Overview of current capabilities and research and technology developments for planetary protection

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Abstract

The pace of scientific exploration of our solar system provides ever-increasing insights into potentially habitable environments, and associated concerns for their contamination by Earth organisms. Biological and organic-chemical contamination has been extensively considered by the COSPAR Panel on Planetary Protection (PPP) and has resulted in the internationally recognized regulations to which spacefaring nations adhere, and which have been in place for 40 years. The only successful Mars lander missions with system-level “sterilization” were the Viking landers in the 1970s. Since then different cleanliness requirements have been applied to spacecraft based on their destination, mission type, and scientific objectives. The Planetary Protection Subcommittee of the NASA Advisory Council has noted that a strategic Research & Technology Development (R&TD) roadmap would be very beneficial to encourage the timely availability of effective tools and methodologies to implement planetary protection requirements. New research avenues in planetary protection for ambitious future exploration missions can best be served by developing an over-arching program that integrates capability-driven developments with mission-driven implementation efforts. This paper analyzes the current status concerning microbial reduction and cleaning methods, recontamination control and bio-barriers, operational analysis methods, and addresses concepts for human exploration. Crosscutting research and support activities are discussed and a rationale for a Strategic Planetary Protection R&TD Roadmap is outlined. Such a roadmap for planetary protection provides a forum for strategic planning and will help to enable the next phases of solar system exploration.

Keywords: Planetary protection; Human space exploration; Spacecraft sterilization; Planetary protection policy

Abbreviations: ATLO, assembly test and launch operations; ATP, adenosine triphosphate; COSPAR, Committee on Space Research; DHMR, dry heat microbial reduction; EDL, entry descent and landing; EtO, ethylene oxide; FTE, full-time equivalent; HEPA, high-efficiency particulate air filter; ISRU, in-situ resource utilization; LAL, linus anamehcyte lysate; MAVEN, Mars volatile environment mission; MER, Mars exploration rover mission; MPPG, Mars program planning group; MRO, Mars reconnaissance orbiter mission; MSL, Mars science laboratory mission; MSR, Mars sample return mission; OSIRIS-REx, origins spectral interpretation resource identification security regolith explorer mission; PCR, polymerase chain reaction; PP, planetary protection; PPO, Planetary Protection Office; SCC, supercritical carbon dioxide cleaning; TRL, technology readiness level; VHP, vapor phase hydrogen peroxide; ZBR, Zone of Minimum Biological Risk

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1. Introduction

Over the past several decades, scientific exploration has revealed ever-increasing insights into potentially habitable environments in the solar system. The National Research Council’s Committee on the Planetary Science Decadal Survey lists “Planetary Habitats” as one of three crosscutting themes motivating future missions for the decade 2013–2022 (NRC, 2012). However, direct investigation of planetary habitats in which Earth life could survive has the potential to seed them with Earth organisms, unless appropriate precautions are taken to preclude this. Planetary protection (PP) collectively refers to the set of policies and practices designed to maintain the present and future scientific value of potential habitats from deterioration caused by terrestrial biological contamination (“forward contamination”), as well as to protect Earth’s biosphere from any potentially harmful extraterrestrial organisms found in returned samples (“backward contamination”).

The Planetary Protection Subcommittee of the NASA Advisory Council (May 2012 meeting minutes, NASA, 2012) has noted that a strategic Research & Technology Development (R&TD) roadmap would be very beneficial to encourage the timely availability of effective tools and methodologies to implement planetary protection requirements on ambitious future exploration missions. In support thereof, this report first provides an overview of current and emerging approaches to planetary protection implementation and technology development, followed by a more detailed discussion of the rationale for and advantages of a strategic R&TD roadmap.

1.1. Overview of planetary protection policy and relevant concepts

International planetary protection policy is developed and maintained by the Committee on Space Research (COSPAR), and is in line with Article IX of 1967 Outer Space Treaty. National and regional space agencies, for the past 50 years, have adhered to COSPAR planetary protection policy, at minimum, as the international consensus on requirements and implementation. In accordance with this policy, solar system exploration missions are categorized based on the mission type (flyby, orbiter, lander, or sample return) and whether the target bodies might provide information about organic compounds in the solar system (in which case documentation is required), or could provide habitats for Earth or indigenous life (in which case the number of viable Earth organisms must be reduced). In the case of Mars, categorization also depends on whether the mission carries life detection experiments or investigates “special regions” which are defined as regions, including in the subsurface, in which terrestrial organisms are likely to replicate, based on parameters of water activity and temperature, or as regions interpreted to have a high potential as habitats for extant Martian life forms. Table 1 provides an overview of mission categories based on mission type and planetary targets.

For missions that target planetary locations where Earth life might propagate, the “microbial burden” (also “bioburden”) of a mission or mission element is of primary concern, as this represents a measure of viable microbial spores present on the spacecraft.

For Mars spacecraft, the total microbial burden may be subdivided into the bioburden on exposed surfaces (that are likely to contaminate the planetary environment under nominal landing conditions), mated surfaces (joined by fasteners rather than adhesives), and the encapsulated bioburden (buried within non-metallic materials). Table 2 provides an overview of the maximum allowable bioburden depending on sub-categorization of Mars missions.

All but three target bodies in the solar system are currently considered unlikely to have accessible environments where Earth life could grow: missions to such targets have no limits on bioburden carried, beyond assembly in typical spacecraft cleanroom conditions. Likewise, missions returning samples to Earth from locations considered to have minimal potential for indigenous life are not required to contain returned samples.

Only missions investigating planetary targets where Earth life might persist, currently Mars, Europa, and Enceladus, are required to undergo microbial reduction, or other methods to prevent harmful contamination of the target planetary environment. Some additional planetary targets with potential subsurface liquid water environments (e.g. Titan, Ganymede, other large icy objects) require analysis to demonstrate that viable Earth organisms will not be introduced into habitable environments. Samples returned from these targets (unless previously sterilized to a sufficient level of confidence) require containment, at a level equivalent to that applied to highly biohazardous materials on Earth (Biosafety Level 4). Furthermore, containment is a necessary, but not sufficient element in controlling the sample, which may also include test protocols and other measures to assure safety. Approaches to implementing these requirements are discussed in more detail in the following sections.

1.2. Context of research and technology development for planetary protection

As forthcoming missions place an increasing focus on life detection and habitability, compliance with planetary protection requirements will become even more critical to preserving the integrity of immediate and future scientific discoveries. Beyond considerations around destinations for future solar system exploration, continued development

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1 http://www.state.gov/t/isn/5181.htm.

2 In the context of this manuscript, “harmful contamination” refers to the potential to jeopardize the value of scientific investigations. This mirrors the use of the phrase in Article IX of the 1967 Outer Space Treaty.
of planetary protection methods, technologies, and implementation approaches, is required to address the increasing complexity of robotic spacecraft themselves. This is manifested in terms of new materials, complex instrumentation, and increasingly demanding mission profiles.

In outlining a technology investment profile for future solar system exploration requirements, the NRC report “Vision and Voyages for Planetary Science in the Decade 2013–2022” put forth by the Planetary Science Decadal Survey committee listed planetary protection as a key capability supporting “science instrumentation” and “in situ exploration” technology elements (NRC, 2012, p. 312). Future life detection, sample return, and human exploration missions in particular entail unique challenges for planetary protection implementation, which have to be studied in greater detail prior to implementation. To date, most R&T&D for planetary protection occurs on the project or program level, with the most significant efforts by the NASA Mars technology program (Lin, 2006). However, given the increasing breadth of missions requiring bioburden reduction, beyond Mars, a consolidated roadmap would enable integration and coordination of individual R&T&D efforts, while allowing for technology diffusion throughout NASA and with international partners.

The following survey of basic technologies and methods focuses particularly on the current status and future potential of each research avenue. Although this summary is intended to be reasonably comprehensive, it is not exhaustive, particularly in the realm of concepts in very early development. The recent “Assessment of Planetary Protection and Contamination Control Technologies for Future Planetary Science Missions”, conducted by the Strategic Missions and Advanced Concepts Office at the Jet Propulsion Laboratory, provides an overview of the current status of several methods discussed herein from a mission-focused implementation perspective, and provides a complementary view of mission needs and priorities (Belz and Beauchamp, 2013).

This assessment follows earlier efforts to summarize technology needs for planetary protection, including the development of NASA-internal roadmaps (Belz et al., 2013). Ultimately, an updated and strategic high-level roadmap is required that considers new planetary science priorities (accounting for variability and budget uncertainties), and recent technological advancements. Furthermore, future roadmapping efforts for planetary protection should be transparent and accessible to a broad audience of research communities, contractors, and advisors. Given the long-term and sometimes uncertain time horizons for ambitious future planetary missions, a strategic roadmap should be capabilities-driven to identify and anticipate strategic needs, as a complement to the mission-driven development efforts that address immediate requirements.

2. Microbial reduction and cleaning methods

Methods contained within this section are focused on reducing the pre-launch biological burden, either by cleaning surfaces to mechanically remove contaminants or by means of microbial reduction methods that reduce the number of viable “spores” (this is a shorthand term for organisms that grow in the NASA Standard Assay after a heat-shock step, and does not represent a biologically-relevant category of organisms). Also, note that the term ‘sterilization’ is falling out of use in planetary protection terminology, because a ‘sterilization’ process depends critically on the organisms being monitored: every spacecraft launched to date has been absolutely sterile, if all that’s counted is elephants.

Depending on the mission category and implementation option, for categories III and IV, a spacecraft may be subjected to bioburden reduction of either the total bioburden,
Table 2
Overview of bioburden constraints for Category IV Mars missions. Please note that this table is intended to provide a broad overview or examples only, and may not accurately reflect all aspects of bioburden requirements.

<table>
<thead>
<tr>
<th>Sub-category</th>
<th>Type</th>
<th>System level</th>
<th>Soft-landed hardware(^a) (SL)</th>
<th>Hard-impacting hardware(^c)</th>
<th>Total spacecraft(^h)</th>
<th>Accountable bioburden(^f) (spores)</th>
<th>Enclosed bioburden density(^g) (spores/m(^2))</th>
<th>Total bioburden(^h) (spores)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVa</td>
<td>No life detection</td>
<td>Full-system</td>
<td>&lt;3 (\times) 10(^5) (\text{sBb}_{SL}) (spores)</td>
<td>5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>&lt;5 (\times) 10(^5)</td>
<td>1000</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>IVb</td>
<td>Life detection</td>
<td>Full-system</td>
<td>&lt;30 (\text{sBb}_{SL}) (spores)</td>
<td>5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>&lt;5 (\times) 10(^5)</td>
<td>1000</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Life detection</td>
<td>Sub-system</td>
<td>&lt;3 (\times) 10(^5) (Total (\text{sBb}_{SL}))</td>
<td>&lt;3 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>&lt;5 (\times) 10(^5)</td>
<td>1000</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life detection</td>
<td>Sub-system</td>
<td>Full-system</td>
<td>&lt;3 (\times) 10(^5) (\text{sBb}_{SL}) (spores)</td>
<td>5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>&lt;5 (\times) 10(^5)</td>
<td>1000</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>IVc</td>
<td>Special region is within the landing ellipse</td>
<td>Full-system</td>
<td>&lt;30 (\text{sBb}_{SL}) (spores)</td>
<td>1.5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>–</td>
<td>0.1</td>
<td>&lt;1.5 (\times) 10(^4)</td>
<td></td>
</tr>
<tr>
<td>Special region is outside or sub-surface to the landing ellipse</td>
<td>Sub-system</td>
<td>&lt;3 (\times) 10(^5) (\text{sBb}_{SL}) (spores)</td>
<td>1.5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>–</td>
<td>0.1</td>
<td>&lt;1.5 (\times) 10(^4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Special region is outside or sub-surface to the landing ellipse</td>
<td>Sub-system</td>
<td>&lt;3 (\times) 10(^5) (\text{sBb}_{SL}) (spores)</td>
<td>1.5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>–</td>
<td>0.1</td>
<td>&lt;1.5 (\times) 10(^4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Missions that may induce or create a special region</td>
<td>Sub-system</td>
<td>Full-system</td>
<td>&lt;3 (\times) 10(^5) (\text{sBb}_{SL}) (spores)</td>
<td>1.5 (\times) 10(^5) (-\text{sBb}_{SL}) (spores)</td>
<td>–</td>
<td>0.1</td>
<td>&lt;1.5 (\times) 10(^4)</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) For all missions, the soft-landed hardware must be protected from recontamination due to the hard-impacting hardware and other components of the spacecraft.

\(^b\) Includes only hard-impacting hardware that is within 3 \(\sigma\) of the landing ellipse.

\(^c\) Includes all hardware (soft-landed and hard-impacting hardware) that is within 3 \(\sigma\) of the landing ellipse.

\(^d\) Includes only accessible or exposed surfaces.

\(^e\) Includes all surfaces and encapsulated and mated materials of the hard-impacting hardware.

\(^f\) Includes components of the spacecraft that may release spores into the environment, including the accessible surfaces of the soft-landed hardware and all components of the hard-impacting hardware.

\(^g\) Includes all non-accessible surfaces of the soft-landed hardware.

\(^h\) Includes all surfaces and encapsulated and mated materials of the soft-landed and hard-impacting hardware.

\(^i\) Full-system option will be employed if the spacecraft carries a long-term heat source (e.g. plutonium) or failure modes analysis of the landing event indicates that debris field could contaminate a special region at a probability >1%.

\(^j\) Sub-system option may be employed if failure modes analysis of the landing event indicates that debris field would not contaminate a special region at a probability >1%.

\(^k\) Full-system option will be employed if failure modes analysis of the landing event indicates that debris field could create a special region at a probability >1%.

\(^l\) Sub-system option may be employed if failure modes analysis of the landing event indicates that debris field will not create a special region.
which includes all spores on free and mated spacecraft surfaces as well as spores encapsulated within non-metallic materials, or, for Mars missions with Category IVa–c, the accountable bioburden, which refers to items not isolated from the environment (e.g. by means of a HEPA filter). Bioburden reduction can be achieved at the component and subsystem level in concert with re-contamination control methods, or by application of an additional “terminal” process that occurs after final spacecraft assembly.

Currently, dry heat microbial reduction (DHMR) is the only approved full-system microbial reduction method that is effective on both surface and encapsulated bioburden. DHMR was demonstrated successfully at a terminal full system level with the Viking missions.

Specifications for Vapor-Phase Hydrogen Peroxide (VHP) have recently been approved as an alternative microbial reduction method to DHMR, which can be applied either as a terminal or component level method for surface microbial reduction. Several other methods of microbial reduction and cleaning methods exist in various levels of qualification, each with distinct advantages and disadvantages. The most notable current and emerging microbial reduction and cleaning methods discussed below, along with an indication of further development potential. Table 3 provides a summary of the microbial reduction and cleaning methods discussed here.

### 2.1. Physical cleaning methods

For missions or subsystems requiring a basic level microbial reduction and cleaning without complete or penetrating microbial reduction, physical cleaning of exposed surfaces using alcohol wipes is an effective method for achieving the required cleanliness. This is also part of the typical intake procedure to bring items into a cleanroom environment. Hardware that is maintained in a cleanroom environment may be assumed to have lower levels of biological burden than that in uncontrolled environments: conservative ‘specification values’ for both surface and encapsulated bioburden are provided in planetary protection documentation, that may be assumed as the bioburden on hardware if an overestimate of bioburden is not problematic.

Any cleaning effort must be supported by an effective biological assay procedure that verifies the subsequent level of microbial reduction. The required cleanliness and biological burden is achieved by the effect of mechanically removing contaminants using a solvent such as ethanol or isopropyl alcohol. Physical cleaning is typically sufficient for Mars missions that do not focus on life-detection or the exploration of Mars special regions, and the method may be augmented by reduction to the encapsulated bioburden of components by other methods (e.g. manufacturing processes, contamination control bake-outs, or targeted DHMR or autoclaving) if total bioburden is limiting. Because the cleaning and assay procedures typically are conducted manually during clean room assembly, this approach requires integration of time and personnel resources into the assembly flow, which also must accommodate strict clean room procedures. These procedures include the wearing of protective clothing, adherence to protocols, use of sterile equipment, and frequent changing of gloves and wipes, but even so a risk for recontamination and clean room fallout remains. This can be mitigated by frequent monitoring of cleanliness, covering of hardware when not in work, and in some cases may require that subsystems treated to reduce bioburden prior

<table>
<thead>
<tr>
<th>Method</th>
<th>Application</th>
<th>Implementation status/examples</th>
<th>Related R&amp;TD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical cleaning</td>
<td>Microbial reduction on spacecraft surfaces by physical removal of contaminants</td>
<td>Default cleaning method for surface bioburden during ATLO</td>
<td>Performance on rough or otherwise challenging surfaces, use of alternative solvents or cleaning agents</td>
</tr>
<tr>
<td>Supercritical carbon dioxide cleaning</td>
<td>Physical removal of contaminants, including organic matter</td>
<td>Use in the medical industry; under study for planetary protection use</td>
<td>Further validation of achieved cleanliness for planetary protection purposes, scalability and performance on spacecraft materials/surfaces; possibility of in situ applications using the Martian atmosphere</td>
</tr>
<tr>
<td>Dry heat microbial reduction</td>
<td>Bulk sterilization of components, including enclosed or mated bioburden</td>
<td>Widespread adaptation on the component/subsystem level. Pioneered by Viking on the full-system level</td>
<td>Material compatibility, facility development for system sterilization of new, large flight systems</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>Electron beam and gamma ray sterilization of surfaces or limited penetration of various materials</td>
<td>Widespread implementation in the food industry. Applied on Beagle 2 parachute, due to incompatibility with DHMR</td>
<td>Further verification and relative assessment of various methods; material compatibility; development of specifications/standards for planetary protection</td>
</tr>
<tr>
<td>Vapor phase hydrogen peroxide</td>
<td>(Low temperature) surface sterilization</td>
<td>Widespread use in the medical industry. Recently approved as NASA standard method. Component size limited by size of the VHP chamber</td>
<td>Scalability for larger assemblies or system-level surface sterilization; material compatibility</td>
</tr>
<tr>
<td>Ethylene oxide</td>
<td>Surface sterilization</td>
<td>Use in the medical industry; under study for planetary protection use</td>
<td>Safety and environmental control of EtO processes; material compatibility with respect to DHMR and VHP</td>
</tr>
</tbody>
</table>

Table 3
Summary of microbial reduction and cleaning methods and potential R&TD avenues.

to integration (e.g. DHMR on a sampling mechanism) must be protected using a bio-barrier to prevent recontamination.

Although cleaning methods have been employed effectively on Category III and IV Mars missions, the increasing complexity of future missions will require more careful integration of planetary protection into normal processes to ensure compliance. Many spacecraft surfaces can tolerate physical cleaning without compromising the material; however, some surfaces cannot be cleaned effectively by physical wiping, such as certain paints and coatings, and areas of the spacecraft that are difficult to access. The earlier that cleanliness controls can be employed, the better to reduce bioburden numbers: requirements on or assessment of the cleanliness of subsystem assembly environments can ensure low bioburden inside hardware components, while taking into account manufacturing processes and combining contamination control bake-outs with microbial reduction treatments can effectively reduce overall stress to hardware.

The Mars Science Laboratory (MSL) mission represents the most complex mission that relied on physical cleaning for the bulk of microbial reduction, in addition to DHMR and other methods at the component and subsystem level.

Kern et al. (2006) investigated standard aerospace precision cleaning protocols, using standards, and cleaning via liquid boundary layer disruptions, including variations in the cleaning solutions chemistry. Precision cleaning using Freon degreasing and acid washes, which has also been employed on the Sojourner Rover of the Mars Pathfinder mission, as well as elements on the Mars Exploration Rovers (MER) as a secondary cleaning method (NRC, 2006, p. 142). Future areas of research and development opportunities include assessing the cleaning of rough and non-standard surfaces, fabrics, and materials of differing textures, as well as the evaluation and identification of alternative cleaning solvents.

2.2. Supercritical carbon dioxide cleaning

A more aggressive form of mechanical removal cleaning uses liquid or supercritical CO$_2$. Both supercritical and liquid CO$_2$ cleaning have recently been shown to attain high levels of cleanliness, by removing organic matter and other contaminants, for both contamination control and planetary protection implementation (Lin et al., 2010).

As a solvent, CO$_2$ cleaning primarily functions by chemically dissolving and physically removing contaminants from the surface, with some ability to penetrate substrates. This method is an effective microbial reduction method as applied to medical devices (White et al., 2006). Lin et al. (2010) evaluated CO$_2$ cleaning methods in the context of contamination control for planetary missions and planetary protection, suggesting cleanliness levels of $\sim$10 ng/cm$^2$ for hydrophobic contaminants. Furthermore, their research includes experiments under supercritical conditions using a Martian air mix consisting of 95% CO$_2$ as preliminary research towards potential in situ cleaning and microbial reduction for future Mars missions. CO$_2$ methods have yet to be fully validated: some limitations include system scalability and the geometry of the components to be cleaned, as well as material compatibility. Nevertheless, given the potential applications for both contamination control and microbial reduction, CO$_2$ cleaning methods may become well suited, particularly in situ at Mars, for achieving high levels of cleanliness for critical components, such as sample handling and containment devices, and science instruments.

2.3. Dry heat microbial reduction

The Viking program pioneered DHMR as a method for reducing both surface and encapsulated bioburden in the early 1970s—the majority of the cost for planetary protection on that project was spent to validate a range of electronic and other components for compatibility with temperatures between 110 and 125 °C (Bionetics, 1990). DHMR was the only pre-launch microbial reduction technique approved by NASA for use as a parametric process until the approval of VHP in 2012. Even now, it is considered the “gold standard” for microbial reduction, and remains the only NASA-approved method for penetrating microbial reduction of encapsulated bioburden.

Accordingly, missions needing to reduce encapsulated and mated bioburden, such as those carrying long-term heat sources or intending to dispose of hardware on Europa or Enceladus, are likely to employ DHMR as a major aspect of their planetary protection strategy. DHMR also allows for effective reduction of surface bioburden at lower time-temperature combinations. Following extensive validation efforts carried out jointly by NASA and ESA (e.g. Kempf et al., 2008), DHMR specifications were recently expanded beyond the original Viking specifications in order to allow a total bioburden reduction up to 6 orders of magnitude, as well as providing for a greater range of acceptable humidity control. This extension allows missions to account for microbial reduction that occurs during heating as part of many flight hardware manufacturing and treatment processes. It should be noted that although the new specifications allow for uncontrolled humidity, the baseline method is still a “dry” heat process, and thus will herein be referred to as “DHMR” for the purposes of clarity and consistency with previous documentation.

The relevant metric for these specifications is the “D-value,” which corresponds to the time needed for a 90% (one log) reduction of the microbial population. The specifications provide D-values for a temperature range from 100 to 200 °C for dry, vacuum, and uncontrolled humidity conditions, and allow for a spacecraft spore population reduction from 2 to 6 orders of magnitude.
including no humidity control requirements on the specifications above 3 orders of magnitude reduction. D-values for microbial populations on mated surfaces are twice the corresponding values for microbial populations on exposed surfaces. D-values for microbial populations encapsulated in non-metallic material are 10 times the corresponding value of populations on exposed surfaces.

As of the time of this report, the Viking landers are among the few missions that applied DHMR on a system level. However, DHMR has been used routinely at the component level prior to clean room assembly, surface cleaning, and, where required, bio-barrier integration. A facility at the NASA Kennedy Space Center is under consideration to be adapted for system-level DHMR microbial reduction for a potential future Europa Orbiter Mission (Europa Study, 2012). Beyond the implementation of the new DHMR specifications, future technology developments, that focus on the system-level effects of DHMR on non-standard materials, complex mechanical assemblies, and material interactions (e.g. batteries, precision instrumentation, coatings etc.), would be of benefit.

2.4. Ionizing radiation

Ionizing radiation, such as γ rays and electron beams, are routinely employed for microbial reduction in the medical and food industries, although the technology is not often used by NASA for planetary protection. Most recently, γ radiation was employed to reduce bioburden on the parachute of ESA’s Beagle 2 Mars probe (Pillinger et al., 2006). Although DHMR has been employed for parachutes of other Mars landers, the material chosen for Beagle 2 was not compatible with high temperatures, while the thin material made it a suitable application for penetrating γ rays.

Electron beams utilized in the food industry have been proposed for penetrating microbial reduction of spacecraft components. However, the specific methods differ widely in the required levels of power, penetration depth, material properties and geometry, as well as microbial reduction potential. Pillai et al. (2006) and Urgiles et al. (2007) present preliminary research demonstrating the effectiveness of electron beams for planetary protection purposes.

One complication in applying active radiation to reduce bioburden pre-launch, for Europa or Enceladus missions, is that the overlap with anticipated passive radiation from the post-launch environment, for example in the Jovian system, would need careful analysis. Open questions remain about the potential effects of passive radiation on resistant organisms due to their mechanisms of resistance, as well as the contribution of new materials and spacecraft geometries on the actual radiation doses. As a cross-cutting research activity, studying the effects of high energy radiation on both microorganisms and spacecraft systems could benefit operational analyses to determine post-launch microbial reduction, as well as aiding the development of pre-launch microbial reduction techniques. Should credit for post-launch reduction by radiation be important for compliance, pre-launch reduction using a non-overlapping method, such as DHMR, would be preferable.

2.5. Vapor phase hydrogen peroxide

In a joint effort, ESA and NASA have recently approved Hydrogen Peroxide vapor (H₂O₂) as a surface microbial reduction method, following extensive research and validation efforts (e.g. Klapes and Vesley, 1990; Rohatgi et al., 2002; Chung et al., 2006, 2008). The advantages of VHP methods include effective microbial reduction that can be applied either in small chambers or scaled up to entire rooms, thus greatly facilitating application to large surfaces and complex geometries. This quality also makes it suitable for both component-level and terminal treatment. Furthermore, H₂O₂ is generally considered to be a safer alternative to other gaseous or vapor-phase chemicals, such as ethylene oxide.

The new specifications have been developed for 2–6 orders of magnitude reduction in controlled ambient and vacuum conditions, as well as complete ‘sterility,’ for purposes of spacecraft cleanliness, at higher concentrations. It should be noted that unlike DHMR, the VHP bioburden reduction process is not a parametric process, but rather depends on the distribution of vapor on the spacecraft hardware, and therefore a biological indicator (e.g. Geobacillus stearothermophilus) is required to verify process efficacy. The indicators must be placed at a location representative of the minimum dose of VHP applied; the ‘least accessible’ point on the hardware, from the perspective of the VHP treatment. Bioassay is required prior to VHP application, as one can only apply log-reduction to a known starting number of organisms.

The VHP process is considered a promising alternative to DHMR for surface microbial reduction, particularly for applications where material compatibility precludes the use of DHMR. However, as a strong oxidant, H₂O₂ has the potential for unfortunate chemical interactions with certain materials, and thus presents its own unique implementation challenges.

Although some material compatibility studies have been conducted internally by ESA and NASA, the application of this method would benefit from a comprehensive material compatibility study that considers both VHP and DHMR, and additionally focuses on alternative materials as well as combinations of materials and subassemblies from a systems engineering standpoint.

Furthermore, the scalability of VHP would potentially allow application to entire spacecraft assembly clean rooms, transport containers, pre-launch processing facilities, or even launch vehicle payload fairings. Although this would require significant investment and re-thinking of Assembly, Test and Launch Operations (ATLO) procedures, integration on such a broad level has the potential to simplify operations and greatly reduce the consequences of re-contamination during launch vehicle integration or transport.
2.6. Ethylene oxide

Ethylene oxide (EtO) is commonly used in the medical industry as a sterilization agent, and has been considered for use in spacecraft microbial reduction applications during the early development of interplanetary spacecraft.\(^3\) However, due to inherent health and explosive hazards, it has not seen widespread use for planetary protection purposes, and development for terminal microbial reduction has focused on DHMR and VHP as alternatives. Recent advances by the medical industry could alleviate some of these concerns as well as other environmental control limitations, and may allow for safe implementation of self-contained EtO processes (Mendes et al., 2007).

EtO has a different material/process compatibility compared to VHP, and has been considered for use on instrumentation by the Goddard Space Flight Center (Belz and Beauchamp, 2013). EtO methods may be proposed for specific uses, but this should be weighed against existing alternatives and the advantages of standardizing procedures on an agency and inter-agency level. Detailed material and process compatibility studies focusing on differences between DHMR, VHP and EtO would be a useful preparatory activity.

2.7. Other methods

Although the above methods represent some of the most commonly used processes for planetary protection implementation, a number of other microbial reduction and contamination control methods exist beyond those listed that could be employed for planetary protection purposes on some level. Autoclaves use a combination of high pressures, temperature, and steam, and are among the most commonly used microbial reduction methods in hospitals and industrial processes. The use of damp heat could damage many spacecraft components, although autoclaving could be used on some ground support equipment, and may be useful for initial microbial reduction of tolerant materials.

Other gas-phase chemicals, such as formaldehyde, could possibly be used for microbial reduction, although they are typically less favorable than the aforementioned alternatives based on factors of toxicity, material compatibility and microbial reduction potential.

Several gas-plasma based methods, often derived from the medical and computer industry, also have the potential for planetary protection applications. Most notably, the Beagle 2 spacecraft employed hydrogen peroxide gas plasma for components incompatible with DHMR, including batteries and electronic assemblies (Pillinger et al., 2006). Cold atmospheric plasma technology is used in the medical sector. The cold atmospheric plasmas consisting of “a highly reactive mix of ions and electrons, reactive molecules, excited species, electric fields and to some extent also UV radiation” demonstrate antimicrobial activity (Mogul et al., 2003). Major plasma designs and their main benefits have recently been described by Isbary et al. (2013).

The effectiveness and applicability of plasma-based methods strongly depend on gas composition and hardware design. Thus, further research is warranted, especially when considering material compatibility issues, the need for standardizing procedures, and possible synergies with other applications (e.g. component level and in situ microbial reduction).

3. Recontamination control and bio barriers

After components, subassemblies, or entire spacecraft have been subjected to microbial reduction methods, there exists the potential for subsequent re-contamination during ATLO. Re-contamination may occur at any stage from initial assembly through rework, launch, cruise, and EDL. Of particular concern are during transport between facilities pre-launch, by particulate transfer between the launch vehicle’s payload fairing and the spacecraft during launch, or for some life-detection experiments though mobilization of volatile organic compounds during cruise/EDL/deployment. For certain mission scenarios, implementing recontamination control techniques also allows for the application of more stringent microbial reduction methods to the most critical components, such as drills or life detection instrumentation, while eliminating the need to maintain more than basic cleanliness for the remaining components of the spacecraft. HEPA filters also have been used reduce the potential for recontamination by reducing the transport of particulates from and into enclosed spaces.

While recontamination prevention facilitates compliance where forward contamination is a concern, these approaches are even more critical to prevent backward contamination, as for a Mars Sample Return (MSR) mission. Given the very low risk tolerance for potential contamination of the Earth’s biosphere, and strong public as well as scientific interest in the detection of Mars life, extremely reliable methods for clean sample acquisition and containment must be developed, including mechanisms employed by the spacecraft as well as infrastructure required on the ground.

3.1. Clean room and aseptic assembly

Nearly all spacecraft, after a certain level of sub-assembly, are assembled in clean rooms in order to provide a general level of particulate and contamination control, regardless of concern for biological or organic contamination. Class 100,000 (ISO8 equivalent) clean rooms, which contain less than 100,000 particles of sizes greater than or equal to 0.5 µm per cubic foot, are typical in the assembly of spacecraft and spaceflight hardware.

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\(^3\) [http://hdl.handle.net/2060/19670021820].
\(^4\) [http://hdl.handle.net/2060/19720013398].
Integration in Class 100,000/ISO8 clean room is not sufficient to meet bioburden requirements for category III and IV without employing additional microbial reduction methods and verification via bioassays. Nevertheless clean rooms can aid in the prevention of recontamination following cleaning procedures or other microbial reduction methods.

Aseptic assembly, commonly used for pharmaceuticals and medical devices manufacturing, is a much more stringent cleanroom assembly process that was employed for the Beagle 2 Mars mission. Enabled by the relatively small size of the lander, initial assembly of the spacecraft occurred in a Class 100/ISO5 clean room, which is by definition at least three orders of magnitude cleaner than the typical Class 100,000/ISO8 clean rooms. Following completion of the assembly process, the probe was “closed” and protected by a HEPA filter during fit checks with the Mars Express spacecraft and launch vehicle integration in Class 100,000/ISO8 clean rooms (Pillinger et al., 2006). The stringent recontamination control requirements and clean room procedures inherent in the aseptic assembly process limit the number personnel in contact with the spacecraft at any time, and require longer preparation times for components and clean room attire. Some instruments provided to the InSight mission may be assembled under Class 100/ISO5 conditions, which meet the surface bioburden specification values for a planetary protection Category IVa mission. Aseptic procedures are also useful for post-reduction access to spacecraft components, for example in situations requiring re-calibration or assaying of sensitive instrumentation. The incorporation of advanced remote manipulation/telerobotics would also greatly benefit the aseptic assembly and integration procedures, as this would minimize exposure to the inevitable bioburden associated with human contact.

3.2. Recontamination prevention

As an early example of recontamination prevention, the Viking missions were encapsulated in a bioshield prior to terminal microbial reduction via DHMR. The sample handling pathway was cleaned extensively at the subsystem level, integrated, and then protected from recontamination under purge with a hot gas to ensure adequate organic cleanliness. This was verified by sampling the purge efflux, and the sampling/analysis hardware was subsequently retained in an overpressure condition to prevent influx of Earth atmospheric contaminants during subsequent operations until landing on Mars. The outer surfaces of the heat shield and back shell would experience sufficient microbial reduction from atmospheric heating upon entering the Martian atmosphere to meet the overall bioburden requirement. The overpressured interior of the life-detection instrumentation and sample handling pathway was effective in maintaining extremely stringent cleanliness levels, verified pre-launch, through delivery of the instrumentation to Mars.

More recent organic detection instruments have either not used a pressure differential across the biobarrier (Phoenix), or have employed vacuum seals that were not as effective as anticipated (Mars Science Laboratory). Based on this experience, an overpressure approach using a verifiable method for ensuring cleanliness will be strongly encouraged for purposes of implementing planetary protection on future life detection missions, whether in situ at Mars or returning samples to Earth.

Bio-barriers are employed to prevent recontamination of components requiring a lower bioburden than the rest of a spacecraft, or to contain bioburden within areas of a spacecraft that cannot be cleaned effectively. Salinas et al. (2007), describe the development of bio-barriers at the Jet Propulsion Laboratory. The Phoenix mission used a deployable bio-barrier to protect its DHMR-treated robotic arm, used for trenching and sampling, from recontamination. Bio-barriers typically represent a single-point failure element for mission critical components, which adds risk, reducing which could be a focus of further research and development. Other research opportunities may include material selection and component compatibility with microbial reduction methods, including newly developed specifications for VHP. Advanced bio-barriers and bio-shields will be required for eventual MSR or human missions, with potential needs for increased scalability, long-term reliability, and ideally a rescaling capability. Table 4 summarizes recontamination control methods and potential R&T&D avenues.

HEPA filters are sometimes used for environmental control while limiting the “accountable” surface area by isolating internal spaces, though use should be minimized. The approach can only be used on missions that do not require bulk bioburden reduction, and surface bioburden behind the HEPA filter is limited to an average of 1000 spores/m², in recognition of the fact that some amount of leakage is possible. Also, HEPA filter performance degrades and therefore they are not completely impermeable over time.

3.3. Restricted sample return handling and containment

Sample containment is extremely critical to prevent backward contamination for restricted sample return missions, those returning samples from (currently) Mars, Europa, or Enceladus. Although sample containment applies for all restricted sample return missions, present planning is primarily concerned with returning samples from Mars. There are insufficient scientific data to make conclusive statements about the potential for microbial life in martian material, or about the possible consequences martian organisms could have if introduced into the Earth’s biosphere. It seems unlikely that this uncertainty can be resolved by anything less than returning a sample to Earth for detailed study and therefore stringent precautions must be taken in the acquisition, containment and study of the sample. Barenholdt (2000) provides an overview of planetary protection issues for Mars sample return missions.

Material ejected from Mars regularly impacts Earth in the form of meteorites; however, this meteoritic material spends a significant time in space, and is considered very unlikely to contain viable Mars microbes (NRC, 1998). Mars samples deliberately collected for transport to Earth have a much higher potential to contain viable organisms, and thus are to be treated with the greatest concern for purposes of planetary protection.

Although retrieved Mars samples could be treated with some sort of ‘sterilization’ process prior to Earth return, this approach is currently not favored, given the greatly reduced science return and the considerable uncertainty regarding how to ‘sterilize’ unknown organisms possibly present in samples.

A large number of studies and architectures have been proposed for Mars Sample Return since the 1970s (e.g. Mattingly et al., 2004; iMars, 2008), and a recent MPPG report outlined several options for MSR mission concepts (MPPG, 2012). Samples collected at Mars and transported to Earth are required to undergo a life detection protocol for planetary protection purposes, so cleanliness requirements are those required for life detection missions, of which the exemplar is Viking. Most MSR architectures feature the same basic elements: First, the sample must be acquired and cached without contaminating the sample or the source region. Materials and mechanisms used for sample collection must be compatible with the pre-launch cleaning and microbial reduction processes appropriate for life detection missions. A sample cache would be delivered to a putative Mars Ascent Vehicle (MAV) either by the same or a subsequent landed spacecraft. The MAV would then deliver the sample container to a spacecraft orbiting Mars, which in turn would deliver the sample to Earth’s surface via a reentry vehicle. At one or multiple points during the process of collecting, sealing, and transporting the cache to an Earth Return Vehicle, procedures must be implemented to ‘break the chain of contact’ with Mars, such that no uncontained Mars material is delivered to the Earth, either on the outside of the hardware carrying the cache or associated with other parts of the Earth Return spacecraft.

To ensure that the Earth Return Vehicle does not impact Earth accidentally, the spacecraft is targeted away from Earth until just prior to release of an Earth Return Capsule that provides for protection of the cache through entry and landing on Earth, to an appropriate level of confidence in containment of the samples. The return capsule is retrieved and transferred to a sample handling facility that must operate at the highest biosafety containment level (BSL-4) and also protect the very valuable Mars samples from contamination by Earth material through retrieval, opening, and analysis in containment.

A draft test protocol for detecting possible biohazards in Martian samples returned to Earth has been developed by Rummel et al. (2002), which includes testing and decision making guidelines for studying, establishing safety, and releasing the sample from containment. Operational concepts and high-level requirements for a Mars Sample Receiving Facility have been the subject of several studies, (e.g. Rummel et al., 2002; Beatty et al., 2009; NRC, 2002a, 2009; ESF, 2012), but there remains a need for more focused and detailed research to ensure the availability of a suitable infrastructure for future Mars sample return missions. Beyond technical concerns, public, political, and ethical considerations must also be weighed in the development of statistically valid, comprehensive, and internationally agreed upon requirements and procedures for sample release.

To this end, an extensive research and development effort is essential to address these issues prior to full

Table 4
Summary of recontamination control methods and potential R&TD avenues.

<table>
<thead>
<tr>
<th>Method</th>
<th>Application</th>
<th>Implementation status/examples</th>
<th>Related R&amp;TD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean room assembly &amp; integration</td>
<td>Recontamination control during ATLO</td>
<td>Typical assembly in Class 100,000 clean rooms. Requirements for Category III and IV missions are more stringent cleanliness levels than standard Class 100,000 cleanrooms provide. Beagle 2 probe assembled “aseptically” in Class 100 clean room</td>
<td>Scalability of aseptic assembly &amp; integration for larger spacecraft or subsystems; procedures and system design for minimally invasive ATLO procedures from assembly to launch. Development of aseptic integration, calibration, and testing procedures to be performed following system-level sterilization of the flight system (e.g. for heat-sensitive assemblies integrated after DHMR)</td>
</tr>
<tr>
<td>Bio barriers</td>
<td>Minimizes recontamination following microbial reduction or aseptic assembly</td>
<td>Bio-shield encapsulating entire spacecraft pioneered by Viking missions. Deployable bio barriers pioneered on the Phoenix Mars Lander to maintain cleanliness of robotic arm</td>
<td>Scalability and reliability of deployable bio barriers and bio shields</td>
</tr>
<tr>
<td>Restricted sample return handling and containment</td>
<td>Isolating samples from acquisition through evaluation in a sample handling facility</td>
<td>Draft protocols for sample handling exist and conceptual designs of caching and Earth return vehicles, but need to be further developed. Some lessons from lunar sample handling pertain, as well as unrestricted sample return missions</td>
<td>Design of sample acquisition and assured containment mechanisms (caches and Earth entry vehicles) that “break the chain” of contact with Mars; requirement definition and conceptual design of sample receiving facility, including life detection protocols, security, and release criteria</td>
</tr>
</tbody>
</table>

implementation of an MSR mission. In the interim, collabora-
tion with planned unrestricted sample return missions, notably OSIRIS-REx and Hayabusa-2, could be leveraged to maximize lessons learned and to gain vital experience in clean sample handling processes in a low-risk environment.

These missions are subject to contamination control for scientific purposes, but have only limited planetary protection documentation requirements as part of their categorization.

4. Operational analysis

In addition to bioburden reduction, a number of analytical methods are used to account for further bioburden reduction or to provide additional means of demonstrating compliance. The implementation and availability of these methods is dependent on the type of mission and destination. Mars missions are subject to overall accountable bioburden requirements “at launch,” whereas missions to Europa, Enceladus, and other large icy objects are required to use a probabilistic approach in determining the overall risk of contaminating a habitable subsurface liquid water environment.

4.1. Trajectory and impact analysis

An essential aspect of meeting planetary protection requirements for missions to objects of planetary protection concern is to demonstrate, with sufficient confidence, that spacecraft hardware will not impact an object when this is not intended. This is done by ensuring that the initial mission trajectory is biased away from the target object, with later course corrections used to bring the spacecraft on an encounter trajectory after systems have been confirmed to be functioning properly. For missions conducting fly-by or orbital science for which close approaches are desirable, this involves a tradeoff between spacecraft reliability and control with planetary protection probabilistic assessments. This is of particular importance to missions to Jupiter or Saturn that include orbits or fly-bys of Europa or Enceladus.6,7

For mission phases with high impact risks, such as close flybys of protected planetary bodies or low perigee orbits, the impact energy of a potential collision between the spacecraft and the planetary body can be taken into consideration as part of the planetary protection plan. For sufficiently high impact velocities, which need to be demonstrated through analysis, it can be shown that all organisms carried on spacecraft hardware would be killed due to the energy of impact, and the typical requirement for low probability of collision may be waived for those particular cases. This type of analysis was applied most recently during the trajectory design for the Juno mission to the Jovian system (Lam et al., 2008).

Mars-bound spacecraft are subject to an “at-launch” bioburden requirement, as opposed to probabilistic measures; however, the upper stages of launch vehicles for spacecraft encountering Mars must maintain a trajectory that avoids impacting Mars for 50 years after launch, at a sufficiently high probability. In all cases, trajectory analysis for planetary protection purposes must be included in the mission development and science planning and requires knowledge about spacecraft subsystem reliability, as well as the environment (e.g. micrometeoroids).

Similar trajectory analysis and biasing is required for backward contamination purposes, when robotic or human missions are returning from Mars, or other locations possibly hosting indigenous life, and could carry material of concern back to Earth.

4.2. Burn up and break up analysis

For missions to Mars that include spacecraft components that do not meet the 50-year orbital lifetime requirement, mission planners may request a deviation from at-launch bioburden requirements to use a ‘burn-up and break-up’ analysis to demonstrate additional microbial reduction on hardware that is exposed to sufficiently high temperature during entry into the Mars atmosphere. Estimating temperatures on the surface of a vehicle that is designed to survive atmospheric entry is relatively straightforward; however the analysis is much more challenging for spacecraft and components that are expected to break-up during the thermal and mechanical stresses of atmospheric entry.

Determining which components and surfaces of an orbiter or cruise stage will be exposed to sterilizing temperatures during atmospheric entry strongly depends on spacecraft configuration, attitude and dynamics, materials, and variable atmospheric conditions. Tools for analysis of Earth orbital debris and reentry are being adapted for use with Mars spacecraft, but these are not yet standardized. This analytical approach also benefits from refinements in atmospheric models based on telemetry data from Earth and Mars atmospheric entries.

The applicability and results of this type of analysis is strongly mission-dependent, and therefore is performed by each project on a case-by-case basis, in close collaboration and consultation with the PPO and consulting staff. This approach was first implemented on the Mars Reconnaissance Orbiter (MRO) mission (Barengoltz and Witte, 2007; Witte et al., 2004) and was implemented by the mars volatile environment (MAVEN) project. For MAVEN, bioburden control was determined to be the preferred approach because the low periapsis of the science orbit precluded demonstration of compliance with orbital lifetime and impact avoidance requirements.

A related and possibly synergistic activity is the application of thermal analysis on the outer surfaces of reentry
vehicles, which are prone to recontamination during ATLO and launch processes. In many cases, thermal heating during reentry can be used to account for microbial reduction on these surfaces. Advanced entry vehicles under study for Mars include hypersonic aerocapture vehicles and inflatable or expendable heat shields, which will be able to accommodate increased landed masses beyond an MSL-sized mission, including components for human exploration. Evaluation of the entry heating characteristics of advanced Mars entry vehicles, beyond the typical blunt-body, rigid aeroshells used so far, could be important for demonstrating planetary protection compliance on such future missions. Table 5 shows a summary of operational analysis methods and potential R&T&D avenues.

4.3. Post-launch microbial reduction

The myth that the space environment is hostile to Earth life is unfortunately widespread; in reality, many organisms from spore-forming microbes to desiccation resistant animals have been shown to survive not only laboratory thermal vacuum and radiation environments, but also exposure to the exterior of the International Space Station (e.g. Novikova et al., 2010; Onofri et al., 2012). Nevertheless, for planetary protection on non-Mars missions, high-energy ionizing radiation may be considered to reduce the number of viable spores on a spacecraft over time (NRC, 1998), which is particularly useful to missions remaining within Jupiter’s magnetosphere. Radiation encountered in space can penetrate materials to varying degrees, and can destroy living organisms depending on the capability of the organisms to repair damage, cumulative dose as a function of time, radiation intensity, and spacecraft configuration.

The Juno mission serves as a good example of how interplanetary radiation can be coupled to the reduction in spacecraft bioburden. In addition to the use of radiation-hardened electronics, Juno’s most critical electronic systems were placed within a shielded compartment. Such design features can result in areas where proportionately higher numbers of microbial spores survive the radiation exposure over time. Therefore, different areas of the spacecraft must be considered individually, and may drive the need for component-level or system-level microbial reduction prior to launch.

The Juno mission used a stacked-plate mass model of the spacecraft to analyze impacts with Europa, and was able to show that impact released sufficient energy to kill any remaining Earth organisms possibly present on the spacecraft. Future Europa or Enceladus missions may choose to design their spacecraft such that impact energy would be delivered preferentially to the more shielded parts of the spacecraft.

5. Planetary protection concepts for human exploration

Human exploration represents unique challenges to planetary protection, because humans unavoidably carry commensal microbial organisms with us, some of which can survive (Osman et al., 2008) or grow (Schuerger et al., 2013) under Mars surface conditions if provided with nutrients and protection from UV radiation. Mars remains the most enticing target for near-term human exploration as well as the search for life, and therefore the development of human exploration systems must be done in the context of planetary protection requirements for future human Mars exploration. Crewed missions to Mars will undoubtedly include objectives regarding the search for life, thus, forward contamination remains of great concern.

In addition to forward contamination concerns, maintaining and monitoring crew health during the mission, as well as avoiding backward contamination of Earth are critical and difficult problems with poorly-understood engineering solutions. For example, avoiding exposure of astronauts on the Martian surface to the local environment is likely to be extremely challenging, thus astronauts themselves represent a probable vector for bringing Mars contamination to Earth.

Crewed missions are included in COSPAR policies, although implementation details and specifications remain under development. Criswell et al. (2005) outline a comprehensive list of planetary protection issues and necessary research activities towards human exploration of Mars. Plans and architectures for crewed missions continue to

<table>
<thead>
<tr>
<th>Method</th>
<th>Application</th>
<th>Implementation status/examples</th>
<th>Related R&amp;T&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burn-Up &amp; break-up analysis</td>
<td>Determine microbial reduction caused by atmospheric entry heating</td>
<td>Implemented by MRO and MAVEN. Approved by PPO on case-by-case basis</td>
<td>Development of analysis tools and analytical models, including modeling of entry heating on the surfaces of advanced Entry, Descent and Landing (EDL) systems</td>
</tr>
<tr>
<td>Trajectory and impact analysis</td>
<td>Impact avoidance of potentially habitable planetary bodies, or demonstration of sufficient impact energy to assure sterilization on impact</td>
<td>Widespread adaptation in biasing spacecraft trajectories (including upper stages of launch vehicles)</td>
<td>Probabilistic risk assessment tools</td>
</tr>
<tr>
<td>Planetary radiation environments</td>
<td>Passive sterilization through exposure to ionizing radiation, e.g. as found in Jupiter’s magnetosphere</td>
<td>Juno takes “credit” for surfaces sterilized by radiation performance</td>
<td>Probabilistic risk assessment tools, modeling of radiation environments and shielding performance</td>
</tr>
</tbody>
</table>

evolve, based on space policy and technological capabilities, and considerations for planetary protection must be included. The following represent a number of broad research topics relevant to planetary protection for the human exploration of Mars.

5.1. Architecture and operations

The most straightforward approach for protecting human explorers and the Mars environment is to avoid human landings, at least on early missions. Analogies with oceanographic exploration and deep-water drilling suggest that robotic exploration of dangerous environments, while human operators remain in close and direct control but in much safer surface (orbital) conditions, can be very effective. Although such an approach is far preferable from the standpoint of planetary protection, socialization of the concept among ‘boots on the ground’ explorers represents a significant barrier to implementation.

For landed human missions, planetary protection considerations should be integrated into the architectural design of the mission itself in order to minimize risks to crew health and forward/backward contamination, rather than attempting to develop technologies to be “applied to” a pre-existing architecture that are supposed to render it compliant. McKay and Davis (1989) discuss issues and general approaches for human exploration of Mars, including evaluation of habitability and contamination on a local level associated with the exploration sites, as well as the use of robotic sample return as a precursor for human missions.

The Human Exploration of Mars Design Reference Architecture 5.0 calls for landing within a Zone of Minimum Biological Risk (ZBR) (Drake, 2009). To be designated a ZBR, the area would need to be identified in advance as sufficiently safe for human exploration, which would be done as part of the landing site characterization process. The Aeronautics and Space Engineering Board also conducted a study on “Precursor Measurements Necessary to Support Human Operations on the Martian Surface,” which included consideration of potential biological hazards (NRC, 2002b). Carr et al. (2012) further assert that a robotic Mars sample return mission is fundamentally important prior to human exploration, in part due to knowledge gaps related to forward and backward planetary protection.

Landing site selection for human missions also must consider the potential for human-associated contamination to be transported to areas of higher concern for planetary protection. While human traverses could be conducted anywhere within the ZBR, the architecture, and COSPAR policy, requires that access to Mars special regions be accomplished via robotic systems, cleaned to the relevant standard, that would collect and analyze samples aseptically. The presence of human explorers would still be invaluable in the operation and maintenance of any robotic elements, as well as conducting science planning in situ and in real-time. Human-based exploration of Mars, therefore, is critically dependent upon understanding human–robotic interfaces and interactions, with both components (human and robotic) adhering to different yet interconnected planetary protection requirements.

5.2. Contamination control methods for crewed missions

Under current landed mission architectures, astronauts will spend several months on the Martian surface before embarking on a return trip. During this time, human activity and life support systems may accumulate large quantities of potential contaminating material in the form of waste, byproducts or leakage of life support systems, or even in situ resource utilization (ISRU) processes. To the greatest extent possible, human systems should be ‘closed-loop’, meaning that by products are recycled rather than being thrown away. The “Life Support and Habitability and Planetary Protection Workshop”, held in April 2005 to address concerns regarding life support and habitation systems with regard to human exploration of Mars, addressed some of these issues. The workshop participants concluded that early and regular coordination between the PPO and the differing scientific, planning, engineering, operations and medical communities is needed to develop workable and effective designs for human operations on Mars, and that identifying several research and technology development needs is critically important (Hogan et al., 2006).

A key advantage to deploying robots alongside humans is the human’s ability to repair and service robotic equipment, which would subsequently require re-cleaning using an appropriate in situ approach. A combination of operations planning and contamination control methods for human exploration missions will be needed to protect the science return, as well as the astronauts and Earth’s biosphere itself.

5.3. Crew health monitoring

The effects of Martian materials on the human body are unknown, even without consideration of the potential for martian biota, and the synergistic effects of spaceflight with exposure are difficult to predict. Regular monitoring of astronaut health and associated microbial populations will be important to identify and understand any potential changes resulting from exposure to extraterrestrial material. Rummel et al. (2010) provide a rationale and conceptual overview for integrating medical support of a crewed mission to Mars with planetary protection requirements.

Conducting accurate medical diagnostics in reduced gravity and within the confines of a spacecraft or habitat requires further research and technology development. Although medical research on the ISS has advanced the state of the art considerably, current research has mainly focused on the effects of zero gravity and the radiation
environment on the human body, rather than microbial commensals.

More targeted research programs on Earth, aboard the ISS, and on human missions beyond low-Earth orbit will be important to advance technologies for crew health monitoring, and collect a database of background information for planetary protection purposes. Crew monitoring on a Mars mission must not only identify potential effects of exposure to martian materials, but also collect information to support the contention that the underlying origins of any illnesses or microbial alterations as being Earth-based. Table 6 provides a summary of planetary protection considerations for human exploration missions.

### 6. Crosscutting research and support activities

Integration of the topics discussed in this review into the practice of planetary protection is a challenge for up-coming missions and researchers in the field. Through judicious and strategic selection of mission-centered technologies, significant cross-cutting savings can be realized in terms of both budgets and time. Hence, the following topics carry the potential to significantly improve the implementation process, in consultation with the PPO regarding refinement of requirements.

#### 6.1. Material and component compatibility

Previous missions have traditionally approached material and component compatibility as a main driver in determining microbial reduction and decontamination strategies, but now consideration of the reverse paradigm – selecting components for compatibility, or exposure to conditions during manufacturing processes that reduce encapsulated bioburden – is becoming increasingly of use. Components manufactured to military specifications, or for use in extreme environments such as deep drilling, often are resistant to conditions that make compliance with DHMR time–temperature conditions trivial in comparison.

Component compatibility concerns have been identified as a common thread for many of the methods discussed in earlier sections. This is typically the result of constantly changing spacecraft materials, use of increasingly sensitive instrumentation, or the development of new microbial reduction methods. Component compatibility concerns are especially critical for full-system microbial reduction methods. Future missions intended to explore potentially habitable environments in situ continue to grow in complexity and are approaching the limits of subsystem-level microbial reduction techniques. Therefore, system level microbial reduction may be advantageous in terms of both minimizing the achievable bioburden (particularly for mated and enclosed values) and resource intensiveness of implementation plans.

An aspect of compatibility that has received little attention since Viking is the potential to design the whole spacecraft to facilitate a particular planetary protection implementation strategy.

Selecting components that undergo high-temperature manufacturing processes or tolerate high-temperature operational conditions is ‘free’ bioburden reduction relative to the cost of subsequent treatments. Designing spacecraft to have smooth surfaces and minimal exposed hardware attachments, to minimize nooks and crannies that are difficult to clean, has the potential to enable dramatic reductions in accountable surface bioburden.

Designing for burnup-and-breakup or impact lethality is another novel concept, although some relevant practices are being developed by the Earth-orbiting satellite community to minimize the consequences of orbital debris obligations. The Juno project made no attempt to maximize lethality of the spacecraft’s impact into Europa; however, it might be possible to design a future Europa orbiter, though impacting at much lower velocity, in such a way that the impact itself creates high-temperature conditions to kill organisms carried in the most radiation-shielded parts of the spacecraft – which would not have been killed by the pre-impact radiation environment.

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Table 6
Summary of planetary protection considerations for human exploration missions.

<table>
<thead>
<tr>
<th>Category</th>
<th>Planetary protection considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission architecture and operations concepts</td>
<td>Formulate precursor measurement requirements, operation concepts for Zones of Minimum Biological Risk (ZBRs), human–robotic interfaces and protocols, local contamination transfer, traverse restrictions and boundaries, landing site selection</td>
</tr>
<tr>
<td>Contamination control methods for human missions</td>
<td>Risk analysis of contaminant release from life support systems, EVA suits, large-scale bio-shields for landed hardware, in situ sterilization of robotic equipment, tools, instruments, and sample caches</td>
</tr>
<tr>
<td>Human-associated microbial populations</td>
<td>Resistant strains have been isolated from spacecraft assembly facilities. Identification of new extremophiles informs the limits of habitability and sterilization methods. Genetic Inventory of spacecraft assembly facilities at NASA JPL has been conducted</td>
</tr>
<tr>
<td>Comprehensive monitoring of human health and habitats</td>
<td>Health consequences of human exposure to planetary materials are not well understood. Developing techniques to collect comprehensive information on the interaction of humans with non-living target materials (Moon, asteroids, etc.) will improve understanding of interactions with Mars material, and could support return of ill astronauts to Earth</td>
</tr>
</tbody>
</table>
6.2. Biological assay methods

Conducting biological assays and associated accounting on a large modern bioburden controlled mission employs approximately 3–10 FTE, depending on mission phase, with ATLO requiring the largest effort. The current NASA standard assay method derives from the Viking project, for which ~20 people conducted more than 6000 assays, averaging a minimum of 1000 assays on each landed spacecraft. On MSL, employing 4–6 people to execute planetary protection, more than 47,997 petri dishes were cultured.

Assays and specification values are used early during assembly to determine the initial level of contamination from which microbial reduction can be calculated, and also used to monitor cleanliness during ATLO processes. Methods are currently available that allow for rapid evaluation for a need to re-clean hardware prior to further assembly, with numerical ‘standard’ colony readouts requiring overnight or three days, depending on the procedure. None of these methods are intended to provide a comprehensive representation of bioburden present on a spacecraft: rather, they are designed to evaluate a relevant indicator that is used as proxy for overall spacecraft cleanliness. For example, the NASA standard assay utilizes sterile cotton swabs or wipes to collect samples, after which aqueous extracts are heat shocked by exposure to 80 °C (176°F) for 15 min, and then spread plated on tryptic soy agar and incubated for 72 h. The heat-shock step in the NASA standard assay serves both to kill the majority of organisms collected that are not heat-tolerant, as well as to stimulate germination of certain types of true spores that are counted in the subsequent colony-based assay.

Bioburden estimates are calculated from the number of colonies observed at 24 h increments. The statistical analyses by which total bioburden is calculated from colonies observed have undergone extensive review jointly by NASA and ESA, with the consequence that a simple Viking-style statistical approach, involving calculating mean values after allowing for efficiency of the sampling tools, will be required for future missions.

This approach is adopted in recognition of the need to allow for the use of diverse sampling tools, such as the nylon-flocked swabs (Probst et al., 2011) which were found to provide much higher recovery efficiencies over cotton swabs. The more complex statistics that were used on recent missions such as MSL did not take into account the efficiency of the sampling tools using instead a 3-sigma estimate of the bioburden (e.g. Beaudet, 2013), and will no longer be acceptable for bioburden accounting purposes.

For rapid ‘clean/dirty’ readouts, the Limulus Amebocyte Lysate (LAL) and Adenosine Triphosphate (ATP) assay methods are of use (e.g. Venkateswaran et al., 2003; Morris et al., 2010). Each of these assays provides a rapid evaluation of a biochemical metric for biological cleanliness, which when present at a sufficiently low threshold level can be taken as indicating that no spores would be collected from the assayed surface in a culture-based assay.

Originally developed for the pharmaceutical industry, LAL tests for the presence of microbial cell wall components by means of an enzyme cascade isolated from the blood cells (amebocytes) of the horseshoe crab (Limulus polyphemus). The method is sensitive to lipopolysaccharide (endotoxins) and beta glucan, which is present in Gram-negative bacteria, yeast, and mold, which could provide a proxy for spacecraft bioburden. Among considerations when evaluating LAL assay are high sensitivity, rapid processing times (15–30 min), and reactivity with the lipopolysaccharides from live, dead, and non-cultivable organisms.

The biochemical fuel, ATP, is a compound generated by all living cells, although it can also be found in dead cells. In a method pioneered by the food industry to assess bacterial contamination, the ATP assay is based upon formation of a bioluminescent product that can be measured and quantitated with a portable luminometer, thus yielding results within approximately one hour. The level of bioluminescence is directly proportional to the amount of ATP in the sample; however, because the amount of ATP per cell varies based on metabolic state, direct correlation between the amount of ATP and the total cell number is not feasible. This means that ATP is a fair threshold indicator of biological contamination, but like LAL is not quantitative for viable organisms.

6.3. Resistant organisms and microbial genetic inventory

Current planetary protection policy utilizes conservative assumptions regarding the survivability of microorganisms, particularly of the spore-forming variety, when exposed to microbial reduction methods or planetary environments. This approach is warranted given the isolation of multiple cultivable extremophile microorganisms (both spore and non-spore forming) from spacecraft assembly facilities (La Duc et al., 2007; Gosh et al., 2010). Advanced DNA sequencing techniques have also revealed the presence of diverse communities of archaea, bacteria, and fungi in cleanroom facilities, and now routinely demonstrate the presence of non-culturable microorganisms that may or may not be removed by standard cleaning techniques (Venkateswaran et al., 2012). By design and for this reason, the NASA Standard Assay is used only as a proxy for the estimation of spacecraft bioburden.

The range of biological capabilities exhibited by known Earth organisms continuously expands- an observation of considerable concern for planetary protection. Efforts to understand the capabilities of terrestrial biology include

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8. Personal correspondence with Robert Koukol, JPL.
9. Background information on LAL and ATP methods can also be found at http://planetaryprotection.nasa.gov/methods.

measuring the limits of life in the context of interplanetary radiation, surface and sub-surface planetary conditions (for example, of Mars and Europa), and on (or within) differing spacecraft materials. Laboratory simulations that take into account the effects of UV and ionizing radiation, atmospheric reactions, aridity, temperature conditions, surface oxidation, salinity and acidity and aeolian processes are all relevant to refining controls on forward contamination. These efforts are also relevant to astrobiology in elucidating additional novel characteristics of Earth organisms which are not investigated otherwise, such as the capability of Serratia liquefaciens, which lives on cheese in refrigerators and in the human mouth, to grow in sheltered Mars surface conditions (Schuerger et al., 2013). The European Space Agency Microbial Strain Collection (DSMZ) disseminates cultures collected as a result of this strategic knowledge gathering.

6.4. Understanding habitable planetary environments

Mission categorization and planetary protection requirements are based on the best available scientific information regarding our understanding of potentially habitable regions in the solar system. Due to the evolving understanding of the solar system, planetary protection requirements are subject to revision, although not on an approved mission after the Planetary Protection Plan is signed. It is normal to include in the Planetary Protection Plan a clause requiring missions to take additional action to protect newly discovered potentially habitable regions, as the Galileo spacecraft did when it impacted Jupiter to avoid Europa, or to further broaden the area of exploration (or constrain areas of special concern) if new data conclusively rule out the presence of a habitable environment, as was done by limiting the areas on Mars for which stringent bioburden reduction is required to ‘special regions’.

The concept of “special regions” on Mars was introduced by COSPAR in 2002 (Beaty et al., 2006). The recognition of special regions on Mars resulted in the addition of category IVc. In general, the habitats for the hardiest Earth organisms are currently used as proxies for possible habitats for Mars life. As an example, spores of certain species of lichens have been shown to survive simulated Martian environments (de Vera et al., 2004).

For implementation purposes, special regions are designated based on chemical availability of water (water activity) and temperature. This includes subsurface areas, polar regions, and areas of hydrothermal activity. Mars orbiter observations and in particular the presence of hydrated minerals on Mars trace the history of surface water and the global atmosphere and climate cycle (e.g. McEwen et al., 2011). Ultimately, planetary protection implementation and requirements may be further revised based on the availability of new information concerning special regions, hardy organisms, and spore transfer mechanisms, which include geophysical processes as well as mission events (e.g. impacts, drilling, roving, heat generation etc.). Table 7 summarizes cross-cutting research and support activities.

7. Rationale for a strategic planetary protection R&T D roadmap

Traditionally, R&T D for planetary protection purposes has focused on advancing capabilities within the framework of individual missions or on a program level. Examples include the pioneering of dry heat microbial reduction for ‘full-system sterilization’ of the Viking missions in the 1970s and the more recent development of deployable bio barriers funded by the NASA Mars program that ultimately benefitted the Phoenix Mars lander.

Table 7
Summary of cross-cutting research and support activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Status</th>
<th>Related R&amp;T D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component and material compatibility</td>
<td>Small-scale studies exist, but typically focus on particular combinations of materials and sterilization/cleaning methods</td>
<td>Generate and maintain comprehensive data on compatibility on the subsystem and assembly level, including the interaction of materials under various combinations of microbial reduction and assay methods in relevant environments</td>
</tr>
<tr>
<td>Biological assay methods</td>
<td>NASA Standard Assay as default method, augmented by LAL/ATP to validate cleaning criteria</td>
<td>Develop additional methods with quantitative equivalence to the NASA Standard Assay</td>
</tr>
<tr>
<td>Resistant spores &amp; genetic inventory</td>
<td>Resistant strains have been isolated from spacecraft assembly facilities. Identification of new extremophiles informs the limits of habitability and sterilization methods. Genetic inventory of spacecraft assembly facilities at NASA JPL has been conducted</td>
<td>Further characterization of extreme organisms, as well as further characterization of the genetic inventory of spacecraft assembly facilities</td>
</tr>
<tr>
<td>Habitable planetary environments and spore transfer</td>
<td>Conservative view of “habitable environment” required given we do not have full understanding of the range of life on Earth. Some studies conducted on environmental transfer between surface and subsurface of Europa and other icy bodies, as well as initial studies conducted on the transfer of material between Mars and its satellites</td>
<td>Modeling and science observations of potential planetary habitats</td>
</tr>
</tbody>
</table>

While missions and specific programs will and should continue serving important roles in research and development of new technologies and methods, there are several benefits to leveraging early development (i.e. low TRL) activities at a more centralized level. This could include more direct involvement of the Planetary Protection Officer (PPO) in close consultation and cooperation with external consultants, other space agencies, advisory committees such as ad hoc panels of National Research Council and the NAC Planetary Protection Subcommittee, COSPAR, as well as other NASA offices such as the Office of the Chief Technologist (OCT) and the Office of the Chief Engineer (OCE). It should be noted that while this section is primarily focused on items specific to NASA from the perspective of the authors, any strategic efforts towards a planetary protection focused R&TD program should involve partnerships with other international space agencies. A future R&TD roadmap may be mirrored, or even augmented, by similar documents drafted in parallel by the individual agencies, geared towards their respective and specific needs. Alternatively, a unified roadmap could feasibly be drafted that considers national and international R&TD efforts in context of each other.

Advantages of defining and implementing a planetary protection roadmap include increasing the level of strategic direction, facilitating compliance by advancing technologies and methods, and also centralizing a more comprehensive knowledge capture and management structure. Fig. 1 depicts the relationships between strategic planning, mission implementation and knowledge management for planetary protection. Each of these factors is addressed in more detail in the following sections.

7.1. Strategic planning

Technology development for planetary protection methods has historically been tied to a particular mission’s requirements. As such, development efforts are necessarily constrained by the immediate planning horizon of the project, and the particular mission design. While this provides focus for a specific technological avenue, a strategic development program can integrate discrete achievements into a portfolio that has a value greater than the sum of its individual parts. Integrating these efforts into a strategic roadmap has two major advantages that are not achievable on a purely mission-oriented basis.

First, a more expansive planning horizon allows greater integration with overarching exploration roadmaps. This can include complex, multi-phase robotic missions such as a Mars Sample Return (MSR) program, as well as future human exploration. Technology development for such ambitious concepts should commence well before the missions are formally approved, as they may require radically new contamination control and sample handing methods and infrastructure.

Secondly, a strategic roadmap would serve to identify crosscutting capabilities and leverage synergies between individual research efforts. Maintaining collective oversight of technology development activities can therefore facilitate, and provide greater incentives for, information transfer and adaptation of resulting technological advances. Without a strategic plan, important overarching requirements may not be included in the original design of particular technologies and resulting hardware.

As a general example, a Mars mission may not require bio-barrier materials or mechanisms to withstand the same environmental conditions encountered during an outer planets mission – or the reduction method applied to it prior to launch. Likewise, a capability-driven development program can aggregate “lessons learned” from sources external to a particular program, for example aspects of lunar sample curation that may be relevant to eventual Mars sample handling. The NASA PPO already facilitates cross-agency dialogues, and uses input from a variety of sources to address top-level issues and priorities. However, additional resources are needed to formally synthesize these activities as part of a strategic roadmap.

It is certainly important not to unduly burden technology development efforts for the benefit of a particular mission by imposing requirements perceived to be peripheral to the mission, but the transfer of technologies can be severely inhibited unless long-term requirements are traceable beyond the mission’s immediate needs. Given the broad array of mission planning activities being pursued today, greater strategic direction including international agreements is needed to expand the planning horizon of planetary protection technology development tracking.

7.2. Facilitating mission compliance

The second tier of the rationale for a strategic technology development roadmap for planetary protection implementation is a drive to facilitate compliance for future missions. This is achieved by providing more options, as well as more detailed specifications and verifications, for contamination control to mission planners through technology development and supporting research activities.
While mission-driven research and development efforts may produce useful niche capabilities as applied to the particular science objectives of the mission, any deviation from or non-standard application of formally approved planetary protection practices incurs a burden on the mission to prove suitability and compliance. Depending on the exact nature of the deviation, this places significant cost and schedule burdens on the mission, especially if the deviation is the result of late emerging issues.

Integration with a technology-focused program may therefore provide a vehicle for supporting research and development that may otherwise be neglected in a time of de-scoped missions and more stringent controls for cost and risk on a mission level. As an added benefit, a more solution-agnostic approach opens the possibility of potentially “game-changing” capabilities that would exceed the scope (and risk-tolerance) of mission-driven technology development, and therefore could enable missions subject to particularly stringent planetary protection requirements that may not be feasible otherwise.

Of primary concern are microbial reduction and contamination control methods. A diverse portfolio of these methods is needed based on the many distinct and evolving requirements for implementation, including the degree of cleanliness sought, material compatibility concerns and application mode on surfaces, subsystems or whole-system microbial reduction. Beyond microbial reduction and cleaning methods, re-contamination control methods and operational analysis can be employed to meet compliance.

Furthermore, supporting research activities may assist mission planning and even policy development, for example by further constraining habitable regions and microbial transfer. Ultimately, increasing the available options for compliance reduces cost and schedule burdens typically associated with planetary protection implementation.

### 7.3. Knowledge management

The value of the knowledge gained via research & development efforts is directly proportional to the number of its benefactors. Therefore, steps must be taken to make any derived information as transparent and broadly accessible as possible. While the technology development roadmap itself would serve as a central document providing an overview of research activities, as well as their relative priorities, readiness and applications, a knowledge management strategy must be in place to maximize its utility.

A centralized roadmap at an agency-wide level serves to bridge two types of impending knowledge gaps. The first are knowledge gaps that occur between individual research efforts, either resulting from lack of mutual awareness, or deliberate competitive tendencies. This can occur on multiple levels, ranging from mission-to-mission, program-to-program, program-to-contractor, or even across different facilities or industries (e.g. awareness of advances in the bio-medical industry). A roadmap would enable greater resources to be devoted to curating and archiving information under the direction of the PPO, as well as providing a framework for targeted studies and reference materials, such as material and component compatibility data.

The second type of knowledge gap occurs when continuity between missions is not guaranteed. This aspect is closely tied to the skilled workforce and the accumulated knowledge contained within it. Planetary protection requires a very particular set of skills applied to a highly specialized field, thus maintaining a trained workforce is critical to successful implementation. Workforce retention can be particularly challenging in a budget constrained environment, especially if there are multi-year gaps between planetary science missions, and potentially even longer gaps between those missions that require significant attention to planetary protection (i.e. Category III or higher).

Although sustaining even a core group of planetary protection implementation experts requires long-term investment, recovering lost expertise and re-training individuals can be costly, if not devastating to entire missions. A technology development program funded separately from missions may serve as a mechanism to not only retain talent, but also to further it by augmenting experience in

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**Fig. 2.** Description of the Planetary Protection Office’s role in bridging the gap between implementers and facilitators by acting as a hub for knowledge management and strategic planning.
implementation with exposure to technology development and verification of new specifications in anticipation of future missions. This rationale is synergistic with the aforementioned advantages of facilitating compliance, as it allows the same individuals who will ultimately implement planetary protection procedures to gain experience in the development of the same procedures.

The relationship between actors and impending knowledge gaps is depicted graphically in Fig. 2. Bridging these gaps in institutional knowledge and capabilities would be a key benefit of a strategic technology development platform that has a mission-independent funding stream.

8. Conclusions

In conclusion, a number of research and technology development avenues have the potential to advance the field of planetary protection, which in some cases are required to enable ambitious future planetary exploration missions. The time horizon and multi-disciplinary nature of these research avenues can best be accommodated by developing an over-arching program that integrates capability-driven developments with mission-driven implementation efforts. Such a program will need additional resources beyond those currently allocated to NASA’s planetary protection activities, in terms of staff, personnel, and funding streams. Additional benefits of a strategic, integrated approach include improved knowledge management and data accessibility. Ultimately, a strategic roadmap for planetary protection provides a forum for strategic planning, facilitates compliance, and acts as an overall knowledge management framework. If adequately supported, it will help to enable the next phase of solar system exploration, including the search for life, sample return missions, and human exploration, while safeguarding scientific results and Earth’s biosphere.

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