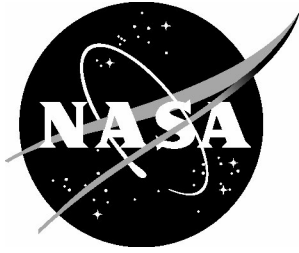


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# Science Mission Directorate's Science & Planetary Protection in Advance of Human Missions Workshop Report

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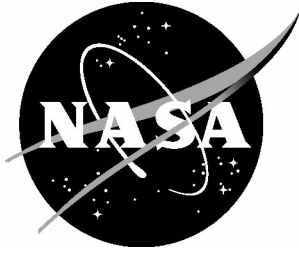
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October 30, 2024

National Aeronautics and  
Space Administration

NASA Headquarters  
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December 2025

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# Science Mission Directorate (SMD) | Science and Planetary Protection in Advance of Human Missions Workshop Report

October 30 to November 1, 2024

# Final Report

Released September 2025



## Science Mission Directorate’s “Science and Planetary Protection in Advance of Human Missions Workshop” Report

This document is the final report of the National Aeronautics and Space Administration’s (NASA) Science Mission Directorate’s “Science and Planetary Protection in Advance of Human Missions Workshop,” held virtually October 30 to November 1, 2024.

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### **Planetary Protection in Advance of Human Missions Website**

<https://sma.nasa.gov/sma-disciplines/planetary-protection/smd-workshop-fall/agenda>

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## Executive Summary

NASA's Mars Exploration Program hosted the Science and Planetary Protection in Advance of Human Missions to Mars Workshop as the pathbreaker for a new series developed for the purpose of engaging the Mars science community in the planning process for precursor science, and ultimately human exploration, on Mars.

NASA's Mars Exploration Program hosted a two-day virtual seminar July 31 to August 1, 2024, as a primer to provide a foundation for the science needs and Planetary Protection (PP) background on microbial survivability on Mars, transport on Mars, locations where the search for life is of interest, identification of perceived human impacts to the Mars surface and environment, and tools and operations that may be necessary to monitor human health and associated impacts of the Mars environment. A follow-on virtual workshop was held October 30 to November 1, 2024, focusing on life detection in the context of PP, analog environments and future exploration, Mars environments and terrestrial biology, risk mitigation for PP, instrument and technology development, science investigations prior to crew, and an “astronaut reality check.” The seminar and virtual workshop are summarized within this report as a factual record of the technical discussion, summary, and findings for each of the breakout groups, but do not represent a consensus position.

Below are thematic distillations from each of the subsection findings, as well as the NASA response.

### Life Detection in the Context of Planetary Protection

#### Thematic Distillation:

Life detection strategies could inform PP implementation mitigations. A dedicated and strategic precursor mission could inform and mitigate science and crew risks. A probability of microbial growth on Mars framework (Pg) that could directly feed into the PP probability of contamination (Pc) model needs to consider crew compliance. The framework could address metabolic adaptations of putative Martian life, well-established ecological habitability indexes, the potential for transient brine formation, etc. In addition to addressing parameters for the Pc model, the Pg framework could be used to inform life-detection strategies and landing site selections.

#### NASA Response:

We concur that precursor information is a crucial way to inform and mitigate risks and believe that this could be achieved with either a dedicated mission or individual instruments that collect relevant data. There are upcoming plans for Mars Exploration Program (MEP) activities and work supported by the NASA Astrobiology Program that may be used to address these goals. Work to understand the probability of contamination is ongoing and planned to enable crewed missions, and the identified additional concepts can be incorporated into

these activities. There will be many inputs to landing site selection processes and life detection investigation planning, and the findings identify good additions.

### **Analogs and Future Exploration**

Thematic Distillation:

An open science type of approach can be applied that serves as a data repository and establishes a community of practice working group. This group's charter could include developing community standard guidance around sample and data collection. Such a repository could also serve as a focal point for collecting reference analog studies.

NASA Response:

We concur that efficient use of existing resources, mechanisms, and programs to establish a community of practice is a viable path forward.

### **Mars Environmental and Terrestrial Biology**

Thematic Distillation:

Probability of release (Pr) and probability of survival (Ps) frameworks can be developed using our current understanding for Mars transport and Mars biocidal factors on the survival of terrestrial microorganisms for Mars exploration.

NASA Response:

We concur with the importance of following established protocols. Addressing key knowledge gaps for crew policy is an ongoing activity.

### **Mitigating Risk for Planetary Protection**

Thematic Distillation:

Risk communication continues to be a vital part of the planned National Environmental Policy Act (NEPA) process. Dust mitigation is also of interest in terms of particle transport and interactions for both engineering reliability, crew health, and science. Adaptation of Earth-based microbes could be a concern for crew health.

NASA Response:

We concur with the importance of risk communication and mitigation strategies. MEP and the Office of Planetary Protection (OPP) understand that there are crew safety concerns regarding microbial adaptation and, as this is out of scope for PP, will relay this concern to the Office of the Chief Medical Officer.

## Instruments and Tech Development

### Thematic Distillation:

The community desires deployment of astrobiological instruments on the Mars surface. These instruments could be deployed throughout a mission life cycle to not only assess science, but also to verify the Pc and identify associated risks.

### NASA Response:

We concur that the science to be achieved by further missions will require instrument and technology development along many lines and appreciate the detailed state of the science described in these findings. MEP is planning to support significant instrument development for payloads to be delivered to the Mars surface to advance this objective. Additionally, the Astrobiology Program supports the advancement of astrobiological instrumentation in coordination with NASA technology development programs.

## Science Investigations

### Thematic Distillation:

Update organic contamination working group inputs from Science Definition Team with updated level of detection (LOD), signal-to-noise ratio (SNR), and updated Mars science inputs since 2013, and incorporate Martian dust considerations. Consider analog environments and operations for optimizing exploration.

### NASA Response:

We concur with the importance of the investigations identified here and understand that this list may be somewhat limited in the light of the focused direction given to this workshop on the interface and connectivity between life detection science and PP.

From the summary and findings, the NASA MEP and OPP have distilled this feedback and are currently working with the following themes to address knowledge gaps in advance of crew to Mars:

- **End-to-end solution:** Integrated solution of science, engineering, and operations that focuses on architecting from the right. Understand and identify the types of science that are likely on the first crew mission and work backward to determine science needs to prepare for the crew arrival.
- **Precursor missions:** Since the 1990s, various studies [NASA, European Space Agency (ESA), Race et al. 2008] have recommended to NASA that precursor missions are needed to ensure that not only can the maximum science be done before human contamination is present, but perhaps more importantly, that a hazard assessment is done to inform crew safety.

- **Mars weather:** As a recognized knowledge gap (Spry et al. 2024), microbial transport is a necessary parameter in understanding both spatial and temporal transport of contamination in the Martian environment. The current transport models do not provide the fidelity and resolution needed to understand how microbial-associated particles move, both on a global and localized level. Having additional missions that monitor wind velocity and humidity at a higher fidelity will help to develop and validate these models.

These themes will be incorporated into the science, research, and technology development planning to close crew PP knowledge gaps.

## 1. Abstract

NASA's Mars Exploration Program hosted the Science and Planetary Protection in Advance of Human Missions to Mars Workshop as the first in a new series developed to engage the Mars science community in the planning process for precursor science, and ultimately human exploration, on Mars.

The PP discipline focuses on preventing harmful contamination during space exploration activities as well as eliminating adverse impacts to Earth's biosphere from returned materials, referred to as forward and backward PP, respectively. Unlike robotic exploration where the potential for harmful contamination can be controlled and mitigated prior to launch and during operations, the unique requirements of human exploration introduce elevated and fluctuating levels of microbial bioburden and organic loads.

When humans go to Mars, they will not be living in a closed system; the crew will be exposed to Martian materials, and the Martian surface will be exposed to terrestrial materials.

With these considerations in mind, MEP asked workshop participants to discuss the overall sequence of Martian exploration. Among many findings, attendees placed significant emphasis on the importance of returning samples collected by the Perseverance rover to Earth in advance of crewed exploration, as a path to closing key knowledge gaps such as contamination transport (weather) and dust characteristics with implications for human mission execution. Additionally, a significant segment of the participants recommended that NASA make further attempts to look for life on Mars using robotic missions before sending crewed missions. This would be a conservative strategy for mitigating against unprecedented potential for terrestrial contamination associated with a crewed mission. However, there was not unanimity among attendees on whether it should be mandatory for such investigations to be completed before the first crewed mission.

Beyond knowledge gap closure and life detection, participants argued strongly for preparatory precursor activities to support the science activities that would be conducted on a crewed mission. For example, attendees highlighted high-fidelity surveillance of human landing sites (using orbital assets or drones, for example) as one method to increase efficiency of crewed traverses. Contributors also advocated for NASA to send robotic missions to pre-select samples and pre-deploy drilling payloads in the interest of maximizing efficient use of crew time.

Overall, the workshop continued to reinforce the need for precursor missions to characterize Mars and determine the presence or absence of human-affective biohazards from the Mars environment. Ideally, this would happen before crew arrives on the surface, with Mars weather, landing site characterization, and pristine science being the three principal drivers.

## 2. Introduction

The PP discipline is focused on preventing harmful contamination during space activities as well as prevention of adverse impacts to Earth's biosphere through sample return, referred to as forward and backward PP, respectively. An international consensus standard for PP policy has been established and is maintained by the Committee on Space Research (COSPAR) Panel on Planetary Protection (COSPAR 2024). These international consensus standards are intended to provide a viable means for commercial and governmental entities to ensure compliance with the Outer Space Treaty (OST) of 1967 (UN 1967). Forward PP objectives focus on ensuring that contamination from spacecraft activities doesn't impact current or future science investigations, thereby enabling science. Science informs PP requirements, and as more information is known from a science perspective, the community can be more informed on PP policy based on this consensus. Meanwhile, when restricted Earth return samples<sup>1</sup> are brought back from Mars, our primary objective is to ensure biosafety so these activities do not adversely impact Earth's biosphere for backward PP.

Chemical and biological contamination is an inevitable byproduct of spaceflight activities, but the science and PP implications of these contaminants are not well understood. Whether in robotic or crewed exploration activities, this has been an issue recognized by the science community dating back to the early Ranger Mission activities in the 1960s (Meltzer 2011). Contamination is managed by both the science and PP disciplines with science integrity and science needs defining the detailed cleanliness requirements (e.g., such as that for a rover going to the Martian surface). Since the requirements to date have addressed only robotic Mars missions, only robotic mission requirements are developed in detail, but high-level guidance exists for crewed policy (COSPAR 2024; NASA 2020). Along with this guidance, the PP community identified an extensive series of knowledge gaps covering topics including microbial monitoring, contamination mitigation technologies, and Mars environmental transport modeling (Spry 2024).

Unlike robotic exploration where the contamination potential is a fixed point that can be controlled and mitigated prior to launch and during operations, introducing crewed exploration brings forward a set of implications including fluctuations of bioburden and organics (Seigel 2025). Development of a roadmap to coordinate research activities to address these knowledge gaps was recognized as a next step (Olsson-Francis 2023). The community has accepted that when sending crew to Mars, the crew habitat is not a closed-loop system. Interactions will occur from the built environment to the Mars surface, and the crew will be exposed to Martian materials (NRC 2002; COSPAR 2024).

One of the international community's recommendations prior to sending crew to the Martian surface was to appropriately characterize any human landing or operational site for any organic constituents. This is to establish a baseline understanding of the environment to maximize science returns before any contamination by crew, as well as inform hardware or operations to ensure crew and backward PP safety.

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<sup>1</sup> Samples from a "habitable" solar system target that have a non-zero probability of containing biological material of extraterrestrial origin.

So, what science measurements would need to be considered in this baseline? Are there critical science measurements that have to be completed? What would the desired thresholds be? To address these questions, a Mars surface science seminar and workshop was held with the following objectives:

- a) Identify science priorities for robotic missions in advance of humans arriving on Mars
- b) Inform development of PP guidelines for crewed missions to Mars
- c) Develop a framework for how forward and backward contamination control can be incorporated into human elements for Mars research activities

A two-day virtual seminar on July 31 and August 1, 2024, convened by the Mars Exploration Program was used as a primer to provide a foundation for the science needs and PP background. The seminar was also used to gauge external stakeholder interest and identify topics for the Fall workshop. The seminar was organized in two half days where there was a series of introductory talks followed by breakout sessions to facilitate small group discussion. These discussions focused on microbial survivability on Mars, transport on Mars, locations where the search for life is of interest, identification of perceived human impacts to the Mars surface and environment, and tools and operations that may be necessary to monitor human health and associated impacts of the Mars environment. Breakout session questions included:

- What are the priority knowledge gaps in our understanding of survival of terrestrial microbes, building on the existing literature (Final Report of the COSPAR Planetary Protection Knowledge Gaps for Human Mars Missions Workshop Series and Paths to Knowledge Gap Closure)?
- What measurements do we want to prioritize?
- What research can we conduct in advance of human arrival on Mars to ensure future science integrity?
- What tools (including crew-robot interface) could crew utilize on the Mars surface to preserve scientific integrity of samples?
- What aspects of guidance for crewed science missions could use further discussion, are missing, and/or work well?
- What are the prioritized science tasks to achieve before humans arrive?
- What scientific research is desired to be conducted before humans arrive, and will it inform the activities of the human explorers once they are on the surface?
- What research will the crew themselves be doing, and how will forward and backward contamination control be incorporated into those research activities (e.g., science and engineering)?

A brief summary of the seminar is provided here for context, and a more detailed report can be found in Appendix A.

From the breakout sessions, the community discussed developing the following:

- A further understanding of extremophiles and their ability to survive on Mars

- Robust sample collection and analysis methods that minimize the impacts of crew-associated contamination
- A notional concept of the research needed before crew arrival to Mars
- A framework for collaboration and interdisciplinary work

Specifically, the group emphasized the need for understanding the effects of Martian environmental factors on microbial survival. Minimizing crew contamination impacts were important in developing robust sample collection and analysis methods with the need to focus on sterilization of tooling and developing efficient decontamination procedures. This includes conducting detailed surveys of potential landing sites, studying the survival of microbes in unique environments, and developing models to predict the spread of contamination. For knowledge sharing, participants recognized that more concerted framework was needed across different fields, such as astrobiology, life support, and PP, to develop more comprehensive solutions for future missions than has been done to date.

Themes identified for the Fall workshop included future topics of life detection at the interface of PP, analog sites in future exploration, and instrument and technology development.

Upon establishing topics for the seminar, the Fall workshop was planned and abstracts were solicited from the community to help shape the workshop. The objectives for this Fall workshop were to:

- Identify science priorities for robotic missions in advance of humans arriving on Mars, understand life on Mars through Mars missions and research on Earth, and monitor surface weather on Mars to better understand dust movement and weather patterns to inform transport models for forward PP/contamination.
- Inform development of PP guidelines for crewed missions to Mars, leverage past missions to understand future PP requirements, and monitor and study the human microbiome.
- Develop a framework for how forward and backward contamination control can be incorporated into human elements for Mars research activities, noting the approach to developing PP must be science-led (and not just planetary science-led, but all science including virology and evolutionary expertise that can weigh in on the actual risks of Mars-sourced biology on Earth biology and ecological impact).

The virtual Fall workshop, convened by MEP, took place October 30 to November 1, 2024, as half-day meetings comprised of sessions from the abstracts submitted, panels, and a crew mission scenario exercise with focused breakout discussion. The topics for the panels and sessions focused on life detection in the context of PP, analog environments and future exploration, Mars environments and terrestrial biology, risk mitigation for PP, instrument and technology development, science investigations prior to crew arrival, and an astronaut reality check.

## 3. Workshop Proceedings

### 3.1 Life Detection in the Context of Planetary Protection

(Section written by Edgard Rivera-Valentín, Johns Hopkins Applied Physics Laboratory)

#### Introduction

The first session of the conference focused on reviewing historical and environmental context to set the stage for discussions about PP in advance of human missions to Mars. The three speakers included:

- Dr. Carol Stoker from NASA Ames Research Center, who presented on her abstract titled, “We must search for extant life on Mars prior to human exploration.”
- Dr. Steven Benner, from the Foundation for Applied Molecular Evolution, who presented on his abstract titled, “Searching for extant life on Mars before human arrival.”
- Dr. Edgard G. Rivera-Valentín, from Johns Hopkins Applied Physics Laboratory, who presented on their abstract titled, “An astroecological approach for planetary protection operations on Mars.”

The talks in the session reviewed results from previous missions to Mars, as well as recent modeling results and adaptations of terrestrial ecological models to Mars, advocating for a strategic approach to operationalizing PP in preparation for human missions to Mars.

#### Technical Content

Crewed exploration of the Martian surface presents a heightened forward contamination risk when compared to robotic exploration, and, as advocated by Stoker et al. (2024), necessitates a precursor mission dedicated to the search for extant life. A primary driver for astrobiology is finding life beyond Earth. The means for this search is rightfully informed by PP policies, in particular those set by the OST, to ensure a robust in-situ detection of indigenous life. Although Martian global conditions are drastically hyperarid and cold, conditions typically beyond those considered suitable for terrestrial life (e.g., Price and Sowers 2004; Rummel et al. 2014; Paris et al. 2023), microenvironments associated with buried ice and hygroscopic salts may provide transient and potentially suitable conditions for Martian life in the recent past (Stoker et al. 2024).

Thermal models and remote sensing measurements, including observations of exposure by recent impacts (e.g., Piqueux et al. 2019; Dundas et al. 2021), demonstrate that shallow subsurface ground ice is presently abundant on Mars from high latitudes into the mid-latitudes. The regolith-ice interface is of astrobiological interest because liquid water may form there through salt-ice interactions or deliquescence, where salts absorb moisture to create brines under suitable temperature and humidity conditions. Although present-day conditions on Mars may not lead to the formation of brine environments suitable to terrestrial-like life (e.g., Rivera-Valentín et al. 2020), the quasiperiodic variation of the Martian orbital parameters (e.g., obliquity, eccentricity) would have led to ground-ice redistribution and potentially improved

conditions with respect to habitability (Mellon et al. 2024). Indeed, Mellon et al. (2024) showed that high obliquity periods may have led to seasonally favorable conditions at the ice-regolith interface. Life that made use of these environments may presently lie dormant, sealed within ground-ice (Stoker et al. 2024). Sampling strategies for life-finding missions can be informed by the location of ground-ice that may have previously experienced conditions suitable to terrestrial-like life. Drilling systems, such as those developed for the lunar Volatiles Investigating Polar Exploration Rover (VIPER), can be used to search for dormant life buried within Martian ice (Stoker et al. 2024).

However, despite robust robotic international exploration of Mars by both orbiters and landers, a dedicated extant life-finding mission has not occurred since the twin Viking landers in 1976. Viking 1 landed in Chryse Planitia (22.7°N, 312.05°E), a smooth plain near the end of several outflow channels, and Viking 2 landed in Utopia Planitia (48.27°N, 225.99°E), a plain unit within a large, ancient impact crater where subsequent evidence of buried ice was found (e.g., Stuurman et al. 2016; Dundas et al. 2021). The missions included three twin biology experiments: (1) the gas exchange experiment, which assessed potential metabolic products released after applying a liquid complex of nutrients and water to a regolith sample, (2) the pyrolytic release experiment, which investigated photosynthetic activity by incubating regolith in the presence of radiolabeled nutrients under simulated Martian conditions, and (3) the labeled release experiment, which measured the response of inoculated Martian regolith with a radioactively tagged aqueous nutrient solution. The missions additionally included a gas chromatograph-mass spectrometer (GC-MS) intended to measure the organic content of the Martian regolith.

As summarized by Benner's workshop presentation, the missions observed the fixation of  $^{14}\text{C}$  from  $^{14}\text{CO}_2$  and  $^{14}\text{CO}$ , the emergence of  $^{14}\text{CO}_2$  from  $^{14}\text{C}$ -food fed to the regolith, and the release of  $\text{O}_2$  from the regolith when moistened, indicating the presence of reactive oxidants and providing evidence suggestive of extant life. In particular, the results from the labeled release experiment have been interpreted as positive identification of biologic activity (Levin and Straat 1977; Levin and Straat 2016). However, the GC-MS measurements indicated no significant traces of organic molecules in the Martian regolith (Biemann et al. 1976), providing a potential explanation for the observed regolith reactivity. The later discovery of perchlorates in the regolith by the Phoenix lander (Hecht et al. 2009) provided a possible explanation for this detection: the decomposition of organics by perchlorates (Navarro-González et al. 2010). Additionally, Navarro-González et al. (2006) showed the GC-MS may have not been sensitive enough to the low levels of organics on Mars and that an iron- and salt-bearing regolith may have affected the detection of organics. Indeed, these authors advocate for improved designs for future organic detection instrumentation to Mars.

Although the Viking biology experiments remain inconclusive with ongoing debates over biotic and abiotic interpretations, Benner (2024) highlights the need for future missions to consider the potential unique metabolic adaptations of putative Martian life, particularly in low-oxygen environments. Their bacterial autotrophs respiring with stored oxygen for overnight metabolism (BARSOOM) model postulates autotrophic organisms that store oxygen during the day for

overnight respiration, offering a plausible explanation for Viking's results. By accounting for (or being agnostic to) such conceivable metabolic pathways, future life-detection missions can better tailor strategies to detect extant Martian life (Benner 2024).

Furthermore, ecological frameworks can be used to better inform life-detection missions to Mars (Mautner et al. 2002; Mendez et al. 2021; Meurer et al. 2024). In particular, as advocated by Rivera-Valentín et al. (2024), habitat suitability index (HSI) models can help prioritize landing sites by evaluating the habitability of environmental conditions. HSI models are quantitative ecological frameworks for evaluating the degree to which an environment can support a specific species or model organism. They leverage species-environment relationships—such as temperature tolerances and dependencies on growth—to predict survival, reproduction, and development, as well as the potential for species recruitment. Given the available in situ and orbiter environmental measurements, as well as predictions from global circulation models, HSIs can inform PP considerations, as well as life-finding strategies, by identifying locations on Mars that may be the most suitable to life in both a temporal and spatial context.

An advantage over traditional approaches is that HSIs and similar ecological frameworks provide a continuum of values that reflect varying degrees of suitability, rather than a simple binary approach. As such, HSIs can capture the suitability uncertainty arising from the potential for microenvironments when using large spatial-scale environmental measurements. This is because while microenvironments may exist, their conditions are unlikely to deviate significantly from the broader environmental context. Quantitative continuum approaches account for this by recognizing that the probability of a highly suitable microenvironment emerging within a generally unsuitable region is inherently low, and vice versa.

For Mars, landed meteorological packages have demonstrated that the hyperarid conditions lead to an inverse relationship between temperature and relative humidity with respect to liquid, whereby when temperatures are below 215 K, relative humidity is high (>50%), and when temperatures are above 240 K, humidity is <5% (Rivera-Valentín et al. 2024). As such, stable, pure liquid water is precluded on present-day Mars, but brines may form through salt-ice interactions and deliquescence of the most hygroscopic salts (e.g., Rivera-Valentín et al. 2018; Rivera-Valentín et al. 2020). However, surface conditions do not permit the formation of a brine that meets the PP Special Regions criteria [i.e., locations where simultaneously temperature >255 K and humidity >60% exist (Rummel et al. 2014)]. Nevertheless, microenvironments, which are more relevant for microorganisms, may deviate sufficiently, allowing for transient favorable conditions. As advocated by Rivera-Valentín et al. (2024), by leveraging models of brine stability together with HSIs, locations on Mars can be identified that, relatively speaking, provide the most dynamic suitable conditions for life, providing a more targeted strategy of landing site selection for future life-finding missions needed prior to human exploration.

## **Discussion and Summary**

The three presentations in this session collectively argue that the heightened forward contamination risk posed by crewed missions necessitates a rigorous in-situ search for extant

life that is guided by PP principles and lessons learned from past missions. Stoker et al. (2024) emphasized the astrobiological significance of the shallow ground-ice interface, where transient brine-forming processes may have supported past life and may today contain dormant microbial life. Benner (2024) revisited the twin Viking biology experiments, advocating for future missions that consider non-Earth-centric metabolisms and improved instrumentation capable of detecting low levels of organics. Rivera-Valentín et al. (2024) extended these frameworks by proposing the use of ecological models, such as habitat suitability indices, combined with brine stability predictions to identify landing sites with the highest potential for supporting life, especially considering microenvironments. These abstracts converge on the conclusion that a modern, purpose-built life detection mission that is grounded in ecology, microbiology, and our knowledge of the dynamic Martian climate, is essential to the responsible exploration of the Martian surface by humans.

## Findings

1. Before human missions to Mars, a dedicated and strategic life-detection mission is needed to prevent the forward contamination of Mars and mitigate associated risks.
2. Sampling strategies for life-finding missions can be informed by the location of ground-ice that may have previously experienced conditions suitable to terrestrial-like life.
3. Future life-detection missions to Mars should consider the potential unique metabolic adaptations of putative Martian life, particularly in low-oxygen environments, to inform life-detection strategies.
4. Landing site selection for future life-finding missions to Mars should be informed by well-established ecological frameworks, such as habitat suitability index models, as well as the potential for transient brine formation on the Martian near-surface.

### 3.2 Analogs and Future Exploration

(Section written by Heather Smith and Jessica Lee, NASA Ames Research Center)

#### Panel Information and Introduction to the Topic

The panel session on Analogs and Future Exploration featured a discussion, moderated by Lane Painter (Operations Specialist at NASA HQ), between researchers experienced in working with a variety of Mars environment analogs. Alex Mahnert (Medical University of Graz) discussed his work on analog crew studies and monitoring microbial populations in enclosed environments with personnel. Charity Philips Lander (Southwest Research Institute) described work in icy and permafrost environments that are analogs to the Martian subsurface, specifically looking at the creation of micro-habitable niches. Alexandra Pontefact (Applied Physics Laboratory, Johns Hopkins University) discussed her work in hypersaline systems and studies of how habitability and biosignature preservation relate to water activity and chaotropy, as well as the creation of habitat through impact craters. Frankline Besonge-Bokanda (University of Bologna, Botswana International University of Science and Technology) related their experience working at the Makgadikgadi Pans (Botswana), an analog for playa environments on Mars.

#### Technical Content (Based on Discussion)

The discussion was initiated with the question: *What are some of the key environments we'd like to focus on to drive key decision-making for analogs in future exploration?* Dr. Lander responded by highlighting the work presented in the previous session by Dr. Rivera-Valentín, modeling habitat suitability across Mars environments. She pointed out that this modeling work laid out a good case for the kinds of habitable environments that might exist on Mars, which should be prioritized for study. Primarily, this means habitats with a multiplicity of simultaneous stressors (e.g., radiation, low temperature, low water activity). Dr. Pontefact agreed and added that the logical next step is to identify how to reproduce these environments in the lab, because many known environmental analogs on Earth are not only difficult to access but vary seasonally, therefore making it difficult to conduct controlled studies regarding the survival limits of organisms. Dr. Mahnert followed up to point out that many environmental analogs also unavoidably include factors such as an oxygenated atmosphere and available organic compounds, which are not present on Mars; laboratory infrastructure and experiments would be necessary to eliminate these factors.

The discussion moderator followed up to ask: *Are there any particular analog environments that have not yet been explored but should be?* In response, the panelists had few specific recommendations. Dr. Bokanda pointed out that no single Earth environment can be considered a true and complete analog for Mars, though each features a specific set of Mars-relevant characteristics (e.g., the Makgadikgadi Pans is an environment relevant to understanding the dynamics of hydrated minerals on Mars). The community may want to identify gaps in the current suite of analog environments to identify new ones which answer specific scientific questions that cannot currently be addressed otherwise.

Dr. Kennda Lynch presented a third discussion question: *What kind of cross-correlation work do we need to do across analog studies and sites?* Drs. Lander and Pontefact both responded to this question, citing frustration at the current lack of comparable datasets across different study sites, making it difficult to draw broad scientific conclusions. Dr. Lander suggested conducting systematic studies across many environments of a particular type to try to narrow down the range of variables at play and increase understanding of how the sites relate to each other. Dr. Pontefact expressed a desire to see the community agree on standards for what kinds of data should be recorded across all analog-site studies (regardless of whether they are specifically required by the current research) to better facilitate meta-analysis and cross-comparison. There was widespread agreement that a white paper describing these visions would be useful to the community. Dr. Mahnert added that not all analog studies have the same purpose: there might be interest not only in how organisms evolve in a particular environment, but also the possibility for human-associated organisms to survive in those environments if introduced, implying that any community standards for environmental measurements and data recording should cover both astrobiological and PP interests. Dr. Lynch responded with a suggestion that presence and persistence of human-associated organisms be explicitly studied across analog sites.

As a final discussion question, the moderator asked: *What are some of the key programs or groups that we should all be tracking?* Dr. Mahnert cited the research community supported by the Sloan Foundation Program on Microbiology of the Built Environment, which was initiated around a decade ago. In particular, he mentioned Jack Gilbert (University of California, San Diego), Elizabetta Caselli (University of Ferrara), and Erica Hartmann (Northwestern University) as researchers studying the interaction of humans, microorganisms, and our environments, and developing interventions for healthier microbial environments.

Dr. Lander cited the climate change community, pointing out that work being done to evaluate emerging diseases, polar microbiology, and others in the climate change area are concerned with how microbial communities shift with changes in environment and adapt to extremes, which are relevant to questions of PP for Mars. Dr. Pontefact emphasized that she would like to see more work being done using metagenome-associated genomes (MAGs) to understand the metabolic capabilities of microorganisms/microbial communities and the metabolic costs of carrying out those activities in various extreme environments to understand habitability. She noted the work of Tori Hohler (NASA Ames Research Center) and Rachel Moore (Georgia Tech) and collaborations between modeling of habitable environments [such as that by Edgard Rivera-Valentín of Johns Hopkins University Applied Physics Laboratory (JHU APL), and Jacob Buffo of Dartmouth] and experimentation to reproduce and study those environments in the lab. Dr. Pontefact also mentioned that the Applied Physics Laboratory (APL) is initiating a sample repository to archive and share samples from analog environments and is seeking support from the community to make it a reality.

## **Findings**

In summary, the discussion panel included perspectives from working on analogs, both from the perspective of astrobiology and habitability, and from the perspective of the microbiomes of crew and their built environments.

1. Increased integration between modeling and experimentation is needed to prioritize relevant environments and develop robust laboratory analogs.
2. Cross-correlation of analog environment studies should be strengthened through systematic multi-site investigations and standardized environmental data collection.
3. Centralized repositories are recommended for sample archiving and data sharing to enhance collaboration and reuse.
4. The PP community can benefit from practices and insights developed by the built microbiome and climate change research communities.

### 3.3 Mars Environmental and Terrestrial Biology

(Section written by Joel S. Levine, William and Mary)

#### Introduction

As we plan for the first human mission to Mars, several aspects of this mission must be addressed that were never considered in our earlier robotic missions to Mars: forward contamination due to the presence of humans on the surface of Mars and backward contamination since we have never returned any humans or samples back to Earth from Mars. Clearly, we considered forward contamination in all previous robotic missions to Mars and spent considerable time, effort, and money to sterilize the Mars landing probes using high temperature and ultraviolet techniques. With a crewed mission to Mars, sterilization by high temperature and ultraviolet radiation is not an option. Mars is a dusty environment. We know on Earth that wind-blown atmospheric dust from the Earth's deserts are carriers of microbes for thousands of miles through the atmosphere, and the microbes on the atmospheric dust are alive and viable upon landing. This session dealt with the forward and backward contamination associated with a human mission to Mars, monitoring dust in the atmosphere of Mars, and the survivability of microbes on the surface of Mars and in interplanetary space.

#### Technical Content

Moogega Cooper, Fei Chen, and Ioannis G. Mikellides discussed aseptic assembly procedures from the Mars 2020 Perseverance rover as a reference for protocols to prevent forward and backward contamination on human missions (Mikellides et al. 2017 and 2020; Cooper et al. 2023; Cooper et al. 2024). The Mars 2020 Mission's meticulous approach to biological and molecular contamination control of the rover and its component hardware offers valuable insights that can be adapted to the design and operation of spacesuits for future humans to Mars endeavors. Given the stringent requirements for PP, spacesuits intended for human Mars missions must (1) prevent the forward contamination of Mars, ensuring that terrestrial microorganisms do not compromise Martian environments for sample science or future sample return missions, and (2) prevent the backward contamination of the Earth by way of the habitat and the returned astronauts or the returned vehicle. The Mars 2020 Mission successfully employed hardware design, transport modeling, cleaning, and aseptic assembly procedures to achieve levels of cleanliness. These practices can be translated into spacesuit protocols through a multi-faceted strategy that emphasizes biological contamination control at every stage, from design to operational use on Mars.

Joel Levine discussed the role of the omnipresent windblown dust in the atmosphere of Mars (Martin 1995; López-Cayuela 2023; Levine 2024) as a mechanism for transporting Earth microbes around Mars and inadvertently bringing potential Mars microbes back to Earth, along with the lifetime of potential Mars microorganisms in space (Kinard et al. 1994; Horneck, Bückner, and Reitz 1994). The many problems with lunar dust on the Apollo missions were reviewed during the NASA Engineering and Safety Center's (NESC) "Workshop on Dust in the Atmosphere of Mars and Its Impact on Human Exploration" at the Lunar and Planetary Institute (LPI) in Houston, TX June 13 to 15, 2017 (Winterhalter, Levine, and Kerschmann 2018; Levine,

Winterhalter, and Kerschmann 2018). The four highest-priority recommendations from this workshop were:

1. The question of life in the atmospheric dust on Mars can and should be addressed via Mars Sample Return (MSR).
2. Future Mars missions should include instrumentation to obtain missing toxicologically relevant in-situ measurements, preferably at multiple locations, and especially for respirable dust <10 microns for both regolith-based and wind-borne dust.
3. MSR materials should be examined to provide information on the missing toxicology (R-2), either by direct studies on native material or indirectly through the use of returned samples to validate authentic simulants.
4. Measure the size distribution and flux of dust particles on the Martian surface in the ambient air, continuously for an extended period of time (multiple seasons), preferably on multiple platforms.

Two recent publications examined the role of Mars atmospheric dust on human missions to Mars and on PP considerations for returning samples and astronauts from Mars (Spry et al. 2024; Whetsel et al. 2025).

Montabone discussed continuous, simultaneous global monitoring of Martian weather, particularly Mars atmospheric dust storms, a potential carrier of Earth and Mars microbes (Montabone and Forget 2018, Montabone 2024). Humans will be affected by weather on Mars as much as they are affected by weather on Earth. While Earth's weather is dominated by the water cycle, on Mars, the dust cycle plays a crucial role in driving weather patterns. At the same time, weather phenomena, such as baroclinic waves and thermal tides, influence Martian dust storms, which pose significant challenges to human missions. They can affect visibility, power generation, and the operation of surface systems, while also impacting human health and habitats. Moreover, beyond the direct impact of dust storms, human explorers must consider how their activities might contribute to contamination and pollution of the Martian environment. A critical concern is how aeolian processes could facilitate the transport of microbial contaminants introduced by human explorers.

Schuerger and Moores considered the synergism among multiple biocidal factors for microbial survival and growth under simulated Mars conditions and on the potential of microbial proliferation in the "Special Regions" on Mars (Schuerger et al. 2003, 2006, 2013, 2019, 2024; Moores and Schuerger 2020). The top seven biocidal factors were (in approximate priority order):

1. Solar ultraviolet radiation (200-280 nm) on the surface
2. Desiccation
3. Low pressure (6-10 mb)
4. Anoxic CO<sub>2</sub> atmosphere
5. Volatile oxidants (e.g., O<sub>2</sub><sup>-</sup>, O<sup>-</sup>, H<sub>2</sub>O<sub>2</sub>, etc.)
6. Extremely low temperatures (global average of -61 °C)
7. Potentially biotoxic soils due to high salt concentrations and extremes in acidity/alkalinity in the surface regolith

The dominant biocidal conditions for interplanetary space were:

1. Solar heating on external surfaces
2. Solar ultraviolet radiation on external surfaces
3. High vacuum
4. Extreme desiccating conditions
5. Space ionizing conditions

The authors concluded that synergistic interactions of multiple biocidal factors on Mars and in interplanetary space have the capacity to significantly enhance the lethality of these environments on spacecraft bioburdens. Due to the complexity of conducting multi-factorial experiments—especially when treatments exceed three parameters—single-factor experiments are often preferred for simplicity. Thus, it is likely that the “true” biocidal natures of the Martian surface and interplanetary space are currently being underestimated because experiments are limited, in general, to single-factor experiments.

## **Findings**

1. It is very important all robotic and crewed missions that land on the surfaces of a planet or a planetary moon be properly sterilized according to the COSPAR protocols to prevent forward contamination. The experience outlined and discussed in the sterilization of the Mars 2020 Perseverance rover indicates that we have a good understanding of the robotic spacecraft sterilization process.
2. It is very important to better understand the role of dust in the atmosphere of Mars as a possible mechanism for inadvertently transporting potential Mars microorganisms on returning robotic sample missions and human missions.
3. It is very important to better understand the impact of the Mars to Earth interplanetary medium on the lifetime and survival rates of potential Mars microorganisms during the return to Earth of robotic sample return missions and human missions. Conditions to be experienced in the interplanetary medium include solar heating on external surfaces, solar ultraviolet radiation on external surfaces, high vacuum, extreme desiccating conditions, and space ionizing conditions.

### 3.4 Mitigating Risk for Planetary Protection

(Section written by Chelsi Cassilly, NASA Marshall Space Flight Center)

#### Introduction

Planetary Protection includes both forward PP (currently robotic, future crewed) and backward PP (the return of samples to Earth). While NASA has developed expertise and knowledge on how to assess and mitigate risk for forward PP on robotic missions, backward PP of a restricted returned sample has yet to be fully realized in a mission. In addition, the risks involved for maintaining forward PP when humans are added to the equation become significantly more challenging when compared with robotic missions. Evaluating new risks and developing mitigation approaches will include careful consideration of multiple topics in order to sustain and implement PP while also achieving mission success within a resource-constrained project environment. Additionally, such risks and their mitigations need to be communicated to relevant stakeholders.

#### Technical Content

*A Hierarchy of Potential Hazards: Improving Stakeholder Engagement Through Science-Informed Discussions of Backward Planetary Protection Risks (Douglas Isbell, NASA Jet Propulsion Laboratory) (Isbell 2024)*

Risk communication involves fostering effective discussions with stakeholders about potential topics of public safety, often involving low-probability, high-consequence events such as potential adverse effects on Earth's biosphere related to backward PP. This process can be challenging, especially for missions receiving heightened public attention. The MSR concept is an example of a mission that will receive particular public scrutiny. It cannot be stated for certain whether there is extant life on Mars and, if there is, what hazards may be present. For instance, what are the odds of ecological displacement and/or non-host specific interactions (i.e., a bioactive material that can directly interact with an Earth organism but is not specific to the host)? It is challenging to bound these hazards since they are unknown, and resolving every concern is impossible due to the complexity and costs associated. However, we can begin to make some likelihood assumptions. It is known that Mars is an extremely inhospitable environment (e.g., high solar UV radiation levels, low water activity). In the decades since the first Mars flybys and landings, we have data that shows there's a very low likelihood that we will find intelligent or complex multicellular beings. It is also understood that, even if viruses, prions, or even gene transfer agents exist on Mars, it is doubtful they would be hazardous to Earth's biosphere because these would typically require co-evolution with a host organism. Thus, in risk communication and decision-making, NASA should focus on the hazards the science indicates we are most likely to encounter.

To this end, NASA has a responsibility to educate the public and commit to providing accurate information regarding scientific consensus, current knowledge, and risk estimates using transparent processes. Such communication should avoid traditional imagery in science fiction,

and instead rely upon the fundamental laws of physics, chemistry, and biology. NASA should develop and sustain ongoing and open dialogues about actual challenges and measures that are implemented to ensure safe exploration. These efforts should be proactive and could include activities such as speaker events, panels, debates, and Q&A sessions, supported by active use of social media. Discussions should be high-quality, well-documented, and easily accessible for a wide variety of audiences, including nonexperts and the international community. Additionally, the activities should involve both experts in space missions and PP, as well as experts in related topics, including evolutionary biologists, virologists, and researchers involved with invasive species. Communication and dialogue must be grounded in the scientific community's understanding of potential hazards, using context from analogous hazards on Earth and drawing expertise from other fields or applications (e.g., Centers for Disease Control, Environmental Protection Agency).

*Biological Potential of Aeolian and Subsurface Material at Jezero (Brian Clement, NASA Jet Propulsion Laboratory) (Clement 2024)*

The MSR plan to bring samples back for detailed analyses on Earth also represents an opportunity to better understand how to implement backward PP of a restricted sample for the first time. There are significant challenges for developing requirements for restricted returned materials, which are made still more complicated by the ubiquitous and unavoidable dust on Mars. There are two types of dust involved in the MSR: aeolian (windborne) and subsurface (a result of the sample drilling process). The MSR mission must better define assumptions about the dust and its possible associated bioburden in order to accurately and effectively implement backward PP for the MSR mission and subsequently for the first crewed mission.

The risks associated with Martian dust can be managed by:

1. Operational constraints to avoid accumulation (e.g., limit time that covers/doors are open)
2. Minimizing transfer of accumulated dust (e.g., aseptic transfer systems)
3. Mechanical barriers (e.g., dust covers or nose cones)
4. Neutralization of potential bioburden (e.g., active or passive UV exposure to achieve bioburden reduction)
5. Design considerations based on modeling and analysis

Each of these methods permeate through every level of project development. Scientific evidence collected on Mars (chemical composition as well as physico-chemical properties of Martian materials) can aid in the assumptions used to estimate the biological load on Mars. Calculations and data from Mars can help refine those assumptions. For example, the National Academies' study on Japan Aerospace Exploration Agency's (JAXA's) MMX mission assumed that  $10^5$  cells per gram of Mars material was reasonably conservative. Shortly after that report was published, Sholes et al. (2019) published a study that estimated a maximum subsurface biomass on Mars and reported a global average of  $10^3$  microbial cells per gram in the top kilometer based on use of the abundant radiolytically-generated CO as an energy source and simulated biological sinks of CO into the subsurface. These and other studies will assist in the

estimation of biomass limits and potential risk, which allow us to make a more informed approach for various mission scenarios.

*The Need for Earth-Based Experiments to Inform Microbial Evolution on Planetary Surfaces (Chelsi Cassilly, NASA Marshall Space Flight Center) (Cassilly 2024)*

Spacecraft built in NASA cleanrooms are exposed to extremophilic microbes, which represent the greatest challenge for maintaining hardware cleanliness. Forward PP for landed robotic spacecraft is managed by stringent cleaning and bioburden measurement to limit the number of microbes present on the spacecraft at launch. However, when humans go to Mars, we will bring along billions of bacteria that are continually replenished. For example, human skin harbors bacteria, fungi, and viruses that include halotolerant and desiccation-resistant species (Sengupta et al. 2024). Furthermore, years of monitoring the International Space Station have demonstrated that astronauts change and influence the microbial populations present. Similar populations and microbial loads are expected to be aboard crewed vehicles destined for Mars. These microbes will be forced to reproduce in gradually changing environments—a perfect recipe for evolution. For instance, the potential for evolutionary change will begin upon launch when the microbes encounter new conditions during the months-long cruise to Mars. Landing and crew transfer to a habitat on the Martian surface will provide new pressures to which microbes must adapt. Further, due to general leakiness, venting, or extravehicular activities, microbes will escape into the immediate vicinity of the habitat. The induced environments surrounding the habitat may provide another opportunity for microbial evolution. Finally, these potentially modified terrestrial microbes may be transported elsewhere on Mars via wind or dust storms, potentially landing in an environment that is favorable for survival. Such microbial adaptation could have significant impacts on the crew and the science conducted on Mars. Thus, mitigation approaches for microbial release must be considered for crewed missions.

Preparatory campaigns for human missions must define: (1) What can we do before we go? and (2) What can we do while we are on the way? Current science knowledge must be harnessed to inform us of the potential risks of microbial evolution on Mars. Examples of long-term evolution experiments include those from the labs of Richard Lenski (*E. coli*) and Michael Baym (single mutations resulting in antibiotic resistance) (Lenski et al. 1991; Baym et al. 2016). No Earth-based simulated experiment can reproduce every aspect of a space environment, nor can we anticipate all unknowns. However, by drawing upon evolutionary science, we can study model systems similar to the expected environments, develop analysis models to predict potential outcomes, and prepare mitigation approaches to prepare for crewed missions.

## **Discussion and Summary**

PP is challenging to implement at every level, but to achieve the highest success, we must let science lead us. Science should inform the way we communicate with the public, the claims we make, and the risks we propose to take. It should also underlie the strategies we use for safely returning with Mars-origin samples to Earth. It should also guide the research we partake in to prepare ourselves (and society) for the unprecedented event of humans landing on Mars.

## **Findings**

1. NASA must be committed to keeping the public informed and encourage the science community to support bringing samples back from Mars for study on Earth. Appropriate communication strategies would equip the public with the necessary understanding to have well-informed opinions about NASA's goals. Thus, done well, these risk communication efforts should be mutually beneficial for the agencies and their stakeholders.
2. Science-led dust mitigation strategies will inform future methods and development for other sample return missions and future crewed missions.
3. When humans go to Mars, microbes will go with them and will be released into their environment. We do not know how microbes will adapt to life on Mars. Studies are needed to address such evolutionary changes to understand risks to crew safety as well as the science conducted on Mars.

### **3.5 Instruments and Tech Development**

(Section written by Christopher Temby, Agnostic Life Finding Association (ALFA); and Débora Dummer Meira and Matheus Correia Casotti, Federal University of Espírito Santo)

#### **Introduction**

The workshop hosted a panel to discuss “Instruments and Technology Developments” that need investment and development to better inform the risks related to PP for future crewed missions. Panel members and abstract contributors included Dr. Morgan Cable (NASA Jet Propulsion Laboratory), Dr. Jan Špaček (Firebird Biomolecular Sciences), Dr. Débora Dummer Meira (Federal University of Espírito Santo), Dr. Michael Hecht (Massachusetts Institute of Technology's Haystack Observatory), and Christopher Temby (Agnostic Life Finding Association (ALFA)).

By this point in the workshop, participants established general agreement that a high-priority scientific objective should be to search for an extant Martian biosphere before humans arrive, and the panel continued that line of thought. The panel discussion touched upon which techniques should be used to conduct a Search for (extant) Life (SFL). Due to the nature of the topic, no agreement arose regarding which instruments and/or biosignature targets should have priority in this SFL, but general mission approaches were summarized from the short conversation.

#### **Technical Content**

The arrival of humans, with their associated microbiomes, will contribute significantly to the amount of forward contamination on the Martian surface. A search for life on Mars is the only space endeavor that cannot wait, given the risk that human-associated biological contamination would hinder any subsequent studies of a tenuous Martian biosphere. The Mars Exploration Program and the Astrobiology community should prioritize a search for extant life (including indigenous Martian and introduced terrestrial/forward contamination) on Mars prior to human arrival.

This search for extant life needs to investigate the Martian near-subsurface ice, brine, and/or water, and characterize the geochemical context of astrobiological samples to inform observations (see Appendix A: Summary of Seminar 5). The instruments conducting SFL analyses ideally would (1) analyze high-confidence biosignatures to enable an unambiguous detection of life, (2) be able to analyze sufficiently large sample volumes to overcome sensitivity and signal/noise issues, and (3) provide measurements with sufficiently high sensitivity to determine with confidence whether or not biological materials can be detected in the samples [note that a negative result at one location does not mean Mars does not host an active biosphere at another location (Kminek et al. 2022)].

It was discussed that a suite of orthogonal detection techniques and strategies would be appropriate, each addressing high-confidence biosignatures in the ladder of life detection (Neveu et al. 2018). Temby indicated that polymers that support information storage and

transfer are an example of such a biosignature. Furthermore, the Polyelectrolyte Theory of the Gene (Benner and Hutter 2002; Benner 2017) describes how and why these informational biopolymers are required to enable Darwinian evolution, and why detection of polyelectrolyte informational biopolymers would be sufficient to provide a confident, unambiguous detection of life.

Addressing the second point (*the instruments conducting SFL analyses ideally would be able to analyze sufficiently large sample volumes to overcome sensitivity and signal/noise issues*), large sample volumes would potentially be garnered through use of in-situ resource utilization (ISRU) efforts. Currently, concepts for crewed missions include scenarios where extraction of tons of Martian ice/regolith would be used to manufacture propellant and provide human consumables. These operations will therefore see the acquisition of unprecedentedly large material volumes (100s cubic meters) from Mars, some of which (concentration from ~1,000L seemed plausible) could be used in life-detection approaches.

Regarding the third point (*the instruments conducting SFL analyses ideally would provide measurements with sufficiently high sensitivity to determine with confidence whether or not biological materials can be detected in the samples*), sample concentration and analysis techniques may be able to use the unprecedentedly large ISRU sample volumes to provide unprecedented sensitivity for astrobiological measurements. High levels of preconcentration may be required because a Martian biosphere should be expected to be very sparsely populated (reflecting the oligotrophic state of Mars). The subsequent measurements must be sensitive enough to confidently detect biosignatures in the most extreme and sparsely populated Mars-analog regions on Earth (Azua-Bustos et al. 2023).

Furthermore, given the potentially shortened timeline to assess a Martian biosphere before crew arrival, the team considered that it is insufficient to merely provide a “life” or “no life” result (like the Viking Labeled Release experiment). Therefore, any payload should: (1) begin studying the extant life in order to inform risks related to PP and crewed missions; (2) enable the observation of a “whole ecosystem,” as identified in NASA’s Civil Space Shortfall document ID:1601 (NASA 2024); and (3) enable the detection and monitoring of forward contamination to (a) avoid false positives, (b) attenuate the background noise to avoid false negatives, and (c) provide baseline forward contamination levels on Mars before and after human arrival (NASA 2024; STMD Shortfall ID:1590).

The development of advanced instruments and technologies is pivotal for NASA’s PP efforts and the success of future Mars missions. Instrumentation plays a critical role in enabling precise in-situ analysis, reducing contamination risks, and supporting both scientific discovery and human health. According to Spry et al. (2024), significant knowledge gaps remain regarding contamination control for human Mars missions, necessitating innovative approaches to monitor microbial presences and ensure compliance with stringent PP standards. Similarly, Chen et al. (2023) highlighted the Mars 2020 Mission’s robust contamination mitigation protocols, which demonstrated the importance of advanced bioburden reduction techniques for preserving the scientific integrity of returned samples.

Agnostic biosignatures are universal patterns or features of all living systems. A number of agnostic biosignatures and associated detection methods were mentioned in the panel discussion. The panelists also noted that technologies developed for life detection on Mars can be leveraged for subsequent missions to search for extant life elsewhere in the solar system. Mars is currently easier and less expensive to study than, say, the surface of Europa, and thus should serve as a “proving ground” for future water-world life-detection investigations. The following discussion includes instruments and technologies that the team thought should be prioritized and developed to facilitate a search for life on Mars, which will advance the closure of PP knowledge gaps (Spry et al. 2024).

Field-portable technologies, as Young et al. (2018) argue, have transformative potential in planetary surface exploration. By integrating geochemical analyzers and imaging instruments, these tools enable real-time, high-precision analysis of Martian environments, enhancing scientific outcomes during extravehicular activities. The focus on miniaturization and integration of instruments, emphasized by Morrison et al. (2024) in the development of the Miniature Total Organic Carbon Analyzer, underscores the importance of compact, efficient systems for space missions. These innovations reduce logistical burdens and ensure adaptability to the constraints of Mars’ environment, particularly in a mission concept where ISRU-scale sampling (discussed previously) is absent.

Sharma et al. (2024) further demonstrate the utility of multi-instrument correlation, which enhances the interpretive power of data collected in situ. This approach, combined with engineering advancements in robotics and automation discussed by Chien et al. (2024), creates a robust framework for deploying intelligent, adaptive systems capable of operating in the challenging Martian terrain. Such systems are essential for supporting both human and robotic exploration while maintaining strict PP standards.

Abercromby et al. (2024) identify Earth-independent technologies as a cornerstone for human Mars missions, emphasizing the need for durable, multifunctional instruments. This aligns with Klonicki-Ference et al. (2023), who stress the importance of defining environmental and sampling constraints early in mission planning to ensure instrument reliability and effectiveness. By addressing risks and dependencies during the design phase, NASA can optimize instrumentation for Mars’ unique challenges, fostering both exploration and sustainability.

## **Discussion and Summary**

Through multidisciplinary collaboration and continual innovation, NASA’s efforts in instrument and technology development not only advance PP, but also establish the technical foundation for sustained human and robotic presence on Mars. These advancements promise to unlock new scientific frontiers while safeguarding the integrity of interplanetary ecosystems.

The panel continued a discussion about the abstracts submitted to the Science and Planetary Protection in Advance of Human Missions Seminar October 30 to November 1, 2024 (on the theme of Instruments and Technology Developments). The panelists presented highlights from

the abstracts, discussed aspects of the technical content, and summarized a survey of the central points.

The search for extant life on Mars represents a critical yet underexplored frontier in astrobiology, particularly as human missions to the planet approach. Christopher Temby, President of the Agnostic Life Finding Association (ALFA), highlighted the need to prioritize this search, given Mars' potential as a habitat for microbial life due to its geological history, widespread subsurface water-ice, and confirmed presence of organic molecules. However, no mission since the Viking landers in 1976 has focused on direct life detection, largely due to interpretations of data from the Viking GC-MS, which reportedly failed to detect volatile organic compounds in the Martian soil samples. Subsequent studies suggest that no organics were detected due to the presence of contaminant chemistries in the sample. The erroneous conclusion that Mars holds no organic compounds delayed further investigation for decades, despite subsequent missions validating the presence of organics in ancient crater-like regions, according to Temby.

Temby emphasized the urgency of addressing PP policies and knowledge gaps, as crewed missions are planned for the next two decades and risk contaminating a potential Martian biosphere with Earth-origin microorganisms. Such contamination could obscure scientific efforts to detect indigenous Martian life and compromise PP goals. ALFA supports the development of the Agnostic Life Finder (ALF) (Špaček and Benner 2022), an innovative instrument concept designed to detect signs of extant life, including alien life that is independent of Earth's natural history and biochemistry. Temby said ALF highly concentrates and analyzes polyelectrolyte genetic biopolymers, which are universally recognized as biosignatures, potentially making it a critical tool to transform the field of astrobiology. Informed by discoveries in synthetic biology (Benner and Hutter 2002), polyelectrolytes, or charged information-storage biopolymers (like DNA or RNA) (Neveu et al. 2018), are believed to be required to enable Darwinian evolution and are therefore an agnostic biosignature. The Charged Information-storage Polymer Preparation System (ChIPPS) (Ricco 2021) is an example of an instrument designed to prepare these types of polyelectrolyte molecules for nanopore-based analysis from extremely small volumes of liquid.

As Temby presented to the panel, the ALF is a more robust technology designed to concentrate and isolate sparse polyelectrolytes from larger volumes of water. ALF is a concentration device that utilizes electrodialysis with porous membranes. It is designed to be a low-mass, add-on instrument to water mining operations on Mars, suitable for future ISRU technology demonstrations as well as large-scale ISRU projects (Heldmann et al. 2021). ALF's design integrates three key concepts: the "Lasagna Ice" phenomenon (Špaček and Benner 2021), ISRU infrastructure, and the Polyelectrolyte Theory of the Gene (PETOG). The "Lasagna Ice" concept leverages Mars' aeolian processes and mid-latitude glaciers as natural repositories for potential microbial records, akin to Earth's glacial archives. ISRU infrastructure, essential for long-term human survival on Mars, offers a unique opportunity to access subsurface ice for both water extraction and life detection. By aligning ALF's operations with ISRU activities, the system can monitor contamination risks while advancing astrobiological research, Temby noted.

PETOG underpins ALF's ability to detect genetic polymers as universal biosignatures. Using electro dialysis and advanced techniques such as mass spectrometry and metagenomic Polymerase Chain Reaction (PCR), ALF isolates and analyzes these polymers from melted ice, maximizing the chance of detecting sparse microbial populations. ALFA plans phased development of ALF, aiming for space-ready deployment by 2028, with initial testing in Earth analog environments like the Arctic.

ChIPPS and ALF are complementary technologies designed to analyze water samples for genetic biopolymers by utilizing different sample volumes. In order to acquire these Martian water samples, technologies to extract subsurface water need to be developed. A leading technology in this role is Honeybee Robotics' RedWater RodWell system (Mellerowicz et al. 2022). The development of this system, or a similar one, is vital for future Mars surface operations. Importantly, any drilling system to mine and extract water from the subsurface needs to also provide a sample acquisition and have a preparation process that controls or eliminates forward biological contamination and volatile loss. Given the recent motivation to conduct a search for life on Mars (National Academies of Sciences 2022), NASA should consider developing the aforementioned technologies in order to close PP knowledge gaps (Spry et al. 2024) and to enable a search for extant life on Mars and other water worlds.

In addition to uncertainties of extant life on Mars, NASA needs to close additional knowledge gaps (Spry et al. 2024) related to crewed exploration. The community needs to develop quantitative assessments of aeolian and hydrologic processes that facilitate the transport of microbial contamination. Additionally, to minimize both forward and backwards contamination, robust mitigation approaches need to be developed, including orthogonal sterilization techniques incorporating multiple biocidal factors (Schuerger et al. 2019).

It is understood that, over geologic timescales, aeolian processes are sufficient to distribute material, including biological contamination, across the entire Martian surface. Therefore, pre-human and initial human missions need to quantify microbial contamination abundances and spreading rates. This can be done by conducting Earth-based research, developing advanced models and incorporating in-situ measurements from deep space, lunar, and Martian test locations. Additionally, enhanced sterilization techniques are needed. These will reduce costs and simplify systems for sample-return missions. Several techniques are being developed, including a highly cost-effective and efficient radioisotope-based sterilization system capable of in-situ sterilization.<sup>2</sup> Including this in sample-return operations could be vital for providing deeper sample penetration to ensure a thorough sterilization process. This type of sterilization technique is passive because no external power is required, and isotopes like Cs-137 have long half-lives and emit ionizing radiation continuously during their operational life.

Earth-based research is needed to understand how microbial contamination can exist and spread on the Martian surface and subsurface. This work needs to characterize microbial survivability and evolution within the multiply-biocidal environment (Schuerger et al. 2019). Schuerger maintains that single-[biocidal]-factor experiments are often preferred for simplicity,

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<sup>2</sup> <https://www.planet.enterprises/post/savemsr>

whereas it is likely that the “true” biocidal natures of the Martian surface and interplanetary space are currently being underestimated because experiments are limited, in general, to single-factor experiments. A recommended technology that can facilitate more robust Earth-based research is the Multi-Planet Surface Simulator (MPS2) (Mitra et al. 2024). This technology is designed to improve Earth-based research to understand the conditions expected on planetary environments and can be used to simulate how microorganisms interact with the Martian surface’s geochemical conditions. The MPS2 technology is designed to allow for: (1) the ability to conduct a chemical reaction after the attainment of equilibration of the reactants with the surface environment, (2) the continuous monitoring of numerous different chemical components during the course of the reaction without disturbing the experimentation setup, and (3) the ability of the same chamber to be adaptable to simulate the surface conditions of different planetary bodies. The research facilitated by MPS2 should consider the interaction between microbes and spacecraft surfaces, cavities, and (radiation) shadows.

In conjunction with this Earth-based research, improved aeolian transport models need to be developed. These models would integrate in-situ measurements from the local and regional environments. The panel members were not experts in this field and thus do not have specific instrument or technology development recommendations. However, to provide quantitative data for the spreading rate models, the team suggested that an initial human mission could deploy contamination monitoring stations at multiple radii from a landing location. This would require extremely sensitive observations with a capability to identify and monitor constituent species and potentially individual organisms on multiple temporal and spatial scales. Advanced aeolian models must be able to quantify microbial contamination abundances and spreading rates across the Martian surface.

PP is fundamental to space exploration, aiming to prevent harmful biological contamination between Earth and other celestial bodies while enabling the discovery of extraterrestrial life, should it exist. Matheus Correia Casotti (Federal University of Espírito Santo) emphasized the challenges of managing contamination risks, particularly for human missions to Mars, where guidelines remain incomplete, despite established protocols for robotic missions. Collaborative efforts by COSPAR, NASA, and the International Mars Exploration Working Group aim to bridge these gaps by advancing microbial monitoring and contamination control.

Traditional culture-based microbial monitoring methods, unchanged for over 50 years, while providing a reliable and robust assay of cleanliness, fail to capture the full diversity of microorganisms. Modern -omics and molecular techniques, however, enable precise detection through microbial “fingerprints,” identifying species-specific markers and improving contamination control via personalized sterilization methods. Concurrently, the miniaturization of scientific instruments, such as mass spectrometry (MS) and nuclear magnetic resonance (NMR), has revolutionized planetary exploration. These compact, efficient tools potentially allow real-time, high-sensitivity analysis of microbial signatures, enhancing PP efforts.

Casotti explained his ideas and project in the abstract titled, “*From equipment miniaturization to universal microbial testing: a real-time, personalized, and portable planetary protection.*” (Casotti 2024) His research group (led by Dr. Débora Dummer Meira) operates at the intersection of

Genetics and Biochemistry and has recently spearheaded the establishment of an Astrobiology research initiative at the Federal University of Espírito Santo, with the strategic objective of securing financial support to propel their investigations forward. Equipped with groundbreaking ideas, they now seek partnerships to transform these conceptual frameworks into tangible scientific advancements.

Dr. Meira explained that the group's biggest challenge in bringing this project to life is the miniaturization and coupling of equipment in the series. Additionally, it is necessary to collect material directly from the soil or from cavities protected from ultraviolet rays; therefore, a drilling probe will be required. The idea of coupling a DNA sequencer, NMR, and MS to chromatography equipment is essential for accessing a large amount of paired materials (and information) in real-time, whether to identify proteins, DNA, metabolites, or volatile compounds.

The central question guiding the effort is: *"If viable microorganisms cannot be obtained, could their presence be estimated through the signatures they left behind that have been preserved over time?"*

One of the main challenges is the coupling of sensitive equipment in series. Moreover, material must be collected directly from the soil or from cavities shielded from ultraviolet rays, necessitating the use of an efficient drilling rig to achieve this goal. The exploration methods used in oil and pre-salt reserves, along with the technologies developed so far, also serve as a source of inspiration for this project. The concept of creating a robot and coupling equipment such as a DNA sequencer, nuclear magnetic resonance, and mass spectrometry to chromatography equipment is fundamental to access a large amount of paired materials (and information) in real-time, whether to identify proteins, DNA, metabolites, or volatile compounds. The project aims to develop a robotic system capable of coupling these instruments for real-time analysis of biomolecular signatures from soil samples, with key challenges including equipment miniaturization, direct sampling from UV-shielded cavities, and the detection of preserved microbial traces under Mars-like conditions.

The team recognizes that microorganisms on Mars might have developed strategies to stabilize their structures or modify their cell cycles to ensure successful reproduction. The accuracy of DNA replication and repair mechanisms may be compromised since, for example, high pressures can cause DNA to adopt conformations not typically observed at lower pressures. Additionally, high pressures can slow down cellular activities, including growth. However, microorganisms in such environments often exhibit slow growth rates as an adaptation to both the pressure and the limited availability of nutrients, where their metabolic pathways are precisely adapted to balance energy requirements with extreme conditions, supporting survival and reproduction over extended periods.

Proteomics and metabolomics are pivotal for identifying microbial communities and studying their niches in extreme environments like Mars. MS can generate proteomic fingerprints by analyzing peptides and proteins from planetary regolith, providing reliable identification when compared to reference libraries. Additionally, combining proteomic data with environmental factors would provide insights into microbial survival and adaptation. Metabolites and microbial

volatile organic compounds (VOCs) further enhance analysis, with VOC profiling offering high precision in identifying unique metabolic signatures and characterizing biomass. Integrating NMR and MS streamlines non-invasive, cost-effective protocols for microbial studies.

These advancements extend to metabolic pathway analysis and synthetic biology. Casotti highlights the potential for engineering biosensors based on genetic or protein sequences to detect unique environmental metagenomes, offering compact and portable tools for real-time microbial detection on Mars. Integrating bioinformatics and artificial intelligence enables automated analysis of microbial signatures, supporting PP and advancing astrobiological research.

Developing these tools requires a multidisciplinary approach, ensuring their efficiency, portability, and durability in Mars' harsh environment. These innovations not only protect planetary ecosystems, but also facilitate resource utilization and scientific discoveries, expanding the scope of space exploration and addressing critical challenges related to microbial contamination and extraterrestrial life detection.

Finally, Casotti noted that the analysis of any of these biological signatures must also consider the changes that occurred over the years pre- and post-collection, as well as the inhospitable conditions of Mars.

## Findings

1. Contamination by terrestrial microorganisms associated with future crewed missions could obscure signs of Martian life.
2. Pre- and post-mission monitoring requires sensitive detection stations across multiple wavelengths to establish contamination baselines prior to human arrival.
3. Advanced sterilization techniques must integrate orthogonal methods (multiple biocides, passive radioisotope sterilization) for robotic missions and sample return efforts.
4. Priority should be given to the search for extant life in Martian ice, salts, and subsurface water before sending humans.
5. High-confidence biosignatures may focus on unambiguous signals (e.g., informational polyelectrolytes like DNA/RNA as defined by the Polyelectrolyte Gene Theory).
6. The use of ISRU involving ice/regolith to concentrate hundreds of liters will provide a strategy for analyzing large sample volumes, improving sensitivity and signal-to-noise ratio.
7. Detection targets comparable to Earth's oligotrophic regions enhance sensitivity to prevent false negatives.
8. Universal life patterns (agnostic biosignatures) do not depend on terrestrial biochemical affinity and serve as a foundation for future missions beyond Mars.
9. The simultaneous use of informational polymer analysis, mass spectrometry, metagenomics, and other techniques maximizes the robustness of life detection and Martian analysis.
10. Concentration agents—such as ALF and ChIPPS—enable the isolation of polyelectrolytes from large volumes of extracted water.

11. Integration with propellant and potable water production operations transforms ISRU into a scientific sampling platform.
12. Advances in portable instrumentation will facilitate real-time analysis using geoanalyzers and integrated in-situ cameras on the Martian surface.
13. Multi-instrument correlations involving data cross-referencing and adaptive robotics will advance in-situ operations on Mars.
14. Terrestrial planetary simulators—such as MPS2—replicate Martian geochemical and photoradioactive conditions, enabling the study of microbial survival and dispersion in that environment.
15. Miniaturized -omics strategies—such as Next Generation (DNA) Sequencing (NGS), NMR, and MS—coupled with chromatography systems for serial analysis of proteins, metabolites, and VOCs directly from in situ Martian soil samples may elucidate unique biological signatures.
16. Synthetic biosensors based on bioengineered systems to detect specific genetic or proteic signatures in real time, supported by AI for automated analysis, will contribute essential biological insights to support human survival on Mars.

### 3.6 Science Investigations

(Section written by Becky McCauley Rench, NASA Headquarters)

#### Introduction

Three panelists were invited to discuss what kinds of measurements we can make prior to and during crewed exploration and the types of scientific investigations that can be imagined. The panel included:

- Dr. Mary Beth Wilhelm, a Research Scientist at NASA Ames Research Center with background in organic geochemistry specializing in how organic biosignatures may get preserved in the Martian environment and the instrumentation one may be able to use to detect such biosignatures
- Dr. Laura Fackrell, a Staff Scientist at Rhodium Scientific with a geochemistry background specializing in sustainable space agriculture
- Dr. Christopher Carr, a Professor at Georgia Tech who runs the Planetary eXploration Laboratory and specializes in integrating commercial methodology and instrumentation to support single molecule detection

Dr. Wilhelm opened the panel with a short presentation, sharing the white paper report from the Biosignatures Standards of Evidence Workshop (2021) supported by the Network for Life Detection (NfoLD) Astrobiology Research Coordination Network.

#### Technical Content

*Organics.* Understanding of the organic history of Mars is still immature, and we need high-level understanding both for astrobiology and PP, as well as to feed forward into successful crewed exploration. There needs to be a greater understanding of the organic variability on Mars, both past and present, with current estimates varying widely. MSR will help understand the surface and the presence of organics more completely. Such objectives complement what needs to be known about astrobiology on Mars and what is useful for successful crewed exploration.

*Contamination.* Gaining more information about organics on Mars will feed into an understanding of acceptable levels of contamination. In laboratories on Earth, scientific analyses can be completed, despite potentially high sources of organic contamination. On Mars, we expect the background levels of organics to be lower, so there is a need to understand that at each step and then implement best practices to screen out such contamination, rather than trying to keep contamination to zero. Scientists also want to understand what will happen with that contamination and how it may travel from a habitat to be distributed locally or globally. Understanding the geology of Mars' surface is important for both astrobiology and crewed exploration. For example, understanding the salinity and soil conditions on Mars will provide insights into what any potential Martian life would have evolved with, but also has implications for future human use of Martian regolith for in-situ agriculture methods.

*Mars Dust Composition.* While there is some knowledge about the composition and behavior of fine particles on Mars, we do not yet have sufficient knowledge to understand the potential impact of those materials on equipment and crew on Mars. On the Moon, we learned in the Apollo era that the dust was very different than on Earth, which had impacts on degradation of spacesuit components. Similar knowledge about Martian dust is needed so we can keep crew and equipment safe and functional. For example, understanding of particle distribution size on Mars is incomplete. While we know that weathering by dust is more similar to Earth than the Moon, there is more to learn since Mars has an atmosphere.

*Lunar Precursor Work.* There is value in the work that can be done on the Moon as a feed forward and preparation for improving engineering performance on Mars. The limits of engineering can be pushed to see how far the performance of minimizing leaks from space suits and habitats, and the monitoring of that, can be done on the Moon. This is crucial information to find balance between the engineering costs to minimize contamination and identifying the most critical areas to reduce for maximal impact. Knowing how far contamination actually travels from lunar habitats and spacesuits is important to gain a more accurate understanding of what may be observed on Mars, while acknowledging that no analog is perfect. This data could be used to improve Mars' global circulation model accuracy and further develop our understanding and expectations for distributing contamination, but this is a limit on the lunar environment with its lack of atmosphere. There is currently very little empirical data to ground-truth models of potential contamination transport on Mars. Additionally, the lunar environment could be an important test case for working with low biomass samples and the challenges with materials that are difficult to extract organics from. There is potential to conduct comparative testing on the Moon where two locations are studied, one with crew and one with robotics only, and gather data to understand the differences.

*Human-Robotic Partnership.* Crewed Mars exploration opens up possibilities that are difficult to manage with robotics alone. Ultimately, both crew and robotics have a role to play in exploring Mars, and that partnership, if developed thoughtfully, is a powerful one. Humans may be able to go places that are difficult for robotic explorers to get to, and robots can access areas that may be more sensitive for PP or science goals to potential human contamination. While it may not be advisable to have humans access the areas that should remain pristine right away, it may be possible to continually expand the areas where crew can work as more knowledge is gained and there is a better understanding of the potential risks. Additionally, humans may bring dexterity and the capability to process greater quantities of sample as compared to robots. Deep drilling is an example where human crews can significantly improve probability of success. There are architectures that can be developed that leverage both the value of crew and robots, and it is best that these conversations about potential contamination take place early in the mission architecture development to protect the field sites and samples as best as possible. There is value to having humans locally controlling robots. A better understanding of contamination and what we are trying to protect will assist us in knowing when mitigations are needed and what the thresholds look like. Factors that must also be taken into consideration are the indirect benefits of crewed activities on the crew's physical and mental health; this is

something that comes up when growing plants because, while you can have a robot do it, there are many indirect benefits to having the crew care for crops.

*Knowledge Base of Crew.* Unforeseen circumstances are bound to arise when exploring Mars. There is a time delay that is significant between Mars and Earth that makes real-time guidance on protocols more difficult than that experienced on the Moon or on the International Space Station. Large Language Models (LLM) may be of use to provide real-time guidance to crew when making decisions about science protocols. Additionally, some data analysis work could be done using artificial intelligence tools. Use of microdisplays and interfaces to support crew and expand their toolset will be important for mission success.

*Variety of Stakeholders.* One of the biggest challenges to Mars exploration is not technical, but rather lies in advocacy and diplomacy amongst academic, commercial, Government, and international stakeholders. Finding a path toward a common interest and protection of Mars is key. Mars exploration will provide a profound discovery for humankind, regardless of whether there is life on Mars or it is uninhabited, as both are amazing discoveries. Once there is widespread terrestrial contamination on Mars, there is no returning to pristine world status. In addition, human safety must be prioritized over PP, and the risks associated with terrestrial microbial survival and replication weighed, which may be impossible on the surface. The timescale of contamination and the factors that influence it must be understood.

*Instruments.* Dr. Carr discussed his group's Single Molecule Analysis of Life and Liquids (SMALL) instrument that uses three instruments to interrogate a cell for various cellular structures. Dr. Wilhelm discussed the instrument being developed in her lab to integrate and automate methods to investigate lipid biomarkers. The path to developing instruments is a long process that takes many years. Additionally, we want to make sure there are sufficient materials to test the level of accuracy of such instruments to answer the stated scientific objectives. We should take advantage of all opportunities to get payloads to Mars and expand our abilities to land on Mars, including cooperation and partnerships with the commercial space sector.

## **Discussion and Summary**

The panel of experts discussed scientific investigations for crewed Mars exploration, including understanding organics, contamination, Martian dust, utilizing lunar work, optimizing human-robotic partnerships, and addressing challenges like communication delays and stakeholder diplomacy. Panelists and workshop participants discussed some of the most important challenges and considerations for Mars exploration we need to address prior to crewed exploration. Overall, there are gaps in our knowledge and understanding that should be filled in preparation for human exploration. Some of those gaps can be filled through research and technology development here on Earth, while others require more data and research on Mars.

## Findings

When looking for life, researchers are interested in making a wide array of measurements and want to prioritize those measurements that provide high confidence in the conclusions. There is significant overlap between search for life and PP, and much work can be done in supporting areas of mutual interest. Researchers should:

- Expand our understanding of organics on Mars, including types and quantities
- Understand contamination based on what would be considered acceptable levels, how it may be transported, and what can be done to minimize contamination through engineering and operational constraints
- Utilize the Moon as a potential testing ground that can feed forward to Mars, albeit not as a perfect analog
- Obtain more information about Martian dust that will prevent unwanted impacts to crew and equipment on Mars
- Optimize the complementary skills that humans and robots bring to the table in Mars exploration so those skills can be maximally utilized to attain our scientific and exploration goals

Mars' communication delay prompts a need to create and rely on more local resources for crewed exploration. Additionally, one of the primary challenges is not technical, but rather diplomacy and advocacy amongst all stakeholders toward a common goal. Instrument development often takes many years, and various opportunities for payload delivery should be pursued.

### 3.7 Scenario Exercise: Crew on Mars

(Section written by Andy Spry, NASA Headquarters)

#### Introduction

Attendees were divided into small groups to complete a scenario exercise considering the topic, “Science Operations on the First Crewed Mission to Mars.”

As a well-understood location, the target landing site for the exercise was at Jezero Crater, as we have sufficient data about it, and it contains enough scientific interest. However, its choice should not be construed as a statement of intent by NASA.

In the exercise, science payload was delivered predominantly in a cargo mission one full launch window ahead of the crew, affording opportunity to use drones/rovers to survey/image the landing site and beyond before the crew arrived, increasing travel efficiency and enabling pre-planning of research destinations/tasks. More “sensitive”/time-limited science payload could be delivered with the crew.

It was assumed that this was an all-up mission: everything needed for crew landing and the return to orbit was taken to the surface as part of the mission (i.e., no ISRU requirements for fuel, etc.). Visual representations of both single- and multi-lander concepts for the start of the crewed phase of the mission were included for orientation, as well as where a Zone of Minimum Biological Risk (ZMBR) was established (notionally positioned in the center of the Jezero Crater), where crew had no PP-based operational constraints (i.e., no harmful contamination will occur, but also where no Special Regions/Mars extant life candidates were present). This was defined by an ellipse centered on the crew landing site, dimension minimum 2km from the landing site to the ellipse boundary, and ellipse major axis: minor axis ratio was 3:2, oriented to ESE-WNW (the prevailing wind direction).

Participants were given the following equipment/capabilities for the mission:

- A pressurized rover with crew living accommodation (10kph max, battery range 400km but with 20km “walk-back” safety constraint to the landing site)
- Two surface crew, equipped with planetary surface Extra-Vehicular Activity (EVA) suits
- Two robotic rovers (solar-powered)
- 2000kg of science payload delivered to the landing site, including instruments, sampling devices, consumables, drones, refrigeration, and transportation containers
- A base camp/landing site with power, the Mars Ascent Vehicle (MAV) [for End of Mission (EOM) return to orbit], fuel, and food depots (i.e., everything needed for survival and return to orbit).

The Mars Transfer Vehicle remained in Mars 1 sol elliptical parking orbit (~250 - 33,000 km) with two orbiting crew/comms/remote imaging capability aboard. (This was also the vehicle for return to Earth at EOM.)

The mission concept allowed for three science sorties of five days each beyond the limit of the ZMBR. Day-to-day science activities were also permitted within the ZMBR. An 8-hour science workday was used for planning, which included EVAs (max 16) and traverses between study sites. However, other robotic devices could operate autonomously 24/7 and/or with support from orbiting crew and/or surface crew.

It was made clear that COSPAR guidelines for crewed missions continue to apply [no crew access to Special Regions; pristine samples to be considered Category V (restricted) sample return until after return to Earth, etc.], and the maximum total return sample science payload mass was 100kg, including primary containers.

## **Discussion Topics**

With the overall goals of the workshop as a backdrop, the participants were asked to consider the following question set as prompts to their discussions:

1. With Mars Exploration Program Analysis Group (MEPAG) Goals (from the Goals Document, provided as additional information) in mind, what investigations/science campaigns would you conduct on a first crewed Mars mission? What does this campaign need to look like (recon., early experiments, EVAs, returned samples)?
2. Suppose PP constraints meant that EVAs could not be permitted, and all the operations had to be conducted from within the pressurized rover. How would that change the mission?
3. What if return sample payload mass constraints were relaxed to allow 400kg? How would that change the mission?
4. What if science payload was reduced from 2000kg to 500kg? How would that change the mission?
5. What does planning the crewed mission science reveal about what is needed from earlier robotic missions?

The groups received guidance that suggested 80% of their time should be spent on Question 1, with the remaining 20% effort spent on Questions 2-5. Groups were instructed to record any assumptions made in generating each answer.

## **Breakout Discussion**

Overall, the discussion highlighted the need for a comprehensive, multi-faceted approach to science on the first human mission to Mars, focusing on the unique combination of human and robotic capabilities, advanced technologies, and a commitment to PP. All groups anticipated utilizing data from MSR as a key input to planning for the first crewed mission to Mars, emphasizing the importance of pre-mission planning, precursor activities, incorporation of available technological advancements, and the unique capabilities humans bring to the endeavor.

The bulleted list below (unprioritized) summarizes the conversation related to the science goals considered, based on the breakout groups' discussion of the scenario.

## Science Goals and Campaigns

- **Leveraging Existing Data:** The team stressed the need to utilize pre-existing data, particularly from robotic missions, to inform mission planning and prioritize research objectives.
- **Pre-Survey and Refugia:** Pre-mission surveys should focus on identifying potential life detection/refugia near the landing site that are not only science targets, but also could shield any terrestrial microorganisms released from the human mission.
- **Habitat Architecture and Contamination Mitigation:** The team advocated for studying the impact of mission architecture/hardware and exploring methods to minimize the transfer of human-associated materials to the Martian environment (e.g., ground covers, clean room “tacky mat” techniques).
- **Debilitated Crew Ground Tests:** Conducting ground-based experiments with simulated Mars conditions, including a period of crew adjustment, was suggested for assessing human functionality and scientific capability to maximize the productivity of the short time on the Mars surface.
- **Initial Sample:** The team advocated for caching a sample from the surface as soon as the crew landed, both as the biological control and as a contingency (early departure) sample.
- **Tiny Robots with Labs-on-a-Chip:** Deploying small, sterilizable robots equipped with labs-on-a-chip for rapid sample collection and analysis was identified as a significant advantage, offering greater flexibility and speed.
- **Sample Encapsulation:** Developing robust methods compatible with PP for encapsulating and returning samples from the crewed mission was deemed essential.
- **Crew Analysis:** Identifying how a human body changes/adapts to Mars conditions (low gravity, radiation, circadian rhythms, magnetic field) should be measured by daily blood collection.
- **Helicopters for Environmental Sampling:** Utilizing small helicopters with cameras and sample collection capabilities would allow for rapid scouting of the environment both for future crew exploration and for collection of smaller, targeted samples.
- **Subsurface Ice Exploration:** Prioritizing drilling for subsurface ice to investigate life signatures was advocated. The team highlighted the value of having human crew present for adaptability and troubleshooting during drilling operations to the necessary depth (several meters).
- **Pre-EVA Robotic Work:** The team recognized the potential for robotic systems to collect initial samples and perform preliminary tasks before crew arrives and/or while the crew adapted to Martian conditions.
- **Forward Contamination Monitoring:** A comprehensive program for monitoring and quantifying forward contamination was essential, including regular sampling of regolith, suits, and equipment.
- **Volatile Analysis:** The importance of in-situ volatile analysis was stressed, recognizing the complexity of trying to do that in (aged) samples after Earth return.

- **Low-Mass Terrestrial Technology:** The team suggested exploring/exploiting low-mass technology developed for terrestrial applications (e.g., military and medical device industries) for use on the Martian surface.
- **Samples Acquisition Planning:** Advanced planning was advocated to ensure samples of highest value were acquired (e.g., from caves, recent impact craters), with appropriate triage for analysis/return.
- **Crew-Driven Sample Processing:** Humans can reduce contamination risk during sample processing compared to robotic systems.
- **Astrobiology Experiments:** The team proposed conducting in-situ astrobiology incubation experiments and "set-and-forget" experiments that could be left behind, such as plant growth demonstrations in Martian regolith.
- **Instrumenting a Site:** Humans could instrument an entire site more effectively and to a greater extent than robots. The team proposed long-term weather stations, multiple seismometer stations, and subsurface detectors for continuous monitoring.

### Impact of Crewed EVA Prohibition

The question of how more rigid PP constraints (in the form of the EVA prohibition) would affect the mission prompted the response that decisions about mission architecture need to be determined far in advance so the appropriate technologies can be developed to allow for successful science operations. Groups commented that it would still be possible for robotically collected samples to be delivered to the habitat while protecting the environment (e.g., like the double-wall isolator proposed for the Mars sample receiving facility).

Others in the team challenged the need for such a constraint at all, pointing out that, for forward contamination concerns, the risk may be acceptable based on the harsh environmental conditions on the Martian surface. Although the Martian biocidal environment is not a 100% lethal option for killing terrestrial microorganisms, it may be acceptable to our science goals. If the backward contamination concern is limiting EVA, it prompts the question: "*Why send humans in the first place?*" If PP constraints result in no EVAs, then it limits the operations to robotically-collected materials that will be collected and packaged for return. This would shift the science to be more on human-factor experiments and environmental studies within the pressurized rover.

Still others in the team pointed out that the advantage of being on Mars is to shorten the communication delay and take advantage of human dexterity/laboratory/decision-making on-site. Even when eliminating the human dexterity in sampling, we can still have astronaut technicians analyzing samples in the pressurized rover and do much more science in situ. Should it be available, humans with Neuralink/similar human-robotic interfaces would be able to use that enhancement for precise robotic operations.

### Impact of an Increased Sample Return Mass

If the returned sample mass was increased, the team saw the potential to collect a wider range of samples, including swabs and wipes for microbial analysis and enrichment cultures. More

regolith (e.g., for plant growth analysis) and more variety of geologic samples could be added. Intact (as opposed to partial) cores could potentially be viable.

### **Impact of a Reduced Science Payload**

If science payload was reduced from 2000kg to 500kg, the team noted this would change the capability of the lab facilities at the surface. Responses included reducing the mass of various instruments but still including specific capabilities [e.g., bringing an ExoMars-type ablatable mass spec, some kind of wet chemistry, and X-Ray Diffraction (XRD)]. However, it was noted that mass reduction comes with other problems: the smaller the sample, the harder it is to keep it clean, and small instruments with small sample sizes require short sample pathways. However, other technologies may miniaturize effectively, such as Fourier Transform Infrared Spectroscopy (FTIR).

One breakout group noted that a crew habitat would probably provide sufficient protection for commercial off-the-shelf hardware; radiation hardness of instruments would become less important than in previous robotic missions.

Another strategy suggested the crew work on sample concentration to get around detection limits. This is something that crew could do more effectively than robotic systems.

Sample up-selection was noted as another advantage of humans on Mars. If the capability to process or return an entire lot of samples was reduced, the crew could select the few most important samples.

Changing the focus from in-situ experiments to bringing back samples is another strategy the team suggested for the reduced mass version of the scenario. In this case, keeping the deep drill capability is seen as essential; ideally, the ability to drill from surface to several meters. While 1m shields most of the radiation, drilling deeper is better for protected samples.

### **Implications for Precursor Missions/Technology Development**

The key implications for precursor missions and future technology development were identified as follows:

**Sample Return Mission Data:** The data from a sample return mission from Jezero Crater (or the actual landing location, if different) was viewed as essential in informing the requirements for the crewed mission.

**Technology Development and Demonstration:** Long timelines are required to develop new technologies for Mars deployment. Precursor missions would be invaluable for testing and validating key technologies, such as lab-on-a-chip instruments; helicopters with miniaturized cameras and sampling; detectors of specific biosignatures, such as hopanoids; and crew health strategies, such as microbiome reseeded.

**Dust Mitigation:** Analyzing the dust–behavior, lift, transport, contamination of the EVA suits, chemical composition, and hazards to astronauts–is needed before launch.

**Robotic Life Detection:** Multiple members of the team considered that the robotic search for and study of extant life should be continued before humans arrive.

### **Key Takeaways From the Scenario Exercise**

- **Humans as Adaptable Scientists:** The team stressed the unique advantages that human crew offer—including adaptability, problem-solving, and decision-making capabilities—over robotic mission alternatives.
- **Balancing Technology and Human Capabilities:** Developing and deploying the right combination of robotic systems and human expertise is key to maximizing scientific return in the constrained mission environment.
- **Early Planning and Technology Development:** It is crucial to plan early and invest in developing the necessary technologies for both the pre-launch, cargo deployment, and crewed phases of the mission.
- **Prioritizing Planetary Protection:** Maintaining a robust approach to PP will be essential for the success and sustainability of future missions.

### **3.8 Crew Perspective from NASA Astronaut Kate Rubins**

(Section written by Erin Lalime, NASA Goddard Space Flight Center)

Dr. Kate Rubins, a NASA astronaut who has spent more than 300 days in space and has extensive space suit design experience, hosted a question-and-answer session on science and PP needs from a crew perspective. She described working in a spacesuit as “putting on some oven mitts and some roller skates and trying to do neurosurgery” when describing the bulky suits and decreased dexterity. She pointed out that tools used by astronauts during EVAs must be specially designed to be manageable. When asked if suits for Mars EVA would be less bulky, Dr. Rubins said that many of the same design considerations would be driving a Mars EVA suit, including internal pressure against the low-pressure Mars atmosphere, the ability to reject heat, and the potential need for additional layers to protect the suit from the impact of Mars dust.

Mars dust is a concern for crew health, impact on mission hardware, and transport of contamination. Dust transport from Mars weather (dust storms) as well as human movements (dust disturbed during land, roving, or EVAs) needs to be considered. Microbial release from spacesuits could come from existing leak rates, which could be addressed in the engineering of spacesuit design. Handling of the spacesuits inside the habitat environment would be an additional source of contamination transfer due to microorganisms transferred to the exterior of the spacesuit. To understand the potential impact of human movements on contamination transport, Dr. Rubins advocates for metagenomic studies during lunar exploration to measure the footprint of human exploration on the lunar surface in preparation for Mars exploration.

On the topic of crew capabilities compared to robotic capabilities, she pointed out that robots can be precise but have limited task sets and can require significant preparation before use, so they will likely be slower and not as flexible in decision-making relative to crew EVAs for now. Fine dexterity robots may be applicable in something like a glovebox inside the habitat, to augment fine dexterity during an EVA, or as independent units accessing special regions that have more stringent contamination control environments.

## 4. Conclusions and Next Steps

The Science and Planetary Protection in Advance of Human Missions workshop further identified science priorities for robotic missions, informed the development of PP guidelines for crewed missions, and supported the development of a framework for contamination control for a reference architecture. With more than 120 members joining the seminar and over 50 members attending the workshop, a broad set of scientific and engineering technical considerations were captured representing commercial, academia, Government, and international stakeholders.

The detailed topics from this workshop included identification of potential exploration goals on Mars and the ability of analog environments to serve as precursors, an assessment of Mars environments and terrestrial biology requiring further study, and flight instrument and technology developments that could fill knowledge gaps within a near-term and realistic development cycle. Integration of a broad set of stakeholder interests throughout the mission life cycle and the reinforced need for precursor missions were the two predominant conclusions that resulted from this workshop.

Compared to a standard mission to the International Space Station or a mission planned to conduct Lunar surface science, it was recognized that many more complexities and associated stakeholders would be necessary to plan and operate a successful Mars crewed mission. As a result, this group continued to reinforce this messaging with the need for engagement throughout the mission life cycle to include development and early formulation through to operations. To begin, the mission design needs to consider a common exploration risk posture that is balanced with evidence-based criteria to develop a risk-driven and case-assured implementation approach. As we move into operational phases, a feedback loop is essential to include members of the science, operations, engineering, crew health and performance, and PP communities. Both comprehensive planning and continued learning and adaptation were key takeaways from this workshop. For comprehensive planning, the need for a multi-faceted integrated approach ensuring science objectives, technology development, crew safety, and PP protocols were all addressed as part of the development and design cycle was identified as critically important. From the operations phases, the need for continual learning and adaptation based on lessons learned from the missions' activities was highlighted, given the constant data gathering and analysis that would be occurring.

One example of the type of coordination and feedback activities that was discussed in detail was how analog environments could be used by the community to not only advance the scientific knowledge base, but to be leveraged to develop interface frameworks between studies and disciplines. The workshop concluded that the science value of these analog sites would be to verify microbial adaptation and stressor models to better integrate the modeling efforts in the design of experiments needed from these analog sites. Establishing a common repository and a working group were two of the interfaces that were identified to help work towards a framework of cross-correlating studies and developing standardized approaches to future data collection.

This workshop continued to reinforce the need for precursor missions to characterize Mars and determine the presence or absence of human-affective biohazards from the Mars environment,

ideally before crew arrives on the surface (DeVincenzi et al. 1991, NRC 1992, Criswell et al. 2005, NRC 2002, NRC 2006, Kminek et al. 2022, Race et al. 2008, NASA NID 8715.129). Mars weather, landing site characterization, and pristine science were the three drivers discussed in this workshop, as follows:

- **Mars weather.** Mars weather observations are necessary to obtain the fidelity of models needed to verify relevant contamination transport scales of concern, capturing organic and microbial associated particles. Meaningful observations would include both localized and global transport.
- **Landing site characterization.** To enable the maximum science return, a landing site contamination forward PP assessment would be necessary to mitigate and control any potential harmful contamination impacting future science investigations, as well as to map out those future science investigations.
- **Pristine science.** Both a localized and global harmful contamination forward PP assessment should be conducted to ensure that sensitive science needs are understood prior to crew landing on Mars. This assessment should include the impact of crew contamination on Mars and a plan to mitigate any potential risks in preparation for crew.

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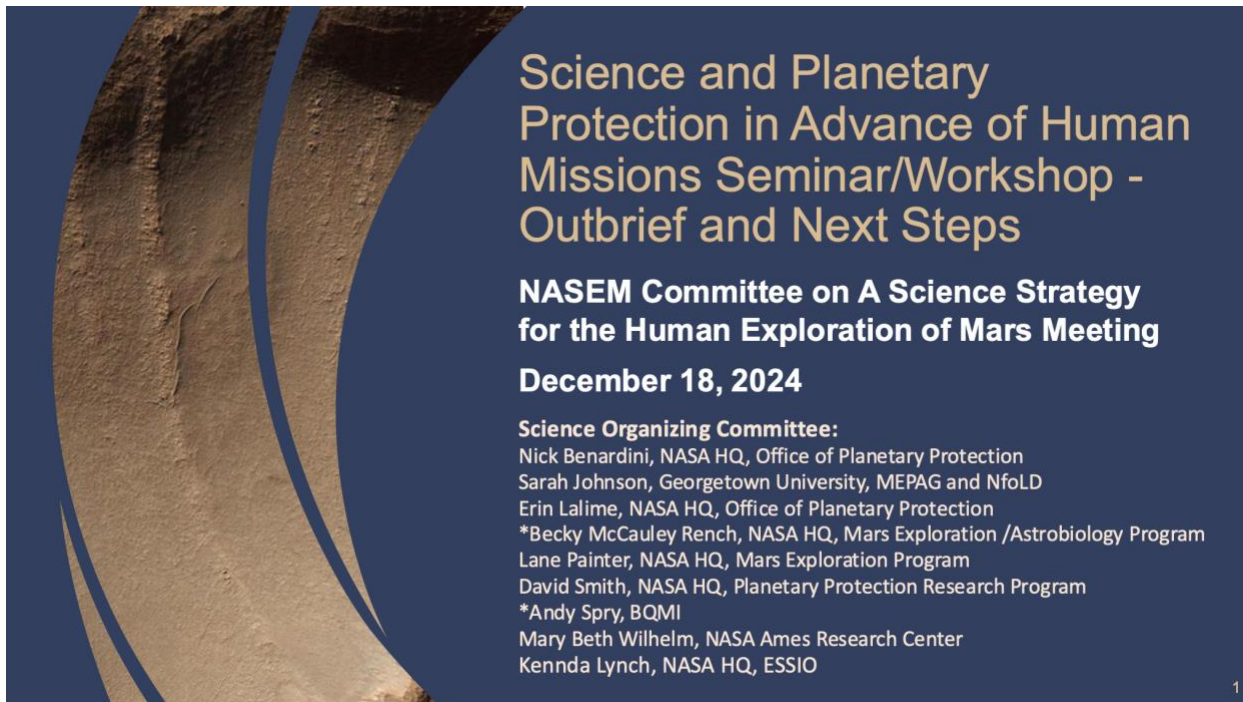
<https://doi.org/10.1029/2018ea000378>.

## Appendix A: Acronyms

ALF	Agnostic Life Finder
ALFA	Agnostic Life Finding Association
APL	Applied Physics Laboratory
BARSOOM	Bacterial Autotrophs Respiring with Stored Oxygen for Overnight Metabolism
ChIPPS	Charged Information-storage Polymer Preparation System
COSPAR	Committee on Space Research
EOM	End of Mission
ESA	European Space Agency
EVA	Extra-Vehicular Activity
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatograph-Mass Spectrometer
HSI	Habitat Suitability Index
ISRU	In Situ Resource Utilization
JAXA	Japan Aerospace Exploration Agency
JHU APL	Johns Hopkins University Applied Physics Laboratory
LLM	Large Language Models
LOD	Level of Detection
LPI	Lunar and Planetary Institute
MAGs	Metagenome-Associated Genomes
MAV	Mars Ascent Vehicle
MEP	Mars Exploration Program
MEPAG	Mars Exploration Program Analysis Group
MPS2	Multi-Planet Surface Simulator

MS	Mass Spectrometry
MSR	Mars Sample Return
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NESC	NASA Engineering and Safety Center
NfoLD	Network for Life Detection
NGS	Next Generation (DNA) Sequencing
NMR	Nuclear Magnetic Resonance
OPP	Office of Planetary Protection
OST	Outer Space Treaty
PCR	Polymerase Chain Reaction
PETOG	Polyelectrolyte Theory of the Gene
PP	Planetary Protection
SFL	Search for Life
SMALL	Single Molecule Analysis of Life and Liquids
SMD	Science Mission Directorate
SNR	Signal-to-Noise Ratio
VIPER	Volatiles Investigating Polar Exploration Rover
VOCs	Volatile Organic Compounds
XRD	X-Ray Diffraction
ZMBR	Zone of Minimum Biological Risk

## Appendix B: Briefing of the First Seminar to the NASEM Committee on A Science Strategy for the Human Exploration of Mars

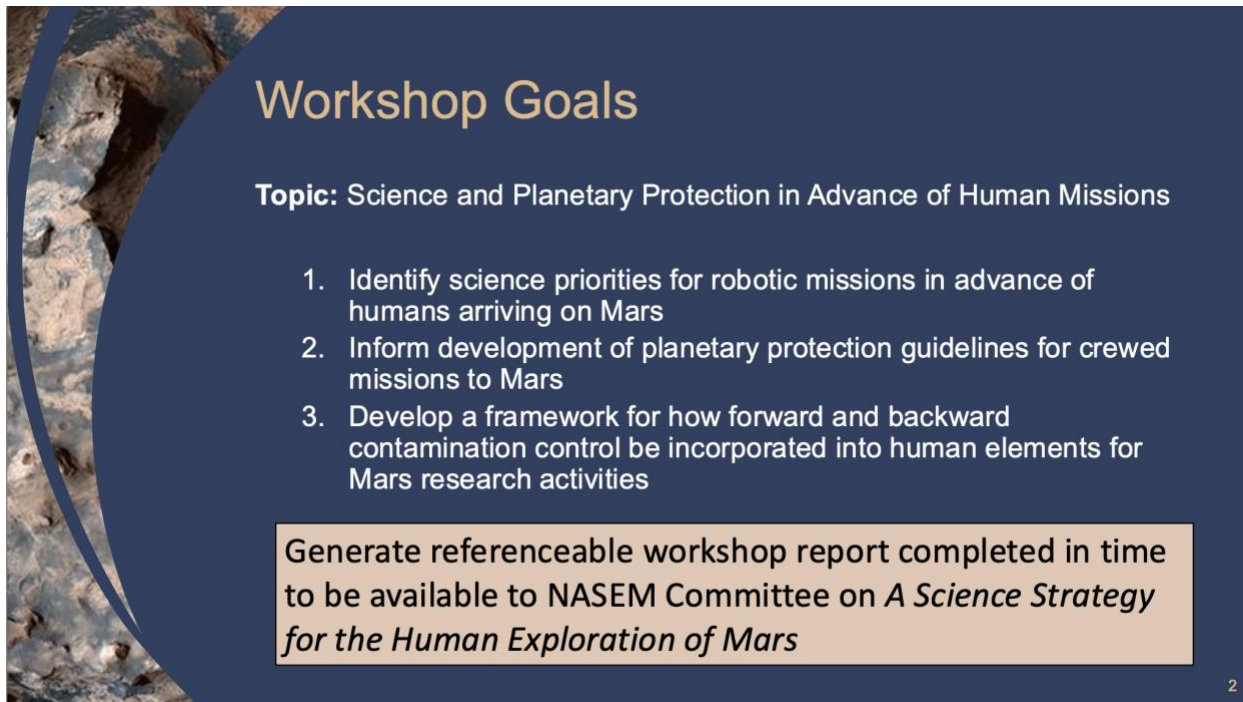


### Science and Planetary Protection in Advance of Human Missions Seminar/Workshop - Outbrief and Next Steps

**NASEM Committee on A Science Strategy for the Human Exploration of Mars Meeting**  
**December 18, 2024**

**Science Organizing Committee:**  
Nick Benardini, NASA HQ, Office of Planetary Protection  
Sarah Johnson, Georgetown University, MEPAG and NfoLD  
Erin Lalime, NASA HQ, Office of Planetary Protection  
\*Becky McCauley Rench, NASA HQ, Mars Exploration /Astrobiology Program  
Lane Painter, NASA HQ, Mars Exploration Program  
David Smith, NASA HQ, Planetary Protection Research Program  
\*Andy Spry, BQMI  
Mary Beth Wilhelm, NASA Ames Research Center  
Kennda Lynch, NASA HQ, ESSIO

1



### Workshop Goals

**Topic:** Science and Planetary Protection in Advance of Human Missions

1. Identify science priorities for robotic missions in advance of humans arriving on Mars
2. Inform development of planetary protection guidelines for crewed missions to Mars
3. Develop a framework for how forward and backward contamination control be incorporated into human elements for Mars research activities

Generate referenceable workshop report completed in time to be available to NASEM Committee on *A Science Strategy for the Human Exploration of Mars*

2



## Interdisciplinary Approach

### Science Organizing Committee

Nick Bernardini, NASA HQ, Office of Planetary Protection  
Sarah Johnson, Georgetown University, MEPAG and NfoLD  
Erin Lalime, NASA HQ, Office of Planetary Protection  
Becky McCauley Rench, NASA HQ, Mars Exploration Program/Astrobiology Program  
Lane Painter, NASA HQ, Mars Exploration Program  
David Smith, NASA HQ, Planetary Protection Research Program  
Andy Spry, BQMI  
Mary Beth Wilhelm, NASA Ames Research Center  
Bob Collom, NASA HQ, SMD Policy  
Kennda Lynch, NASA HQ, ESSIO

### Sponsoring Organizations

Office of Planetary Protection,  
Mars Exploration Program,  
Mars Exploration Program Analysis Group (MEPAG),  
Astrobiology Program, &  
NfoLD (an Astrobiology Research Coordination Network)

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SCIENCE MISSION DIRECTORATE  
**SCIENCE AND PLANETARY  
PROTECTION IN ADVANCE OF  
HUMAN MISSIONS**



### Seminar - Jul 31 and Aug. 1, 2024

- 4-hours / day across 2 days
  - 20 min “briefing” talks, followed by
  - ~1.5h breakout session; ~30min report outs from each breakout group
- Topics included
  - Overview of Planetary Protection, MEPAG Goals, NASEM Science Objectives for Human Surface Missions
  - Microbial survivability on Mars
  - Transport on Mars
  - Target locations for the search for life
  - Potential human impacts to Mars
  - Tools and Operations to Monitor Human Health and Impacts

### Workshop - Oct 30 – Nov 1, 2024

- 4-hours / day across 3 days
  - 3 sessions; ~1hr long of 20 min talks based on abstracts submitted
  - 3 panels; ~1 hr long panel discussion, with Q&A from audience on a topic based on abstracts submitted
  - Scenario Exercise; ~1.5hr all participants discuss a crew mission scenario in breakouts, and ~2h of report outs from each breakout group with large group discussion
- Topics included
  - Life detection in the context of Planetary Protection
  - Analogue environments and future exploration
  - Mars environments and terrestrial biology
  - Risk mitigation for Planetary Protection
  - Instrument and technology development
  - Science investigations prior to crew
  - An astronaut reality check

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A photograph of a rocky, reddish-brown landscape, likely Mars, showing a deep crevice or shadowed area.

## First seminar in MSSW series, “Science and Planetary Protection in Advance of Human Missions”

July 31 and Aug. 1, 2024

A square QR code with a small black silhouette of a person in the center.

Brainstorming Session(s) and Key Questions

- What are the priority knowledge gaps in our understanding of survival of terrestrial microbes, building on the existing literature (Final Report of the COSPAR Planetary Protection Knowledge Gaps for Human Mars Missions Workshop Series and Paths to Knowledge Gap Closure).
- What measurements do we want to prioritize and what research can we conduct in advance of human arrival on Mars to ensure future science integrity?
- What tools (incl. crew-robot interface) could crew utilize on the surface to preserve scientific integrity of samples?
- What aspects of guidance for crewed science missions could use further discussion, are missing, and/or work well?
- What are the prioritized science tasks to achieve before humans arrive?
- What scientific research is desired to be conducted before humans arrive and will it inform the activities of the human explorers once they are on the surface?
- What research will the crew themselves be doing, and how will forward and backward contamination control be incorporated into those research (e.g. science and engineering) activities?

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## Seminar Participant Poll

- Are there precursor planetary protection and/or science investigations necessary in advance of human exploration?
  - 86% answered “absolutely”
- Are the current planetary protection standards and guidelines sufficient for human exploration?
  - 79% answered between “getting there” and “need major revision”

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SCIENCE MISSION DIRECTORATE  
SCIENCE AND PLANETARY  
PROTECTION IN ADVANCE OF  
HUMAN MISSIONS

### Seminar Key Questions

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\*\*Note: Key takeaways based on AI summary of breakout notes and human-created content


## Science Seminar Key Takeaways


- **Understanding the survival of terrestrial microbes under Martian conditions:** This includes studying a wider range of organisms, focusing on extremophiles, and understanding the effects of Martian environmental factors on microbial survival.
- **Developing robust sample collection and analysis methods:** This includes minimizing contamination from humans and spacecraft, using sterile tools, and developing efficient and effective decontamination procedures.
- **Prioritizing research before human arrival:** This includes conducting detailed surveys of potential landing sites, studying the survival of microbes in unique environments, and developing models to predict the spread of contamination.
- **Creating a framework for collaboration and interdisciplinary work:** This includes sharing knowledge across different fields, such as astrobiology, life support, and planetary protection, to develop more comprehensive solutions for future missions.

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Workshop  
Oct 30 – Nov 1, 2024

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SCIENCE MISSION DIRECTORATE  
**SCIENCE AND PLANETARY  
PROTECTION IN ADVANCE OF  
HUMAN MISSIONS**



**Brainstorming Session(s) and Key Questions**

- Are there key analogue environments that we should be focusing on to help drive decision making?
- What analogue extreme environmental variables would you consider and why? Is there a “must-have”?
- What are the key technology development needs that we need to enable key measurements before humans arrive? (Should be achievable and realistic in the next 5 years etc...)
- If you had to choose 1-3 technology developments in the near-term, what would they be? What about the longer-term?
- What’s your “non-starter”, we must understand “this” science before we send humans, and why?
- How would you delineate the line between robotic and crew activities? Are there specific activities that you would bin one way or another?
- With MEPAG Goals (from Goals Documents) in mind, what investigations/science campaigns would you conduct on a first crewed Mars mission? What does this campaign need to look like (recon., early experiments, EVAs, returned samples)?
- What does planning the crewed mission science reveal about what is needed from earlier robotic missions?

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\*\*Note: Key takeaways based on AI summary of breakout notes and human-created content

## Science Workshop Key Takeaways

**Collaboration and Communication Across Disciplines:** Need for a multi-faceted approach to Mars exploration, integrating geology, biology, human factors, and technological advancements. Collaboration among scientists, engineers, and industry partners to address the complex challenges of human exploration, including building on lessons learned from past missions.

**Use of Analog Sites:** Need to better understand how the limitations of individual analog sites can be shored up by lab analogs, modeling, or by the broader selection of analog environments on Earth and beyond.

**Planetary Protection as a Priority:** Science-led planetary protection protocols are paramount to protect both the Martian environment (of which its biological potential is still inconclusively studied) and Earth from potential contamination.

**Investing in Technology:** Develop advanced technologies, particularly in the areas of life detection, sample return, and robotic capabilities.

**Preparing for Human Presence:** Understand human adaptation to Martian conditions and mitigating risks to human health and safety, as well as human impacts to the Mars environment.

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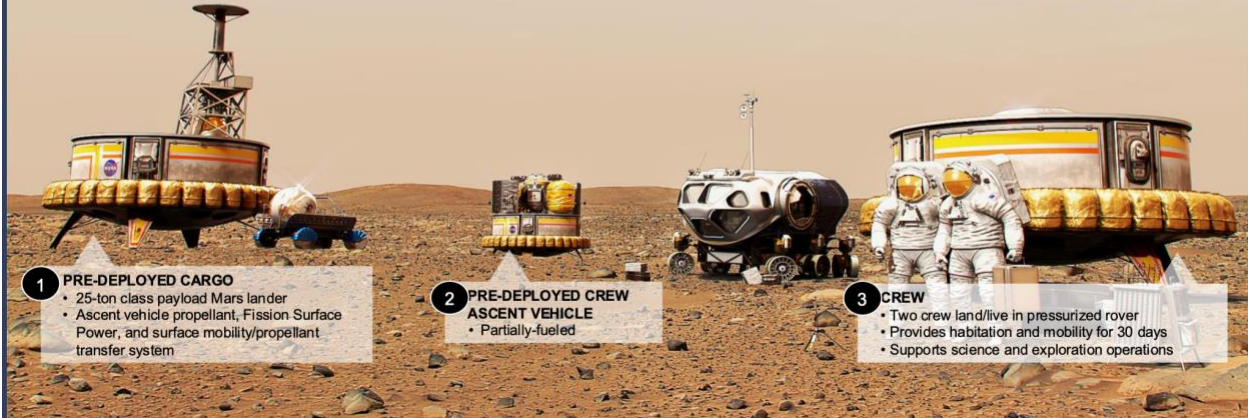
## Scenario Exercise

### Scenario Exercise Guidelines

- Target landing site is at Jezero Crater; no ISRU requirements
- A Zone of Minimum Biological Risk (ZMBR) is established where crew have no PP-based operational constraints
- Three science sorties of 5 days each, are planned beyond the limit of the ZMBR.
- A notional 8hr science workday, which includes EVAs (max 16)
- COSPAR guidelines for crewed missions continue apply

### TRANSIT HABITAT (TH) AND HYBRID NUCLEAR ELECTRIC PROPULSION (NEP) / CHEMICAL STAGE

- Supports four crew on the transit to Mars
- Two crew remain in orbit while two crew visit the Mars surface



- 1 PRE-DEPLOYED CARGO**
- 25-ton class payload Mars lander
  - Ascent vehicle propellant, Fission Surface Power, and surface mobility/propellant transfer system

- 2 PRE-DEPLOYED CREW ASCENT VEHICLE**
- Partially-fueled

- 3 CREW**
- Two crew land/live in pressurized rover
  - Provides habitation and mobility for 30 days
  - Supports science and exploration operations

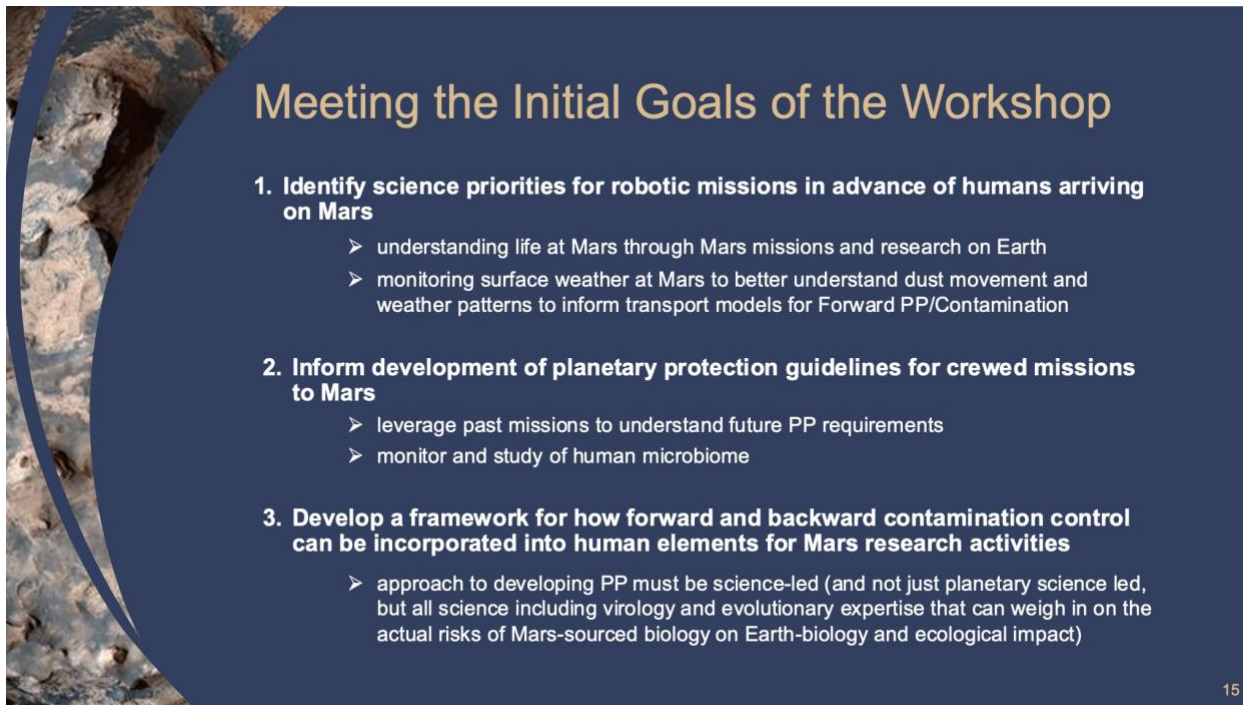
## Workshop Key Scenario Exercise Discussion

The breakout rooms engaged in a lively discussion about the scientific goals, logistical challenges, and critical considerations for a first crewed mission to Mars, at the specified target, Jezero Crater. While each room explored different aspects of the scenario, a common thread emerged: the need for a balanced, multi-faceted approach that balances science, technology, and human factors.

**Human-Robot Collaboration:** The discussion demonstrated a strong appreciation for the unique combination of human ingenuity and robotic capabilities for achieving scientific goals on Mars.

**Comprehensive Planning:** Successful mission planning requires a multidisciplinary approach, integrating scientific objectives, technology development, crew safety, and planetary protection protocols.

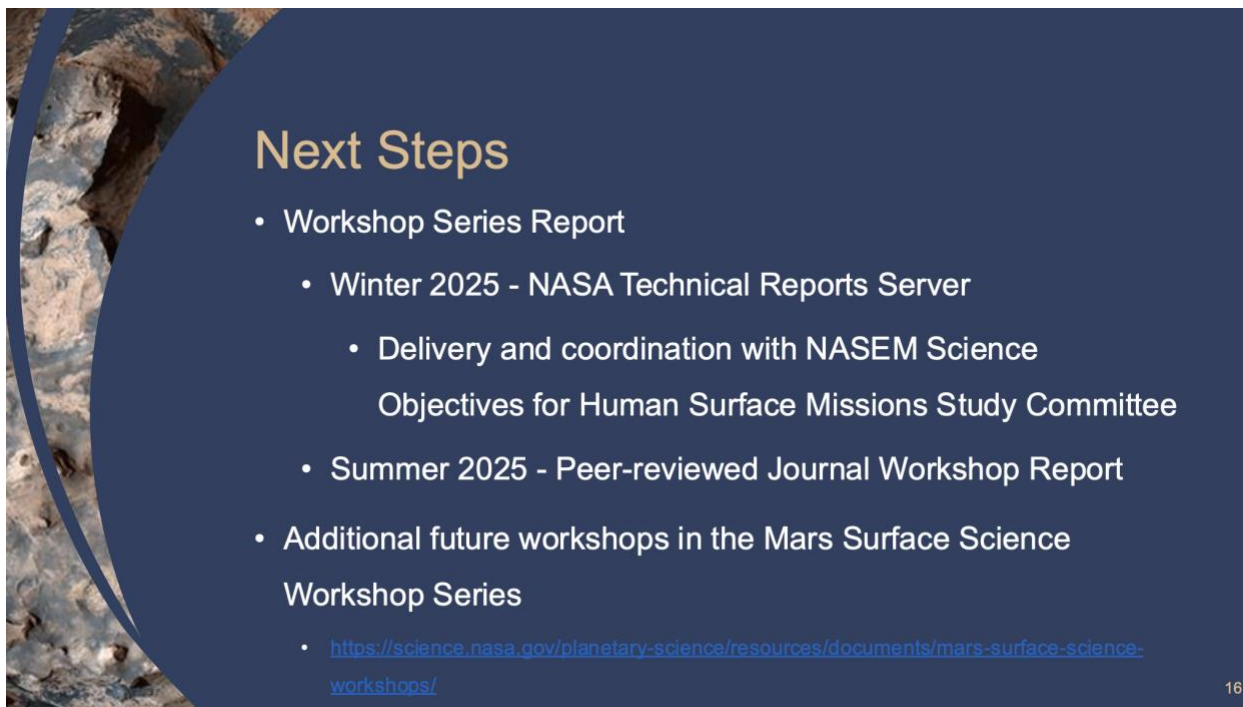
**Continuous Learning and Adaptation:** Future missions to Mars will benefit from the lessons learned from the first crewed mission, requiring a constant cycle of data gathering, analysis, and adaptation.



## Meeting the Initial Goals of the Workshop

- 1. Identify science priorities for robotic missions in advance of humans arriving on Mars**
  - understanding life at Mars through Mars missions and research on Earth
  - monitoring surface weather at Mars to better understand dust movement and weather patterns to inform transport models for Forward PP/Contamination
- 2. Inform development of planetary protection guidelines for crewed missions to Mars**
  - leverage past missions to understand future PP requirements
  - monitor and study of human microbiome
- 3. Develop a framework for how forward and backward contamination control can be incorporated into human elements for Mars research activities**
  - approach to developing PP must be science-led (and not just planetary science led, but all science including virology and evolutionary expertise that can weigh in on the actual risks of Mars-sourced biology on Earth-biology and ecological impact)

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## Next Steps

- Workshop Series Report
  - Winter 2025 - NASA Technical Reports Server
    - Delivery and coordination with NASEM Science Objectives for Human Surface Missions Study Committee
  - Summer 2025 - Peer-reviewed Journal Workshop Report
- Additional future workshops in the Mars Surface Science Workshop Series
  - <https://science.nasa.gov/planetary-science/resources/documents/mars-surface-science-workshops/>

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