

Planetary protection and humans on Mars: NASA/ESA workshop results

Margaret S. Race^{a,*}, Gerhard Kminek^b, John D. Rummel^c,
Participants of the NASA/ESA planetary protection Workshop¹

^a SETI Institute, 515 N. Whisman Rd., Mountain View, CA 94043, USA

^b European Space Agency, Human Spaceflight, Microgravity and Exploration Directorate, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands

^c Science Mission Directorate, NASA Headquarters, Washington, DC 20546, USA

Received 7 June 2007; received in revised form 28 February 2008; accepted 6 March 2008

Abstract

Planetary protection requirements for future human missions to Mars will strongly influence mission and spacecraft designs, particularly those related to the operation of advanced life support systems (ALS), extravehicular activity (EVA), laboratory and *in situ* sampling operations, and associated environmental monitoring and control systems. In order to initiate communication, understanding and working relations among the ALS, EVA, and planetary protection communities in NASA and ESA, a workshop was held (May 2005; ESA/ESTEC; Noordwijk, The Netherlands) to focus on mission-specific planetary protection issues associated with future human missions to Mars. The “Mars Planetary Protection and Human Systems Research and Technology Joint NASA/ESA Workshop” considered the range of knowledge and information necessary to establish planetary protection requirements with respect to ALS and EVA systems, including the identification of potential contaminants, contamination pathways, and potential off-nominal events typical of such systems and of space exploration. The top-level workshop goal was to determine how compliance with planetary protection requirements should be implemented before, during, and after human Mars missions, and what standards of contamination control should apply to human explorers. Workshop discussions considered operations and technology concerns, science operations, backward contamination prevention requirements, and the protection of both the human habitat on Mars and the Earth upon crew return. A list of future research and development needs were also identified for ALS, EVA and Mars robotic missions, including specific precursor mission information necessary to understand and prepare for human support systems and science operations on long duration Mars missions. This paper summarizes the findings and recommendations of the workshop including an overall approach to contamination control, waste and consumable management, and off-nominal events, as well as the research and development necessary to cope with planetary protection requirements during future human missions to Mars.

© 2008 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Planetary protection; Human missions; Mars

1. Background

1.1. Overview

With both NASA and ESA initiating long-term plans for their respective sequencing of robotic and human missions, it

is necessary to consider how planetary protection controls for the eventual human exploration of Mars can be accomplished in ways that ensure the preservation of scientific opportunities as well as human health and safety, both on Mars and upon return to Earth. Planetary protection requirements will strongly influence mission and spacecraft designs, particularly those related to the advanced life support systems (ALS), extravehicular activity (EVA), and operations and support (Ops; e.g., activity scheduling, laboratory and *in situ* sampling operations, and associated

* Corresponding author. Tel.: +1 925 947 1272.

E-mail address: mracemom@aol.com (M.S. Race).

¹ Participant names and affiliations listed in the Acknowledgments section.

monitoring and control systems). In order to initiate communication, understanding and working relations between the ALS, EVA, and planetary protection communities in NASA and ESA, a special workshop “The Mars Planetary Protection and Human Systems Research and Technology Joint NASA/ESA workshop” was held May 19–20, 2005 at the European Space Research and Technology Centre (ESTEC), Noordwijk, Netherlands to focus on mission-specific planetary protection issues during future human missions to Mars. The top-level workshop goal was to determine how planetary protection requirements will be implemented during human missions, and what standards of contamination control will apply to human explorers.

Deliberations at the workshop built upon the findings of a number of earlier reports and studies on planetary protection and human missions (Criswell et al., 2005; Hogan et al., 2006; Beaty et al., 2005). Two important principles guided the workshop deliberations: (1) planetary protection requirements will not be relaxed solely in order to accommodate human missions,² given that one major advantage of a human presence on Mars is to aid in the scientific search for evidence of life, and (2) the Mars robotic precursor program will attempt to determine the presence or absence of human-affective biohazards on the Martian surface. This determination is required to establish what the US National Research Council referred to as “Zones of Minimal Biological Risk” in their ‘Safe on Mars’ report (NRC, 2002).³ Workshop discussion also built on the following set of starting assumptions:

- Safeguarding the Earth from potential backward contamination is the highest planetary protection priority in Mars exploration.
- The greater capabilities of human explorers can contribute to the astrobiological exploration of Mars only if human-associated contamination is controlled and understood.
- It will not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems.
- Crewmembers exploring Mars will inevitably be exposed to Martian materials.

The specific overall goals and objectives of the workshop aimed to:

- Initiate communication, understanding and a working relationship between the ALS, EVA, and planetary protection communities in NASA and ESA.
- Identify knowledge necessary to establish planetary protection requirements with respect to ALS and EVA systems,

including the identification of potential contaminants, contamination pathways, and potential off-nominal events typical of such systems.

- Explore operations and technology issues concerning the potential disruption of an extraterrestrial ecology via EVA and/or ALS operations, including interplanetary and planetary surface waste disposal, etc.
- Explore the requirements posed by the astrobiological/geological exploration of Mars, and examine how EVA and ALS systems may affect them.
- Examine how ALS and EVA systems interact with backward-contamination prevention requirements to protect both the human habitat on Mars and the Earth upon crew return.
- Identify future research needs for ALS, EVA, and Mars robotic-missions, and define precursor mission requirements to understand and prepare for human support systems for a Mars mission.

1.2. Workshop format, subgroups and tasks

The workshop participants included 39 individuals selected for their combined expertise and experiences in areas relevant to ALS, EVA, Operations, and planetary protection.⁴ The workshop began with a series of tutorial presentations providing overview information on planetary protection and the detailed findings of two previous planetary protection workshops focused on human missions (Hogan et al., 2006; Criswell et al., 2005). Subsequently, participants were assigned to one of three independent subgroups: (1) Extravehicular Activities (EVA), (2) Advanced Life Support (ALS), and (3) Operations and Support (Ops), each with an overall charge of determining how planetary protection requirements will be implemented during human missions to Mars (contrasting initial human missions versus later human missions, if appropriate) and understanding the impact of planetary protection requirements on the design of various human support systems. Each subgroup was asked to debate the following four broad questions during their deliberations:

1. What is the overall approach to contamination control, including: Forward & backward contamination levels in different areas (e.g., zones of contamination control), and Quarantine requirements (for crew and samples)?
2. What is the approach to waste & consumables management, focusing on: Different mission phases; (e.g., transit, planetary surface) and Different types of wastes & consumables, and their levels of contaminants and dispersion properties?
3. What are the off-nominal events that could potentially lead to contamination of Mars or the terrestrial bio-

² It is assumed that any changes in planetary protection policy will be supported by appropriate science findings and justification, rather than made to accommodate human missions *per se*.

³ Zones of minimum biological risk are *not* the same as the COSPAR “special regions.”

⁴ A list of participants and their affiliations is provided in the Acknowledgement section at the end of the paper.

sphere? Identify the consequences and suggest mitigation strategies.

4. What are the research and development activities required to cope with planetary protection requirements? Identify research and development requirements for both human- and associated robotic-precursor missions.

Subsequently, plenary discussion of the subgroup findings led to a set of overall conclusions and recommendations that are presented in the final section of this paper, along with a summary of the important research and development issues identified.

2. Subgroup deliberations and findings

The following sub-group summaries represent information submitted by their respective chairs; as such they have different formats and levels of detail about their deliberations. In reporting this information, no attempt was made to reconcile differences in coverage between the findings of the different subgroups, nor to add information if omitted (e.g., list of research needs). In addition, findings and suggestions were not evaluated in detail for overall feasibility. Upon presentation and discussion of all the sub-group findings in plenary session, workshop participants reached a consensus list of overall workshop conclusions, as presented in Section 3 of this paper.

2.1. Overview of EVA subgroup deliberations

The EVA Splinter Group decided to emphasize Question #1 (approach to contamination control) because of its importance for addressing all other questions. In doing so, their discussions also considered the assumptions and basic concepts underlying planetary protection, and discussed how they *might* evolve in the future to facilitate technically achievable and effective scientific exploration, planetary protection, and support during human missions.

In considering the overall approach to contamination control, the EVA subgroup first addressed specific issues associated with forward contamination. In particular, they focused on the science goals associated with future missions (as outlined in MEPAG, 2004)⁵ and acknowledged that one of the primary purposes of planetary protection policy is to enable future scientists to make and confirm a life-related discovery. This necessarily involves the avoidance of false positives and an understanding of Earth-sourced organic contamination, whether living or non-living. It also requires a focus on both local and global contamination perspectives.

2.1.1. EVA and forward contamination considerations

Two kinds of spacecraft contaminants have the potential to interfere with investigations of possible martian life:

live organisms and *non-living organic material*, both of which are impossible to remove completely from spacecraft prior to launch. Live organisms can be transformed to dead ones by sterilization (e.g., heating), but they often cannot be quantitatively removed. Thus, an important challenge will be distinguishing evidence of organic material or life originating on Mars (“signal”) from organic material or life we bring with us (“noise”), recognizing that it will not be possible to eliminate the noise altogether. Since each type of life-related contaminant has a different potential to interfere with science measurements, effective contamination control strategies are essential parts of the logic for future missions designs and science investigations.

The organic contaminants on landed spacecraft (whether living or non-living) *will* contaminate the site of the landed operations, necessitating the continued use of methodologies to acquire clean, sterile samples from a platform that is ‘dirty’, and transfer these samples to clean, sterile instruments. A much greater threat lies in the fact that live organisms, because of their potential to reproduce, have the potential to multiply and spread and amplify the signal, even from a small initial contamination event. For this reason, the subgroup concluded that forward planetary protection strategies must include a distinction between ‘local’ and ‘global’ contamination events.

2.1.2. Global vs. local contamination

The subgroup asserted that protecting Mars will require that the concepts of global vs. local contamination be incorporated into forward planetary protection policy. They suggested that this could be accomplished by modifying the current COSPAR definition of “special regions” to distinguish areas within which contamination would have local effects only, vs. those within which contamination could spread to other environments, potentially on the planetary scale. For discussion purposes they were referred to as *regions of local contamination risk*, and *regions of global contamination risk*. Although it is not possible at this time to provide scientific details associated with the two different categories, establishing this dual policy option will encourage the collection of relevant information for future missions.⁶

Considering a three-dimensional perspective, already it is known that certain regions on Mars are likely to have higher potential for extant indigenous life (and also for the support of introduced Earth microbes) due to important parameters such as temperature, inferred presence of water, and protection from ionizing radiation. All of the potential places identified to date occur either as broad

⁵ MEPAG: Mars Exploration Program Analysis Group, a science planning group that provides input to NASA.

⁶ Note: the EVA group did *not* suggest modifications of planetary protection policy, per se. Instead the subgroup considered a conceptual plan based on likely future scenarios and additional scientific data from precursor missions. They presumed that the future categorization of zones on Mars would be accomplished when we have additional information and greater certainty about the potential for microbial survival and spread in the martian environment.

regions (e.g., the region of the polar ice cap), or as large populations of specific features (e.g., gully systems). It will be important to investigate such places, even though doing so also will introduce a potential for microbial contamination of the site. Nonetheless, if such contamination is of local impact only, it is a very different matter than if the contamination has the potential to amplify and expand to either regional or global extent. The degree of uniqueness of the site to be visited must also be considered in assessing whether or not contamination should be allowed.

2.1.3. Proposed three-zone system

Building on the existing defined “special regions” (COSPAR, 2002), the subgroup proposed amplifying the categorization into three zones.

Proposed zone 1. Non-special region. The inverse of a special region. A site for which *growth or propagation of Earth organisms is unlikely, and which has low potential for the existence of extant Martian life.* By definition, this kind of region is *not* of interest for extant life detection investigations (but may be of interest for extinct life investigations).

Proposed zone 2. Region of local contamination risk. A region where terrestrial organisms are likely to propagate or where there is high potential for the existence of extant Martian life, *but where biological contamination can reasonably be expected to have local effects only* (global propagation, within TBD time scale, is considered to be of low probability). By definition, this kind of region is of interest for extant (and extinct) life detection.

Proposed zone 3. Region of global contamination risk. A region where terrestrial organisms are likely to propagate or where there is high potential for the existence of extant (and extinct) Martian life, *but where biological contamination has the potential to spread in a global sense.* By definition, this kind of region is of interest for life detection.

Possible implementation implications: The EVA subgroup also discussed the varied implications of their three-zone scheme, noting that regions of global contamination risk need a much higher level of protection than regions of local contamination risk. As an example, if an acceptable case can be made that a mission’s activities would contaminate only the immediate area, and that the biologic contamination could not spread either to a much larger volume of ground ice, or to a possible underlying aquifer, one could argue that the consequences of site contamination are acceptable. In contrast, if contamination of the site would likely spread beyond the local site, the consequences would be unacceptable, and preventive restrictions would need to be applied.

There should also be a way to consider the uniqueness of Martian features or areas if a mission is proposed for local contamination as per Zone 2 above. It is important to protect unique or rare Martian geologic phenomena, either

currently known or yet to be discovered. For example, if a geyser were discovered on Mars, it should be explored with extreme care, even if a case could be made that contamination would have local effect only. Thus, in addition to considering local vs. global, there needs to be provisions to protect rare occurrences.

The subgroup also discussed the implications of their new zoning categorization in relation to current COSPAR standards and bioload levels and offered thoughts about the issues and possible evolution of policy using their proposed three zone categorization.

They also noted that an important implementation consideration will be to ensure that specified cleanliness levels are below the detection thresholds of the instruments used in searching for organic compounds, to avoid false positives from detecting terrestrial contamination. In the past, this has been hard to implement in a practical sense—sensor technology is such that it hard to avoid measuring the background. In any case, there clearly is value in working on cleanliness technologies, control and on how to maintain the cleanliness chain.

2.1.4. Relationship to human missions

To date there is no general agreement on the scientific objectives that would be assigned to the first and/or subsequent human missions to Mars. If one of the objectives of the first human mission were to carry out extant life investigations, the mission would need deliberately to seek out places that have high biological potential, which in turn could lead to unacceptably high planetary protection risks. Reduction of that risk involves sending precursor missions to determine whether or not biological hazards are present at the landing site (see e.g., Beatty et al., 2005). Sending human missions to places with negative precursor findings may seem counterproductive scientifically. However, sending humans to a place with positive precursor results may result in exceeding acceptable risk thresholds for forward and/or backward contamination. One way to resolve this paradox may be if the human mission is designed to investigate extinct Martian life (which would not have a backward contamination risk).

2.1.5. EVA and backward contamination considerations

Maintaining a livable and healthy environment in Mars surface habitats will be imperative. However, numerous planetary protection concerns and backward contamination pathways will during arise during normal EVA surface operations. The subgroup identified the many types of pathways and operations that will take place on a daily to weekly basis during a human mission, including:

- Airlock operations: Transport of dust & regolith materials from surface into airlock and subsequently into habitat living areas.
- Crew contamination during don of spacesuits; inhalation/ingestion during EVA; inseparable transfer into habitat & to Earth.

Return from remote EVA worksites & surface traverses:

- Transport of “non-documented/classified” surface materials back into airlock/habitat living areas.

Geologic/astrobiological sample collection activities (surface & sub-surface ops):

- All of the above concerns associated with human-assisted operations.
- Handling of samples (*in-situ*) or in habitat laboratory for analysis.

Transfer EVA prep/servicing/maintenance items into habitat

- Surface contaminants and contaminants in cavities, seal regions, porous materials, between layers, etc.
- Limitations of practicable cleaning processes prior to airlock entry/in airlock

In situ resource utilization (ISRU) operations phase:

- All of the above concerns; perhaps magnified based on the extent of operations.

2.1.6. Implementation implications

In considering the backward contamination implications of the return mission, the following thoughts were suggested for avoiding the transport of hazardous materials to Earth's biosphere:

Implementation option 1: All martian material contained or sterilized. Breaking the chain of contact is achievable by robotic missions, but this is not practical for nominal human missions (while it may be possible to contain or sterilize returning martian materials on both robotic and human missions, obviously, it is not possible to similarly break the chain for crew members.)

Implementation option 2: Site not hazardous. If prior missions have established the site is not hazardous (but not necessarily dead), breaking the chain of contact will not be required. This will apply to both robotic missions and early human missions feeding forward to later human missions.

Contingency capability required: Empower the astronauts to respond to possible unexpected indications of extant life and/or possible exposure. The mission will need the tools and training to assess and control possible Martian biology if encountered, such as:

- On-board capability to detect and understand hazard
- Sterilization capability (method shall be effective)
- Personnel isolation capability

Emergency procedure if a hazard is discovered: We need to have a plan for returning astronauts to Earth, even if they have been contaminated by Martian life.

– Need emergency crew transfer capability to quarantine facility on Earth.

For backward contamination, there is an interesting trade-off between science and planetary protection. Minimizing the risk of contamination for astronauts (and consequently bringing the biohazard to Earth) would suggest landing and staying in Zone 1. However, collecting samples for exobiological examination would suggest a need to access Zone 2 or Zone 3 where the probability of contamination is the highest.

2.1.7. EVA planning and suit engineering

The EVA community needs realistic requirements for EVA planetary protection that (a) are tolerant of EVA hardware systems design feasibility limitations, (b) have technical practicality, (c) have tolerable impact to mission planning and operations, (d) have an architecture so as not to significantly affect human functional performance capabilities, and (e) are acceptable to both the planetary protection and science communities. Because planetary protection requirements will be costly, a reasonable way to mitigate these costs is to identify these requirements early in the development cycle.

Although the EVA community knows what gases vent from current suit designs, it does not know what levels of these constituents are acceptable from a forward contamination standpoint. In addition, the EVA community does not know what level of biological and organic material is contained within these gas releases during the course of normal operations. Thus, human space suit chamber tests using sample tracer elements or markers will be important to determine biological and chemical signature characterizations generated by space suit system venting and leakage effluents.

2.1.8. Prototype future planetary protection requirements for EVA

Based on their deliberations, the EVA subgroup developed an extensive list of possible planetary protection requirements for further consideration and discussion. These requirements focused on bioburden requirements for future missions to both ‘special’ and ‘non-special regions’; linkage of cleanliness levels and contamination allowances with scientific objectives; consideration of both local and global contamination risks for setting categorical designations and cleanliness levels; filtering of all vented gaseous materials from spacecraft, landers, habitats and rovers; contained disposal of all solid and liquid wastes; isolation of human explorers from direct contact with martian materials; and provision for appropriate quarantine capability for both the entire crew and individual astronauts in the event of uncontrolled contacts and exposures with martian materials. Like requirements for robotic missions, all samples collected from uncontrolled or untested areas of Mars should be considered potentially hazardous, and subjected to a series of rigor-

ous tests and/or sterilization before release from containment. In concluding, the subgroup identified several topics needing further discussion including bio-burden verification procedures, organic cleanliness protocols and definition of what constitutes “regional” or “global” impacts.

2.2. Overview of advanced life support subgroup (ALS) deliberations

Advanced life support (ALS) represents a suite of enabling capabilities necessary to support human exploration missions (e.g., air revitalization, water recovery, thermal control, solid waste management, and advanced food technology and crop systems). As integrated technologies, they provide the necessary transport, exchange, and recovery of gases, liquids, solids and thermal regulation required to maintain human life in the space environment. For future planetary missions, new advanced life support systems are needed to decrease dramatically the dependency on resupply consumables, as well as to decrease the mass, energy and volume of future spacecraft and payloads. Key design aspects of ALS systems include “closing the loop” to recover usable mass; decreasing the requirements for expendables, energy, volume, heat rejection and crew time; utilizing *in situ* resources; and providing a high degree of reliability.

Advanced life support systems for missions to Mars will not be completely closed, however, and accordingly have the potential to contribute to both forward contamination of Mars and backward contamination of Earth. It is reasonable to expect that materials cycling within human-rated habitats will be highly contaminated with microbial life that, if released outside of the habitat, can potentially be a significant source of forward contamination. Conversely, conservative plans would assume that any Martian life forms transported into the habitat would have the potential to become established either in humans or in life support system materials and hardware. These organisms may then be transported back to Earth on the return voyage, leading to potential backward contamination. Planetary protection thus represents an additional set of requirements that may influence ALS system design. For example, current cabin air management systems typically employ external venting to reject unwanted gas streams, including concentrated carbon dioxide, methane, and other contaminants. Planetary protection requirements may require that certain components be removed from these streams or decreased in amount. Waste management systems may also involve venting gaseous products to the Martian atmosphere, but will also need to comply with planetary protection requirements that control the extent and character of organic inventory and storage of potential forward contaminants (i.e., wastes).

Likewise, scientific investigations that are designed to search for current or past life on Mars may also influence

ALS system design. Science priorities would include elimination of contaminants that would confuse or obscure the science measurements. Of particular interest to scientists will be the control over the release and dissemination of specific materials from humans, foods, wastes and hardware that may be designated as biosignatures or biomarkers.

Since it is anticipated that planetary protection requirements may influence ALS technology selection and system design for future missions, these requirements should be incorporated into technology development programs, including those for the Moon if there is expected to be technology carry-forward into Mars exploration.

As part of their starting deliberations, the subgroup determined it would *not* contrast early vs. later missions in their workshop discussions. They reasoned that planetary protection requirements will not likely become more relaxed in later missions, since a conservative approach will be followed if there is continuing uncertainty about martian life. On the other hand, if extinct or extant life is found in the future, planetary protection requirements may become even stricter, not less so.

In considering the design of human support systems, the subgroup agreed that planetary protection and science-based requirements may influence ALS technology trade options, technology selection, system design, and system development costs. In addition, planetary protection requirements may affect the kind of operations, processes, and functions that can take place during future planetary exploration missions. Forward contamination requirements may limit the discharge of liquids, solids, and gases. Crew protection and backward contamination requirements may influence ISRU operations, particularly those that create resources that are transported into the habitat and can be inhaled or consumed by the crew. Additionally, waste, water and air management systems will need to handle contaminants that enter the habitat through crew ingress/egress, and returning samples or hardware.

The recommended approach is to design ALS systems to limit leakage/contamination to TBD levels, bearing in mind that closed systems are the ideal. Sterilization and decontamination capabilities will be required for generated wastes, spacecraft volumes (habitats and labs), and associated equipment. The subgroup also addressed the specific assigned questions as follows:

2.2.1. ALS sub-group responses to assigned questions

Question 1 – What is the overall approach to contamination control?

The ALS subgroup began discussions by debating whether unmanned missions transporting ISRU or ALS assets to Mars prior to human landing would be considered robotic missions (and accordingly fall under planetary protection requirements for robotic missions) or human missions (and fall under their planetary protection

requirements). Since the objectives and payload envelope of these precursor missions are more closely aligned with human missions than robotic science missions, the subgroup suggested a revision in wording for the conceptual approach as follows: “Human missions to Mars, *including associated missions to emplace assets (e.g., ISRU, ALS consumables)* shall not affect or otherwise contaminate “special regions” of Mars, as defined in the COSPAR Planetary Protection Policy of October 2002.”

There was also considerable discussion about the realities of forward contamination during human missions, in which bioburden will necessarily increase during transit. The subgroup noted that while it may be appropriate to require that “No quantitative bioburden requirements should be applied to landing systems or habitats, other than cleanroom assembly,” it will be necessary to impose additional controls to address in-transit contamination issues such as:

- the generation of additional (post launch) human-associated contamination including solids and liquids in general and microbes in particular, and
- the transfer of this contamination and its effect on the current and subsequent mission objectives.

Discussions also focused on quarantine requirements for the entire crew vs. quarantine for an individual crewmember. If there is a requirement for *individual* quarantine, then a *separate* ALS will be needed within the facility to test and/or evaluate individual crewmembers. No unique ALS capability is required for the quarantine of the *entire* crew. In either case, the Earth entry segment of the mission would require a leak-proof ALS in order to break the chain of contact with Mars as much as possible.

Question 2 – What is the approach to waste & consumable management for different mission phases?

Waste and consumable management strategies were considered for both the transit portion and the surface mission phases. From a planetary protection perspective, the best approach for managing wastes generated during the transit portion would be to ensure that they are not brought to the surface. During Mars transit, water would be recovered from wastes to stabilize them, and the dry solids would be contained. Ideally, these contained wastes would then be actively jettisoned (with a kick motor or other propulsive device) such that they would not enter the Martian atmosphere. All active jettisoning would be done in such a way that the outside surfaces of the spacecraft were not contaminated. Any wastes that were brought to the Martian surface would require containment and/or sterilization.

For planetary surface mission operations, both short stay (30–60 days) and long stay (300 day) scenarios were considered. The waste management approach was the same for both durations. All wastes would be contained for a TBD period and/or sterilized, and left on the surface. It

was recommended that wastes should not be buried. Prior to leaving the planet, decontamination of the habitat or stabilization of the bioburden within the habitat would be required.

Although it was recognized that various types of wastes and consumables have different bioburden and contamination potentials, there was insufficient time at the workshop to address this issue fully. The initial recommendation was to use an overkill approach and make no differentiation between waste and consumable types and assume a high bioburden on everything.

Question 3 – What are the off-nominal events that could potentially lead to contamination of Mars or the terrestrial biosphere? (also: Identify consequences and suggest mitigation strategies)

There are many off-nominal events related to ALS systems that could potentially lead to contamination of Mars or the terrestrial biosphere (e.g., off-nominal leakage from the habitat, airlocks or other vessels; malfunction of the airlock/transferlock/dustlock; contingency venting during off-nominal overpressurization; premature failure of waste containers or waste management systems; ISRU resource generation and use; and unintentional discharges from life support equipment). In virtually all cases the root cause of contamination would be either a breach of containment, the failure of sterilization/decontamination systems, or exposure to the Martian environment. Mitigation strategies include identification of best design practices for reducing risk, and development of operations and procedures for contingency/off-nominal response.

Question 4 – What is the R&D required to cope with planetary protection requirements?

The ALS subgroup identified a list of topics needing future R&D attention, including:

- On-line, real-time genetic identification of biological organisms in ALS.
- Near field and far field models for contamination transport to guide adequacy of planetary protection requirements for human missions.
- Quantitative and qualitative knowledge of ALS system process streams (air, water, waste, etc.) to assist in assessing potential forward contamination risks, and in developing mitigation approaches.
- Prediction or measurement of how the Martian environment (e.g., radiation, temperature, chemistry) would contribute to passive mitigation of forward contaminants.
- Characterization of contaminant releases from the cabin via leakage, intentional venting and general mission operations.
- Identification of pertinent air, water and waste management technologies for processing, containment, and disposal that comply with anticipated planetary protection and science-based constraints (for surface and interplanetary space).

- System analyses to determine the viability of the surface waste storage concept for various waste processing scenarios.
- Re-examine and modify ALS reference mission designs as necessary to harmonize with planetary protection and science-based requirements.

2.3. Overview of operations and support (Ops) subgroup deliberations

The Ops subgroup used the basic workshop assumptions, conceptual approach and a focus on “special regions” as they deliberated about the assigned questions. Their findings about forward and backward contamination and their suggestions on R&D topics are summarized below:

2.3.1. Ops and forward contamination considerations

- Human mission planning, including landing site selection, base location, and mission objectives, should follow from precursor robotic information and evaluations made at those sites and/or from information developed from a sample return mission or missions.
- Definition is needed for a system describing and categorizing martian sites of special scientific interest (special regions) and their level of contamination concern. The classification system shall be developed and employed in future planetary protection protocols, as well as in operational plans for later human missions to Mars.
- Additional development and design attention is needed to characterize exploration, sampling, and base activities both to assure effective operation and provide the required level of planetary protection assurance. In particular:
 - The processes associated with EVA egress/ingress must be characterized and optimized.
 - An inventory of microbial populations carried aboard and potentially released by human-associated spacecraft and suits should be established and maintained in support of both planetary protection and crew-health objectives.
 - An inventory of organic materials carried by, or potentially produced by, the mission should be established and maintained.
 - Systems should be provided to allow controlled, aseptic, subsurface sampling operations, so that uncontaminated samples can be returned to the surface, and so that human-associated contaminants are not introduced to the subsurface.
- Quantitative requirements to limit human-associated contamination in different zones shall be derived based on requirements for protection of “special regions” and applied to missions, with the following stipulations:
 - No quantitative bioburden requirements should be applied to landing systems or habitats at launch, other than cleanroom (ISO 8 or better) assembly of Mars-contacting components.

- Spacecraft, landers, habitats, and rovers shall (to the maximum possible extent) filter material vented as gases, and shall not allow uncontained disposal of solids or fluids.
- Hardware elements involved with accessing “special regions” shall be subjected to a sterilizing process prior to use.

2.3.2. Ops and backward contamination considerations

- All operations of a human mission to a new site on Mars shall include isolation of humans from directly contacting martian materials until initial testing (either precursor-mission or on-mission robotic testing) can provide a state-of-the-art verification of the landing site as a “zone of minimum biological risk” (provide for the informed consent of the crew).
- Exploration, sampling, and base activities should be accomplished in a manner to limit inadvertent exposure to the subsurface or to otherwise-untested areas of Mars
- A means for allowing controlled access to those areas shall be provided.
- A site classification system and a biological plausibility map of the martian surface and subsurface, based on remote sensing data and on-mission testing, shall be employed during a mission to limit potential crew exposure to areas on Mars that might support martian life.
- A quarantine capability for both the entire crew and for individual crewmembers shall be provided during and after the mission, in case potential contact with a martian life-form occurs. In particular:
 - As part of normal crew health monitoring and in support of the assessment of possible quarantine measures, basic tests of the medical condition of the crew and their potential response to pathogens or adventitious microbes shall be defined, provided, and employed regularly on the mission.
 - A quarantine capability and appropriate medical testing shall be provided for the crew upon return to the Earth (Moon or Earth-orbit) and if necessary, implemented in conjunction with a health monitoring and stabilization program.
- Samples returned by the crew from uncharacterized or otherwise-untested areas of Mars shall be considered as potentially hazardous, and shall not be released from containment unless they are subjected to a sterilizing process, or until a series of tests determines that they do not present a biohazard.

2.3.3. Research & development tasks related to Ops

- Describe the potential impacts on the near-field martian environment of human support activities expected in the operation of a human-occupied martian base (e.g., breathing oxygen, food supply, waste management, etc.) to determine the zone of contamination

associated with a human landing, and the plausible limits of zones of non-contamination that can be preserved nearby.

- Define the spatial dispersion of dust and human-associated contaminants on Mars by wind and other means.
- Determine the survivability of Earth organisms and their component molecules in the ambient Mars environment, and in the conditions of the martian near-subsurface.
- Examine future ALS designs and concepts with respect to planetary protection needs, especially with respect to organic and microbial contamination, to assess the potential effects of human activities in pressurized habitats and human-carrying rovers.
- Examine future EVA designs (thermal control, gas control, material leakage) with respect to planetary protection needs, especially with respect to organic and microbial contamination, to assess the potential effects of human activities on the martian surface away from pressurized habitats and human-carrying rovers.
- Develop EMC technology required for life detection and potential pathogen detection within the habitat or EVA system, with a focus on sensitivity and specificity of tests needed to identify potential microbes of unknown origin.
- Develop field-deployable systems to monitor human-associated biological contamination released into the martian environment (autonomous/automatic, rapid, reusable, and/or low-consumable recharge).
- Determine how to conduct human-associated robotic operations on Mars to be consistent with planetary protection concerns, both for those robotic resources deployed independently during precursor missions and for those deployed in conjunction with human landings.
- Define and develop planetary protection protocols for use on human missions. Develop and test methodologies for implementation of those protocols using Earth-based simulations (laboratory and field), lunar experience, and an improving knowledge of the martian environment based on precursor missions. Define and implement a training plan for the crew and other personnel involved with the mission.
- Ensure that human factors research and design for human Mars missions will address biosafety considerations associated with planetary protection.
- Provide robust and field-deployable systems to securely contain materials (wastes, propellants, etc.; for TBD durations) that may contaminate the martian environment.
- Provide for containment of Mars samples within human-occupied spaces, and for those returned to Earth.
- Develop mitigation techniques to deal with human-associated contaminants released on Mars, and with contamination of human-occupied spaces by martian materials.

3. Overall workshop conclusions

The workshop format provided ample time for plenary presentation and discussion of the various subgroup findings, which in turn led to the following overall workshop conclusions related to planetary protection, which are intended to focus on the broad conceptual approaches and issues, rather than implementation details. The list below reflects what was covered by the various sub-groups, although it is recognized that many other issues related to planetary protection will also need attention before human missions are feasible (e.g., emergency crew transfers, crew return requirements, quarantine details, breaking the chain of contact with Mars prior to Earth entry, microbial identification for habitat and suits, etc.). Overall conclusions by specific areas indicated below:

3.1. Policy

- It does not make sense to have separate planetary protection policies for human and robotic mission. The reasons for protecting Mars and Earth are independent of mission implementation.
- Planetary protection requirements imposed 'at launch' (as done for robotic missions) are not entirely sufficient for human missions. Evaluation of the biological contamination on the spacecraft will be mandatory throughout the mission because of its potential for both forward and backward contamination.
- Planetary protection requirements for early human missions should be based on a conservative approach consistent with our continuing uncertainties about martian life. Planetary protection requirements for later missions should not be relaxed without scientific review, justification, and concurrence.
- There will be a need to develop a comprehensive planetary protection protocol for human missions that encompasses considerations of forward and backward contamination for both robotic and human aspects of the mission, and includes associated sample handling and science activities on both Mars and Earth (similar to the comprehensive protocol developed for robotic sample return missions; e.g., Rummel et al., 2002).

3.2. Special regions

- For outbound spacecraft on human missions, pre-launch cleanroom assembly will be required of all systems regardless of planned landing site.
- For those systems that will land in or be deployed in 'special regions,' appropriate quantitative bioburden reduction requirements will apply.
- Neither robotic systems nor human activities shall contaminate 'special regions' as defined by COSPAR policy.
- Special Regions should be further considered in relation to the potential for local vs. global distribution of biological contamination.

3.3. Operations and crew

- Any uncharacterized martian site must be evaluated by robotic precursors prior to crew access. Information may be obtained by either precursor robotic missions or a robotic component on a human mission.
- Any pristine samples or sampling components from any uncharacterized sites on Mars shall be treated according to current planetary protection Category V, with restricted Earth return and appropriate handling and testing protocols.
- An onboard crewmember should be given primary responsibility for implementation of planetary protection provisions affecting the crew during the mission.
- Human factors (psychological, physiological or other possible impairments) need to be considered along with planetary protection issues for human missions.
- Crew protection and backward contamination requirements may influence ISRU operations. Of particular concerns will be those activities that may create resources or materials that can be transported into the habitat and can be inhaled or consumed by the crew.

3.4. Waste management

- Any solid or liquid waste produced on Mars will require containment or sterilization prior to disposal
- No uncontained liquid or solid waste products should be buried on Mars.
- Any vented gaseous products should be filtered prior to release (e.g., from spacecraft, habitat, suits, rovers etc.)
- Prior to leaving the planet, decontamination of the habitat (and equipment left behind) is required &/or stabilization of the bioburden within the habitat.

3.5. Research & development

Areas of important science research and technology development identified by the workshop include understanding and evaluating:

- Survival of spacecraft associated terrestrial organisms and their molecular components in the ambient Martian environment
- Near and far-field contamination transport models
- Quantitative & qualitative life support system process streams (air, water, wastes, etc.) for crew rated systems (e.g., habitat, EVA, suits etc)
- The impact of planetary protection requirements on various types of ISRU operations & systems.

In addition, there is need to develop the following:

- Real-time monitoring system(s) for potential 'unknown' biology within pressurized volume (e.g., spacecraft crew compartments, habitats, suits, etc.)
- Sterilization and decontamination capabilities for generated wastes, spacecraft volumes (habitat, EVA, suits etc.) and associated equipment and samples
- Containment capabilities for generated wastes, spacecraft volumes, associated equipment, samples and crew (quarantine).

Clearly there will be a need for significantly more discussion and planning about the complex interconnected systems required for future human missions. In the meantime, this workshop provided additional overview information on the importance of integrating planetary protection considerations into early mission planning. Planetary protection controls are essential not only for implementing safe human missions, but also for maintaining the integrity of scientific information and protecting environments both on Mars and upon return to Earth.

Acknowledgements

The workshop organizers (J.D. Rummel and G. Kminek) acknowledge the efforts of all participants in the workshop. Their collective expertise and insight during workshop deliberations contributed to the overall workshop recommendations and this paper. The workshop organizers also thank M. Race for preparing this workshop report.

EVA subgroup	ALS subgroup	OPS subgroup
Chair: J. Kosmo, JSC	Chair: Ch.Lasseur, ESA	Chair: B. Ward, JSC
D.A. Agnolon, ESA	K. Buxbaum, NASA JPL	B. Clark, Lockheed Martin
D. Anderson, SETI Inst.	R. Fisackerly, ESA	J.F. Clervoy, ESA
D. Beaty, NASA JPL	P. Heeg, Univ. Tuebingen	D. Eppler, SAIC
A. Debus, CNES	S. Hoffman, SAIC	G. Horneck, DLR
S. Hovland, ESA	M. Kliss, NASA	J.P. Pereira, ESA
F. Marty, ESA	R. Lindner, ESA	M.S. Race, SETI Inst.
C. McKay, NASA Ames	P. Mani, Tecrisk, Ltd.	F. Raulin, LISA-CNRS
	J.A. Spry, Open Univ.	J.L. Vago, ESA
	P. Stabekis, Windermere Group	

References

- Beaty, D.W., Snook, K., Allen, C.C., Eppler, D., Farrell, W.M., Heldmann, J., Metzger, P., Peach, L., Wagner, S.A., and Zeitlin, C. An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Missions to Mars. Unpublished white paper, 77 p, posted June, 2005 by the Mars Exploration Program Analysis Group (MEPAG) at <http://mepag.jpl.nasa.gov/reports/index.html>.
- COSPAR. Planetary Protection Policy, Oct. 2002 as amended, March 2005. <http://www.cosparhq.org/scistr/PPPolicy.htm>.
- Criswell, M.E., Race, M.S., Rummel, J.D., Baker, A. (Eds.). Planetary Protection Issues in the Human Exploration of Mars, Pingree Park Final Workshop Report, NASA/CP-2005-213461. NASA Ames Research Center, Mountain View, 2005.
- Hogan, J.A., M.S.Race, J.L.Fisher, J.A.Joshi, J.D.Rummel. Life Support and Habitation and Planetary Protection Workshop Final Report, NASA, Ames Research Center, Moffett Field CA, NASA/TM-2006-213485, 2006.
- MEPAG. Scientific Goals, Objectives, Investigations, and Priorities: 2003, Unpublished document, 22 p, posted April, 2004 by the Mars Exploration Program Analysis Group (MEPAG) at <http://mepag.jpl.nasa.gov/reports/index.html>.
- National Research Council. "Safe On Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface." National Academy Press, Washington, D.C., www.nap.edu, 2002.
- Rummel, J.D., Race, M.S., DeVincenzi, D.L., Schad, P.J., Stabekis, P.D., Viso, M., Acevedo, S.E. (Eds.). A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth, NASA/CP-2002-211842, Washington, D.C., 2002.