

Planetary-Protection Controls for Additive Manufacturing Materials and Equipment: Bioburden, Containment and Verification

Qualification of manufacturing hardware and feedstocks without compromising forward-contamination controls or scientific integrity

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ER-449 · Engineering Review · Version 0.1 · 8 October 2026

Abstract

Additive manufacturing introduces reservoirs, internal passages, powders or liquids, moving hardware and post-processing steps that can complicate planetary-protection control. Compliance is not achieved by sterilising the finished printed part alone. Material lots, printer interiors, reusable tools, recovered feedstock and maintenance interventions can all become contamination pathways. This review translates planetary-protection principles into a manufacturing-control framework centred on mission category, bioburden accounting, sterilisation compatibility, containment, recontamination prevention, witness sampling and verification.

Keywords: planetary protection; additive manufacturing; bioburden; sterilisation; containment; recontamination; verification; Mars; spacecraft cleanliness

1. Significance and scope

Planetary protection exists to preserve scientific integrity and, for relevant missions, limit harmful biological contamination. International planetary-protection guidance treats this as a shared mission responsibility rather than a universal cleanliness number [1].

This review owns additive-manufacturing material and equipment controls within that framework. It does not set mission category or regulatory authority; it defines the manufacturing evidence needed once those requirements are established.

2. Planetary protection is mission-specific

A printer adds surfaces, cavities, filters, feed lines, resin reservoirs and maintenance tools that may not exist in conventionally fabricated hardware. Bioburden control must therefore include the manufacturing system as well as the part.

Recovered powder or resin is particularly important because reuse can mix exposure histories and reintroduce organisms from previously opened process volumes. Lot identity and reuse rules should be part of the contamination-control plan.

Sterilisation method must be compatible with the material and with the instrument function. Reviews of spacecraft sterilisation emphasize that heat, radiation, plasma, chemical and other methods have different penetration and material-compatibility limits [2].

3. Manufacturing creates new contamination reservoirs

A post-print dry-heat cycle that reduces bioburden but distorts a precision part is not a successful process. Sterilisation compatibility should be demonstrated on the final material state, including residual monomer, adhesives, coatings and embedded components.

Where a resin or powder cannot tolerate the selected terminal process, bioburden may need to be controlled upstream through sterile or low-bioburden feedstock, contained manufacturing and validated aseptic transfer rather than repaired afterward.

4. Sterilisation must preserve material function

Containment should define which process volumes are clean, which are exposed and how material crosses the boundary. Door opening, cartridge replacement, filter service and failed prints are all contamination events that require disposition.

Recontamination control continues after a successful sterilisation cycle. Packaging, storage, transport to the launch vehicle and on-mission access can all invalidate the verified state.

Witness coupons and environmental monitoring should be linked to the actual manufacturing batch and equipment state. A cleanroom average does not prove the bioburden of an internal resin line or porous printed surface.

Bioburden measurement method should match the requirement and acknowledge its detection limits. Culture-based spore counts, molecular methods and surface sampling answer different questions; none should be treated as a complete inventory of viable organisms without justification.

5. Containment, recontamination and device-level verification

Device-level verification should challenge the hardest-to-clean and hardest-to-sample locations, not only accessible exterior surfaces. Internal channels and porous structures may require process controls precisely because direct terminal verification is difficult.

Materials used to print life-detection or sample-contact hardware also need chemical cleanliness controls so that sterilisation residues, leachables or manufacturing contaminants do not create false scientific signals.

Change control is essential. A new resin, printer lubricant, filter material or cleaning agent can alter both bioburden and assay background even if geometry is unchanged.

Axis	Measurement	Failure mode
Requirement	mission/category basis	generic cleanliness target substituted
Bioburden	feedstock, printer, part, reuse state	finished part sampled in isolation
Sterilisation	method, dose/time, material compatibility	microbial reduction separated from function
Containment	process boundaries and interventions	recontamination pathways omitted
Verification	sampling, witnesses, detection limits	cleanroom average treated as article evidence

Table 1. Domain-specific qualification matrix for planetary-protection controls in additive manufacturing.

6. Transfer limits and minimum reporting dataset

The manufacturing plan should distinguish forward-contamination control from crew or product sterility. They may overlap operationally, but planetary protection is tied to preservation of extraterrestrial environments and science objectives [3].

Report applicable mission/category requirements, material lots, printer clean state, bioburden-reduction method, exposure parameters, sampling plan, containment boundaries, reuse policy and recontamination controls.

Verify both microbial and material-function endpoints after the complete process, and preserve batch traceability through packaging and mission integration.

7. Minimum qualification framework

A minimum planetary-protection programme should map material and equipment flows against the applicable mission category and identify every step where bioburden can be introduced, retained, redistributed or released. Controls should cover raw material, resin preparation, printer internals, post-processing, waste and maintenance tools rather than focusing only on the final printed part.

Verification requires defined sampling locations, recovery methods, detection limits, positive/negative controls and acceptance criteria. Sterilisation or cleaning methods must also be shown compatible with the material and hardware state they treat; a process that reduces bioburden but damages optics, seals or cured parts can create a different mission risk.

8. Engineering conclusions

Planetary protection for additive manufacturing is therefore a verified containment-and-cleanliness system, not a one-time sterilisation claim. Qualification must preserve traceability between mission policy, bioburden control, equipment design, process steps and the evidence used to release hardware or material for flight.

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Competing interest

Juan Segurola is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and related additive-manufacturing technologies. This review is an engineering analysis and does not constitute a product-performance claim or a device qualification.