

Photopolymer Seals, Windows and Fluidic Components for Extraterrestrial Habitats: Leakage, Dust and Cycling

Qualification of exposed polymer components where atmosphere retention, optical throughput and fluid control share the same environment

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Abstract

Seals, windows and fluidic components in extraterrestrial habitats face a coupled environment of pressure differential, abrasive dust, vacuum, thermal cycling and radiation. Photopolymerisation can create complex geometries and integrated channels, but geometric freedom does not establish leakage performance or optical durability. Lunar-dust studies show strong abrasion and adhesion risks for polymeric and transparent surfaces. This review defines component-specific qualification for photopolymer seals, optical windows and fluidic parts, emphasizing leakage, dust ingress, abrasion, surface damage, dimensional drift and cycling rather than bulk coupon properties alone.

Keywords: habitat; seal; optical window; fluidic component; photopolymer; leakage; lunar dust; abrasion; thermal cycling; qualification

1. Significance and scope

Extraterrestrial habitat components are defined by function at interfaces: a seal must retain atmosphere, a window must transmit an optical signal and a fluidic part must transport a medium without unacceptable leakage or contamination. Bulk resin strength is therefore only supporting evidence.

This review owns photopolymer seals, windows and fluidic components after manufacture. ER-445 owns uncured-resin handling; ER-446 owns radiation ageing of the material itself.

2. Leakage is a component property

Seal leakage depends on geometry, contact pressure, surface finish, compliance, thermal expansion and contamination. A printed elastomer or rigid gasket material cannot be qualified from Shore hardness or tensile strength alone.

Leakage should be measured across the expected pressure differential and temperature range, including repeated assembly or cycling if the seal will be reused. Permanent set and surface damage should be recorded with the leak result.

Lunar dust is angular, abrasive and capable of occupying contact interfaces. Abrasion-index work and seal-focused testing show why particle interaction mode and exposure zone must be part of qualification rather than treated as a generic dust condition [1].

3. Dust changes contacts and optical surfaces

Dust can prevent full seal contact, scratch optical surfaces, change wetting and obstruct small channels. Cleaning itself can introduce additional abrasion, so both contaminated and post-cleaning states should be evaluated.

Optical windows require transmission, haze, scatter, surface roughness and dimensional stability after dust exposure. Erosive-wear experiments with lunar simulant demonstrate that transparent materials can lose optical performance even when they remain structurally intact [2].

4. Windows require throughput and surface-state metrics

Surface coatings or charge-dissipative layers may reduce dust adhesion, but they introduce their own optical, adhesion and durability requirements. Graphene/polymer coatings on polyimide illustrate that dust mitigation can be tuned through surface state rather than bulk material alone [3].

A printed window also carries cure-induced stress and potential birefringence. Optical qualification should therefore include the wavelength, angle and polarisation sensitivity relevant to the actual instrument or habitat use.

Fluidic components add internal wetting, dead volume and pressure cycling. Channel dimensions measured dry do not establish flow performance when the working fluid swells, plasticises or wets the network differently.

Cleanability and extractables matter where the fluid is life-support water, reagent or analytical sample. A photopolymer that is acceptable as an external bracket may be unacceptable in a sensitive fluid path.

5. Dust, cycling and device-level verification

Pressure cycling should be coupled to temperature because thermal expansion changes seal load and channel dimensions. Dust-contaminated interfaces should be cycled rather than tested only once after contamination.

Device-level tests should use representative flange, window mount or fluidic manifold geometry. Interfaces and fasteners should match the intended design because local stress and surface contact dominate many failures.

Witness coupons can help separate bulk ageing from interface damage, but component leakage or optical throughput remains the acceptance metric.

Axis	Measurement	Failure mode
Seal	leak rate, contact state, pressure	bulk hardness used as sealing evidence
Dust	simulant, loading, interaction mode	clean surface treated as mission state
Window	transmission, haze, roughness	structural survival treated as optical survival
Fluidic path	flow, wetting, extractables, pressure	dry dimensions used as performance
Cycling	temperature, pressure, assembly cycles	single exposure treated as lifetime

Table 1. Domain-specific qualification matrix for photopolymer seals, windows and fluidic habitat components.

6. Transfer limits and minimum reporting dataset

Repairability should be considered explicitly for long missions: a seal that can be replaced, a window that can be shielded or a manifold that can be flushed may justify different material margins than a buried non-serviceable component.

Report printed material state, post-cure, dimensions, surface finish, mating materials, seal load or mount condition, pressure, temperature, dust simulant/state, cycle count and cleaning method.

Measure leak rate, optical throughput or fluidic transfer directly, alongside dimensional and mechanical diagnostics that explain failure.

7. Minimum qualification framework

A minimum component programme should qualify the interface that performs the function: sealing contact for a seal, optical path for a window and wetted flow path for a fluidic component. Dust loading, assembly condition, pressure, temperature and cleaning history should be treated as controlled variables rather than peripheral test notes.

Acceptance should include repeated cycling and post-cycle inspection because leakage, haze, abrasion and channel obstruction can accumulate without a dramatic bulk-material failure. Where repair or replacement is planned, the qualification boundary should state the allowed maintenance action and the performance required after it.

8. Engineering conclusions

Extraterrestrial-habitat components made from photopolymers must therefore be judged at device level. Bulk resin properties remain necessary inputs, but leak tightness, optical throughput and fluid transfer under dust and cycling are the functions that determine serviceability.

References

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Competing interest

Juan Segurola is founder, CEO and CTO of 3Dresyns by Resynr 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.