminal cycle	Yes	No	No	No	No
Recontamination prevention					
Biobarrier architecture	Yes	No	No	No	Yes
Physical barrier	Bioshield	Aeroshell	Aeroshells	Aeroshell	Aeroshell
HEPA filter use	No	One	No	Many	No
Final estimated bioburden	30	0.3x10^5	3x10^5	2x10^5	<<3x10^5

* Would have been Category IVB according to contemporary definitions.

3.0 Mission Impact of Planetary Protection Systems Technologies

3.1 Framework for Analysis of Planetary Protection Technologies

By its nature, Planetary Protection involves both specific technologies, such as development of components tolerant to sterilization, as well as the use of systems architecture and engineering tools, ranging from probability analysis to spacecraft assembly techniques. In order to understand the needs at each systems level, the assessment team framed the problem in a hierarchy, shown below in Figure 3.1-1.

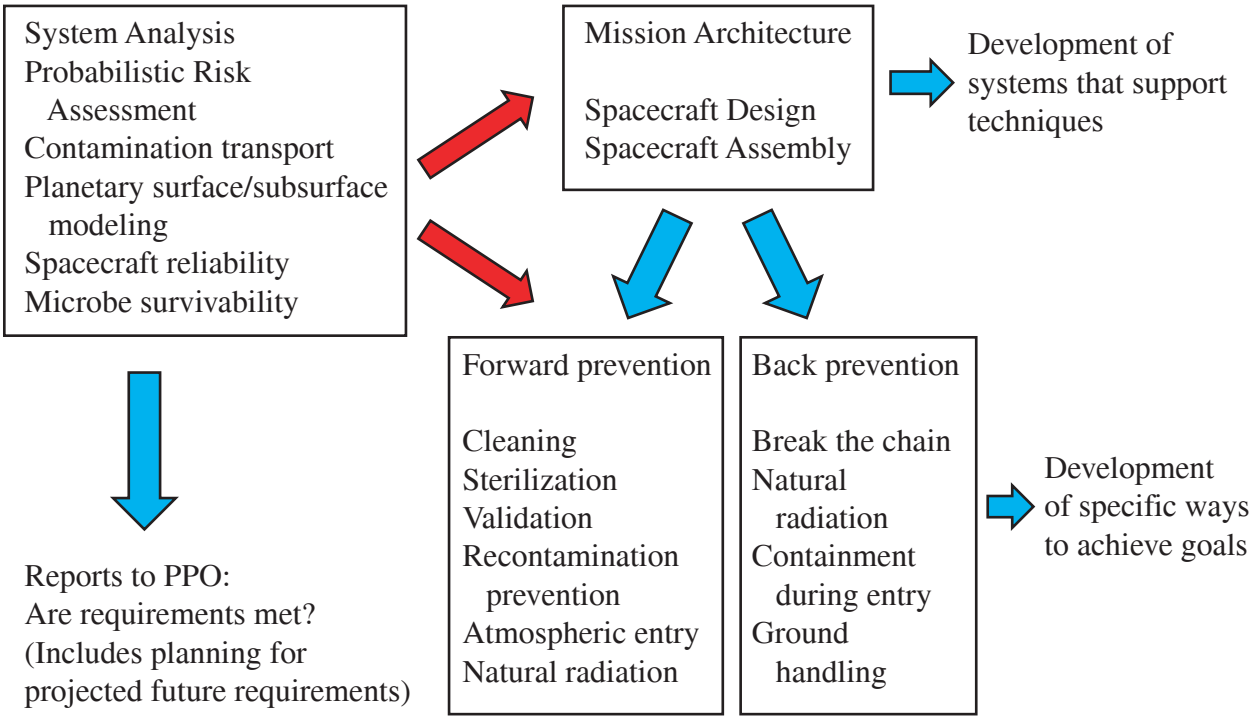


Figure 3.1-1. Framework for Analysis of Planetary Protection Technology Needs

3.2 Mission Set

The Science Missions Directorate implements a mix of strategic missions planned many years, sometimes decades, in advance, as well as competitive missions selected through periodic announcements of opportunity. For strategic missions, the mission designs are reasonably well defined and mission impacts are comparatively straightforward to discern. For competitive missions, even the nature of these missions is uncertain and mission impacts of technology are less well defined.

The two themes of greatest impact from Planetary Protection technology development are the Mars Exploration Program (MEP) and the Exploration of the Solar System (ESS), sometimes collectively referenced as Solar System Exploration (SSE). While the MEP theme primarily consists of strategic missions, missions in the ESS theme, which covers exploration of all solar

system bodies except the Sun, the Earth, and Mars, are generally competitive missions. The ESS missions have been subdivided into Outer Planet Exploration and Small Body Exploration.

Brief discussions of the missions and COSPAR categories follow, although the COSPAR categories are discussed more fully in Appendix A.

3.2.1 Mars Exploration Program

COSPAR specifies different bioburden requirements for missions to "special regions" on Mars, defined as regions within which terrestrial organisms are likely to propagate, or regions interpreted to have a high potential for the existence of extant life forms. This applies to regions where liquid water is present or may occur and includes, but is not limited to, subsurface access in an area or at a depth where liquid water may exist; access to polar caps; and access to areas of hydrothermal activity.

The mission categories examined included orbiters, surface missions (landers, rovers), aerial platforms (balloons, airplanes) probes and sample return.

Mars Orbital Missions are Category III.

Aerial Platform Missions are generally Category IV.

Mars Surface Missions are Category IV. As described in Appendix A, a subcategory of a, b, or c is applied, depending on whether the mission is designed for life detection and if it is to go to special regions. For all intents and purposes, interesting surface missions are likely to be subject to Category IVc requirements in order to conduct life detection science in areas showing signs of water.

Mars Sample Return missions are Category V restricted Earth return.

The Mars Exploration Program foresees a growing need for Planetary Protection technology to support future missions. New discoveries are identifying target areas that are more biologically interesting. This will increase the need for Planetary Protection measures to handle forward contamination. Specifically, for the sample return mission, a set of requirements and guidelines have been defined and are in the process of being implemented. Landed missions are discussed in more detail below.

In addition, the Mars Reconnaissance Orbiter (MRO) mission is scheduled for launch in August 2005, and will investigate global atmospheric transport processes, conduct global observations of aqueous sediments and hydrological process indicators, and collect high-resolution images of the surface of Mars. The MRO mission is classified Category III for Planetary Protection purposes, and operates in a low orbit of limited duration. Accordingly, Planetary Protection measures are being taken to mitigate contamination in the event of atmospheric entry.

3.2.2 Outer Planet Exploration

Outer planet missions include orbiters in the New Frontier class, some orbiters using nuclear propulsion, electrical power or heating atmospheric probes, and icy body landers such as the Titan Explorer.

New Frontier Class Orbiters are likely to be Category III and would use radioisotope power generation systems. These missions are characterized by an unusually long cruise stage (typically 10 or more years), presenting special challenges to spacecraft reliability engineering and related issues.

Nuclear Reactor Powered Missions, such as the Jupiter Icy Moon Orbiter (JIMO), present unique challenges because of the possible interaction of the nuclear reactor with the surrounding environment, such as the icy crust of Europa. While orbiters are generally classified as Category III, the presence of the ocean on Europa and the associated risk of contamination in the event of an off-nominal landing would make this a Category IV mission.

Outer Planet Atmospheric Probes are likely to be Category III.

Icy Body Landers, such as those envisioned for Europa, would be Category IV. Any lander on the surface would likely require meeting stringent Planetary Protection requirements. The remarks made in connection with Mars that exploring areas of increasing biological interest will require progressively more stringent (forward) Planetary Protection requirements also apply here.

3.3 Target-Specific Planetary Protection Standards

3.3.1 General

The COSPAR requirements are expressed differently for missions to Mars and Europa. Specifically, Mars missions conform with Category III requirements if they achieve bioburden levels equivalent to the Viking lander pre-sterilization total bioburden; namely, missions without life-detection experiments are limited to a bioload of 300,000 spores and an average areal spore density of $300/m^2$. Missions with life-detection experiments must undergo additional procedures to ensure that the total bioload does not exceed 30 spores. These requirements derive from a probabilistic assessment performed during the Viking period. On the other hand, for Europa missions, forward contamination requirements are expressed in probabilistic terms. Specifically, missions for Europa flybys, orbiters and landers must demonstrate that the probability of inadvertent ocean contamination is less than 1×10^{-4} per mission.

These paradigm differences will express themselves in the specific requirements for each mission, discussed further below. This set of challenges, which varies with mission target, power source, and mission goals, is summarized in Table 3.3-1. The missions described are Phoenix, Mars Science Laboratory (MSL), Mars Sample Return (MSR), Jupiter Icy Moons Lander (JIML), and Europa Astrobiology Lander (EAL).

Table 3.3-1. Planetary Protection Implementation Plans for Selected Future Missions

	Phoenix	MSL	MSR	JIML	EAL
Planned launch date	2007	2009	2013	2014	2016
Status	Formulation	Formulation	Pre-project	Concept	Concept
Science					
Life detection	None	No	Yes (samples)	Yes	Yes
Organics investigations	Yes	Yes	Yes (samples)	Yes	Yes?
Power source	Solar	RPS or solar	Solar	RPS or battery[+]	RPS or battery
PP Categorization	IVc equivalent	IVc	V (restricted)	IV*	IV *
Planned PP and CC implementation					
Cleaning					
Clean Room Assembly	Class 100K	Class 100K	Class 10K?	Class 10K?	Class 10K
Sterilization					
Hydrogen Peroxide	No	Possibly	Possibly	Possibly	Possibly
Natural Radiation	No	No	No	Yes	Yes
DHMR: Components	Yes	Yes	Yes	Yes	Yes
DHMR: System level terminal cycle	No	Possibly	Possibly	Possibly	Possibly
Recontamination prevention					
Biobarrier architecture	Yes	Possibly	Possibly	No	No
Physical barrier	Aeroshell	Aeroshell	Aeroshell	Aeroshell	Aeroshell
HEPA filter use	Yes	Yes	Yes	No	No

* Category IV with appropriate requirements for Europa.

[+] The power source for the next orbiter to Europa has not been determined as of the time of the writing of this report.

3.3.2 Mars

Currently planned missions to Mars include Phoenix, with the proposed Mars Science Laboratory for 2009, and a possible Mars Sample Return mission in the future. Each poses increasing levels of challenge and will be discussed briefly below.

Phoenix, the first in a series of Mars Scout missions, is planned for launch in September 2007 and will land in the northern polar region of the planet. The Phoenix spacecraft will collect samples of ice and soil for in-situ analysis. Scientists hope to find more evidence about the geological history of water on Mars and search for possible evidence of habitable conditions for life in the boundary region between the polar ice and soil. This mission will likely be classified Category IVa for Planetary Protection purposes.

MSL, currently being considered for launch in 2009, would possibly be powered by a radioisotope power source (RPS). MSL is not being planned to land in a special region in the nominal landing case. However, it is possible that in an off-nominal landing, the RPS could cause melting of ice in the subsurface, thus inadvertently producing a special region. Because of this possibility, extra precautions beyond those stipulated by COSPAR requirements may be taken.

MSR, being considered for launch no earlier than 2013, faces a number of distinct issues due to the challenges of bringing an uncontaminated sample from Mars back to Earth. These issues are summarized by Barengoltz (2000). The majority of the costs associated with this mission's Planetary Protection implementation are estimated to be necessary for back contamination control, defined as preventing the inadvertent contamination of Earth on the return leg while delivering the intact sample to a receiving facility.

Mission-specific issues and implementation considerations are summarized in Table 3.3-2 and are described more fully below.

Table 3.3-2. Planetary Protection Requirements for Missions to Mars

Requirement	Quantitative Design Guideline	Implementation considerations
1. Forward contamination of Mars by live terrestrial organisms within accepted limits/ probabilities	$<3x10^{-5}$ viable microbial spores per landing event; <300 spores/m^2 on the lander <30 spores on sample acquisition and handling Accidental impact of H/W other than intended landed elements $<10^{-4}$	Bulk cleaning/ spacecraft component sterilization and recontamination control especially of sample acquisition and handling Trajectory biasing; additional considerations for orbit decay of orbiter without landed elements
2. Additional forward requirements (MSL)		RTG may create "special region" is off-nominal landing.
3. Enable protocols for life detection and hazard assessment using returned samples in Earth labs(s) (MSR)	Probability of single unrecognizable live Earth microbe in sample $< 10^{-2}$ Low, but as yet TBD, level of dead Earth-sourced biological material	Sterilization of all landed elements (to Viking levels); or Contact hardware sterilization and recontamination control
4. Assure no inadvertent release of untested Mars material to Earth's biosphere, including Moon (MSR only)	Probability that sample containment not assured $<10^{-6}$	Break the chain (BTC) of contact with Mars: No Mars materials on outside of capsule or Earth Entry Vehicle.

3.3.2.1 MSL probabilistic risk assessment (PRA)

MSL has been developing an approach to the assessment of DHMR component sensitivities. All flight elements have been classified into four levels based on their sensitivities to DHMR. Early testing is recommended to ensure a complete grasp of the issues and to reduce cost and risk uncertainty. The most sensitive components appear to be the telecommunications components with radio frequency (RF) isolators. Two components have been identified as vulnerable to instabilities, due to crystal frequency shifts or saturation effects. If subjected to DHMR, certain components will require recalibration in the ATLO test and integration plans.

The MSL team has performed a probabilistic risk assessment of the Planetary Protection issues associated with off nominal landings. This work has resulted in a White Paper, currently in review, describing the issues associated with DHMR for the MSL components in detail. MSL has engaged experts from the Viking era (Israel Tabak and Gentry Lee) in determining costs of meeting Planetary Protection requirements using DHMR. They have determined nominal, minimum and maximum costs for DHMR based on the Viking criteria of 110° C and a specified number of hours.

3.3.2.2 MSL organic contamination control

The Organic Contamination Space Science Group (OCSSG) assembled in 2003 to address key issues in conducting quality science experiments on MSL and compiled an available white paper summarizing their work (Mahaffy, et al., 2003). A major conclusion was that the contamination of the sample, and not that of spacecraft surfaces, is the issue of interest. Methods of spacecraft contamination control are of interest to the extent that they bear directly on the sample contamination. Therefore, contamination transport is of major interest to the MSL science team. At the moment, there is little known on this topic, which is thus the subject of further discussion in this report. However, the OCCSG has set targets for specific organic contaminants on the samples themselves; these targets have been adopted by the MEPAG and MSL.

It is critical to manage the relationship between the science-driven organic contamination control efforts and classical Planetary Protection. These efforts are inextricably coupled. While some efforts to control bioburden can, in certain circumstances, be effective in reducing organics, others may work against the science goals. A classic example is the use of alcohol, long favored by spacecraft engineers, for cleaning surfaces; alcohol is used by biologists to precipitate DNA and thus may not remove all the biomolecules.

From the standpoint of a technology program, there is no justification for separate and uncoupled efforts. Therefore, of the many Planetary Protection technology initiatives described in this report, the cleaning and contamination control are most directly linked to science requirements. It will be important to maintain good lines of communication between these groups in order to satisfy both the science and policy mission requirements.

3.3.2.3 MSR forward protection

Activities associated with forward contamination prevention are reasonably well defined by previous mission planning efforts and utilize the knowledge base of previous successful Mars missions. In addition to cleaning, sterilization, and validation, these needs include recontamination prevention, such as aseptic assembly and inclusion of a biobarrier.

Sampling challenges for MSR are, like MSL and other landers, driven by the need to extract clean samples in a dirty environment. A number of concepts, discussed in the following section, are currently in development and require integration with the mission architecture.

Extensive modeling efforts are underway to evaluate contamination risks at various points in the process. Again, these efforts dovetail with modeling efforts related to MSL planning. However, due to the back-contamination concerns, the modeling and associated risk assessment are more critical here.

3.3.2.4 MSR back protection

The implementation issues of back protection range from maintaining the sample's uncontaminated state to protecting it during the return flight in a process known as sample containment and Earth return (SCER). In principle, while back protection implementation begins with the point at which contact with Mars is broken (known as "break-the-chain" (BTC)), it clearly must be integrated with the sample collection and forward protection measures to ensure an uncontaminated sample.

Upon launching the uncontaminated sample back to Earth, different back protection issues dominate the mission plan. This plan is derived from studies of the late 1990's, when preliminary plans were first made for a sample return mission from Mars by conducting an initial probabilistic risk assessment (PRA) (Gershman, 2004). The goal of the PRA was to provide determination of which of the potential threats to mission success warranted the greatest focus. One major conclusion of the PRA was that the micrometeoroid flux was estimated to pose a threat to the sample during the return cruise, thus requiring risk mitigation at the mission architecture level. The risk assessment also demonstrated the need for high heritage heat shield materials for sample preservation.

In addition to preservation of sample integrity, the PRA must demonstrate that the sample will not inadvertently contaminate the Earth. At the mission architecture level, this requires the integration of sensors able to detect breaches in the sample's integrity, as well as a flight plan with the flexibility to conduct an orbit deflection maneuver to avert terrestrial contact.

While the back protection challenges are primarily driven by mechanical engineering rather than biology, modeling efforts link the two systems. The set of efforts required to make MSR a successful mission form the backbone of the back protection roadmap.

3.3.3 Europa

Initial studies for a lander on the surface of Europa have been conducted previously by several study teams, as well as by the Jupiter Icy Moons Orbiter (JIMO) Science Definition Team. Galileo results suggested that Europa is covered by a crust consisting of liquid water and ice (Carr et al., 1998), making an environment which may potentially be conducive to microbial propagation, and thus posing special Planetary Protection challenges.

The Jupiter Icy Body Lander concept, is envisioned to be approximately 350 kg, while the Europa Astrobiology Lander concept, would be larger at approximately 1000 kg. Both mission concepts result from the identification of astrobiology as a high science priority and therefore must be designed for life detection capabilities.

Table 3.3-3. Planetary Protection Requirements for Missions to Europa

Requirement	Quantitative Design Guideline	Implementation considerations
1. Forward contamination of ocean on Europa by live terrestrial organisms within accepted limits/ probabilities/ timescale	Probability of growth of a single organism < 10^{-4}	It is difficult, but possible, to reduce the probability of contaminating the ocean Europa to <10^{-4}
	Accidental impact of H/W other than intended landed elements <10^{-4}	Biological control of a spacecraft is therefore necessary
2. Other issues		Use of a reactor-powered orbiter conceivably presents additional concerns for the surface of Europa

3.3.3.1 Probabilistic risk assessment

Unlike risk assessment for Mars, the probability of contaminating the ocean on Europa is factored in the following way:

$P_c = P_{imp} P_{ocn/imp} P_{grw/ocn}$

where:

P_c	=	probability of contamination
P_{imp}	=	probability of orbiter impact with Europa surface
$P_{ocn/imp}$	=	probability of reaching an ocean, given surface impact
$P_{grw/ocn}$	=	probability of survival and growth of one or more Earth organisms, given impact in the ocean.

The proposed JIMO project conducted an initial study to estimate the probability of contamination (Kohlhase, et al., 2004) and determined that the length of the cruise period would be approximately 12 years to reach Europa, such that spacecraft reliability is an important factor.

The second term in this expression is also problematic because the surface of Europa is estimated to be approximately 60 million years old (Zahnle, 2003), suggesting that in that time, the entire surface is replaced by new ice and the older ice is submerged into the ocean. However, the mechanics of the ice and ocean are poorly understood and have led to a number of models with associated timescales to produce conduits to the ocean. These models suggest different rates at which an object on the surface will reach the ocean, although they must presumably converge at the surface age of 60 million years.

The COSPAR requirements do not specify the timescale of interest for the contamination of Europa, leaving some room for ambiguity in the interpretation of these requirements. One exit strategy considered by the proposed JIMO project was to reach a very high orbit with a stability of approximately 5,000 years in the event of a system failure, though the mass penalty of this option was not definitively determined.

In summary, the spacecraft failure rates and the rate at which the surface contacts the ocean are considered to be relatively high and satisfying the COSPAR requirements is challenging. While alternative mission architectures have been considered, the most likely option is to meet the requirement by reducing the bioburden by sterilization, both pre- and post-launch.

3.3.3.2 Microbial diversity

The surface of Europa is exposed to high radiation levels, characterized primarily by heavy ions generated at Io. Some organisms (namely *D. radiodurans*) are known to have strong tolerance to radiation and desiccation, and represent organisms which might propagate on the surface of Europa; however, they may be effectively removed by conventional sterilization techniques, such as DHMR.

Given the ubiquity of terrestrial organisms filling various physicochemical niches, even if a particular organism is well understood and sterilized, another microbe is likely to step into that

niche. Therefore, it will be important to determine the goals of a microbial radiation study, since understanding one organism thoroughly is unlikely to solve the problem of general microbial radiation tolerance. In addition, the tolerance to radiation may be mitigated by application of another pre-launch sterilization, such as dry heat, simple heat shock, or hydrogen peroxide. Furthermore, other potential contaminant organisms may experience bioreduction in the natural radiation. Therefore, it will be important to identify the candidate contaminant organisms and the bioreduction techniques available both pre- and post-launch.

3.3.4 Comets

Two missions are currently planned to recover samples from comets and return them to Earth: Comet Surface Sample Return and Comet Cryogenic Sample Return. (Stardust, launched in 1999, is scheduled to return its sample of comet dust in January 2005.) The Comet Surface Sample Return mission concept would obtain a sample from the surface of an organic-rich comet nucleus and to make *in situ* measurements to study chemical evolution of pre-biotic molecules. It would therefore be equipped to conduct organic analysis *in situ* as well as satisfy the requirements for a sample return mission. The Comet Cryogenic Sample Return mission would extract samples from the comet nucleus from up to 10 m depth.

Like Europa, these missions deliberately reach a surface about which little is known, requiring strict attention to the possibility of inadvertent contamination (Orgel et al., 1998). The classification of a mission as "Restricted Earth Return" depends on the evidence for organic materials or liquid water on the comet and must be answered for each body intended for sampling. These evidence requirements are listed in Appendix A.

Table 3.3-4. Planetary Protection Requirements for Missions to Comets

Requirement	Quantitative Design Guideline	Implementation considerations
1. Forward contamination of comet by live terrestrial organisms within accepted limits/ probabilities	TBD, anticipated to be equivalent to Category II.	Bulk cleaning/ spacecraft component sterilization
2. Enable protocols for life detection and hazard assessment using returned samples in Earth labs(s)	Probability of single unrecognizable live Earth microbe in sample < 10^{-2} Probability of presence of liquid water and organic matter must be determined	Sterilization of all landed elements (to Viking levels); or Contact hardware sterilization and recontamination control Analysis of target body for liquid water and organic matter
3. Assure no inadvertent release of untested comet material to Earth's biosphere	Probability that sample containment not assured <10^{-6}	Break the chain (BTC) of contact with comet: No comet materials on outside of capsule or Earth Entry Vehicle.

3.3.5 Titan

The Titan Explorer mission concept that would be launched no earlier than 2020, is intended to be a landed mission that may be operated in conjunction with an orbiter. Its scientific objectives

are to characterize prebiotic organic chemistry and search for past life, in addition to providing a comprehensive surface and subsurface analysis. This mission would pose new challenges in life detection analysis in an organic-rich environment. In addition, inorganic analysis will be similarly challenged by the organic matrix. Requirements for Titan were covered broadly in a past SSB report (Orgel et al., 1998); however, it is anticipated that, in light of the successful Cassini-Huygens probe landed by ESA in 2004, the SSB may revisit the Planetary Protection requirements for Titan.

Table 3.3-5. Planetary Protection Requirements for Missions to Titan

Requirement	Quantitative Design Guideline	Implementation considerations
1. Forward contamination of Titan by live terrestrial organisms within accepted limits/ probabilities	TBD.	Bulk cleaning/ spacecraft component sterilization

4.0 Emerging Capabilities in Planetary Protection

This section contains a discussion of the capabilities under development for the next generation of Solar System Exploration missions that would begin late the present decade. The assessment includes capabilities for system level architectures compatible with implementation of Planetary Protection requirements in the framework described in Section 3.1, Figure 3.1-1. The technology needs in Planetary Protection and contamination control are divided into three broad areas: Forward protection, back protection, and systems analysis.

Forward protection encompasses the studies generally seen as "classical" Planetary Protection, including cleaning, sterilization, and validation; however, here it is more broadly defined to include inorganic and organic molecular contamination prevention. In addition, post-launch sterilization techniques, such as atmospheric heating at Mars and radiation near Europa, are included in this area under the general category of "environmental sterilization". Sampling techniques are also included in forward protection because they guarantee the scientific integrity of a sample under study *in situ*.

Back protection is unique in that it applies only to sample return missions, and therefore impacts a smaller subset of missions in the planning stages. This area broadly includes the returned sample integrity activities (that guarantee the scientific integrity of a returned sample), and the sample return success activities (that determine the likelihood that the sample will be returned to Earth successfully).

Systems analysis includes the modeling efforts that support the Planetary Protection risk assessment and are generally coupled to experimental validation efforts. In general, focused microbiology activities, such as understanding the extremophilic organisms relevant to a specific environment, are included here, as are general contamination transport studies. The last component of systems analysis is integrated modeling, which includes such efforts as probabilistic risk assessments.

4.1 System Architecture and Design

System architecture and design is the process for conceiving, designing and evaluating different approaches to meeting the Planetary Protection requirements on the mission. The goal is to find effective, reliable and affordable solutions. The system designer will draw from a repertoire of solutions that may involve the design of the mission, as well as the Planetary Protection features built into the spacecraft. For instance, a project may implement DHMR at the system level, DHMR of a subsystem, DHMR of components to be aseptically assembled, or other solutions, such as terminal surface sterilization by hydrogen peroxide.

In the past, such system level approaches have been applied extremely effectively to missions such as Viking, where substantial resources were available for reaching a solution. However, today the expertise for system design for Planetary Protection is not easy to identify, as many of these experts are at or near retirement age and there are few new people coming into the field. Accordingly, there has been little recent innovation in the development of systems solutions for

Planetary Protection, resulting in a tendency to design spacecraft and missions in conventional fashions and then apply Planetary Protection considerations as an afterthought.

JPL has recognized this problem and has begun a three-year initiative addressing the challenges of Planetary Protection systems. The goal of the initiative is the development of innovative system architectures enabling affordable system and subsystem sterilization and aseptic assembly, as well as the development of spacecraft designed from initial concept for Planetary Protection compatibility.

This initiative will apply JPL's core expertise in systems engineering and in the design, fabrication and assembly of interplanetary spacecraft and instruments to the development of a new paradigm: a Planetary Protection compliant exploration system. Instead of accepting the design of spacecraft and developing Planetary Protection processes to accommodate it, the initiative will take a fundamental look at spacecraft design in the context of the Planetary Protection needs. This program will engage a multidisciplinary team of spacecraft and instrument architects, chief engineers, Planetary Protection engineers and microbiologists to explore new ways of designing affordable spacecraft and instruments.

The assessment team endorses this initiative and urges NASA to follow its progress and to consider developing a larger and more comprehensive program in Planetary Protection systems and architectures.

4.2 Forward Protection

In the years since the discovery of the Allan Hills meteorite, JPL has spent considerable effort developing expertise in forward contamination prevention, particularly in pre-launch techniques to be applied during the ATLO process. This work may be generally organized into a few key areas: cleaning, sterilization, validation, and contamination control.

4.2.1 Pre-Launch Processes

4.2.1.1 Cleaning

In general, spacecraft hardware currently undergoes routine gross cleaning to remove major contaminants, followed by precision cleaning in selected cases. Assembled flight-hardware surfaces are also routinely cleaned with isopropanol wipes. However, some contaminants are resistant to this technique. Recent work (Venkateswaran, et al., 2001) has demonstrated that many of the cultivable species found in spacecraft assembly facilities were spore-formers. In addition, the precipitation of biomolecules with alcohol is currently being examined.

A commercially available semi-aqueous, multiple-solvent (SAMS) cleaning process, common in the microchip industry, was studied for its effectiveness in cleaning spacecraft hardware and was found to be unsatisfactory for biological sampling hardware. The treatment not only appears to lyse (or open) spores, but also the surfactant acted as a culturing media for the model organisms used in the study, enabling the spores to germinate. On the other hand, the JPL cleaning technique described in the State of Practice was found to clean surfaces rather well. This work

(Lin, et al., 2003; Venkateswaran, et al., 2004) is being refined for final protocol definition, but it does not lack the major pieces for effective cleaning control.

The Planetary Protection group has conducted extensive studies of various surfaces common in spacecraft assembly, including titanium, aluminum (chemfilmed and anodized), stainless steel, quartz, paint, and representative epoxies and silicates. In addition, these materials were studied for their compatibility with sterilization by ultraviolet radiation or exposure to hydrogen peroxide. This work identified specific problems with two epoxies and also uncovered a negative response of anodized aluminum to hydrogen peroxide vapor. This work will be critical in determining the specifications for the hydrogen peroxide vapor sterilization protocol.

In addition, a great deal of attention has been given to understanding the tolerance of aluminum and titanium to cleaning protocols. Recent work has demonstrated that, relative to aluminum, titanium demonstrates superior ability to be cleaned to sterility, partly due to its resistance to damage during treatment by nitric acid. The Planetary Protection group has recommended that titanium (Ti 6Al-4V) should be considered superior to aluminum (Al 6061) for use in spacecraft sampling hardware, both for its potential to be cleaned to sterilization and for its compatibility to the most effective cleaning protocols. This study also serves as a model for examining other surfaces for the ability to tolerate cleaning protocols.

A high priority in the future will be to address not just biological cleanliness, but also inorganic and organic contaminant levels. These molecular contaminants will need to be strictly monitored in order to produce quality scientific results. For this reason, cleanliness techniques satisfying Planetary Protection requirements as well as science requirements should be developed for broad use.

4.2.1.2 Sterilization modalities

While the process of Dry Heat Microbial Reduction (DHMR) is reasonably well understood, the practice is still under exploration, particularly by the MSL engineering team. The duration given by NPG provides for one order of magnitude reduction and is based on heating the coldest spot in the target piece of hardware (this duration is known as the "D-value" and is described more fully in Appendix D). In practice, DHMR is performed for the full four orders of magnitude reduction credit allowed by the specifications. Current use includes additional padding for time and temperature to account for thermocouple calibration uncertainty, as well as the possibility that the thermocouple is not necessarily located in the coldest part of the hardware. For delicate hardware and more expensive heating chambers, additional analysis is performed to reduce this padding.

In summary, engineers are still fully determining the parameter space of DHMR, as the NPG guidelines currently give only few data points. This process is particularly important for new materials used in contemporary hardware.

Because of its pervasive nature, DHMR is currently the only technique approved to sterilize both components and bulk hardware, and is therefore the only option for terminal level sterilization for assembled subsystems. However, there is not currently an operating facility to sterilize large subsystems (i.e., masses on the orders of hundreds of kg). For environments which may be more

conducive to microbial propagation, such as Europa, this may prevent the mission from achieving appropriate bioburden levels prior to launch.

Hydrogen peroxide vapor sterilization has been studied extensively as an alternative surface cleaning technique and is in the process of satisfying NASA certification requirements. The work funded at JPL will culminate in delivery to the NASA PPO of recommendations on the use of the technique with all pertinent documentation. This technique has been widely used in Europe on missions including Mars 96 and Beagle 2; those teams have been in contact with the NASA PPO.

The evaluation work is being done by Steris Corporation. A full suite of lethality experiments on hydrogen peroxide is planned or in process to extend this sterilization technique to a useful standard process, given constraints on the materials and component compatibilities. It may be possible that individual projects can apply the technology without going through the entire approval process. The NASA qualification will not specify necessarily how the technique would be used – either in system or subsystem sterilization. However, it is likely that it will be useful in sterilizing exposed polymer surfaces or other materials for which DHMR is not suitable.

4.2.1.3 Validation techniques

A number of techniques have been studied at JPL and are in various states of advancement. The full spectrum of techniques is summarized in Appendix D, but technologies of higher readiness levels are listed here.

The approved protocol is to sample the surface, then grow the sample aerobically in a rich medium for seventy-two hours. Not only is this protocol biased toward organisms which will grow in the medium, the process is labor-intensive and thus not economical. For this reason, JPL has actively pursued and has nearly completed the development of a rapid spore assay with automation capabilities.

One process is based on spectrophotometric detection through bioluminescence of adenosine triphosphate (ATP), a key molecule in cellular metabolism. A parallel test detects the production of lipopolysaccharide (LPS), a substance found in the cell walls of Gram-negative bacteria. However, this presents a weakness in spore detection because dormant spores do not produce these substances. The LPS is measured with a limulus amebocyte lysate (LAL) assay, taking advantage of an enzyme produced in the horse-shoe crab blood cells (known as limulus amebocytes) as an immune response to a microbial infection. Since it only measures Gram-negative microbial contamination, it requires combination with another technique able to detect Gram-positive microbes.

Both these assays are commercially available kits and do not require a high degree of operator skill for their implementation. The assay involves swabbing the hardware surface, transferring all of the cells present on the swab to a small tube, and then adding the requisite components for the reaction to proceed. In addition, these assays take place on time scales of 8 hours, rather than the 72 hours currently required by NASA standard protocols. An ATP assay was submitted to the PPO for approval in early 2005 (Kern et al., JPL document D-30970); upon approval, it will present an alternative cost-effective validation technique for consideration by project

management. The NASA approval process is detailed in Appendix B and has not been previously published in official NASA documentation related to Planetary Protection. Briefly, the PPO receives the proposed protocol and then submits it to a peer-review board. The PPO then takes action to approve or revise the process, based on the recommendations of the peer-review board.

4.2.2 Recontamination Prevention

Recontamination is the increase in the number of spores after the biological contamination has been validated. Historically, HEPA filters were used to isolate some regions so that their spores did not have to be counted against the requirements; however, this use implies that a crash does not occur. More sophisticated approaches are currently under development.

4.2.2.1 Non-biobarrier architectures

Recontamination prevention for missions to Mars currently consists primarily of the integration of HEPA filters in the mission design and assembly in clean rooms. This infusion has improved significantly from Pathfinder, which used one HEPA filter, to MER, which used several filters. However, for more challenging missions, it will likely be important to develop biobarrier technology and aseptic assembly techniques. For instance, a final sterilization might be implemented by running hydrogen peroxide vapor through the launch vehicle fairing prior to launch. A cleaning process integrated with the launch vehicle has not previously been implemented.

4.2.2.2 Biobarrier architectures

For MSR, a number of mission design options are under study. Key enclosure models include:

- Total spacecraft, in which the bioshield is released in orbit before the lander de-orbits. This approach was used successfully by the Viking mission.
- "Garage," in which the rover is held in a protected region and surrounded by a biobarrier, while the rest of lander is not as thoroughly protected.
- "Arm," in which a sampling tool and associated arm are protected in a biobarrier. The lander or rover then delivers the arm to the sampling area, where it is unsheathed.

Clearly, the biobarrier design will need to be integrated early in mission design.

However, while biobarrier architecture for a mission to Mars may provide useful guidance for missions to other targets, it is likely that subsystem level isolation (such as provided by a garage or arm) may require novel strategies, as well as materials, for wet environments. Recontamination prevention therefore needs to be considered independently for each target of interest; these preliminary studies have not yet been undertaken for environments representative of the additional target bodies.

4.2.3 Environmental Sterilization

4.2.3.1 Mars surface and subsurface

One issue facing Mars missions is the sterilizing property of the surface and subsurface. While the surface is known to experience high intensity, and thus biologically damaging, UV fluxes, other sterilizing properties have not been fully described. This is particularly important for future missions with anticipated drilling programs.

In addition, better understanding of the subsurface will aid the analysis of the probability of microbial propagation in the event of an off-nominal landing of a spacecraft with a radiothermal generator, such as that planned for MSL, where the additional heat load may liberate frozen water from the mineral matrix. The surrounding matrix will define the propagation likelihood and may provide additional sterilizing properties.

4.2.3.2 Mars atmospheric entry

A key issue for Mars orbital missions is the effectiveness of atmospheric heating and ablation in the reduction of bioload during atmospheric entry. In order to acquire high resolution observations of the surface of Mars, future orbital missions will need to orbit close to the planet in orbits that have short lifetimes because of atmospheric drag. Therefore, a spacecraft will impact fairly soon after a system failure or at the end of the mission. Studies have been conducted at JPL for some time and work has been peer-reviewed twice by a committee selected by the PPO; the JPL work remains unpublished. Related studies by Lockheed Martin demonstrated that atmospheric entry provided adequate bioreduction for the surfaces on MRO; however, results suggested that the possible sources of bioburden, such as buried sources or organisms subject to early release and consequent survival, required further examination for future missions.

These studies need to be unified and completed; however, many of the atmospheric models are well developed and the bioreduction is reasonably well understood.

4.2.3.3 Radiation in the Jovian system

In principle, the heavy ion radiation in the vicinity of Europa may be used as an additional sterilization modality. However, it is currently difficult to assign the appropriate risk factors because environmental sterilization is widely discussed and poorly understood. For instance, microbial radiation tolerance is not well understood for the case of ultraviolet radiation like that on Mars or heavy ions at rates comparable to those seen at the surface of Europa. In the case of radiation, specific work is needed in understanding microbial diversity and radiation tolerance in an environment appropriate for a specific mission. Also, the dose throughout the spacecraft requires a special radiation transport analysis for the minimum dose at each location. Because the typical analysis is concerned with the maximum dose, a systematic effort is needed to expand this base of knowledge.

4.2.3.4 Environment of Titan

A preliminary analysis is still under development for the surface of Titan. However, it is clear that the organic ice will provide different challenges to Planetary Protection. The linkage between microbial propagation and the surface characteristics need to be fully explored during the early phases of mission planning.

4.2.4 Sampling Techniques

4.2.4.1 Covered sampling on Mars

Covered sampling is the process of collecting uncontaminated samples from an extraterrestrial surface which may be dusted with Earth origin microbes or organic contaminants. Improved covered sampling techniques will protect the integrity of sampling for landed missions. In addition, requirements for sample return missions state that the sample must contain less than one viable terrestrial spore in 100 returned missions, although no requirements have been expressed yet for organic compounds.

Sample acquisition strategies are critical to mission architecture because they involve key decisions such as integrating the sampler with the lander or using a rover. Other key design elements involve the integration of the scoop on the arm, the possible use of a sieve. This task provides a potentially low risk approach to collecting clean samples, with the additional benefit of reducing the mission cost by enabling the use of a "dirty" spacecraft, with lower associated Planetary Protection requirements prior to launch.

There are currently three principal ideas under consideration for the covered sampling tool, all of which make certain assumptions regarding the sterilization properties of extraterrestrial microbes:

- Sterilizing hood, in which a region of the surface is covered and then sterilized with heat or chemical processes. A door would then open and expose a tool on the sterilized region.
- Covered scraper, in which a scraper is used to expose a clean area. A tool would then extend onto the area, newly cleaned by dilution via scraping.
- Heated door, in which contaminants are driven down against the surface. A heated tool surface would then sterilize the region.

The mechanism of sample transfer is still under study. The canister could either be integrated directly with the sampling tool, or an intermediate container may be used. This set of issues will be discussed further below, with back protection.

4.2.4.2 Drilling instruments for multiple targets

It is anticipated that drilling tools will be developed for sampling from any of the mission targets under consideration. It is clear that these tools will vary as a function of the target body; for instance, a drill on for the ice on Europa will likely be designed differently than a drill for Mars.

This instrument development will need to take place independently and early for each mission currently under study.

4.3 Back Protection

Planetary Protection concepts have been developed for a baseline Mars Sample Return mission design in which a lander would be launched to Mars, where it would collect a sample using the covered sampling tool in the forward contamination prevention discussion. This sample would be collected and placed in an Earth-clean environment in the Mars Ascent Vehicle (MAV) for launch, where it is known as the orbiting sample (OS). After leaving the atmosphere of Mars, the MAV would release the OS for capture by the Earth Return Vehicle (ERV). The ERV would release the Earth Entry Vehicle (EEV) for return to Earth.

The major systems requiring attention are the break-the-chain (BTC) system and the Earth return system. Containment after the return to Earth and during science analysis (i.e., the Mars Returned Sample Handling (MRSH) project) requires additional attention. This assessment does not examine issues related to containment after the return to Earth, but is limited to Planetary Protection considerations prior to landing.

4.3.1 Returned Sample Integrity

Returned sample integrity describes the process of maintaining a scientifically clean sample for analysis upon return to Earth. It consists of two major activities: Sample acquisition and break-the-chain mechanisms.

4.3.1.1 Sample acquisition

In recent years, various proposals have been based on the hypervelocity, or "clipper" method of sample acquisition. This technique offers benefits compared to the conventional landed mission, such as the ability to execute the sample acquisition and return with a single spacecraft. Returned sample acquisition is therefore a top-level mission architecture decision with its own set of technology needs. However, projects currently in the planning stages are still primarily conventional landed missions with associated acquisition systems.

Returned sample acquisition is intimately related to sterilization, as another option for returned sample missions is to sterilize the sample in-situ or in-flight. An example is to integrate an oven into the sample return system to expose the sample to high temperatures prior to Earth return.

4.3.1.2 Break-the-Chain mechanisms

Break-the-chain (BTC) refers to the process of breaking the chain of contact between the returned sample vehicle and the planetary surface. This process includes the container sealing and leak detection, as well as dust mitigation, to be discussed below.

Container sealing must be intimately related to the covered sampling methodology. A number of concepts are currently under study to determine the appropriate time to seal the container and to conduct further sterilization. The major concepts currently under study are explosive welding,

which uses soft-seal technology to seal the canister, and simultaneous separation, seaming, and sealing using brazing (S^3B). While the explosive welding method may be at a slightly higher readiness level, the S^3B methods comprise a number of techniques at high readiness level, requiring primarily a system integration effort rather than technology development. This task is currently underway and the system integration efforts are promising.

Container transfer is also strongly related to the covered sampling tool task because of its dependence on the sampling tool design, as well as on the selected sealing mechanism. This activity is further related to the strategic selection of sampling from a lander or from a rover, because transfer to the MAV may not be able to be accomplished cleanly from the lander, thus necessitating another sterilization treatment. The specific technology needs associated with container transfer are largely addressed by the other tasks on the "giving" and "receiving" ends of the sample, but are identified here as presenting another set of contamination control challenges.

4.3.1.3 Dust mitigation

Models of the aerodynamic forces on the MAV's launch and ascent suggest that for particles smaller than 10 microns, the lift is not sufficient to remove the particles adhered to the surface. As a result, the MAV would enter orbit with approximately 1 million particles adhered to the surface, with a mean diameter of 3 microns. Therefore, dust mitigation strategies may be necessary to prevent transfer of dust from the MAV's external surface to the OS upon ejection.

The principal concepts currently under consideration include a "second skin" on the MAV that ejects the dirty surface, or conversely, an extremely "sticky" surface to prevent the dust from leaving the MAV surface. These concepts are still in the early stage of development and in addition to requiring understanding of the dust characteristics and transport processes on Mars, studies are needed to understand the various options to prevent the dust transfer. This is still in the early stages of development.

4.3.1.4 Ice mitigation

The MSR container design under consideration has specific properties relevant only to the Mars sample return. Sample return from comet surfaces, such as for the Comet Surface Sample Return and Comet Cryogenic Sample Return mission concepts, impose additional requirements in order to contain a possibly organic-rich ice. These mitigation strategies and associated Planetary Protection requirements have not yet been addressed for ice-rich samples.

4.3.2 Sample Return Success

Sample return success has largely been examined by the MSR team. This area does not address the cleanliness of the sample, but instead the threats to sample return by the cruise and Earth return stages. In general, the major threat to mission success in the return cruise, identified by early MSR studies (Gershman, 2004) is micrometeoroid damage, which may damage the thermal protection system. Earth entry concerns include the structural and navigation needs, as well as the sample containment upon landing on Earth.

4.3.2.1 Micrometeoroid protection

The major threat to the external thermal protection systems of the OS and the EEV is micrometeoroid damage. While the OS does not require further technology development to be protected while in Mars orbit, the EEV's size dictates a more massive shield than is currently feasible. Therefore, meteoroid protection for the EEV has arisen as a major issue in mission design, subject to the constraint that the entry, descent, and landing systems must remain unaffected. The current study includes materials appropriate for the shielding, in addition to the jettison mechanism upon entering the Earth's atmosphere. Similarly, breach detection prior to Earth entry is critical, with technology possibilities including photodetectors, conductive stripe break gauges, or acoustic detectors. Applications of these technologies for breach detection are currently at low technology readiness levels.

The major drivers of the shield sizing are the duration of the EEV detached cruise and the EEV's size. Therefore, this system, and specifically its mass, will ripple through the entire mission architecture and will feed back into the EEV design. Because another option is to release the EEV later in order to remove the need for the micrometeoroid shield, this task is also closely related to the navigation reliability analysis.

4.3.2.2 Earth entry system

The Earth entry system comprises the ERV and the EEV. However, specific systems have been identified as key drivers in the risk assessment and are discussed here as areas requiring technology development.

The current plan for the EEV is to use a simple, robust design including a passive blunt body shape, heritage thermal protection systems, and a landing impact absorption system. The design will be driven primarily by containment assurance.

The spacecraft reliability and end-to-end navigation performance must meet the required performance for Earth return targeting, EEV release, and Earth deflection for the ERV. If many other factors were constrained, the 2001 Probabilistic Risk Assessment (Gershman, 2004) determined that Earth targeting presented a sizable risk factor. Therefore, spacecraft reliability poses a major contribution to the mission PRA and impacts the system size, trades, and project cost. This analysis is currently in progress and needs for technology development are being assessed.

It may be necessary to construct another vessel to contain the OS during Earth impact and capture the OS dust. This containment vessel would be made of an elastomeric material. Its necessity will be driven primarily by the simulations of the entry, descent, and landing systems, and its design would depend on the OS size, as well as the results of the dust mitigation study to determine the possible need for additional heat sterilization. Furthermore, its inclusion would impact the EEV design and mass constraints.

4.3.2.3 General capabilities

There are a number of additional issues associated with sample return, including contingency plans, landing site selection, and the returned sample handling facility. While some contingency planning is integrated with the spacecraft and navigation reliability tasks, in general these activities are beyond the scope of this technology assessment and are therefore not discussed here.

It is noteworthy that the contingency planning and returned sample facility construction would benefit future returned sample missions, regardless of the target body. For that reason, it is important to consider these needs in the context of broader planning activities than strictly MSR.

4.4 Systems Analysis

The development of planetary exploration systems has become increasingly reliant on modeling and simulation for predicting and understanding the behavior of complex systems in a variety of environments. The objective is to provide assurance that those systems will accomplish the required tasks with minimal risk and substantial margins for error. Modeling and simulation methods are needed in Planetary Protection to assure compliance with policy requirements, as well as to assess the ability to meet scientific requirements. As with all applications of modeling and simulation, experimental data and validation methods are needed to ensure that the critical parameters in the models are correct and that the models produce results that describe the physical reality accurately.

4.4.1 Microbial Systems Analysis

A number of papers have been published by the Planetary Protection group demonstrating the diversity of organisms found in a clean room associated with ATLO of the Mars Odyssey Orbiter, using it as an example of an extreme environment (Venkatswaran, et al., 2001; Venkatswaran, et al., 2003; La Duc, 2003). Detected organisms presented varying degrees of resistance to potentially hostile environments, including 1 Mrad gamma radiation and possibly hydrogen peroxide. Further development of this work will enable models to evaluate which organisms are most likely to populate a spacecraft's bioburden, thus pointing to sterilization techniques most likely to be effective; however, it will be critical to focus these efforts on the organisms associated with the ATLO process and the environments of interest in order to answer the mission-specific needs.

It will be critical to focus the microbial diversity studies on mission-specific risk mitigation studies and not to construct a broad program of research in extremophilia. For that reason, it will be important to integrate these activities with mission architecture and systems engineering at an early phase and not to conduct the biodiversity studies in isolation. The activities envisioned to fall in this area include the identification and enumeration of relevant organisms, followed by environmental survivability studies specific to each mission and timed for inclusion in the mission planning phases.

4.4.2 Transport Analysis

Transport analysis describes the model and experimental efforts associated with understanding contaminant transport in each environment of interest. Like the microbial systems analysis, this area is envisioned to be initiated by a broadly applicable understanding of the adhesion properties of spores on spacecraft. This activity should then be followed by specific studies of the transport properties for each target body of interest.

4.4.2.1 Spore adhesion studies

This work, which has just received its initial funding, focuses on the size distribution of contaminant particles in a clean room and the relationship between spore density and particle size, with separate analyses to be conducted on small (less than 1 micron diameter) and large particles. This work further examines the adhesion mechanism to spacecraft materials through experimental studies. This phenomenological approach is needed to provide data on transport within a clean room and from the spacecraft once it arrives on the surface of Mars. These data will be incorporated in models for the dispersion of contaminations in the Mars environment and is expected to link closely with the computer modeling efforts. This work is expected to form a cornerstone of planning for all Mars missions.

4.4.2.2 Contaminant transport on the Mars surface

Currently, contamination transport models from point and line sources in a uniform wind have been described and are useful for estimating contamination concentrations at large distances (100 m to 1 km) from a lander. For applications involving sampling near a lander, point and line sources are crude. JPL has recently initiated a research effort to develop an appropriate particle transport model. The work may use a structure based on particle physics models; however, it will also require significant input from experts in fluid dynamics to describe winds, as well as electrostatics to describe surface adhesion properties. In principle, this work is to be validated with measurements at NASA Ames Research Center and Arizona State University; however, the modeling effort is still premature and significant effort is needed to realize this collaboration.

The spore adhesion studies conducted at JPL are expected to feed data into these models and further validate them. Validation of these models in simulated Mars environments is a key element in assuring their utility and requires significant effort.

4.4.2.3 Contaminant transport in subsurface environments

One of the key issues in both missions to multiple targets is the risk of contamination transport under conditions of off nominal landings in special regions. This requires an understanding of how spacecraft components are transported downward into geological media consisting of mixtures of icy and rocky materials and other components. Modeling contaminant transport in this system involves understanding the environment and its effects on the formation and persistence of liquid water, as well as the growth rate of representative organisms of interest. While significant expertise resides at JPL in the planetary science issues, little attention has been paid to the implications to satisfying Planetary Protection requirements for missions to targets other than Mars. Preliminary studies have not engaged many of the major experts on the

planetary dynamics of targets such as Europa, Titan, and comets, and will require major input prior to approval by the NASA PPO.

4.4.3 Integrated Modeling

Integrated modeling describes the simulation activities designed to quantify the risk of contamination. These activities receive input from the other systems analysis modeling activities and include the effects of improved technology development. The product of these efforts is a risk analysis.

4.4.3.1 In-situ sample integrity

This set of activities quantifies the contamination level for both science and Planetary Protection. It incorporates the other modeling efforts used for technology development, as well as the improved contaminant transport analysis. These efforts must address each target specifically.

4.4.3.2 Returned sample preservation

These efforts quantify the risk associated with sample return missions. They are target-specific in that they include the effects of sample containment, which will differ for samples recovered from dust (Mars) versus ice (comet).

5.0 Roadmaps

5.1 Study Goal

The goal of the Office of Space Science and the Solar System Exploration Division in sponsoring this study was to determine the gaps and to identify most productive areas of investment in Planetary Protection technology. Developing new technology and infusing it into space science missions is expensive and Planetary Protection must be integrated at a system level in order to be most effective. Accordingly, two factors must be considered in selecting the investment areas of highest priority and in formulating the technology roadmaps for these areas:

- Impact of the potential advance in Planetary Protection technology on the portfolio of future space science missions

- Prospects for achieving the needed technological advance with acceptable risk and affordable investment

The portfolio of future space science missions was derived from the Design Reference Missions used by the Solar System Exploration Directorate. These missions and associated launch dates are consistent with those used by NASA strategic planning groups during FY05.

The roadmaps assume the following development approach:

- Pursue parallel technology developments where alternative approaches exist and there is significant uncertainty as to which approach is most likely to succeed. Use readiness gates to monitor progress and down-select to the most promising technology for maturation of the technology at the earliest feasible time.

- Conduct a test and validation program to demonstrate the success of Planetary Protection technologies. In this connection, it may be necessary to augment and modernize the existing infrastructure at various NASA centers as needed to support missions.

- Technology must reach Technology Readiness Level 6 approximately 4-5 years before the projected launch date in order to be infused into the mission.

- Because contamination levels are determined as top-level requirements, these technologies are mission enabling. Therefore, metrics are expressed strictly for technical performance and do not implicitly include the impact on mission cost. Technology-specific down-select processes will include risk assessments and mission-specific cost assessments.

The full roadmap and budgetary requirements are detailed in document D-31975 (NASA internal). All listed mission milestones are projected technology readiness review deadlines and not launch dates, as those are most relevant to the mission-driven technology development program.

5.2 Required Capabilities

The capabilities needed to reach the more stringent anticipated goals for forward and back protection are listed in Table 5.2-1. Capabilities extend past microbiology and sterilization to include various mechanical and chemical engineering capacities. In addition, modeling capabilities would address many of the needs expressed by the current and anticipated future requirements.

Table 5.2-1. Required Capabilities for Planetary Protection and Contamination Control

Process	Capabilities needed
Pre-launch processes	
Cleaning	Materials and methods analysis
Sterilization	Sterilization; thermal, chemical, materials analysis
Validation	Biomolecular and organic analysis; ability to assay non spore-formers
Recontamination prevention	
Non-biobarrier	Mechanical design; sterilization
All biobarriers	Mechanical design; sterilization; aseptic assembly
Environmental sterilization	
Mars: surface	Dust transport and winds; modeling
Mars:subsurface	Soil chemistry and hydrogeology, modeling
Mars: atmospheric entry	Architecture; atmospheric, burn and break-up modeling
Europa: radiation	Radiation modeling
Titan: environment	Organic ice modeling
Sampling techniques	
Covered surface sampling	Mechanical design; surface modeling
Subsurface techniques	Mechanical design; subsurface modeling; thermal diffusion; chemical design
Returned sample integrity	
Sample acquisition	Mechanical design
Break the chain/containment	Mechanical design, modeling (dust transport)
Sample return success	
Micrometeoroid protection	Mechanical design, modeling (space environment effects)
Earth return	Aerothermal dynamics analysis
Ground handling	Environmental science, chemical engineering

5.3 Roadmaps for Forward Protection.

Forward protection measures are identified chronologically in the course of a mission. Sterilization techniques are expressed in decades of bioburden reduction (BBR), and therefore rise with increasing efficacy. On the other hand, contaminant dilution factors are expressed in parts per million (ppm), and therefore decrease as contamination control improves. Each phase in which forward protection can be implemented is considered separately.

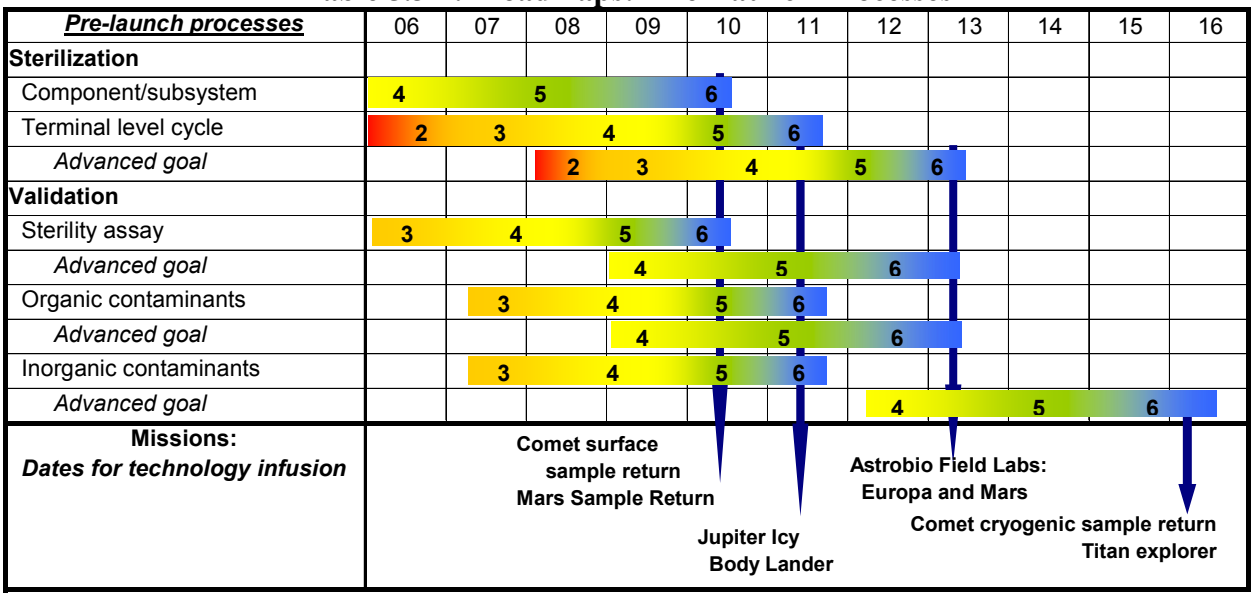
5.3.1 Pre-Launch Processes

Pre-launch processes comprise the "classical" Planetary Protection processes of cleaning, sterilization, and validation. The current state of the art of techniques under development at JPL is discussed in Appendix D. Table 5.3-1 lists the performance metrics, which vary from sterilized mass for a terminal cycle to parts per million contamination levels. The refinement of the sterility validation will produce a shorter assay time and is therefore measured in hours. Table 5.3-2 depicts the necessary roadmap to infuse these technologies into mission planning.

Table 5.3-1. Performance Goals: Pre-Launch Processes

Pre-launch processes	***Metric (BBR = bioburden reduction)***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL 6)***
Sterilization				
Component/subsystem	Decades of BBR	4	4	4
Terminal level cycle	Sterilized mass (kg)	5	350	1000
Validation				
Sterility assay	Hours for assay	72	8	4
Organic contaminants	Parts per million (ppm)	100	10	1
Inorganic contaminants	Parts per million (ppm)	10	1	0.1

Table 5.3-2. Roadmaps: Pre-Launch Processes



5.3.2 Recontamination Prevention

Recontamination prevention techniques are defined as the active prevention of the introduction of new spores, and the associated development activities are divided according to the use of biobarriers. Table 5.3-3 lists the performance goals, measured as the contaminant dilution factor for a non-biobarrier architecture, accomplished principally through the use of HEPA filters. For biobarrier architectures, the biobarrier complexity scales with the surface area, which is thus an

appropriate measure. This plan considers the development of biobarriers for each of the targets of interest to proceed independently, as Mars, Europa, and Titan are likely to present different constraints on material selection. Table 5.3-4 illustrates the roadmap that will keep this development consistent with mission planning.

Table 5.3-3. Performance Goals: Recontamination Prevention

Recontamination prevention	***Metric***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL6)***
Non-biobarrier architectures				
HEPA filter architecture	Contaminant dilution (ppm)	Never done	1	0.1
Biobarrier architectures				
Dust (Mars)	Surface area (m^2)	Never done (since Viking)	5	40
Ice (Europa)	Surface area (m^2)	Never done	5	40
Organic ice (Titan)	Surface area (m^2)	Never done	5	40

Table 5.3-4. Roadmaps: Recontamination Prevention

Recontamination prevention	06	07	08	09	10	11	12	13	14	15	16
Non-biobarrier architectures											
HEPA filter architecture	4	5			6						
Biobarrier architectures											
Dust (Mars)	3	4		5	6						
Advanced goal				3	4		5	6			
Ice (Europa)	2	3		4	5	6					
Advanced goal				4		5		6			
Organic ice (Titan)						2	3		4	5	6
Missions: ***Dates for technology infusion***				Comet surface sample return Mars Sample Return		Jupiter Icy Body Lander		Astrobio Field Labs: Europa and Mars		Comet cryogenic sample return Titan explorer	

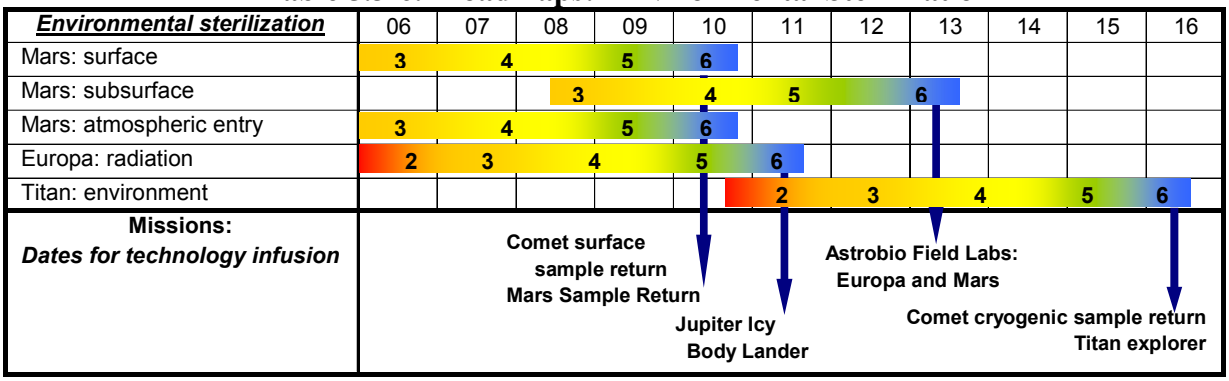
5.3.3 Environmental Sterilization

After launch, various possibilities for additional bioburden reduction exist and require study. The goals are listed in Table 5.3-5 and identify the projected number of decades of BBR from each option. Mars presents several options because burn and break-up during atmospheric entry offers additional heat deposition. However, there are added challenges because of the possibility that in an off-nominal landing, water may be released from the mineral matrix, thus posing an extra contamination risk; adequate understanding of the soil and hydrogeology is needed here. Missions to Europa, on the other hand, would experience increased radiation and may therefore benefit from bioreduction by heavy ion bombardment. The sterilization properties of the Titan surface have yet to be understood and require study as well. The timescales on which these studies need to take place are described in the roadmaps of Table 5.3-6.

Table 5.3-5. Performance Goals: Environmental Sterilization

Environmental sterilization	***Metric (BBR = bioburden reduction)***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL6)***
Mars: surface	Decades of BBR	Never done	1	2
Mars: subsurface	Decades of BBR	Never done	1	2
Mars: atmospheric entry	Decades of BBR	2	3	3
Europa: radiation	Decades of BBR	Never done	2	3
Titan: environment	Decades of BBR	Never done	1	2

Table 5.3-6. Roadmaps: Environmental Sterilization



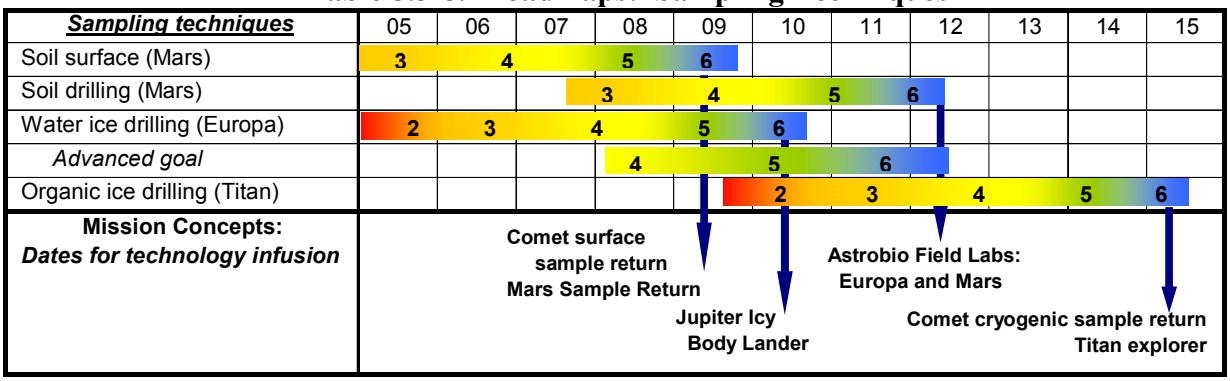
5.3.4 Sampling Techniques

The final set of forward protection activities is related to surface sampling. This is necessary in order to protect the integrity of the science results, and therefore the goals identified in Table 5.3-7 address the contaminant dilution factor (expressed here in ppm). The subsurface techniques depend on the matrix, and therefore the target, of interest. Table 5.3-8 describes the roadmap for infusion of these techniques into mission planning. While these metrics have technically not been executed on past missions, contaminant levels in ground tests may demonstrate that the State of Practice is defined better than "Never done".

Table 5.3-7. Performance Goals: Sampling Techniques

Sampling techniques	***Metric (Contaminant dilution)***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL6)***
Soil surface (Mars)	ppm	Never done	1	0.1
Soil drilling (Mars)	ppm	Never done	1	0.1
Water ice drilling (Europa)	ppm	Never done	1	0.1
Organic ice drilling (Titan)	ppm	Never done	1	0.1

Table 5.3-8. Roadmaps: Sampling Techniques



5.4 Roadmaps for Back Protection

Planetary Protection risk budgets may be allocated over various steps in the mission. For that reason, it is important to identify the contamination risk associated with each step in the mission architecture and to set the associated risk tolerance level. In this assessment, back protection measures are identified chronologically in the course of a mission and divided broadly into activities affecting the sample integrity and those affecting the success of a return mission. For that reason, goals are expressed either in terms of contaminant dilution factor (in parts per million) or in probability of mission success. The mission set depicted in the roadmaps is smaller than those affected by forward protection activities because not all projects are sample return missions.

In addition, it is important that because this assessment does not describe contingency planning and landing site selection, these activities are not included in the roadmap, although they are key to mission success for a sample return mission. Similarly, ground handling tasks are not included in this assessment.

5.4.1 Returned Sample Integrity

Sample acquisition strategy, identified as a "hyper-velocity" or "clipper" mission, refers to missions which are not landed. On the other hand, conventional sample acquisition refers to landed missions, where use of a rover is optional. Break-the-chain techniques are an integral part of mission architecture and are divided into container sealing and transfer, and matrix (i.e., dust or ice) mitigation. Naturally, the technology development is tied into the break-the-chain timing; namely, whether contact with the target body is severed on the ground, in orbit, or in some combination. Goals and roadmaps for returned sample integrity activities are listed in Tables 5.4-1 and 5.4-2, respectively.

Table 5.4-1. Performance Goals: Returned Sample Integrity

Returned sample integrity	***Metric (Contaminant dilution)***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL6)***
Sample acquisition				
Conventional landers	ppm	Never done	1	0.01
Hyper velocity ("clippers")	ppm	Never done	1	0.01
Break the chain				
Container sealing/transfer	ppm	Never done	1	0.01
Dust mitigation (Mars)	ppm	Never done	1	0.01
Ice mitigation (comet)	ppm	Never done	1	0.01

Table 5.4-2. Roadmaps: Returned Sample Integrity

Returned sample integrity	06	07	08	09	10	11	12	13	14	15	16
Sample acquisition											
Conventional landers	3	4		5	6						
Hyper velocity ("clippers")						3	4		5	6	
Break the chain											
Container sealing/transfer	3	4		5	6						
Advanced goal						3	4		5	6	
Dust mitigation (Mars)	3	4		5	6						
Ice mitigation (comet)						2	3	4	5	6	
Missions: ***Dates for technology infusion***					**Comet surface sample return Mars Sample Return**					**Comet cryogenic sample return**	

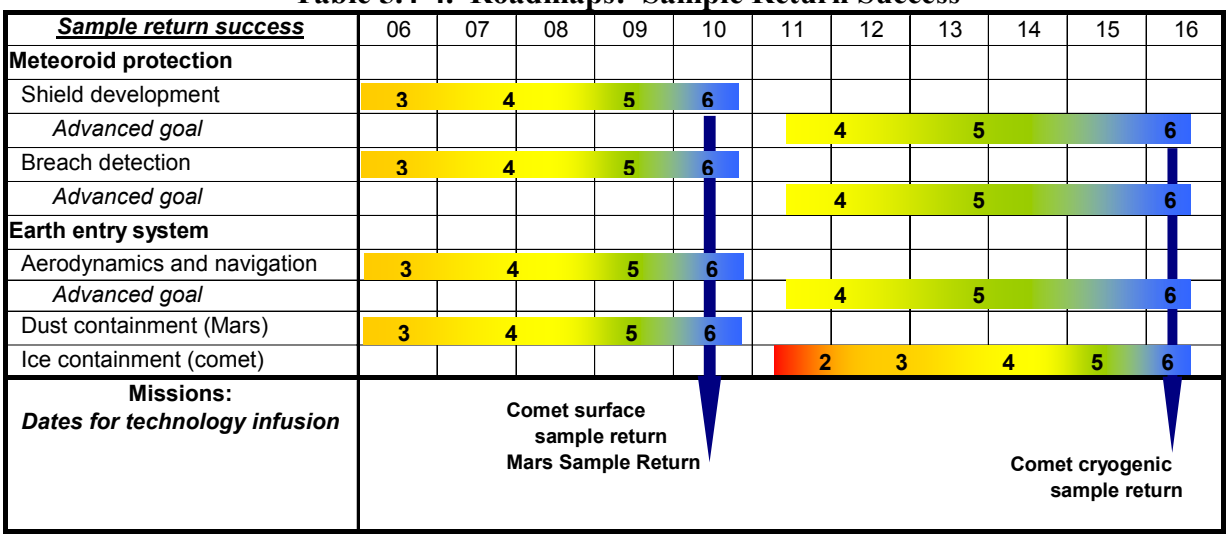
5.4.2 Sample Return Success

These processes are unlikely to contaminate the sample, but strongly determine mission success. They are divided broadly into the meteoroid protection development and the Earth entry system. The mission target influences these activities primarily through the additional containment needs of the Earth entry system. The metric of interest in these activities is the probability of success of that specific mission phase. The goals and roadmaps for sample return success activities are listed in Tables 5.4-3 and 5.4-4, respectively.

Table 5.4-3. Performance Goals: Sample Return Success

Sample return success	***Metric (Contaminant dilution)***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL6)***
Meteoroid protection				
Shield development	%	Never done	90	95
Breach detection	%	Never done	90	95
Earth entry system				
Aerodynamics and navigation	%	Never done	90	95
Dust containment (Mars)	%	Never done	90	95
Ice containment (comet)	%	Never done	90	95

Table 5.4-4. Roadmaps: Sample Return Success



5.5 Roadmaps for Systems Analysis

The systems analysis activities apply to both forward and back protection and, in many cases, provide the underlying foundation for the success of the technology development program. Because these are largely modeling efforts, the metric of interest is the model's relative uncertainty; further development is expected to provide for improved fidelity as models are refined and new science input is included. As charted here, these systems analysis tools are typically initiated by research providing the underpinnings, and then followed by target-specific development activities.

5.5.1 Microbiology Systems Analysis

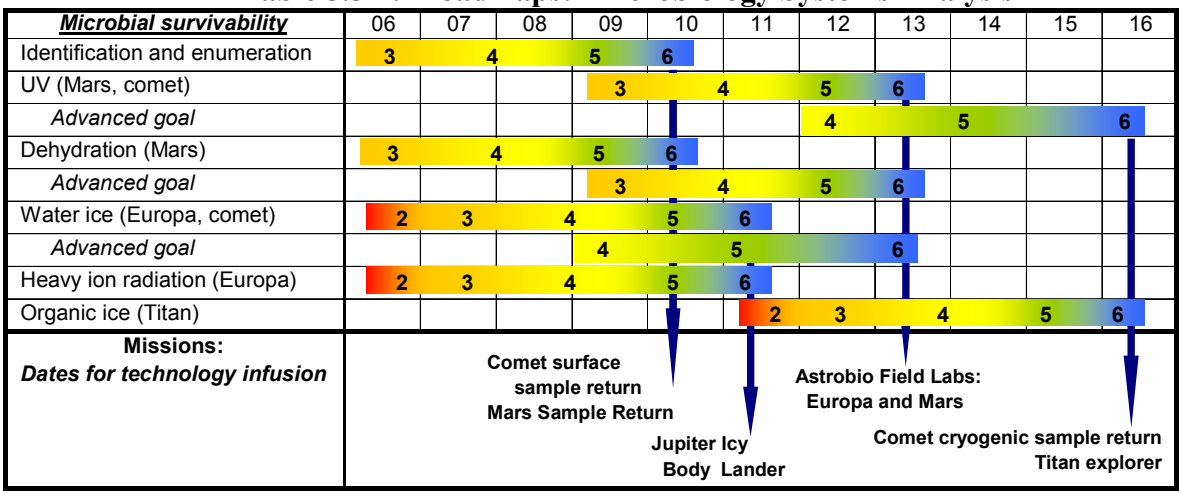
This field describes the environmental microbiology needed to better understand contamination probabilities. The foundation of this work is microbe identification and enumeration, designed to identify the organisms most relevant in contamination or round-trip studies. The activities which follow are intended to evaluate survivabilities as a function of target environment and should be closely linked to the transport analysis activities, described below.

The metric used to determine success is the relative uncertainty in the model; i.e., determination of the fidelity of the model (for instance, "good to a factor of 10", etc.). Current State of Practice is determined approximately and requires further study for a better determination. The goals of improved model fidelity are described in Table 5.5-1 and roadmaps are shown in Table 5.5-2.

Table 5.5-1. Performance Goals: Microbiology Systems Analysis

Microbial survivability	***Metric***	***State of Practice***	***5 year goal***	***10 year goal***
Identification and enumeration	%	500	50	10
UV (Mars, comet)	%	500	50	10
Dehydration (Mars)	%	500	50	10
Water ice (Europa, comet)	%	1000	50	10
Heavy ion radiation (Europa)	%	Never done	500	200
Organic ice (Titan)	%	Never done	500	200

Table 5.5-2. Roadmaps: Microbiology Systems Analysis



5.5.2 Transport Analysis

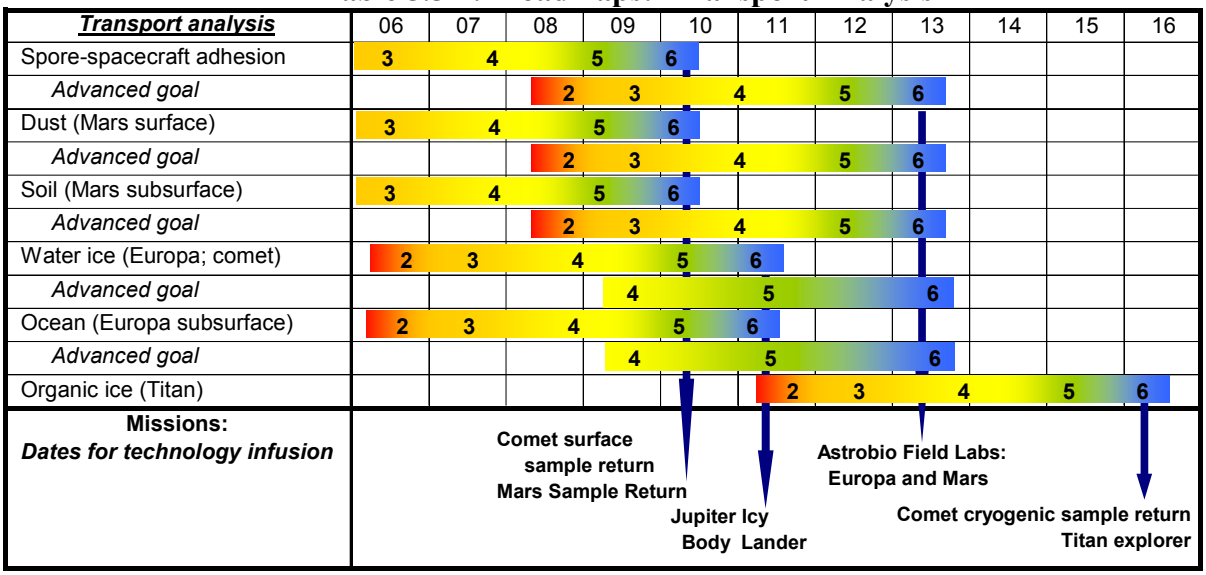
These activities model the spore transport in the environments of interest. The basis for this work is a currently funded preliminary effort to describe spore adhesion properties on a number of surfaces of interest, including spacecraft materials. The subsequent activities then describe the spore transport mechanisms on each target of interest.

Like the microbiology systems analysis, the performance goal is the model fidelity. Current State of Practice is determined approximately and requires further study for a better determination. The goals of improved model fidelity are described in Table 5.5-3 and roadmaps are shown in Table 5.5-4.

Table 5.5-3. Performance Goals: Transport Analysis

Transport analysis	***Metric (Relative uncertainty)***	***State of Practice***	***5 year goal (TRL 6)***	***10 year goal (TRL6)***
Spore-spacecraft adhesion	%	500	50	10
Dust (Mars surface)	%	500	50	10
Soil (Mars subsurface)	%	Never done	500	100
Water ice (Europa; comet)	%	Never done	500	200
Ocean (Europa subsurface)	%	Never done	500	200
Organic ice (Titan)	%	Never done	500	200

Table 5.5-4. Roadmaps: Transport Analysis



5.5.3 Integrated Modeling

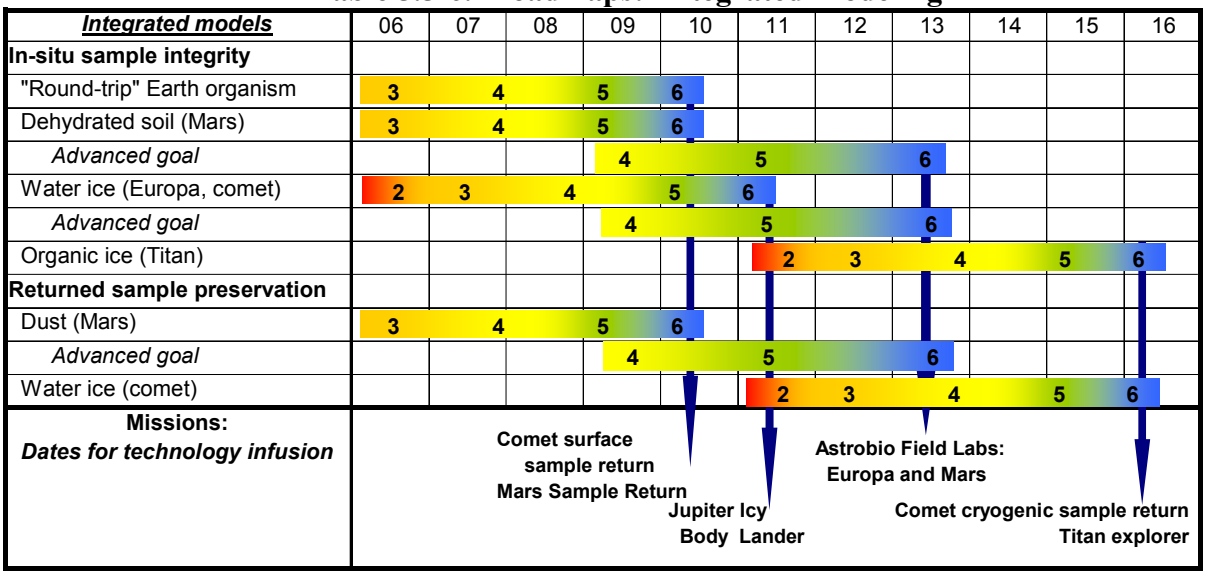
These activities encompass the development of the Probabilistic Risk Assessments (PRAs), or other tools used to evaluate contamination probabilities. They are divided into the in-situ sample integrity tasks and the returned sample preservation. In-situ sample integrity integrates the forward protection techniques as well as the covered sampling analysis. In-situ integrity also includes the analysis of the probability of a viable Earth organism making a "round-trip"; this is included here because this term threatens the scientific integrity of the results of a sample return mission. Returned sample preservation encompasses both sample return integrity and the mission success for the return leg.

As with other systems analysis tasks, the performance goal is the model fidelity. These integrated models are anticipated to have a fidelity determined by the individual components, and therefore the State of Practice is still approximate. The goals for integrated models are listed in Table 5.5-5, while the roadmaps are described in Table 5.5-6. Most of these integrated models do not yet exist and will be required for better quality trade studies in the early stages of mission design.

Table 5.5-5. Performance Goals: Integrated Modeling

Integrated models	*Metric (Relative uncertainty)*	*State of Practice*	*5 year goal (TRL 6)*	*10 year goal (TRL6)*
In-situ sample integrity				
"Round-trip" Earth organism	%	1000	500	200
Dehydrated soil (Mars)	%	1000	500	200
Water ice (Europa, comet)	%	Never done	500	200
Organic ice (Titan)	%	Never done	500	200
Returned sample preservation				
Dust (Mars)	%	Never done	500	200
Water ice (comet)	%	Never done	500	200

Table 5.5-6. Roadmaps: Integrated Modeling



6.0 Summary

A number of issues have arisen in Planetary Protection policy since the time of Viking. Recent scientific discoveries suggest that liquid water may have been present on Mars and that it is likely currently present under the ice crust on Europa. In addition, a new appreciation of extremophilia have expanded the suite of environments that were previously seen as hostile and are now viewed as possible hosts for unique metabolisms. While these factors lend a new excitement to the coming space exploration missions, they present new challenges to mission planning.

Some of the major findings of this study address management issues. At the top level, few systems engineers are currently engaged in the planning phase and Planetary Protection remains a lower level requirement rather than one that is integrated into the design. In addition, Planetary Protection technology for missions to Outer Planet targets still lags far behind that of missions to Mars.

Another lesson dating from the Viking era is that the science requirements for low background contamination for sample analysis have much in common with Planetary Protection requirements. The technological solutions for both the science and Planetary Protection have much in common and should be considered jointly. As a result, techniques for conducting science in superficially dirty environments should be further developed. Furthermore, appropriate cleaning, sterilization, and validation techniques will be relevant to meeting science requirements. Recent developments in the biotechnology industry have made a number of technologies available to NASA for use in validation of sterilization efficacy. However, the studies have previously not been organized in a systematic way to allow for a rigorous down-select process coordinated with mission planning activities. It will be important to focus the research efforts and identify redundancies.

Investments with high rates of return can be identified for a few key areas. A major gap in current Planetary Protection support is satisfactory modeling expertise and associated particle transport models. Many models currently in use in new research initiatives are inappropriate and poorly understood. Extensive modeling will be critical in evaluating the contamination risk associated with missions to special regions on Mars and for all sample return missions. The importance of developing a modeling group dedicated to Planetary Protection has not previously been recognized. Among other needs, the modeling effort needs to address the following areas: The properties of microbial adhesion to dust and very fine particles; organic contaminant adhesion properties; contaminant transport mechanics on spacecraft; planetary surface and subsurface mechanics. Systems analysis will be key to linking these efforts together and constraining them with appropriate validation experiments.

In addition, it was found that the NASA approval process for new technologies is not widely understood and is not published. The time for verification and adoption of new Planetary Protection technologies is long and unsynchronized with other mission planning activities, and the time for technology development has not been constrained by project review milestones. On the other hand, the NASA approval process may not indicate parameters, such as materials

compatibility, thus requiring further post-approval research to design a protocol useful to mission design engineers.

A number of technology needs are not specific to microbiology or contaminant detection, but rather require expertise from mechanical systems design. This need is particularly strong for sample return missions, but also expresses itself in the sampling acquisition strategies for traditional landed missions without sample return capabilities.

These findings suggest that systems engineering will be key to managing the major classes of tasks associated with Planetary Protection and contamination control. These disciplines include microbiology research, particle transport modeling, planetary science, and mechanical design. However, the interesting science developments of the last few years make it imperative that these tasks are led in a coherent fashion in order to continue the discovery process.

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Appendix A

COSPAR Definitions and Requirements

(20 October 2002)
Approved by the Bureau and Council, World Space Council, Houston, Texas, USA
Prepared by the COSPAR/IAU Workshop on Planetary Protection, 04/02,
with updates 10/02

A.1 Categorization of Missions

This section summarizes general mission categories according to COSPAR. Complete definitions can be found in the COSPAR Policy document.

Category I includes any mission to a target body which is not of direct interest for understanding the process of chemical evolution or the origin of life. No protection of such bodies is warranted and no Planetary Protection requirements are imposed by this policy.

Category II missions comprise all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration. The requirements are for simple documentation only.

Category III missions comprise certain types of missions (mostly flyby and orbiter) to a target body of chemical evolution and/or origin of life interest or for which scientific opinion provides a significant chance of contamination which could jeopardize a future biological experiment. Requirements will consist of documentation (more involved than Category II) and some implementing procedures, including trajectory biasing, the use of cleanrooms during spacecraft assembly and testing, and possibly bioburden reduction. Although no impact is intended for Category III missions, an inventory of bulk constituent organics is required if the probability of impact is significant.

Category IV missions comprise certain types of missions (mostly probe and lander) to a target body of chemical evolution and/or origin of life interest or for which scientific opinion provides a significant chance of contamination which could jeopardize future biological experiments. Requirements imposed include more documentation, including a bioassay to enumerate the bioburden, a probability of contamination analysis, an inventory of the bulk constituent organics and an increased number of implementing procedures. The implementing procedures required may include trajectory biasing, cleanrooms, bioload reduction, possible partial sterilization of the direct contact hardware and a bioshield for that hardware. Generally, the requirements and compliance are similar to *Viking*, with the exception of complete lander/probe sterilization.

Category V missions comprise all Earth-return missions. The concern for these missions is the protection of the terrestrial system, the Earth and the Moon. For solar system bodies deemed by scientific opinion to have no indigenous life forms, a subcategory "unrestricted Earth return" is defined. Missions in this subcategory have Planetary Protection requirements on the outbound phase only, corresponding to the category of that phase (typically Category I or II). For all other Category V missions, in a subcategory defined as "restricted Earth return," the highest degree of

concern is expressed by the absolute prohibition of destructive impact upon return, the need for containment throughout the return phase of all returned hardware which directly contacted the target body or unsterilized material from the body, and the need for containment of any unsterilized sample collected and returned to Earth. Post-mission, there is a need to conduct timely analyses of the unsterilized sample collected and returned to Earth, under strict containment, and using the most sensitive techniques. If any sign of the existence of a nonterrestrial replicating entity is found, the returned sample must remain contained unless treated by an effective sterilizing procedure. Category V concerns are reflected in requirements that encompass those of Category IV plus a continuing monitoring of project activities, studies and research (i.e., in sterilization procedures and containment techniques).

Table A.1-1: Proposed Categories for Solar System Bodies and Types of Missions

	Category I	Category II	Category III	Category IV	Category V
Type of Mission	Any but Earth Return	Any but Earth Return	No direct contact (flyby, some orbiters)	Direct contact (lander, probe, some orbiters)	Earth return
Degree of Concern	None	Record of planned impact probability and contamination control measures	Limit on impact probability Passive bioload control	Limit on probability of non-nominal impact Limit on bioload (active control)	If restricted Earth return: • No impact on Earth or Moon; • Returned hardware sterile; • Containment of any sample.
Representative Range of Requirements	None	Documentation only (all brief): • PP plan • Pre-launch report • Post-launch report • Post-encounter report • End-of-mission report	Documentation (Category II plus) • Contamination control • Organics inventory (as necessary) Implementing procedures such as: • Trajectory biasing • Cleanroom • Bioload reduction (as necessary)	Documentation (Category II plus) • P_c analysis plan • Microbial reduction plan • Microbial assay plan • Organics inventory Implementing procedures such as: • Trajectory biasing • Cleanroom • Bioload reduction • Partial sterilization of contacting hardware (as necessary) • Bioshield Monitoring of bioload via bioassay	Outbound Same category as target body/ outbound mission Inbound If restricted Earth return: • Documentation (Category II plus) • P_c analysis plan • Microbial reduction plan •Microbial assay plan • Trajectory biasing • Sterile or contained returned hardware • Continual monitoring of project activities • Project advanced studies/research. If unrestricted Earth return: • None

A.2 Category-Specific Listing of Target Body/Mission Types

Category I: Flyby, Orbiter, Lander: Venus; Moon; Undifferentiated, metamorphosed asteroids; others TBD

Category II: Flyby, Orbiter, Lander: Comets; Carbonaceous Chondrite Asteroids; Jupiter; Saturn; Uranus; Neptune; Pluto/Charon; Kuiper-Belt Objects; others TBD

Category III: Flyby, Orbiters: Mars; Europa; others TBD

Category IV: Lander Missions: Mars; Europa; others TBD

Category V: Any Earth-return mission. "Restricted Earth return": Mars; Europa; others TBD; "Unrestricted Earth return": Moon; others TBD.

A.3 Category III/IV/V Requirements for Mars and Special Regions

Category III/IV Requirements for Mars

Category III. Mars orbiters will not be required to meet orbital lifetime requirements* if they achieve bioburden levels equivalent to the *Viking* lander pre-sterilization total bioburden. (*Defined as 20 years after launch at greater than or equal to 99% probability, and 50 years after launch at greater than or equal to 95% probability.)

Category IV for Mars is subdivided into IVa, IVb, and IVc:

Category IVa. Lander systems not carrying instruments for the investigations of extant martian life are restricted to a biological burden no greater than *Viking* lander pre-sterilization levels

Category IVb. For lander systems designed to investigate extant martian life, all of the requirements of Category IVa apply, along with the following requirement:

The entire landed system must be sterilized at least to *Viking* post-sterilization biological burden levels, or to levels of biological burden reduction driven by the nature and sensitivity of the particular life-detection experiments, whichever are more stringent; **OR**
The subsystems which are involved in the acquisition, delivery, and analysis of samples used for life detection must be sterilized to these levels, and a method of preventing recontamination of the sterilized subsystems and the contamination of the material to be analyzed is in place.

Category IVc. For missions which investigate martian special regions (see definition below), even if they do not include life detection experiments, all of the requirements of Category IVa apply, along with the following requirement:

Case 1. If the landing site is within the special region, the entire landed system shall be sterilized at least to the *Viking* post-sterilization biological burden levels.
Case 2. If the special region is accessed though horizontal or vertical mobility, either the entire landed system shall be sterilized to the *Viking* post-sterilization biological burden levels, **OR** the subsystems which directly contact the special region shall be sterilized to these levels, and a

method of preventing their recontamination prior to accessing the special region shall be provided.

If an off-nominal condition (such as a hard landing) would cause a high probability of inadvertent biological contamination of the special region by the spacecraft, the entire landed system must be sterilized to the *Viking* post-sterilization biological burden levels.

Definition of "Special Region"

A Special Region is defined as a region within which terrestrial organisms are likely to propagate, **OR** a region which is interpreted to have a high potential for the existence of extant martian life forms.

Given current understanding, this is applied to regions where liquid water is present or may occur. Specific examples include but are not limited to:

- Subsurface access in an area and to a depth where the presence of liquid water is probable
- Penetrations into the polar caps
- Areas of hydrothermal activity.

Category V: Sample Return Missions from Mars

Category V. The Earth return mission is classified, "Restricted Earth return."

- Unless specifically exempted, the outbound leg of the mission shall meet Category IVb requirements. This provision is intended to avoid "false positive" indications in a life-detection and hazard-determination protocol, or in the search for life in the sample after it is returned. A "false positive" could prevent distribution of the sample from containment and could lead to unnecessary increased rigor in the requirements for all later Mars missions.
- The sample container must be sealed after sample acquisition. A redundant, fail-safe containment with a method for verification of its operation before Earth-return shall be required. The integrity of the flight containment system shall be maintained until the sample is transferred to containment in an appropriate receiving facility.
- The mission and the spacecraft design must provide a method to "break the chain of contact" with Mars. No uncontained hardware that contacted Mars, directly or indirectly, shall be returned to Earth. Isolation of such hardware from the Mars environment shall be provided during sample container loading into the containment system, launch from Mars, and any in-flight transfer operations required by the mission.
- Reviews and approval of the continuation of the flight mission shall be required at three stages: 1) prior to launch from Earth; 2) prior to leaving Mars for return to Earth; and 3) prior to commitment to Earth re-entry.
- A program of life detection and biohazard testing, or a proven sterilization process, shall be undertaken as an absolute precondition for the controlled distribution of any portion of the sample.

A.4 Category III/IV/V Requirements for Europa

Category III and IV. Requirements for Europa flybys, orbiters and landers, including bioburden reduction, shall be applied in order to reduce the probability of inadvertent contamination of the ocean to less than 1×10^{-4} per mission. These requirements will be refined in future years, but the calculation of this probability should include a conservative estimate of poorly known parameters, and address the following factors, at a minimum:

- Bioburden at launch
- Cruise survival for contaminating organisms
- Organism survival in the radiation environment adjacent to Europa
- Probability of landing on Europa
- The mechanisms and timescales of transport to the europan subsurface
- Organism survival and proliferation before, during, and after subsurface transfer

Preliminary calculations of the probability of contamination suggest that bioburden reduction will likely be necessary even for Europa orbiters (Category III) as well as for landers, requiring the use of cleanroom technology and the cleanliness of all parts before assembly, and the monitoring of spacecraft assembly facilities to understand the bioload and its microbial diversity, including specific problematic species. Specific methods should be developed to eradicate problematic species. Methods of bioburden reduction should reflect the type of environments found on Europa, focusing on Earth extremophiles most likely to survive on Europa, such as cold and radiation tolerant organisms (SSB 2000).

Category V. The Earth return mission is classified, "Restricted Earth return."

- The outbound leg of the mission shall meet the contamination control requirements given above. This provision should avoid "false positive" indications in a life-detection and hazard-determination protocol, or in the search for life in the sample after it is returned.
- The sample container must be sealed after sample acquisition. A redundant, fail-safe containment with a method for verification of its operation before Earth-return shall be required. The integrity of the flight containment system shall be maintained until the sample is transferred to containment in an appropriate receiving facility.
- The mission and the spacecraft design must provide a method to "break the chain of contact" with Europa. No uncontained hardware that contacted Europa, directly or indirectly, shall be returned to Earth. Isolation of such hardware from the europan environment shall be provided during sample container loading into the containment system, launch from Europa, and any in-flight transfer operations required by the mission.
- Reviews and approval of the continuation of the flight mission shall be required at three stages: 1) prior to launch from Earth; 2) prior to leaving Europa or the europan environment for return to Earth; and 3) prior to commitment to Earth re-entry.
- A program of life detection and biohazard testing, or a proven sterilization process, shall be undertaken as an absolute precondition for the controlled distribution of any portion of the sample (SSB 1998).

A.5 Small Solar System Bodies

Categories I/II/III/IV to Small Solar System Bodies

Category I, II, III, or IV. The small bodies of the solar system not elsewhere discussed in this policy represent a very large class of objects. Imposing forward contamination controls on these missions is not warranted except on a case-by-case basis, so most such missions should reflect Categories I or II. Further elaboration of this requirement is anticipated.

Category V: Sample Return Missions from Small Solar System Bodies

Category V. Determination as to whether a mission is classified "Restricted Earth return" or not shall be undertaken with respect to the best multidisciplinary scientific advice, using the framework presented in the 1998 report of the US National Research Council's Space Studies Board entitled, *Evaluating the Biological Potential in Samples Returned from Planetary Satellites and Small Solar System Bodies: Framework for Decision Making* (SSB 1998). Specifically, such a determination shall address the following six questions for each body intended to be sampled:

1. Does the preponderance of scientific evidence indicate that there was never liquid water in or on the target body?
2. Does the preponderance of scientific evidence indicate that metabolically useful energy sources were never present?
3. Does the preponderance of scientific evidence indicate that there was never sufficient organic matter (or CO_2 or carbonates and an appropriate source of reducing equivalents) in or on the target body to support life?
4. Does the preponderance of scientific evidence indicate that subsequent to the disappearance of liquid water, the target body has been subjected to extreme temperatures (i.e., >160° C)?
5. Does the preponderance of scientific evidence indicate that there is or was sufficient radiation for biological sterilization of terrestrial life forms?
6. Does the preponderance of scientific evidence indicate that there has been a natural influx to Earth, (e.g., via meteorites, of material equivalent to a sample returned from the target body)?

For containment procedures to be necessary ("Restricted Earth return"), an answer of "no" or "uncertain" needs to be returned to all six questions.

For missions determined to be Category V, "Restricted Earth return," the following requirements shall be met:

- The outbound leg of the mission shall meet contamination control requirements to avoid "false positive" indications in a life-detection and hazard-determination protocol, or in any search for life in the sample after it is returned.
- The sample container must be sealed after sample acquisition. A redundant, fail-safe containment with a method for verification of its operation before Earth-return shall be required. The integrity of the flight containment system shall be maintained until the sample is transferred to containment in an appropriate receiving facility.

- The mission and the spacecraft design must provide a method to "break the chain of contact" with the small body. No uncontained hardware that contacted the body, directly or indirectly, shall be returned to Earth. Isolation of such hardware from the body's environment shall be provided during sample container loading into the containment system, launch from the body, and any in-flight transfer operations required by the mission.
- Reviews and approval of the continuation of the flight mission shall be required at three stages: 1) prior to launch from Earth; 2) prior to leaving the body or its environment for return to Earth; and 3) prior to commitment to Earth re-entry.
- A program of life detection and biohazard testing, or a proven sterilization process, shall be undertaken as an absolute precondition for the controlled distribution of any portion of the sample (SSB 1998).

Appendix B

NASA Procedure to Approve New Planetary Protection Processes

As dictated to the Planetary Protection Group at the Jet Propulsion Laboratory by the NASA Planetary Protection Officer, September, 2004.

The NASA process to certify new techniques has the following components:

B.1 Concept Originator Responsibilities

- Identify sterilization modality of interest
- Generate statistically valid data to provide proof of the process effectiveness at the intended scale of application
- Prepare supporting documentation and reports with recommendations
- Conduct peer review of documentation and reports using NASA-appointed experts
- Deliver recommendation by review committee to NASA Planetary Protection Officer (PPO)
- Deliver to NASA PPO all pertinent documentation and reports with recommendations

B.2 NASA HQ Responsibilities

- NASA Planetary Protection Officer (PPO) and his staff decide on the appropriate implementation and then prepare and present the amended information to the NASA Planetary Protection Advisory Committee (PPAC)
- The PPAC reviews presented material and makes recommendations to the Associate Administrator for Space Science for approval or disapproval
- The PPO issues the appropriate specifications for the new method and enters it into the appropriate NPG as an option for future use by flight projects

Appendix C

Implementation of Planetary Protection Measures on Selected Past and Operating Missions[1]

As given by NASA's Planetary Protection website in November, 2004: http://planetaryprotection.nasa.gov/pp/index.htm.
This list is organized by launch date and has not been updated since the MER landings.

C.1 Galileo

NASA's Galileo mission to Jupiter was launched on October 18, 1989, and arrived at Jupiter in December 1995. The spacecraft spent nearly eight years collecting vast amounts of scientific data on the planet and its moons.

The Galileo mission was classified Category II for Planetary Protection purposes, requiring documentation only reporting probabilities of impact, contamination control procedures used during assembly, and disposition of all launched hardware at completion of the mission. Microbiological assays were not required, though extensive documentation was prepared.

The End of Mission Report included the option of taking steps to ensure that the spacecraft would not inadvertently impact a place of potential interest to astrobiological investigators. Because Galileo collected evidence of water on Europa, Ganymede and Callisto, this end-of-mission option was exercised. On September 21, 2003, mission managers sent Galileo into the atmosphere of Jupiter to burn up at the end of its operating life, thereby preventing inadvertent collision with and possible contamination of one of Jupiter's icy moons.

C.2 Mars Observer

The Mars Observer spacecraft, launched on September 25, 1992, was intended to study the geology, geophysics, and climate of Mars. This mission was classified Category III for Planetary Protection purposes. NASA lost contact with the spacecraft in August 1993, just as it was about to enter orbit around Mars. Though the fate of Mars Observer is not known, it is possible that pieces of the spacecraft could have inadvertently impacted the surface of Mars, posing a risk of forward contamination.

[1] While this summary describes missions implemented by NASA and other international space agencies, it is not complete, particularly with respect to the efforts of the former Soviet Union.

C.3 Mars Pathfinder

Mars Pathfinder was launched on December 3, 1996, landed at its destination on July 4, 1997, and delivered the small rover Sojourner to the surface of the planet. Since the Pathfinder Lander and Sojourner Rover were intended make contact with the surface of Mars, this mission was categorized Category IV-A for Planetary Protection purposes, and subject to appropriate requirements for preventing forward contamination.

C.4 Cassini

The Cassini mission, launched on October 15, 1997, is an international collaboration among three space agencies: NASA, the European Space Agency, and the Italian Space Agency (which provided the spacecraft's high-gain antenna). The Cassini spacecraft entered orbit around Saturn on July 1, 2004, and sent ESA's Huygens probe into the atmosphere of Saturn's moon Titan in January 2005.

The Cassini Saturn Orbiter will spend four years studying the planet, its rings, and moons. The Huygens Probe conducted in-situ analyses that should provide further details about the environment of Titan, which may feature organic chemistry of interest to scientists studying the origin of life. The Cassini mission is classified Category II for Planetary Protection purposes. As Cassini nears the end of its mission, there may be procedures taken to ensure that the orbiter does not inadvertently enter the atmosphere of Titan.

C.5 Mars Global Surveyor

The Mars Global Surveyor orbiter was launched on November 7, 1996 and entered orbit about Mars on September 11, 1997. The mission has studied the Martian surface, atmosphere, and interior during the past eight years. This mission is classified Category III for Planetary Protection purposes, imposing specific limitations on the probability that any launched hardware would inadvertently impact Mars during a specified time period after launch. Global Surveyor's orbit may be raised at the end of its mission to ensure against inadvertent entry into the planet's atmosphere.

C.6 Mars Climate Orbiter

Mars Climate Orbiter (MCO), launched Dec. 11, 1998, was intended to function as an interplanetary weather satellite and a communications relay for the Mars Polar Lander. The MCO mission was classified Category III for Planetary Protection purposes. NASA lost contact with the MCO spacecraft on Sept. 23, 1999, upon its arrival at Mars. Though the cause of the loss of MCO is not certain, the spacecraft most likely inadvertently entered the atmosphere of Mars and probably burned up during entry. If, instead, MCO survived entry to impact the surface of Mars, the debris could pose the possibility of forward contamination.

C.7 Mars Polar Lander

The Mars Polar Lander mission, launched January 3, 1999, was intended to perform surface science and to sample and analyze water ice near the planet's south polar cap. The mission also

included two small Deep Space 2 probes, which were intended to impact the surface of Mars to perform sub-surface science and test new technologies. NASA lost contact with the lander and the probes upon their arrival at Mars on December 3, 1999. This mission was classified Category IV-A for Planetary Protection purposes. Since the lander and the probes were intended to contact the surface of Mars, they were subject to appropriate Planetary Protection requirements aimed at preventing forward contamination. Bioburden reduction for the lander met a requirement of less than 300,000 spores at launch, with a surface distribution of no more than 300 culturable bacterial spores per square meter of surface area. The bioburden on the lander was reduced by the alcohol wipe method, dry heat microbial reduction, and assembly in a class 100,000 cleanroom. The interior surfaces of the probes were also subject to Planetary Protection mission requirements. The probes were assembled in Class 100 clean benches, and integrated into an aeroshell that prevented recontamination of accountable interior surfaces. Much of the probe hardware was dry heat processed, although some encapsulated burden was not adequately subjected to this process.

C.8 Mars Odyssey

Mars Odyssey, launched on April 7, 2001, is an orbiting spacecraft designed to remotely determine the composition of the planet's surface, to detect water and shallow buried ice, and to study the radiation environment, in part to determine its potential effects on the health of future human explorers. The spacecraft arrived at Mars on October 24, 2001, and its primary science mission is scheduled to end in August 2004. Following its primary science mission, the spacecraft will function for up to an additional Martian year as a communication relay system for spacecraft sent to the surface of Mars.

This mission is classified Category III for Planetary Protection purposes. Mars Odyssey's orbit may be raised at the end of its mission, to ensure against inadvertent entry into the planet's atmosphere.

C.9 Genesis

NASA's Genesis mission, launched in August 2001, collected samples of the solar wind for return to Earth in September 2004 for laboratory analysis. The sun and the planets in our solar system are believed to have originated from the gravitational collapse of a cloud of gas, dust and ice. Scientists hope to learn more about the origin and nature of the planets by examining the solar wind, particles emanating from the surface of the sun.

This mission was classified Category V, unrestricted Earth return, for Planetary Protection purposes. The Genesis spacecraft's sample collection hardware was cleaned and assembled in a Class 10 cleanroom, containing no more than one 10-micron-size particle per cubic foot of air. Solar wind samples collected and returned to Earth by Genesis will be stored and cataloged under ultra-pure cleanroom conditions, and made available to the scientific community for study.

C.10 Mars Exploration Rovers

NASA's Mars Exploration Rover spacecraft — Spirit and Opportunity — were launched in June and July 2003, respectively, and landed on Mars in January 2004. Mars is considered a prime site

for astrobiological investigation, and MER mission science is focused on how past water activity on Mars has influenced the planet's environment over time. Mars has surface water ice, and many scientists believe that liquid water may still exist beneath the surface of the planet.

This mission is classified Category IV-A for Planetary Protection purposes. Planetary protection policy dictated evaluating that the rovers met the biological requirements set forth by the requirements for Category IV-A missions. Both rovers were developed by NASA's Jet Propulsion Laboratory. Final assembly of the rovers took place at the Kennedy Space Center, where they underwent bioload reduction and biological contamination prevention techniques. Spacecraft parts with large surface areas (e.g., the airbags used during landing) that could tolerate high temperatures were subjected to dry microbial heat reduction processes to reduce bioload. High-efficiency particulate arrestor (HEPA) filters were used to protect electronic boxes and other sensitive areas from external biological contamination, and techniques such as alcohol wiping were used during assembly to maintain the cleanliness of each rover. Planetary protection technicians sampled spacecraft surfaces during assembly and prior to encapsulation in the aeroshell to check for microbial spores. Testing showed that the total spore count on both Spirit and Opportunity was well below the allowable level.

C.11 Stardust

The Stardust spacecraft, launched in February 1999, made its rendezvous with Comet Wild 2 in January 2004, collecting samples of dust from the comet's coma—the gas and dust envelope that surrounds its nucleus—for return to Earth. The Stardust mission is the first mission designed to return samples to Earth from a comet.

This mission is classified Category V, unrestricted Earth return, for Planetary Protection purposes. The Comet and Interplanetary Dust Analyzer aboard the Stardust spacecraft contains two parts considered sensitive to contamination: a dust detector and an aerogel tray of dust collection surfaces. These components were cleansed by a nitrogen purge before the spacecraft was launched. The Stardust sample return capsule (SRC), which contains the aerogel tray, is designed to keep out other materials that could interfere with analyses of the dust samples. The SRC features filtered vents to limit the potential for contaminating samples during reentry.

The Stardust SRC is expected to parachute to Earth at the U.S. Army's Utah Test and Training Range in early 2006. Once on the ground, the SRC will be enclosed in a dry nitrogen environment and flown to NASA's sample curation laboratory at Johnson Space Center, where samples—expected to total 1 microgram in mass—will be carefully handled and contained to preserve their pristine condition for scientific studies. Approximately six months of preliminary investigation will precede the release of dust samples to the science community. During this preliminary investigation period, scientists plan to document the state of the collected sample and determine the best way to proceed with sample distribution and analysis.

C.12 MUSES-C (Hayabusa)

Japan's MUSES-C mission, now known as Hayabusa, is the first solar system exploration mission designed to return a sample of an asteroid to Earth. Hayabusa is sponsored by the Japan Aerospace Exploration Agency (JAXA), and NASA is participating in the mission. The

Hayabusa spacecraft was launched on May 9, 2003. It is scheduled to rendezvous with the asteroid Itokawa in 2005, collect a sample and return it to Earth in 2007.

The mission is in compliance with COSPAR Planetary Protection policy and is classified Category V, unrestricted Earth return, for Planetary Protection purposes. Precautions have been taken to prevent contamination of the sample collection equipment and the sample return container, and ensure that sample material can be preserved in its pristine condition upon return.

C.13 Mars Express

The European Space Agency's Mars Express mission was launched in June 2003 and arrived at Mars on December 25, 2003, to collect data on the planet's atmosphere and surface. NASA provided components for science instruments, and will provide support for American scientists selected to participate in several investigations. Upon arrival, the spacecraft deployed a lander, called Beagle 2, to the surface of Mars to conduct exobiological and geochemical investigations. Beagle 2 entered the Martian atmosphere, but was lost during entry, descent and landing operations.

The Mars Express mission, classified Category IV-A for Planetary Protection purposes, is in compliance with COSPAR Planetary Protection policy, which, like NASA's policy, establishes strict sterilization requirements for Mars landers carrying instruments intended to search for evidence of biological activity.

Appendix D

Appendix D: Analysis of Forward Protection Techniques Under Development

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November, 2004

D.1 Introduction

Technology development impacting mission architecture may be broadly classified into four categories: Cleaning, sterilization modalities, detection techniques, and contamination transport. Current initiatives in these categories have been analyzed and their progress toward approval has been determined according to a new, simplified framework. These initiatives and the analysis are described in this Appendix.

D.2 Cleaning

Cleaning research took the form of surface characterization or organic contamination; effectively, this breakdown sought to answer the question of whether the surface or the solvent yielded a greater effect on producing a clean surface. While this task is obviously critical to Planetary Protection and contamination control, it does not impact mission architecture or require as sophisticated a down-select mechanism.

Multiple-solvent cleaning is described in JPL document FS505146C, General Cleaning of Materials, Rev. E (Anonymous, 1990). Surfaces are treated by ultrasonic cleaning with acetone and IPA, followed by alkaline cleaning with Oakite 61B (Chemetall; Bletchley, UK). Subsequently, surfaces are rinsed with deionized water and dried with clean, dry nitrogen. Differences in material tolerance to this cleaning protocol are not addressed under current NASA protocol.

Table D.2-1: Cleaning Efficiency on Various Surfaces[2].

	Percent spores remaining on select surfaces	
Technique	**Aluminum**	**Titanium**
Isopropanol wipes	1	3.5
Water wipe	1	3
JPL method	.5	0
Ultrapure water rinse	.5	1
Commercial semi-aqueous multiple solvent	62	0

[2] Measurements were conducted on 25 cm^2 coupons.

A recent study in the Planetary Protection group compared three swab materials for spacecraft sampling. The materials studied were cotton, polyester, and ESD polyester, while the representative spacecraft surfaces were aluminum, graphite composite, and epoxy black paint. In general, swab head recovery was determined to be ~85% for cotton and ESD polyester, and only 62% for polyester. Furthermore, polyester swabs absorbed liquid at slower rates than cotton and ESD polyester and were only able to absorb 100 µl liquid.

This is particularly important in light of the fact that the cotton swabs, composed of cellulose, are likely to leave behind various biological materials at levels of interest to science experiments. These results identifying better swabs will be included in the ATP/LPS protocols, discussed below with the validation techniques.

D.3 Sterilization Modalities

The guidelines of NPG 8020.12C, derived from studies in the *Viking* era, specify that dry heat microbial reduction (DHMR) is the only approved sterilization modality. These guidelines assign parameters for various D-values; where D-values are defined as the time required to reduce the microbial population by a factor of 10, such that 90% of the population is destroyed. The D-values at 125°C for various surfaces are listed in Table D.3-1:

Table D.3-1: D-Values According to NPG 8020.12C

Surface	Parameter name	D-value: Time (h) at 125°C
Exposed surface	D_{S125}	0.5
Mated	D_{M125}	1
Buried or encapsulated	D_{B125}	5

A corrected time D may be applied to materials unable to tolerate the 125°C requirement by assuming that:

$$D = D_{125} \times 10 ** (125\text{-}T)/21$$

where $D_{125} = D_{S125}$, D_{M125}, or D_{B125}, as appropriate for that surface. This correction is only defined for temperatures as low as 100° C.

DHMR leads to a number of challenges in mission planning. In order to have a terminal sterilization step, the final spacecraft must be assembled and then heated, necessitating an appropriate sterilization facility. However, if another technique were available to provide surface sterilization upon assembly, then DHMR could be used for bulk sterilization of various subsystems prior to ATLO.

A number of alternative techniques have been considered and are currently being brought to maturity. These techniques have been discussed in the main body of this document and are briefly summarized here. Hydrogen peroxide vapor sterilization is effective to sterilize surfaces but the specifications and material compatibility issues are still under study.

Environmental sterilization describes a number of techniques, including ultraviolet radiation at Mars, atmospheric entry at Mars, and ambient radiation at Europa. However, use of these techniques requires extensive modeling, and in the case of Europa, more effort in understanding the behavior of various extremophiles is required, as well.

D.4 Detection Techniques

It is now known that less than 10% of known microbes form spores, and of these, less than 1% of are amenable to culturing. Thus, the simple measure of culturable spores underestimate the population of microbes, and thus the hardware bioburden, by a factor of at least 1000. In addition, the standard NASA method does not measure any of the nonviable organisms, biosignature molecules, or eukaryotic biological contamination which are now a part of hardware cleanliness validation. The newer, more comprehensive methods of hardware validation are described below.

The NASA standard assay, given in NPG 5340.1C (NASA Standard Procedure for the Microbial Examination of Space Hardware), requires sampling a 26 cm^2 portion of the hardware using a sterilized cotton swab wetted with sterile, distilled water. The swab is then vortexed and sonicated in distilled water to remove the microbes and other bioburden species. The solution is heat-shocked at 80^o C to kill all cells, except for spores able to survive this heat treatment. The solution containing these spores is then transferred onto a plate containing tryptic soy agar (TSA). The plates are allowed to grow for three days at 32^oC prior to counting of colony forming units. This is currently the only assay approved for spore counting.

Adenosine triphosphate (ATP) and Lipopolysaccharide (LPS) detection

Adenosine triphosphate (ATP) detection is a bioluminescent-based, spectrophotometric technique. ATP is a key molecule in cellular metabolism. In this assay, the bioluminescence generated when ATP reacts with a specific enzyme is measured spectrophotometrically. As intracellular ATP is released from the cells, the resulting bioluminescence intensity is directly proportional to the ATP quantity.

Lipopolysaccharide (LPS) is produced by Gram-negative bacteria and measured with the limulus amebocyte lysate (LAL) assay, which takes advantage of an enzyme produced in the horse-shoe crab blood cells (known as limulus amebocytes) as an immune response to a microbial infection. Since it only measures Gram-negative microbial contamination, it requires combination with another technique able to detect Gram-positive microbes.

Both these assays are commercially available kits and do not require a high degree of operator skill for their implementation. The assay involves swabbing the hardware surface, transferring all of the cells present on the swab to a small tube, and then adding the requisite components for the reaction to proceed. In addition, these assays take place on time scales of less than 3 8 hours, rather than the 72 hours currently required by NASA standard protocols.

In addition, new bio-assay techniques for efficiently sampling spacecraft surfaces have been developed with funding by the Mars Planetary Protection office. Besides portability, accuracy, and speed benefits, automating this process is also a possibility. The development work was completed in 2004 and the reports were submitted to NASA for peer review in early 2005.

Rapid spore assay

In conjunction with the ATP work, the JPL Planetary Protection group has sought to accelerate the analysis time for cultures used to assay spacecraft surfaces. One major drawback to current NASA protocol is the 72 hours needed to culture organisms on TSA plates, thus using an enormous number of man-hours in waiting for results. The ability to count spore-formers more rapidly would result in an enormous cost savings in labor.

To that end, extensive work has taken place in reviewing commercial systems for rapid counting. A candidate system able to produce good results in less than 8 hours has been identified and the protocol is being finalized. This work will be presented to NASA headquarters for certification in conjunction with the ATP assay.

RNAse

RNAse detection is currently available as a qualitative detection technique. The fluorescent substrate is a modified ribonucleic acid (RNA) molecule containing a fluorophore and a quencher. When RNase cleaves this RNA oligonucleotide, the fluorophore is separated from the quencher and a green fluorescent signal is emitted and measured by a fluorometer. The assay is monitored kinetically and is read by a fluorometer capable of utilizing a 96-well format. Fluorometers that are capable of real-time or kinetic measurements are particularly useful for monitoring the RNAseAlert Assay since the rate of fluorescence increase is proportional to the amount and activity of contaminating RNAses. Preliminary collaborations between industry (Ambion, Inc.) and JPL have led to a quantitative assay capable of measuring RNase levels between 0.1pg and 5pg.

This assay is still early in its development but has great potential application for biodetection because RNA is ubiquitous to all life on earth. This assay will provide for the monitoring of spacecraft cleanliness regardless of the type of microbial contamination source.

Q-PCR

Ultrasensitive analysis of the DNA of the microbes and other surface biocontaminants can be achieved using quantitative-polymerase chain reaction (Q-PCR). PCR not only may detect small amounts of DNA, but it is also capable of sequencing the DNA present, leading to highly specific identification of the biocontaminants. To conduct PCR, the DNA must be extracted from the surface through the use of generic primers (short DNA fragments chosen to target genes found in most microbes). The extracted DNA sequences are then replicated (amplified) and then separated. Through repeated cycles, this process proceeds geometrically.

While PCR is a powerful method for identifying the nature of the hardware biocontaminants, it cannot be used to readily quantify the bioburden. PCR can be rendered quantitative by the addition of a competitor molecule at known quantities into the reaction tubes, separating the amplification products, usually by size, and then comparing the amounts. Further work is needed to improve the accuracy of this process, but it presents a compelling possibility for accurate validation of cleaning and sterilization processes. Q-PCR faces challenges from reagent contamination since a contaminant will be amplified just as readily as the DNA of interest.

DPA

Dipicolinic acid (DPA, or 2,6-pyridinedicarboxylic acid) is present in high concentrations in the core of bacterial spores. For all known lifeforms, DPA is unique to bacterial spores and is released into bulk solution upon germination, which is the process of transformation from spore to vegetative cell. DPA thus serves as an indicator molecule for the presence of bacterial spores. DPA is particularly interesting because it serves as a classic inorganic ligand that binds metal ions with high affinity. DPA binding to terbium ions triggers intense green luminescence under UV excitation, indicating the presence of bacterial spores; the intensity of the luminescence can be directly correlated to the number of endospores.

This technique shows promise for many reasons. Due to the atomic physics, terbium does not show strong luminescence unless it is in coordination with aromatic chromphores, such as DPA, making false positives due to simple atomic excitations unlikely. In addition, potential interferents such as sugars, nucleic and amino acids are present in much lower concentrations in endospores and vegetative cells and have binding constants for terbium that are approximately six orders of magnitude less than that of DPA, making this method relatively immune to these interferences.

Preliminary results have demonstrated that DPA triggered terbium luminescence allows the quantification of bacterial spores on the timescale of minutes with a detection limit of 5000 spores/ml. This technique is currently being further refined by better understanding of the physical limits of the luminescence process.

AMP

Detection of adenosine monophosphate, or AMP, is a variation of the ATP detection method that takes advantage of recent reports that spores produce higher levels of AMP than ATP. This results from the observation that in the dormant spore state, it is energetically favorable to bind adenosine in AMP, a lower energy molecule than ATP. Whereas ATP measures vegetative cells utilizing energy, AMP may present a better biomarker for dormant spore detection.

Experimentally, detection of AMP takes place with commercially available kits that chemically transform AMP into ATP. The standard ATP assay is then used to measure the initial quantity of AMP. This work is still under early development.

Epifluorescence

Direct epifluorescent microscopy (DEM) allows the opaque hardware to be illuminated and examined from above. In principle, DEM has attractive features for validation of cleaned hardware; however, studies at JPL demonstrated that in addition, the background fluorescence from some hardware materials made it difficult to quantify results. Furthermore, a number of other factors, including the need to recover the cells to a separate filter and the difficulty in automating the process, made this an unattractive technique. For this reason, a preliminary selection determined that it was not cost effective to continue research on DEM.

D.5 Contamination Transport

Contamination transport consists primarily of spore adhesion research and modeling efforts. These are critical analyses contributing to a number of technology development efforts. The interaction of biomolecules and dust will also be important to monitor in order to satisfy science requirements with minimal organic contamination. The modeling efforts span a number of systems, including both the planetary surfaces and subsurfaces of Mars and Europa. There are several components to be integrated into a coherent probabilistic risk assessments and the current level of uncertainty remains very high.

Biodiversity is also loosely included in contamination transport. This field refers to the diverse studies describing microbial extremophilia, as well as the behavior of microbes common in manufacturing and ATLO. Preliminary research has indicated that several distinct organisms are present in spacecraft assembly clean rooms, making a good starting point for candidate organisms for the environmental research.

D.6 Progress Toward Approval

In order to better synchronize the Planetary Protection technology development with mission planning, we recommend that major initiatives be organized in a simplified scheme similar to the Technology Readiness Levels (TRL) categories. As shown in Table D.6-1, Planetary Protection technologies may fall into Phases A, B, or C; these phases are defined as the research, verification, and peer review stages. Because these techniques require NASA certification prior to infusion in mission planning, an important milestone for these projects is NASA's peer-review process, the major principal driver in approval by the PPO.

Table D.6-1. Planetary Protection Process Approval Scheme

Phase	Description	TRL Range	Funds	Primary Responsibility/ Sponsorship	Exit Gate	Criteria
A	Research	TRL 1 to 4	$100K - $2M	Mars Technology Program, SBIR program, PPO	Internal review by Technology Program	Effectiveness of technique, comparison with other options.
B	Verifications	TRL 4 to 5	$500K - $3M	Planetary Protection	Independent review by Center planetary protection program	Effectiveness, range of applicability, interactions with other techniques
C	NASA Peer Review	TRL 5 to 6	$500K - $3M	Planetary Protection	Peer review by NASA Planetary Protection Officer	Readiness for prime time for routine use in SSE/Mars missions

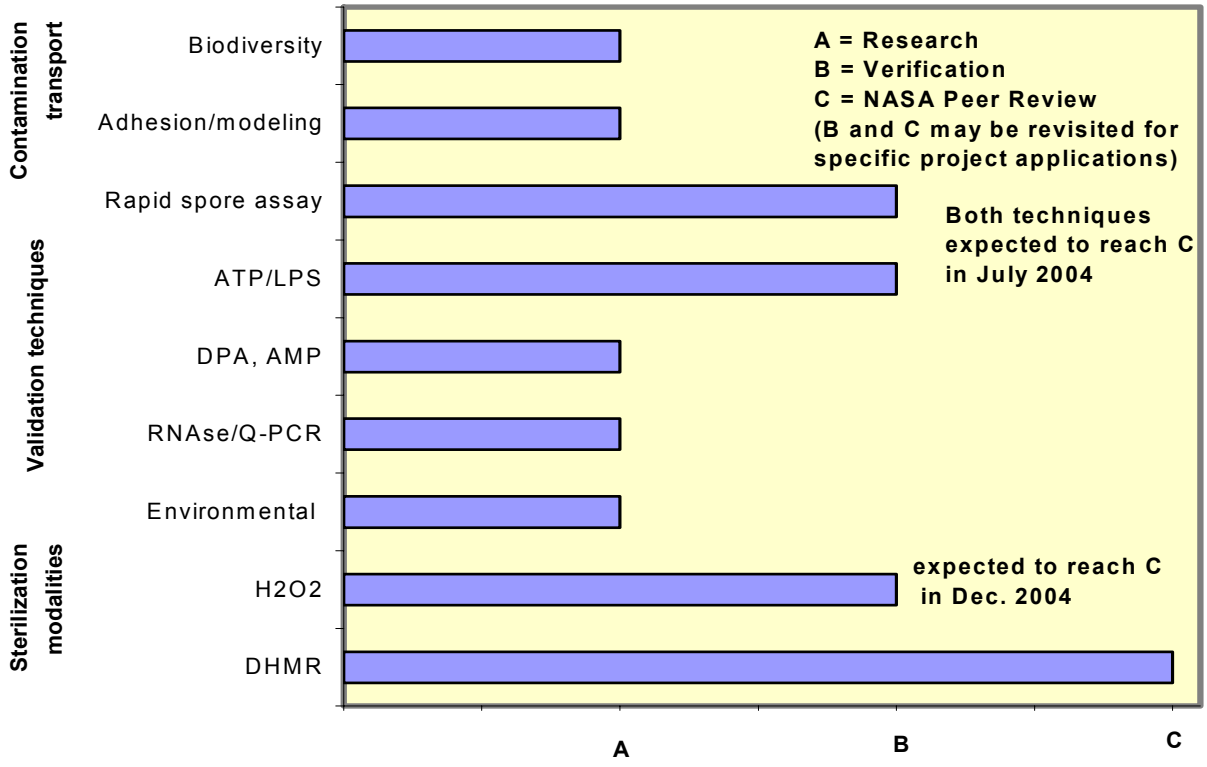

Figure D.6-1. Planetary Protection Technologies and Progress Toward Approval

It is important to note that while this list illustrates select techniques currently under study, not all of them will be necessary to achieve the specified goals. Therefore, it is not expected that

each technique will reach Phase C. Instead, certain techniques will be removed from the list in a down-select scheme.

D.7 Summary

The sterilization tasks are the most advanced of the forward protection tasks considered here. DHMR has been approved since the time of Viking and its applicability continues to be refined. Hydrogen peroxide is expected to be submitted for approval in December, 2004. However, environmental sterilization is poorly understood and requires further research.

A number of biomolecular validation techniques are in early stages of readiness. One combination of a molecular detection and a rapid analysis have been submitted were expected to be submitted to the PPO for approval in July, 2004. In conjunction with a better understanding of microbial metabolism, it is possible that very few of these techniques will be necessary to carry to maturity. In addition, it is expected that these techniques will benefit from the rapid advances of the biotechnology industry.

The contamination transport research, consisting primarily of adhesion experiments and modeling efforts, significantly lag the other activities in the Planetary Protection group. It will be important to accelerate these tasks for infusion into technology development for both forward and back protection efforts.