Contamination Control (CC) and Planetary Protection (PP) Implementation and Verification

Scope Description
The CC and PP subtopic develops new technologies or supports new applications of existing technologies to clean spacecraft, instrumentation, or hardware, while assessing for molecular and biological contaminants to improve NASA's ability to prevent forward and backward contamination.

CC prevents the degradation of the performance of space systems due to particulate and molecular contamination. For CC efforts, understanding and controlling particulate and molecular contaminants supports the preservation of sample and science integrity and ensures spacecraft function nominally. NASA is seeking analytical and physics-based modeling technologies and techniques to quantify and validate submicron particulate contamination; low-energy surface material coatings to prevent contamination; modeling and analysis of particles and molecules to ensure hardware and instrumentation meet organic contamination requirements; and improved technologies for the detection and verification of low levels of organic compounds on spacecraft surfaces.

PP prevents forward and backward contamination in order to protect planetary bodies, including the Earth, during responsible exploration. Forward contamination is the transfer of viable organisms and bacterial endospores from Earth to another planetary body. Backward contamination is the transfer of biological material, with the potential to cause harm, from a planetary body to Earth's biosphere. Understanding potential CC and PP contaminants and preventing the contamination of our spacecraft and instruments in general also supports the integrity of NASA sample science and mitigates other potential impacts to spacecraft function.

NASA is seeking innovative approaches to address these challenges through:

- Improvements to spacecraft cleaning and sterilization that are compatible with spacecraft materials and assemblies.
- Prevention of recontamination and cross contamination throughout the spacecraft lifecycle.
- Advanced technologies for the detection and verification of organic compounds and biologicals on spacecraft, specifically for microbial detection and assessments for viable organism and deoxyribonucleic-acid-(DNA-) based verification technologies and that may encompass sampling devices, sample processing, and sample analysis pipelines.
- Active in situ recontamination/decontamination approaches (e.g., in situ heating of sample containers to drive off volatiles prior to sample collection) and in situ/in-flight sterilization approaches (e.g., UV or plasma) for surfaces.
- Development of analytical and modeling-based methodologies to address bioburden and probabilistic risk assessment biological parameters to be used as alternatives to demonstrate requirement compliance.
- Enabling end-to-end sample return functions to ensure containment and pristine preservation of materials gathered
on NASA missions (e.g., development of technologies that support in-flight verification of sample containment or in-flight correctable sealing technologies).

Examples of outcomes:

End-to-end microbial reduction/sterilization technology for larger spacecraft subsystems.
Microbial reduction/sterilization technology for spacecraft components.
Ground-based biological contamination/recontamination mitigation system that can withstand spacecraft assembly and testing operations.
In-flight spacecraft component-to-component cross-contamination mitigation system.
Spacecraft sterilization systems for target body ground operations.
Viable organism and/or DNA sample collection devices, sample processing (e.g., low biomass extraction), and sample analysis (e.g., bioinformatics pipelines for low biomass).
Real-time, rapid device for detection and monitoring of viable organism contamination on low-biomass surfaces or in cleanroom air.
Bioburden spacecraft cleanliness monitors for assessing surface cleanliness throughout flight and surface operations during missions.
DNA-based system to elucidate abundance, diversity, and planetary protection relevant functionality of microbes present on spacecraft surfaces.
An applied molecular identification technology to tag/label biological contamination on outbound spacecraft.
Molecular mapping and detection technology for organic contamination on outbound and returned spacecraft and spaceflight hardware.
Low surface area energy coatings.
Molecular adsorbers ("getters").
Technologies to assess human contamination vectors and safety for missions traveling to the Earth’s Moon and human missions traveling to Mars.
Experimental technologies for measurement of outgassing rates lower than 1.0×10-15 g/cm2/sec with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (e.g., high-energy radiation, ultraviolet radiation, atomic oxygen exposure).
Physics-based technologies for particulate and molecular transport modeling and analysis for complex geometries with moving elements (e.g., rotating solar arrays, articulating robotic arms) in continuum, rarefied, and molecular flow environments, with additional physics (e.g., electrostatic, vibro-acoustic, particle detachment and attachment capabilities).
A ground-based containment system that protects the Earth from restricted Earth-return samples, protects the samples from terrestrial contamination and allows for hardware manipulation and preliminary characterization of samples (e.g., double-walled isolators).
Expected TRL or TRL Range at completion of the Project
2 to 6

Primary Technology Taxonomy
Level 1
TX 07 Exploration Destination Systems

Level 2
TX 07.3 Mission Operations and Safety

Desired Deliverables of Phase I and Phase II
Research Analysis Prototype Hardware Software
Desired Deliverables Description
Phase I deliverable: As relevant to the proposed effort—proof-of-concept study for the approach to include data validation and modeling.
Phase II deliverable: As relevant to the proposed effort—detailed modeling/analysis or prototype for testing. Areas to consider for deliverables: technologies, approaches, techniques, models, and/or prototypes, including accompanying data validation reports and modeling code demonstrating how the product will enable spacecraft compliance with PP and CC requirements.

State of the Art and Critical Gaps
PP state of the art encompasses technologies from the 1960s to 1970s Viking spacecraft assembly and test era along with some more recent advancements in sterilization and sampling technologies. The predominant means to control biological contamination on spacecraft surfaces is to use some combination of heat microbial reduction
processing and mechanical removal via solvent cleaning processes (e.g., isopropyl alcohol cleaning). Notably, vapor hydrogen peroxide is a NASA-approved process, but the variability of the hydrogen peroxide concentration, delivery mechanism, and material compatibility concerns still tend to be a hurdle to infuse it on a flight mission with complex hardware and multiple materials for a given component. Upon microbial reduction, during spacecraft integration and assembly, the hardware then is protected in a cleanroom environment (ISO 8 or better) using protective coverings when hardware is not being assembled or tested. For example, terminal sterilization has been conducted with recontamination prevention for in-flight biobarrriers employed for the entire spacecraft (Viking) or a spacecraft subsystem (Phoenix spacecraft arm). In addition to the hardware approaches developed for compliance, environmental assessments are implemented to understand recontamination potential for cleanroom surfaces and air. Biological cleanliness is then verified through the NASA standard assay, which is a culture-based method. Although the NASA standard assay is performed on the cleanroom surfaces, DNA-based methodologies have been adopted by some spaceflight projects to include 16S and 18S ribosomal-ribonucleic-acid- (rRNA-) targeted sequencing, with metagenomic approaches currently undergoing development. Rapid cleanliness assessments can be performed, but are not currently accepted as a verification methodology, to inform engineering staff about biological cleanliness during critical hardware assembly or tests that include the total adenosine triphosphate (tATP) and limulus amoebocyte lysate (LAL) assays. Variability in detector performance thresholds in the low biomass limit remain a hurdle in the infusion of ATP luminometers for spaceflight verification and validation. Moreover, with recent missions leveraging probabilistic modeling for biological contamination, modeling has become a key tool in demonstrating compliance and helping to drive biological assurance cases for spacecraft cleanliness. Given the complexity of upcoming missions, this is rapidly becoming an emerging need in the discipline to help define parameters and develop upstream models for understanding biological cleanliness, distributions of biological contamination, behaviors of these biologicals on spacecraft surfaces, transport models, etc. In summary, the critical PP gaps include the assessment of DNA from low-biomass surfaces (CC requirements and practices are also evolving rapidly as mission science objectives targeting detection of organisms and life are driving stricter requirements and improved characterization of flight-system- and science-instrument-induced contamination. State-of-the-art CC includes:

Testing and measurement of outgassing rates down to 3.0×10-15 g/cm2/sec with mass spectrometry, under flight conditions (low and high operating temperatures) and with combined exposure to natural environment (high-energy radiation, ultraviolet radiation, atomic oxygen exposure).

Particulate and molecular transport modeling and analysis for forward contamination scenarios of simple and complex spacecraft geometries with electrostatic, vibro-acoustic, particle detachment and attachment capabilities in continuum, rarefied, and molecular flow environments.

Modeling and analysis of particulate flux for assessment of backward contamination scenarios using dynamic approaches (e.g., direct simulation Monte Carlo (DSMC) and Bhatnagar–Gross–Krook (BGK) formulations).

Relevance / Science Traceability

With increased interest in investigating bodies with the potential for life detection such as Europa, Enceladus, Mars, and maybe other bodies, and the potential for sample return from such bodies, there is increased need for novel technologies associated with planetary protection and contamination control. The development of such technologies would enable missions to be able to be responsive to PP and CC requirements as they would be able to assess viable organisms and other particulate and organic contaminants; establish microbial reduction and protective technologies to achieve acceptable microbial bioburden and organic contamination levels for sensitive life detection in spacecraft and instruments to mitigate risk and inadvertent “false positives”; ensure compliance with sample return planetary protection and science requirements; and support model-based assessments of planetary protection requirements for biologically sensitive missions (e.g., outer planets and sample return).

References
Planetary Protection: https://planetaryprotection.nasa.gov/
JPL Planetary Protection Center of Excellence: https://planetaryprotection.jpl.nasa.gov/
Handbook for the Microbial Examination of Space Hardware: https://explorers.larc.nasa.gov/2019APSMEX/SMEX/pdf_files/NASA-HDBK-6022...