Preventing the Forward Contamination of Mars: Concerns, Questions, and Required Actions

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Abstract—New data are now forthcoming about the nature of the martian environment and its potential to harbor Earth organisms introduced by space missions. The Mars Exploration Rovers have determined that standing liquid water existed on Mars for long periods of time in the past, and the Mars Global Surveyor mission and Mars Odyssey continue to uncover evidence about past water, ice, and the dynamic nature of the planet. Recently, the National Research Council (NRC) issued a report making recommendations to NASA concerning measures required to prevent future missions from contaminating Mars and to allow continued astrobiological exploration of the planet. Interim requirements recommended by the NRC include surface-sterilization of all spacecraft landing on Mars until “special” regions on Mars can be objectively differentiated from “non-special” regions, and a continuing evaluation of martian environments, microbial survival, and spacecraft contamination. This paper will discuss the report, its application to future NASA missions and potentially by other space agencies, and the actions required to protect Mars from Earth microbes and to support the continuing exploration of Mars.

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1. INTRODUCTION

Preventing Earth-source biological contamination from becoming established and widespread on Mars is essential to our ability to achieve high-priority science goals on Mars. The search for life and an understanding of the martian organic environment, and even the future use of martian resources, may be compromised if microbes carried by spacecraft grow and thrive on Mars.

That being said, there are many factors to be considered in assessing the ability of microbial life to grow and reproduce in such an alien environment (see Table 1), and the many daunting challenges facing potential martian colonists. Mars is extremely cold and dry, bathed in lethal ultraviolet radiation during the daytime, and significantly challenged by solar and galactic cosmic radiation at all times. Nonetheless, Earth microbes have been seen to thrive in particularly difficult environments here (e.g., pH < 1, temperatures > 120° C), so it is not simple to discount the possibility that they could eke out a living somewhere on Mars.

Because Mars is cold, but not always, and extremely dry, but perhaps not everywhere, the concept of a “special region” on Mars was developed as a way to refer to those places where the conditions on Mars might be conducive to microbial growth. Based on data returned from the Mars Global Surveyor and Mars Odyssey missions, showing evidence for more recent water flow and/or ice flow on the martian surface (Fig. 1) and the possibility of massive amounts of subsurface ice near the polar regions (Fig. 2), it was thought likely that such places might exist—if not on the surface, then potentially underground, even deep underground. The special-region concept was a way to address the likelihood of such places as a way to meet the requirements of planetary protection in avoiding the contamination of Mars by Earth organisms. The definition of special region is conceptually related to the astrobiological search for evidence of life and life-related molecules on Mars, but with no attempt to embody all the considerations pertaining to life that are listed in Table 1.

COSPAR and NASA currently define a special region to be “a region within which terrestrial organisms are likely to propagate, or a region which is interpreted to have a high potential for the existence of extant martian life forms. Given current understanding, this applies to regions where liquid water is present or may occur” [1, 2].

Recently, the NRC Space Studies Board’s Committee on Preventing the Forward Contamination of Mars (PREVCOM) recommended a series of steps to be taken to better understand the potential of contaminating Mars, and
Table 1. Some considerations affecting the survival and growth of Earth microbes on Mars

- Water availability and activity
  - Presence and timing of liquid water
  - Past/future liquid (ice) inventories
  - Salinity, pH, and Eh of available water
- Chemical environment
  - Nutrients
    - C, H, N, O, P, S, essential metals, essential micronutrients
    - Fixed nitrogen (the biggest unknown)
    - Availability/mineralogy
  - Toxin abundances and lethality
    - Heavy metals (e.g., Zn, Ni, Cu, Cr, As, Cd, etc., some essential, but toxic at high levels)
    - Oxidants (identification and stability)
- Energy for metabolism
  - Solar [surface and near-surface only]
  - Geochemical [subsurface]
    - Oxidants
    - Reductants
    - Redox gradients
- Conductive physical conditions
  - Temperature (temperature minima for spacecraft contaminants)
  - Pressure (a low-pressure threshold for terrestrial anaerobes?)
  - Radiation (UV, ionizing)
  - Climate/variability (geography, seasons, diurnal, and eventually, obliquity variations)
  - Substrate (soil processes, rock microenvironments, dust composition, shielding)
  - Transport (aeolian, ground water flow, surface water, glacial)

measures to be undertaken to protect against contamination in the interim period while we learn more about Mars and about Earth organisms that may be taken to Mars by spacecraft. By including the special-regions definition in their report (and by applying it, in essence, to the entire planet), PREVCOM endorsed the special-region concept, but their recommendations were quite a bit more comprehensive than that.

Of the recommendations made by PREVCOM, several focused on better understanding the potential microbial load on spacecraft, and the capabilities of those microbes in martian environments that may be encountered by spacecraft. New molecular methods, already in work at NASA, were recommended for adoption as spacecraft processing standards, and future work on a comprehensive listing of all microbes going to Mars was advocated. In addition, PREVCOM called for additional methods of spacecraft sterilization to be researched and adopted, and for basic research work to understand such things as the level of microbial contamination carried in non-metallic assemblies and parts—emphasizing the use of molecular methods.

Figure 1. This image, taken by the Mars Orbital Camera on the Mars Global Surveyor, shows a tongue-shaped feature on Mars, ~4 km in length and 800 m wide, can be interpreted as a glacier of ice and rock flowing down a crater wall in the eastern Hellas region of Mars.(Image courtesy of JPL/Malin Space Systems and [3]).
2. A WORKING DEFINITION OF SPECIAL REGIONS—FROM PARAMETERS TO MAPS

A key PREVCOM recommendation is that “NASA’s Mars Exploration Office should assign high priority to defining and obtaining measurements needed to identify special regions on Mars”[4]. To allow the Mars Exploration program to establish an interim definition of measurements needed to identify special regions and to allow the application of those measurements to complete an interim identification and mapping of special regions (or more particularly, to allow for the identification of regions referred to in the NRC report as “non-special,”) the following parameters were developed and provided to the Mars Program (by the Planetary Protection Officer–PPO). It is expected that these parameters will be the first step in a definitional process that will continue to improve and be iterated between the program and the PPO as new data about both Mars and extreme organisms on Earth are gained. Lessons learned in attempting to apply these parameters to available martian data sets within such a framework will allow for maps to be constructed both from direct data and from models that can extend the utility of the information available.

In the list below, the parameters defined by the PPO are given as they are referenced to the “catalog of potentially accessible special regions on Mars” given in the PREVCOM report (chapter 4 in [4]). In some cases, a single parameter definition has been used to apply to multiple regions defined by the NRC.

**Special Regions and Initial Parameters to Define Them**

1. Near-surface Liquid Water

Temperature and pressure conditions at the surface in low-altitude portions of Mars may permit the transient occurrence of relatively pure liquid water at the surface, and surface water films and liquid brines may potentially exist anywhere on Mars during the warmer parts of the day. It should be noted that, on Mars, these small amounts of water may be exposed to large amounts of UV radiation, and even frosts exposed to UV radiation on Mars may yield radicals that can have detrimental effects on living organisms and their spores.
Pure water freezes at 273° K and quickly evaporates under the ~7 mb pressure of the martian lowlands. Brines typically have depressed melting points and evaporate less quickly. Their formation is consistent with the elemental composition of Mars as measured by Viking, Pathfinder, and the Mars Exploration Rovers.

Parameter: The existence of liquid water in “pure” form, or in compositions ranging through strong brines up to the equivalent of 5.5 M calcium chloride

2. Geothermal Hot Spots

Abundant evidence of volcanism on Mars and widespread evidence of past and perhaps current liquid water either on or under the planet has led to the speculation that extant hydrothermal and geothermal areas might some day be found. If so, those areas would be attractive places to look for life, and would also be areas where at least some Earth microbes could find conditions suitable to growth and reproduction. To date, no such regions have been detected.

Parameter: Regions of current active volcanism or enhanced heat flow (as yet unknown)

3. Segregated Ground Ice

4. Ice-rich Frozen Ground

5. Polar Caps and Surface Ice

Given the paucity of available information, these three regions from the PREVCOM report are considered together in the initial parameterization. As pointed out by PREVCOM, “The presence of embedded solutes or pockets of brine, the purposeful or accidental melting of massive ice as a consequence of exploration activities...could result in the production of substantially more liquid water where segregated ground ice occurs than would be produced for dispersed ice in soil under equivalent environmental conditions” [4].

Other arguments, including a current lack of knowledge of the small-scale surface characteristics of any of these icy situations, prejudices a need for caution in exploring them.

Parameter: Frozen water, in the form of permafrost through 100% water ice. This may be in the form of frost complexed with regolith, as compacted snow and ice interlayered with dust, or in the nearly pure form thought to exist in the polar caps

6. Subpermafrost Groundwater

Some microbes like liquid water!

Parameter: Any subpermafrost groundwater

7. Gullies

Widespread evidence for gully landforms on crater walls and other steep slopes have been interpreted, in some cases, as geomorphic evidence for recent seepage and runoff of liquid water. Other interpretations include basal melting of periodically emplaced snowpack/hanging glaciers.

The timescales for hydrological activity of such gully forms is not well constrained, and it is likely that some gully forms (cf., dune gullies) may be the result of processes that do not involve liquid water in either artesian or snow-melt form.

Parameter: Gully systems that may be interpreted as indicative of recent (<50,000 yrs) water activity

3. APPLICATION OF PARAMETERS

It is intended that “special regions” ("non-special regions" and "regions of uncertainty") on Mars be defined in four dimensions, with the parameters applicable to the identification of these special regions being applied over the course of approximately 100 years (a period of biological exploration—not intended to extend until the next phase of the martian obliquity cycle).

Scaling these parameters to the applicable region is not easy with current assets. Microbial contamination may occur at scales far smaller than the human eye can appreciate, and missions may access many different types of terrain without even being aware of the distinctions important to microbial growth. As PREVCOM stated it, “because variations in regolith thermal and diffusive properties—capable of preserving liquid water or ice at shallow depth—can occur at small scales, an understanding of the distribution and state of subsurface H₂O at as high a resolution as practically possible (ideally, at a scale equivalent to that defined by the operational activities and landing accuracy of the investigating robotic spacecraft) would provide the greatest level of assurance in our ability to access or avoid special regions” [4].

It is recognized that there will be many mismatches in the scale of data available to address these parameters, and the scale at which these parameters are of interest. For practical application, however, it has been stipulated that “surface” measurements may include data as deep as possible (and as deep as a rover may wish to spin its wheels), up to 1 m depth, while “subsurface” may be applied to any environment below the surface itself, and certainly below the direct effects of solar radiation impinging on Mars.

An obvious limitation in the interim classification of martian “special regions” will be mismatches in the horizontal scale of the data sets available. It is expected that interpolation and modeling, coupled with correlative data from other available sensors, will be used to apply specific broad data types in as constraining a way as possible,
thereby allowing a map of special regions to be produced based on such derived products, rather than from direct data sets alone.

4. SUMMARY

Mapping special regions on Mars in a definitive fashion, and providing a means to maintain and update that definition, is a challenge for the Mars Program. It is also something that the program will be required to do, both for regulatory reasons within NASA and the US and to enable joint missions to be productively planned with international partners. Accordingly, it is anticipated that COSPAR will be used as a forum to agree upon and monitor the implementation of a Mars environmental geographical information system, or its equivalent, to aid the international Mars community in understanding where martian special regions exist, and why [5].

The Mars Program must make an investment to meet this planetary protection requirement, both in terms of support for the process and product of the mapping, but also in terms of the observations that will have to be made in the future to provide appropriate data that will support future refinement and mapping of the special regions. The alternative would be to accept the definition that all of Mars is “special,” per the precautionary principle espoused in the NRC report (see Table 2 for attendant requirements for all but Category IVn missions [lander missions to “not special” regions]). The program would then need to plan that all future Mars landed missions (beginning with the 2011 launch opportunity, which is the beginning of what NRC describes as the “interim period” of planetary protection requirements for Mars exploration) should be at least surface sterilized, no matter where on Mars they go.

This approach, however, may not be the worst approach to take. Based on the parameters given above, as well as the likelihood that somewhere on Mars there will be conditions amenable to Earth microbes, and perhaps to martian life, it

<table>
<thead>
<tr>
<th>Level</th>
<th>Requirement</th>
<th>Representative Scenario</th>
</tr>
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<tbody>
<tr>
<td>Level 1</td>
<td>Viking lander pre-sterilization total bioburden (fewer than $3 \times 10^5$ total spores on the spacecraft) and 300 spores per square meter.</td>
<td>IVn [lander missions to “not special” regions]</td>
</tr>
<tr>
<td>Level 2</td>
<td>Viking pre-sterilization levels required for the bulk spacecraft plus Viking post-sterilization on all exposed surfaces.* The latter is to be understood as an areal measurement. Explicitly, Viking post-sterilization levels correspond to a reduction of $1 \times 10^{-4}$ times the Viking pre-sterilization upper limit of 300 spores per square meter.</td>
<td>All IVs [lander missions to “special regions”]</td>
</tr>
<tr>
<td>Level 3</td>
<td>Viking pre-sterilization levels required for the bulk spacecraft plus Viking post-sterilization on all surfaces, including those not exposed under nominal (e.g., no-crash) conditions. Explicitly, Viking post-sterilization levels correspond to a reduction of $1 \times 10^{-4}$ times the Viking pre-sterilization upper limit of 300 spores per square meter.</td>
<td>Category III missions [orbiters] that do not meet existing probability for orbital lifetime requirements.</td>
</tr>
<tr>
<td>Level 4</td>
<td>Viking post-sterilization bioburden reduction for the whole spacecraft. Currently, this would likely mean baking the spacecraft in a manner similar to that employed in the Viking mission, though the committee encourages NASA to investigate other technologies to this same end.</td>
<td>IVs missions accessing locations determined to have long-lived liquid water</td>
</tr>
<tr>
<td>Level 5</td>
<td>The committee cannot at present specify the technology that could become available to attain zero microorganisms on Mars-bound spacecraft. Bioburden reduction techniques more effective than those applied today may be or may soon be available for use on spacecraft. A level 5 bioburden reduction level would represent the implementation of these techniques, to achieve bioburden reduction significantly more rigorous than that obtained for the Viking landers.</td>
<td>IVs missions accessing locations determined to have long-lived liquid water</td>
</tr>
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*An exposed surface is a surface that freely communicates with the martian atmosphere or surface. All external surfaces on a lander would count as exposed surfaces, but interior surfaces might do so as well, if they are not fully enclosed or shielded from the atmosphere by submicron filters.
would be reasonable to assume that future landed missions to the highest priority sites for astrobiology will require Viking-level sterilization, at minimum, and perhaps a more stringent protocol than that. Accepting such a requirement for all future landers would have advantages in the development of common thermal designs (assuming dry heat sterilization), materials and parts compatibility, and assembly and launch practices. Overall, these significant commonalities may allow for the full spectrum of mission goals to be attained—no matter where on Mars scientific and exploration requirements may lead.

REFERENCES


BIOGRAPHY

John Rummel is the NASA Planetary Protection Officer in the Science Mission Directorate. He has undertaken multiple assignments for NASA, separated by four years as Director of Research and Education at the Marine Biological Laboratory in Woods Hole, Massachusetts. His B.A. is from the University of Colorado, and his Ph.D. in Biological Sciences is from Stanford.