Planetary Protection Technologies: Technical Challenges for Mars Exploration

Karen L. Buxbaum
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109-8099
818-393-1135
Karen.Buxbaum@jpl.nasa.gov

Abstract— The search for life in the solar system, using either in situ analysis or sample return, brings with it special technical challenges in the area of planetary protection. Planetary protection (PP) requires planetary explorers to preserve biological and organic conditions for future exploration and to protect the Earth from potential extraterrestrial contamination that could occur as a result of sample return to the Earth-Moon system. In view of the exploration plans before us, the NASA Solar System Exploration Program Roadmap published in May 2003 identified planetary protection as one of 13 technologies for "high priority technology investments." Recent discoveries at Mars and Jupiter, coupled with new policies, have made this planning for planetary protection technology particularly challenging and relevant. New missions to Mars have been formulated, which present significantly greater forward contamination potential. New policies, including the introduction by COSPAR of a Category IVc for planetary protection, have been adopted by COSPAR in response. Some missions may not be feasible without the introduction of new planetary protection technologies. Other missions may be technically possible but planetary protection requirements may be so costly to implement with current technology that they are not affordable. A strategic investment strategy will be needed to focus on technology investments designed to enable future missions and reduce the costs of future missions. This presentation will describe some of the potential technological pathways that may be most productive.

TABLE OF CONTENTS[1,2]

1. INTRODUCTION 1
2. HISTORIC PERSPECTIVE 1
3. STATE OF THE PRACTICE 2
4. UPCOMING MISSIONS OF THE MARS PROGRAM 3
5. SPECIFIC TECHNICAL CHALLENGES FOR MARS 3
6. CONCLUSIONS 5
REFERENCES 6
BIOGRAPHY 6

[1] 0-7803-8155-6/04/$17.00© 2004 IEEE Correct 2005 number in August.
[2] IEEEAC paper #1554, Submitted October 28, 2004

1. INTRODUCTION

Planetary protection is often defined as a set of regulations or controls imposed on space missions for the purpose of protection future science and exploration efforts and protecting the Earth from importation of life from elsewhere. PP also encompasses the activities necessary to comply with these regulations and controls. Clearly, since planetary protection, formerly planetary quarantine, has been practiced since the 1960's, many of these activities are well understood and rely on mature technologies or practices. In the case of future Mars exploration, however, there are significant new planetary protection implementation challenges and technology needs. Not only will Mars Sample Return involve first-time requirements in the area of back contamination control, scientific advances have caused updates in planetary protection controls with respect to forward contamination a well. In addition, the advent of molecular methods has improved our ability to characterize biological contamination. So, as needs have increased, so have capabilities. To create an environment in which affordable and achievable engineering solutions are available to mission engineers, technology choices will be needed to create system and subsystem level planetary protection solutions.

2. HISTORIC PERSPECTIVE

As the first extraterrestrial biological exploration took shape in the 1950's, the international community, represented by COSPAR, established a set of guidelines resulting in Article IX of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (also known as the UN Space Treaty of 1967) [1]. Consistent with the Space Treaty, NASA then established its first set of guidelines, defining planetary protection as: "The avoidance of contaminating the biosphere of a planet with terrestrial life forms so that the ecology of a planet is maintained in its pristine state during the period of scientific investigation."

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

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

The Viking project represented the first successful landing on Mars to conduct biological investigation and largely still serves as a standard for current planning. Planetary protection was taken seriously by top management at NASA and within the project. (This attitude is noticeably on the rise today as NASA, the Mars Program, the flight project managers, and the scientific community all become more aware, more informed, and more heavily invested in planetary protection as a priority in Mars exploration.) Substantial investments were made in planetary quarantine research and development and the overall cost of the mission was significantly impacted by the planning and implementation of planetary quarantine. Methodologies for cleaning, validation of cleanliness by the NASA standard assay, and sterilization by dry heat microbial reduction were developed for Viking and are still in practice today.

3. STATE OF THE PRACTICE

The foundation for the current practice in planetary protection was established by researchers and practitioners of planetary quarantine for the Viking mission and was applied successfully to Mars missions throughout the last decade. In general, most aspects of forward contamination control may be organized into cleaning, sterilization, validation, and assorted approaches to preventing recontamination. Typically, cleaning consists of standard techniques for preparation of flight hardware including precision cleaning and repeated use of alcohol wipes during assembly. The NASA approved sterilization protocol is dry heat microbial reduction (DHMR). Hydrogen peroxide vapor sterilization has been used in Europe but without the benefit of full characterization and standardization of protocols. Post-launch techniques, such as partial bioburden reduction by atmospheric entry at the planet, are sometimes applicable.

Validation of cleanliness is currently conducted with a microbial assay which takes 72 hours for results of bacterial culture. This is referred to as the NASA Standard Assay, which is fully specified in NHB 5340.1C [2]. Control of recontamination is achieved by conducting assembly in a clean room, following cleanroom practices such as strict garmenting and special handling of hardware during rework. The practices of cleaning, enumeration of residual spores through bioassay, and sterilization using DHMR have changed little since Viking. A paper entitled "A Review of the Approach of NASA Projects to Planetary Protection Compliance" [3] is available elsewhere in these proceedings; it describes how practices and standards have been established and maintained from Viking through the current NASA missions.

For the last six years, there has once again been significant funding for research and development to support implementation of planetary protection requirements, though not at the level of the early planetary quarantine R&D program. Investment areas have recently included forward contamination control (cleaning, sterilization and validation), back contamination control, and research to better understand the nature of the terrestrial microorganisms in the environment. It is important to note that most of the work on sterilization has been focused on developing alternatives to dry heat microbial reduction (DHMR), the primary method used by the Viking mission. Some high technology instrument and spacecraft components are not heat tolerant and techniques not requiring high temperatures could offer significant benefits. New approaches have been used when necessary, such as the Mars Reconnaissance Orbiter (MRO) decision to satisfy biological contamination controls rather than orbital lifetime analysis. In Europe, alternate approaches to sterilization were used for Mars 96 and for the Beagle 2 Lander. And, of course, serious thinking and early technology development has been undertaken in anticipation of MSR and in situ life detection missions.

The Mars exploration missions of the last several years have revealed a planet that appears to have been wetter and potentially more habitable than previously thought. While the complete hydrogeologic history is still unclear, the past presence of liquid water has been suggested in features from km-wide canyons to microscopic mineral deposits. Research here on Earth in recent decades has also expanded our knowledge of microbial diversity and the remarkable ability of microbes to adapt to extremes of conditions as long as they have occasional access to water and an energy source. Thus, environments previously seen as hostile to life

are now known to serve as possible habitats to select organisms. Taken jointly—the history of water on Mars and the improved understanding of extremophiles on Earth—the Mars Program faces new technical challenges in planetary protection.

Recent changes in planetary protection policy, accepted by COSPAR [4] and anticipated soon by NASA, are discussed in more detail elsewhere [5,6]. The most significant changes as they pertain to Mars have been creation of a new category of landed mission, IVc, and incorporation of an implementation option for category IVb missions (life detection landers) other than system level sterilization as performed by Viking in the 1970s. The essence of the new category IVc is to protect martian "special regions" from terrestrial microbial contamination. Before undertaking a mission to the "special regions" on Mars, even if the mission does not include life detection experiments, the Project must either sterilize the flight system, or sterilized the subsystems that directly contact the special region and then assure the community that there are means to prevent recontamination. In addition, subsystem compliance is now permitted, which allows cleaning the subsystems that contact the samples to Viking post-sterilization level standards, provided there is a means of preventing recontamination of the hardware and cross-contamination of the samples obtained.

For both scientific and programmatic reasons, a number of new technologies are under development by NASA and. are planned for use by the Mars Phoenix Scout mission in 2007, the Mars Science Laboratory (MSL) in 2009, by MSR in 2013, and by subsequent missions. In order to be put into practice on missions, some planetary protection technologies must not only reach maturity from the perspective of the project using them, but they must also be validated and approved for use by NASA.

4. Upcoming Missions of the Mars Program

The Mars Exploration Program recognizes a growing need for planetary protection technology to support future missions. Future missions will most likely include orbiters, surface landers with mobility or drills, innovative aerial platforms such as balloons or airplanes, and sample return. New discoveries, from in situ and remote sensing platforms, are identifying target areas that are more biologically interesting. Some of these discoveries increase the need for planetary protection measures to handle forward contamination.

Phoenix

Phoenix, the first in a series of Mars Scout missions, is planned for launch in September 2007 and will land in the northern polar region of the planet. The Phoenix spacecraft will collect samples of ice and soil for in-situ analysis. Scientists hope to find more evidence about the geological history of water on Mars and search for possible evidence of habitable conditions for life in the boundary region between the polar ice and soil. This mission was assigned Category IV-A in accordance with NPR 8020.12B [7], with the additional provision that the portions of the robotic arm that will contact the martian subsurface should meet the equivalent of Category IV-B. This combination is intended to meet the provisions of the current COSPAR planetary protection policy's Category IVc. Thus, Phoenix has new requirements for sterility of any hardware that will touch the martian subsurface and could potentially inoculate it with terrestrial microorganisms.

Mars Science Laboratory (MSL)

MSL, scheduled for launch in 2009, will most likely be powered by a radioisotope power source (RPS). While MSL does not currently plan to land in or target a "special region," as defined in COSPAR Planetary Protection Policy [4], there is concern that in an off-nominal landing, the RPS could cause melting of ice in the subsurface, thus inadvertently *producing* a special region. Because of its "perennial heat source" in the form of the RPS, MSL is likely to be classified as a Category IVc mission. Thus, extra precautions beyond those required for the MER rovers, Spirit and Opportunity, will be required.

Mars Sample Return (MSR)

Scheduled for launch as early as 2013, MSR would be the first extraterrestrial sample return mission since Apollo to deliver to Earth extraterrestrial material with a non-zero probability of containing life forms. MSR thus faces a number of distinct challenges. The major issues addressed in MSR planning are summarized here. [8]

Other Mars Missions of the Next Decade

The Mars Program is planned as a discovery driven program of exploration. Thus, discoveries by Mars Global Surveyor (MGS), Odyssey, and MER are driving plans for Phoenix and MSL. In turn, MRO, Phoenix, and MSL will drive the plans for the next decade. Decisions about missions to seek life, drill to the subsurface, etc. will be timed and tuned by the science discoveries of their predecessors. Each step closer to wetter or potentially more habitable parts of Mars raises the awareness and need for appropriate PP controls.

5. Specific Technical Challenges for Mars

Looking forward, it is possible to group PP technology needs for Mars into four main categories. Prelaunch and operations technologies are used to prepare spacecraft for compliance before launch or operate spacecraft in such a

Table 1. Planetary Protection Technologies

Prelaunch/Operations Technologies

- Cleaning to sterility
- Assays for rapid assessment of cleanliness—cultivable, non-cultivable, molecular
- Particle transport models
- Development of Mars orbital debris analysis code
- Aseptic assembly systems
- H_2O_2 and/or radiation sterilization of assembled subsystem

Launched Hardware

- Lightweight biobarriers for forward contamination prevention
- In situ sterilization systems
- Container sealing systems
- Mechanism or series of mechanisms for "break-the-chain" of contact
- Earth targeting improvements
- Earth entry vehicle for assured containment
- Meteoroid protection on spacecraft

Sample Handling Systems

- Multi-directional containment systems for sample handling
- Systems for analysis of contained samples (Sample Receiving Facility)

Research Required to Inform the Development of Technologies

- Fundamental biology of survivability (microbial characterization in flight hw manufacturing environments)
- Advanced spacecraft designs to provide for sterilization, aseptic assembly, late RPS installation
- Materials screening to enable system/subsystem sterilization

way that they achieve compliance. Although cleaning and some sterilization have been performed on modern spacecraft for planetary protection purposes, in the future, spacecraft material constraints may limit the sterilization cycles used. Additional processes to minimize or eliminate sources of bioburden will be needed to offset these other process constraints. Thus, improved cleaning protocols—even cleaning to sterility—will be needed as options in the future. Also, greater choice for hardware designers can help to offset process constraints. The Mars Program and JPL are investing in full characterization of hydrogen peroxide vapor sterilization, as currently used in the medical industry and elsewhere, so that it may be considered by NASA as an accepted alternate mode of flight hardware sterilization. Additionally, NASA has recently funded Texas A&M in partnership with JPL to develop and characterize the capability to sterilize relevant materials using ionizing radiation. To use any of these cleaning or sterilizing modalities effectively, projects will need to plan early and define any material incompatibility issues so that materials can be replaced or alternate methods of sterilization and packaging developed.

Other prelaunch/operations technologies, which have been identified as necessary to enable or reduce implementation costs for future missions include new assays for rapid assessment of cleanliness. Significant effort has been made in recent years to bring to bear on PP capability new molecular techniques for evaluation of cleanliness of spacecraft surfaces or assembly environments. These are not substitutes for the NASA Standard Assay, which measures the presence of viable aerobic spores, but they can provide a qualitative, rapid and economical assessment of biological cleanliness when necessary. We expect NASA to review the results of this effort and possibly incorporate both an ATP (adenosine triphosphate) and LPS (lipopolysaccharide) assay into the NASA procedural documents for planetary protection.

Now that subsystem compliance is permitted as an option for Category IVb and IVc missions, carrying with it a provision that there be a means of preventing recontamination of the hardware and cross-contamination of the samples obtained, there is new interest and urgency to understand, through experiments and models, the transport of particles (and the transport of microbes on particles) throughout a mission. There is particular interest in contamination transport during launch, during landing, and during surface operations. Currently there is no systematic way to model recontamination or contamination transport and it has been recognized that models are needed which take into account both the numbers of microorganisms carried on particles and the plausible transport mechanisms. Further, aseptic assembly systems will be needed to support production of spacecraft that are free of biological contaminants.

In support of orbiter missions with low elevation trajectories, we have identified the need for development of orbital debris analysis code applicability to the martian atmosphere. This will likely be of importance in the future when missions decide on the planetary protection implementation approach selected by MRO, i.e., bioburden reduction including partial contribution by extreme heating during breakup and entry into the martian atmosphere.

Launched-hardware technology represents one of the four categories of needed PP technology. In this category there are actual hardware items designed to be part of the flight system and capable of fulfilling specific PP needs in flight. Most of these are directly tied to the needs of Mars Sample Return and pertain to assured containment of samples and reliably breaking the chain of contact with Mars prior to Earth return. Technology needs of MSR, with emphasis on "back contamination control" are discussed in detail elsewhere in these proceedings [7]. Other launched hardware technologies that might be applicable to either in situ life detection or sample return are lightweight biobarriers for forward contamination prevention and in situ sterilization systems. In fact, such biobarrier technology is needed by the Phoenix Scout Mission for 2007.

A new aspect of planetary protection, needed for MSR, will be the sample handling systems capable of protecting Earth from returned Mars samples and also protecting the samples from the Earth. Here, we refer to handling of extraterrestrial samples once they are on Earth and ready for analysis. In this unique and new situation, multidirectional containment is required. Such containment systems not only need to be clean and sterile, they need be compatible with repeated cleaning and sterilization as necessary. Furthermore, MSR will need systems for analysis of contained samples in the sample receiving facility. Such systems will have to meet the requirements of the final sample assessment protocol (only the Draft Test Protocol is available until nearer the time of MSR [9]) and support operations that are consistent with the multidirectional containment systems of the facility.

Finally, there are bodies of research required to inform the development of the new technologies listed above. These include new options for system architecture and design, material screening and parts qualification, and information on the fundamental biology of survivability. For example, Viking had an extensive parts evaluation and selection program tied to their plans for subsystem and system level sterilization by heat. Today, with new spacecraft materials in use, special screenings are again required make possible the type of sterilization programs that will be needed. We also need adequate knowledge of environmental microbiology in and around hardware assembly facilities that we can apply adequate, but not excessive, cleaning and sterilization protocols. And very significant in the list above is the need to seek new approaches to architecture selection and flight hardware design to enable system level sterilization of spacecraft when it is required by discovery or mission choice in the future.

In 2003, NASA (through the Mars Technology Program) solicited proposals for technology development in support of planetary protection implementation. The focus of the solicitation was on two aspects of planetary protection: forward contamination avoidance and sample handling systems. In the area of forward contamination avoidance, technology development was solicited that could enable NASA to build, launch, and operate a mission that has subsystems with different planetary protection classifications, specifically for operating a subsystem with cleanliness equivalent to that required of a PP category IVb mission (more clean) from a platform such as a lander or rover with cleanliness equivalent to that required of a IVa mission (less clean). Two specific cases were described and can still be viewed in their entirety at http://research.hq.nasa.gov/code_s/nra/current/nra-03-oss-01/appendA2_20.html (Amendment #5 of the ROSS 2003 call). In the area of sample handling systems, technology research was solicited to address barrier technologies providing the basis for a sample receiving laboratory capable of ensuring BSL-4 level containment of returned Martian samples, as well as class-100 or better protection of the samples themselves while allowing for samples to be analyzed and prepared for biohazard testing or precertification sterilization procedures. Systems were sought that would allow testing and preparation of the newly received samples (exclusive of biological testing) under human or robotic manipulation. Seven planetary protection research proposals were ultimately selected and funded by the MTP Base Technology Program. The specific research tasks selected for funding address cross-contamination risk assessment and prevention; pre-launch bioburden reduction and validation; heating of orbital debris during atmospheric entry at Mars; and sample containment, handling and analysis of Mars returned samples. While the selected tasks will not address all of the technical challenges of planetary protection for the Mars Program, they represent a good start at responding to several of the technology requirements. All of these are tasks are expected to deliver needed knowledge or capability in support of Mars missions scheduled as early as 2009.

6. CONCLUSIONS

One of the nuances in a discussion of planetary protection technical challenges is that many PP technical solutions do not take the form of flight hardware. Thus, there is a poor mapping of maturity metrics for many PP technologies to NASA technology readiness levels, or TRLs. The treatments of hardware to achieve biological cleanliness or the assays to verify the treatments do not lend themselves to description or metrics like flight hardware. We can make some use of NASA TRL descriptions in the early stages, but

the technology maturation and infusion for these prelaunch treatments and process follows a different path.

Some of the needed technologies for PP do lead to hardware development but not for flight. Handling of samples returned from Mars will initially require unprecedented controls and machines to enable safe handling are needed as part of the Mars Technology Program.

Some of the other technical challenges in planetary protection are in the area of knowledge that we lack, such as microbial diversity of the many facilities in which flight hardware is manufactured or assembled. We must be able to make assessment of what we know about organisms living in extreme environments in the context of the full life cycle of hardware that is built, flown to, and operated on Mars.

And finally, a major challenge is, ironically, to be able to sterilize an entire landed system as Viking did in order to enable options for in situ life detection experiments or landing in the most promising sites on Mars to pursue answers to questions about biochemistry and chemical processes that may be important to life and to search for life itself.

Acknowledgements

I would like to acknowledge the James Cutts and Andrea Belz for making available to me a planning document entitled "Planetary Protection and Contamination Control Technologies for Future Space Science Missions" that is currently in draft form but will form the basis for a planetary protection roadmap document in the near future.

REFERENCES

[1] "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," Article IX, U.N. Doc. A/RES/2222(XXI) January 227, 1967; TIAS No. 6347, IN: *U.S. Treaties and Other International Agreements. 18, 2410-2498,* 1967.

[2] NASA Standard Procedures for the Microbiological Examination of Space Hardware, NHB 5340.1B, Rev. B, February 1980.

[3] Jack Barengoltz, A Review of the Approach of NASA Projects to Planetary Protection Compliance, IEEE Aerospace Conference Proceedings 2005, submitted for publication.

[4] COSPAR Planetary Protection Policy, 20 October 2002. COSPAR, Paris, France.

[5] John D. Rummel, Technical Challenges in Meeting the Next Decade's Planetary Protection Requirements, IEEE Aerospace Conference Proceedings 2005, submitted for publication.

[6] Sheryl L. Bergstrom and John D. Rummel, Planetary Protection Considerations For Future Exploration, IEEE Aerospace Conference Proceedings 2005, submitted for publication.

[7] National Aeronautics and Space Administration, "Planetary Protection Provisions for Robotic Extraterrestrial Missions," NPR 8020.12B (*formerly* NPG 8020.12B), Washington, D.C., April, 1999.

[8] Robert Gershman, Planetary Protection Technology for Mars Sample Return, IEEE Aerospace Conference Proceedings 2005, submitted for publication.

[9] National Aeronautics and Space Administration, *A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth,* NASA/CP—2002-211842, Washington, D.C., October 2002.

BIOGRAPHY

Karen Buxbaum *is the Mars Program Planetary Protection Manager. She has worked in the field of planetary protection for over five years, first as supervisor of JPL's Biotechnology and Planetary Protection Group and then as part of the Mars Exploration Directorate. She started her career with JPL as part of the Galileo Mission to Jupiter project team with a focus on science planning for the prime and extended missions and then worked for two years in JPL's Center for In Situ Exploration and Sample Return. She received her B.S. in Biology from Tufts University and her PhD. in Biomedical Engineering from Duke University.*

Comment: ID 485