National Aeronautics and Space Administration

Moon-to-Mars: Managing Knowledge Gaps and Enabling Missions

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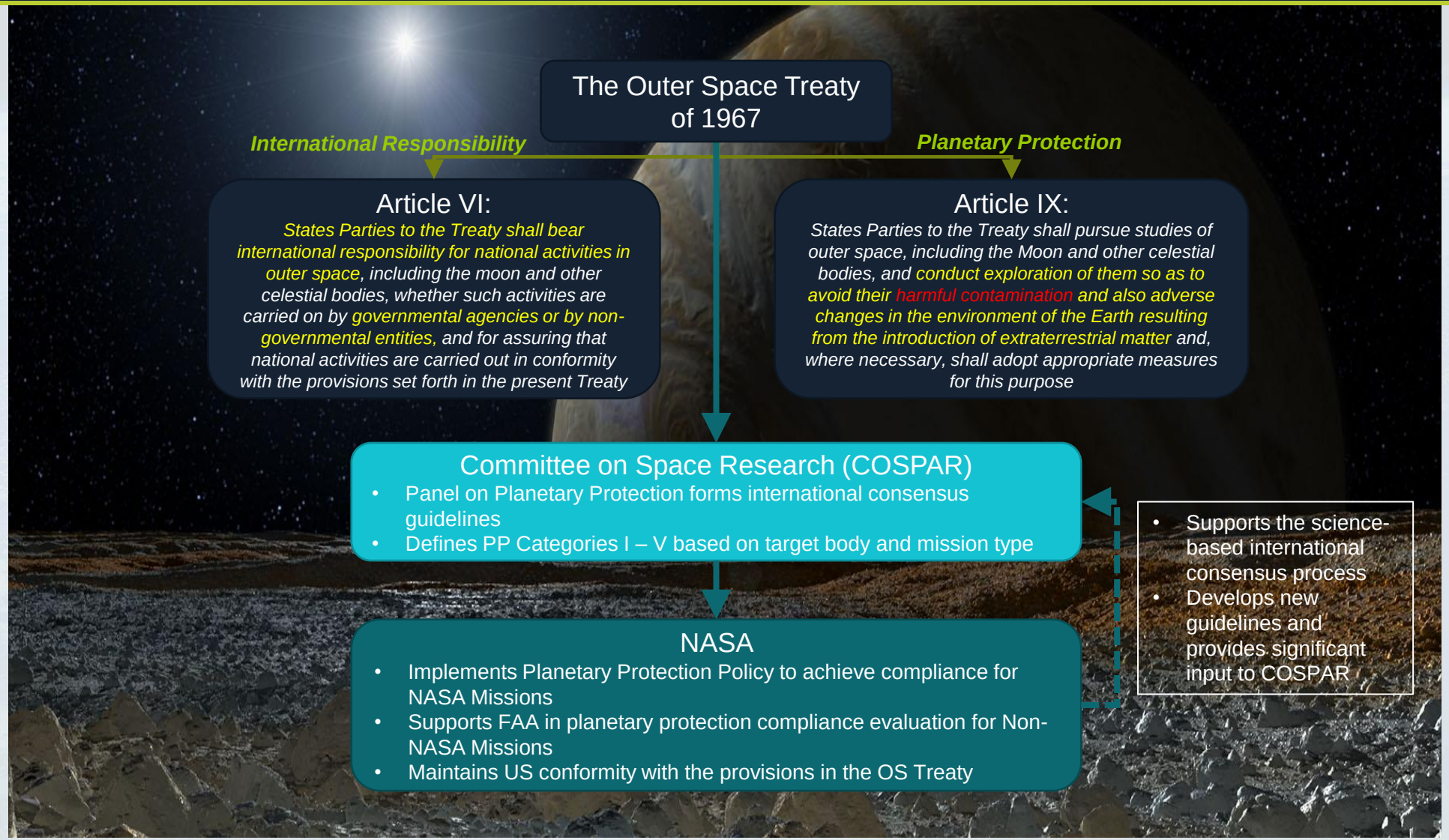
Overview

- Reintroduction to Planetary Protection for Crewed Mars Missions
- Review of the COSPAR Workshop Process and Findings on Knowledge Gaps
- Review of Contamination Threat Assessment for a Crewed Mission Concept
- Framework for Managing Knowledge Gaps and Enabling Missions
- Summary

International Planetary Protection Process



Planetary Protection Categorization

Types of Planetary Bodies	Mission Type	Misson Category
Not of direct interest for understanding the process of chemical evolution. No protection of such planets is warranted.	Any	I
Of significant interest relative to the process of chemical evolution, but only a remote chance that contamination by spacecraft could jeopardize future exploration. Documentation is required.	Any	II IIa, IIb (Moon)
Of significant interest relative to the process of chemical evolution, and/or the origin of life or for which scientific opinion provides a significant chance of contamination which could jeopardize a future biological experiment. Substantial documentation and mitigation is required.	Flyby, Orbiter Mars, Europa, Enceladus	III
As above	Lander, Probe Mars, Europa, Enceladus	IV IVa, IVb, IVc (Mars)
Any solar system body. Unrestricted applies only to bodies deemed by scientific opinion to have no indigenous life forms.	Earth Return Restricted or Unrestricted	V

Planetary Protection Implementation for Robotic Missions

Typical implementation - Orbiter:

- Probability of Mars impact assessment for launcher upper stage and spacecraft
- Launch, cruise to Mars, MOI and orbital mission phases
- Hardware, software and operational reliability
- Micrometeoroid impact and effect analysis

Alternative approach is bioburden control of spacecraft, including break-up/burn-up analysis, to meet and impacted numeric bioburden limit

Typical implementation - Lander:

- Bioburden reduction of flight hardware using solvent cleaning, dry heat, ionizing radiation and gases
- Recontamination prevention using flight and non-flight filters and barrier systems
- Bioburden control of assembly, test and launch operations
- Bioburden verification with assays

Intent is to meet numeric bioburden limit (with the limit being more stringent for IVb/c missions)

a. "Safeguarding the Earth from potential back[ward] contamination is the highest planetary protection priority in Mars exploration."

b. "The greater capability that human explorers can contribute to the astrobiological exploration of Mars is only valid if human-associated contamination is controlled and understood."

c. "For a landed [human] mission conducting surface operations, it will not be possible for all human-associated processes and mission operations to be conducted within entirely closed systems."

d. "[Humans] exploring Mars, and/or their support systems, will inevitably be exposed to Martian materials."

(Originally excerpted as "guidance" from COSPAR 2008 policy language)

COSPAR guidelines for crewed missions

Current guidelines, in place since 2008, address:

- Forward contamination
  - *Orders of magnitude greater threat than robotic missions – crew as "biogenerators"*
  - *Crewed spacecraft systems are not sealed*
- Backward contamination
  - *Want the crew to return home*
  - *Earth's biosphere must be protected*

… But do not yet provide enough detail for engineering design requirements

COSPAR Policy on Planetary Protection, July 2024

Assessment of Knowledge Gaps for future crewed missions

2015	2016	2018	2018 & beyond
NASA Workshop at Ames	1st COSPAR Meeting at LPI	2nd COSPAR Meeting at LPI	COSPAR Working Meeting on Contamination Transport on Mars at LPI, May 2018 COSPAR Working Meeting on Microbial Monitoring & Health at LPI, May 2019 COSPAR Virtual Working Meeting on Spacecraft Systems, May 2020 COSPAR Virtual Working Meeting on Spacecraft Systems, Dec 2022
Identification of Planetary Protection Knowledge Gaps for human missions to Mars	Refinement and prioritization of Planetary Protection Knowledge Gaps for human missions to Mars	Mission Opportunity identification for addressing Planetary Protection Knowledge Gaps for human missions to Mars	Measurements and Payload/Operation Concepts for addressing Planetary Protection Knowledge Gaps for human missions to Mars
What Knowledge Gaps…	…in what order…	…using what missions…	…to make what measurements…

Spry, J. A., et al. (2024). Planetary Protection Knowledge Gap Closure Enabling Crewed Missions to Mars. *Astrobiology*, *24*(3), 230–274. https://doi.org/10.1089/ast.2023.0092

…to establish the right quantitative and implementable planetary protection requirements for safe and sustainable exploration and utilization of Mars.

Assumptions used in development of Knowledge Gaps for future crewed missions

- Human spaceflight hardware leaks (in nominal and off-nominal operation), so the old robotic paradigm of managing a fixed bioload is inappropriate.
- The introduction of a maintained temperate terrestrial environment at the Martian surface affords the opportunity for many more organisms (in type and quantity) to escape into the Martian environment.
- This exploration is taking place in a post-Mars Sample Return (MSR) context where Martian life was NOT (yet?) discovered at the Martian surface/shallow subsurface in returned Mars material, but we know a lot more about Mars from those samples.
- Knowledge gaps need to be understood and preferably closed before launch to protect science return and the Earth.

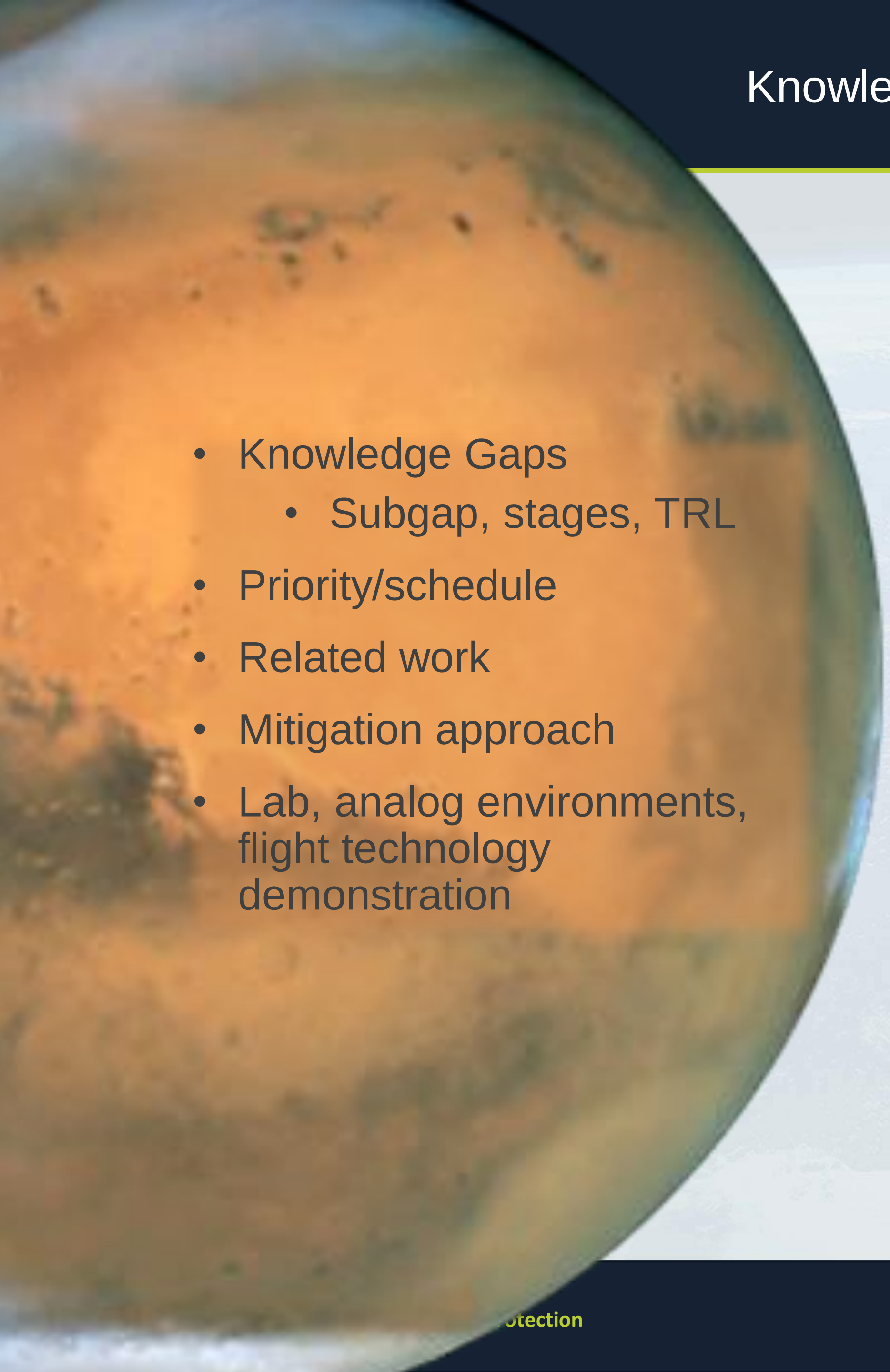
* Developed as ground rules for the 2020 COSPAR "4th Workshop on Refining Planetary Protection Requirements for Human Missions" – see the Conference Documents section at https://sma.nasa.gov/sma-disciplines/planetary-protection

Knowledge Gap Areas

- **Microbial and human health monitoring**
  - *Evaluation and monitoring of microbial communities associated with human systems, both for their initial state and changes over time*
- **Technology and operations for contamination control**
  - *Designs, methods and procedures for controlling contamination release of human spacecraft systems*
- **Natural transport of contamination on Mars**
  - *Understanding the environmental processes on Mars that contribute to transport, survival and replication of microbes released by human activities*

Microbial & Human Health Monitoring
1A. Microbial monitoring of the environment
1B. Microbial monitoring of humans
1C. Mitigation of microbial growth in spacecraft systems
1D. Operational guidelines for planetary protection and crew health
Technology & Operations for Contamination Control
2A. Bioburden/transport/operations during short vs. long stays
2B. Microbial/organic releases from humans and support systems
2C. Protocols for decontamination & verification procedures
2D. Design of quarantine facilities/methodologies at different mission phases
2E. Martian environmental conditions variation over time with respect to growth of Earth microorganisms
2F. Research needed to make ISRU & planetary protection goals compatible
2G. Acceptable contamination level from wastes left behind, including constraints on vented materials
ORIGINAL 2H. DELETED (merged with 2B.)
2I. Approaches to achieve 'Break the chain" requirements
2J. Global distribution/depth of subsurface ice and evidence of extant life
2K. Evolution of planetary protection requirements/goals from robotic precursor through to human missions & exploration zones
Natural Transport of Contamination on Mars
3A. Measurements/models needed to determine atmospheric transport of contaminants
3B. Measurements/models for subsurface transport of contaminants
3C. Effect of biocidal factors on survival/growth/adaptation of microorganisms
3D. Determination of acceptable contamination rates & thresholds
3E. Protection mechanisms for organisms on Mars
3F. Degradation of landed materials by Martian environment
3G. Induced environmental conditions around structures
3H. Sensitivity of non-culturable species to biocidal factors

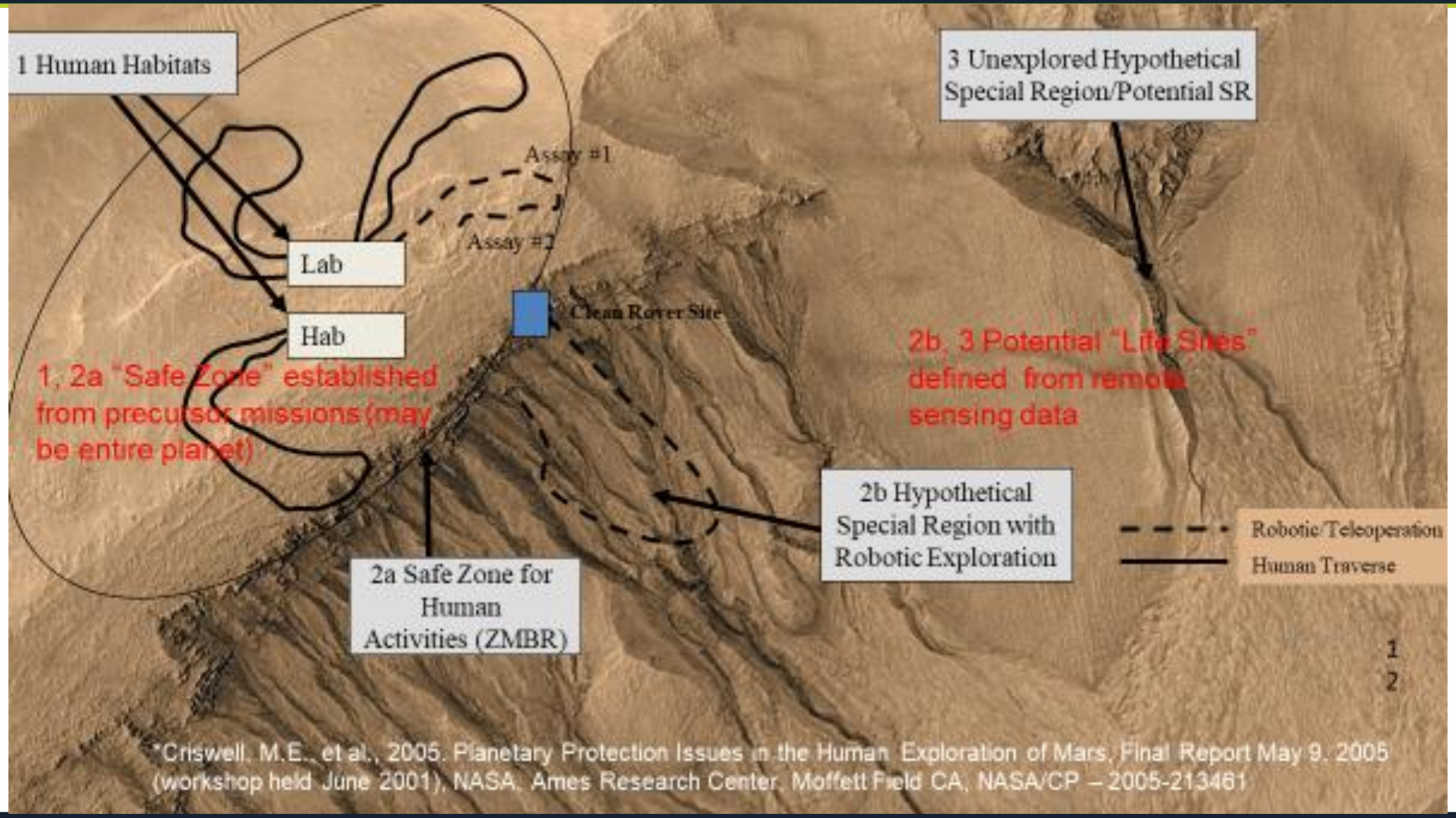
Knowledge Gap tracking at NASA and ESA



- Knowledge Gaps
  - Subgap, stages, TRL
- Priority/schedule
- Related work
- Mitigation approach
- Lab, analog environments, flight technology demonstration

Knowledge Gaps		Fwd	Back							Priority
Microbial & Human Health Monitoring	**Mapping out Solutions**			**Subgaps**	**Step 1**	**Step 2**	**Step 3**	**Step 4**	**Outcome**	**Schedule Technical Cost**
1A. Microbial monitoring of the environment	Sampling end to end MinION Process development Reference database generation and testing Decision support process (Linked to 1B as appropriate)	Y	Y	What systematic microbial monitoring is required? MinION based DNAseq & analysis	Ground development of DNA knowledge library (establishment of model sample suite working in an environment with continuous and unlimited sampling opportunity e.g. JSC cafeteria of crew longitudinal study)	Analog and/or inspace demonstration of system w/space DNA knowledge library (establishment of space normal) 2 YEARS	Update for deployment on MTV 1YEAR		DNA-based decision making tool for monitoring s/c environments at acceptable confidence limits TBD	Schedule H Risk H Cost MH
		Y	Y	What monitoring is required on human missions? TBD based on analog findings and micro monitoring tech dev		CHAPEA Preliminary study to establish baseline end-to-end monitoring approach (sampling locations/articles, frequency, depth) N x 1YEAR	Inspace demonstration of system 1YEAR		DNA-based decision making tool for monitoring s/c environments at acceptable confidence limits TBD	Schedule H Risk H Cost H
		Y	Y	What is the mutation rate/consequence in flight? TBD based on ISS and (TBD) Gateway/lunar data	Inspace research to reach decision 3 x 1YEAR				DNA-based analysis of pathogenicity threat change based on the monitoring of s/c environments TBD	Schedule L Risk H Cost H
1B. Microbial monitoring of humans	(Linked to 1A as appropriate) Establishment of healthy crew baseline microbiome (on ground, in analogs/related industries & environs TBD, and inflight). Need to demonstrate fluctuations w/ cause & effect. Need to establish link to orthogonal health indicators (of other illness).	Y	Y	What signals would indicate the introduction of an unknown for human health? Change in microbiome of baseline	(cell L3 & M4 precursor activities)	Ground Study to detect change in microbiome of baseline and link to orthogonal health indicators and discriminate from other health conditions	Inspace verification of Ground Study to detect change in microbiome of baseline and link to orthogonal health indicators and discriminate from other health conditions		DNA-based decision making tool for monitoring crew health at acceptable confidence limits	Schedule H Risk H Cost MH
		Y	Y	What exactly we are concerned about? Crew response to Martian organism then public health response to Martian organism/biosphere response to Martian		This is covered in cell M6 above			N/A	Covered in P6
		Y	Y	Is there a problem for human health that may be caused by keeping things too clean? Is beneficial microbiology being		Healthy biome definition will emerge from medical research - no need for NASA to do new work: adopt best			Update w/ current knowledge and update into M6 best practice	Covered in P6
		Y	Y	Should we leverage analogous environments (e.g. how the ecology of Navy submarines evolves? Or what has the Air Force learned from monitoring air force cadets? Should we look at		This can feed into other Ground Studies (NASA prefers Antarctica to submarine analogs)			DNA-based decision making tool for monitoring crew health at acceptable confidence limits developed through deployment on ground/analogs. Feed forward into P6	Covered in P6
		Y	Y	Gateway – which could largely be untended. It was also suggested that witness coupons be developed that could be deployed on the ISS and on new	Should be done as part of contamination knowledge capture				DNA-based baseline for monitoring crew health at acceptable confidence limits developed through deployment on inspace analogs. Feed forward into	Covered in P6
1C. Mitigation of microbial growth in spacecraft systems	Design and select materials that inhibit microbial growth on Earth and test final candidates in a space environment. Design sterilization methods and disinfectants, taking into account H/W integrity	Y	Y	How do we design for planetary protection? Testing of materials in analog environs of Schuerger lab, Chapea or on ISS	Standard practice, but need to integrate with h/w requirements.	Space environment testing 5 x 1YEAR			Approved PP equipment list for relevant Parts & Materials, giving confidence that flight material will be no dirtier than test articles	Schedule H Risk H Cost H
				How do we design for planetary protection? Testing of sterilization methods on ground is needed.	Testing of methods in breadboard/brassboard setting to downselects 2 YEARS	Ground analog with selected methodology 1YEAR	Flight test with selected methodology 1YEAR		Flight selected and tested sterilization method (or 2, or 3) We NASA can do this, or other partners	Schedule H Risk H Cost MH
1D. Operational guidelines for planetary protection and crew health	Advance science underpinning human space travel. Advance and standardize techniques for	Y	Y	What do we need to do to develop PP measures for human missions? Downselect from available (developed in 1A-1C) technologies to develop tailored	Develop tailored protocols for each downselected hardware system/subsystem/operational activity				Workable operational guidelines developed and tested ahead of deployment	Schedule L Risk H Cost H
Technology & Operations for Contamination Control										N/A
2A. Bioburden/transport/operations during short vs. long	Solution not mapped due to low priority assignment	Y		None listed	N/A				N/A	
2B. Microbial/organic releases from humans and support systems	What is/are the allowable microbial levels on the Martian surface? (No consensus on how much is too much - need to develop approach HERE) How do allowable microbial levels translate into allowable leak rates from the vehicle? For air? For liquids? For waste? For heat? For other parameters?			1.What are acceptable levels for releasing contamination? (No consensus on how much is too much - need to develop approach HERE, potentials include; bioburden	Understand release rates from hardware elements (ground research with multiple elements increasing in fidelity) through to end of mission disposal /end of period of biological	Understand dispersion (Section 3)	Understand growth rates (Section 3)	Understand release rates from hardware elements using flight tests with actual flight hardware [Moon & Gateway] 2 YEARS	For each leak source, nominal and non-nominal microbial leak rates, total leaked amounts and characterized released microbial population is described.	Schedule H Risk H Cost MH
				2.What is the likelihood of transport of biological matter into a Special Region at Mars? (Need understand transport/survival which is addressed in group 3A-H)	n/a				N/A	Covered in P55
		Y		Bioburden assessment of existing Mars analog locations, i.e. Antarctic field sites, Haughton Crater - North Pole to	Leads into L16 above 5 YEARS				understanding of occurrence and dispersion/distribution of microbial populations at analog locations	Schedule H Risk H Cost H

Planetary Protection Concept* for a Crewed Mission to Mars



*Criswell, M.E., et al., 2005. Planetary Protection Issues in the Human Exploration of Mars, Final Report May 9, 2005 (workshop held June 2001), NASA, Ames Research Center, Moffett Field CA, NASA/CP – 2005-213461

Assessment focused in a “realistic” first crewed mission concept

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

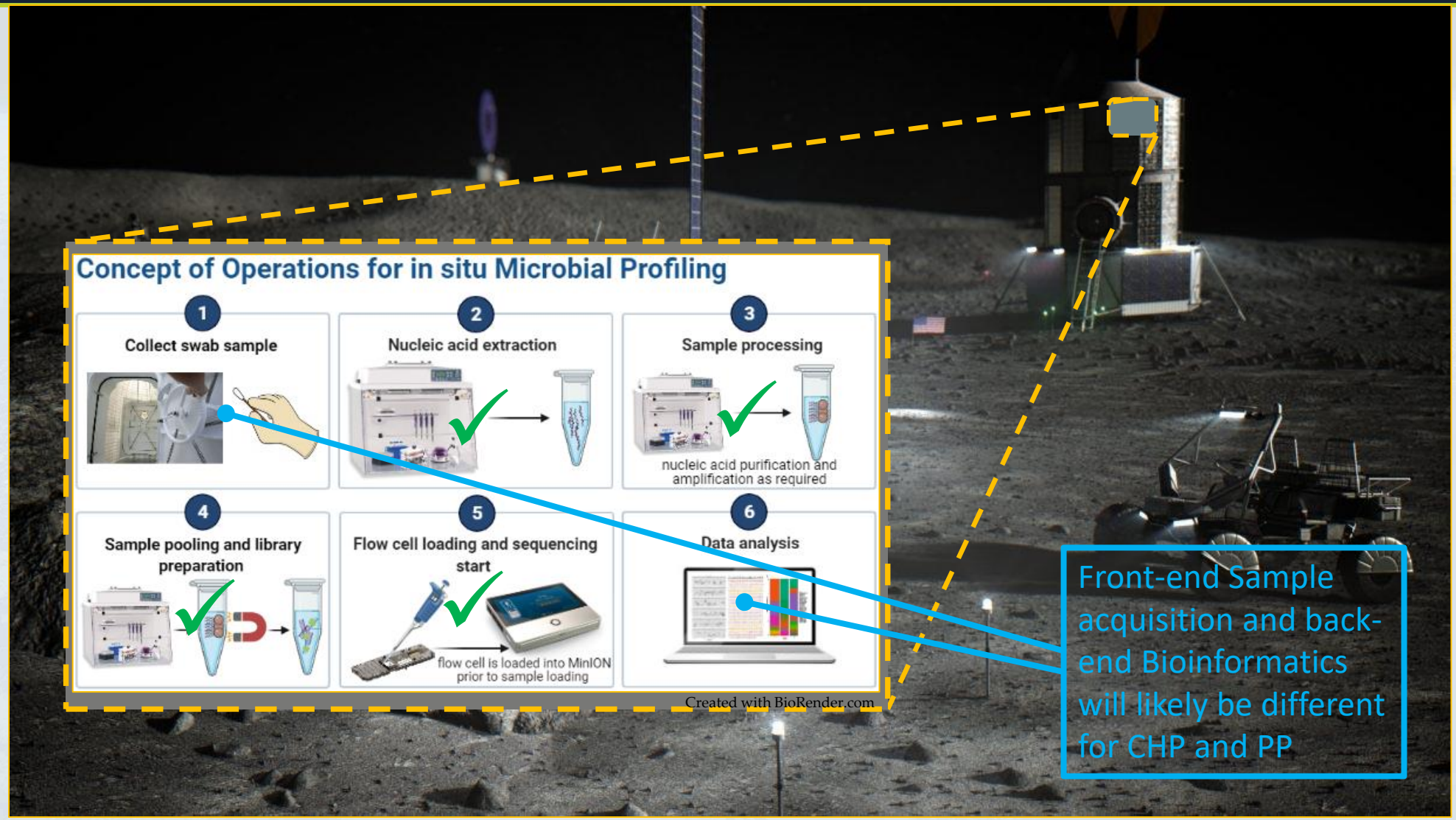
Disposition of Planetary Protection KGs at the end of the COSPAR Meeting Series – 1) Microbial and Human Health Monitoring

Microbial & Human Health Monitoring Knowledge Gaps	Parameter	Figure of Merit/Current Best Estimate	Notes
1A. Microbial monitoring of the environment	Detection and monitoring of microorganisms inside the habitat and in the Mars environment	TBD based on data from analog research to establish baseline information and decision-making strategies	MinION technology with appropriate front-end (sampling) and back-end (bioinformatics) processing (Conclusion of the 3rd Meeting)
1B. Microbial monitoring of humans	Detection and monitoring of microorganisms on/in crew	TBD based on data from analog research to establish baseline information and decision-making strategies	MinION technology with appropriate front-end (sampling) and back-end (bioinformatics) processing (Conclusion of the 3rd Meeting)
1C. Mitigation of microbial growth in spacecraft systems	Monitoring of microorganisms inside the habitat and establishment of action limits.	Establish (sub)-system requirements based on (sub)-system design and release limits (2B)	Conclusion of 5th Meeting
1D. Operational guidelines for planetary protection and crew health	Ability to distinguish between benign and hazardous fluctuations in metagenome data	TBD: Outcome dependent on 1A & 1B	MinION technology with appropriate front-end (sampling) and back-end (bioinformatics) processing. Discussion at the 3rd Meeting.

- Needed technology is identified to be able to address KGs in Microbial & Human Health Monitoring
  - Demonstrated on ISS for crew monitoring
  - Data needs to be generated to create a framework for developing PP decision-making processes

Key:	
	Knowledge Gap response approach is mature and/or addressable as policy
	Knowledge Gap response is actively being addressed and planetary protection application and outcome is clear
	Knowledge Gap response or path to closure is identified but planetary protection acceptability and/or outcome is not clear
	Knowledge Gap is not being addressed or work to closure is not started or new data acquisition is still needed

Microbial Monitoring Technologies for Planetary Protection



Disposition of Planetary Protection KGs at the end of the COSPAR Meeting Series – 3) Natural Transport of Contamination on Mars

Natural Transport of Contamination on Mars Knowledge Gaps	Parameter	Figure of Merit/Current Best Estimate	Notes
3A. Measurements/models needed to determine atmospheric transport of contaminants	Measurements to establish a mesoscale predictive model (baseline performance levels assuming appropriate instrument suite)	Air Pressure 4Hz cf MSL Air Temp. 4Hz 150-300K +/-0.1K Ground Temp. 1/Hr 150-300K +/-1K Wind (in 3D) 10Hz 0-50m/s +/-0.5m/s: 360deg +/-5deg Humidity 1/Hr 0-100% +/-5% Upwelling shortwave & IR 1/hr w/ TBD Range & Accuracy Downwelling Solar flux 4Hz w/ TBD Range & Accuracy UV-C flux 4Hz with TBD Range & Accuracy Total dust opacity 4Hz 0-6 +/-0.03 Dust size & conc. 4Hz >0.2um +/-0.05um @1-5000/cm^3 Dust saltation mass flux 4Hz >0.65um +/- 10um @1-30m/s	Conclusion at the 2nd Meeting (minimum specs quoted)
3A. Measurements/models needed to determine atmospheric transport of contaminants	Instrument suite to establish a mesoscale predictive model	Few 10s of Kgs high fidelity instrument suite supported by three low fidelity instrument suites	Conclusion at the 2nd Meeting
3A. Measurements/models needed to determine atmospheric transport of contaminants	Application of a mesoscale predictive model	TBD time/distance concern for viable organisms in the Martian atmosphere/surface	Discussion at the 2nd Meeting
3B. Measurements/models for subsurface transport of contaminants	Develop and prove drill sterilization strategies	TBD case-by-case development of planetary protection compatible operational plan	Conclusion at the 2nd Meeting
3B. Measurements/models for subsurface transport of contaminants	Analyze contamination pathways for sterile drilling	TBD time/distance/depth concern for viable organisms in the Martian subsurface	Discussion at the 2nd Meeting
3H. Sensitivity of non-culturable species to biocidal factors	Demonstration of equivalent sensitivity compared to cultivable population	Establishment of a factor (if not 1.0 cf 3C data) for lethality to allow assessments under 3D to be made	Discussion at the 2nd Meeting

- Understanding the Natural Transport of Contamination on Mars allows us to answer the question “How much contamination is too much?”
  - Data needs to be generated to create models of transport at Mars (particularly for the aeolian distribution case)
  - Data is also needed on the ability of contaminant terrestrial microorganisms to survive in the Mars environment

Disposition of Planetary Protection KGs at the end of the COSPAR Meeting Series – 2a) Technology & Ops for Contamination Control

Technology & Operations for Contamination Control Knowledge Gaps	Parameter	Figure of Merit/Current Best Estimate	Notes
2A. Bioburden/transport/ operations during short vs. long stays	N/A	N/A	Since only short stay missions are considered, this KG was left open. (Discussion at 4th Meeting)
2B. Microbial/organic releases from humans and support systems	Is it required for an airlock volume to be sterilized prior to egress.	Yes, degree of filtration/ sterilization processing TBD based on threat of organisms released	Expectation that Hydrogen Peroxide vapor and UV technologies might be suitable for this purpose. Conclusion
2B. Microbial/organic releases from humans and support systems	Is it required for an airlock volume to be sterilized prior to ingress.	Yes, degree of filtration/ sterilization processing TBD based on threat of organisms released	Expectation that Hydrogen Peroxide vapor and UV technologies might be suitable for this purpose. Conclusion
2B. Microbial/organic releases from humans and support systems	Is it required for suits/ tools/ instruments/ robots to be sterilized prior to egress	Yes, if required for pristine sample acquisition/processing	Consideration that pass-through glove box technology with hydrogen peroxide technology might be suitable for this
2B. Microbial/organic releases from humans and support systems	Is it required for suits/ tools/ instruments/ robots to be sterilized prior to ingress	Yes, if exposed to pristine/Special Region or unknown Mars environments/materials	Consideration that pass-through glove box technology with hydrogen peroxide technology might be suitable for this
2C. Protocols for decontamination & verification procedures	Bioburden reduction technology compatible with spaceflight systems	TBD based on data from analog research to establish performance of candidate technologies	Conclusion of 5th Meeting

- The COSPAR meeting series considered Technology and Operations for the first crewed Mars mission, leading to paths forward to address:
  - Contamination from spacecraft systems
  - Mitigation of contamination
  - Waste handling
- The discussions and findings give confidence that these topics are a tractable problem set for an end-to-end planetary protection implementation solution.

Disposition of Planetary Protection KGs at the end of the COSPAR Meeting Series – 2b) Technology & Ops for Contamination Control

Technology & Operations for Contamination Control Knowledge Gaps	Parameter	Figure of Merit/Current Best Estimate	Notes
2D. Design of quarantine facilities/methodologies at different mission phases	Crew Quarantine	Crew quarantine considered as a unit (not as individuals)	Conclusion of 6th Meeting
2D. Design of quarantine facilities/methodologies at different mission phases	Crew Quarantine	Crew isolated from Mars samples on mission Earth-return leg	Conclusion of 6th Meeting
2D. Design of quarantine facilities/methodologies at different mission phases	Crew Quarantine	Crew isolated on return (21 days [tbd] cf. Apollo)	Conclusion of 6th Meeting
2I. Approaches to achieve 'Break the chain" requirements	Pristine sample containment (defined as a sample that could be used to test for extant and (TBD) extinct Martian life	Consistent with current Special Region containment for "pristine" samples	Conclusion of 6th Meeting
2I. Approaches to achieve 'Break the chain" requirements	"Regular" sample containment	TBD by policy for determining Consistent with current Special Region containment for "pristine" samples	Discussion in 6th Meeting

- The Technology and Operations to address backward planetary protection for the first crewed mission reflects a conservative approach
  - Containment of Mars samples (even if a prior MSR mission detected no life)
  - Quarantine of crew on return

COSPAR Perspective

The COSPAR Panel on Planetary Protection will continue to work with the different national and international space agencies, the scientific community, and other stakeholders (e.g., the private sector and industry) to develop a roadmap for coordinating research activities addressing the identified knowledge gaps.

Olsson-Francis, et al. (2023) Life Sciences in Space Research, 36, 27-35.

Assessment focused in a “realistic” first crewed mission concept

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

Returning to the "How Much is too Much?" Question: Contamination Assessment – Detailed Analysis

Item	Basis	Specification (if any)	Notional	Conversion factor (mass etc. to CFU)	Start Condition:Day -3 (DST Hatch Closure)	End condition: Day 33 (MAV Arrival at DST & Waste left behind)
Food for 36 days	0.294kg/crew/day reduced stock over time arrives with lander 3	<10000cfu/kg	10000cfu/kg	2.94kg/d	2116800	0 TBD based on margin policy
Crew Microbiome	constant, arrive with lander 3	1E+13/person	1E+13/person	2 crew	2.00E+13	2.00E+13
Urine (0.320ml/d)	accumulates over time: dropoffs at logistics/waste transfer EVAs	<10000/ml	1000/ml	1000ml = 1kg; 320ml/d	1920000	21120000
Solid (fecal) Waste (Kg)	0.3kg/crew/day accumulates over time: dropoffs at logistics/waste transfer EVAs	1E+14/kg	1E+14/kg	0.6kg/day	1.8E+14	1.98E+15
Shed Waste (all sources)	accumulates over time: skin cells, hair, etc.: air filter dropoffs at logistics/waste transfer EVAs TBD	NA	TBD	Estimate to difficult, based on Ganesh et al 2019 and Checinska et al. 2015 + others: use Equilibrated Crewed	NA	NA
Equilibrated Crewed Environment (PR =10 m3)	Assume PR is equilibrated to ISO9 cleanliness by the time it reaches the Martian surface	8320000/m3 @>2um 293000/m3 @>5um	10% of particles >2ur	Estimate, based on Ganesh et al 2019 and Checinska et al. 2015 + others	8320000	8320000
Clothing	Starts clean, goes to dirty/waste	NA	400g clothing/astronaut/ 2days =30x400=12kg	Whitehead et al. 2023 dirty = 415 bacteria/g/day	(Assume sterilized)	9960000
Hygiene Products 0.4L	Starts clean, goes to dirty/waste	100	100	400g, not cleaner tha	2640	1095600
Drinking Water (36d?)	Starts clean ends up as urine	0	0	2.79L/d min.	0	(margin?)
Breathable Air (36d?)	Starts clean, ends as	0	0		0	(margin?)

Returning to the "How Much is too Much?" Question: Contamination Assessment – Key Takeaways

Item	Basis	Specification (if any)	Notional	Conversion factor (mass etc. to CFU)	Start Condition:Day -3 (DST Hatch Closure)	End condition: Day 33 (MAV Arrival at DST & Waste left behind)
Food for 36 d						
Crew Microbi						
Urine (0.320n						
Solid (fecal) V						
Shed Waste (sources)						
Equilibrated C						
Environment (PR =10 m3)	ISO9 cleanliness by the time it reaches the Martian surface	293000/m3 @>5um		Ganesh et al 2019 and Checinska et al. 2015 + others		
Clothing	Starts clean, goes to dirty/waste	NA	400g clothing/astronaut/ 2days =30x400=12kg	Whitehead et al. 2023 dirty = 415 bacteria/g/day	(Assume sterilized)	
Hygiene Products 0.4L	Starts clean, goes to dirty/waste	100	100	400g, not cleaner tha	2640	
Drinking Water (36d?)	Starts clean ends up as urine	0	0	2.79L/d min.	0	(margin?)
Breathable Air (36d?)	Starts clean, ends as	0	0		0	(margin?)

Key Contamination Risk Assessment Takeaways:

~ 2.0 x10^{15} Organisms introduced to Mars in 3-lander crewed mission

Comprising:

~ 1.98 x10^{15} Organisms associated with solid (fecal) metabolic waste

~ 2.0 x10^{13} Organisms associated with the crew (who leave at EOM)

~ 2.1 x10^{7} Organisms associated with urine waste storage

~ 2.29 x10^{8} Organisms associated with pressurized/unpressurized hardware

~ 1.5 x10^{7} Organisms associated with other waste articles

~ 2.0 x10^{7} Organisms associated with potential operational activities

Siegel, B., Spry, J. A., Seasly, E., & Benardini, J. N. (2025). Status update of NASAs assessment of the biological contamination threat of crewed Mars surface missions. *Life Sciences in Space Research*, *45*, 25-33.

Knowledge Gap/Policy Framework

	Pre-Mission (Earth- Mars)	Mars Surface Mission (Ops)	Post-Mission (Mars- Earth)	Post-Mission (Earth Return)
Hardware	Bioburden Management	Bioburden Management Containment Monitor and Mitigation	Bioburden Management Containment - Isolate	Bioburden Management Containment - Facility
Mars Environ.	Mission Design	Monitor and Mitigation	N/A	N/A
Crew	Monitor	Monitor Containment	Monitor Isolation	Monitor Quarantine
Samples	Bioburden Management	Containment	Containment	Containment - Facility Sample Safety Analysis Bioburden Management

Knowledge Gap/Policy Framework: Hardware

Pre-Mission (Earth- Mars)	Mars Surface Mission (Ops)	Post-Mission (Mars- Earth)	Post-Mission (Earth Return)
Bioburden Management At launch threshold(s) At Mars threshold(s) Differential thresholds -(Static vs Mobile H/W) -(SR vs Av Mars) Nominal vs Off-nominal Scenarios	**Bioburden Management** In theater performance threshold(s) **Containment** In theater operational performance Differential performance -(Static vs Mobile H/W) -(SR vs Av Mars) **Monitor and Mitigation** Comparison vs baseline Decision-making support Local cleanup capability reqt	**Bioburden Management** In theater performance threshold(s) **Containment** - **Isolate** Containment hardware functional design and performance	**Bioburden Management** N/A (assumes passive containment @Mars) **Containment** - **Facility** Analogous to Mars Samples
1A, 1C, 1D, 2K	**B: 1A, 1C, 1D, 3D** **C: 2B, 2E, 3A, 3B, 3C, 3D** **M: 2C, 2D, 2J**	**B: 1A, 1C, 1D, 3D** **C: 2C, 2D, 2J**	**B: 1D, 2G** **C: 2C, 2D, 2J**

Knowledge Gap/Policy Framework: Mars Environment

Pre-Mission (Earth- Mars)	Mars Surface Mission (Ops)	Post-Mission (Mars- Earth)	Post-Mission (Earth Return)
Mission Design Landing site selection Arrival timeline (cadence, day/night, season)	**Monitor and Mitigation** Comparison vs baseline Decision-making support Local cleanup capability reqt	**N/A**	**N/A**
2E, 3A, 3B, 3G	**1C, 2B, 2C, 2J, 3A, 3B, 3C, 3D, 3E, 3G, 3H**		

Knowledge Gap/Policy Framework: Crew

Crew health is principally a HMTA responsibility: PP is a stakeholder for missions to Mars

Pre-Mission (Earth- Mars)	Mars Surface Mission (Ops)	Post-Mission (Mars- Earth)	Post-Mission (Earth Return)
Monitor Establish baseline	**Monitor** vs established baseline Decision support tool **Containment** Performance reqt. on h/w	**Monitor** vs established baseline Decision support tool **Isolation** Performance/capability reqt. (NB: This may be considered a HMTA, not PP, topic)	**Monitor** vs established baseline Decision support tool **Quarantine** Performance/capability reqt. cf. MSR
1B	**M: 1B, 1D, 2B, 2C, 2K, 3D** **C: 2G**	**M: 1B, 1D, 2C, 2I** **I: 2D**	**M: 1B, 1D, 2C, 2I** **Q: 2D**

Knowledge Gap/Policy Framework: Samples

Pre-Mission (Earth- Mars)	Mars Surface Mission (Ops)	Post-Mission (Mars- Earth)	Post-Mission (Earth Return)
Bioburden Management (and contam. knowledge capture of sample containment hardware: pristine vs av. Mars)	**Containment** (life detn vs non-life detn samples)	**Containment** (life detn vs non-life detn samples)	**Containment - Facility** Life detn. samples have Sample Safety Analysis Bioburden Management reqt.
1A, 1D	**1D, 2B, 2C, 2D, 2I, 2J, 2K, 3G**	**1D, 2I, 2K**	**1D, 2I, 2K**

Summary

- The COSPAR Planetary Protection Policy and Guidelines include approaches for controlling forward and backward contamination at Mars.
- Approaches for robotic missions are well developed and have successfully guided exploration and preserved scientific integrity for over 50 years.
- Approaches for crewed missions are still in development, but require a paradigm shift from robotic methods.
- A path to achieving that shift is already identified through closure of knowledge gaps identified in the COSPAR workshop series.
- Work to develop a knowledge-based Risk-informed Decision Making process is under way using the Framework as a management tool.
- Seeking to leverage planetary protection KGs to inform technology developments and parameters.
- Knowledge gap closure will be a team effort – with room for everyone to contribute!

Questions?

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