

# Low-Earth-Orbit Exposure of Photopolymer Materials: Vacuum, Radiation, Thermal Cycling and Contamination

*Separating coupled orbital hazards from material-state effects so that ground tests support a defensible LEO service envelope*

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## Abstract

Low-Earth orbit exposes polymeric materials to hard vacuum, ultraviolet and ionising radiation, thermal cycling, atomic oxygen, contamination and particulate impact. Photopolymer parts add cure-state, residual extractables, printed interfaces and surface roughness as material-state variables. A useful qualification programme therefore cannot treat a single accelerated exposure as an orbital lifetime surrogate. It must track mass loss and condensable species under vacuum, optical and chemical change under radiation, dimensional and mechanical drift during thermal cycles, and the interaction of contamination with exposed surfaces. Flight exposure programmes such as LDEF and MISSE show why combined environments matter and why ground-equivalence claims require explicit dose, fluence, temperature and sequence records. ER-381 defines the minimum evidence needed to qualify a photopolymer for a declared LEO mission window without converting screening data into an unsupported life prediction. [1-5]

**Keywords:** low Earth orbit; photopolymer; vacuum; radiation; thermal cycling; contamination; qualification

## 1. Mission envelope before material screening

A LEO qualification begins with orbit, attitude, mission duration and exposure orientation because the relative importance of atomic oxygen, ultraviolet radiation, charged particles, temperature cycling and contamination changes with trajectory and surface view. Flight evidence from LDEF and MISSE demonstrates that apparently similar polymers can respond differently when orientation and shielding change. [2-4]

For a printed photopolymer, specimen state is recorded at equal resolution: formulation, print orientation, layer thickness, cure and post-cure history, cleaning, residual volatile content, surface finishing and any coating. These variables determine outgassing, surface chemistry and the stress field developed during thermal cycling.

## 2. Vacuum is a transport problem, not just a pressure value

Low-Earth-orbit qualification requires the material state to be defined before exposure. Residual photoinitiator, unreacted oligomer, absorbed cleaning solvent, moisture and post-cure conversion can all influence outgassing, vacuum response and radiation chemistry. Kondyurin, Lauke and Vogel showed directly that photopolymerisation under simulated free-space conditions can be altered by high vacuum and temperature variation, including evaporation of low-molecular components and changes in cure kinetics. Their UV-curing composite was not a modern VPP coupon, but the experiment provides direct evidence that curing state and volatile inventory are mechanistically coupled to the space environment. [1-4,6]

Outgassing and dimensional change should therefore be measured before interpreting later optical or mechanical degradation. Mass loss alone is insufficient because a small volatile fraction may contaminate nearby optics even when structural properties remain stable. A useful test sequence records preconditioning, vacuum mass-loss kinetics, condensable products where relevant, dimensions and modulus before introducing ultraviolet or particle exposure. This separates loss of mobile species from bond-scission or crosslinking damage in the network. [1-3,6]

Hard vacuum removes volatile species and shifts gas transport from convective to molecular regimes. Loss of low-molecular components can change mass, dimensions, optical properties and near-surface stiffness; released species can then condense on colder neighbouring surfaces. Grossman and Gouzman identify outgassing and contamination as integral parts of polymer behaviour in LEO rather than independent housekeeping issues. [1]

**Table 1. LEO exposure variables that must remain linked to response.**

| Exposure variable      | Required record                                          | Material response                                                |
|------------------------|----------------------------------------------------------|------------------------------------------------------------------|
| vacuum and temperature | pressure history, specimen temperature, duration         | mass loss, dimensions, volatile release or witness contamination |
| radiation              | spectral or particle field, dose or fluence, orientation | optical shift, chemistry, embrittlement or dielectric drift      |
| thermal cycling        | temperature extrema, dwell, ramp and cycle count         | warping, crack initiation, interface damage                      |
| combined exposure      | sequence or simultaneity of hazards                      | non-additive response relative to single-factor controls         |

## 3. Radiation and optical-property drift

LEO is not a single-dose environment. Vacuum, ultraviolet and particle radiation act concurrently with repeated thermal excursions, while atomic oxygen is strongly altitude- and orientation-dependent. Experiments on carbon/epoxy composites have shown that vacuum thermal cycling to 2000 cycles between approximately -175 and 120 degrees C can generate microvoids and interfacial sliding. The quantitative

result is not transferable to neat printed photopolymers, but it demonstrates why cycle count, temperature extrema, dwell and vacuum level must be reported together rather than replaced by an equivalent exposure time. [7]

Synergy should be tested explicitly. Sequential UV-then-thermal or vacuum-then-radiation protocols may not reproduce simultaneous exposure if one process changes oxygen availability, free volume or surface chemistry for the next. A factorial design comparing isolated and combined stresses is more informative than accumulating nominal doses. The response set should include mass, dimensions, surface chemistry, optical transmission or colour where relevant, glass transition, modulus and fracture response, because different degradation channels can move in opposite directions. [2-5]

Ultraviolet and charged-particle exposure can alter chromophores and network chemistry. Optical change is often surface dominated while mechanical embrittlement can be more distributed, so qualification uses at least one optical metric and one functional mechanical or dielectric metric. POSA and MISSE experience show that solar absorptance, emittance and transmission can move materially during flight exposure. [2,3,5]

#### 4. Thermal cycles expose interface and residual-stress weaknesses

Printed geometries contain corners, thickness transitions and bonded regions whose thermal strain is not represented by a uniform coupon. Dimensional mapping before and after cycling is therefore paired with microscopy or another damage-sensitive method. A part that returns to nominal dimensions while accumulating microcracks is not considered stable.

#### 5. Contamination must be measured with a witness strategy

Contamination risk should be treated as a source-and-sink problem. The printed component can emit species under vacuum and can also collect condensable products from neighbouring materials. Surface witness samples placed near the specimen can distinguish self-outgassing from chamber background. If the intended function is optical or dielectric, contamination metrics should be tied to that function rather than judged only by total mass loss. [1-3]

Surface erosion, bulk radiation chemistry and thermomechanical damage should be diagnosed separately. XPS or FTIR can track surface oxidation; gel fraction or spectroscopic conversion can indicate network change; microscopy or micro-CT can detect cracking; and mechanical tests determine whether those changes matter structurally. A qualification failure should be assigned to the first functionally relevant mechanism, not merely to the most visually obvious surface change. [2-5]

A qualification chamber can itself generate contaminants. Witness coupons or cold surfaces are used to distinguish material outgassing from facility background and to determine whether condensable species modify optical or adhesive surfaces. Without this control, a change can be attributed to the wrong mechanism.

#### 6. Ground-to-orbit equivalence

Equivalence is established response by response. A laboratory test can reproduce a defined radiation dose or thermal cycle count yet still miss AO, contamination or the ordering of exposures. ER-381 therefore permits acceleration only when the accelerated variable and the response used to bridge to service are explicitly stated; exposure hours alone are not a transfer variable. [1-4]

**Table 2. Evidence gates for a LEO service claim.**

| Gate                  | Evidence that closes it                                              | Failure of the gate                                                 |
|-----------------------|----------------------------------------------------------------------|---------------------------------------------------------------------|
| material-state gate   | complete print, cure, cleaning and surface record                    | flight or chamber data cannot be transferred to the candidate state |
| environment gate      | dose/fluence, pressure and temperature histories tied to orientation | accelerated test cannot be mapped to declared mission exposure      |
| response gate         | mechanical/optical/dimensional response plus contamination control   | no functional bridge between test and service                       |
| combined-effects gate | single-factor controls or justified sequence study                   | synergistic ageing remains unresolved                               |

#### 7. Qualification outcome

ER-381 does not assign a universal LEO lifetime to photopolymers. It closes only a mission-specific envelope in which the material state, exposure history and measured functional drift remain bounded. Where combined-environment evidence is missing, the result is explicitly a screening qualification rather than a lifetime prediction. Scope boundary: ER-381 integrates the LEO mission envelope; AO erosion and protection are treated in ER-382, and combined UV/VUV-vacuum-thermal ageing in ER-383. Those results inform, but do not replace, integrated mission qualification.

#### 8. Metrology and uncertainty for mission-relevant drift

Failure attribution should use a decision tree. A mass decrease with little chemistry change points first to volatile loss; increasing carbonyl or oxidised surface signatures with roughening suggests radiation or AO-mediated surface chemistry; crack formation without large mass change points toward thermomechanical mismatch; and optical-film contamination on witness coupons indicates transported condensables. More than one branch can be active, so the purpose of the tree is not to force a single cause but to ensure that each plausible mechanism is measured with at least one independent observable. [1-6]

Specimen orientation is part of the exposure state. Ram-facing and wake-facing surfaces can receive different atomic-oxygen fluence, solar exposure and contamination flux, while shadowing by the spacecraft changes thermal cycling and UV history. Ground tests should therefore reproduce the intended surface function and orientation conservatively rather than treating a material as having one universal LEO lifetime. [1-6]

The uncertainty budget should separate facility uncertainty from specimen scatter. Radiation fluence, temperature, vacuum level and contamination background are exposure uncertainties; print-to-print variation, residual conversion and thickness are specimen

uncertainties. Combining them into one broad standard deviation can hide a biased simulator. Reporting both classes allows an engineering margin to be assigned where it belongs. [1-6]

Scaling from coupons to parts must consider thickness and thermal time constants. Thin coupons can equilibrate rapidly and lose volatiles faster than thick printed walls, while a large component may experience larger temperature gradients and restraint. A representative subcomponent should therefore be included when dimensional stability, bonded interfaces or contamination are mission-critical. [1-6]

A credible pass decision requires retained function after the combined exposure, not survival of the specimen. For a structural support that means a defined mechanical margin; for an optical mount it may mean dimensional and contamination stability; for an electrical housing it may mean dielectric integrity. The same environmental history can therefore produce different dispositions for different component functions. [1-6]

The remaining research gap is direct long-duration LEO evidence for modern VPP networks with controlled print and post-cure states. Until that evidence is available, the strongest approach is mechanism-based qualification using separately measured volatile inventory, radiation response, thermal-cycle damage and contamination susceptibility, followed by a conservative combined-environment verification. [1-6]

Mission transfer requires exposure variables to be converted into state variables. Fluence, spectrum, thermal-cycle count, vacuum pressure and orientation are inputs; retained modulus, mass, optical properties, crack density and volatile inventory are outputs. Acceleration is valid only when it preserves the dominant mechanism. Raising UV intensity, temperature or oxygen flux can change reaction pathways and diffusion balance, so equivalent total dose does not automatically imply equivalent damage. [2-5]

A practical qualification envelope should include at least a pristine state, a vacuum-conditioned state, individual stress exposures and a combined stress state. Replicate statistics matter because printed defects can amplify environmental damage heterogeneously. Requalification is triggered by formulation, post-cure, build orientation or coating changes that alter the network, surface or volatile inventory. [1-6]

Mass-change measurements are conditioned by balance resolution, specimen handling and adsorbed moisture; optical measurements require stable geometry and calibrated wavelength response; dimensional mapping requires a defined coordinate system and repeatable temperature. These uncertainties are carried to the engineering decision instead of reporting only nominal before/after values.

For combined-environment testing, uncertainty also includes exposure nonuniformity. Radiation and AO fields can vary across a chamber, and specimen temperature may differ from fixture temperature. At least one mapped or independently monitored exposure quantity is used when spatial gradients could alter the interpretation.

## 9. Minimum reporting set for transfer

A minimum evidence package should also retain raw environmental histories. Average chamber temperature or nominal radiation dose hides excursions and interruptions that may control damage. Time-stamped pressure, specimen temperature and source output allow anomalies to be reconciled with property changes and make later model updates possible without repeating the exposure. [1-6]

Photopolymer-specific controls should include dark-stored and thermally matched references. A UV-exposed specimen should be compared with a specimen that receives the same temperature history without UV; a vacuum test should include a specimen held at the same temperature in inert atmosphere when practical. These controls identify whether the observed drift is environmental chemistry or simply thermal post-cure and physical ageing. [1-6]

Interfaces require their own acceptance logic. A printed insert, coating or bonded joint can fail through differential expansion even when the bulk resin retains modulus. Interfacial inspection and pull-off, peel or leak tests should therefore be selected according to the component function rather than inferred from bulk coupons. [1-6]

Optical materials need wavelength-resolved measurements. A small broadband transmission change can hide a large loss at a sensor or communication wavelength. The same principle applies to fluorescence or scintillation: the metric should follow the functionally relevant spectral band and geometry. [1-6]

Where atomic oxygen is not the focus, its exclusion must still be justified by mission location, shielding or material placement. Otherwise an apparently complete UV-vacuum-thermal programme may underrepresent the actual LEO surface environment. Scope separation between ER-381, ER-382 and ER-383 is methodological, not permission to ignore a mission-relevant stressor. [1-6]

**Table 3. Minimum ER-381 reporting set.**

| Block                    | Minimum report                                                                                                   |
|--------------------------|------------------------------------------------------------------------------------------------------------------|
| specimen state           | formulation identifier, print orientation, layer thickness, cure/post-cure, cleaning, surface finish and coating |
| mission/test environment | vacuum, spectral/particle exposure, thermal cycle, AO relevance if applicable, orientation and sequence          |
| response                 | mass, dimensions and at least one mission-functional optical, mechanical or dielectric metric                    |
| contamination control    | facility blank or witness strategy and disposition of deposited material                                         |
| transfer statement       | which orbital hazard is represented, which is not, and what response anchors equivalence                         |

A report that omits state history or exposure sequence can still document a laboratory result, but it cannot support transfer to a specific LEO mission. The transfer statement is therefore a required conclusion, not an optional discussion item.

**References**

1. Grossman E, Gouzman I. Space environment effects on polymers in low earth orbit. Nuclear Instruments and Methods in Physics Research Section B. 2003;208:48-57. doi:10.1016/S0168-583X(03)00640-2.
2. de Groh KK. Durability of Polymers in the Space Environment. NASA Glenn Research Center, GRC-E-DAA-TN67242; 2019.
3. Finckenor MM. Further Analysis of MISSE Polymeric Materials at MSFC. NASA Marshall Space Flight Center, M09-0536; 2009.
4. Young PR, Slemple WS. Characterization of selected LDEF: Exposed polymer films and resins. NASA Langley Research Center, NTRS 19930003599; 1992.
5. Jaworske DA. Changes in the Optical Properties of Materials Are Observed After 18 Months in Low Earth Orbit. NASA Lewis Research Center, NTRS 20050188450; 1999.
6. Kondyurin A, Lauke B, Vogel R. Photopolymerisation of composite material in simulated free space environment at low Earth orbital flight. European Polymer Journal. 2006;42(10):2703-2714. doi:10.1016/j.eurpolymj.2006.04.018.
7. Park SY, Choi HS, Choi WJ, Kwon H. Effect of vacuum thermal cyclic exposures on unidirectional carbon fiber/epoxy composites for low earth orbit space applications. Composites Part B: Engineering. 2012;43(2):726-738. doi:10.1016/j.compositesb.2011.03.007.

**Competing interests**

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-381 contains no comparative recommendation between commercial products.

**Data availability**

ER-381 is a literature-based engineering review; no new experimental dataset was generated.