

Category IVa

Mars Planetary Protection Primer

A Quick-Start Guide for Landed Missions

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1 Introduction to Planetary Protection for Mars Missions

On Earth, microbes are ubiquitous, and millions cover every surface we interact with. Microbial species compete for resources and occupy every environmental niche imaginable. Microbes can survive harsh conditions, including space travel, multiply quickly to colonize a habitable area, and adapt readily to new environments. We know from Earth's history that microbes are able to shape the geology, chemistry, and climate of a landscape. Planetary protection aims to protect space environments, mission science, and Earth's biome from the potential biological impacts of space exploration by minimizing microbial contamination of space craft hardware and preventing the release of microbes from one planet on another.

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 an international consensus guideline for how this principle is implemented in practice and is an accepted means for compliance. For NASA and NASA-partnered missions, COSPAR guidelines are used to inform the NASA technical standard NASA-STD-8719.27 [3] and NASA procedural requirement NPR 8715.24 [4].

Missions are assigned an outbound and inbound (if sample return) planetary protection category based on three main factors: the target destination, how the spacecraft will interact with that target destination, and the science goals of the mission. The category assignment frames requirements and scales precautions to the appropriate contamination risk. For celestial bodies that have conditions that may be able to support life, forward planetary protection precautions aim to prevent the contamination of these environments with terrestrial microbes. The possibility of contamination depends not only on the cleanliness of the spacecraft but also on the hospitability of the environment, considering factors such as radiation, temperature, and water availability.

Although the planetary protection categories are distinct, they all share the same goal: to prevent the introduction of a single viable organism into a habitable environment in which it could proliferate, particularly in cases where it could interfere with origin-of-life or life-detection science. The categories serve as a useful way of framing mission constructs into levels of effort and requirements needed to meet these goals.

1.1 Purpose and Intended Audience of This Primer

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

- A streamlined decision framework for Category IVa 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 multiple planetary protection documents with generalized solar system applicability

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.

1.2 Focusing on Category IVa Missions to Mars

Any mission that interacts directly with the Martian surface will be assigned a Category IV or above, depending on the target landing site, science goals, and plan for sample return. Sample return missions are assigned two categories, one for the outbound leg and one of the two options under Category V for the Earth return leg. Mars sample return missions are assigned Category IVb for the outbound leg and Category V(r), Restricted Earth Return, for the inbound leg, as they have to undertake extra precautions to protect science in the returned Mars samples as well as in Earth's biosphere. Landed missions with any science goals of life detection are also assigned Category IVb, with the responsibility to reduce and characterize any biological contamination whose biosignatures may convolute science data. Missions interacting with icy or wet regions of Mars (i.e., "special regions") must take extra precautions to not deliver a viable microbe to a potentially habitable environment featuring liquid water, as described for Category IVc. Note that categories IVb and IVc are not exclusive. A life-detection mission visiting a special region and performing sample return would be simultaneously assigned IVb, IVc, and V. If the mission is going to the Martian surface and is neither Category IVb nor Category IVc, it will be assigned **Category IVa** (Table 1).

Table 1: Category IV subcategories (from NASA-STD-8719.27, Table 4-1).

		Life Detection Goals	
		No	Yes
Special Region Access	No	IVa	IVb
	Yes	IVc	IVb and IVc (both sets of requirements)

This primer focuses on Category IVa. Note that the requirements for Categories IVb and IVc start with the requirements for IVa and continue with additional requirements, so this document will outline the requirements that are shared by all three subcategories of Category IV.

A related predecessor document, the **Mars Planetary Protection Primer** [5], covers Category III Mars missions.

1.3 Special Regions and How to Avoid Them

COSPAR designates special regions on Mars as areas that may be able to support Earth microbes delivered to the Martian surface by spacecraft. The guidelines have converged on the following definition criteria [6]: a region with a temperature equal to or above 255 K and a water activity of at least 0.60. Water activity here refers the measure of unbound water that is available for microbial use. Different classes of microbes can proliferate in different levels of unbound, bioavailable water, and this selected water activity and temperature combination would support the hardiest of organisms on Earth.

Though it is rare to find regions on Mars that meet these criteria, a few considerations must be noted. While the low atmospheric pressure of Mars quickly evaporates pure water, different conditions, including the addition of salts and solutes, can slow this process and help water persist. A region of suspected persistent surface water, such as in the case of recurring slope lineae, would be considered a special region requiring extra precautions (i.e., Cat. IVc) or the proposed flight project would have to demonstrate that the observed features do not represent a special region. Alternatively, the heat of a spacecraft radioisotope thermoelectric generator (RTG) may contribute to the risk of

inducing a special region either in off-nominal landing scenarios or in proximity of surface ice [7]. Operations, too, must be examined if the mission goals involve melting, drilling, or accessing Martian ice.

Mapping resources such as the Surface Water Ice Mapping (SWIM) data products (Figure 1) offer a good starting place for understanding whether planned operations may access a potential special region.

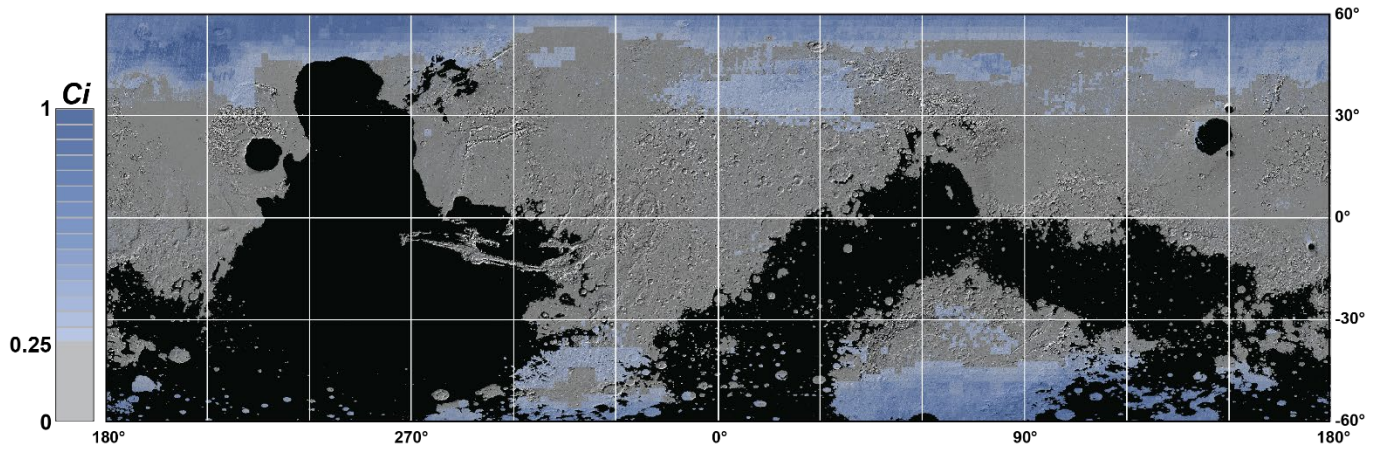


Figure 1: Ice presence on Mars, from the surface down to ~5 m depth, from the SWIM dataset [8].

2 The Planetary Protection Decision Tree

The decision tree (Figure 2) is the core tool of this primer. The branches of the tree are derived from the 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 the branches, a mission team can determine whether their Mars lander mission:

- Can satisfy planetary protection requirements via a bioburden analysis approach, with or without mitigation approaches or analysis credits, or
- Must pursue a probabilistic analytical approach, demonstrating a sufficiently low probability of biological release

In either case, the mission will need to track the vehicle's bioburden and meet other requirements as well, including trajectory analysis of the upper stage (and any other delivery vehicle not intended to impact Mars).

The process is outlined in this section, and the individual decisions and processes are described in more detail in the remainder of this primer.

Illustrative case studies in Section 9 show how real missions have demonstrated compliance.

The box below summarizes the five main planetary protection requirements for Category IVa Mars missions.

Category IVa Planetary Protection Requirements

- (1) Must be built in **ISO 8 cleanroom** or better (Section 8.1.1; NASA-STD-8719.27 Section 4.4.3 [3])
- (2) Provide relevant **documentation** according to a schedule negotiated with the Office of Planetary Protection and documented in the Planetary Protection Requirements Document (Section 4; NASA-STD-8719.27 Appendices A–G [3])
- (3) **Inventory Organic and Biological Materials** (Section 4.1; NASA-STD-8719.27 Section 4.3 [3])
- (4) **Launch vehicle upper stage or cruise stage** compliance paths (choose one):
 - (4a) **Trajectory Analysis:** Chance of Mars impact $<1 \times 10^{-4}$ in 50 years (Section 5; NASA-STD-8719.27 Section 4.5.4.1a [3])
 - OR
 - (4b) **Bioburden Approach:** Less than 500,000 (5×10^5) total spores at launch (Section 6; NASA-STD-8719.27 Section 4.5.4.1b [3])
- (5) **Landed element** compliance paths (choose one):
 - (5a) **Bioburden Approach:** Less than 500,000 (5×10^5) total spores, 300,000 (3×10^5) surface spores, and 300 spores/m² (Section 6; NASA-STD-8719.27 Section 4.6.2.1a [3])
 - OR
 - (5b) **Probabilistic Analytical Approach:** Probability of biological inoculation $<1 \times 10^{-4}$ (Section 7; NASA-STD-8719.27 Section 4.6.2.1b [3])

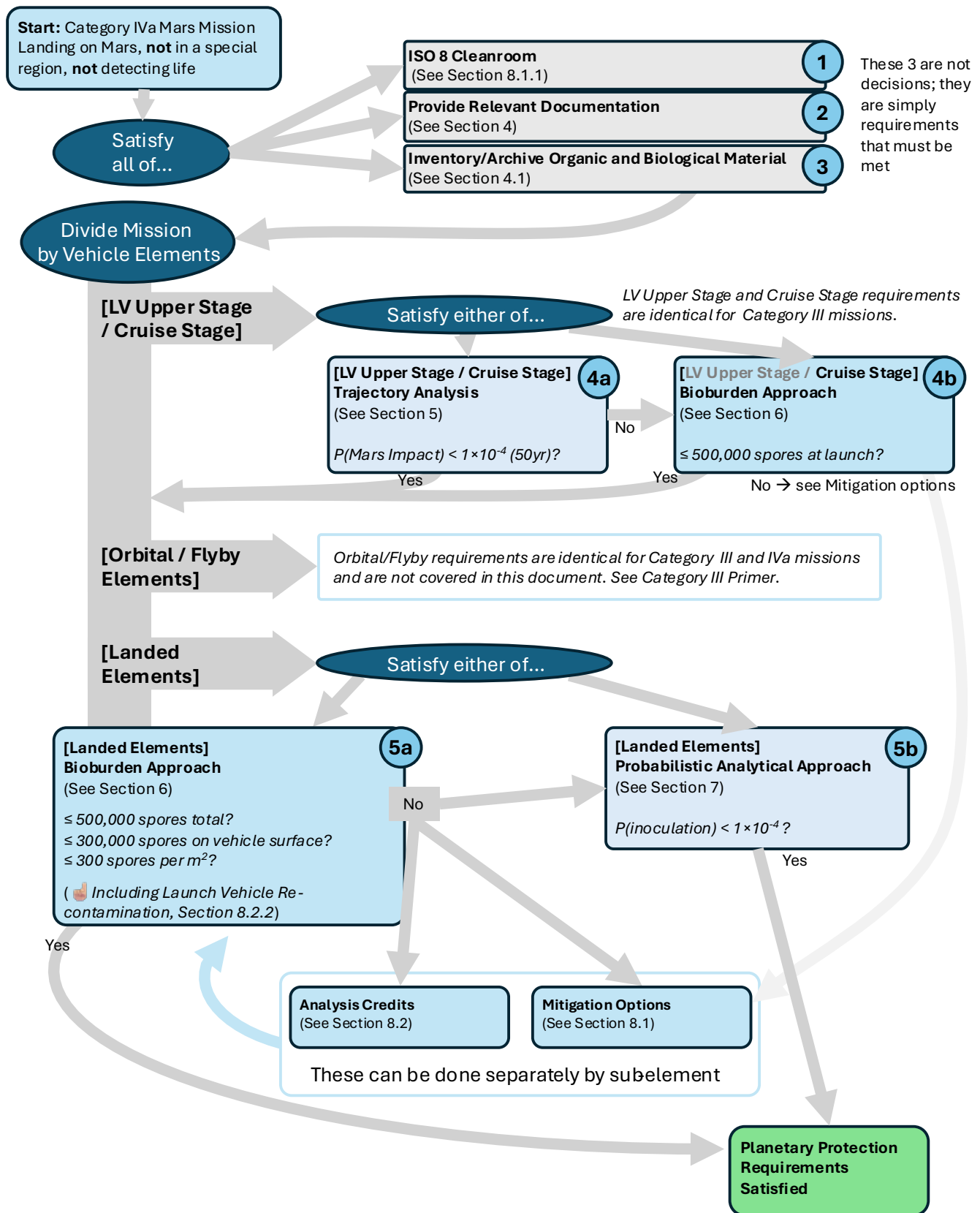


Figure 2: Planetary protection decision tree for Category IVa missions to Mars. Note that a mission may propose alternative approaches, as noted in Section 1.2.6 of NASA-STD-8719.27 [3].

2.1 Nondecision Requirements

Every Category IVa mission must meet the following three requirements:

- (1) Must be built in **ISO 8 cleanroom** or better (Section 8.1.1; NASA-STD-8719.27 Section 4.4.3 [3])
- (2) Provide relevant **documentation** according to schedule (Section 4; NASA-STD-8719.27 Appendices A–G [3])
- (3) **Inventory Organic and Biological Materials**. 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 4.1; NASA-STD-8719.27 Section 4.3 [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

- (4a) Show that the chance of the upper stage or cruise stage impacting Mars is $<1 \times 10^{-4}$ within 50 years. (Section 5; NASA-STD-8719.27 Section 4.5.4.1a [3])

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 (including trajectories with positive characteristic energy [$C_3 > 0$]), after spacecraft separation, the upper stage will be in a heliocentric orbit with the potential to bring it close to Mars. If nothing were done, there could be a risk of impacting and contaminating Mars. For direct ballistic transfer trajectories, 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 5 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 and never puts itself on a Mars-impacting trajectory, this trajectory analysis path might also be achievable.

2.2.2 Upper Stage and Cruise Stage Bioburden Approach

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 (Section 6; NASA-STD-8719.27 Section 4.5.4.1b [3])

This can be done separately from other vehicles and analyzed using a PPEL approach. See Section 6 for the related compliance branch for spacecraft and for further explanations of bioburden accounting, and see Section 8 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 flyby and orbiter spacecraft, NASA-STD-8719.27 does not specify a path for demonstrating bioburden upon impact with the Martian surface rather than at launch, but there is room for alternate methods to be considered. However, note the case of the Mars Cube One (MarCO) mission, for which 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. MarCO does not appear as a case study in this document but can be found in the predecessor document for Category III missions [5].

2.3 Orbital and Flyby Elements

It is possible that a mission which will go to the surface, and is Category IVa, will *also* have vehicle elements that are intended to fly by or orbit Mars. For any such elements, the requirements are identical to those for Category III Mars missions. It is even plausible that such elements could be categorized separately, as Category III elements (see Section 3). A relevant trajectory analysis approach is found in Section 5, but this primer does not include a complete treatment of Flyby and Orbital elements; instead, please refer to the companion primer for Category III missions [5].

2.4 Main Compliance Decisions for Category IVa Mars Spacecraft

There are two main branches of the planetary protection compliance tree for all components of Category IVa Mars surface missions that are intended to reach the surface of Mars: the bioburden approach (5a) and the probabilistic analytical approach (5b).

2.4.1 Bioburden Approach

Planetary protection compliance for a Category IVa missions can be achieved by a bioburden tracking and analysis approach (referred to in this document as the “bioburden approach”), by satisfying the following:

(5a) Bioburden Approach: Less than 500,000 (5×10^5) total spores, 300,000 (3×10^5) surface spores, and 300 spores/m² (Section 6; NASA-STD-8719.27 Section 4.6.2.1a [3])

As with (4b), this is achieved by the use of PPEs (Appendix B), which;

- Track spacecraft components and environments
- Apply conservative specification values for spore densities (from NASA-STD-8719.27 [3])
- Are used to estimate a total spores count and a count specifically of surface spores as well as a surface spore density

If all three bioburden requirements are met (for total spores, surface spores, and surface spore density), then the requirements are satisfied. Otherwise, the project will require mitigation options or will need to pursue analysis credits (see Section 8).

2.4.2 Probabilistic Analytical Approach to Compliance

Mars surface missions have the alternative option of taking a probabilistic analytical approach to planetary protection compliance:

(5b) Probabilistic Analytical Approach: Probability of biological inoculation $<1 \times 10^{-4}$ (Section 7; NASA-STD-8719.27 Section 4.6.2.1b [3])

Taking this path will almost certainly still require tracking the bioburden; if the mission can meet the bioburden requirement, this need not be considered. But if the bioburden requirement will be challenging to meet, the project can instead show analytically that, considering all aspects of the mission, the probability of biological inoculation is below a 1×10^{-4} threshold. This approach was originally applied to Viking and has been used in the outer solar system with limited precedent. Note, however, that since Viking, NASA Mars landers have used a bioburden-based approach. More information can be found in Section 7, but a detailed guide is not presented in this primer.

3 Co-Manifesting, Secondary Payloads, and Vehicle Separations

The planetary protection mission categories and requirements are determined primarily based on where a mission is going. However, a single mission may have physical elements that are going to different places. And different missions may share a ride on a common launch, or on a common transit vehicle. In these cases, how are missions categorized? What planetary protection requirements are they subject to?

There isn't a single prescriptive approach to this in the NASA guidelines, but generally speaking, missions should plan to be categorized and to deal with planetary protection requirements in a way that makes sense. As per NPR 8715.24, the mission proposes its categorization and identifies its applicable requirements, which the Mission Directorate Associate Administrator approves and with which the Chief of Safety and Mission Assurance (SMA) concurs, respectively. The multi-element mission should propose a categorization and planetary protection approach that aligns with the intent of NASA-STD-8719.27.

The approach in this primer, then, is as straightforward as possible and is coherent with the intent of NASA-STD-8719.27, even if some of the guidance here is not specifically prescribed by that document.

The following basic principles can be used as guidance in the classification of separable vehicles.

Separating Elements by Mission

If elements are part of a separate distinct mission, with separate development and purpose, and are just sharing a ride to Mars, they should be categorized separately (though they might still end up in the same category; Figure 3). Note, however, that this guidance may not apply if they are going to the same physical location on Mars (see the microprobe counter-example under Separate Budgets for Separate Landings).

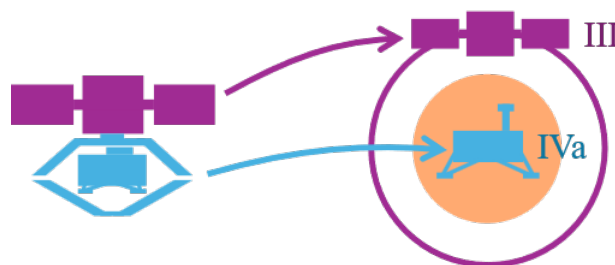


Figure 3: Separate missions can be classified separately.

- **Example:** The MarCO mission consisted of two 6U CubeSats that shared a launch (though not a carrier vehicle) with the InSight Mars Lander. MarCO was a flyby mission and was Category III, whereas InSight was Category IVa.

Separating Elements by Final Destination

If elements are part of the same mission but will have distinct final operating locations that imply different classifications, they are subject to different requirements and can be classified separately. However, if all elements are going to Mars, they don't need separate classifications per se; the requirements for Category IV missions are already written with this multi-element approach in mind (Figure 4).

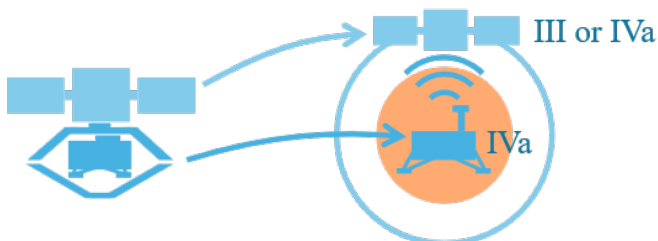


Figure 4: Elements with distinct final locations can be classified separately, or can share a classification.

- **Example:** An orbiter and a lander share a ride to Mars and are part of the same mission. If they were classified separately, the orbiter would be Category III, and the lander would be Category IVa. However, the whole mission

can be classified as Category IVa, because orbiter and flyby elements of Category IV missions are already subject to the Category III requirements (see NASA-STD-8719.27 paragraph 4.5.4.2) [3].

Separating Delivery Elements

If separable components are used to deliver a landed element, they should be classified along with the delivered element, and missions should use the language in NASA-STD-8719.27 to describe their requirements (Figure 5).

- **Cruise Stages:** Cruise stages are called out specifically in NASA-STD-8719.27, paragraph 4.5.4.1 [3], and are shown in Figure 2 in branch 4a and 4b. They can comply by via either a probability of impacting Mars approach or a bioburden approach.
 - **Example:** In past missions, cruise stages have released their landed elements just prior to atmospheric entry and have been designed to hit Mars. They have therefore used a bioburden approach, usually with modifications to account for heating sterilization during entry. Compliance via a probability of impact would likely require a substantially different architecture. See case studies in Section 9 for Mars Pathfinder, Mars Exploration Rover (MER), Mars Polar Lander, InSight, and Mars 2020.
- **Other Delivery Elements:** Elements such as parachutes and heat shields generally end up on the surface close to the element they are delivering and are therefore pooled together with their delivered landed element as part of “all landed hardware” (see NASA-STD-8719.27, paragraph 4.6.2.1 and Table 4-4 [3]).
 - **Example:** On Mars 2020, the parachute, heat shield, back shell, and descent stage all shared a single bioburden allowance with the Perseverance Rover that they delivered.

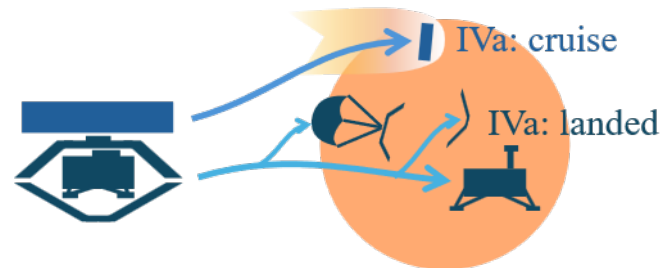


Figure 5: Cruise stages have special language in the NASA standard and can be classified along with what they deliver. Other landed hardware (e.g., a parachute) is also classified along with, and shares a pooled bioburden allowance with, what it delivers.

Separate Budgets for Separate Landings

If different elements will be landing in different locations, with 3σ confidence landing ellipses that don’t overlap, it would be reasonable to propose that they each be allowed a full budget of 500,000 spores (Figure 6). Note, though, that this is not explicitly called out in NASA-STD-8719.27.

- **Example:** Two landers separate at different times and on different trajectories from a carrier vehicle, then land at distinct locations on Mars. It can be shown with high confidence that they will not land in close proximity to each other. They each receive a distinct full allocation of 500,000 spores, 300,000 surface spores, and 300 surface spores/m².

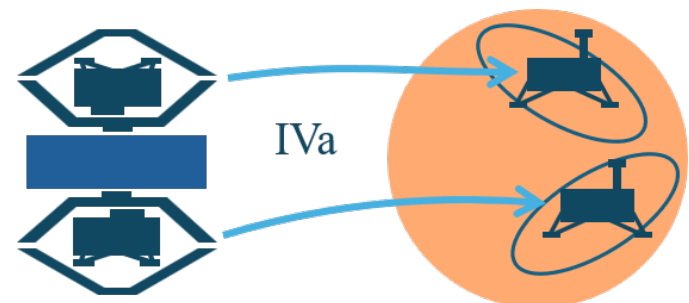


Figure 6: Elements landing at distinct locations can receive distinct full bioburden allocations.

- **Counter-Example:** The Mars Polar Lander mission carried two microprobes (Deep Space 2), each of which deployed separately from the cruise stage and had its own entry vehicle. Mars Polar Lander was released from the cruise stage first, followed shortly by the microprobes. All three elements were targeting the same part of Planum Australe near the Martian South Pole, and they shared a common landing ellipse. The bioburden allocation was therefore shared between all three vehicles.

Cross-Contamination

In all these cases, when multiple elements are subject to different bioburden budgets, the possibility of cross-contamination/recontamination between elements must be considered. For example, projects will generally have to perform analysis and take measures to deal with recontamination of a vehicle from the launch vehicle fairing, which is not subject to specific planetary protection requirements; the launch vehicle upper stage, which is itself usually handled with probability-of-impact requirements rather than bioburden accounting; and even the mission's own cruise stage, which may itself be subject to bioburden accounting but with its own separate budget. See Section 6.3 for more details on launch recontamination.

- **Example:** The Mars Science Laboratory performed a conservative analysis of recontamination of the vehicle due to spores from the interior of the fairing and the upper stage of the launch vehicle during launch. It was assumed that all particles on all surfaces within the fairing were dislodged during launch, and then evenly redistributed across all spacecraft surfaces.

4 Timeline and Documentation

Planetary protection compliance is negotiated with and demonstrated to the Planetary Protection Officer (PPO) at NASA Headquarters, who provides a recommendation to the NASA Chief of SMA, who then signs off on launch approval for the mission. The primary deliverables for a planetary protection team are a series of gate product documents, captured in Table 2. The timing of these documents largely coincides with project milestones.

Table 2: Example documentation schedule for Category IVa missions.

Document	Submittal	NASA Office of SMA Concurrence
Planetary Protection Categorization Document	Before Mission Concept Review (MCR)	By SRR
Planetary Protection Requirements Document	Before System Requirements Review (SRR)	Before SRR
Planetary Protection Implementation Plan	90 days prior to Preliminary Design Review (PDR)	60 days prior to PDR
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

Final schedule to be negotiated with the Office of Planetary Protection and documented in the Planetary Protection Requirements Document. Concurrence is obtained from Chief of SMA based on recommendations from the Office of Planetary Protection for all documents except the Implementation Plan, for which concurrence is obtained from the Office of Planetary Protection.

- **Planetary Protection Categorization Document:** 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, as well as the spacecraft's interactions with those environments. The response is due by 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 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 concurrence from 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 compliance activities and outcomes occurring from the issuance of the Pre-Launch Report 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].

4.1 Organic and Biological Inventories

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, originating on Earth, 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 serves as a starting reference point for future studies. As such, it should be as thorough as possible to include manufacturer, part numbers, and an estimate of mass delivered to the surface. Common materials added to the list are lubricants such as Braycote or dry film, tapes such as polyamide or polyester with acrylic or silicone adhesives, paints such as Aeroglaze, lubricants, adhesives, epoxies, lacing thread, and propellant. These must be documented if they are present on the spacecraft in amounts greater than 1 kg. 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.

For any of these materials present in amounts greater than 25 kg, the project must physically archive 50 g of material. This is also documented in the Planetary Protection Pre-Launch report. See NASA-STD-8719.27 Section 4.3.7 [3].

Additionally, any intentionally included biological payload must be documented in a biological inventory, regardless of the amount. This is also documented in the Planetary Protection Pre-Launch report. More information can be found in NASA-STD-8719.27 Section 4.3.6 [3].

5 Spacecraft Trajectory Analysis for Planetary Protection Compliance

Trajectory analysis for a Cat IV mission applies primarily to elements that do not nominally intend to impact Mars. This includes the launch vehicle upper stage and cruise/carriers that intend to either fly by Mars or enter Mars orbit. Cruise stages that will separate minutes before entry and end with surface impact must comply with bioburden (Section 6) or analysis requirements (Section 7). Note that a cruise/carrier that intends to fly by or enter Mars orbit could be classified separately as a Category III vehicle or could be classified as a component of a Category IV mission (see Section 3); in either case, the requirements are exactly the same. The project can demonstrate a probability of impact of less than 1% for 20 years after launch and less than 5% from 20 to 50 years after launch, or it may choose to keep bioburden below 500,000 spores (NASA-STD-8719.27 paragraph 4.5.4.2 [3]). Note that because the requirements for a purely spaceborne vehicle (flyby or orbiter) are exactly the same as for a Category III mission, these requirements are not shown in the main flowchart in Figure 2; for a flowchart view, refer instead to the companion document for Category III missions [5].

Where appropriate, compliance “guardrails” are given in the form of a Green/Yellow/Red relative safety of a given approach. (Regardless of how safe a mission design may seem, a sufficient analysis will always be required to show compliance). The guardrails describe approaches in general that are:

- **Green:** Sufficiently robust to reasonably assume no impact ($\ll 1\%$ 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 $>1\%$

5.1.1 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:

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

where $P(F)$ is the probability of catastrophic spacecraft failure over a defined segment of the mission.

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:

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

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 [9].

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 of 1×10^{-4} for launch vehicle elements and 1×10^{-4} for any other nonimpacting elements.

5.1.2 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 2). If the impact avoidance probability cannot be met, then the element must meet the total bioburden requirement of $<5 \times 10^5$ 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.

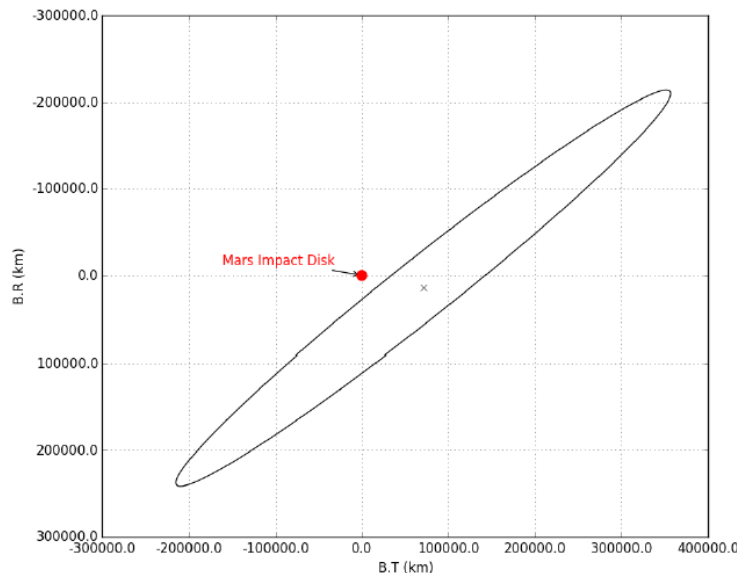


Figure 7: Upper stage uncertainty ellipsoid biasing at Mars close approach.

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 7. 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).

Even after the initial Mars closest approach by the upper stage, 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 [10] and Appendix 5 of the Planetary Protection Handbook [11] 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 $C_3 \sim 2\text{--}10 \text{ km}^2/\text{s}^2$). 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.

5.1.3 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 8). It provides a convenient 2-D framework for targeting and visualizing flyby, capture, or entry 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.

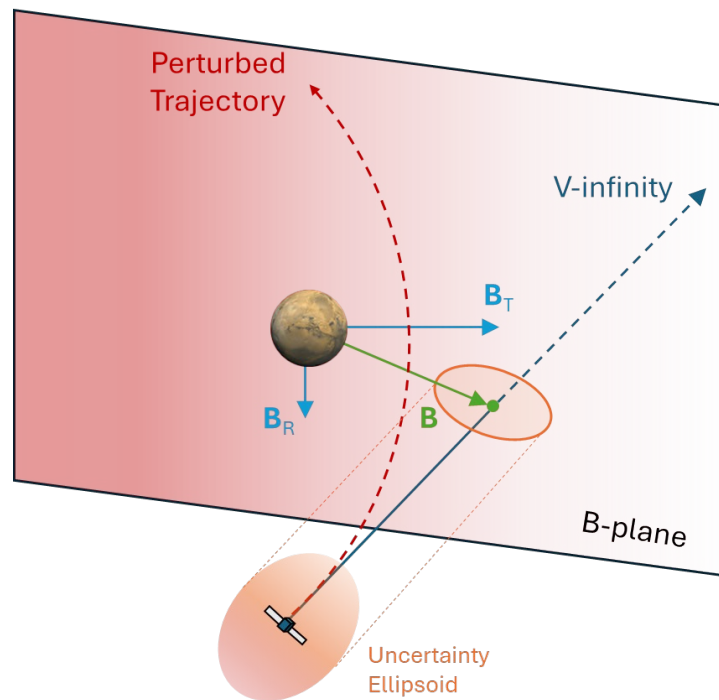


Figure 8: B-plane diagram for targeting Mars orbit insertion or Mars miss distance, including uncertainty ellipsoid.

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 9.

Compliance guardrails:

- **Green:** Closest approach of nominal B-plane 3σ 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.

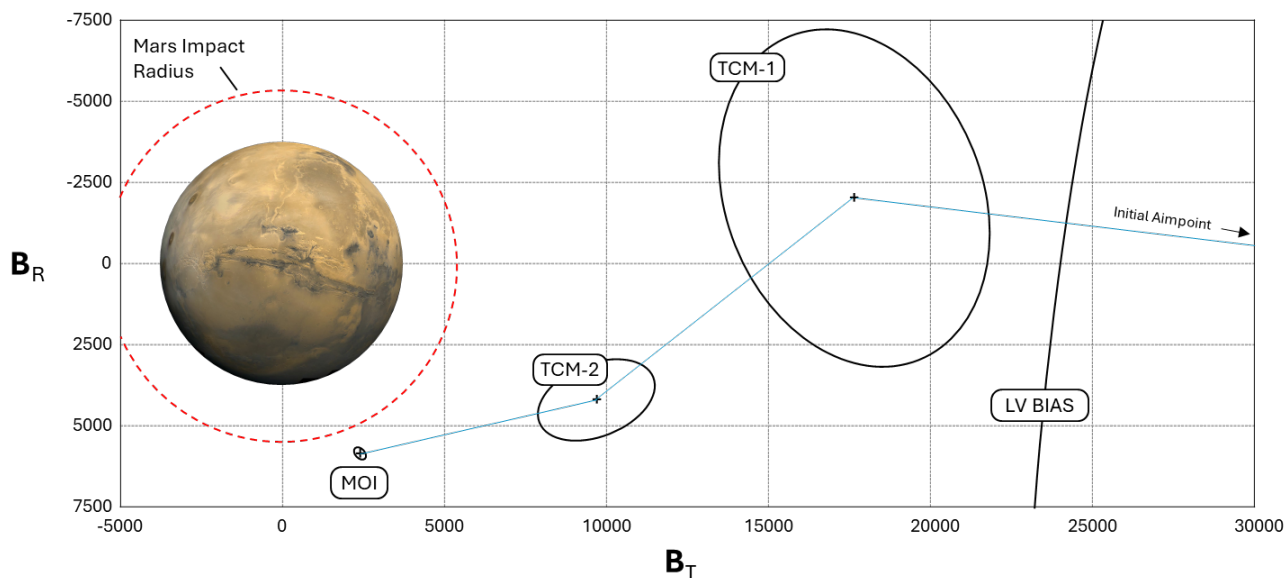


Figure 9: Representative B-plane aimpoints for Mars orbital insertion targeting. The initial aimpoint at launch is intentionally biased well away from Mars due to large uncertainties and launch vehicle upper stage disposal. Each TCM moves the aimpoint closer to Mars and decreases the navigational uncertainty ellipse.

5.1.4 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 10). 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.

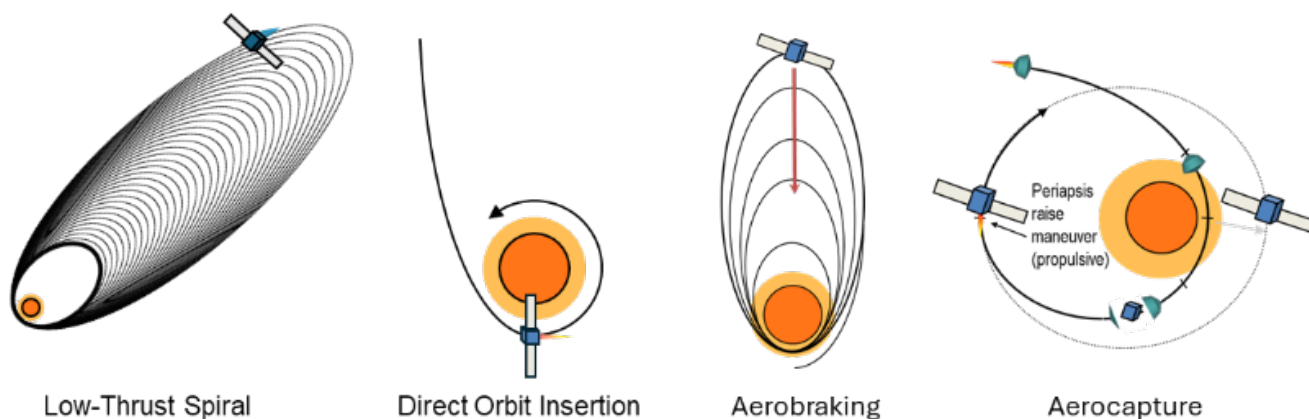


Figure 10: Methods for Mars capture and orbital insertion.

6 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. Bacterial spores pose a risk to our goal of preventing contamination, since this dormant state may persist thousands of years until the spore finds itself in a habitable environment again. If the project has chosen to meet compliance by the bioburden route, the first step is to understand the cleanliness of the hardware being flown.

6.1 Understanding the Category IVa Bioburden Requirements

The bioburden requirements for a Category IVa mission are established to best protect the Martian surface from terrestrial contamination. In addition to the total bioburden limit of 500,000 spores at launch, there is a requirement that only 300,000 of those spores be on exterior-facing spacecraft surfaces. For the bioburden route, there is also a requirement that there are no more than 300 spores/m² on these spacecraft surfaces. These two additional requirements are affected by launch recontamination analysis and necessitate a deeper understanding of the hardware than a simple spore limit might. They also serve to protect against any one part of the Martian surface-facing hardware carrying a disproportional amount of the allocated bioburden.

6.2 Introduction to PPELs

The Planetary Protection Equipment List (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 nonmetallic pieces of hardware, having this data available is crucial. Recall that for Category IVa missions, bioburden is tracked as overall spores as well as a surface bioburden density limit. 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 bioburden reduction treatments.

Appendix B describes the companion document to this primer, which is the PPEL template. Look to this document for an example of how bioburden is calculated for a project.

For PPEL accounting, use the following definitions of hardware categories:

- **External, exterior, or exposed surfaces:** Any hardware with a line of sight to the surface in the landed or the deployed configuration
- **Mated surfaces:** Two surfaces closed out by installs and mated by fasteners, epoxies, or both
- **Internal surfaces:** Surfaces behind high efficiency particulate air (HEPA) filters or with a “tortuous path” between the enclosed space and the exterior surface, prohibiting microbial transport; they do not contribute to, or are not accountable to, the spore bioburden allocations for soft-landed hardware because the assumption is that those surfaces will never become exposed
- **Volumes:** Nonmetallics such as paints, epoxies, propellant, freon, or lubricants in which spores may be trapped

6.2.1 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/m²). A CFU is a spore that has returned to a metabolically active state and has begun reproducing, forming a bacterial colony, in a bioassay. 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/cm³). 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 IVa missions.

6.2.2 PPEL Hardware Grouping

Separatable hardware used specifically for cruise, entry, descent, or landing may be subject to different mission design outcomes, requiring different treatment for bioburden accounting. In the successfully landed Mars missions to date, several pieces of hardware, making up a large portion of the flown surface area, are all attributed to components used for the safe delivery of the primary payload. To stay within bioburden limits, missions apply multiple different bioburden reduction techniques, combined with strategic and conservative analyses, to ensure the bioburden requirements are met at the time of launch.

Look to Figure 11 and the Mars 2020 example that follows to see how that mission's multiple elements were accounted for and treated.

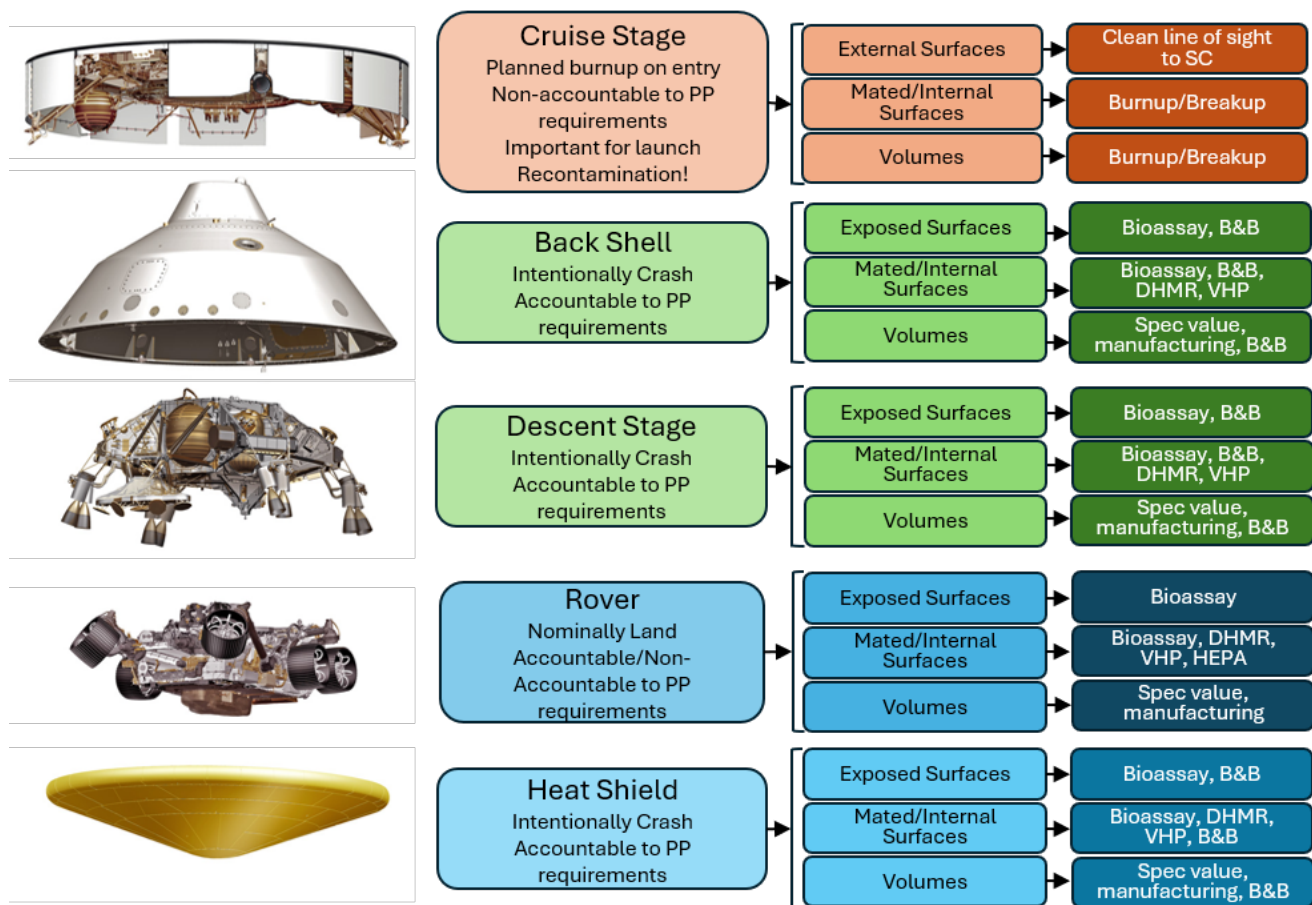


Figure 11: Breakdown of hardware treatment and overview of potential bioburden mitigations for the Mars 2020 project

Mars 2020—the Perseverance Rover mission—employed a substantial set of hardware to achieve its entry, descent, and landing operations, and that hardware accounted for a large amount of the bioburden budget.

Cruise Stage: The cruise stage was designed to burn up in the atmosphere, which was analyzed to reach temperatures sufficient to achieve hardware sterilization. Since no unsterilized components would reach the Martian surface, bioburden calculated for this component did not count toward the landed bioburden allocation. However, since the cruise stage was attached to the rest of the spacecraft during launch, the bioburden of the exterior surfaces of the cruise stage were still calculated and considered for launch recontamination analysis.

Back Shell and Descent Stage: The back shell and descent stage were designed to intentionally crash a safe distance from the payload after they had completed their parts of the descent sequences. The conservative assumption is that the hardware is completely pulverized, releasing every surface, mated, internal, and encapsulated spore from the hardware to the Martian surface. Though not part of the primary payload, these pieces of hardware have the potential to take up a large amount of the bioburden budget.

Lander: The complexity of the lander may pose a challenge, as the requirements must be considered in every planned configuration and operation. However, the soft landing holds a benefit. Internal surfaces are non-accountable to bioburden requirements if the vents are HEPA filtered. A tortuous path case may be made, too, if certain vent paths are too convoluted for a spore to incidentally be dislodged and make its way out of the hardware. The bioburden in these areas must be monitored for reporting purposes in the case of an off-nominal landing but are exempt from consideration in the overarching spore bioburden limits. Likewise, mated surfaces and spores encapsulated in materials such as tapes and epoxies are assumed to remain trapped in a nominal soft landing scenario. These would only count toward the total spores at launch, not toward the surface bioburden allocation.

Heat Shield: Much like the back shell, the heat shield was intended to crash into the surface, and the assumption was that every spore on and in the hardware was released to the surface. The heat shield differed only in that it was able to take an amount of bioburden reduction credit for the heat sterilization the hardware would experience upon entry. Though this reduction occurred after launch, the Office of Planetary Protection concurred that the project was still able to take credit for it on the basis that it reduced the number of spores delivered to the Martian surface.

6.3 Launch Recontamination Analysis

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. [12]. In this conservative model, the large interior surface area of the fairing can 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.

7 Probabilistic Analytical Approach to Compliance

Rather than only tracking bioburden, a Category IVa project may choose to pursue a probabilistic analytical approach to planetary protection compliance (branch 5b in Figure 2). In this approach, the project evaluates the probability that its mission causes a biological inoculation event at Mars and must show that this probability is less than 1×10^{-4} . Here, a biological inoculation event is defined as the “introduction of a viable organism to a solar system body capable of providing nutrients and environmental growth conditions such that the organism can replicate” [3].

This approach, therefore, requires a great deal more information about the target Martian environment and requires more modeling than the bioburden approach. For Mars, this approach has only been taken by one mission, Viking (1975). Viking was the first Martian lander, with objectives to learn about the habitability of Mars, and the Viking mission planners were necessarily missing information about said habitability [13]. Nonetheless, their framework is still relevant. Their first submodel assessed the bioburden present on the spacecraft at launch, and the survival of microbes to the surface. Subsequent submodels assessed the probability of release, transport to a habitable environment, and reproduction.

If a mission takes a bioburden approach to planetary protection compliance, NASA’s planetary protection policy makes the simplifying assumption that low bioburden is sufficient and the subsequent survival, release, and transport elements of contamination do not substantially vary between Mars surface missions. The habitable environment component is addressed with the concept of “special regions” and the Category IVa / Category IVc distinction. There is a final assumption that if an organism reaches a *habitable* environment, it *will* reproduce. It is therefore only the bioburden element that needs to be reassessed for each mission. Note, however, that even in the bioburden framework, it is common to also take credit for reductions in survival or release, which can be bookkept in units of bioburden (Sections 8.1.4 and 8.2.1).

If, on the other hand, a mission adopts a probabilistic analytical approach to compliance, it has the opportunity to reassess all elements in the chain: bioburden, release, and transport to a habitable environment. There is again a final assumption that if an organism reaches a *habitable* environment, it *will* reproduce; however, missions may find it useful to explore whether environments identified as habitable based on a limited number of variables (e.g., temperature and water activity) limit growth in other ways. For example, if cultivation-independent surveys of the spacecraft and assembly environments found only contamination with aerobic organisms, the low oxygen content of Mars atmosphere could factor into the definition of habitable for a specific mission.

Since Viking, at least two other missions have taken a probabilistic analytical approach to planetary protection: the Juno mission to orbit Jupiter and the Europa Clipper mission, en route to investigate Jupiter’s moon Europa as of this writing [14]. While orbital missions, they both offer a window into the comprehensive nature of a probabilistic approach, which could be used by a Mars mission, because they had to assess the implications of contacting a protected body—Europa. Juno relied on impact avoidance, in-flight radiation, and survival-after-impact calculations [15]. Europa Clipper went further, concluding that for an organism to reach a habitable environment, it would first need to be transported below the surface of Europa by geological resurfacing, a surface renewal phenomenon that is believed to occur on both small regions ($<100 \text{ km}^2$) and large scales (up to millions of km^2) over millions of years, with large uncertainties as to the causal mechanisms at play. In contrast, a Mars mission would have better data on the environment into which the particles might be released and whether a given site is actually habitable. Lethality factors (such as UV-C exposure during transport) would also be assessed.

One advantage of the probabilistic analytical approach over the bioburden approach is that it may not require the project to maintain engineering teams to sample the spacecraft and access the spacecraft in cleanrooms during integration and testing. Early (typically conservative) bioburden estimates in the PPEL are typically sufficient for inputs to the modeling. Another advantage of the approach is that it can be done early in the project's formulation. Concept studies such as Europa Lander greatly benefited from this approach when scoping their planetary protection protocols, determining contamination risk drivers and performing relevant flight system architecture trades.

Scientific understanding of the Martian environment has progressed substantially since Viking, with information from multiple orbiters, landers, and rovers. NASA's Office of Planetary Protection is funding work to mature and update the Mars analytical approach with physics-based models (e.g., aerothermal models), current tools (e.g., computational fluid dynamics, or CFD), current scientific knowledge of Mars and biology, and rigorous mathematics and uncertainty quantification. Figure 12 shows a diagram of the Mars Probability of Contamination Model in development. In the meantime, for any mission considering an analytical approach, the papers from Viking [13], Juno [15], and Europa Clipper [14] are a good place to start.

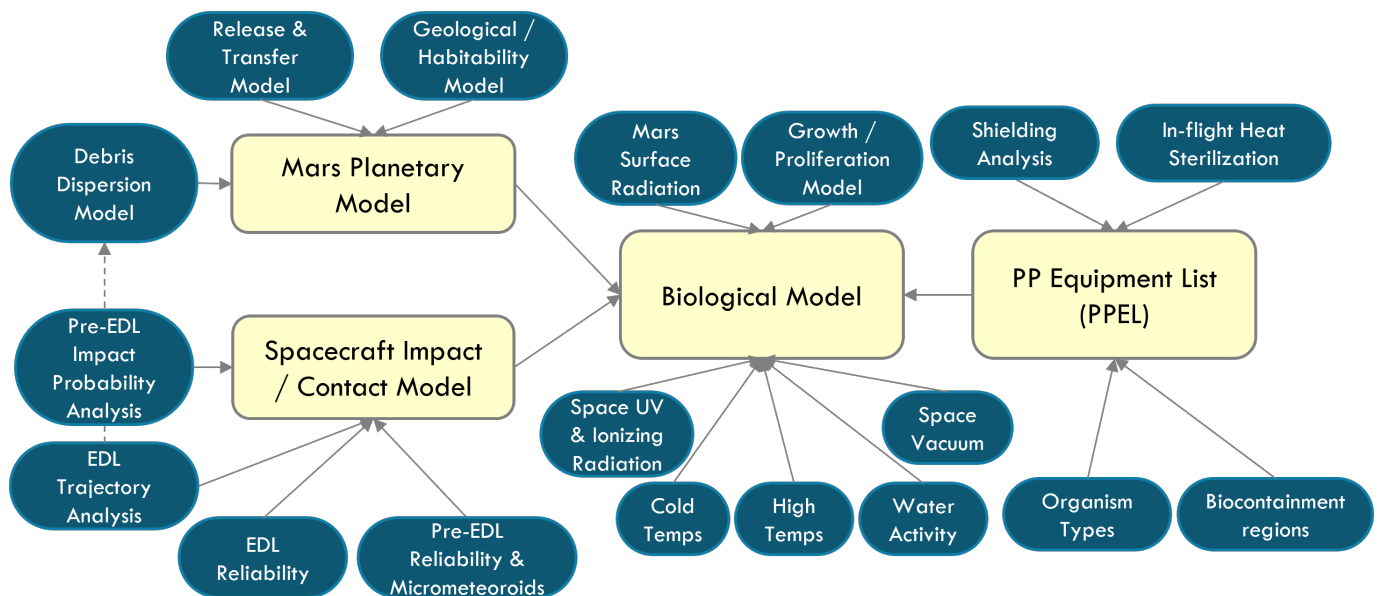


Figure 12: Mars Probability of Contamination Model diagram.

The NASA compliance standard document [3] itself provides a good framework for this probabilistic analytical approach (see section 4.4.4b). The calculation of the probability of contamination shall include a conservative estimate of poorly known parameters, and address the following factors, at a minimum:

1. Bioburden at launch
2. Probability of encountering or impacting Mars in nominal and off-nominal scenarios, including spacecraft reliability
3. Mechanisms and timescales of transport to a potentially habitable environment
4. Probability of surviving the journey from launch on Earth to a habitable region on Mars
5. Proliferation of one or more viable organisms on Mars within a specified period of biological exploration

For Category IVa Mars missions, Point 1 would set the baseline for how many potentially viable organisms begin the trip to Mars and should include any recontamination during launch. Point 2 would consider off-nominal impacts due

to failures after maneuvering onto a Mars intercept trajectory and could involve burnup and breakup analyses as well as impact debris dispersion analyses. Point 3 would include modeling of transport by wind or subsurface penetration, and would depend on the geography of the landing site. Point 4 would require both discrete lethality calculations for cruise and continuous lethality modeling for lethality effects after landing and prior to or during transport in the Mars atmosphere. Point 5 needs careful attention to develop a credible model of proliferation on Mars. Or a conservative approach can be taken that assigns a probability of one to an organism proliferating when it survives transport to a habitable region.

The model infrastructure being developed by NASA Headquarters will set a foundation for this work that projects can reuse and need not develop themselves. As shown in Figure 13, once the infrastructure is in place, a project will just need to provide its spacecraft design, trajectory information, PPEL, plan for any pre-launch bioburden reduction protocols, and concept of operations (ConOps). The project may also need to perform mission-specific debris analysis and reliability analysis.

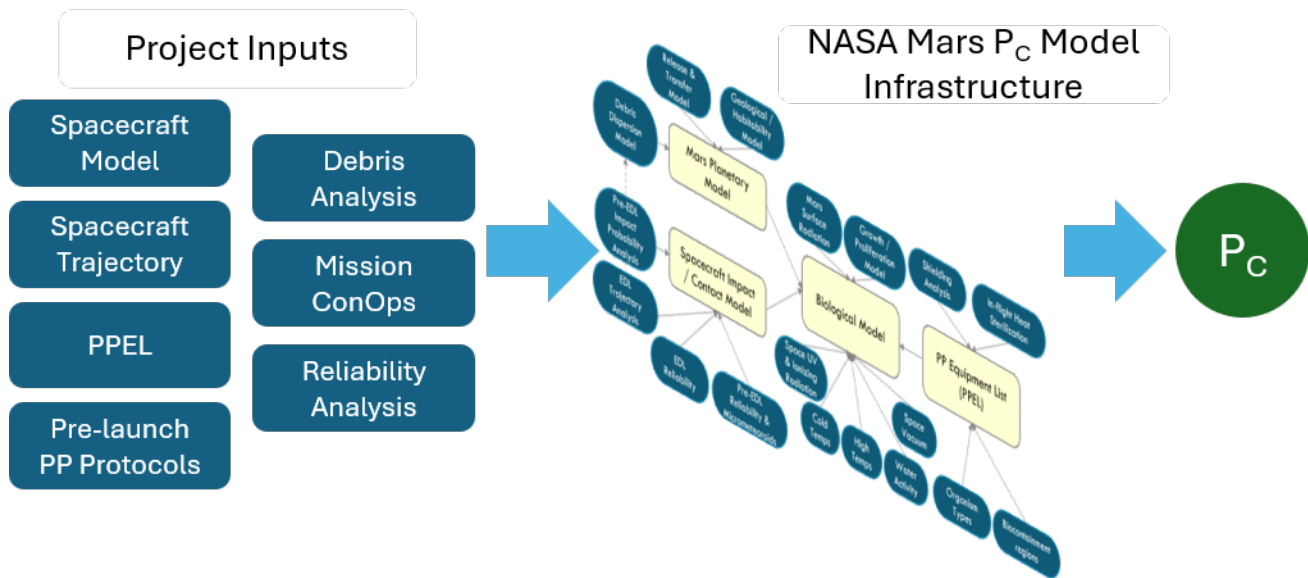


Figure 13: Interface between the project and modeling framework being developed by NASA Headquarters to provide an estimate of the probability of contamination (P_C).

8 Bioburden Compliance 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, the increased surface area likely 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. In turn, these strategies may also influence hardware design. These sections outline several bioburden reduction strategies that can be strategically applied to select hardware to bring the total number of spores under the limits of 500,000 total, 300,000 on the surface, and 300 spores/m² surface density. Also described are analytical approaches that are useful in conjunction with bioburden-based strategies to help meet planetary protection compliance (Figure 14).

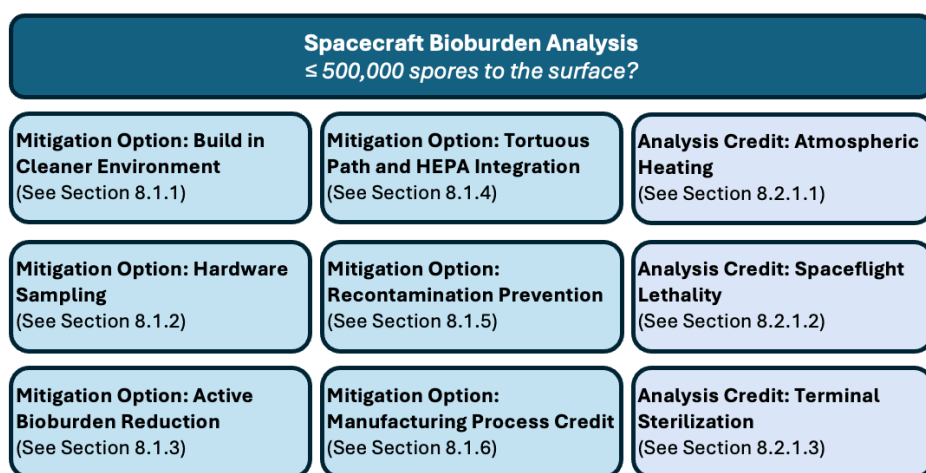


Figure 14: Options for bioburden mitigation and bioburden analysis credits.

8.1 Spacecraft Bioburden Mitigation

8.1.1 Build in Cleaner Environment

Cleanrooms are work environments in which air temperature, humidity, and, most importantly, airborne particulate concentrations are controlled and monitored. Internationally recognized standards, outlined in ISO 14644-1:2015 [16] specify different particulate concentrations for nine different classes of cleanroom, where Class 9 is uncontrolled and Class 1 is the most tightly controlled. Additional standards in the ISO 14644 series provide guidance on monitoring, maintenance, and operational practices.

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. The HEPA filtration removes both biological and non-biological particles from the air, and the degradation-resistant surfaces and regular cleaning make the cleanroom an inhospitable place for microbes. Additional precautions, such as gowning procedures and limiting the number of people in the space, 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.

Section 4.4.3 of NASA-STD-8719.27 [3] states the requirement to build a Category IV spacecraft is an ISO 8 or better cleanroom. From a bioburden accounting perspective, the specification value for an ISO 8 environment is an

order of magnitude lower than for an uncontrolled environment, reducing the bioburden on exposed surfaces assumed in the absence of spore burden measurements.

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 specification value across the applicable surface areas. When a higher-class cleanroom is not available or impractical to implement, 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, small flow hoods can create small ISO 5 environments in which to build a subset of hardware. Coupled with proper gowning and usage, this can protect critical hardware, such as instruments or optics from harmful contamination.

The NASA-STD-8719.27 [3] document delineates surface bioburden density estimations, the specification values, for the different manufacturing environments, which are assumed for the surfaces of hardware assembled in that environment.

8.1.2 Hardware 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.
- Microbes 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 kill any non-spore microbes.
- The liquid solution is aliquoted into bacterial growth media for culture.
- The media plates are incubated for three days. A single spore becomes visible once it returns to a vegetative state and proliferates, creating a visible microbial colony—this is referred to as a colony-forming unit, or CFU. Colonies are counted at 24, 48, and 72 hours after plating.
- 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 specification values in Table C-1 of NASA-STD-8719.27 [3] are conservative bioburden density estimations and, while useful proxies for non-assayed hardware, these generally represent significant overestimates of bioburden for regularly cleaned hardware maintained in controlled environments. Therefore, sampling is an effective method to lower the overall accounted bioburden of a piece of hardware.

8.1.3 Active Bioburden Reduction

There are multiple options for bioburden reduction on hardware surfaces, including exposure to heat, application of liquid or gas phase sterilants, or mechanical cleaning with solvents/biocides. Low-sensitivity components with large surface areas or accountable volumes are ideal candidates for bioburden reduction before hardware delivery and integration. The resulting reduction in bioburden only remains valid if cleanliness is maintained between the treatment and integration. Typical cleanliness maintenance strategies include double bagging or storage in small, clean volumes until cleanroom ingress and/or spacecraft integration. Note that while the surfaces of hardware

always require procedures for maintaining cleanliness after bioburden reduction, the internal volumes of some components would not if there is no contamination pathway into the volume. Thus, applying bioburden reduction at select steps in assembly can minimize bioburden and the potential for recontamination.

Dry Heat Microbial Reduction

Dry heat microbial reduction (DHMR) is an effective method for reducing the number of viable spores on and in a piece of hardware. This is a useful approach in difficult-to-clean, high-surface-area hardware, such as wire harnesses and pump assemblies because heat penetrates complex assemblies. The calculations for DHMR require defining the temperature, pressure and humidity according to the guidance in the European Cooperation for Space Standardization document ECSS-Q-ST-70-57C [17]. The time at any one temperature required to achieve a desired reduction magnitude varies based on the conditions (pressure, humidity) and whether the hardware represents an enclosed volume, mated surface, exposed (free) surface, or some mix thereof.

Bioburden reduction by this method is log-linear; at any one temperature, the $\log_{10}$ of the initial bioburden density, either measured or assumed as a specification value, is reduced such that the time required to reduce bioburden 10,000-fold is twice that required to reduce it 100-fold. Reductions can also be calculated by integration over an exposure profile, provided the temperature values are derived from the coldest location on or in the hardware over the interval assessed. The target temperature can be tuned to the requirements of the hardware and its heat tolerance. Lower-temperature bakeouts may be implemented for longer exposures to achieve a similar microbial reduction result as a shorter, higher-temperature exposure.

Contamination control bakeouts, where hardware is exposed to high temperatures under vacuum to allow outgassing of volatile substances, are a convenient way to perform DHMR as part of spacecraft assembly. The applied vacuum satisfies both humidity and pressure requirements for DHMR, and the temperature and time can be coordinated with contamination control needs such that one well-planned bakeout meets both outgassing requirements as well as bioburden reduction goals. Like all bioburden reduction treatments, the preservation of hardware cleanliness after DHMR and before integration is critical and must be planned prior to placing the hardware in the treatment chamber.

VHP and EtO

Similar to a bakeout, vaporized hydrogen peroxide (VHP) and ethylene oxide (EtO) are gas phase bioburden reduction strategies that can be applied to smaller pieces of hardware, with the understanding that the cleanliness state is only valid while the hardware is protected from recontamination in uncontrolled environments. Guidelines for VHP also follow an ECSS standard, found in ECSS-Q-ST-70-56C [17].

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

8.1.4 Tortuous Path and HEPA Filter Integration

In soft-landed, nonimpacting hardware, volumes that are closed off from the environment with no viable escape-route to the Martian surface may be considered nonaccountable to planetary protection requirements. These accommodations are built in at the design stage, providing space accommodations for HEPA filters covering vents, or by making a case that the path a microbe would need to travel to escape the hardware is too convoluted to be feasible. By blocking routes for bacterial spores to escape the hardware, a project can consider the bioburden inside the enclosed area as “nonaccountable,” meaning it doesn’t contribute to the overall bioburden count. The nonaccountable bioburden still needs to be assessed, by bioburden sampling and/or the use of specification values, so that contamination assessments can be made in the event of an off-nominal landing that may compromise the enclosed area.

8.1.5 Recontamination Prevention

More than a particular mitigation, recontamination prevention is a set of habits and personnel behaviors that promote a clean environment to protect the hardware. Cleanroom practices such as gowning, periodic cleaning, and controlled ingress procedures help mitigate contamination distribution from dirtier areas to the cleaned hardware, reducing bioburden and the effort required to reclean hardware. Examples follow:

- Hardware that is baked out or exposed to DHMR for planetary protection and contamination control purposes, should be transported back to the cleanroom in two layers of clean bagging material. The outer bag should be wiped down and removed in the airlock during ingress. The inner bag should be wiped down and removed once in the cleanroom.
- Proper gowning procedures are crucial to proper cleanroom use. People are the largest source of contamination in a cleanroom, and proper application of the gowning materials can mitigate a lot of this effect. Face masks, hairnets, beard covers, shoe covers, and gloves each contribute to contain contamination when used in conjunction with cleanroom garments.

Other good cleanroom practices include:

- Periodic cleaning of high-contact areas such as desks, door handles, ladder rails, and chairs, since gloves may contain bacteria on people’s hands, but gloved hands are able to transfer bacteria between surfaces
- Controlling the number of people allowed in a cleanroom at once, to not overwhelm the air turnover and filtering capacity of the cleanroom
- Quarterly walkthroughs of the cleanroom facility to check for door seal integrity, dust accumulation in low-traffic areas, and any potential sources of contamination

8.1.6 Manufacturing Process Credit

Some component manufacturing processes include steps that effectively reduce bioburden, such as putting hardware through bakeouts to cure epoxies or solvent baths to remove chemical contamination. If there is no recontamination potential and the manufacturing process parameters that result in bioburden reduction are both verified and traceable, the project may take credit for the reduced bioburden on and in the component(s). In this way, the specification bioburden density may be substantially reduced without additional treatment or cleaning.

8.2 Spacecraft Bioburden Analyses

The compliance paths of more complicated projects tend to rely on a mix of physical bioburden reduction and analytic tools. The following sections offer some strategies that have been successfully applied on flown missions or have been approved in mission planning stages.

8.2.1 Bioburden at Mars

NASA-STD-8719.27 requires $\leq 500,000$ spores on the spacecraft at time of launch to meet requirements. Previous missions have been granted a waiver for relief of this requirement, changing the mission requirement to be $\leq 500,000$ spores on the spacecraft upon reaching the surface of Mars. This allows for the accounting of bioburden reduction that occurs between launch and contact with the Martian surface.

Atmospheric Heating

Taking advantage of an “at Mars” waiver, hardware such as a heat shield may be able to receive bioburden reduction credit from the sterilizing heat experienced as it enters the Martian atmosphere. This would follow the same principle as DHMR bakeouts of log-reduction earned by time at specific temperatures, to be applied to the starting bioburden of the hardware experiencing the temperature.

Spaceflight Lethality

Space is an unforgiving environment for terrestrial life, and this fact may be leveraged in calculating bioburden delivered to Mars. Conservative calculations for the lethality of spaceflight may be applied to the bioburden on surfaces appropriately exposed to the lethality factor in question. Thermal and vacuum stress as well as UV radiation doses may all be considered in bioburden reduction calculations if calculating delivered, instead of launched, bioburden.

Terminal Sterilization

Terminal sterilization is the deliberate application of a lethality factor to a spacecraft or hardware at the end of its mission. Though this method has not yet been applied in practice at Mars, using a planned high-heat event at the end of a spacecraft’s mission could prevent contamination if natural processes might release microbes from the spacecraft after operations cease. Bioburden deposition to the Martian surface through nominal mission operations would still need to be considered, as would any credible off-nominal scenarios that would threaten this sterilization procedure.

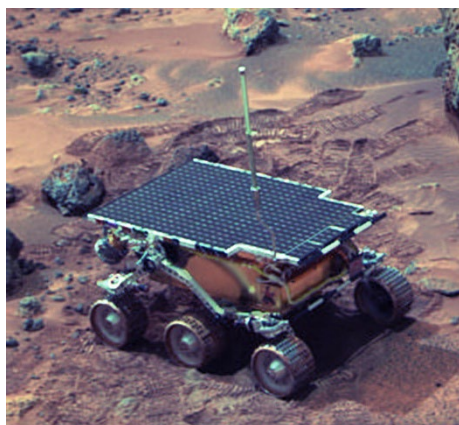
9 Planetary Protection in Practice: Case Studies from Category IVa Missions

A number of Category IVa missions have landed on the Martian surface, shown in Table 3. The following section includes brief descriptions of the NASA missions shown in the table and how they complied with planetary protection requirements.

Table 3: Category IVa missions to Mars (non-NASA missions are italicized).

Mission	Launch Date	Mars Landing	Type	Landed Mass	Notes
Mars Pathfinder	4-Dec-96	4-Jul-97	Lander/Rover	360 kg	10 kg Sojourner rover
Mars Polar Lander	3-Jan-99	3-Dec-99	Lander	290 kg	South Pole (failed)
DS-2	3-Jan-99	3-Dec-99	Microprobe	2.4 kg	Failed with MPL
MER (Spirit Rover)	10-Jun-03	4-Jan-04	Rover	185 kg	Gusev Crater
MER (Opportunity Rover)	7-Jul-03	25-Jan-04	Rover	185 kg	Meridiani Planum
MSL (Curiosity Rover)	26-Nov-11	6-Aug-12	Rover	899 kg	Gale Crater
InSight	5-May-18	26-Nov-18	Lander	358 kg	Elysium Planitia
Mars 2020 (Perseverance Rover and Ingenuity Helicopter)	30-Jul-20	18-Feb-21	Rover and Helicopter	1.8 kg	Mars 2020 mission is Category V(r)/IVb; the helicopter is Category IVa
<i>Beagle (ESA)</i>	<i>2-Jun-03</i>	<i>25-Dec-03</i>	<i>Lander</i>	<i>33 kg</i>	<i>Failed</i>
<i>Schiaparelli (ESA)</i>	<i>14-Mar-16</i>	<i>19-Oct-16</i>	<i>Lander</i>	<i>577 kg</i>	<i>ExoMars EDM (crashed)</i>
<i>Tianwen 1 (China)</i>	<i>23-Jul-20</i>	<i>14-May-21</i>	<i>Lander/Rover</i>	<i>240 kg</i>	<i>Zhurong Rover</i>

9.1 Mars Pathfinder



Mars Pathfinder, launched in 1997, was designed as a technology demonstration mission. It delivered both a static instrumented lander, the Carl Sagan Memorial Station and the first Mars rover, Sojourner.

The mission followed a bioburden approach to planetary protection. All external surfaces (that is, accountable surfaces that could interact with the Martian environment in a nominal mission scenario) were either cleaned with alcohol or processed with DHMR. A number of small surfaces could not withstand either and were accounted for in the bioburden budget.

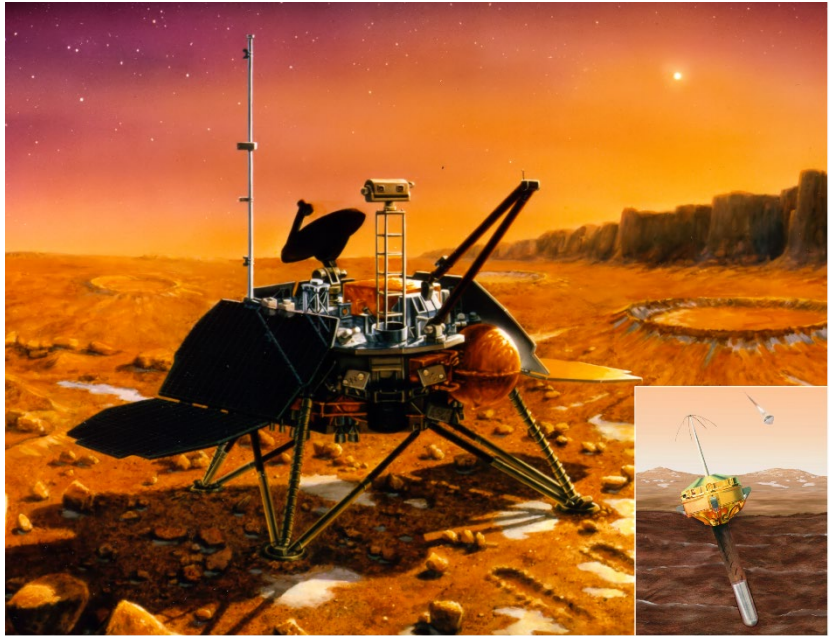
The one major exception was the outside of the heat shield and aeroshell.

For those, the team showed by analysis that heating during entry was sufficient to sterilize the outside surfaces during atmospheric entry, and the project was allowed (by an exemption) to use the post-entry sterilized values rather than “at launch” values.

9.2 Mars Polar Lander and DS2 Probes

The Mars Surveyor 98 Lander (later renamed the Mars Polar Lander, or MPL) and its additional Deep Space 2 (DS2) microprobes launched in January of 1999 and crashed on Mars in December. The lander, its payloads, the aeroshell, and the DS2 microprobes were all treated collectively as a single “landed system.” The DS2 probes were only allocated 10,000 spores of the 300,000 surface spores allowed. They were assembled on a Class 100 clean bench and achieved ~1,500 exposed spores combined.

The lander, on the other hand, had major challenges. The internal free surfaces of the lander’s structural composite core were



initially assumed to be sterile via a vacuum dry-heat process during manufacturing. Post-launch evaluations revealed that the manufacturing vacuum pressure was too high and lacked active pumping to evacuate outgassed moisture, invalidating the standard dry-heat sterilization claims. Additionally, while the heat shield thermal protection system (TPS) was processed at temperatures sufficient for sterilization, the back shell TPS was cured at only 57°C, leading to an unexpected and massive encapsulated bioburden of 5.7×10^6 spores (i.e., 20× the limit).

The mission had several other notable instances of exemptions and noncompliance:

- The cruise stage was entirely exempted based on expected atmospheric breakup and component heating above 500°C. But later analysis showed that an unseparated entry failure scenario would have shielded internal components and released up to 3×10^5 additional spores.
- The Thermal and Evolved Gas Analyzer (TEGA) possessed highly heat-sensitive wax actuators that made both dry-heat processing and physical integration assays impossible. The project implemented a strict contamination control regimen in a ISO Class 10,000 cleanroom, and its pre-launch spore burden was estimated analytically rather than verified through direct biological sampling.
- The injection trajectory of the launch vehicle’s third stage (Star 48) slightly exceeded the required 1×10^{-4} impact probability limit on two late launch days, though its average over the launch window remained compliant.
- The trajectory analysis team failed to notify the planetary protection officer of a substantial late TCM that significantly increased the probability of accidental impact prior to executing the burn.

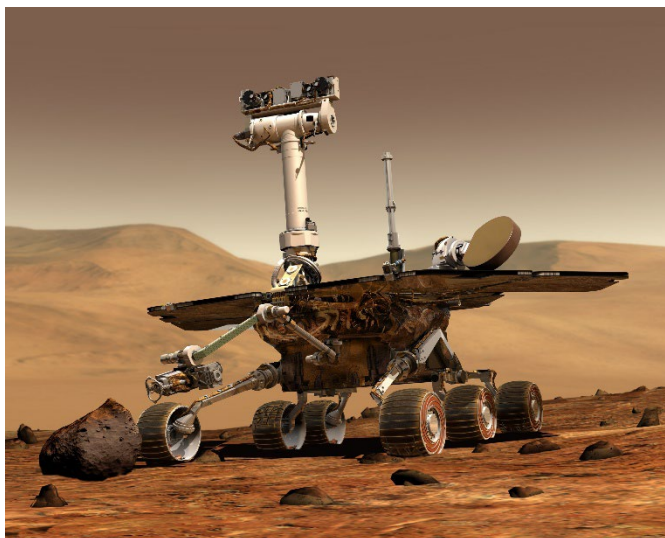
Following the eventual loss of both the MPL and DS2 on December 3, 1999, the end-of-mission report concluded that since the impact velocities were insufficient to cause high-velocity pulverization of the back shell and lander structure, the vast majority of the encapsulated spores remained safely isolated within the structural matrices and did not violate the NASA limits.

9.3 MER Rovers

The MER mission sent two robotic rovers, Spirit and Opportunity, to Mars to search for evidence of ancient water, landing in January 2004. The entire mission shared a 5×10^5 spore limit, allocating 2×10^5 for hard impacting components of the entry, descent, and landing system. The mission implementation team took the following approach in satisfying planetary protection requirements:

- **Cruise Stage:** The cruise stage was exempted from bioburden constraints after analysis showed entry heating would be sufficient to sterilize the surface. Bioburden was still measured for launch recontamination of the back shell.
- **Entry Vehicle:** The heat shield was designed to crash into the Martian surface, while the back shell was planned to bounce and be dragged along by the attached parachute after disposal. Much of the entry vehicle was analyzed to reach temperatures sufficient to convey sterility during entry. Due to the nature of the nominal landing of the hard-impacting hardware, all of the surfaces were considered exposed to the Martian environment for the bioburden density requirement and exposed bioburden requirement.
- **DHMR:** DHMR was applied to 62% of rover accountable area and 94% of lander accountable area, reducing the bioburden and the amount of bioassay sampling that needed to be completed.
- **HEPA:** Within the rover and lander, HEPA filters were applied to the vents of enclosed areas, such as electronics boxes, marking the areas nonaccountable and exempting 13% of hardware items.

The two MER rovers and their accompanying entry, descent, and landing hardware launched with a total bioburden of 1.21×10^5 and 1.15×10^5 , respectively, against an allocated 2.0×10^5 each.



9.4 Mars Science Laboratory

MSL was originally given Category IVc (special regions) but was later shifted to Category IVa. In order to make the shift, Gale Crater was verified to be free of special regions within 1 m depth. MSL complied by pre-installing a drill bit on the turret, performing organic sampling of other drill bits post-DHMR, and agreeing to a wheel trenching rule to not go below 30 cm.

MSL was a very large mission that had to spread the Cat IV spore limits (surface, mated, and encapsulated) across multiple elements. It met planetary protection requirements through a meticulous bioburden approach. All in all, they tracked over 4,500 individual hardware items on a master PPEL and processed 3,541 swabs and 1,312 wipes using weighted statistical algorithms. The following approaches were employed:

- **Rover:** Curiosity used HEPA-filtered chassis enclosures to exempt complex internal electronics. The team relied heavily on DHMR (treated ~90% of the total surface area) and careful IPA cleaning.

- **Aeroshell:** Took aerothermal sterilization credit for the heat shield exterior, but multi-layer insulation (MLI) and back shell could not prove sterilization and were a large part of the bioburden.
- **Descent Stage:** Sky Crane and cruise stage were treated as impacting hardware.
- **MMRTG:** Nuclear heat from the multi-mission radioisotope thermoelectric generator (MMRTG) self-sterilized its central housing and primary fin surfaces, but the nonsterilized fin tips had to be assayed using surrogate sampling on the RTG adapter.

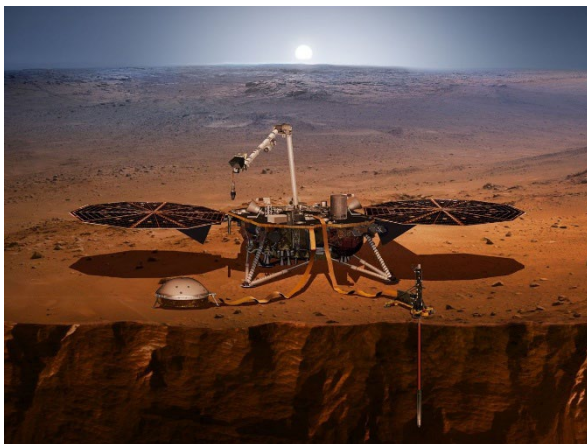


The cruise stage separated via 10 pyro devices with a 0.038% estimated failure risk (primarily driven by micrometeoroid impact risk rather than pyrotechnics). Burnup and breakup analysis showed that the outer and primary structures were exempted by entry heating ($>500^{\circ}\text{C}$).

The interior of the 5 m Atlas V fairing was precision-cleaned by United Launch Alliance (ULA) and maintained under Class 5,000/ISO 8 conditions. Assays revealed an extraordinary payload fairing interior cleanliness of 4.65 spores/ m^2 (far cleaner than the historical 500–1,000 spores/ m^2 allocation model).

At launch, MSL achieved 5.64×10^4 spores for landed hardware (19% of limit), 36 spores/ m^2 average surface density (12% of limit), and a total system bioburden of 2.78×10^5 spores (56% of limit).

9.5 InSight Lander



The InSight mission landed on Mars in November 2018 to study the interior of the planet by measuring seismic activity and subsurface temperature. The mission landing site was limited by the need to access the Martian subsurface and the Category IVa requirement to avoid special regions. Previous missions' data were leveraged to select a landing site at which no ice was within 5 m of the surface, where it could be contacted by subsurface components of the Heat Flow and Physical Properties Package (HP³) instrument.

This mission's launch was shared with the Mars Cube One (MarCO) interplanetary CubeSat mission. As a Category III, MarCO had less restrictive surface bioburden requirements than InSight, and precaution was taken to “do no harm” to InSight's more stringent cleanliness.

The total bioburden of InSight at launch was 1.1×10^5 spores, giving the project a margin of 77% against requirements. The exposed surface bioburden was 1.0×10^5 spores, with a 67% margin.

9.6 Mars 2020 and the Ingenuity Helicopter



The Mars 2020 mission included the Perseverance Mars rover as well as the Ingenuity helicopter technology demonstration. Perseverance is the first leg of a Mars Sample Return campaign. As of this writing, it is taking rock core samples and storing them in tubes, which are intended to be returned to Earth by a later mission. As such, Mars 2020 has two classifications: as a participant in an Earth return leg from a planet of biological

significance, it is a Category V Restricted (V(r)). For the leg of the mission that goes to Mars, Mars 2020 was also categorized as IVb for having a life detection goal because the samples are being taken in part to determine whether Mars ever harbored life.

Relevant to this primer, however, the requirements for Category V(r) and Category IVb are written such that the parts of the system that contact the sample need to show very high levels of cleanliness, but everything else is held to Category IVa requirements. For all landed elements, the project met requirements through bioburden accounting, holding itself to a total of 500,000 spores.

The Ingenuity helicopter was considered an instrument and a part of the Mars 2020 mission. It did not contact the samples, so it was not subject to Category IVb requirements. It was treated as a Category IVa component and was given a bioburden suballocation from the Mars 2020 total landed allocation. Ingenuity was assembled in an ISO Class 8 cleanroom, cleaned with alcohol, and double-bagged when moved.

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.

Biological Inoculation. Introduction of a viable organism to a solar system body capable of providing nutrients and environmental growth conditions such that the organism can replicate.

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.

Special Region. An environment at Mars within which terrestrial organisms are likely to replicate. Also, any region which is interpreted to have a high potential for the existence of extant Martian life forms is also defined as a Special Region.

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 Template

PPELs provide a method for tracking bioburden spores (whether from estimates or assay) using entries from the vehicle's MEL (Figure 15). The PPEL Template (see 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 1 kg 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 4.

Table 4: 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	1×10 ³ /m ²
ISO 8 cleanroom, particle controlled	1×10 ⁴ /m ²
Uncontrolled manufacturing	1×10 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 4 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 5) 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 5: 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:

$$\text{“Total Final Bio Burden”} = \text{“Spore Burden (add prev 3 columns)”} / 10^{\text{“Reduction Credit(log scale)”}}$$

The total is then compared against the 500,000 spore bioburden limit.

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.

The **surface final bioburden** is calculated as the subset of spores that are calculated from the surface area. The total of this is to be counted against the 300,000 spore surface bioburden limit.

The **surface final spore density (spores/m²)** is the surface final bioburden divided by the area. The bottom row has an **average** value, calculated as the total surface bioburden divided by the total area, which is compared against the 300 spore/m² limit.

Mission Title or Description																	
				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 <i>(bold underline values from assay) If unknown, fill "Spores from Surface Area" only</i>				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	Goal is <300,000	Goal is <300/m2	
Subsystem/Component	Quantity or # MLI Layers	Mass per Unit [kg]	Mass [kg]	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 (spores)	Surface Final Bio Burden (spores)	Surface Final Spore Density (spores/m2)	Notes
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
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			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
			0.00		0.00	Uncontrolled	0	0	0	0				0	0		
TOTALS:			0		0		0	0	0	0				-	-	#DIV/0!	
Allowable														500,000	300,000	300	

C. References and Further Reading

Table 6 lists reference documents relevant to planetary protection.

Table 6: 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.
Mars Planetary Protection Primer: A Quick-Start Guide for Lower-Cost Orbiters or Flybys , March 2026	This primer is designed as a quick-start guide for lower-cost orbiters or flybys. It offers a streamlined decision framework for Category III missions, practical tools to help teams estimate their spacecraft's bioburden, and clear entry points to compliance.

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