Incorporation of Planetary Protection Knowledge Gaps into Agency Capability Development Planning

(A report of the December 2020 COSPAR and ESA/NASA virtual meeting on the Planetary Protection for Human Missions to Mars – version 1.0)

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I.Introduction

COSPAR (the Committee on Space Research) maintains the international consensus policy on planetary protection[1] that is widely accepted[2] as the methodology for how spacefaring nations should address the "avoidance of harmful contamination" described in Article IX of the Outer Space Treaty.[3] The COSPAR planetary protection policy states, first that the Earth must be protected from the potential hazard posed by extraterrestrial matter carried by a spacecraft returning from an interplanetary mission, and second that the conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized.

While approaches to achieve these goals are well refined for robotic exploration missions, and previously the Apollo Program had developed strategies for addressing planetary protection for crewed lunar missions, currently we do not have the know-how for doing this on a crewed mission to Mars.

As part of planning for future crewed space exploration, COSPAR, together with participating space agencies, has supported a series of interdisciplinary meetings to consider next steps in addressing knowledge gaps (KGs) in the planetary protection discipline, ahead of future human missions beyond low Earth orbit.

As a follow-on to the 2015 NASA[4], and 2016, 2018 and 2019 COSPAR workshops[5] on planetary protection for human missions to Mars, two COSPAR-supported meetings were held (virtually) in 2020. The earlier meetings had first, identified, and then prioritized important knowledge gaps in science and technology areas related to planetary protection for crewed missions, including developing a timeline to assist in ensuring timely closure of the knowledge gaps. Subsequent meetings had considered implementation of strategies to close these knowledge gaps in the areas of "Microbial and human health monitoring" and in the "Natural transport of contamination on Mars". Remaining to be addressed, and the subject of the 2020 virtual meetings described in this paper, is the topic of "Technology and operations for contamination control", to determine potential strategies in managing the contamination in- and outflow of crewed systems at the surface of Mars.

The earlier (May 2020) meeting functioned as a briefing to the interdisciplinary community, with the later (Dec 2020) meeting partitioning into virtual breakout groups to discuss and generate responses on the following knowledge gaps brought forward from earlier meetings:

KG 2B: What level of microbiological and organic release from humans and their support systems is acceptable?

KG 2C: What decontamination, verification, & monitoring protocols (inside & outside pressurized systems) are required for remediation after potential releases from humans and their support systems?

KG 2G: What is considered acceptable regarding waste handling and disposal?

Each KG was addressed in turn, starting with KG 2G, in a series of three breakout group sessions as described in each section below. The sub-questions around the topic were provided to the breakout groups for consideration in each section. Summary responses from each breakout group are provided in tables for easy cross-comparison, with additional explanation in the text. Note that Groups 1 & 2 were tasked to focus on operations as applied to a fixed habitat, whereas groups 3 & 4 were requested to address the topics as applied to a mobile system (pressurized rover or crew in a spacesuit). In the end, the reporting from all groups addressed aspects of both scenarios, so all of the data is reported together. As-reported responses provided by the individual breakout groups are preserved in the appendices at the end of the report.

II. Knowledge Gap "2G" What is considered acceptable regarding waste handling and disposal?

A. Is surface or subsurface disposal preferred or required?

This question addresses whether trash and waste should be buried. In general, the breakout groups indicated that burying risked undetected leakage over time, particularly when the regolith at Mars may have oxidative properties. Also burying requires work, which (unless done robotically) would deplete one of the key mission resources (crew time) in essentially a non-productive task. For the first mission at least, surface storage was preferred. This could be at grade, in a depression (to further reduce exposure to wind), or even raised on a platform (which would allow access for a future mission, with more capability to process and recycle the waste).

B. How long should any container be expected to provide its containment?

The consensus was that waste containment should be designed to be effective for 50+yr. This assessment was reached based on a number of factors, including subjective assessment of what might be possible for a containment system in a mass-limited environment, some notion the cadence of crewed exploration, consideration of estimates of decay of the biological threat, and anticipation about the trajectory of our knowledge about the Mars environment and the need for planetary protection constraints to protect future science.

C. Should trash etc. be "sterilized" prior to disposal?

For this question, there was no clear single answer. Although an active sterilization process is an effective approach to achieving planetary protection goals, this is potentially a mass and power overhead for the mission. In addition, the mission would have to be able to accommodate a failure of the sterilization process, due to e.g., equipment malfunction. Effective containment of unsterilized waste, potentially taking into account passive sterilization processes at Mars, may be sufficient. An engineering trade study needed to evaluate this issue in more detail.

D. Should bulk containment be used to surround trash to prevent interaction with wind?

There was broad agreement that multiple layers of containment (at least two, potentially three) should be used, with the outer layer being a larger container that was resistant to the Mars environment.

E. What degree of containment is required?

Here, two more detailed sub-questions we also considered: First, is a sealed container (for pressure) but with no special microbial mitigation to trash a viable option? And second, is a sealed container with specific microbial mitigation to contents and container exterior required? In some groups, sealing was preferred. In others, closure but with venting through a HEPA filter (and potentially also a molecular scrubber) was the solution. In particular, the issue was identified that a sealed vessel will leak eventually. Given the absence of a clear answer, an engineering trade study is needed to address this issue.

F. What degree of contents (microbial) tracking is required?

The groups concurred that some degree of microbial tracking is required, in the sense of understanding the initial bioload so that the risk can be assessed. There was not a consensus that monitoring the bioload over time was necessary.

G. Is a single dedicated disposal site near the habit preferred or can disposal occur along the path of a rover?

Groups 3 and 4 that considered this trash management question recommended that a single site adjacent to the landing site be used for waste disposal. The rationale was pragmatic in the sense that, for the short duration mission planned, there is no need to dispose of waste material en route, and returning the waste to the landing site location makes it easier for tracking, allows for potential resource recovery by processing at the landing site by later missions, and potentially allows for sterilization at the landing site, e.g., by exposure to irradiation from the "Kilopower" surface power elements that may be present[7].

Table 1: Summary Responses to KG 2G by Breakout Groups

Breakout Group 2 – Day 2	Group 1	Group 2	Group 3	Group 4
(December 2, 2020)	**Habitat**		**Suits/Vehicles**	
Summary Question (from KGs): What is considered acceptable regarding waste handling and disposal (2G)?				
Q. Is surface or subsurface disposal preferred or required? ***A. Surface***	Depends on how waste is contained -surface disposal has a risk for aerial distribution, subsurface disposal carries the risk for leaching	Sealed container inside the habitat, **triple contained**. No need to relaunch waste.	Bags will be placed in a hard wall/metal container (including filter for emissions)	Should store waste on the surface in a container away from the environment
Q. How long should any container be expected to provide its containment? ***A. 50+yr***	At least 50yr (100 and 250 considered)	40-50yr (after biology is dead)	50yr	At least 50yr cf orbital assets (until we answer life detection question)
Q. Should trash etc. be "sterilized" prior to disposal ***A. (No clear answer – Engineering trade study needed)***	Yes – filter gases, heat/radiation sterilize liquids/solids	Mars will sterilize for us? 50:50 vote to sterilize vs. not (alternative is to use passive Mars processes). Sterilizing waste before disposing them to the sterilizing conditions of Mars is double the work.	Stabilizing prior to containment may be beneficial to stop degradation/gas emission Sterilization not reqd.	Waste should be sterilized to reduce microbial activity and then stored in a leak tight container (complete containment is ideal) that can withstand the Martian environment.

Q. Should bulk containment be used to surround trash to prevent interaction with wind? ***A. Yes***	Containment is preferable (also can containment be an alternative to sterilization?)	Seal them and vent them, from the engineering systems is the optimal design	Yes - Smaller containers would be placed into larger containers	
Q. What degree of contents (microbial) tracking is required? ***A. Microbial Tracking Required***	Characterization may be necessary to verify sterilization Barcode system for waste bags		Monitoring should be a requirement	We want to identify the microorganisms in our waste before we dispose of it, not track the waste over its lifespan
Q. What degree of containment is required?	Heat sealed baggies?	Mission architecture fidelity needed to provide the best approach. Equivalent System Mass (ESM) is the driver. For short missions we might not need to have as strict requirements. A little engineering goes a long way. Preparation is key.	As humans or robots pass smaller waste containers into larger one, could have something like a tunnel/chute that could sterilize	The container needs to be environmentally resistant (e.g. UV, temperature, freeze-thaw, ice deposition, dust deposition, etc.) and last at least until we answer life detection questions
Is a sealed container (for pressure) but with no special microbial itigation to trash a viable option	Preference is to sterilize and have fewer requirements for containment but could make the container part of the sterilization method	Contain at equal pressure and vent		
Is a sealed container with specific microbial mitigation to contents and container exterior required? ***(No clear answer – Engineering trade study needed)***	Not if we are sterilizing the waste		Want it contained, but can find advantages to different ways – will be dependent upon needs	
Q. Is a single dedicated disposal site near the habit preferred or can disposal occur along the path of a rover? ***A. Single***			Leave on rover until get to trash disposal area	For initial missions there should only be one waste disposal site to reduce how much we need to bring/build, but if sterilization and containment strategies are sufficient, we can develop multiple sites.

Table 1: Summary Responses to KG 2G by Breakout Groups (contd.)

III. KG "2B" What level of microbiological and organic release from humans and their support systems is acceptable?

A. What gas/liquid/microbial discharges are acceptable?

The common presumption was that, by the time of the first crewed Mars mission, chemical discharges will not be the concern: Only release of viable microbes (potentially attached to particles) would be the concern. The solution for this would be for HEPA filtration of gas releases and for storage of liquids, with the goal of preventing release of viable microbes into the martian environment. One of the groups considered that it may be acceptable for some low biomass gas waste streams to not be filtered, provided that it could be acceptably demonstrated that the martian environment would effectively sterilize that waste stream (e.g., potentially space suit joint leakages).

B. Is it required for an airlock (and residual air in it) to be sterilized prior to egress for an EVA? Is it required for an airlock (and residual air in it) to be sterilized prior to ingress from an EVA?

Discussion reflected that, at the very least, for egress the atmosphere/surfaces in the airlock ought to be bioburden reduced (with acceptable levels TBD). Similarly for reentry into the pressurized environment from an EVA. However, there was not a clear consensus, so a "use case" needs to be developed, so that needed requirements can be identified and addressed. One of the groups highlighted that recovered gas (collected during depressurization) should be HEPA filtered.

C. Is it required for e.g., suits and tools to be sterilized prior to egressing for an EVA? Is it required for e.g., suits and tools to be sterilized to ingress from an EVA?

Potentially, for egress, depending on the use. The expectation is not that robotic mission-level bioburden cleanliness levels are maintained throughout, but that gross contamination is prevented and that pristine Mars samples (free of terrestrial microbial contamination) can be acquired. Discussions reflected that bulkier items such as suits should be bioburden reduced on an ALARA-type basis[8], while tools intended to acquire samples or potentially contact the Mars subsurface could potentially be sterilized prior to use. As long as it has not been determined whether Mars is an abode of current life, steps need to be taken to minimize the opportunity for potential Martian biota to encroach into the interior of crewed systems, so processing of tools, suits etc. would be needed prior to ingress. One of the groups highlighted the need for a separate airlock (or other pathway) for tool egress and ingress from the pressurized volume.

For both the airlock atmospheres and the materials moving in and out of the pressurized volume, a more detailed use case would be helpful in developing and optimizing approaches for egress and ingress.

D. What planetary protection constraints are required for using bio-regenerative systems or plants for consumption?

In general, plants and bioregenerative system waste were considered similarly to other terrestrial contaminated waste: sterilize and/or contain prior to departure, while minimizing (eliminating?) uncontrolled release into the Mars environment. That said, it was communicated to the breakout groups that a full bioregenerative life support system was unlikely for the first mission to the martian surface, so the large biomasses that might be associated with full-scale versions of these systems were not given significant consideration as a threat to the martian environment at this meeting.

IV. KG "2C" What decontamination, verification, & monitoring protocols (inside & outside pressurized systems) are required for remediation after potential releases from humans and their support systems?

A. How can unacceptable discharges be made acceptable?

This question was mainly addressed by Group 2 through considering mitigation of spills. First have controls to reduce accidental spillage; second, have protocols ready in case spills do occur. Group 3 considered EPA/OSHA-style treatment of spills (control spread and stabilize; collect, minimize and isolate). In this, group 3 considered protection of special regions[9] at Mars and the potential for bioburden reduction by whatever means is appropriate and available. Overall there was no clear consensus across the groups, demonstrating the need for integration with ConOps planning and one or more future engineering trade studies.

Table 2: Summary Responses to KG 2B by Breakout Groups

Breakout Group	Group 1	Group 2	Group 3	Group 4
(Dec 3, 2020)	**Habitat**		**Suits/Vehicles**	
Summary Question (from KGs): What level of microbiological and organic release from humans and their support systems is acceptable (2B)?				
Q. What gas/liquid/microbial discharges are acceptable? ***A. Filter gas*** ***Store liquid*** ***Prevent micro release***	Filtration: HEPA for gas/0.2um for liquid Store liquid Sterilize on departure Use daylight UV Condition before departure 50-100yr requirement	Filter by HEPA Contain human waste – 3 layer Take advantage of natural conditions Some risks need to be accepted	Low biomass (e.g. suit leaks) – vent and rely on Mars HEPA for others Need risk assessment 1um cutoff for particles Shower space? – trust but verify	Assume concern is microorganisms O2 loss is OK Research needed to ID performance requirement
Q. Is it required for an airlock (and residual air in it) to be sterilized prior to egressing for an EVA? ***A. Reduce bioburden***	Yes – filter (2 layers?)		Bioburden reduction (not sterilization per se)	
Q. Is it required for e.g. suits and tools to be sterilized prior to egressing for an EVA? ***A. Potentially (develop use case to prove)***	Separate airlock for tools	Sterilize/ Sanitize on ALARA basis Reduce Bioburden	Depends on use – life detection instrument vs mechanical fixings Tools: manage by – witness plate use, material selection (cleanable), contamination	Minimize cross contamination. Sterilization may be preferred but weigh against ops burden/ cost

			knowledge, make clean, keep clean	
Q. Is it required for an airlock (and residual air in it) to be sterilized prior to ingress from an EVA? ***A. No clear consensus – use case needed***	Yes – separate system		Need a mudroom? Visibly clean may be acceptable Ground testing needed	
Q. Is it required for e.g. suits and tools to be sterilized to ingress from an EVA? ***A. Potentially (develop use case to demonstrate)***	UV in airlock to sterilize Need to manage dust problem	Reduce risk Likelihood x Consequence type of risk analysis Coveralls - problematic for suits; mobility, logistics		Sterilization may be preferred but assess against operations burden/ cost
Q. What planetary protection constraints are required for using bio-regenerative systems or plants for consumption? ***A. Manage (eliminate?) release into Mars environment***	Not an additional risk in the Hab. Need to destroy on leaving	Inside – no problem Outside – no plant pathogens	Same as human systems and waste Could sterilize seeds, soil Manage bioreactors as a contamination source	Mitigate via sterilization

Table 2 (contd.): Summary Responses to KG 2B by Breakout Groups

B. Microbial/chemical monitoring capability is assumed: What microbial detection/monitoring of the habitat environment is required?

For limiting forward contamination, bioburden control and monitoring was baselined. DNA sequencing to obtain microbiome information[10] was recommended by three of the four groups, although additional work is needed to develop an appropriate detection end point for such assays. One group suggested that this should be in parallel with classical culturing, although another group pointed out that deliberately culturing terrestrial microorganisms in a mission to another planet would be something that should probably be avoided. One group suggested other technologies alongside sequencing, using witness plates and/or a direct detection methodology. A use case scenario needs to be developed to evaluate the various options.

C. What microbial detection/monitoring outside the habitat environment is required?

First, it was identified that there needs to be the ability to detect (and potentially to mitigate) a change, which implies the ability to establish a baseline. Again, multiple groups identified DNA sequencing as a desirable methodology, combined with a physico-chemical method such as uv (blacklight) inspection or a chemical detection methodology.

D. What constitutes a biomarker for forward contamination purposes (what do we care or not care about)?

On this issue, no clear consensus was achieved. There was comment that very small particles (close to the size of a microorganism) would be degraded by martian uv, and so can be disregarded. However, use of artificial tracers to track contamination was considered to be a threat to detection of martian biomolecules and should be avoided. Once again, a use case is proposed to evaluate options.

E. How is backward contamination to be detected and measured?

This topic was very much unresolved in the meeting. On the one hand, the bulk sources of the contamination are left behind at Mars, and so crew are being "quarantined" from the Mars environment on the return journey to Earth. However, the astronauts, their equipment and any samples being brought back will have been exposed to Mars. ATP (adenosine triphosphate) was suggested as a detection methodology, but it is recognized that in a crewed mission there may be signal to noise issues. The need for a glove box capability was suggested for analyses en route, but this may be in conflict with quarantining requirements. Another group advocated for simple miniaturized monitoring technologies, but there was no clear consensus, indicating that again, a use case study is needed.

F. How should non-nominal spills/leaks be addressed (in contingency planning and surface operations)?

This final topic was how to treat spills, particularly from vehicles. Some groups had partially addressed this in earlier discussions, but in this final analysis groups 3 and 4 considered spills occurring during a traverse. Both groups identified that crew safety would be prioritized, but beyond that, the strategy should be based on containment rather than some kind of disinfection treatment: Mars is cold and dry, so spills of liquid will most likely freeze, then sublime, rendering the biologic contamination frozen and desiccated, and therefore unlikely to cause harmful contamination.

Table 3: Summary Responses to KG 2C by Breakout Groups

Breakout Group	Group 1	Group 2	Group 3	Group 4
(Dec 3, 2020)	**Habitat**		**Suits/Vehicles**	
Summary Question (from KGs): What decontamination, verification, & monitoring protocols (inside & outside pressurized systems) are required for remediation after potential releases from humans and their support systems (2C)?				
Q. How can unacceptable discharges be made acceptable? ***A. No clear consensus - Engineering trade study needed***		Do controls Have protocols ready	Special regions consideration Bioburden reduction	
Q. Microbial/ chemical monitoring capability is assumed: What microbial detection/ monitoring of the habitat environment is required? ***A. No clear consensus – use case needed***	Mixed culture and Next Gen Sequencing	Witness plates Materials coatings	Leak checks Sampling Look for step function changes	No culturing – DNA sequencing/ATP
Q. What microbial detection/ monitoring outside the habitat environment is required? ***A. Ability to detect (and mitigate?) a change***		Establish the baseline & detect changes UV light inspection MinIon	Monitor Look for step function changes	Chemical signature and DNA analysis is ideal
Q. What constitutes a biomarker for forward contamination purposes (what do we care or not care about)? ***A. No clear consensus – use case needed***		Tracers are false contamination		
Q. How is backward contamination to be detected and measured? ***A. No clear consensus – use case needed***		ATP? (signal to noise problem?) Glove box detection en route for returning mission		Assume not a problem (sources left behind). Use simple miniaturized technologies
Q. How should non-nominal spills/leaks be addressed (in contingency planning and surface operations)? ***A. Basis should be containment rather than treatment (Mars is cold)***			Crew safety prioritized EPA/OSHA approaches: control spread, stabilize, collect, minimize & isolate	"spill kit" (to collect, contain, track is better [easier] than disinfection?)

V. Agency Considerations

While this COSPAR-led activity has been multi-agency in its support and participation, of the agencies taking part, only NASA currently has a significant level of work in the architecture planning for crewed exploration of Mars, through its Moon to Mars program. Within NASA, the planetary protection discipline is being incorporated into planning and preparation activities for the current 30-day surface mission architecture study for the first crewed mission to Mars. Much of the paradigm created by the COSPAR studies has been adopted (albeit temporarily) in NASA's Interim Directive, NID8715.129[11] that entered into effect on July 9th, 2020. Planning within NASA continues to integrate planetary protection considerations into the work of the HEOMD SE&I (Systems Engineering and Integration) group, with significant coordination activities ongoing with other organizations engaged in hardware development and knowledge generation. Much of this work is pertinent to developments in the planning for crewed lunar exploration because of the intent to use the Moon as a venue for testing planetary protection approaches before deployment at Mars. Also there are significant cost advantages to redeploying technologies and hardware developed for use at the Moon onto the first crewed Mars mission.

VI. Conclusion and Future Work

The virtual meetings were successful in addressing the three knowledge gaps highlighted (2B, 2C, 2G), and agency representatives are considering how best to incorporate these topics into ongoing portfolios of activity. However, a number of gaps remain unaddressed in the "Technology and operations for contamination control" topic area. In particular, issues around approaches to quarantine and pristine sample handling have not been addressed in the era of the current NASA Mars transit/30 day short-stay mission architecture (KGs 2D. and 2I. from the 2016 workshop). The intention is to convene a further virtual meeting and a final in-person meeting to wrap up these topics and provide an opportunity to update previous findings, in order to provide the COSPAR community with a current, comprehensive perspective on planetary protection knowledge gaps for human missions to Mars ahead of the 2022 Athens General Assembly.

References

[1] COSPAR Policy on Planetary Protection (2020) Space Research Today 208 pp10-22

[2] Fisk, L, "Planetary Protection: The COSPAR Perspective" Presentation to the National Academies of Science, Engineering & Medicine (NASEM) Committee on the Goals, Rationales, and Definition of Planetary Protection, Irvine, CA 27-28 June 2017

[3] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty) United Nations (1967) accessible at: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html

[4] Spry, J. A., J.E. Johnson, M.S. Race, B. Siegel, and C. A. Conley, (2015) Planetary Protection Concepts in the Context of the Evolvable Mars Campaign. Paper ICES-2015-311, 45th International Conf. on Env. Systems, July 2015, Bellevue, Washington.

[5] Race, M.S., J. A. Spry, B. Siegel, C. A. Conley and G. Kminek (Eds), (2019) 2nd COSPAR Workshop on Refining Planetary Protection Requirements for Human Missions, COSPAR, Paris accessible at: https://sma.nasa.gov/docs/default-source/sma-disciplines-and-programs/planetary-protection/cospar-

2019-2nd-workshop-on-refining-planetary-protection-requirements-for-human-missions-and-work-meeting-on-developing-payload-requirements-for-addressing-planetary-protection-gaps-on-nat.pdf

[6] Spry, J. A., B. Siegel, L. M. Pratt and G. Kminek (Eds), (2021) 5th COSPAR Workshop on Refining Planetary Protection Requirements for Human Missions, COSPAR, Paris accessible at: https://sma.nasa.gov/sma-disciplines/planetary-protection#planetaryProtection_conferenceDocuments

[7] Patrick R. McClure, David I. Poston, Marc A. Gibson, Lee S. Mason & R. Chris Robinson (2020) Kilopower Project: The KRUSTY Fission Power Experiment and Potential Missions, Nuclear Technology, 206:sup1, S1-S12, DOI: 10.1080/00295450.2020.1722554

[8] CDC recommendations on Radiation and your Health, accessible at: https://www.cdc.gov/nceh/radiation/alara.html#:~:text=ALARA%20stands%20for%20%E2%80%9Cas%20low,time%2C%20distance%2C%20and%20shielding.

[9] Rummel, J.D. et al., (2014) A new analysis of Mars "Special Regions": findings of the second MEPAG Special Regions Science Analysis Group (SR-SAG2) Astrobiology 14, 887-968 DOI: 10.1089/ast.2014.1227

[10] Be N.A. et al., (2017) Whole metagenome profiles of particulates collected from the International Space Station Microbiome 5:81. https://doi.org/10.1186/s40168-017-0292-4

[11] National Aeronautics and Space Administration, (2020) NASA Interim Directive on Biological Planetary Protection for Human Missions to Mars (NASA Publication No. NID 8712.129 accessible at: https://nodis3.gsfc.nasa.gov/OPD_docs/NID_8715_129_.pdf).

Appendix A: Group 1 Report

	Group 1
Topic	Habitat
What is considered acceptable regarding waste handling and disposal (2G)? **(All Groups: Habitat/Vehicles). Is surface or subsurface disposal preferred or required?**	• depends on how waste is contained? -MSB • SH: surface disposal has a risk for aerial distribution, subsurface disposal carries the risk for contaminated aquifers, or providing a more favorable environment for microbial growth • Perry: subsurface is not ideal for storing trash; How good is the container? • [10:25 AM] Lawrence, Justin D It seems timescale of containment might be useful to determine first? • Michael Mischna: Is surface storage more self sterilizing than the subsurface (radiation, desiccation, oxidation etc.) • Gerhard Kminek: similar to issues w. nuclear waste, might be useful to put the waste somewhere where we can access it again later on • Maria-Paz: Could store waste in caves but caves are a special region on Mars, are we creating an artificial special region by enclosing/encapsulating • Perry: Should we be focusing on short or long duration missions or both o Answer: pick a scenario but consider how it would change for different scenarios • MSB: Might be beneficial to think about the different kinds of waste o different levels of toxicity o different requirements for contamination control o e.g. wipes will be one of the major waste products these will be easier to contain than human waste • SH: Wipes are used now may be used differently on future missions o wipes do contain volatiles • Perry: should there be a single location for waste or is it ok to have multiple locations for disposal • Norm: How sterilizing is the surface of Mars? • Perry: totally exposed waste should be sterilized within a matter of hours o would lean towards depending on surface sterilization for a 30 day mission o won't have as much waste for this short mission • MSB: even if you are sterilizing you are leaving behind dead bugs as biomarkers/ biosignatures • Gerhard: concern for PP is if something is dispersed before it is sterilized o less optimistic on sterilization efficiency that Perry o nooks and crannies in non-ideal samples will be shielded from some of the sterilization effects of UV • Ionizing radiation as a secondary method? o Gerhard says it's not that bad • Michael Mischna: Is there any advantage to dispersal rate is fast dispersal worse than a slow dispersal? o [10:44 AM] Zorzano, Maria-Paz https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1016%2FS0032-0633(01)00113-1?_sg%5B0%5D=mT2YQP6y_pfmY13Skr42L_dZq1xsAOBCPSeomERvGqdgdqjBGCYJqAjKsGScv9mAXbY54K_tgglj_BuhPDhHuNdpzQ.5b5b_dpLye8XsFQSkDUzs3Z7IUsFkeQntPSaXvw7xIjTamY7qEbsA1NFfYB5WnrcOUI4pG2natR9Qdi98G9zEQ

	o Sterilization of Martian surface by cosmic radiation https://www.sciencedirect.com/science/article/pii/S0032063301001131?via%3Dihub o 30,000 years to kill something on the surface with Martian Cosmic Rays • What waste are we discussing: o Wet waste • SH: there may be solid items, like broken equipment but will those impact future science o gases from life support o liquids: urine, water in leftover food, o solid waste • Maria-Paz: I would suggest to set a limit of requirement <500.000 spores total "landed" (inert) element as we do with landed missions • JL: how long do you need to keep the waste contained for?
How long should any container be expected to provide its containment? (This will drive verification testing and mass very strongly.)	50 years is the current requirement for robotic missions o How long will the search for life continue on mars? o JL: 50 years seems like a short time to investigate the entire planet o Perry: it is a rolling 50 years for robotic missions, assumption is that once we have more than 2 or 3 crewed missions we will have effectively contaminated the planet o JL: global contamination might not be a guarantee for o MSB: Should we assume that we have no information at all about where to look for biomarkers on Mars MPZ: subsurface is very close to the surface, may need to adjust our risk tolerance depending on where we land o MSB: some regions might be ok for surface disposal special region's o [11:04 AM] Lawrence, Justin D To sum my thought earlier, I wonder about the question of balancing the time frame we think we need to investigate all of the target habitable environments (caves, subsurface, subglacial lakes etc) for both extant life or biomarkers, relative to the timescale of how long until crewed missions contaminate the planet, or need contain waste. 50 seems too short to satisfy the astrobiology community and comes from robotic missions with lower bioburden and contamination risk. Is 250 years or greater better? o GK: 100 years is another metric used in PP for orbital debris/ disposal o SH: Consensus is that 50 years may be too short? o MPZ: have to be able to scientifically justify whatever number we decide on PS: at what point will human habitats be constructed, req. should apply at least until then o PS: 30 day mission will probably not target a special region o SH: requirement: 30 mission should not target or be upwind of a special region
Should components, consumables, trash etc. be “sterilized” prior to disposal (what should happen in the event of a sterilizer failure)?	Filter sterilize gases and liquids - GK • MSB: certain kinds of connectors or joints are problematic for filtering • MPZ: waste with high bioburden e.g. solid human waste should be heat sterilized o Bring waste back if you are out in the rover so it can be sterilized

	• SH: different ways to use a rover, could spend multiple days in the rover without returning to the landing site o conservation of mass applies o will need to design containers to transport it back to central locations, there are implications to doing this • MSB: Having a central waste depot may be preferable • MPZ: Could Radioiostope thermal generators be used to provide power and sterilize waste? • PS: where can we relax the requirements to help facilitate a 30 day mission o non-solid human waste and pieces of instrumentation could be distributed along the way • SH: Could urine be dumped along the way? o Perry says yes • JL: example from Antarctica is pack everything out, not sure if the mass required to contain it is that extra • MSB: in non-protected areas there is some disposal • SH: minimum temperature and time? o 140C for several hours o standard procedures for autoclaving or dry heat sterilization or radiation • MSB: Are there other methods we should consider? • GK: tradeoffs in terms of consumables required o heat only needs power • Fault tolerance multiple systems to mitigate risk of failure • Solar power to generate heat for fault tolerance • SH: small fission reactor is definitely being considered for crewed missions
Should bulk containment be used to surround components/trash/consumables (can prevent direct interaction with wind, could be sealed for pressure (may allow lighter structure/bag if not sealed)).	• NW: could the rover be used as a container at the end of the mission? • SH and MSB: rover could have utility after the people leave, maybe not a good first choice, maybe other • Containment is preferable • NW: can containment be an alternative to sterilization?
Is a sealed container (for pressure) but with no special microbial mitigation to trash a viable option?	• PS: Preference is to sterilize and have fewer requirements for containment • MSB: probably a favorable mass trade off for this scenario • GK: Make the container part of the sterilization method • MSB: heat sealed baggies? •
Is a sealed container with specific microbial mitigation to contents and container exterior required?	Not if we are sterilizing the waste

What degree of contents tracking (identification and quantity) is required (Is microbial characterization required for every disposal, periodically, once, or not at all)?	PS: tracking may not be necessary, but having coordinates of disposal locations is important • GK: characterization may be necessary to verify sterilization • ABR: May be useful to add a chemical tracer to the waste to rule out later dispersal e.g. IODP tracer • MSB: is it possible/easy to characterize the microbiome of waste before sterilization o similar to microbiome research on ISS o collect saliva, fecal samples etc. • Barcode system for waste bags • MPZ: estimate of mass of waste and contents • JL: Estimate Delta of what you brought vs. what you left
	Additional Notes from Cam Abbot I agree with Gerhard and Perry that sterilisation of waste first is preferable, as this then simplifies further containment options. Justin's idea of adding a tracer to waste to distinguish it from any potential life detected in other missions, such as used by the International Drilling Protect, is a very good consideration. Gerhard also raised a good point early on that UV on Mars is good at sterilisation, so I wondered how much we can use the natural environmental conditions as possible in our waste handling and disposal protocols. Can the sterilising containers for example be made of a clear material which still allows the natural UV to act upon waste? Another point I wondered about is equipment that will be taken on a first human mission. For example, are we planning on taking a 3D printer to practise creating structures/habitats from the Martian regolith? If so, could we create a shield to protect against any dispersal via wind? The dispersal of microorganisms via wind, especially dust storms, is a particular concern. We know that on Earth microorganisms can travel long distances on the wind and be deposited far from their origin (e.g. cosmopolitan, as opposed to endemic, bacteria detected in the Antarctic) and although the Martian environment is very hostile it only takes a few mm of shielding to allow organisms to persist. Contamination of Special Regions, in particular via wind dispersal, would be a big issue in terms of interfering with life detection experiments. I'm sure this issue will crop up tomorrow with regards to microbiological release from humans and support systems. It is a shame we cannot deploy a large bubble upon landing on the surface of Mars to create an enclosed environment to minimise contamination as much as possible until the astrobiological questions are answered!

Appendix B: Group 2 Report

<table>
<tr><th></th><th>Group 2</th></tr>
<tr><th>Topic</th><th>Habitat</th></tr>
<tr><td>What is considered acceptable regarding waste handling and disposal (2G)? (All Groups: Habitat/Vehicles). Is surface or subsurface disposal preferred or required?</td><td>
Worst disposal is human waste. Difficult to contain.
Take it with you as first option, leave the rest for other type of consideration.
Leaving it in the planet is not a good premise. Leave some structure behind on the planet. Sealed container inside the habitat, triple contained. No need to relaunch waste.
Use as many resources from waste as possible and then contain the residual waste.
Consider the volume for the length of stay.
Reduce the mass as much as possible.
If we assume that Artemis is a precursor to the Mars mission. Mars program will need to be structured in a similar manner. Critical to know how to dispose of waste first.
Human waste used as fertilizer, comment for short missions not useful to deal with mass/energy at the beginning, then use waste later. ESM concerns.
Only recycle and use for extended missions.
Dependent on landing site.
Ice-rich (as a resource for habitation)
</td></tr>
<tr><td>How long should any container be expected to provide its containment? (This will drive verification testing and mass very strongly.)</td><td>
Focused on 30-day mission. How long you keep it is a concern. How long the container will have to last. Container that will outlast the length of Mars exploration mission.
Mars environment is very harsh, if we could imagine a habitat that has an external surface that would most likely will be sterilized. Underside of habitats and in other protected areas from the Mars harsh environment. 1 or 2 decades to keep it simple, 3-4 decades would be a number. Keep it simple.
What about if we have life on Mars and discover it. New technologies are much more advanced that can explore and find life on Mars.
Depending on landing site, how many landing sites, what exploration parameters.
Leak question, how leaky is that container?
Equalize the pressure of container left out on the surface and will be reaching equilibrium from outside and inside. How do we verify that? There is some natural decay of materials that will happen, particularly in the Mars harsh environment.
Mars simulations, modeling has suggested that survival is in the tens of years and not thousands of years. (A. Schuerger, publications as ref).
Get data and information from the Apollo missions. Perhaps schedule a mission to recover the waste left during the Apollo missions. If those microbes and the containers are still working, we get a data point to depart from to get an idea how to set up for Mars missions
Anchor to something to something we know on Earth, Antarctica missions.
</td></tr>
</table>

	◦ Bacterial communities are being killed rapidly vacuum; 40-50 years should be enough to sterilize the microbial contamination. (References available). ▪ Set of recommendations for the missions planned. • Anchor to something we use on Earth when looking for extremophiles to understand the processes and make recommendations. • Engineering science focused till now. Why would we want to leave the waste? Is it interfering with the science? • Forward contamination focused. Phase of the exploration is critical of the design for the waste management systems. When we search for life and investigations… • Philosophical question, cost and engineering. What risk are we willing to accept? Risk of contamination in the future. Compromise of what we want to do.
Should components, consumables, trash etc. be "sterilized" prior to disposal (what should happen in the event of a sterilizer failure)?	• Mars will sterilize for us? Other views. Within a few tens/decades of Sols might be ok? External surfaces and internal surfaces. External are quick, internal a long time but not on the range of thousands of years. • Antarctica as a good analog to take into consideration. Human waste is not left on the surface of Antarctica. Urine is a huge volume, reduce the volume with 98% water that can be recycled. ISS recycles approx. 92% of water, sweat and urine. It takes a big large equipment to create the system to do the recycle. There is risk of equipment and chemicals for processing. Mass and power for the recycling equipment. • Mission duration is critical, is it worth the investment for the recycling systems to be implemented. Infrastructure is important to set up for long term missions but might not be worth it for short missions. • Centralize the waste to a facility, in the habitat or close proximity to minimize the logistics. • Plan the architecture for the length of the mission. • Should it be sterilized prior the disposal. 8 hands raised for sterilization. 8 hands raised No sterilization. Passive systems to get the maximum containment. Keep all the trash in the rover and then bring back the trash to habitat, sterilize, contain as much as we can prior to leave it permanently. • Human waste is a great radiation shield. Use waste for other practical uses.
Should bulk containment be used to surround components/trash/consumables (can prevent direct interaction with wind, could be sealed for pressure (may allow lighter structure/bag if not sealed)).	• If containment is pressurized, vented and equilibration system, only gas diffusion in an out. Seal them and vent them, from the engineering systems is the optimal design. • Consider other materials, spacesuits, clothing, etc… skin cells, and other materials that is going to be in many different forms that will require the same level of containment as fecal materials.

Assuming components, consumables and trash items are in a container, what degree of containment is required? (Used components, consumables and trash can be disposed of in simple 'gathering' bags (c.f. ISS where e.g. Zip-Lok®, pull string closures are used), but would interact directly with wind).	• Mission architecture fidelity needed to provide the best approach. The model is based on ISS not on planetary protection to the surface.
	• Apollo landing sites, hardware set up on the surface.
	• Engineering concern, huge engineering trade. What is more feasible and cheaper? Containment areas, deal with Planetary Protection requirements.
	  ○ Outside of the vehicles. Lander should be sterilized in transit.
	  ○ When doing EVAs whatever is going outside the external surface is going to be somewhat sterilized (Look at references) design for things that can be vented.
	• Need to clean the instruments used for science and exploration.
	• Simulated Mars experiments show data that would be as extremely conservative as it has been in the past.
	• Mars environment is harsh enough to create a possible reliable enough system for PP . Acquire Data , Low mass-low cost way to verify the hypothesis presented.
	  ○ UV sterilizer would work on liquids.
	  ○ Trash heating to make it biological inactive (ISS).
	  ○ Transit systems, heavy systems for required power. Technical challenges that have not been worked out yet.
	  ○ Liquid waste, jettison trash.
	  ○ Sterilizing waste before disposing them to the sterilizing conditions of Mars is double the work.
	Equivalent System Mass (ESM) is the driver. For short missions we might not need to have as strict requirements.
	A little bit of engineering goes a long way. Preparation is key.

Is a sealed container (for pressure) but with no special microbial mitigation to trash a viable option?	• Contain at equal pressure and vent

Appendix C: Group 3 Report

<table>
<tr><th></th><th>Group 3</th></tr>
<tr><th>Topic</th><th>Suits/Vehicles</th></tr>
<tr><td>What is considered acceptable regarding waste handling and disposal (2G)? (All Groups: Habitat/Vehicles). Is surface or subsurface disposal preferred or required?</td><td>
Assumptions:
Focusing on Surface Operations with surface hab and mobility
There are three phases to approach:
Approaching vehicle – jettison waste prior to arrival
Surface Ops
When the crew leaves

Bio will be released – what risk willing to take?

Already released with previous spacecraft, but qualitatively different than mini-biome of what is released by human/habitat
Biofilms as they desiccate will be protected by the organisms they are released from
10^6 organisms per hour released – have to understand how they are released and if they are protected by each other inherently

PP reqts are going to be more stringent then crew health reqs
Need to push on specifics (ex. What, why, how)
Pull on lessons learnedt
Organisms in martian environment could be left (frozen/dried out) if they are not going to be transported and if you know where they are.
Not landing in an area where brine or ice is located for initial mission
Looking for those regions will be part of the mission
Cost of waste retrieval would be high (ex. Billions for 1 lbm)
Waste will be left on Mars (how)
Systems level approach: sterilization/containment (drives break the chain)

Result in more heat, more volume to get through biofilm
Release of material could be sterilized with natural environment

Need to know how transportation works
Environment (radiation and temperature) will take care of most

Needs to be evaluated

Bags will be placed in a hard wall/metal container (including filter for emissions)
Containment may change
Vented system that would allow it to freeze dry or radiative cooling
Humans will probably place the smaller containers into the larger one
Suits, habitats, and rovers will vent/leak
Trash will be collected inside the habitable volume initially (food containers, drink bags, MAGs)
Organic carbon waste is a resource

Is surface or subsurface disposal preferred or required?
</td></tr>
</table>

	• Ultimately falls back to infrastructure and if you need more protection for contents in container; however may need it on the surface to allow environmental exposure
	• Does surface vs subsurface matter if can contain and it will last?
	    o Failure could be caused by gases emitted from degradation/fermentation
	    o Having it on the surface will be better maintained; corrosive elements below the surface possibly – less knowledge of what's below the surface
	    o Risk is transport of the bio on the surface – subsurface may be preferable
	    o Resources associated with creating a hole in the ground
	    o Could build around the container (hold it down and stop windblown dust)
	    o Burying it would lose natural sterilization (GCRs, temp, etc.) if it escapes
	    o If the waste is freeze-dried, leachate won't be a problem
	        ▪ Underground physicochemical conditions might change
	• Potential resource for future missions (what state is it left in?)
	    o Make into bricks
	    o Trash to gas
	    o Don't want to destroy the organic carbon as that is a resource for the next mission
	    o Need to have up front photosynthetic operation (Power Cell – Lynn)
	        ▪ Cotton, Polyester, Kevlar, etc.
	• Organic matter a potential for growth
	• Storage (drying, autoclaving, sterilizing agent, mineralizing, incinerate, etc.)
	• Breach of containment (gets into how long)
	• PP: not to release organisms that could be seen as life on Mars or grow
	    o Ensure not going to have amount of release of biological materials that could corrupt the science
	    o If release life and it propagates, that's a problem
	• Waste Management Categories:
	    o Storage or Containment (w/ or w/o stabilization)
	    o Stabilization: chemically sterilize lyophilize, heat drying
	    o Mineralization: incinerations, wet oxidation, pyrolysis (will vent gases)
	    o Using brine (could liquid brine corrode the container material from the outside)
	        ▪ Not all of Mars is warm enough to have brine (equator too dry for brine to form?)
	        ▪ What could human activities do to create brine?
	    o Benefit after stabilization/heat drying to vacuum-seal waste to minimize volume?
	    o Depending on chemistry (long term corrosion)
	        ▪ If dried or frozen, corrosion would be minimal
	    o Water permeable membrane (Nafion or Tyvek membrane) – freeze dried over time
	        ▪ Could include sterilization

	• Three wastes:
	  ○ Human waste
	  ○ Trash (food containers, wet wipes, etc.)
	  ○ Earth landfill risks: leachate breaching the containment and entering groundwater
	    ▪ If the waste is freeze-dried, leachate won't be a problem

How long should any container be expected to provide its containment? (This will drive verification testing and mass very strongly.)	(This will drive verification testing and mass very strongly.)
	• COSPAR level: not just NASA as an organization, it's other orgs/countries
	• Cadence of crewed mission to Mars similar to going back to the Moon (going back in 50 years)
	  ○ Assume going back to same location
	• More than one organization (Musk 2024-2026) going to Mars, so less than 50 years
	• NASA 2039
	• Attempts: time capsules, glassification of nuclear waste
	• Depending on chemistry (long term corrosion)
	  ○ If dried or frozen, corrosion would be minimal
	• Look at experience of Curiosity and tools to self-examine (paint and metal finishes, MLI materials) to see what happened to them

Should components, consumables, trash etc. be "sterilized" prior to disposal (what should happen in the event of a sterilizer failure)?	• Stabilizing prior to containment would be beneficial to stop degradation/gas emission; as long as it doesn't decrease use as future resource
	• Bags could break down quickly in environment
	• Metal container (MM or corrosion could be issue)
	  ○ Could include Whipple shield
	  ○ Mars atmosphere will take care of MM and if big enough will burn it up
	• As humans or robots pass smaller waste containers into larger one, could have something like a tunnel/chute that could sterilize

Should bulk containment be used to surround components/trash/consumables (can prevent direct interaction with wind, could be sealed for pressure (may allow lighter structure/bag if not sealed)).	• Smaller containers would be placed into larger containers
Assuming components, consumables and trash items are in a container, what degree of containment is required? (Used	(Used components, consumables and trash can be disposed of in simple 'gathering' bags (c.f. ISS where e.g. Zip-Lok®, pull string closures are used), but would interact directly with wind) Is a sealed container (for pressure) but with no special microbial mitigation to trash a viable option? Is a sealed container with specific microbial mitigation to contents and container exterior required?

components, consumables and trash can be disposed of in simple 'gathering' bags (c.f. ISS where e.g. Zip-Lok®, pull string closures are used), but would interact directly with wind).	• Want it contained, but can find advantages to different ways – will be dependent upon needs
	What degree of contents tracking (identification and quantity) is required (Is microbial characterization required for every disposal, periodically, once, or not at all)?
	• If concern in the future to look at what could have leaked out, (life detection mission to find E.coli) would be a contingency situation
	• "In looking for life and you're alive and there, then life gets complicated." – Ott and Canham
	• Do not necessarily need to have tracking due to the (Andy)
	• Monitoring should be a reqt
	    o Remediation is a topic for tomorrow in case of failure
	• Qualification of the system as fault tolerant/failure resistant
	
	Is a single dedicated disposal site near the habit preferred or can disposal occur along the path of a rover?
	• Keeping all in one location is probably preferable
	• Multiple containers – don't want small bag releasing – should be taken back to larger containment
	• Small airlock on rover
	• Somehow stow on outside (seal and measure integrity)
	• Need to avoid getting into backward contamination as well
	• Leave containers along the way? Would still have to have a larger container and emission detection
	• Leave on rover until get to trash disposal area
	• Logistics TIM:
	    o General consensus was to provide capability to remove on an as needed basis for odorous things, but nominally have separate wet/dry trash which you take out once a week. Where it goes was TBD but some ideas were to stow in inflatable modules on the surface, or just in a crater, or return bales of trash to a spent CLPS lander, maybe throw in a used descent tank, etc.

Appendix D: Group 4 Report

<table>
<tr><th></th><th>Group 4</th></tr>
<tr><th>Topic</th><th>Suits/Vehicles</th></tr>
<tr><td>What is considered acceptable regarding waste handling and disposal (2G)? (All Groups: Habitat/Vehicles). Is surface or subsurface disposal preferred or required?</td><td>General assumptions:

There are technologies not currently available to us that may influence these recommendations in advance of the first human missions to Mars.
Kinds of waste: Human waste (fecal matter, urine, vomit, skin, hair, CO2, methane), consumables (wrappers, gloves, swabs, surface suit diapers)
Are we separating liquid and solid human waste? What does the Mars toilet look like? [Follow-up with Jim R – Michelle Rucker]

Waste also includes other equipment, hardware, fuel, etc
<ol type="a">
Consider placing requirements on where we put what we leave

Should there be a Mars Trash authority who decides where/how things are disposed of (e.g. roadway litter)?
Use a “take only pictures, leave only footprints” approach to waste disposal for ideal science and preserving the Martian environment
</td></tr>
<tr><td>How long should any container be expected to provide its containment? (This will drive verification testing and mass very strongly.)</td><td>Open Questions:
How long is the waste on Mars?
Is the waste staying after the crew leaves?
Disadvantages for science/pristineness if it stays
Operational disadvantages (e.g. extra launch mass) if it leaves

How can we reuse mission infrastructure (e.g. empty tanks) for waste storage/containment?
How do we handle what we disturb on Mars (e.g. dirt displaced when we dig a hole)?

Is surface or subsurface disposal preferred or required?
Considerations:

Advantages of Subsurface – Not exposed to wind ergo less dispersal, more contained
Disadvantages of Subsurface – improves the chances of anaerobic propagation, adds to engineering complexity (in a container? In a hole? How do we dig the hole? How long does it take?), places closer to subsurface ice
We see similar problems on Earth storing radioactive materials in salt deposits
And in Antarctica because of freeze-thaw effects that can return buried waste to the surface

Advantages of Surface – ongoing radiation sterilization (as long as it is not in an UV blocking container), more accessible for crew (easy to repurpose useful waste), more control of degradation and gas release, easier to monitor, simpler, lower mass, less operationally complex
Disadvantages of Surface – More environmental exposure,
Recommendation: We should store waste on the surface in a container away from the environment
<ol type="i">
Assumptions:</td></tr>
</table>

	Any waste container exposed to the surface will be made of an environmentally resistant material – something that can stand up to UV radiation, temp swings, etc. (e.g. specialized alloys or polymers Considerations: • We need to be mindful of Martian global dust storms (2-4 year cycle) • Will the waste be transported globally, not will the container be destroyed? • We don't want waste dispersal to impact the "science phase," of Martian exploration, or until we've answered life detection questions; containment until larger human populations arrive at Mars • Orbital/robotic assets need to last at least 50 years – perhaps applicable • Will we still be able to find it after 50 years? – depends on container design (e.g. golf flag) and base location (e.g. dust deposition), but probably • It is important to document where dispose of any waste • We probably can't bring trash home or off the surface of Mars so the container needs to be robust **Recommendation:** The container needs to be environmentally resistant (e.g. UV, temperature, freeze-thaw, ice deposition, dust deposition, etc.) and last at least until we answer life detection questions
Should components, consumables, trash etc. be "sterilized" prior to disposal (what should happen in the event of a sterilizer failure)?	Assumptions: • Martian bio-markers will still be there whether or not terrestrial microbes do spread • But terrestrial bio-marker dispersion definitely complicates things • Things exposed to the atmosphere are sterilized by UV radiation • But, the environmental conditions are such that microbial activity is possible (e.g. the temperature makes it possible) **Considerations**: • Could we incinerate the waste? Or launch it off the surface? • Requires an incinerator or a launch vehicle, both of which add to Earth launch mass • What are the resource requirements of sterilization? • Power, consumables? • How do we verify the containment? Or identify a breach in containment? • What lessons can we learn from terrestrial containment (e.g. for nuclear material) • Compacting the waste (removing the liquid) will make the container more manageable (e.g. size, seals) • Reduces microbial activity • We would like to extract useable material in advance (e.g. water to be recycled, manure as fertilizer, plastics or metals that can be used for additive manufacturing) • Does compacted waste have any other applications (e.g. radiation protection) • Requires a compactor, a big mass hit – needs a justification • Sterilizing before storage will reduce gas production • If we can completely sterilize the waste we do not need to store it in a container

	• Or if our leak rate is less than or equal to the kill rate (via environmental conditions) then it will not meaningfully impact science **Recommendations:** Waste should be sterilized to reduce microbial activity and then stored in a leak tight container (complete containment is ideal) that can withstand the Martian environment. Compacting the waste in advance is advantageous and could be part of the sterilization process.
What degree of contents tracking (identification and quantity) is required (Is microbial characterization required for every disposal, periodically, once, or not at all)?	Assumptions: • Tracking waste will make Mars science easier • We can leverage lessons learned from food safety and on the ISS (e.g. doing sub-samples rather than trying to sample everything) Considerations: • Tracking waste dispersal once the waste is in contamination adds complexity to the container – adds a power requirement, makes dust a bigger problem, etc. • Inert particle methods (e.g. isotopes, florescent nanoparticles) for monitoring waste dispersal are preferable to DNA based methods • Takes lessons from terrestrial methods (e.g. in geology and food industry) • We should not ignore bio-marker methods where applicable. We should take a fully inventory of what is going into the waste (volatiles, organics, etc.) to understand how it will interact with special regions on Mars **Recommendations:** We want to identify the microorganisms in our waste before we dispose of it, not track the waste over its lifespan on the surface. We not <u>need</u> to sample everything, just those microorganisms that might survive the Martian environment. We also only need to monitor a sub-sample, not every sample.
Is a single dedicated disposal site near the habit preferred or can disposal occur along the path of a rover?	Considerations: • It would be more operationally complex to dispose of waste along the way, but it does cut down on the mass the rover carries • One site is less operationally complex and easier to monitor • If our sterilization and containment strategies are good enough it doesn't make a difference how many disposal sites we have • If sterilization and containment are not perfect then one site makes it easier to monitor and track releases. • Temporary waste sites may simplify operations although the waste would still need to be returned to a main waste disposal site if sterilization and containment techniques are not sufficient at the temporary site **Recommendations**: For preliminary missions there should only be one waste disposal site to reduce how much we need to bring/build, but if sterilization and containment strategies are sufficient we can develop multiple sites. Multiple sites would be advantageous for crew/rover mobility.