Moon-to-Mars: Risk Assessment Challenges

Dr. J. Nick Benardini
Planetary Protection Officer
NASA HQ

Dr. Erin Lalime
Acting Deputy Planetary Protection Officer
NASA HQ

Dr. J. Andy Spry
Planetary Protection Senior Scientist, BQMI

Dr. Alvin L. Smith
Project Manager, Mars Sample Receiving Project
NASA JSC

NASEM Committee of Planetary Protection Fall Meeting

Washington, DC

December 9, 2025

- Probabilistic tools need to be developed to enable Mars exploration.

	Current	Future Needs

Forward	• Viking Pc (reports captured)
	• Pc parameter assessment 1990s and special region
	• Europa Clipper model
		• Modernize Mars Pc working model
		  • Updated Mars mathematical framework
		  • Updated biological & environmental parameters

Backward	• Robotic break the chain assurance framework • Sample Safety Assessment	• Crewed break the chain • Crew safety • Biosphere safety

Framework needs developed to:

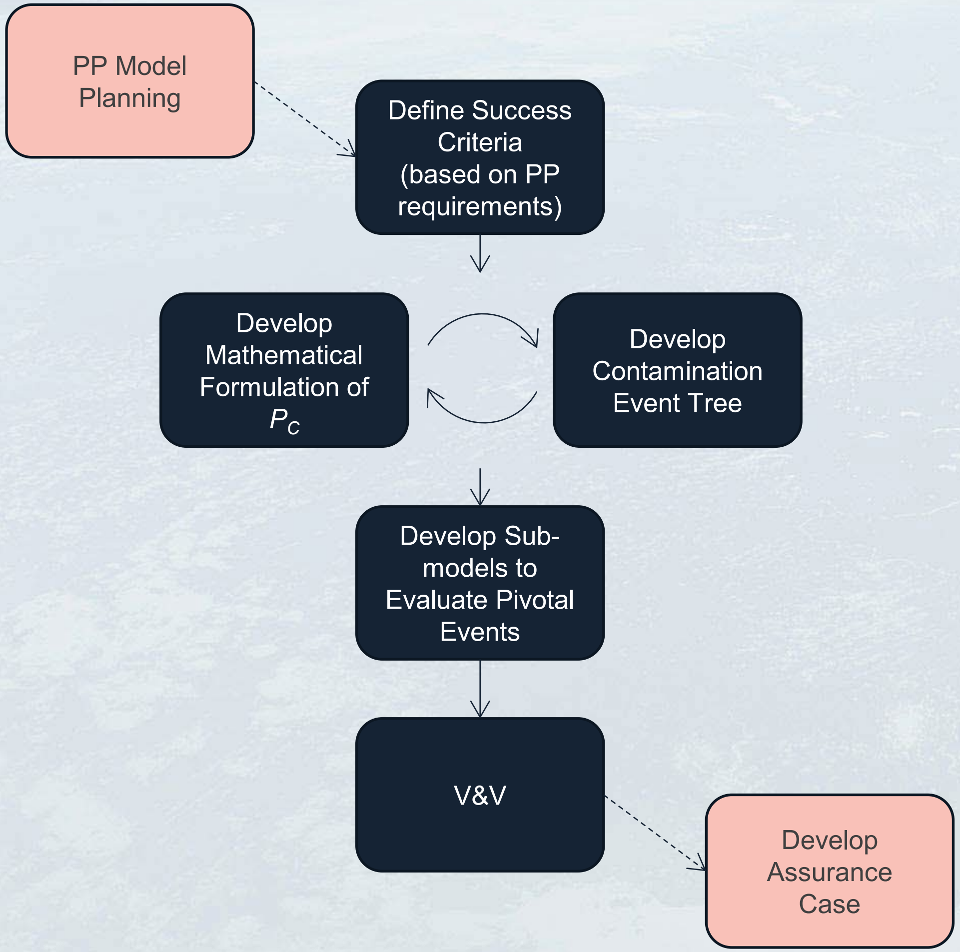
- Harmonize and standardize the PP process.
- Assess the current state of Mars contamination through robotic exploration.
- Inform risk posture trade space.
- Inform technology developments and parameters by assessing modeling sensitivities/uncertainties.
- Support mission planning and execution.

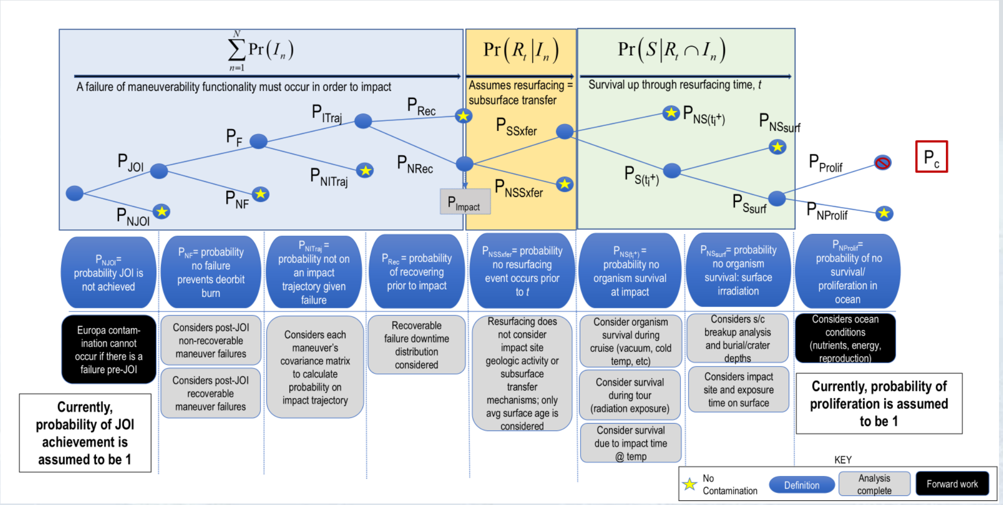
PP Tools

- Forward PP Framework
- Back PP Framework

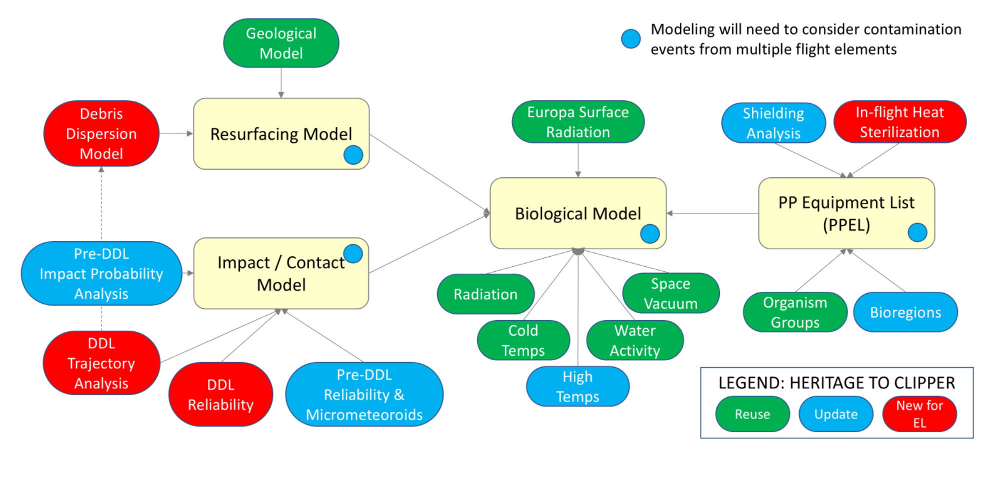
Modeling the Probability of Contamination for NASA Missions

- NASA Handbook SP-20240016475 - Appendix 4





Europa Clipper Contamination Event Tree



Example of the network of submodels and analysis required for an Icy Worlds probability of contamination model.

Forward Planetary Protection Framework

Mars Forward Planetary Protection - Probability of Contamination – Background

- The Viking-based contamination equation is:

$$P_c = \Sigma N_0 P_s P_r P_g$$

  - *where:*
    - *Pc is the probability of contaminating Mars;*
    - *N_0 is the number of organisms present before sterilization;*
    - *P_s is the probability that a randomly selected organism will survive sterilization;*
    - *P_r is the probability of release, and*
    - *P_g is the probability of growth*
- Partial timeline of probability of contamination and probability of growth workshops, publications, and reports.
  - *1964 – COSPAR establishes 10^{-4}*
  - *1970 – SSB report follow up with 10^{-4} - 10^{-6} values*
  - *1974 – Pc Viking report with Sagan Coleman approach - microbial characteristics, lethality of release / transport mechanisms and the martian environment*
  - *1978 – Pg report recommendation Mars regions (i.e., subsurface, polar ice caps)*
  - *1984 – Pc → Categories and simplification of Pc to spore NASA to COSPAR*
  - *1987 – SSB evaluation of Pc*
  - *1991 – Mars Environmental Survey (MESUR) Mission Mini-Review*
  - *1992 – NCR report, NASA workshop*
  - *2002 – Special regions*
  - *2006 – Special Regions Science Analysis Working Group*
  - *2007 – NASEM recommends non-Mars missions convert to Pc (1e-4) / mission*
  - *2014 – Special Regions Science Analysis Working Group 2*
  - *2021 – NASEM CoPP*

Review publication planned for 2026!

- COSPAR §4.6 "*…Accordingly, planetary protection goals **should not be relaxed** to accommodate a human mission to Mars. Rather, they become even more directly relevant to such missions.*"

Robotic = Crew

Forward PP Example

Robotic, Prescriptive

Policy Objective: control the risk of "harmful contamination" → Guidelines: bioburden constraints for a Category IVa mission → Detailed Guidelines: $\leq 5\times10^5$ spores → Implementation: Rover harness needs heat microbial reduction bakeout 150°C, 25 h

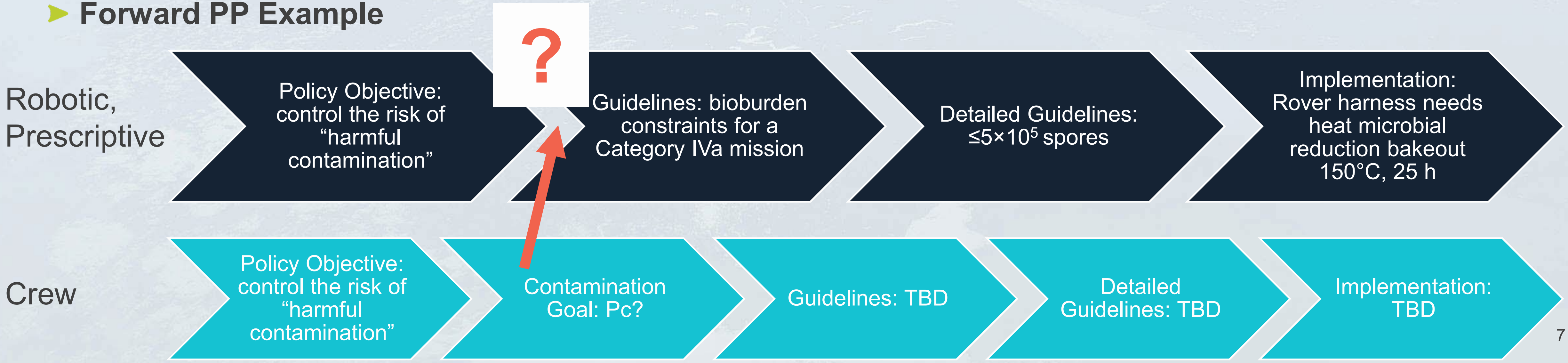
Crew

Policy Objective: control the risk of "harmful contamination" → Contamination Goal: TBD? → Guidelines: TBD → Detailed Guidelines: TBD → Implementation: TBD

- COSPAR §4.6 "…*Accordingly, planetary protection goals* ***should not be relaxed*** *to accommodate a human mission to Mars. Rather, they become even more directly relevant to such missions.*"

Robotic = Crew

- **Forward PP Example**



Mars Planetary Protection Requirement Landscape (3 of 3)

Performance

Robotic and Crew

✓ Cat III Orbiters - Probability of Contamination (**1e-4**)

Probability of Contamination (**1e-3**)

- USA 4.4e-4
- USSR 4.4e-4
- Other nations 1.2e-4

Viking performance pre-sterilization

Viking performance **3.08e-5**

NASEM 2007

Recommends non-Mars missions convert to P_c (1e-4)/mission

Prescriptive

✓ Cat IVa: Pre-Viking Sterilization
ISO 8 or better, 5e5 total spore, 3e5 landed spore, 300 sp/m2

✓ Cat IVb+IVc: Post-Viking Sterilization
ISO 8 or better, 5e5 total spore, 3e5 landed spore, 300 sp/m2, 4-log microbial reduction

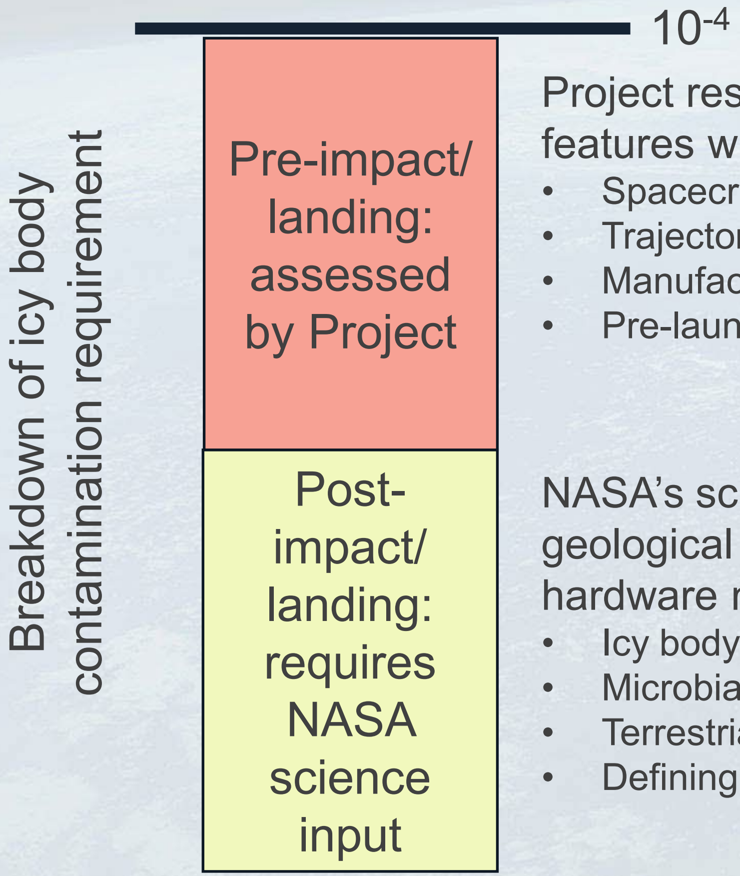
✓ Special Regions

Robotic/Crew – exploration zones

Crew – workshops + studies + n+1

Icy World Probability of Contamination Breakdown – Project vs. Science

COSPAR: *probability of inadvertent ocean contamination ≤1x10^{-4}…*



Project responsibility: risk assessments tied to design or mission features within a Project's control. E.g.:

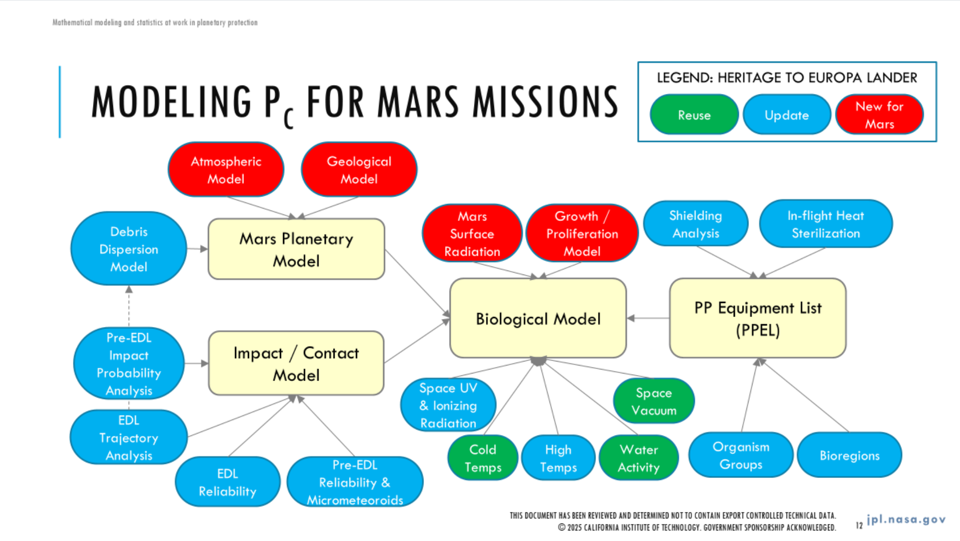
- Spacecraft/instrument reliability and design features
- Trajectory design
- Manufacturing and processing practices
- Pre-launch microbial reduction

NASA's science community responsibility: risk assessments tied to geological and biological features outside a Project's control, given flight hardware makes it to icy body surface. E.g.:

- Icy body subsurface transport processes and geology
- Microbial survival in icy body environment
- Terrestrial microbe proliferation in icy body water
- Defining special regions

Next Steps for the Forward Planetary Protection Framework

- Modernization Mars P_c working model
  - *Mars Planetary Model*
    - *Atmospheric*
    - *Geological*
    - *Transport (Mars 2020 / MSR foundation)*
  - *Biological Model*
    - *Mars biocidal factors*
    - *Space environment*
    - *Growth and proliferation*
    - *Organism groups*
  - *Hardware model*
    - *Material and processes*



Example of the network of submodels and analysis required for Mars missions. Image credit: NASA/JPL Mike DiNicola

- Probability of contamination and probability of growth parameters could benefit from scientific workshops, etc.
    - *Period of biological performance - 50 years from launch?*
    - *Evolving past spores; microbial dark matter etc…*
    - *Do we have technology sweet spots that can generate verifiable requirements? Detection and analysis method must align with the risk.*
    - *Probability of growth? Recommendation of special region parameters to start – temp, availability of water.*

Backward Planetary Protection Framework

Sample Return Options

Sample Safety Assessment

Planetary Protection (PP) guidelines:

Samples would need to be kept under high containment until **biohazard** potential is assessed

Not feasible to equip a high-containment receiving facility with all equipment necessary for comprehensive scientific analyses

If safe, samples should be released from high-containment to enable analysis with the most up-to-date and cutting-edge technology available

Image from Asteroid Bennu sample return *(requires no BPP planning)*
Credit: NASA/Robert Markowitz

Sample Safety Assessment

Overarching goal: Assess the risk that potential returned samples contain modern martian biology that could represent a biohazard

What is a biological hazard? Martian biology capable of causing substantial harm to any component of the Earth's biosphere if allowed out of containment.

Assessing the hazard potential of martian biology would not be feasible: Any modern biology would need to be treated as if hazardous

Need: A protocol to assess sample sample safety and determine the necessary steps for release from high-containment

SSAP-TT Membership

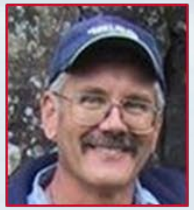
Leadership


Gerry McDonnell

PP Liason


Brian Shirey

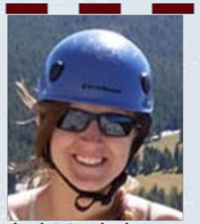
Facilitation


Dave Beaty


Bonnie Teece

Technical Members

Discussion Leaders


Rachel Mackelprang


Noel Cressie


John McQuiston


Lisa Mayhew


Barbara Sherwood Lollar


Andrew Steele


Rick Davis


Nicolle Baird


Mark Sephton


David Relman


Kim Hummel


Jessica Vanhomwegen


Mary Beth Wilhelm


Brooke Ahern

Seconded from MDT*


Heather Graham


Sandra Siljestrom


Kate French


Mihaela Glamoclija

*Measurement Definition Team (MDT)

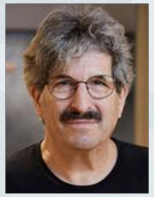
Ex Officio


Richard Mattingly

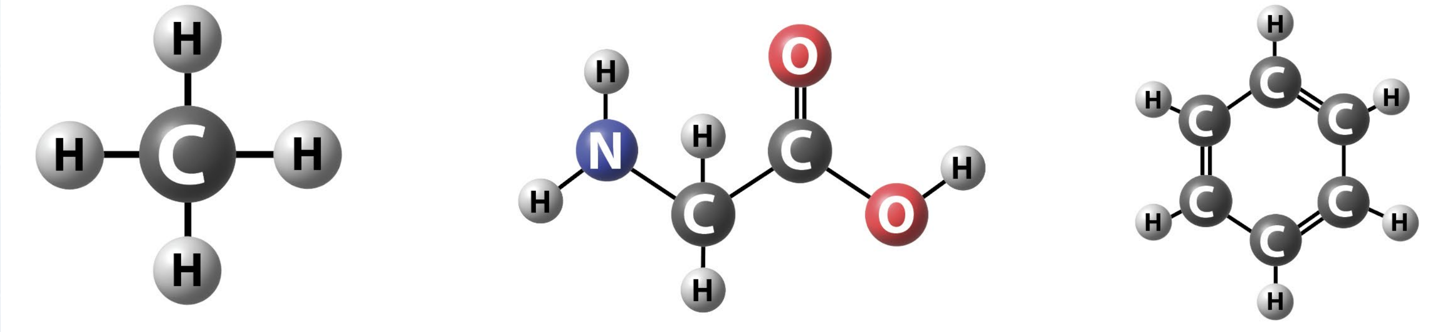

Aaron Regberg


Bill Page


Peter Emmanuel


Gary Rufkun

Abiotic Baseline



Organic molecules are found in biotic and abiotic environments

Complexity, distribution, and abundance of organic molecules produced by biotic chemistry is different than what can be produced by abiotic chemistry

Abiotic Baseline

Abiotic background

Life

Dead life

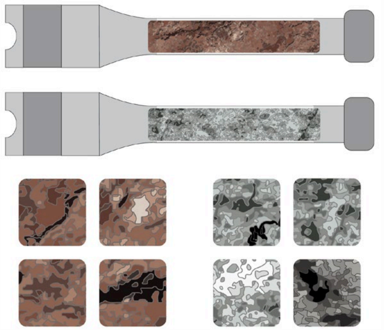
Biotic processes select, assemble, and concentrate molecules into larger molecular structures. Abiotic chemistry produces a large number of monomers or short oligomers

Proposed three step protocol

Centered around the concept of the abiotic baseline

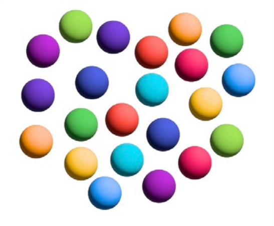
Sample safety assessment protocol overview

Step 1: Sample heterogeneity

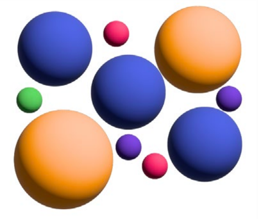


Assess heterogeneity to guide subsampling

Step 2: Abiotic baseline



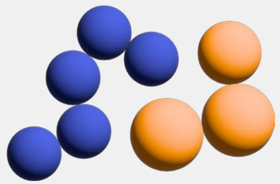
Organic molecules produced by abiotic chemistry



Organic molecules produced by biotic chemistry

Characterize organic molecule inventory. Determine if patterns are consistent with abiotic or biotic processes

Step 3: Biological activity *Contingent*



Biotically produced organic molecules and polymers

If abiotic baseline is exceeded, determine if signal is from contamination, ancient martian biology, or modern martian biology

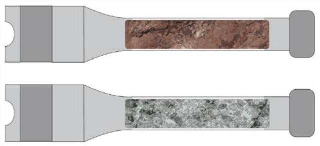
All steps are supported by a Bayesian statistical framework to assess risk

SSAP Overview and Outcomes

SSAP Overview

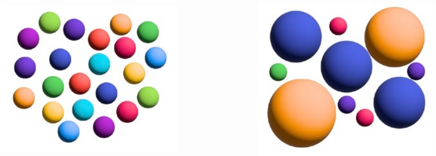
Step 1

Sample heterogeneity



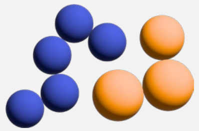
Step 2

Abiotic baseline



Step 3

Biological activity



Bayesian statistical analyses to determine if potential modern martian biology is present at a threshold of acceptable risk

Outcomes

PASS
No evidence of biotic chemistry. Samples may leave high-containment facility.

Hold and review
Evidence of modern martian biology. Hold in high-containment for further investigation.

Why Bayesian?

Frequentist Statistics

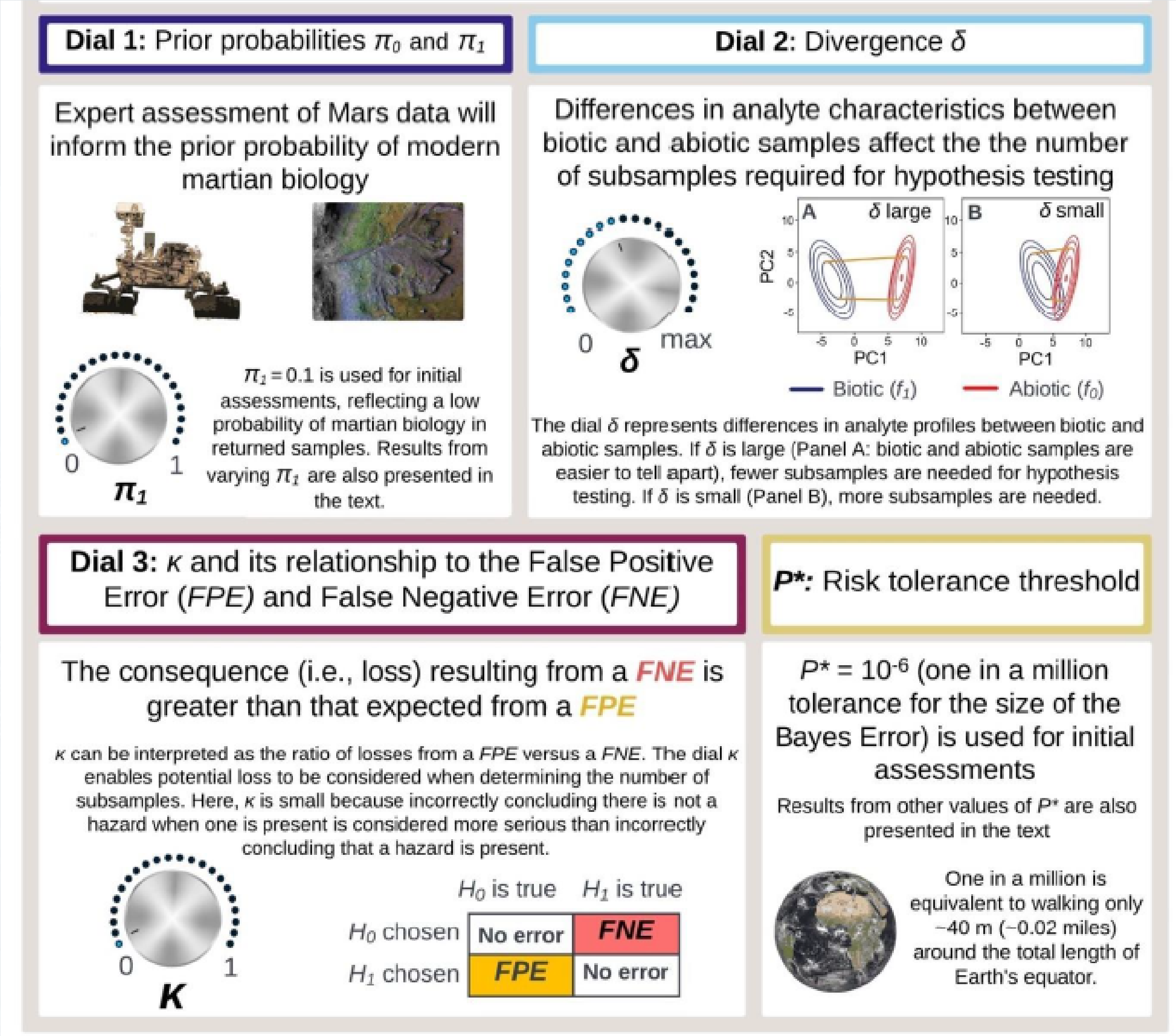
Traditional (frequentist) statistics has a number of disadvantages for planetary protection, which include:

1. An inflexibility that can exclude prior knowledge.
2. Reliance on relatively large sample sizes.
3. Does not directly ensure both False Negative error (FNE) and False Positive error (FPE) are small.

Bayesian Statistics

1. Incorporation of prior knowledge (previous studies and expert assessments).
2. Accommodation of small sample sizes and limited initial data (mitigated by prior information).
3. Able to update priors as new knowledge develops.
4. Amenable to decision-making where posterior probabilities can be used to assess costs and benefits.
5. Specification of prior knowledge makes the analysis more transparent.

Key Statistical Dials and their Roles



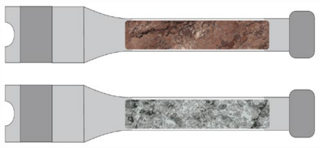
Not Defined

SSAP Overview and Outcomes

SSAP Overview

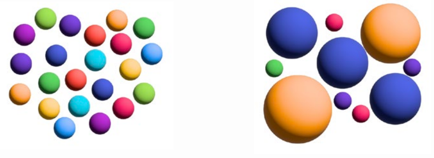
Step 1

Sample heterogeneity



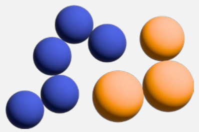
Step 2

Abiotic baseline



Step 3

Biological activity



Bayesian statistical analyses to determine if potential modern martian biology is present at a threshold of acceptable risk

Outcomes

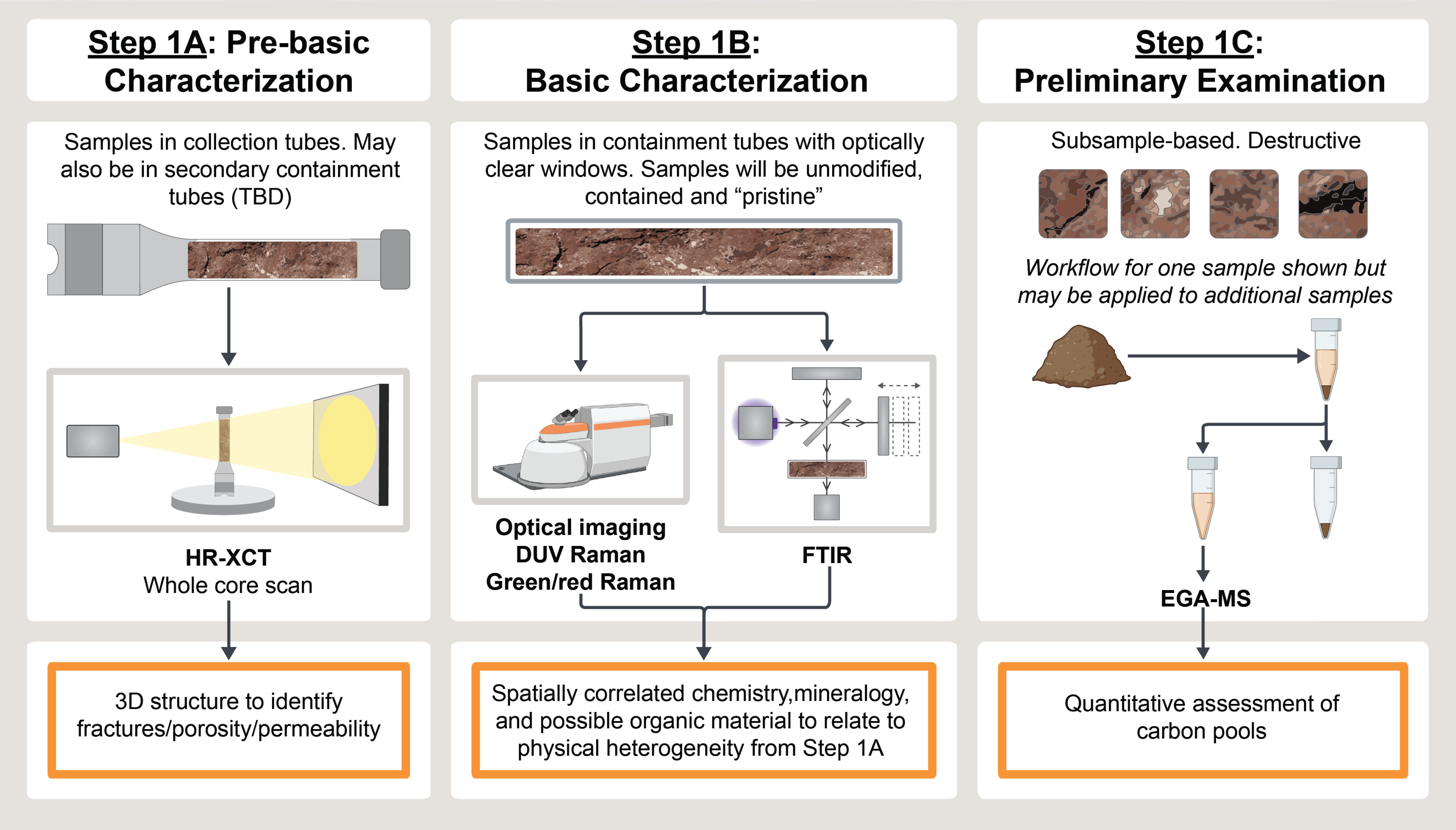
PASS
No evidence of biotic chemistry. Samples may leave high-containment facility.

Hold and review
Evidence of modern martian biology. Hold in high-containment for further investigation.

Step 1: Sample heterogeneity

Goal: Select subsamples representative of sample heterogeneity

Steps 1A & 1B are non-destructive: Samples remain pristine, but resolution is limited

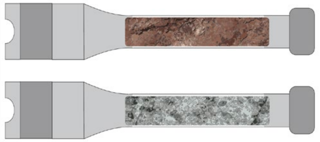


SSAP Overview and Outcomes

SSAP Overview

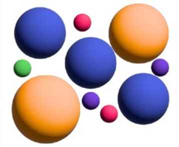
Step 1

Sample heterogeneity



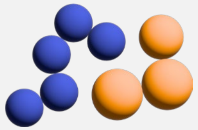
Step 2

Abiotic baseline



Step 3

Biological activity



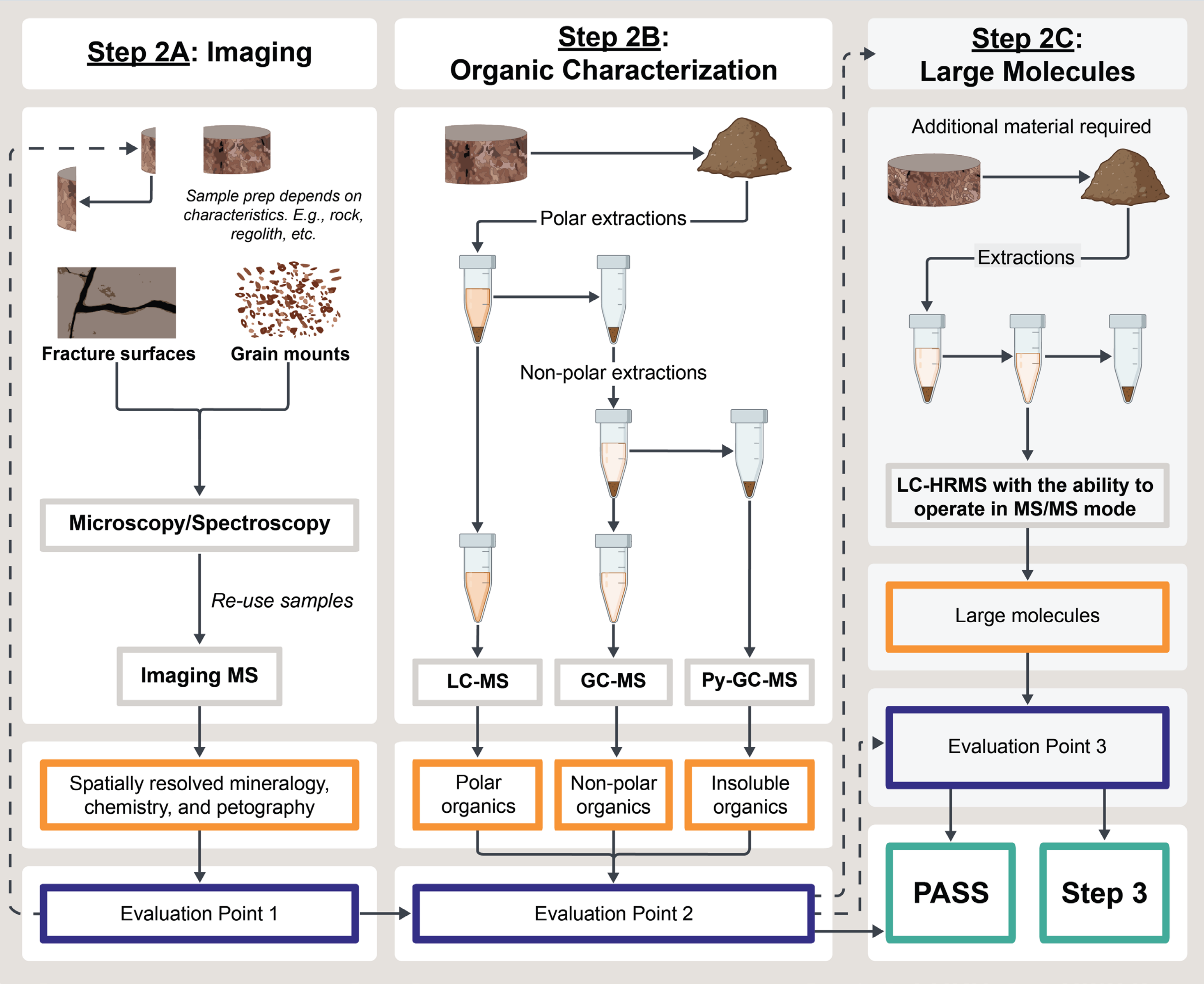
Bayesian statistical analyses to determine if potential modern martian biology is present at a threshold of acceptable risk

Outcomes

PASS
No evidence of biotic chemistry. Samples may leave high-containment facility.

Hold and review
Evidence of modern martian biology. Hold in high-containment for further investigation.

Step 2: Abiotic Baseline

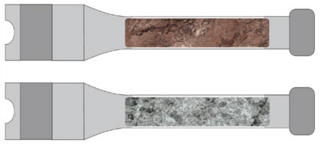


SSAP Overview and Outcomes

SSAP Overview

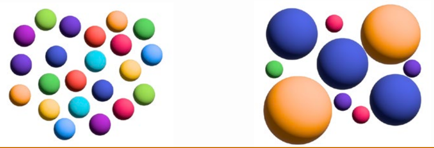
Step 1

Sample heterogeneity



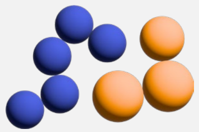
Step 2

Abiotic baseline



Step 3

Biological activity



Bayesian statistical analyses to determine if potential modern martian biology is present at a threshold of acceptable risk

Outcomes

PASS
No evidence of biotic chemistry. Samples may leave high-containment facility.

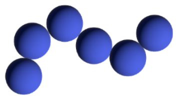
Hold and review
Evidence of modern martian biology. Hold in high-containment for further investigation.

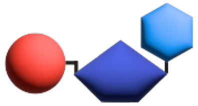
Step 3: Biological Activity (contingent)

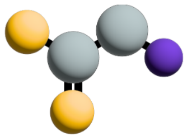
If abiotic baseline is exceeded, determine if signal is from contamination, ancient martian biology, or modern martian biology

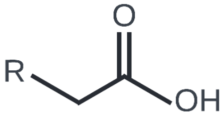
Step 2

Step 3 leverages data produced in Step 2 via further in-depth analyses

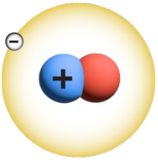

Presence of polymers

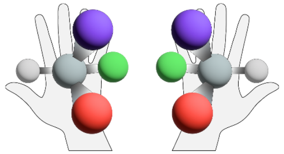

Nucleotides

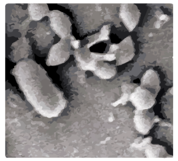

Amino acids



Fatty acids


Isotopes
(Contingent)


Chirality


Morphological data

Step 3A: Recent or ancient?
- **Ancient: PASS**
- **Recent**

Step 3B: Martian or contamination?
- **Terrestrial: PASS**
- **Martian: Hold and review**

Step 3C: Polymer sequencing
- **Terrestrial: PASS**
- **Martian: Hold and review**

SSAP Publications

- **Abiotic Baseline:** Bronwyn L. Teece, David W. Beaty, Heather V. Graham, Gerald McDonnell, Barbara Sherwood Lollar, Sandra Siljeström, Andrew Steele, SSAP Tiger Team, Rachel Mackelprang. The Abiotic Background as a Central Component of a Sample Safety Assessment Protocol for Sample Return. *Astrobiology* 2025 25:10, 671-693
- **Biological Activity:** McDonnell, G., et al. Mars Sample Return Campaign: Biological Risk and a proposed Sample Safety Assessment. *Applied and Environmental Microbiology* (AEM) - Submitted
- **Statistics Publication:** Led by Rachel and Noel, Draft, target journal at present is PLOS One.

- **Conference Paper:** A. Smith, McDonnell, G, NASA/ESA Sample Safety Assessment Protocol Tiger Team (SSAP-TT). What can we learn from the Mars Sample Return mission on risk management and microbial life detection? In, *KILMER Conference 2025: Next Generation Microbiological Quality & Sterility Assurance, Proceedings*. McDonnell G. & A. Benedict (eds). 2025. ISBN # 978-1-57020-913-0.

Next Steps for the Backward Planetary Protection Framework

- Explore the current crew health and performance risk framework to understand if existing processes can be adapted for planetary protection critical decision making.
- Leverage PP knowledge gaps to inform technology developments and parameters.
- Model development and integration of crewed missions
  - *Mars "break-the-chain" modeling*
  - *Crew and Biosphere safety modeling*
- Scientific consensus
  - *Biocontainment needs – quarantine*
  - *Sample decontamination / sterilization*

Questions?

Case Study: Europa Clipper Pc Distributions

COSPAR: *probability of inadvertent ocean contamination ≤1x10^{-4}…*

Probability of contamination - 10^{-7} – 8^{-4}

Breakdown of icy body contamination requirement

Impact/ landing/ops: assessed by Project ≤10^{-2}	Project responsibility: risk assessments tied to design or mission features within a Project's control. • E.C showed probability of impact is 4.2 x 10^{-3} to 2.4 x 10^{-2} (number includes failure probability assessment)
Post-impact/ landing: requires NASA science input ≤10^{-2}	NASA's science community responsibility: risk assessments tied to geological and biological features outside a Project's control. • Expert panel concurred with resurfacing model, showing that given an impact, the probability of subsurface transfer (within 1000 yrs) is 6.5 x 10^{-5} to 3.4 x10^{-2} [2]. This analysis excluded the probability of reaching liquid water and of proliferation • E.C showed probability of ≥1 microorganism survival during spaceflight and on surface (within 1000 yrs) is 7 x 10^{-1} to 9.8 x 10^{-1} [2]

→ E.C. has a relatively high probability of impact (compared to other orbiters/flybys) due to the low altitude flybys required by science objectives.

→ Europa has driving surface transfer properties among the icy satellite family (e.g. youngest surface age, ice thickness)[1]

- Expect other icy bodies to have a probability of subsurface transfer less than or equal to that of Europa

[1] the south pole of Enceladus is arguably equally driving

[2] McCoy, K. et al. 2001. *Europa Clipper Planetary Protection Probabilistic Risk Assessment Summary*. Planetary and Space Science.