Mars Planetary Protection Primer

A Quick-Start Guide for Lower-Cost Orbiters or Flybys

March 24, 2026

NASA **Jet Propulsion Laboratory**
California Institute of Technology

Authors

Akemi Hinzer

Ryan Woolley

Jonathan Murphy

Acknowledgments

Table of Contents

1 Introduction to Planetary Protection for Mars Missions

Planetary protection is both a scientific necessity and a legal obligation, requiring management of organic contamination between Earth and solar system bodies. The 1967 Outer Space Treaty [1] requires nations to conduct space exploration "so as to avoid harmful contamination" of celestial bodies. The Committee on Space Research (COSPAR) Planetary Protection Policy [2] establishes international consensus guidelines for how this principle is implemented in practice. For NASA missions, implementation of the COSPAR guidelines are codified in NASA technical standard NASA-STD-8719.27 [3] and NASA procedural requirements NPR 8715.24 [4].

For Mars, the stakes are high. As one of the most promising places in the solar system to search for life, contamination by terrestrial microbes could compromise the very science that missions are designed to conduct. Introducing Earth organisms into the Martian environment risks false positives in life detection, long-term ecological disturbance, and the loss of pristine environments needed for future research.

Not every Earth microbe on a spacecraft is considered an equal threat. The vast majority of microbes are unable to survive the conditions of space and would die in transit to Mars. Some, however, are able to survive in space. The most well-studied of these are those that form microbial endospores, or spores. These protective structures allow certain microbes to go dormant until favorable conditions are met, allowing the cell to return to a metabolically active state and reproduce. Therefore, a key component of compliance is understanding the spacecraft's bioburden, or density of spores on spacecraft surfaces. A key aspect of planetary protection compliance is ensuring terrestrial spores do not find themselves in such a favorable environment on Mars.

Missions to Mars are sorted into planetary protection categories based on the mission type and on the level of concern for contamination that could compromise future investigations. Category III missions—orbiters and flybys— do not land on Mars but can still pose a contamination risk if impact occurs, whether due to navigation errors, spacecraft failures, or orbital instabilities. Protecting Mars from such contamination ensures the integrity of scientific exploration and upholds international commitments.

Note: For non-NASA missions, NASA planetary protection requirements do not directly apply. However, for U.S.-launched missions, the Federal Aviation Administration (FAA) is the reviewing authority, and the FAA will consult with the NASA Office of Planetary Protection. For non-U.S. missions, local launch licenses will apply. COSPAR [2] is the generally accepted international standard for how to comply with the Outer Space Treaty [1], and many national space agencies align their planetary protection standards with COSPAR, though COSPAR is not itself law.

1.1 Purpose and Intended Audience of This Primer

The NASA Planetary Protection Handbook (2024) [5] provides comprehensive, detailed requirements for all mission categories. However, its depth and scope can be overwhelming, especially for emerging, lower-cost Mars missions such as SmallSats, CubeSats, and commercially sponsored orbiters.

This primer is designed as a quick-start guide. It offers:

- A streamlined decision framework for Category III missions
- Practical tools, including Planetary Protection Equipment List (PPEL) templates (Appendix B) to help teams estimate their spacecraft's bioburden

- Clear entry points to compliance without requiring exhaustive familiarity with every planetary protection document

The intended audience includes:

- Commercial and international mission developers with limited prior experience in planetary protection
- Small, resource-constrained project teams seeking early clarity on requirements
- Mission designers exploring trajectory options, environmental controls, or bioburden mitigation strategies

This primer is not a substitute for official NASA or COSPAR policy. Rather, it is a complementary reference to help teams quickly orient themselves, identify the most relevant compliance path, and know when to seek detailed standards.

The path to compliance with planetary protection policy can feel like a maze of technical and procedural requirements. Mission planetary protection compliance can be achieved by following **prescriptive** guidance from NASA; there is also the flexibility to propose **alternative** approaches to NASA, leveraging this primer as guidance.

This primer frames the process as a **decision tree**, guiding mission teams step by step through a small number of branching choices. At each stage, the team determines whether compliance can be satisfied through mission design or whether they must pursue more resource-intensive options, such as bioburden analysis and mitigation.

This approach provides:

- Early clarity during mission design
- A way to explore different "knobs" (trajectory biasing, build environment, microbial reduction)
- Iterative reuse as mission plans evolve

1.2 Focusing on Category III Missions (Mars Flyby and Orbit)

This primer is restricted to **Category III Mars missions** under COSPAR classification: orbiters and flybys at Mars. It does not address:

- Category I and II missions to places with no potential for indigenous non-Earth life (which does not apply to Mars missions)
- Category III missions to Europa/Enceladus
- Category IV landers/rovers
- Category V sample return missions

2 The Planetary Protection Decision Tree

The decision tree (Figure 1) is the core tool of this primer. The branches of the tree are derived from a standard set of planetary protection requirements found in NASA-STD-8719.27 and represent the most straightforward path to compliance [3]. Note, however, that a mission may propose alternative approaches, as noted in Section 1.2.6 of that same document.

By following these branches, a mission team can determine whether their mission:

- Satisfies planetary protection requirements through trajectory design alone, or
- Must pursue bioburden assessment and mitigation.

The process requires a few key inputs:

- Probability of Mars impact, based on trajectory
- Estimated spacecraft total spores (if mission analysis path cannot demonstrate compliance)

The outputs are clear: Either the mission can demonstrate compliance via mission analysis, or it must apply bioburden accounting and possible reduction measures.

The process is outlined in Section 2, and then the individual decisions and process are described in more detail in the remainder of this primer.

Illustrative case studies in Section 8 show how real missions have demonstrated compliance.

The list that follows summarizes the five main planetary protection requirements for Category III Mars missions.

Category III Planetary Protection Requirements—Mars Orbiter or Flyby

(1) Must be built in **ISO 8 cleanroom** or better (Section 6.1; NASA-STD-8719.27 Section 4.4.3 [3])

(2) Provide relevant **documentation** according to schedule (Section 3; NASA-STD-8719.27 Appendices A-G [3])

(3) **Inventory Organic Material** (only if carrying >1 kg) (Section 3.1; NASA-STD-8719.27 Section 4.3.5 [3])

(4) **Launch vehicle upper stage** or **cruise stage** compliance paths (choose one):
(4a) Trajectory Analysis Path: Chance of Mars impact $<1\times10^{-4}$ in 50 years (Section 4.4.1; NASA-STD-8719.27 Section 4.5.4.1a [3])
OR
(4b) Bioburden Path: Less than 500,000 (5×10^{5}) total spores at launch (Section 5; NASA-STD-8719.27 Section 4.5.4.1b [3])

(5) Main **spacecraft** compliance paths (choose one):
(5a) Trajectory Analysis Path: Chance of Mars impact <1% (1×10^{-2}) in 20 years and <5% (5×10^{-2}) in 50 years (Section 4; NASA-STD-8719.27 Section 4.5.4.2.a [3])
OR
(5b) Bioburden Path: Less than 500,000 (5×10^{5}) total spores at launch or upon impact (Section 5; NASA-STD-8719.27 Section 4.5.4.2.b [3])

Start: Mars Flyby or Orbiter

Satisfy all of...

ISO 8 Cleanroom
(See Section 6.1) — **1**

Provide Relevant Documentation
(See Section 3) — **2**

Inventory Organic Material *(Only if carrying > 1kg)*
(See Section 3.1) — **3**

These 3 are not decisions; they are simply requirements that must be met.

Satisfy either of...

Work closely with Launch Vehicle Provider to satisfy **upper stage** PP requirements via trajectory analysis.

LV Upper Stage or Cruise Stage Trajectory Analysis
(See Section 4.4.1) — **4a**

$P(\text{Mars Impact}) < 1\times10^{-4}$ (50yr)?

Yes / No

LV Upper Stage or Cruise Stage Bioburden Analysis
(See Section 5) — **4b**

≤ 500,000 spores at launch?

Yes / No

Bioburden analysis likely only feasible for *cruise stages*, not LV upper stages

See 3 Mitigation Options below

Satisfy either of...

Spacecraft Trajectory Analysis — **5a**
(See Section 4)

$P(\text{Mars Impact}) < 1\%$ (20yr)?
$P(\text{Mars Impact}) < 5\%$ (50yr)?

Yes / No

Spacecraft Bioburden Analysis — **5b**
(See Section 5)

≤ 500,000 spores to the surface?

(👆 *Including Launch Vehicle Re-contamination, Section 5.2*)

Yes / No

Planetary Protection Requirements Satisfied

Mitigation Option: Build in Cleaner Environment
(See Section 6.1)

Mitigation Option: Hardware Sampling
(See Section 6.2)

Mitigation Option: Microbial Reduction
(See Section 6.3)

Alternative: Burnup/Breakup Analysis
(See Section 7)

May be needed for contamination control anyway
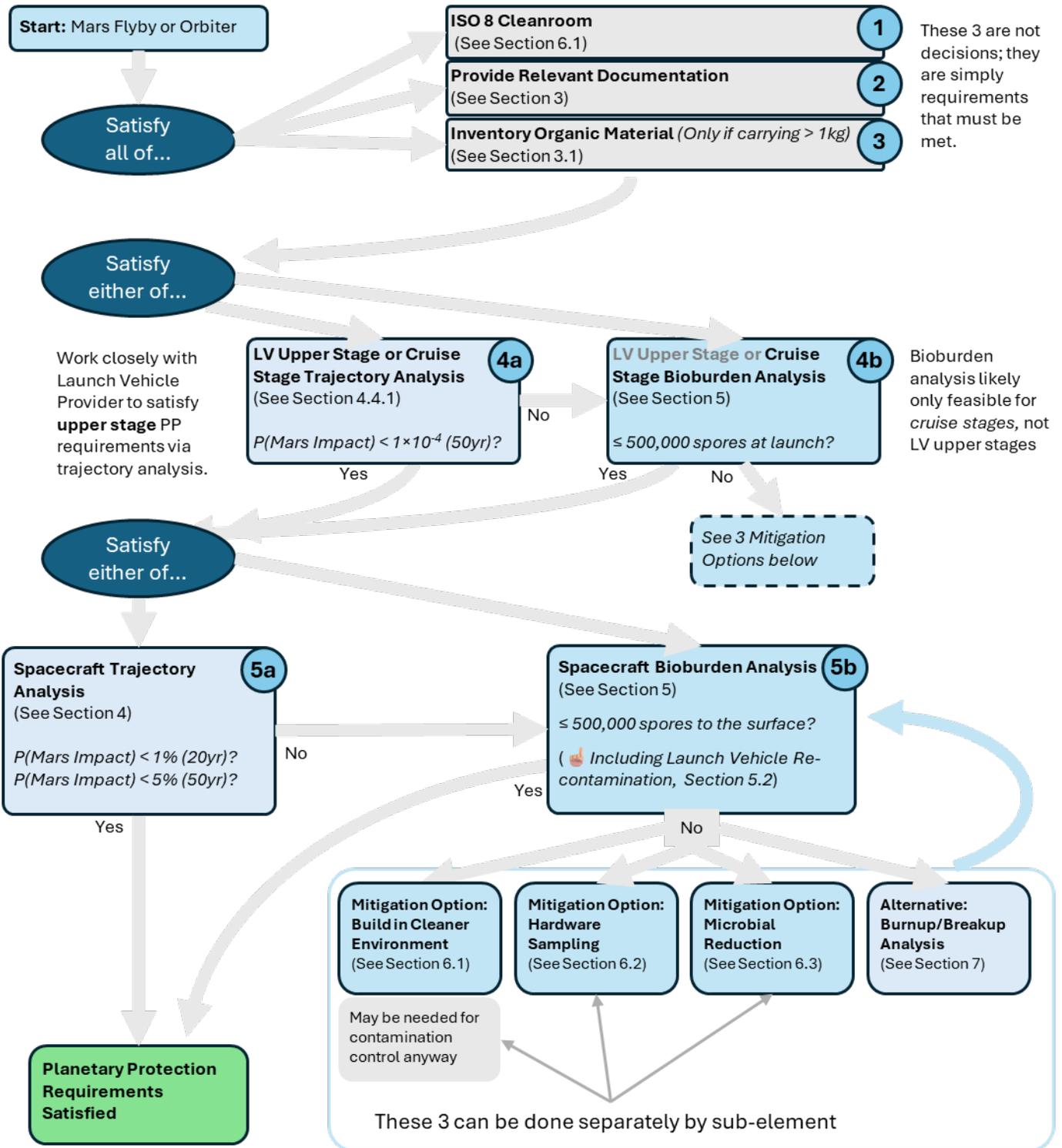
These 3 can be done separately by sub-element

Figure 1: *Planetary protection decision tree for Category III missions to Mars. Note that a mission may propose alternative approaches, as noted in Section 1.2.6 of NASA-STD-8719.27 [3].*

2.1 Nondecision Requirements

Every Category III mission must meet the following three requirements:

> **(1)** The spacecraft must be built in ISO 8 cleanroom or better (Section 6.1; NASA-STD-8719.27 Section 4.4.3
>
> **(2)** The mission must provide relevant documentation according to schedule (Planetary Protection Plan, pre-launch, etc.) (Section 3; NASA-STD-8719.27 Appendices A–G [3]).
>
> **(3)** The mission must inventory organic material (in quantities >1 kg) (Section 3.1). Note that the definition of "organic" is broad, here. It includes tape, paints, plastics, and other hydrocarbon-based materials that might decompose into chemicals that could be interpreted as biosignatures (Section 3.1; NASA-STD-8719.27 Section 4.3.5 [3]).

These are not major design decisions; they are simply requirements that must be met. They are not treated in depth in this primer, but see the noted sections for additional information and references.

2.2 Upper Stages and Cruise Stages

There are two branches for upper stages and cruise stages that leave Earth orbit. The mission may take either path for any such vehicle elements.

2.2.1 Upper Stage and Cruise Stage Trajectory Analysis Path

> **(4a)** Show that the chance of the upper stage or cruise stage impacting Mars is $<1\times10^{-4}$ within 50 years.

The upper stage of the launch vehicle is assumed to be contaminated with bacterial spores. In the case of a high-energy escape trajectory for a typical cruise trajectory to Mars (excluding cases in which the spacecraft uses electric propulsion to follow a low-thrust trajectory), after spacecraft separation, the upper stage will generally be in a heliocentric orbit that brings it close to Mars. If nothing were done, there would be a risk of impacting and contaminating Mars. The typical approach to avoiding this is to bias the launch targets away from Mars, perform a contamination and collision avoidance maneuver (CCAM) after spacecraft separation, then dump or burn all remaining propellant (i.e., blowdown).

The project should work closely with the launch vehicle provider on this. See Section 4.4.1 and NASA-STD-8719.27 Section 4.5.4.1 [3] for further details.

For a cruise stage that will carry a vehicle to Mars, if it separates early enough from other Mars-bound vehicles, this trajectory analysis path might be achievable.

2.2.2 Upper Stage and Cruise Stage Bioburden Path

For a cruise stage that separates very late from a Mars-bound vehicle, impact with Mars may be likely or even unavoidable (e.g., for Mars landers and rovers). In such a case, the cruise stage can comply via a bioburden approach:

> **(4b)** Show less than 500,000 (5×10^{5}) total spores at launch on the vehicle (Section 5, Section 6)

This can be done separately from other vehicles and analyzed using a PPEL approach. See Section 2.3.2 for the related compliance branch for spacecraft. See Section 5 for further explanations of bioburden accounting and Section 6 for strategies to reduce the bioburden if initial analysis shows it will be too high.

For a launch vehicle upper stage, which is large and has unavoidably been exposed to uncontrolled environments, this bioburden path is likely infeasible, and the project should use trajectory design and analysis via path 4a.

For cruise stages and launch vehicle components, unlike for spacecraft, NASA-STD-8719.27 does not provide a path for demonstrating bioburden upon impact with the Martian surface rather than at launch. However, note the case of MarCO (case study in Section 8), where the spacecraft was classified as a launch vehicle component but was able to demonstrate contamination avoidance at the surface with a burnup and breakup analysis.

2.3 Main Compliance Decisions for Category III Mars Spacecraft

For the spacecraft itself, there are two main branches of the planetary protection compliance tree for Category III Mars missions: spacecraft trajectory analysis (5a) and spacecraft bioburden analysis (5b).

2.3.1 Spacecraft Trajectory Analysis Path

The fifth requirement can be satisfied via spacecraft trajectory analysis (5a), as follows:

> **(5a)** Chance of Mars impact <1% (1×10^{-2}) in 20 years and <5% (5×10^{-2}) in 50 years (Section 4)

For most missions, especially for larger spacecraft, this is expected to be the lower-cost approach to demonstrating compliance. Every mission will need to perform some mission analysis anyway, and this can leverage that work.

If the trajectory analysis does not show a satisfactorily low likelihood of Mars impact, or if Mars impact trajectory analysis cannot be performed, then the project must demonstrate compliance via bioburden analysis. Note that in the case of a mission performing Mars aerobraking, the bioburden analysis route will certainly be necessary.

See Section 4 and NASA-STD-8719.27 Section 4.5.4.2.a [3].

2.3.2 Spacecraft Bioburden Analysis Path

If compliance for the spacecraft cannot be demonstrated via trajectory analysis, the mission must proceed to branch 5b, bioburden analysis, which requires the following:

> **(5b)** Less than 500,000 (5×10^{5}) total spores at launch or upon impact (Section 5)

This is done using PPELs (Appendix B), which:

- Track spacecraft components and environments
- Apply conservative specification values for spore densities (from NASA-STD-8719.27 [3])
- Output a total spores count, with recontamination factors included

If spores are ≤500,000, requirements are satisfied. If spores are >500,000, mitigation is required (see Section 6 and Section 7). See Section 5 and NASA-STD-8719.27 Section 4.5.4.2.b [3].

Bioburden Mitigations

If the initial bioburden analysis shows greater than 500,000 bacterial spores, the mission must take mitigation actions to reduce the predicted bioburden below the threshold; otherwise, the mission must perform alternative analysis.

- **Mitigation Option: Build in Cleaner Environment (Section 6.1).** Bioburden can be reduced by building in a cleaner environment. The requirement to build in an ISO 8 cleanroom already reduces bioburden by an

order of magnitude or more relative to an uncontrolled environment. There are opportunities to build in even cleaner environments, which reduce the accounted bioburden further.

- **Mitigation Option: Hardware Sampling (Section 6.2).** By sampling the hardware, the project can get a direct estimate of the actual bioburden on the spacecraft and can remove conservatism from the previously assumed bioburden values in the PPEL.

- **Mitigation Option: Microbial Reduction (Section 6.3).** The bioburden can be reduced via bakeout, chemical vapors, irradiation, or solvent cleaning.

- **Alternative: Burnup and Breakup Analysi**s **(Section 7).** The bioburden requirement applies upon impact to the surface of Mars. If the requirement cannot be met at launch, this approach can demonstrate compliance by showing that the spacecraft would be sterilized upon atmospheric entry such that fewer than 500,000 viable microbes could reach the Martian surface.

3 Timeline and Documentation

From the original mission concept, a project should be able to guess which Planetary Protection Category they will be assigned and plan accordingly. As the design matures, mission categorization must be proposed by the project and concurred by the Mission Directorate Associate Administrator and NASA Office of Planetary Protection. This official categorization will set the actual requirements that the project must work toward and is expected to be determined by the System Requirements Review (SRR). The planetary protection requirements are expected to be set by the Preliminary Design Review (PDR), at which point mission design will have a mature enough understanding of the trajectory to answer the impact avoidance modeling questions for the analysis pathway.

The next step is for the project to write the Planetary Protection Implementation Plan, detailing the strategies and steps that will be taken to meet the appropriate requirements. This plan is concurred by the Office of Planetary Protection and includes any modeling, hardware sampling, bioreduction, and cleanroom use strategies to be employed. The success criteria outlined in this document will be the framework to address in the Pre-Launch Report. As the project formalizes relationships with partners and contractors, the requirements are to be flowed down in those contracts to maintain compliance and traceability before hardware delivery.

In the bioburden accounting path, integration and test phases are the most involved for a planetary protection practitioner. In this phase, cleanroom practices are set and maintained. Here, appropriate bioburden reduction strategies are applied and accounted for in a PPEL.

From here, the requirement compliance is documented and submitted, and mission progress is tracked for any deviations from the original launch and mission design plan.

More than just a checkbox, planetary protection compliance is more of an active conversation. In this workflow, the project is able to choose the methods by which the requirements are satisfied, and periodic checkpoints are implemented to ensure changes to the plan are appropriately captured. The primary audience for these documents is the NASA Office of Planetary Protection, which in turn advises the NASA Chief of Safety and Mission Assurance on the project's compliance and approval. Plan margin for this, as this exchange may take longer than expected.

- **Planetary Protection Mission Categorization Proposal:** This document includes the relevant mission information that is required for categorization, such as target solar system bodies or those that are encountered throughout the tour. The response is due by the SRR. A list of expected elements in this report may be found in Appendix A of NASA-STD-8719.27 [3].

- **Planetary Protection Requirements Document:** This document is a tool to integrate formal requirements into the rest of the project, ensuring project-wide compliance. This is expected by the SRR. A list of expected elements in this report may be found in Appendix B of NASA-STD-8719.27 [3].

- **Planetary Protection Implementation Plan:** This is a report to the NASA Office of Planetary Protection from the project with a dated signature page. It describes a mission overview and defines the project plan to meet planetary protection requirements established by NASA policy. Here, the team outlines the procedures and the approach that the project will implement to comply with requirements. NASA Office of Planetary Protection concurs that the plan is adequate and that the list of requirements is complete. A list of expected elements in this report may be found in Appendix C of NASA-STD-8719.27 [3].

- **Pre-Launch Report:** This report to the NASA Office of Planetary Protection builds on the Planetary Protection Implementation Plan. This report will present, prior to launch, estimated probabilities of impact

of Mars and impact avoidance strategies for any other encountered celestial bodies by all launched hardware. It provides worst-case orbit lifetime, organic materials inventory for all launched hardware, and any changes (relative to the Planetary Protection Implementation Plan) in the mission plan or spacecraft design of significance to planetary protection. This report also contains any required bioburden level reporting and documents the methods by which those estimates were obtained. Any anomalies relevant to planetary protection and their mitigations should also be captured here. The approval of the NASA Office of Planetary Protection will signify satisfactory compliance with all planetary protection requirements measurable before launch. A list of expected elements in this report may be found in Appendix D of NASA-STD-8719.27 [3].

- **Post-Launch Report:** This is a supplement to the Pre-Launch Report sent to the NASA Office of Planetary Protection. This report will summarize and update the Pre-Launch report to document the effects of launch and early post-launch events. A list of expected elements in this report may be found in Appendix E of NASA-STD-8719.27 [3].

- **Extended Mission Report:** In the case that the spacecraft outlasts its original mission duration, an extended mission report may be submitted to evidence the continued compliance for an additional set duration of time. A list of expected elements in this report may be found in Appendix F of NASA-STD-8719.27 [3].

- **End-of-Mission Report:** This is a supplement to the Pre-Launch Report sent to the NASA Office of Planetary Protection. This report will document the actual compliance by the project with the issued planetary protection requirements for the spacecraft and the disposition of all launched hardware after the formal end of the mission. A list of expected elements in this report may be found in Appendix G of NASA-STD-8719.27 [3].

Table 1: Example documentation schedule. Actual timeline to be negotiated with the Office of Planetary Protection.

Document	Submittal	NASA Office of Planetary Protection Approval
Planetary Protection Categorization Proposal	Before MCR	By SRR
Planetary Protection Requirements Document	Before SRR	Before SRR
Planetary Protection Implementation Plan	90 days prior to launch	60 days prior to launch
Planetary Protection Pre-Launch Report	90 days prior to launch	60 days prior to launch
Planetary Protection Post-Launch Report	60 days after launch	90 days after launch
Planetary Protection Extended Mission Report	90 days prior to planned end of mission	60 days prior to planned end of mission
Planetary Protection End-of-Mission Report	60 days after declared end of mission	90 days after declared end of mission

3.1 Organic Inventory

The intent of the organic inventory is to document and understand the nonmetallic components on a spacecraft, so that there is a record of any organic compounds that have been deposited on Mars. Organic molecules detected by future science efforts then have a cross-reference to understand the possible terrestrial origin of these signals. It is impractical to predict material breakdown and transport across the planet for every item, so this list should be as thorough as possible to include manufacturer, part numbers, and an estimate of mass. Any material, such as tapes, adhesives, and paints, should be listed if they are present in quantities of 1 kg or more. More information may be found in NASA-STD-8719.27 Section 4.3.5 [3]. This list is submitted as a supplement to the Pre-Launch Report.

4 Spacecraft Trajectory Analysis for Planetary Protection Compliance

For low-cost missions, the most effective and often preferred method for satisfying planetary protection requirements is through careful mission design and robust analysis. This is done through considerations for each mission phase and spacecraft navigation based on probabilistic calculations. This section lays out a set of mission design choices to aid in the satisfaction of the planetary protection requirements. In some cases, by simplifying choices, a mission can demonstrate compliance without needing extensive bioburden documentation or hardware treatments.

4.1 Establishing Mission Design Guardrails for Category III Missions

Showing a less than 1% chance of Mars impact throughout the entire mission sequence, especially given possible anomalies, can be very difficult. Trajectories and aimpoints must be selected that can be shown to not impact Mars when uncertainties are propagated from any point along the way.

Obviously, intentionally staying well away from Mars is the best way to ensure a low probability of impact, but this is often at odds with science objectives. There is no "magic" altitude or distance from Mars that is always safe since it will also depend on propulsion, navigation, and operational uncertainties throughout the mission. Regardless of how safe a mission design may seem, a sufficient analysis will always be required to show compliance. As conceptualized in Figure 2, general intuition tells us that there are regions that are:

- **Green:** Sufficiently high to reasonably assume no impact (<<1% chance) for a mission with typical conservative assumptions, but demonstrative analysis is still required
- **Yellow:** Possibly safe, but mission-specific performance parameters are needed to calculate the detailed probabilities of impact
- **Red:** Even with detailed analysis, probability of impact is likely >1%

Figure 2: *Representative regions of impact probability given closest approach. These regions indicate the relative likelihood of being able to show planetary protection compliance through trajectory analysis, even with more rigorous methods.*

These regions, or "guardrails," do not remove the need for a thorough analysis but rather give a rough guess at the likely outcome a priori. The regions are principally defined by the closest approach during a flyby, the altitude of orbital insertion, or the B-vector magnitude (see Section 4.4.2 and Figure 5 on the B-plane and B-vector). The probabilistic nature of the planetary protection requirements leads to a probabilistic analysis. For example, the Europa Clipper mission, which flew by Mars en route to Europa in 2025 and received a Category III designation, developed an end-to-end probabilistic risk assessment (PRA) to demonstrate compliance and inform design

decisions [6]. Their PRA was motivated by the desire to determine the proper amount of bioburden reduction required prelaunch. After a thorough effort of statistical modeling, it was determined that the planetary protection requirements were met without the need for any ground-based sterilization efforts. Their novel end-to-end approach set a precedent for how future missions will handle planetary protection. Note that the Europa Clipper approach is included as Appendix 4 of the NASA Planetary Protection Handbook [5].

4.2 Efficiently Determining the Need for Further Trajectory Analyses

No mission trajectory can be considered 100% safe without adequate analysis. It is possible, however, to be judicious in assessing the level of detail that may be needed and in determining the possible "choke points" of the mission where planetary protection compliance may be the most challenging. A quick assessment is recommended to determine whether mission analysis is the best path toward compliance:

1. Start with a coarse assessment of the full mission profile. Does the nominal mission come within 400 km of Mars? If so, the bioburden compliance path may be more efficient than attempting to demonstrate a probabilistic impact avoidance.
2. Early analyses should start with pessimistic but reasonable inputs, such as high spacecraft failure rates, degraded propulsion performance, and poor navigation accuracy. This will establish bounding conditions.
3. Conduct a low-fidelity Monte Carlo propagation. Propagate the trajectory through all major mission phases to identify regions of higher risk. This rough simulation should reveal where more detailed analysis or model refinement is needed.
4. If the 1% probability-of-impact threshold is satisfied with very conservative assumptions, more detailed models may not be necessary.
5. Where the threshold is not met, work to refine assumptions with more reflective values and rerun analyses with higher-fidelity dynamics and updated reliability parameters to confirm compliance or identify required design changes.

This quick assessment method allows for early identification of planetary protection–sensitive mission elements while reserving detailed trajectory modeling for cases where it meaningfully reduces uncertainty or supports compliance documentation.

4.3 Impact Probabilities and Spacecraft Failure Rates

Calculating the probability of impact, $P(I)$, can be simplified to a series of calculations of two conditional terms. These are the probability of failure and the probability of impact given failure:

$$P(I) = \sum P(F)P(I|F), \qquad\qquad (1)$$

where $P(F)$ is the probability of catastrophic spacecraft failure over a defined segment of the mission. For a typical Category III mission, the spacecraft cannot contaminate Mars if an impact does not occur, and an impact cannot occur if a failure does not occur. Therefore, both failure and impact probabilities must be considered.

Unforeseen anomalies often arise during a mission, and some of them can affect whether the mission can continue to meet planetary protection requirements. To maintain compliance, the mission team should be able to monitor spacecraft components and parameters. Single events that could jeopardize compliance include failures in propulsion, guidance and navigational control, avionics, and telecom. Even with monitoring systems in place,

potential anomalies must be considered during pre-launch analyses by estimating failure rates for inclusion in probabilistic assessments.

The probability that a spacecraft remains healthy at time t is given by:

$$R(t) = e^{-\lambda t}, \tag{2}$$

where λ is a general variable for failure rate. Failure rates are typically estimated from historical data of relevant past missions. They can be refined through redundancy, reliability testing, space environment modeling (micro-meteoroids, orbital debris, solar cycle, etc.), and operation plans, for example. One estimate puts the reliability (catastrophic failure rate) of previous missions from 1 failure per 143 years to 1 failure per 38 years [7].

With estimates for reliability and recovery in hand, $P(F)$ over any given segment can be estimated. The probability of impact given a failure, $P(I|F)$, is calculated by propagating state knowledge and navigational uncertainties forward to determine the odds of Mars impact if a failure were to occur at that moment. Equation (1) is then used to accumulate the probability of impact over the entire trajectory. Monte Carlo simulations or covariance-based state-transition methods are commonly used for this purpose. Note, however, that covariance-based methods fail for long propagations (more than half a heliocentric revolution) or if the propagation includes a planetary flyby.

This combined approach of linking system reliability with orbital dynamics ensures a consistent assessment of compliance with the $\leq 1\%$ (or 1×10^{-4} for launch vehicle elements) Mars impact probability requirements.

4.4 Planetary Protection Compliance by Mission Phase

Planetary protection requirements apply throughout the entire mission from launch through disposal. For Mars Category III missions, this means showing compliance during each major mission phase shown in Figure 3, which illustrates a representative sequence for a typical Mars orbiter or flyby. These phases include launch and upper-stage disposal, cruise, Mars approach and closest encounter for flybys, Mars orbital insertion (MOI) for orbiters, operations, and eventual end of mission or disposal. Early phases emphasize trajectory biasing and upper-stage impact avoidance, mid-phases focus on verifying impact probabilities and maintaining system reliability, and later phases address long-term orbital stability and post-mission disposal consistent with NPR 8715.24 [4] and NASA-STD-8719.27 [3].

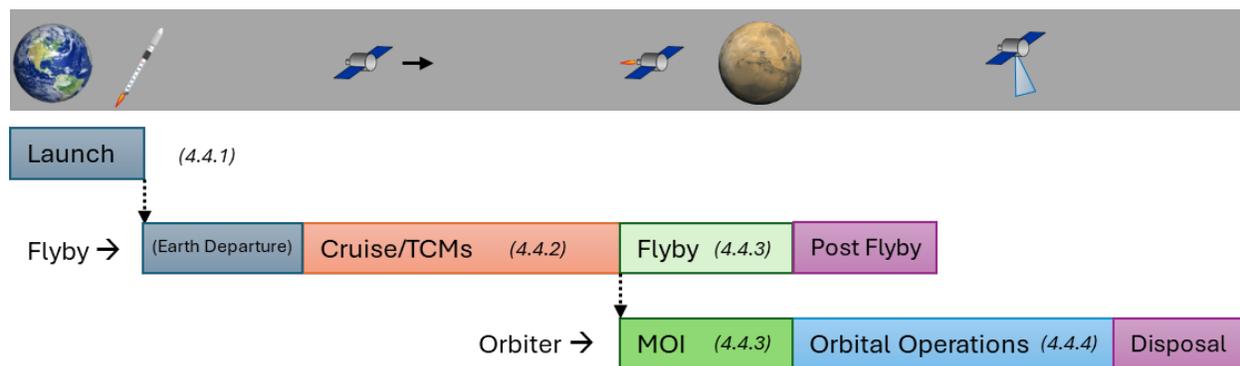*Figure 3: Phases of a typical mars mission.*

These mission segments define a framework for planetary protection compliance that ensures no single phase introduces unmitigated contamination risk. The subsections that follow describe these stages in greater detail and outline the analyses, documentation, and decision points required to maintain planetary protection assurance throughout the mission.

For each mission phase, the project can use the green/yellow/red guardrail framework introduced in Section 4.1 as a practical gauge of planetary protection risk. Green indicates that compliance with planetary protection thresholds is likely even with conservative assumptions, yellow indicates that tightening of assumptions or refined analyses might be needed, and red indicates that compliance probably cannot be demonstrated without mitigation or redesign. Each of the following sections provides representative indicators for applying this framework.

4.4.1 Launch Biasing and Upper Stage Disposal

The upper stage of the rocket body post separation is also on a heliocentric trajectory headed in the same general direction toward Mars. Because the rocket body is inherently contaminated, it must be shown that there is less than 1×10^{-4} chance of impact with Mars within 50 years. This 1×10^{-4} probability includes the probability of an upper stage anomaly. The same is true for any kick stage, transfer vehicle, or cruise stage (see path 4a in Figure 1). If the impact avoidance probability cannot be met, then the element must meet the total bioburden requirement of $<5\times10^5$ spores at launch (path 4b).

After launch, the upper stage typically must perform three tasks: payload separation, CCAM, and blowdown (i.e., dump or burn the remaining propellant). Preceding each task, the upper stage slews to a specified attitude. These slews can be used as control knobs for the final departure vector of the upper stage to allow it to achieve compliance with planetary protection requirements.
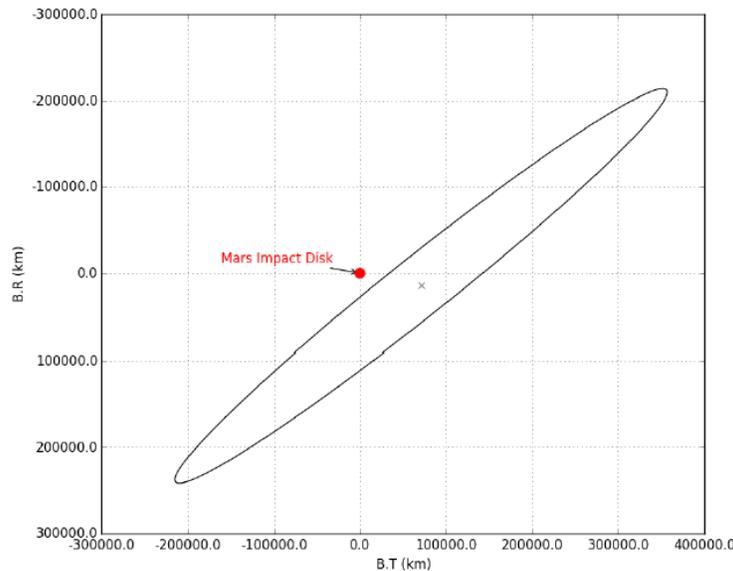

Figure 4: *Upper stage uncertainty ellipsoid biasing at Mars close approach.*

After a successful separation-CCAM-blowdown sequence, the upper stage will fly a ballistic trajectory with no further maneuvers. Nominally, the aimpoint of the closest approach is biased in a direction such that the uncertainty ellipsoid does not overlap with the impact radius of Mars, as depicted in Figure 4. This ellipsoid is calculated by propagating the injection covariance matrix (i.e., uncertainties) forward to closest approach using the state transition matrix, which determines its size and orientation. Anomalies or failures during some stage of the three attitude events require that off-nominal propagations be performed to assess impact probabilities. This must be done through a Monte Carlo approach. The total impact probability is assessed using a Bayesian approach, formulating conditional probabilities at each event following Equation (1).

After the initial flyby, there is still a chance for impact over the next 50 years. The post-flyby trajectory could be in a resonant orbit with Mars, or in the same plane, leading to the possibility of a reencounter. The upper stage could also be perturbed by a subsequent Earth flyby that could then lead to a Mars impact. It is computationally challenging to simulate and rule out all of these possibilities. Even though Mars is extremely small compared to the vastness of space, it turns out that future impacts can rarely be eliminated entirely. Probabilistic strategies laid out by Wallace [8] and Appendix 5 of the Planetary Protection Handbook [5] detail a mathematical approach to reduce the number of Monte Carlo runs needed to demonstrate compliance.

For missions using solar electric propulsion (SEP) for cruise and Mars rendezvous, the optimized Earth departure velocity is often well below the energy needed for a ballistic encounter with Mars (launch C_3 ~ 2–10 km^2/s^2). The natural trajectory of the upper stage will not reach the radius of Mars, leaving the only chance for impact from an unlikely Earth flyby and gravity assist with just the right geometry.

Compliance guardrails:

- **Green:** Upper stage is energetically incapable of reaching Mars due to low launch C_3 (e.g., SEP mission), or the mission begins as a rideshare to an Earth or cislunar orbit with subsequent Earth departure.
- **Yellow:** Preliminary CCAM design without finalized trajectory dispersion or stage depletion analysis. Recommend close coordination with launch vehicle provider and repeat modeling at Critical Design Review (CDR).
- **Red:** No CCAM or blowdown is planned, or upper-stage trajectory still intersects Mars' sphere of influence without mitigation.

4.4.2 Interplanetary Cruise and Mars Targeting

The B-plane is an imaginary plane perpendicular to the incoming asymptote of the spacecraft's hyperbolic approach trajectory relative to Mars (Figure 5). It provides a convenient 2-D framework for targeting and visualizing flyby or capture conditions. By projecting the spacecraft's closest approach vector (the B-vector) and uncertainty ellipse onto this plane, navigators can specify where the spacecraft will pass relative to the planet without being tied to the planet's rotation. Small changes in trajectory correction maneuvers (TCMs) can then be expressed as shifts in the B-plane coordinates, which directly relate to periapsis altitude, inclination, and timing of the encounter. Since the gravity of Mars will bend the trajectory on approach, the spacecraft will actually pass much closer to Mars than the B-vector magnitude. There is a circular region below which impact with Mars will occur.
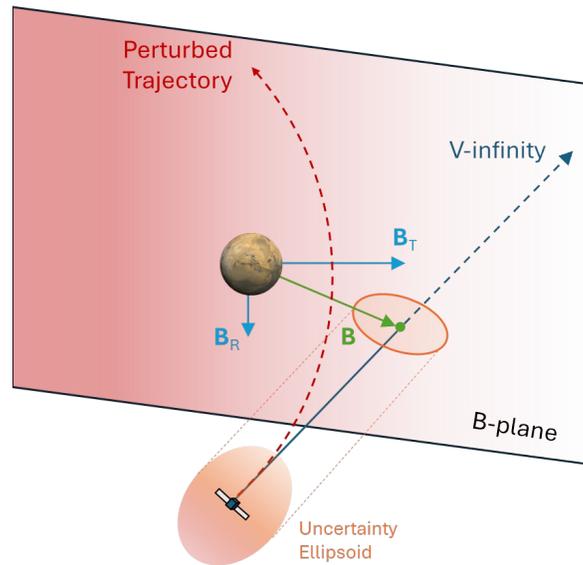
Figure 5: *B-plane diagram for targeting Mars orbit insertion or Mars miss distance, including uncertainty ellipsoid.*

Nominally, a spacecraft is biased well away from Mars after launch in order to keep all trajectories outside of the impact radius. As the cruise phase progresses, the navigational uncertainties are reduced and the uncertainty ellipsoid around the B-vector shrinks. TCMs are performed to clean up errors and move the B-plane vector closer to the desired aimpoint, as illustrated in Figure 6.

Compliance guardrails:

- **Green:** Closest approach of nominal B-plane 3-σ error ellipsoid remains >10,000 km after launch and all TCMs.
- **Yellow:** Post TCM B-plane nominal aimpoints inside 10,000 km.
- **Red:** Navigational uncertainties and/or TCM performance not sufficient to keep error ellipsoids outside impact radius.

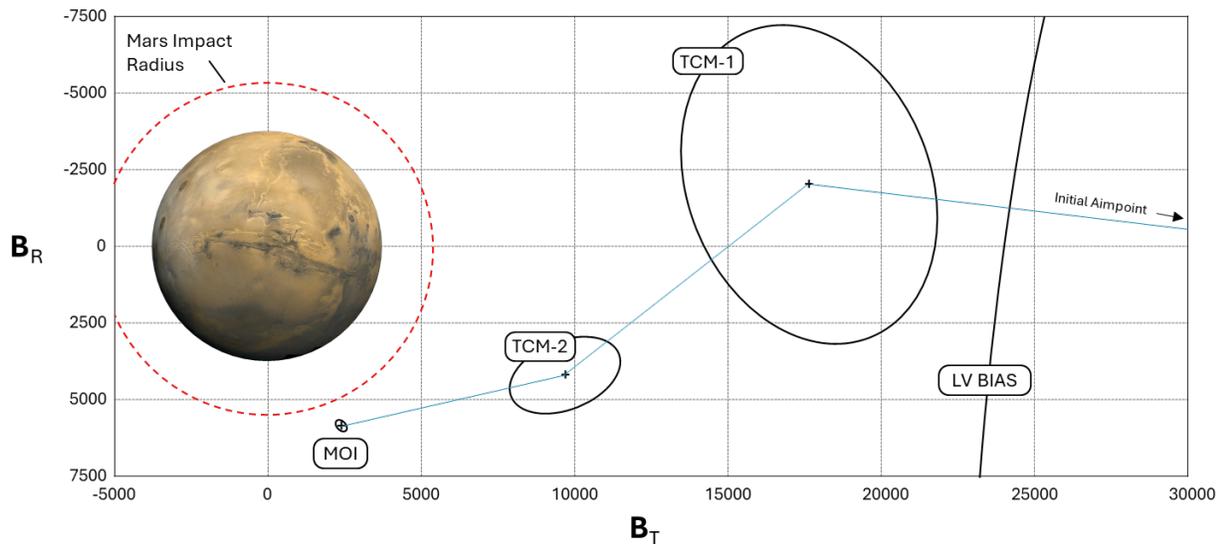**Figure 6:** *Representative B-plane aimpoints for Mars orbital insertion targeting. The initial aimpoint at launch is intentionally biased well away from Mars due to large uncertainties and launch vehicle upper stage disposal. Each TCM moves the aimpoint closer to Mars and decreases the navigational uncertainty ellipse.*

4.4.3 Mars Orbit Insertion or Flyby

Orbiters share a similar cruise and B-plane targeting phase with flyby missions; however, at closest approach, they typically perform an insertion maneuver to establish capture around Mars. Planetary protection compliance extends through the orbit insertion burn and any subsequent altitude-lowering maneuvers that modify the spacecraft's periapsis or orbital lifetime.

The final orbit may be achieved through several methods: low-thrust spiral, high-thrust orbit reduction, aerobraking, or aerocapture (Figure 7). The methods are listed in order of increasing planetary protection risk. Each method introduces different uncertainties in navigation, controllability, and atmospheric modeling that directly affect the probability-of-impact analysis.
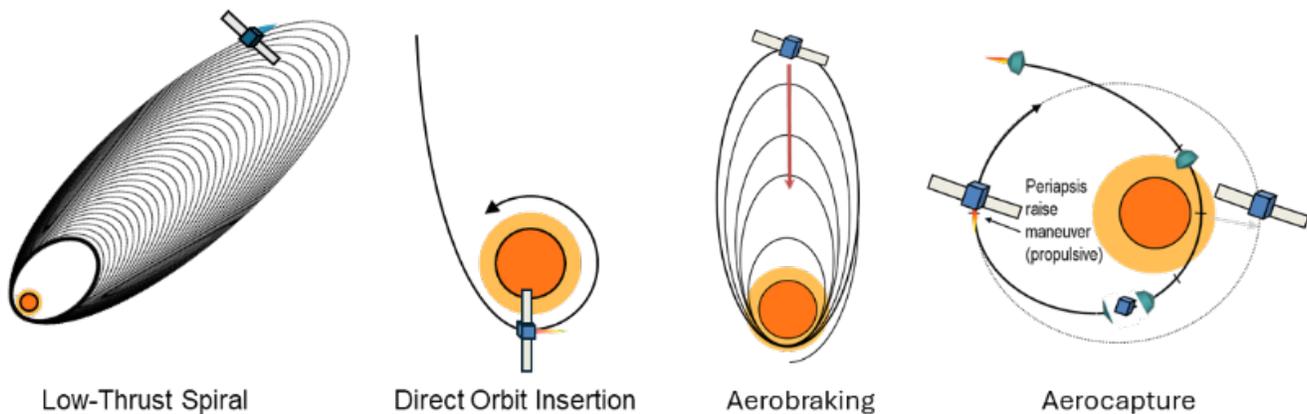

Figure 7: *Methods for Mars capture and orbital insertion.*

4.4.4 Mars Orbit Operations and End of Mission

For Mars orbiters, planetary protection compliance extends beyond insertion. Long-term orbital stability must be demonstrated throughout operations and even after the end of the mission. The spacecraft's orbit should remain stable enough that, even if a total failure occurs at any point, the vehicle will not impact Mars for at least 50 years after launch.

The orbital lifetime depends on several parameters, including altitude, ballistic coefficient, gravity field variations, solar cycle phase, and the atmospheric density model used in analysis. Atmospheric drag becomes perceptible below roughly 400 km, and orbits with periapsis below 300 km rarely survive 50 years. Elliptical orbits can be longer-lived if most of the trajectory remains above the drag-affected region, but long-term gravitational and higher-order perturbations must also be evaluated to ensure stability.

Figure 8 shows estimated orbital lifetimes for low circular orbits given simple assumptions. This plot used a conservative "high" estimate of atmospheric pressure. Over a range of spacecraft ballistic coefficients, orbits that last greater than 50 years begin above 300 km. These results can serve as a starting point for reference, but a more detailed analysis will always be needed for specific circumstances.
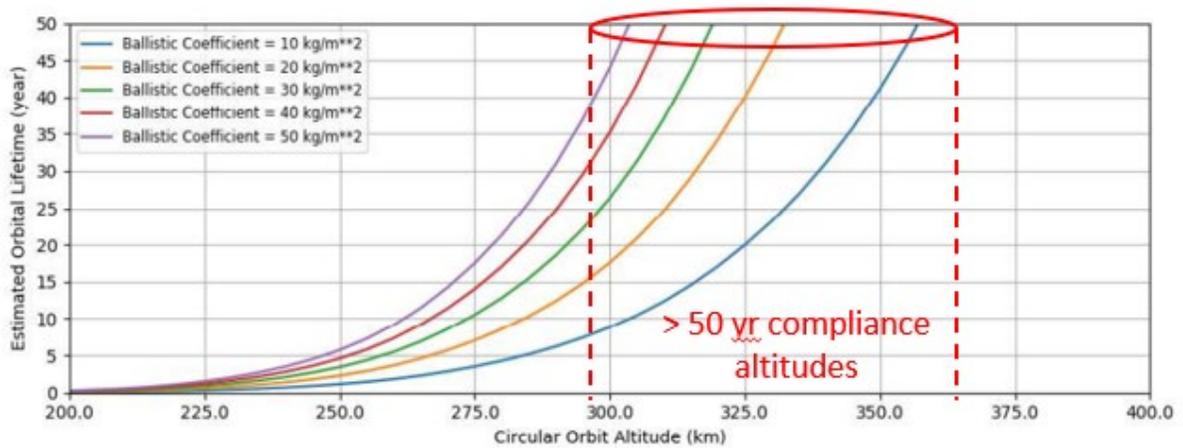
Figure 8: *Circular orbit lifetimes with "high" atmosphere model. "Low" atmosphere models would result in even longer orbital lifetimes. Circular orbits above 300 km–350 km may survive for 50 years in compliance with planetary protection requirements. Higher-fidelity modeling would be needed to prove compliance.*

Compliance guardrails:

- **Green:** Orbits with periapsis above 400 km, showing >50-year lifetime under conservative atmospheric and solar-cycle assumptions.
- **Yellow:** Orbits with apoapses below 400 km.
- **Red:** Orbits with periapsis below 275 km, where 50-year survival cannot be demonstrated.

5 Bioburden Assessment and Tracking

Bioburden refers to the number of microbes on a piece of hardware. For planetary protection, spores—bacteria that are able to form protective structures to survive harsh environments such as space—are the type of microorganism that are counted. In the context of culture-based methods, a single spore becomes visible once it returns to a vegetative state and multiplies into a microbial colony—this is referred to as a colony forming unit (CFU). If the project has chosen to meet compliance by the bioburden route, the first step is to understand the hardware that is being flown.

5.1 Introduction to PPELs

The PPEL is a useful bioburden accounting tool that is based on the project's Master Equipment List (MEL). Because bioburden density is a function of the surface area or volume of a piece of hardware, having this data available is crucial. The distribution of the surface areas between subsystems is a helpful way to track hardware that may have been built in different conditions, may have tighter requirements, or may be exposed to bioreduction treatments.

Appendix B describes the companion document to this primer, which is the PPEL template. For missions using commercial off-the-shelf or heritage components, surface areas for certain parts may be predictably known. This template is intended to guide preliminary estimates for spacecraft.

5.1.1 Assigning Specification Bioburden Values: Surface and Volume

In the absence of ground-truth bioburden analysis, industry-recognized specification values are applied to the hardware surfaces based on the conditions in which the hardware was processed. Look to NASA-STD-8719.27 [3] for these standard values. Flat surfaces are assigned a bioburden density value in colony-forming units per square meter (CFU/m^2). This value is applied across the entire surface area of a piece of hardware, including internal surfaces. A different value is applied to enclosed or mated surfaces. Volumes such as tapes, fuels, lubrications, and adhesives are also assigned a specification value, as a number of colony forming units per cubic meter (CFU/cm^3). These types of materials are difficult to measure exactly, and a conservative estimate of the final amount used should be entered into the PPEL. These bioburden densities are applied across the spacecraft areas calculated in the PPEL for the project, outputting a total spore count. This total number of spores is then compared to the 500,000-spore limit imposed on Category III missions.

5.2 Launch Vehicle Recontamination

The launch event exposes the spacecraft to a harsh and dynamic environment. Here, the air turbulence and sound-induced vibration have the potential to dislodge spores adhered to the external surfaces of the spacecraft and internal surfaces of the launch vehicle fairing. When calculating the 500,000-spore limit on the spacecraft, this potential interaction must be considered. Historically, planetary protection engineers have taken the very conservative stance of assuming all dislodged spores are redistributed solely onto the spacecraft surfaces. An example of this is described in section 2.2.4. of Hendrickson, et al. [9]. In this conservative model, the large interior surface area of the fairing has the potential to have a significant impact on the accounted bioburden for the spacecraft. Current efforts aim to implement computational fluid dynamics modeling for this purpose in the future.

6 Bioreduction Strategies

In many cases, a smaller spacecraft may meet the bioburden limits with specification values taken from the NASA-STD-8719.27 document [3] and having a low accountable surface area. With larger spacecraft, however, it is likely that the increased surface area precludes meeting bioburden requirements by specification value application alone. In the case of a bioburden exceedance, multiple strategies may be selectively implemented to lower the number of spores on the hardware. The strategy chosen will be guided by materials compatibility, facility availability, budget, schedule, and the surface area required to be treated. These sections outline several bioreduction strategies that can be strategically applied to select hardware to bring the total number of spores under the 500,000 limit.

6.1 Impact of Cleanroom Environments on Bioburden

Cleanrooms are controlled work environments with protections built in to control the cleanliness of the air and the temperature, humidity, and particulate burden in a space. These are regularly maintained and certified to internationally recognized standards, outlined in ISO 14644-1:2015 [10]. The standards allow up to a certain number of particles of specific size bins measured per unit volume of air.

While there is no direct control for bioburden in the ISO cleanroom certification process, the environmental regulation and ingress controls serve to lower the bioburden in an assembly facility. Additional precautions such as regular cleaning, gowning procedures, and the low-nutrient environment all work together to help limit contamination. Cleanrooms can help control microbial settling on hardware from the air, and if well implemented, can minimize contact transfer by people working on that hardware.

The controls implemented in a cleanroom environment facilitate the implementation of other disciplines as well, and are likely in the project requirements apart from planetary protection. Contamination control, a discipline that focuses on molecular and particulate contamination on spacecraft hardware, also benefits heavily from cleanroom usage. Many of the practices and procedures to clean and protect hardware will serve multiple purposes to preserve the functional and scientific integrity of a mission.

6.1.1 Cleanroom Standards and Their Application

Section 4.4.3 of NASA-STD-8719.27 [3] states the requirement to build a Category III spacecraft is an ISO 8 or better cleanroom. Compared to an uncontrolled environment, an ISO 8 cleanroom goes a long way to improving the bioburden of the hardware. In a practical sense, the HEPA filtration removes biological particles from the air, and the low-nutrient surfaces and regular cleaning make the cleanroom an inhospitable place for bacteria to exist. From a bioburden accounting perspective, the specification value for an ISO 8 environment is an order of magnitude lower than for an uncontrolled environment, lowering the number of spores accounted on a surface. Including extra precautions in an ISO 8 cleanroom to control biological contamination can reduce the accounted bioburden by an additional factor of 10.

While the requirement is for an ISO 8 cleanroom, building some or all hardware in a cleaner environment is an option, allowing practitioners to apply a lower spec value across the applicable surface areas. When a cleanroom is not available, a laminar flow hood is a viable option for small hardware. With HEPA filtration, laminar flow air, and a certification process to ensure appropriate velocity, these can create small ISO 5 environments in which to build a subset of hardware. Coupled with proper gowning and usage, this can protect hardware from harmful contamination.

The NASA-STD-8719.27 [3] document delineates surface density estimations for the different manufacturing environments, which are directly applied to the hardware surface areas that were assembled in that environment.

6.2 Bioburden Sampling

Directly sampling hardware is the current best method to get a ground-truth estimate of the actual bioburden density of a piece of hardware. The methodology is a standard practice among planetary protection practitioners, with the detailed procedure being outlined in the NASA Standard Assay section of NASA-STD-8719.27 [3]. Proper facilities, training, and laboratory procedures are required to ensure reliability of the results. The high-level steps are as follows:

- Hardware surfaces are directly sampled with sterile swabs or wipes moistened with deionized water, targeting 10% of the hardware surface area with the intent of picking up bacteria on the surface.
- Bacteria are liberated from the sampling device by use of surfactants, sonication, and shaking into a liquid solution.
- The liquid solution is heat shocked to 80°C for 15 minutes to down-select for spore-forming bacteria.
- The liquid solution is aliquoted into bacterial growth media for culture.
- The media plates are incubated for three days, with colonies counted every 24 hours.
- Each colony is assumed to have originated from one viable spore, and this total counted number is adjusted for process efficiency and total hardware surface area to estimate the actual bioburden density.

The bioburden density estimations in Table C-1 of NASA-STD-8719.27 [3] are conservative specification values and, while useful proxies for assayed data, are likely overestimations compared to actual values. Therefore, sampling is a viable method to lower the overall accounted bioburden of a piece of hardware.

6.3 Active Bioburden Reduction

There are multiple options for bioburden reduction on hardware surfaces, including application of heat or gas phase sterilants, or mechanical cleaning with solvents/biocides. Low-sensitivity components with large surface areas are ideal candidates for these strategies to bring the overall bioburden levels down. These are strategies to be implemented before hardware delivery and hardware integration, and can only be valid if the cleanliness is maintained between the treatment and integration. These strategies are often used in concert with a cleanroom to increase efficacy of both strategies.

6.3.1 Bakeout

Also known as dry heat microbial reduction (DHMR), hardware is exposed to high temperatures and vacuum concurrently for a period of time to effectively lower the number of viable spores on a piece of hardware. This can be tuned to the requirements of the hardware. Lower-temperature bakeouts may be implemented for longer exposures to achieve a similar result. Bioreduction by this method is measured in a log-reduction scale. The starting bioburden density, be that sampled or a spec value, is reduced by a certain factor as calculated by the exposure profile. This is a useful approach in difficult-to-clean, high-surface-area hardware, such as wire harnesses and pump assemblies. One thing to consider is the preservation of hardware cleanliness after the bakeout and before integration. External surfaces reexposed to uncontrolled environments must be considered to carry the highest spec value.

The calculations for DHMR follow the guidance as outlined in the European Cooperation for Space Standardization document ECSS-Q-ST-70-57C Section 5.3 [11]. Different values apply to exposed surfaces and enclosed, or mated, surfaces. When planning the bakeout profile for a piece of hardware, coordinate with the contamination control engineer, as one well-planned bakeout may meet outgassing requirements as well.

6.3.2 VHP and EtO

Similar to a bakeout, vaporized hydrogen peroxide (VHP) and ethylene oxide (EtO) are gas phase bioreduction strategies that can be applied to smaller pieces of hardware, with the understanding that the cleanliness state is only valid until the surface is integrated or while the hardware is protected from recontamination in uncontrolled environments.

6.3.3 Solvent Cleaning

There are two main applications of solvent cleaning. For small, difficult-to-clean items such as fasteners, sonication with acetone or isopropyl alcohol (IPA) is an effective cleaning method. For larger or more sensitive surfaces, wiping with a single-use dust-free cloth wetted with IPA is an effective way to reduce the bioburden. Unlike the previous two methods, this method focuses on the physical removal of microbes rather than killing them in situ. This method can be applied in strategic ways:

- Prior to cleanroom ingress from an uncontrolled environment, preferably in an airlock
- On mating surfaces prior to integration and before final sampling
- In combination with routine cleaning of high-traffic areas to prevent contact transfer by engineers to sensitive surfaces

7 Alternative: Burnup and Breakup Analysis

The 500,000-spore requirement applies to the spacecraft as it impacts the surface of Mars, with the assumption that spores do not replicate en route and that the bioburden at Mars arrival is equal to the bioburden at launch. If preliminary analysis shows that the project will not meet the requirement at launch, the project can perform an additional analysis to determine whether heating during atmospheric entry will be sufficient to reduce spore count below the 500,000 threshold. Any component or surface that is shown to reach >500°C for >0.5 s prior to reaching the Martian surface is considered sterilized (or lower temperatures for longer time periods, as specified in an ECSS standard; see ECSS-Q-ST-70-57C [11]).

This "burnup and breakup" compliance path can be resource intensive, requiring high-fidelity modeling of spacecraft materials, reentry dynamics, and thermal response. However, it has been used even for low-cost missions (e.g., the MarCO CubeSats [12]; see case study in Section 8.4). When successful, it can demonstrate compliance even when the bioburden at launch exceeds the Category III or IV thresholds.

References for burnup and breakup:

- NASA Planetary Protection Handbook (2024) section on burnup and breakup models [5]
- COSPAR Planetary Protection Policy (2024 update) [2]
- Paper on planetary protection implementation on Mars Reconnaissance Orbiter mission [13]

This primer acknowledges the burnup and breakup option but does not provide detailed modeling methods. Missions considering this approach should consult the above references and coordinate early with the NASA Office of Planetary Protection.

8 Planetary Protection in Practice: Case Studies from Category III Missions

This section summarizes the paths to planetary protection compliance taken by seven Category III NASA missions, listed in Table 2. Some of these (Dawn, Psyche, Europa Clipper) are not missions to Mars but fly by Mars en route to other destinations and are therefore subject to Mars planetary protection requirements. Some of these missions followed the trajectory modeling path and others the bioburden path, and some pursued both or switched from one path to another.

Table 2: Category III missions and their planetary protection compliance paths.

Mission	Type	Launch Year	Planetary Protection Standard	Main Compliance Path
MRO	Orbiter	2005	NPR 8020.12C	Bioburden path with burnup and breakup analysis
Dawn	Flyby	2007	NPR 8020.12C	Mission analysis path (trajectory biasing for Mars flyby)
MAVEN	Orbiter	2013	NPR 8020.12D	Bioburden path with burnup and breakup analysis and active bioburden reduction
MarCO	Flyby	2018	NPR 8020.12D	Bioburden path with worst-case burnup and breakup analysis
Psyche	Flyby	2023	NASA-STD-8719.27	Mission analysis path (probabilistic impact avoidance for Mars flyby)
Europa Clipper*	Flyby	2024	NASA-STD-8719.27	End-to-end PRA
ESCAPADE	Orbiter	2024	NASA-STD-8719.27	Bioburden path

*Europa Clipper is Category III both because it is a mission to the Jovian moons and because it performs a Mars flyby. It is discussed here in the context of the Mars flyby.

8.1 MRO

The Mars Reconnaissance Orbiter (MRO) launched in 2005 on a mission to map the surface of Mars in high resolution. To achieve this high-resolution imaging, MRO had to operate in a low (255 km x 320 km) Mars orbit. If MRO were to stop maintaining its orbit, the orbit would decay in less than 20 years, so there was no way MRO could comply with planetary protection requirements via the trajectory design path requirements (of <1% for 20 years after the launch date and <5% for 20 to 50 years after the launch date; see branch 5a in Figure 1).

Instead, MRO became the first Mars orbiter to pursue the bioburden accounting compliance route, under the assumption that the spacecraft would enter the Martian atmosphere, and the project demonstrated compliance
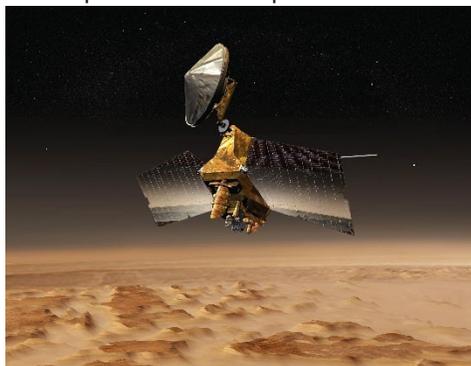
(<500,000 spores upon impact with the Martian surface; see branch 5b in Figure 1) [13]. This meant that the project was not required to demonstrate any further trajectory analysis or any reliability or meteoroid impact analysis, and it was also not required to raise its orbit at the end of the mission.

MRO used a PPEL to calculate and track spore estimates. The size and complexity of MRO meant that it would not be able to meet the 500,000 spore limit without mitigation. MRO therefore employed a series of

mitigations. A burnup and breakup analysis was conducted using computational fluid dynamics and thermal and ablation models. The most conservative scenario (with the least heating) was decay from the operational science orbit, so the burnup and breakup analysis did not need to be performed on any other mission phases (e.g., approach, aerobraking campaign). It was shown that the spacecraft would break up into components over a period of about 20 minutes after atmospheric entry began, in both stable and tumbling entry scenarios. It was shown that all external surfaces of those components would be ablated or would reach at least 500°C for 0.5 s or longer and would therefore be considered sterilized.

What would remain after burnup and breakup was the internal surface area of components, the mated surface area between subcomponents, and encapsulated nonmetallic volumes. For these items, the project used a mix of assessment and mitigations to reduce their spore estimate until they came below the requirement. Some components were estimated to have low spore counts based on their very conservative default PPEL specification values, and no mitigations were taken. Others were assembled in cleaner facilities. Some used direct or proxy burden assays to update the spore counts. Some components were cleaned chemically. Finally, some components, including all the multi-layer insulation (MLI), were treated with dry heat microbial reduction (DHMR).

With this diversity of approaches, and always using conservative assumptions, the project was able to reduce its estimated spore count upon Mars impact to 440,000, just below the required value of 500,000.

8.2 Dawn

The Dawn mission to asteroids Vesta and Ceres launched in 2007 and included a Mars flyby in 2009. Because of this Mars flyby, it was classified as a Category III mission. To comply with planetary protection requirements (at the time specified in NPR 8020.12C), Dawn followed a trajectory design path. The mission was able to show by analysis that the probability of impacting Mars was <1%.

For the launch vehicle upper stage likelihood, the project used a standard analysis and found a negligible likelihood of Mars impact ($<10^{-5}$ vs. the 10^{-4} requirement; see branch 4 in Figure 1).

Because Dawn used a solar electric propulsion (SEP) system, it used continuous thrust arcs rather than discrete maneuvers. The project identified a (still fairly simple) mathematical approach to estimating the probability of impact for continuous thrust arcs. However, due to the trajectory design, a failure during most of the cruise to Mars would simply result in the spacecraft never reaching Mars, for an impact probability of essentially zero. The probability only became nonnegligible in the last 30 days before the Mars flyby. As a conservative simplification, the project took the maximum Mars impact probability during that final period and treated the final 30 days as a discrete maneuver, alongside the high-thrust TCMs that were performed with the spacecraft's chemical propulsion system. A similar approach could be used for post-flyby thrust arcs. This resulted in an estimated probability of Mars impact of ~0.2%, one-fifth of the requirement, and no additional analysis was needed.

8.3 MAVEN

The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission, launched in 2013, faced a significant planetary protection challenge due to its requirement for a low-altitude science mapping orbit. High-resolution science objectives necessitated a periapsis as low as 150 km, with "deep-dip" campaigns reaching 125 km altitudes where atmospheric drag is substantial. Preliminary orbital lifetime analyses revealed that the spacecraft could not satisfy the mission analysis path, as it was unlikely to survive in its mapping orbit for the required 20-year period. The probability of the aging spacecraft surviving long enough to perform a final "quarantine orbit" raise was estimated to be only 85% to 92%, falling short of the 99% threshold (see branch 5a in Figure 1).

To overcome these obstacles, MAVEN adopted the bioburden path, committing to fewer than 500,000 bacterial spores (see branch 5b in Figure 1). Because the large spacecraft's initial bioburden estimate was 13 times higher than this limit, the team leveraged the burnup and breakup analysis strategy pioneered by MRO. This approach allowed the mission to take credit for the sterilization of hardware components that would reach at least 500°C for 0.5 seconds during an unintentional atmospheric entry. Interesting findings from their analysis showed that even the monopropellant hydrazine used in the propulsion system acted as a biocide, effectively sterilizing the fuel tank interior and plumbing. By combining these design credits with rigorous ISO 8 cleanroom assembly and targeted DHMR on components such as cable harnesses and MLI blankets, MAVEN successfully demonstrated that the total biological load delivered to the Martian surface would stay below 500,000 spores.

8.4 MarCO

The Mars Cube One (MarCO) mission was the first interplanetary CubeSat mission and the first to implement planetary protection. Consisting of two 6U CubeSats, MarCO was flown as a technology demonstration using a low-cost, resource-constrained approach. MarCO was treated as a Category III Mars flyby mission and faced the dual challenge of ensuring its own planetary protection compliance while adhering to a strict "do no harm" requirement for the primary InSight lander. Unlike traditional large-scale Mars missions, MarCO could not employ a high-cost contamination control architecture and was carried into space on the outside

(bottom) of the Centaur upper stage, not inside the fairing. Therefore, the two CubeSats were considered **launch vehicle elements** (branch 4 in Figure 1)**.** To satisfy the LV trajectory branch (branch 4a), they needed to demonstrate a probability of impact of $<1\times10^{-4}$ for 50 years. Since they would then fly by Mars, the MarCO spacecraft were *also* considered spacecraft and had to meet the 1% in 20 years and 5% in 50 years non-impact requirement (branch 5a), which would be trivially satisfied if they met the branch 4a launch vehicle trajectory requirement *or* the 500,000 spore bioburden requirement (branch 5b) [12].

For InSight's original 2016 launch date, MarCO met its planetary protection requirements through trajectory analysis and biasing. However, the path to compliance shifted significantly when InSight transitioned from its original launch window to one in 2018. New calculations revealed that MarCO-A could not meet the required 1×10^{-4} probability of impact for 50 years for the launch vehicle requirement without constraining InSight to a subset of its potential launch opportunities. This forced the team to move to the bioburden path, cataloging every surface using conservative uncontrolled manufacturing environment specifications and microbial reduction credits for heating from manufacturing processes where feasible (see branches 4b and 5b in Figure 1). When accounting alone pushed them over the 500,000 spore limit, they leveraged a sophisticated burnup and breakup analysis. By modeling 19 separate spacecraft nodes through atmospheric entry at various entry angles, they demonstrated that even in a worst-case "cold" entry scenario, frictional heating would sterilize or reduce microbial populations on enough components to reduce the spore count from the prelaunch count of 550,000 down to a total surviving bioburden of approximately 420,000 spores—meeting the 500,000 spore requirement with a 16% margin. Note that since MarCO and the launch vehicle were both assembled under uncontrolled conditions, no net bioburden increase was assumed from launch vehicle recontamination; for a spacecraft built in an ISO 8 environment, however, this would be an important factor to consider. Note also that under the current NASA-STD-8719.27, launch vehicle components do not have the explicit option of using burnup and breakup analysis, but the standard *does* allow for alternative approaches, subject to approval (see NASA-STD-8719.27, section 4.4.4, Note 1 [3]). At the time, MarCO was subject to NASA NPR 8020.12D, which was structured differently.

The MarCO team proved that interplanetary CubeSats could satisfy stringent planetary protection standards through smart modeling rather than expensive hardware treatment. They successfully addressed the unique risk of propellant plumes contaminating InSight with spores using bioassays of the propellant and plumbing to show that fewer than one spore would be transferred over the entire mission.

Interesting details:

- 2016 mission design showed compliance with 1×10^{-4} impact, but only some 2018 launch opportunities met this threshold for MarCO-A, leading to spore-count estimation and simple, conservative burnup and breakup approach.

- InSight utilized its first launch opportunity, during which both MarCO-A and MarCO-B met the required impact avoidance threshold, even if neither functioned upon deployment. However, having a bioburden-based solution eliminated the need to maintain this avoidance threshold during Mars approach and flyby. Critically, this meant the MarCO team did not need to reassess impact probability when both CubeSats developed propellant leaks in flight.

- Uncontrolled manufacturing specs say to estimate 100,000 spores/m^2 of surface area. Bioassays of prop unit interiors found 400 spores/m^2—2500 times lower than spec values.

- Worst case spore counts based on spec were ~1,000,000. Standard manufacturing heating reduced this to 550,000.

  - Heat curing the high gain antenna and MLI led to 50% reduction in total spore count pre-launch.
  - Component-level breakup and heating analyses of the worst-case entry profile reduced it to ≤420,000 at impact.

8.5 Psyche
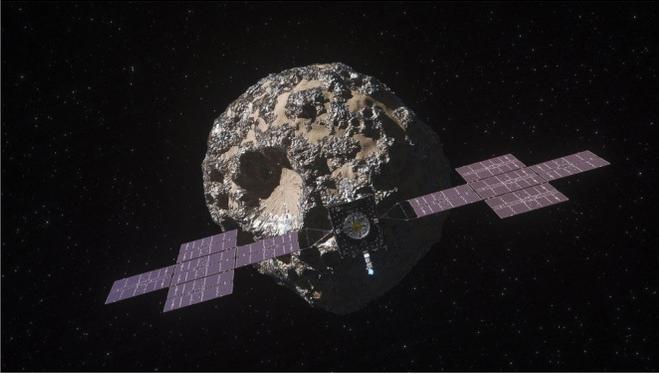
The Psyche mission, launched in 2023 to explore a unique metal-rich asteroid, followed a Category III planetary protection strategy primarily driven by its gravity-assist flyby of Mars. While the target asteroid, 16 Psyche, is not a body of biological concern, the mission was legally obligated to protect the Martian environment from terrestrial contamination. The central challenge for the project was to demonstrate compliance with rigorous Mars impact avoidance requirements while using a novel SEP system. Unlike traditional high-thrust chemical burns, the Psyche spacecraft's nearly continuous low-thrust trajectory necessitated more complex probabilistic modeling to prove that the vehicle would maintain a 99% or higher chance of avoiding Mars impact for 20 years, and a 95% chance for the 50-year post-launch period (see branch 5a in Figure 1).

To satisfy these requirements, the mission prioritized the mission analysis path, using high-fidelity Monte Carlo simulations to propagate tens of thousands of potential trajectories under various failure scenarios. This approach allowed the team to avoid the more resource-intensive path of full hardware sterilization, provided they could mathematically prove the impact risk was sufficiently low. To further mitigate risk, the spacecraft was built in an ISO 8 cleanroom where engineers wore full protective "bunny suits" and air filters strictly limited particulate levels. Compliance was verified through detailed documentation, including a pre-launch report that featured a comprehensive inventory of all organic materials exceeding 1 kg, ensuring a permanent record exists of any terrestrial compounds carried toward the asteroid belt.

Interesting details:

- SEP was a unique challenge for impact analysis. Nearly continuous thrust meant that the probability of impact had to be calculated as a summation of infinitesimal discrete maneuvers along the entire thrust arc.
- Navigation to Mars was simplified by implementing a forced coast during the 60-day pre–Mars flyby period to avoid slight variations in thruster performance, and TCM sequences were used for precise targeting.

8.6 Europa Clipper
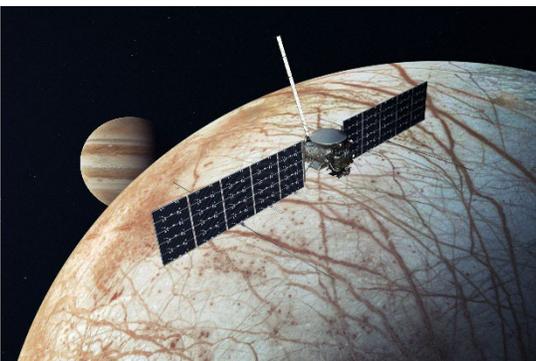
The Europa Clipper mission was given a Category III planetary protection strategy due to a Mars flyby and proximity to Europa. It is the largest spacecraft NASA has ever launched for an outer planet mission, featuring 900 m^2 surface area and basketball court–length solar arrays that required exhaustive cleaning and monitoring. Additionally, the mission has to navigate past Mars and meet strict requirements to avoid contaminating Europa's subsurface ocean with terrestrial life, defined as a probability of less than 1×10^{-4}.

Instead of relying solely on expensive and potentially damaging hardware sterilization, the project adopted a mathematically rigorous end-to-end PRA [6]. This approach integrated three distinct submodels: an impact model to assess spacecraft reliability and trajectory, a resurfacing model to estimate the likelihood of Europa's geological activity transporting debris to the subsurface, and a biological model to calculate microorganism mortality across the mission life cycle. A key finding of this PRA was that the Mars flyby was the driving requirement for bioburden limits. The team demonstrated that the extreme radiation at Jupiter would naturally reduce the spacecraft's biological load to compliant levels before it ever reached Europa, proving that ground-based sterilization was unnecessary. (See also Appendix 4 of the NASA Planetary Protection Handbook [5].)

To ensure scientific integrity and further mitigate risk, the spacecraft was assembled in an ISO 7 cleanroom, a standard 10 times cleaner than the ISO 8 requirement typically levied on Category III missions. This enhanced build environment, paired with trajectory biasing to avoid inadvertent impacts during the early mission phases (see branch 5a of Figure 1), allowed the project to meet all international standards while protecting sensitive electronics. The final compliance was verified through detailed bioassays and high-fidelity Monte Carlo simulations, establishing a new state of practice for future missions to icy worlds.

Interesting details:

- Mars was the cleanliness driver since Jovian radiation would sterilize microbes before arrival at Europa.
- The PRA showed that relying solely on sterilization would require a 13-log reduction in microbes on Earth, but because the mission could prove that the impact risk was so low, only standard techniques were needed.

8.7 ESCAPADE
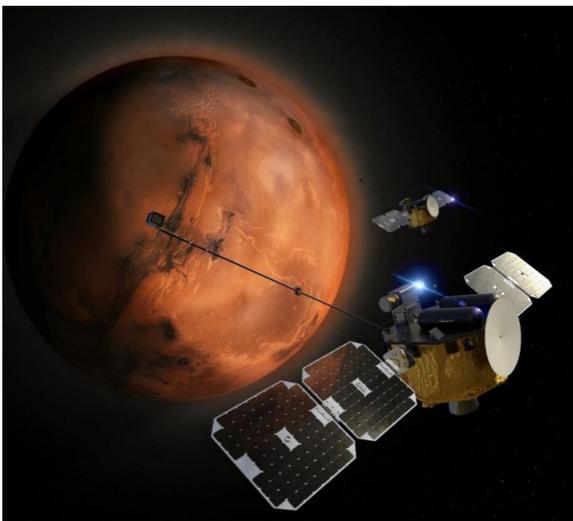
The Escape and Plasma Acceleration and Dynamics Explorers (ESCAPADE) mission was designed as two separate, identical spacecraft. The spacecraft were treated as separate entities, and each was assigned its own 500,000 spore limit. Given the moderate size of the design (~200 kg dry mass), the PPEL approach with the ISO 8 spec value showed the spacecraft would meet its bioburden limit with margin (see branch 5b of Figure 1). Periodic bioburden sampling at key points ensured the ISO 8 precautions were keeping the bioburden within the expected range. The launch vehicle fairing was likewise processed in a controlled environment, a process adjustment driven by contamination control requirements. This allowed the planetary protection team to apply a lower specification value to the fairing interior surface, keeping the bioburden within budget after including launch recontamination analysis.

A. Glossary of Key Planetary Protection Terms

Assay. Collection and analysis of biological contamination with a specified procedure.

Bioburden Accounting. Numerical value applied to a viable count to compensate for incomplete removal of microorganisms from a spacecraft and/or failure to culture microorganisms.

Bioburden. Population of viable organisms on or in spacecraft materials.

Contamination. Unwanted material present on or in the spacecraft/spacecraft assembly environment or introduced into the environment of a solar system body.

Inadvertent Impact. An impact that was not part of baseline operations that could result in harmful contamination addressing both nominal and credible off-nominal trajectories, including orbital insertion anomalies; entry, descent, and landing anomalies; incomplete burnup and breakup; and decay from orbit.

Spores (endospores). Robust and metabolically dormant forms produced from actively replicating bacteria as a response to environmental stressors. Heat-resistant spores are detected using the NASA Standard Spore Assay as an indicator of spacecraft biological cleanliness.

Sterilization. A process designed to reduce bioburden with the intent to destroy or eliminate all forms of viable organisms to a defined assurance level.

Surface Bioburden. Bioburden present on the external and internal surfaces, including surfaces free for gas exchange and surfaces that are sealed from gas exchange.

Total Bioburden (of a spacecraft or system). A bioburden summation of exposed surfaces, mated surfaces, and encapsulated volumes. Inputs can include direct bioassay data, microbial reduction process credits, and standard values based on manufacturing environment cleanliness.

B. PPEL Templates

PPELs provide a method for tracking bioburden spores (whether from estimates or assay) using entries from the vehicle's MEL. The **PPEL Template** (companion Excel file) provides a structure into which the MEL may be imported, converting the surfaces of the spacecraft into a bioburden estimate for the project.

Explanation of columns

The **mass** column can optionally be used to reflect the mass in the mission's MEL. It will be useful for some nonmetallic materials (e.g., adhesives, paints, tapes) whose bioburden estimates may be based on mass (see "spores from nonmetals" below). Organic materials also must be inventoried, and the mass column can be used to track whether the item exceeds the 1kg threshold.

The **current best estimate (CBE) surface area per unit** is the most important input to the PPEL and drives the rest of the estimate calculations. In the template, it is multiplied by the **quantity of the item or by the number of MLI layers** to produce the **total surface area.**

The **manufacturing environment before Assembly, Test, and Launch Operations** provides conditions with which to estimate the initial **spores from surface area**. NASA-STD-8719.27 Table C-1 delineates surface density estimations for spores depending on manufacturing environment, shown in Table 3.

Table 3: *Spore surface density estimates for different manufacturing environments (from NASA-STD-8719.27 Table C-1).*

Manufacturing Environment	Surface Density*
ISO 7 cleanroom or better, biologically controlled	$50/m^2$
ISO 7 cleanroom, particle controlled	$500/m^2$
ISO 8 cleanroom, biologically controlled	$1\times10^3/m^2$
ISO 8 cleanroom, particle controlled	$1\times10^4/m^2$
Uncontrolled manufacturing	$1\times10^5/m^2$

*For estimating surface densities for vegetative microorganisms and not just spores, multiply values by a factor of 10.

In the Excel Template, a table lookup pulls the appropriate surface density value from Table 3 and multiplies it by the CBE surface area to arrive at a total number of spores.

Spores from nonmetals and **spores from electronic piece parts** can be estimated similarly using spore density values from NASA-STD-8719.27 Table C-2 (shown in Table 4) under "Encapsulated Organisms" for substances such as foams or lubricants. These values may not be captured in early design but may become driving later on. If the volume of the item is not known directly, it can be derived from the mass and density.

Table 4: *Spore density estimates for enclosed and encapsulated areas (from NASA-STD-8719.27 Table C-2).*

Substance	Encapsulated Organisms
Electronic piece parts	$3–150/cm^3$
Nonmetallic material, average	$1–30/cm^3$
Other nonmetallic materials	$1–30/cm^3$
Manufacturing Environment	**Enclosed Surface Organism Densities**
Cleanroom—particle and biologically controlled	$0.05–0.5/cm^2$
Cleanroom—only particle controlled	$0.5–10/cm^2$
Uncontrolled manufacturing	$10–100/cm^2$

The total **spore burden** is calculated from adding the three previous columns.

The following three columns provide a way to track spore reduction techniques. The **reduction credit (log scale)** value is integrated into the **total final bioburden** using:

> "Total Final Bio Burden" = "Spore Burden (add prev 3 columns)"/10^"Reduction Credit(log scale)"

Users are encouraged to add columns for anything they see fit (consider spore estimations from potential recontamination or recontamination prevention methods) and to use a conservative approach to avoid irreversible contamination of Mars.

6U CubeSat Magnetometer and Cosmic Ray Detection (High Eliptical Orbit)

Subsystem/Component	Quantity or # MLI Layers	CBE Surface Area per unit [m^2]	Total Surface Area [m^2]	Manufacturing Environment pre ATLO (internal assembly)	Spores from Surface Area	Spores from non-metals	Spores from Electronic Piece Parts	Spore Burden (add prev 3 columns)	Method	Process Details if Needed	Reduction Credit (log scale)	Total Final Bio Burden	Notes
Primary Structure	1.00	0.42	0.4216	Uncontrolled	42158.06	0.00	0.00	42158.06				42158.06	
Sun Sensor	3.00	0.003	0.0098	Uncontrolled	981.30	0.00	0.00	981.30				981.30	
IMU	1.00	0.025	0.0248	Uncontrolled	2483.69	0.00	0.00	2483.69				2483.69	
Avionics Board	1.00	0.02	0.0188	Uncontrolled	1880.00	0.00	0.00	1880.00				1880.00	
Interface Card	1.00	0.00	0	Uncontrolled	0.00	0.00	0.00	0.00				0.00	
Cabling	1.00	0.00	0	Uncontrolled	0.00	100.00	0.00	100.00				100.00	
Solar Arrays	4.00	0.14	0.5502176	Uncontrolled	55021.76	0.00	0.00	55021.76				55021.76	
Batteries	1.00	0.04	0.038481315	Uncontrolled	3848.13	0.00	0.00	3848.13				3848.13	
CubeSat EPS	1.00	0.03	0.0323	Uncontrolled	3225.80	0.00	0.00	3225.80				3225.80	
Propulsion System	0.00	0.00	0	Uncontrolled	0.00	0.00	0.00	0.00				0.00	
Radio	1.00	0.04	0.04	Uncontrolled	4000.00	0.00	500.00	4500.00				4500.00	
Antenna	1.00	0.02	0.02	Uncontrolled	2000.00	0.00	400.00	2400.00				2400.00	
Heaters	1.00	0.04	0.04	Uncontrolled	4000.00	0.00	100.00	4100.00				4100.00	
Magnetometer	2.00	0.00	0.0050356	Uncontrolled	503.56	0.00	0.00	503.56				503.56	
Gamma and X-Ray Detector	6.00	0.0058	0.034632	Uncontrolled	3463.20	0.00	0.00	3463.20				3463.20	
TOTALS:			1.2357		123565.51	100.00	1000.00	124665.51				124665.51	

Figure 9: PPEL Template—CubeSat without propulsion system in early design stage.

16U CubeSat Mission with Propulsion System

Subsystem/Component	Quantity or # MLI Layers	CBE Surface Area per unit [m^2]	Total Surface Area [m^2]	Manufacturing Environment pre ATLO (internal assembly)	Spores from Surface Area	Spores from non-metals	Spores from Electronic Piece Parts	Spore Burden (add prev 3 columns)	Method	Process Details if Needed	Reduction Credit (log scale)	Total Final Bio Burden	Notes
16U CubeSat Structure	1.00	1.12	1.12	Uncontrolled	112000.00	0.00	0.00	112000.00				112000.00	
Propulsion Tanks	4.00	0.34	1.37	Uncontrolled	137141.71	0.00	0.00	137141.71				137141.71	
Thrusters	1.00	0.115	0.12	Uncontrolled	11500.00	0.00	0.00	11500.00				11500.00	
Solar Arrays	2.00	0.024	0.05	ISO 8 PC	482.88	15.69	0.00	498.57				498.57	
Batteries	2.00	0.031	0.06	Uncontrolled	6134.80	42629.34	0.00	48764.14				48764.14	
CubeSat ACU	2.00	0.01	0.02	ISO 8 PC	156.29	0.00	4819.14	4975.43				4975.43	
CubeSat PDU	2.00	0.01	0.01	ISO 8 PC	125.09	0.00	1854.54	1979.64				1979.64	
CubeSat EPS	1.00	0.02	0.02	ISO 8 PC	180.48	0.00	1296.00	1476.48				1476.48	
IRIS V2 Radio	1.00	0.04	0.04	ISO 8 PC	400.00	0.00	500.00	900.00				900.00	
S-Band Antenna	1.00	0.02	0.017224	Uncontrolled	1722.40	0.00	0.00	1722.40				1722.40	
X-Band Antenna	1.00	0.40	0.401505432	Uncontrolled	40150.54	0.00	0.00	40150.54				40150.54	
Nav Camera	1.00	0.01	0.0098832	ISO 8 PC	98.83	0.00	0.00	98.83				98.83	
Reaction Wheels	3.00	0.01	0.0312	ISO 8 PC	312.00	0.00	0.00	312.00				312.00	
CubeSat IMU	1.00	0.00704476	0.00704476	ISO 8 PC	70.45	0.00	929.488	999.94				999.94	
Star Trackers	2.00	0.02526448	0.05052896	Uncontrolled	5052.90	0.00	0.00	5052.90				5052.90	
Sun Sensors	2.00	0.0018766	0.0037532	Uncontrolled	375.32	0.00	0.00	375.32				375.32	
OBC	1.00	0.02147	0.02147	ISO 8 PC	214.70	0.00	950.95	1165.65				1165.65	
Instrument OBC	1.00	0.115	0.115	ISO 8 PC	1150.00	0.00	150	1300.00				1300.00	
Instrument	1.00	0.04487	0.04487	ISO 8 PC	448.70	0.00	0.00	448.70				448.70	
Harnessing	1.00		0	Uncontrolled	0.00	300	0.00	300.00				300.00	
Radiation shielding, MLI, and other protective components	2.00	1.12	2.24	Uncontrolled	224000.00	0.00	0.00	224000.00				224000.00	
TOTALS:			2.7317		541717.09	42945.03	10500.12	595162.25				595162.25	

Figure 10: PPEL Template—CubeSat with propulsion system.

Polar Orbiter Small Sat												
		Use Total Surface Area for All Calculations		Uncontrolled, ISO 8 PC, ISO 8 BC, ISO 7 PC, ISO 7 BC	Initial Bioburden Calculations using total surface area and manufacturing environment (bold underline values from assay) If unknown, fill "Spores from Surface Area" only				Use these Columns to track reductions made through methods of your choice (B&B analysis, Mfr. Reduction, Bakeouts, and Chemical Baths)			Goal is < 500,000
Subsystem/Component	Quantity or # MLI Layers	CBE Surface Area per unit [m^2]	Total Surface Area [m^2]	Manufacturing Environment pre ATLO (internal assembly)	Spores from Surface Area	Spores from Non-Metals	Spores from Electronic Piece Parts	Spore Burden (add prev 3 columns)	Method	Process Details if Needed	Reduction Credit (log scale)	Total Final Bio Burden	Notes
RW4)	3.00	0.09	0.2629	ISO 8 PC	2629.36	0.00	0.00	2629.36				2629.36	
Star Tracker (Sodern Hydra)	2.00	0.20	0.3906	Uncontrolled	39059.84	0.00	0.00	39059.84				39059.84	
Sun Sensor	6.00	0.003	0.0196	Uncontrolled	1962.60	0.00	0.00	1962.60				1962.60	
KVH-1750 IMU	1.00	0.025	0.0248	ISO 8 PC	248.37	0.00	28429.40	28677.77				28677.77	
Sphinx Avionics Board	1.00	0.02	0.0188	Uncontrolled	1880.00	0.00	705.00	2585.00				2585.00	
Interface Card	1.00	0.00	0	Uncontrolled	0.00	0.00	300.00	300.00				300.00	
Primary Structure	1.00	2.44	2.44	Uncontrolled	244000.00	0.00	0.00	244000.00				244000.00	
15" Lightband	1.00	0.38	0.381	Uncontrolled	38100.00	0.00	0.00	38100.00				38100.00	
2-Axis Sollar Array Gimbals	2.00	0.10	0.2099	Uncontrolled	20989.34	0.00	0.00	20989.34				20989.34	
Cabling	1.00	0.00	0	Uncontrolled	0.00	300.00	0.00	300.00				300.00	
Rigid-panel Solar Arrays	2.00	0.60	1.2	Uncontrolled	120000.00	0.00	0.00	120000.00				120000.00	
Li-Ion Batteries	2.00	0.04	0.076962631	Uncontrolled	7696.26	64002.39	0.00	71698.65				71698.65	
CubeSat EPS	1.00	0.03	0.0323	Uncontrolled	3225.80	0.00	120.97	3346.77				3346.77	
COTS Monoprop Propulsion System (MPS-135-8U)	1.00	0.27	0.2728	ISO 7 PC	136.40	0.00	0.00	136.40				136.40	
IRIS v2 Radio	1.00	0.04	0.04	ISO 8 PC	400.00	0.00	500.00	900.00				900.00	
UHF Loop Antenna	1.00	0.02	0.02	Uncontrolled	2000.00	0.00	0.00	2000.00				2000.00	
X-Band Patch Arrays (4x4 patch)	4.00	0.00	0.0128	Uncontrolled	1280.00	0.00	0.00	1280.00				1280.00	
UHF Diplexer	1.00	0.03	0.0321	Uncontrolled	3206.17	0.00	10465.85	13672.02				13672.02	
Radiator	1.00	0.10	0.0990	Uncontrolled	9903.85	0.00	0.00	9903.85				9903.85	
Heaters	1.00	0.08	0.08	Uncontrolled	8000.00	0.00	0.00	8000.00				8000.00	
NIR Spectrometer	1.00	0.04	0.0376	ISO 7 PC	18.80	0.00	0.00	18.80				18.80	
Limb Infrared Radiometer	1.00	0.2099	0.2099	ISO 7 PC	104.95	0.00	0.00	104.95				104.95	
TOTALS:			5.8611		504841.74	64302.39	40521.21	609665.35				609665.35	

Figure 11: PPEL Template—SmallSat.

C. Flown Planetary Protection Category III Missions

The NASA Office of Planetary Protection maintains a list of missions and their planetary protection categories as well as links to relevant planetary protection reports, which can be found on the Office of Planetary Protection's website [14].

The tables in this appendix summarize the subset of those missions since 1990 that have been Mars flybys (Table 5) and Mars orbiters (Table 6). Each of the missions listed has had an approach to planetary protection, and papers describing many of them can be found at the link above.

Table 5: Mars flyby missions since 1990.

Mission	Launch Date	Mars Flyby	Flyby Altitude	Final Destination	Planetary Protection Approach
Galileo	1989-10-18	1990-02-10	960 km	Jupiter	
Dawn	2007-09-27	2009-02-17	549 km	Vesta and Ceres	Mission Analysis (biasing)
MarCO-A	2018-05-05	2018-11-26	1,627 km	Mars flyby	Bioburden with burnup and breakup
MarCO-B	2018-05-05	2018-11-26	1,750 km	Mars flyby	Bioburden with burnup and breakup
Psyche	2023-10-13	2026-05	~500–5,750 km	Asteroid 16 Psyche	Mission analysis (biasing)
Europa Clipper	2024-10-14	2025-03-01	884 km	Jupiter/Europa	End-to-end PRA
Nozomi (Japan)	1998-07-04	2003-12-14	~1,000 km	Mars (failed)	
Rosetta (ESA)	2004-03-02	2007-02-25	250 km	Comet 67P	
Hera (ESA)	2024-10-07	2025-03-12	~5,000 km	Didymos/Dimorphos	

Table 6: Mars orbiter missions since 1990.

Mission	Launch	Orbit	Dry Mass	Aerobraking?	Planetary Protection Approach
MGS	1996	370 × 435 × 93°	674 kg	Yes	
Mars Odyssey	2001	400 × 400 × 93°	332 kg	Yes	
MRO	2005	255 × 320 × 93°	981 kg	Yes	Burnup and breakup analysis
MAVEN	2013	150 × 6200 × 75°	809 kg	No	Bioburden and lifetime
Mars Express (ESA)	2003	250 × 10,100 × 86°	1,123 kg	No	
Mars Orbiter Mission (ISRO)	2013	422 × 77,000 × 150°	852 kg	No	
ExoMars TGO (ESA)	2016	400 × 400 × 74°	2,000 kg	Yes	
Hope (UAE)	2020	20,000 × 43,000 × 25°	1,350 kg	No	
Tianwen-1 (CNSA)	2020	~265 × 11,900 × 86°	~3,175 kg	No	

D. References and Further Reading

Table 7 lists reference documents relevant to planetary protection.

Table 7: Planetary protection reference documents.

Document	Description
NASA Planetary Protection Handbook, NASA/SP-20240016475, December 2024	The Office of Planetary Protection at NASA HQ put together a practitioner's handbook, with in-depth descriptions of approved methods for implementing planetary protection measures.
Editorial to the New Restructured and Edited COSPAR Policy on Planetary Protection, January 2026	COSPAR meets regularly to update and interpret requirements and guidance. This is the most recent guidance from an international policy standpoint.
NASA-STD-8719.27 Implementing Planetary Protection Requirements for Spaceflight	This document outlines the most up to date planetary protection requirements to which applicable missions are expected to adhere.
NPR 8715.24 Planetary Protection Provisions for Robotic Extraterrestrial Missions	This document is a NASA standard of current guidelines for missions complying with planetary protection, including verbiage on the expectations of responsibilities for partnered missions.
Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (the "Outer Space Treaty"), October 19, 1967, Article IX.	This is the document that called into necessity a planetary protection discipline. Policy and guidance derive from this agreement to avoid harmful contamination.
ISO 14644-1:2015, Cleanrooms and associated controlled environments	This document specifies the classification of air cleanliness in terms of concentration of airborne particles in cleanrooms and clean zones as well as separative devices as defined in ISO 14644-7.

References

[1] United Nations, "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," Article IX, 1967. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.

[2] COSPAR, "COSPAR Policy on Planetary Protection," *Space Research Today,* vol. 224, no. 17-39, 2026, doi: https://doi.org/10.60970/012026SRT224/PPP.

[3] NASA, "NASA-STD-8719.27 Implementing Planetary Protection Requirements for Spaceflight," 2022. [Online]. Available: https://standards.nasa.gov/sites/default/files/standards/NASA/Baseline/0/NASA-STD-871927-Baseline.pdf.

[4] NASA, "NPR 8715.24 Planetary Protection Provisions for Robotic Extraterrestrial Missions," 2021. [Online]. Available: https://soma.larc.nasa.gov/lws/vfmo/pdf_files/N_PR_8715_0024_.pdf.

[5] NASA, "NASA Planetary Protection Handbook," 1.0, February 24, 2026 2024. [Online]. Available: https://ntrs.nasa.gov/api/citations/20240016475/downloads/PlanetaryProtection_Hdbk_2024_Final_For508ing_comp.pdf.

[6] K. J. McCoy, M. DiNicola, C. Everline, H. Burgoyne, K. Reinholtz, and B. Clement, "Europa Clipper planetary protection probabilistic risk assessment summary," *Planetary and Space Science,* vol. 196, p. 105139, 2021/02/01/ 2021, doi: https://doi.org/10.1016/j.pss.2020.105139.

[7] T. Imken, T. Randolph, M. DiNicola, and A. Nicholas, "Modeling spacecraft safe mode events," in *2018 IEEE Aerospace Conference*, 3-10 March 2018 2018, pp. 1-13, doi: https://doi.org/10.1109/AERO.2018.8396383.

[8] M. S. Wallace, "A massively parallel bayesian approach to planetary protection trajectory analysis and design," presented at the AAS/AIAA Astrodynamics Specialist Conference, Vail, Colorado, 2015. [Online]. Available: https://hdl.handle.net/2014/45859.

[9] R. Hendrickson *et al.*, "Planetary Protection Implementation of the InSight Mission Launch Vehicle and Associated Ground Support Hardware," *Astrobiology,* vol. 20, no. 10, pp. 1158-1167, 2020/10/01 2020, doi: https://doi.org/10.1089/ast.2019.2099.

[10] ISO, "ISO 14644-1:2015 Cleanrooms and associated controlled environments," 2015. [Online]. Available: https://www.iso.org/standard/53394.html.

[11] ECSS, "ECSS-Q-ST-70-57C Dry heat bioburden reduction for flight hardware " 2013. [Online]. Available: https://ecss.nl/standard/ecss-q-st-70-57c-dry-heat-bioburden-reduction-for-flight-hardware-30-august-2013/.

[12] B. Clement *et al.*, "Planetary protection strategy and implementation for MarCO, the first interplanetary CubeSat mission," presented at the 42nd COSPAR Scientific Assembly, Pasadena, California, USA, July 01, 2018, 2018. [Online]. Available: https://ui.adsabs.harvard.edu/abs/2018cosp...42E.672C.

[13] J. Barengoltz and J. Witte, "Planetary protection implementation on Mars Reconnaissance Orbiter mission," *Advances in Space Research,* vol. 42, no. 6, pp. 1108-1119, 2008/09/15/ 2008, doi: https://doi.org/10.1016/j.asr.2007.10.001.

[14] NASA. "NASA Office of Planetary Protection: Missions." https://sma.nasa.gov/sma-disciplines/planetary-protection#planetaryProtection_missions (accessed February 24, 2026).