Advanced Planetary Protection Technologies for the Proposed Future Mission Set

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Planetary protection is the discipline of protecting solar system objects from harmful contamination resulting from the activities of interplanetary spacecraft, and of similarly protecting the Earth from uncontrolled release of a putative extra-terrestrial organism from returned extra-terrestrial samples. Planetary protection requirements for Mars are becoming further refined as more is understood about the nature of the Martian environment as a potential habitat. Likewise, increased understanding of the limits of life on Earth is informing planetary protection policy. This presentation will discuss recent technology developments, ongoing work and future challenges of implementing planetary protection for the proposed future mission set.

I. Introduction

PLANETARY protection involves avoiding adverse effects to the environment of the Earth when humans bring back other planetary materials, as well as preventing Earth life from contaminating other planetary bodies to preserve those locations for scientific and other purposes. The motivations for planetary protection are well illustrated by H.G. Wells' 'War of the Worlds': in the actual story, both the environment of the Earth and the Martians' physiology were damaged by the actions of organisms transferred between the two. In addition, Orson Welles' radio broadcast of the story, rewritten as real-time news reports from New England, on Halloween night of 1938, generated immediate concern and subsequent widespread outcry regarding the inadequate or misleading public communication. Planetary protection precautions must take into account multiple factors: scientific and technical considerations as well as broader social implications.

Science goals that drive planetary protection involve preserving the capability to find life on other planets without allowing it to be covered up by Earth life that ride along on our spacecraft. We know that life evolved at least once in this solar system, but we don't know whether independent origins of life are a common process or quite unique. The molecules needed to make life like us, containing primarily carbon, hydrogen, nitrogen and oxygen, can be formed by processes that happen in space or on planetary surfaces: one of the major goals of solar system exploration is to understand the distribution of prebiotic compounds that might contribute to an origin of life. However, if Earth life is introduced into these extra-terrestrial environments where it can persist, then any pre-existing record of local extra-terrestrial carbon chemistry is likely to be compromised.

Protecting planetary environments is challenging because planetary bodies are diverse, and objects with surfaces apparently inhospitable to carbon-based life can have quite different conditions in their interiors, and even in the shallow sub-surface. Microbial life on Earth is able to grow in a very wide range of physical conditions, relative to most animals and plants we see today. Some microorganisms thrive in near-freezing water at mid-ocean ridges in the bottom of the ocean, living off the chemicals, or the infra-red photons, released by volcanic processes. Others enjoy nearly boiling acid in hot springs like Yellowstone, while whole communities exist kilometers down in the

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continental subsurface, using as minerals as nutrients and hydrogen released from radioactive decay, with no energy input from the Earth's surface or the Sun.

Introduction of a few Earth organisms into hospitable locations can produce dramatic consequences, as has been demonstrated many times by the actions of invasive species on Earth. A very personal example is food-poisoning: ingesting a small number of salmonella bacteria can have extremely unpleasant consequences for a person's internal ecosystem. This can also be true on a planetary scale: over billions of years, photosynthetic organisms on Earth have absorbed sunlight and released molecular oxygen, which has shifted the surface chemistry of our planet to a chemically-oxidized and reactive state. We don't yet fully understand the capabilities of Earth life, nor potential consequences for future exploration, but we do know of many examples where releases of invasive organisms on Earth have had significant economic and ecological repercussions. It just makes sense to avoid releasing organisms on other planets, when we know we can't effectively predict the results.

II. Regulatory Framework

Considerations around planetary protection have been discussed since before the dawn of the Space Age: beyond H. G. Wells' and others' stories, the international scientific community took up the subject seriously at a meeting of the International Astronautical Federation in Rome in 1956, and following that in 1958 the International Council of Scientific Unions (ICSU; now the International Council for Science), which advises the UN on scientific matters, formed the Committee on Contamination by Extra-Terrestrial Exploration (CETEX). Later in 1958, the United States created both the National Aeronautics and Space Administration, as well as the Space Studies Board which is the body within the U.S. National Research Council tasked with providing scientific advice to on space exploration. Also in 1958, the United Nations formed the Committee on the Peaceful Uses of Outer Space (UN-COPUOS), and ICSU formed the new Committee on Space Research (COSPAR), advisory to UN-COPUOS, into which CETEX was incorporated. UN-COPUOS is the forum for development and elaboration of the 1967 Treaty on the Peaceful Uses of Outer Space, commonly called the Outer Space Treaty, and COSPAR, as the scientific advisory body for UN-COPUOS to this day maintains the international consensus policy on planetary protection.[1] (For a more extensive history see Meltzer, 2011.[2])

The current international policy framework for planetary protection is based on refinements initiated in the mid-1960s, such that the precautions taken by any specific mission are set according to the level of concern that terrestrial biological contamination might persist on the mission's target object(s) and interfere with future research objectives. The motivation for this framework is to ensure that restrictions are applied only where the risk of contamination is considered high enough that the increased cost of a mission can be justified, in consideration of the benefits that exploration would return. Planetary objects that do not contain environments hospitable for Earth life (which include the vast majority of small and most large bodies in the solar system) are protected only to the extent that agency policies require documentation of what operations the mission intends to perform and how well those were completed, which is then reported to COSPAR. For such objects, there are no operational restrictions on either robotic or human missions, and no additional requirements on cleanliness or biological contamination beyond those applied to all spacecraft hardware.

There are currently only three objects in the solar system for which a higher degree of protection is definitely required: missions to Mars, Enceladus, and Europa must demonstrate that they have reduced the bioburden carried on the spacecraft to levels that have been agreed upon as providing an adequate risk/benefit ratio, within the framework of COSPAR policy and recommendations from national scientific advisory organizations.

III. Specific Constraints

For Enceladus, Europa, and other icy bodies where there is insufficient scientific information about the potential for liquid water to be present, planetary protection requirements[3] are formulated in the context of a 'probability of contamination,' and dictate that a project under consideration demonstrate less than a $1x10^{-4}$ probability that that the spacecraft will introduce a viable Earth organism into a liquid water environment, both during and after active mission operations. For this probabilistic formulation, and given an understanding that human missions to these distant objects are beyond the current planning horizon, the timescale of concern is set by the survival capabilities of Earth organisms in the relevant environments, and post-launch conditions such as radiation exposure or impact heating can be used in analyses of bioburden reduction over time. Such analyses benefit from taking Albert Einstein's advice that 'Everything should be made as simple as possible, but not simpler' – and start by evaluating the full mission profile and expected conditions encountered, systematic design of the spacecraft to ensure maximum post-launch reduction of organisms carried within hardware components, as well as information about manufacturing processes of spacecraft hardware, to identify the most likely approaches by which bioburden can be shown with analysis to be reduced. Only subsequently might active pre-launch bioburden reduction of spacecraft hardware, or limitations to mission operations be considered.

For Mars, in contrast, current planetary protection requirements for robotic missions specify numerical limits, both for avoidance of Mars impact by orbital or flyby missions and for the number of viable organisms that spacecraft are permitted to deliver to Mars. Flyby missions that avoid impact with Mars at a probability of 99% do not have cleanliness requirements beyond those typical for spacecraft assembly facilities. Similar requirements apply to orbital missions that can demonstrate both impact avoidance during entry into Mars orbit and avoid Mars impact at a probability no less than 0.99 for 20 years after launch and a probability no less than 0.95 for the period 20-50 years after launch. The most stringent current limits for landed missions are the same ones that the Viking spacecraft met before their successful missions at Mars. Any robotic mission that adopts the Viking approach of cleaning with subsequent full-spacecraft microbial reduction would be allowed to go anywhere on Mars, today. The basis for the landed numerical requirement for "spores"[3] is work done during the Viking program to establish numerical limits on bioburden consistent with meeting the probabilistic contamination requirement then current for Mars: both Viking missions together were allocated a $2x10^{-4}$ probability of contaminating Mars. This probability was sub-allocated to each of the various hardware components, and then a numerical allowed-bioburden value was calculated, utilizing a $1x10^{-6}$ probability estimate that Earth organisms could grow on Mars. To meet the numerical bioburden allocations, all Viking hardware was carefully cleaned during assembly, heat "sterilized" at the sub-assembly level and the fully-assembled lander systems subsequently underwent a heat "sterilization" process to reduce the measured bioburden by several additional orders of magnitude. The act of assaying bioburden after the terminal sterilization process would of course re-contaminate the spacecraft, so after treatment the Viking landers were kept inside the heat-shield and backshell until they left the Earth's atmosphere. That the full Viking treatment was effective is documented by the observation that the Viking Life Detection package did not return data consistent with the growth of Earth organisms, when those experiments were performed on Mars.

No subsequent landed mission to Mars has replicated the full Viking bioburden reduction protocol: the data returned by the Viking missions, and others, suggested that most of the surface of Mars is cold, dry, and irradiated by solar UV light – and therefore quite hostile to Earth organisms. In recognition of these data, the requirements were modified so that the projects were required to document that the bioburden carried by spacecraft is, by use of appropriate cleaning protocols, maintained below $3x10^5$ "spores" for surfaces and $5x10^5$ "spores" carried both on and within spacecraft hardware. This was considered an acceptable risk, relative to the benefit of eliminating the final baking step, because the local environment at Mars should kill this small number of delivered Earth organisms, or at least prevent them from growing.

IV. Current and Future Mars Missions

Recently, requirements and international guidelines for Mars missions have become more complicated, for multiple reasons. First, because human missions have been brought into consideration and also because new data demonstrate that the environment of Mars is considerably more complex and dynamic than was previously understood. Finally, a greater appreciation has been gained for the robustness of life on earth to persist in inhospitable environments, to reemerge when conditions improve.

In the international planetary protection guidelines for human missions to Mars, it is recognized that the availability of human explorers, which could dramatically improve operational capabilities in situ at Mars, can only support scientific investigations if the biological contamination that is inevitably associated with humans is controlled and understood. Fortunately, the equatorial landing locations on Mars that are most feasible from an engineering standpoint, are also locations likely to be inimical to microbial contamination released by those missions: thus, the forward contamination objectives of planetary protection policy can be met, from a risk/benefit standpoint, by requiring that early human missions target only locations where released Earth organisms would be unlikely to grow; minimize release of human-associated microbes; and provide for mitigation of accidental release.

[3] "Spores" in this context refer to organisms that form colonies under the NASA standard assay protocol, including a "heat shock" step. Traditionally, this assay was designed to enumerate spores of heterotrophic mesophilic spore forming bacteria, as a resistant proxy organism for assessing the sterility of spacecraft hardware, but may also include other bacteria able to survive the heat shock step (see also reference 3).

Planetary protection concerns related to exposing humans to unsterilized Mars material, and subsequently returning them to Earth, will be addressed under the section on Sample Return.

The missions to Mars that have been launched in the past 15 years have returned an enormous amount of information regarding martian conditions, that have revealed it to be very different from the dry dead object that Mars was thought to be following the Viking observations. Orbital observations over time have identified many changing features on Mars, from recent gully flows to Recurrent Slope Lineae, that are indicative of dynamic processes probably involving liquid water, though in the form of mixed-saline brines. Observations made near the North Pole of Mars by the Phoenix spacecraft demonstrated directly the presence of water ice within centimeters of the surface, and measured a soil chemistry very different from what had been predicted on the basis of Viking and Mars Exploration Rover data. All of these data support the continued protection of so-called 'Special Regions' on Mars, environments that provide conditions potentially conducive to the growth of Earth organisms. To access Special Regions, robotic spacecraft – or robotic adjuncts to human exploration – must maintain cleanliness levels statistically equivalent to less than a single viable Earth proxy organism or biochemical equivalent, per square meter of exposed spacecraft surface, equivalent to that previously achieved by the Viking Lander spacecraft.

The definition for Special Regions that was internationally accepted in 2008 specifies temperature and water activity (1/relative humidity) parameters, and sets limits on those parameters of -25°C and water activity of 0.5, (relative humidity of 50%) – in equilibrium conditions over a 500 year timescale.[4] A lower limit on timescale under disequilibrium conditions was not addressed, however, it was noted that research on the capabilities of Earth organisms, as well as conditions on Mars, was advancing rapidly, and that the parameter limits should be updated on a regular basis. Research reported in the last few years highlights the need for an update, in particular to address diurnal cycles at the Phoenix landing site, where conditions close to or within the Special Regions parameters were likely attained for short periods of time. The data on soil composition and observations of potential flow-features on Mars have stimulated research into the physics of mixed-ion brine solutions, which can remain liquid over a much broader temperature range than previously understood - and display complex phase diagrams for solubility that could contribute to local micro-environments on Mars having more water available than bulk equilibrium models would predict. Of particular note is the current work of Tolbert's group (Gough et al. 2013[5]) on the stability of liquid brines at low temperature and their potential act as a transport mechanism for terrestrial contaminants. In addition, research on the capabilities of high-alpine and polar desert organisms has demonstrated that a variety of Earth microbes or communities, particularly including lichens, can survive and grow under simulated Mars-like conditions of pressure, temperature, atmospheric composition and diurnal cycles, with water availability above 0.5 for only short periods of time (de Vera et al., 2010)[6]. Many microbes, including some found in human saliva, are capable of growing at 0°C and 7mbar pressure, in Mars atmosphere, if provided with 100%RH, nutrients, and sheltered from UV light (e.g., Nicholson et al., 2012[7]; Schuerger et al., 2013[8]). These data argue for careful protection of Special Regions from the introduction of Earth organisms carried on robotic spacecraft or associated with human missions to Mars.

For the recently-proposed mission that would launch two humans in 2018 to fly by Mars they should be able to meet impact avoidance requirement at Mars. This would involve demonstrating a 99% probability of avoiding impact with Mars during the mission, and it's not unlikely that the human participants would insist on a higher level of confidence. In addition, the mission would need to avoid releasing any hardware components or disposables contaminated with Earth organisms in such a way that they could impact Mars. Although led privately, this proposed human Mars flyby mission will need significant NASA infrastructure support, for which compliance with NASA planetary protection policy for the overall mission is a prerequisite. NASA policy specifies compliance with the 1967 Outer Space Treaty: Article IX of that treaty provides for planetary protection, and COSPAR is the relevant advisory body to UN-COPUOS on implementation of planetary protection policy. Article VI of the Outer Space Treaty further specifies that states parties to the treaty are responsible/liable for the actions of their non-governmental entities.

V. Sample Return Missions

Missions that return planetary materials to Earth, whether robotic or human, fall under an additional set of planetary protection requirements that are designed to protect the Earth from any hazards that might be contained in the planetary samples. Biological organisms, because they could replicate and increase in number, are considered of high concern regardless of whether an individual organism would appear to be harmless: following, of course, on experience gained from observation of invasive species on Earth. Again, planetary protection requirements are graded so as to apply more stringent precautions to samples of higher potential risk. Thus, samples from the majority of objects in the solar system, which are considered to be devoid of life on the basis of the best available scientific evidence and for which no outbound restrictions are imposed, also receive no restrictions for returned samples.

Returning samples from Mars has long been an objective of planetary exploration specifically because Mars is considered likely to host present or past life, and studying Mars samples in laboratories on Earth would permit the most complete characterization of the potential for life to be or have been present. Experience from Viking demonstrates how challenging in situ life detection experiments can be: the data returned from the several instruments in the Viking Life Detection Package did not follow predicted profiles, and were interpreted both as equivocal evidence for life on Mars and as evidence of Earth contamination. Even with very careful precautions taken to remove Earth organisms and organic compounds from Viking hardware, data indicating the presence of chlorinated methane was interpreted as being a consequence of insufficient removal of cleaning fluids used before launch. Data from the labeled release experiment did not follow the expected profile for metabolic activity, and thus most researchers interpreted the results as suggesting the presence of chemically-reactive species that were not alive – but the principal investigator of the instrument to this day contends that his experiment did detect life on Mars. More recently, the Phoenix mission showed perchlorate to be present in Mars polar soils at low percent concentration, which was unsuspected at the time of Viking: the Viking results can now been reinterpreted as evidence for low levels of organic compounds on Mars in the presence of other reactive species such as perchlorate. Had Mars samples been available for follow-on laboratory experiments, these conclusions would have been reached in weeks rather than decades.

The scientific interest in understanding whether Mars has ever hosted life has led to strict limitations being imposed on the amount of organic or biological contamination from Earth that is permitted to be introduced into samples collected for the purpose of life detection, either in situ or during sample return: the Viking missions accomplished this successfully, and the upcoming ExoMars rover is designed to achieve similar performance. The Mars Science Laboratory mission (MSL), with scientific objectives that do not include life detection, was not required to maintain the same stringent level of cleanliness as a life detection mission would have been, although significant organic contamination control activity was done in support of the Sample Analysis at Mars instrument. Lessons learned from MSL will be important for improving future missions, particularly those that must meet life detection requirements. These are still being generated as the mission progresses. Some early data returned by the SAM instrument indicated the presence of significant amounts of methane in an atmospheric sample, which raised considerable excitement in the community until it was recognized that the atmosphere under analysis had come from Florida.

This is important, from the standpoint of planetary protection, because the discovery of potential Mars life would initiate an immediate re-evaluation of the requirements for both robotic and human missions to Mars, with restrictions unlikely to be made less severe. Returned Mars samples, which will undergo extensive testing in Earth laboratories using the most sensitive available equipment, must be protected from contamination by Earth from before collection through to the end of the laboratory analysis: this will be a significant driver of mission design. It would be an unwise use of taxpayer investments to bring Mars samples to Earth only to find, once analyzed, that signals from Earth life are so abundant that indications of potential Mars life are below the noise levels.

In addition, the requirements for containment of Mars material from collection through return to Earth and laboratory analysis are strict. Repeated assessments by the Space Studies Board, and more recently the European Science Foundation, of planetary protection for returned Mars samples specify that the samples must be treated as if hazardous until demonstrated otherwise, and that containment of the returned material should be as stringent as for other known highly hazardous materials. The challenges of performing careful biochemical analyses in high containment are well understood by researchers of human pathogens such as Ebola virus, but planetary scientists are not adjusted to such restrictions.

These combined containment and contamination control requirements make it clear why proposals to return Mars samples for analysis in Earth orbital or lunar laboratories will very unlikely to be practicable: the cost of re-engineering necessary laboratory equipment to function in lunar- or micro- gravity, not to mention delivering this amount of mass into orbit, would be prohibitive. In addition, human factors considerations would likely preclude such an approach, because there would be no way to ensure reliable self-reporting of a containment breach. During the Apollo program, several technicians handling lunar samples, who had been exposed to lunar material during a breach of containment, left the area rather than be put into quarantine along with the astronauts: Who would report being exposed to a Mars sample, if it meant they might never get to come home?

Considerations of astronaut exposure to Mars materials take on a different complexion in the context of landed human missions to Mars: at that point, it is understood that maintaining complete separation humans from Mars materials will be impossible. The Safe on Mars report[9], by several boards of the National Research Council, highlights the need for preliminary investigations to evaluate whether a location is safe for humans to land – this report recommends that, should evidence of organic compounds be found on Mars, that a robotic sample return mission should be required before humans are landed on Mars. Once a human mission is at Mars, robotic assistants should be provided to investigate areas not yet confirmed to be safe for human access, as well as locations (such as Special Regions) where contamination by human-associated organisms would not be permitted. COSPAR guidelines also highlight the need for autonomy in support of rapid response time: some level of quarantine capability should be provided on the mission, and a member of the mission team must have specific responsibility for ensuring that planetary protection protocols are followed. Consistent monitoring of human health indicators, including changes in microbial populations carried by the astronauts and within support hardware, will be essential – both to diagnose any illnesses experienced and also to demonstrate to the population of the Earth that there is a sufficiently low risk of allowing the return of astronauts who have been exposed to Mars materials. Recent technological developments being pursued by the biomedical community, such as the Human Microbiome Project, should be investigated for potential to provide a foundation for development of spaceflight-adapted capabilities.

Although it has is clear that operational restrictions for planetary protection purposes will not be imposed on foreseeable human missions to objects other than Mars, there is a certain level of cross-communication with regard to human support system design strategies that could significantly reduce (or, if not present, increase) the cost of space exploration as a whole. Planetary protection guidelines to minimize release of human-associated volatiles and disposables align well with closed-loop life-support objectives to reduce upmass and downmass requirements, regardless of the mission or target object. Considerations of astronaut health and mitigating the consequences of exposure to planetary materials are congruent with planetary protection objectives: development of technologies that minimize human exposure to planetary materials, and monitor the progression of responses, could be equally valuable for human missions to asteroids or the Moon, as to Mars.

However, if near-term human support systems are designed without taking future objectives at Mars into account, then significant (and expensive) re-design could become necessary. The Apollo space suits, for example, implemented an open-loop cooling system that functioned by evaporation of water carried by the astronauts into the lunar exosphere. Such a system would probably not be allowed on early human missions to Mars, because the unsterilized and unfiltered evaporate would very likely release microbes into the local environment. Training of human spaceflight designers and systems engineers in planetary protection considerations, early in the design cycle for human support hardware, is the most effective approach to reducing these potential downstream cost risks.

VI. Technology

In the context of being clean (or rather, clean enough, from a planetary protection perspective) when you are at your exploration destination, the first activity is to understand the organisms that are present on the hardware and the contamination risk they represent.

In any terrestrial environment, there will be a group of predominant microorganisms, which have metabolic capabilities optimized to that environment. Alongside those, there will be other viable organisms that are present in lower numbers but may be dormant, quiescent or transient. The Baas-Becking hypothesis, which was originally formulated as "Everything is everywhere, but the environment selects" (what grows) seems to be a useful generalization of what happens in the terrestrial environment. This is observed for example of microbial colonization of new land from volcanic activity or of the opening and closing of transient deep sea vents.

Until comparatively recently, our ability to detect what microorganisms are present in an environment was largely limited to what could be grown in a petri dish, with estimates that below 1% of organisms are actually able to be cultivated in this way. More recently, the advent of DNA sequencing led to the ability to penetrate deeper into environmental microbiological communities, allowing the identification by Woese and co-workers of a complete new microbiological Kingdom; the Archaea. The technology that led to this discovery, the use of 16S rDNA sequences to discriminate microbiological species, is now developed to allow hundreds of thousands of DNAs to be analyzed at a time. This makes possible the comprehensive cataloging of microbial communities, and allows the creation of “passenger lists” of the microbial hitchhikers on robotic spacecraft, as described by Venkateswaran[9] at JPL, or present in closed habitat environments such as the ISS.

This is important in the context of exploration of, for example, Europa, where it uncertain what sub-surface ocean conditions are like, in terms of temperature, salinity, or pH; three parameters that would fundamentally change which terrestrial organism would present the greatest risk to the “harmful contamination” we are seeking to avoid. A full understanding of who is present ensures adequacy of the cleaning and sterilization protocols for the spacecraft.

This contrasts with the present approach for Mars, where we continue to assay for mesophilic heterotrophic spore forming organisms as we have done since the Viking era. This is because we do not have a "better mousetrap": for Mars, these organisms are still the best indicator of PP contamination risk for organisms that might survive pre-launch cleaning processes, the environment of interplanetary space, and the Mars environment, to grow and cause problems in a protected niche environment at Mars.

The DNA-based technologies are expected to be an important part of monitoring to assess the "microbial health" of closed environments. Such approaches are unsurpassed in their ability to identify organisms that could be/become problematic for crew health or spacecraft systems, particularly in the context of long duration spaceflight or habitats in extraterrestrial environments.

In the context of such information, it is then important to understand capabilities, but also the limits, of terrestrial biology. In recent history, the scientific community has been repeatedly surprised by the ability of biological systems to eke out a living in what at the time were considered to be uninhabitable locations or conditions. At the time Viking was being launched, its planetary protection implementation was affected by the discovery of "hardy" (compared to the standard reference) organisms, curtailing the lethality effect that was accounted for this mission. As discussed earlier, since Viking, we have discovered organisms that thrive in inhospitable environments, such as hot vents at the bottom of the ocean, in Antarctic ice cores, in the stratosphere and in the deepest mines. With reference to the ice core work, the particularly impressive aspect is the longevity of microorganisms in these environments, which has direct bearing on the duration over which the planetary protection discipline has to "care about" terrestrial contamination of "similar" extraterrestrial environments.

NASA has historically used dry heat microbial reduction (DHMR – baking in a controlled humidity environment) as the principal mode of bioburden reduction. Engineers are familiar with the thermal performance and limitations of their hardware, so this technique is within their design "comfort zone". Part of the need to understand who is present, from a biological perspective, is to be able to develop processes to adequately eliminate what's there. Following a significant amount of work by Schubert[10] and others, NASA is in the process of launching a revised scope to the current specification, allowing a broader range of conditions to be used for bioburden reduction. This is the first revision of this specification since the Viking era.

A chemical method of surface sterilization has recently been added to NASAs approved bioburden reduction methods: vapor hydrogen peroxide processing is a powerful surface sterilization technology that is likely find application in the sterilization of hardware that is not compatible with dry heat, or in re-sterilization of hardware, for example during mate/de-mate assembly and testing activities where sterility is needed to be maintained. Looking to the future, it is also a candidate sterilization technology for activities where resterilization of hardware is needed in support of human exploration, such as habitation environments, airlocks and robotic support equipment.

Beyond the sterilization processes, there is also a need to understand how to keep hardware clean to the required levels for the complete end-to-end mission process. There is little point in deploying heroic levels of effort in developing a capability to sterilize a sensitive piece of hardware, if it cannot be kept sufficiently clean until it reaches its destination, for example during launch through the terrestrial atmosphere, or through proximity with some other spacecraft hardware with a lower level of cleanliness. For this reason, greater use of filters, seals and biobarriers is likely for the more sensitive future missions, together with resterilization capabilities such as those described above. In the context of a future Mars sample return mission, the ability to clean sampling tools to below minimum detection limits of terrestrial instruments, and then protect to those levels is drawing particular attention at present. Alongside each of these will need to be the verification and monitoring approaches for each of the approaches and technologies deployed.

VII. Conclusion

In the end, getting the right answer to the question "are we alone in the universe?", or for the time being, in the solar system, strongly depends on not contaminating these environments with terrestrial biology. That is, at least until we understand what's going on there, the so called "period of biological exploration" in the original COSPAR language.

For robotic missions, this still requires biological cleanliness based on bioburden reduction methodologies. For manned missions to Mars or other PP sensitive targets, a more sophisticated PP solution will be needed to accommodate the tendency of humans to act as large-scale fermenters of a broad variety of microbes.

In summary, we need to be able to first of all "count 'em all" – know who is there from a microbiological perspective. Then we need to "kill 'em all" – or at least be able to, to the extent that it is needed to meet the mission intent without compromising the "unharmed" status of the target body. Finally, whole process needs to be clean enough so that we don't spoof the results of the data analysis with biological contaminants of terrestrial origin.

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