

Atomic-Oxygen Erosion of Photopolymer Materials: Surface Recession, Oxidation, Coatings and Ground Simulation

Qualifying AO durability by erosion yield, protected-surface defect tolerance and simulator relevance rather than by exposure time alone

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Abstract

Atomic oxygen is a dominant surface-reactive species in low Earth orbit and can erode organic polymers by repeated oxidation and volatile-product formation. For printed photopolymers, roughness, pores, cure gradients and thin protective coatings can convert nominally uniform exposure into highly localized recession. The engineering quantity is therefore not merely mass loss after a test, but erosion yield or recession per fluence linked to surface chemistry, roughness evolution and coating-defect growth. Ground plasma and beam facilities are useful only when atomic-oxygen energy, flux, fluence and collateral ultraviolet or ion exposure are known well enough to interpret equivalence. Protective coatings introduce a second problem: small defects can dominate long-duration attack by allowing undercutting and local erosion of the substrate. ER-382 defines a qualification route that separates intrinsic substrate susceptibility, coating integrity and simulator bias. [1-5]

Keywords: atomic oxygen; low Earth orbit; erosion yield; photopolymer; protective coating; ground simulation

1. Erosion quantity and surface state

Atomic-oxygen durability is expressed through fluence-normalised mass loss or surface recession, not exposure time. The exposed area, density used for conversion, initial roughness and post-exposure morphology are recorded because a rough printed surface can present more reactive area than a polished reference. [3,4]

2. Oxidation, volatile products and recession

Atomic-oxygen erosion is a surface-reaction problem whose engineering consequence depends on geometry. A coating can show low planar erosion yet fail at recesses, sharp features or layer steps where coverage is incomplete. A 2026 oxygen-plasma study on 3D-printed PLA found that increasing ALD Al₂O₃ coverage strongly reduced erosion and that recessed print features were preferential low-cycle failure sites; 1000 ALD cycles suppressed measurable erosion under the reported test. The substrate is not a photopolymer, so the numerical coating performance is not transferable, but the geometry-coverage mechanism is directly relevant to printed surfaces. [1-4,6]

Erosion yield should be accompanied by surface chemistry and morphology. Mass loss can underestimate early oxidation if oxygenated groups form before volatile products leave the surface, while roughness can increase even at modest net recession. XPS, profilometry and microscopy therefore complement gravimetry. For a printed part, the measurement locations should include upward, downward and recessed surfaces because line-of-sight exposure and coating thickness can differ systematically. [1-3,6]

AO attacks susceptible organic bonds and generates oxidised fragments that can leave the surface as volatile products. The resulting recession changes not only dimensions but also roughness and optical response. For thin walls and functional microfeatures, a small average mass loss can conceal a locally critical change.

Table 1. AO observables and the mechanism each constrains.

Observable	Primary interpretation	Confounder to control
mass loss per fluence	net erosion yield	contamination deposition or desorption
profilometric recession	local thickness loss	initial roughness and fixture shadowing
surface chemistry	oxidation/passivation state	air exposure between test and analysis
roughness evolution	nonuniform attack and pit growth	print-layer texture present before AO

3. Protective coatings are defect-controlled systems

Ground simulation must reproduce the energy and chemical form of the incident oxygen closely enough to preserve the damage mechanism. Plasma systems can include ions, photons and thermal loads that are not equivalent to hyperthermal neutral AO. The reference fluence, species distribution and sample temperature should be reported, and Kapton or another accepted witness material can be used to normalise facility exposure when appropriate. [1-4]

Ultraviolet radiation can modify AO response. Simulated studies of polyimide have shown that UV exposure can promote desorption of carbon oxides from an AO-exposed surface, demonstrating that combined fields can change erosion kinetics. Therefore an AO-only test cannot establish durability in a mission where UV and AO act together. Sequential and simultaneous exposures should be compared when coating chemistry or oxide formation is expected to evolve under light. [4,5]

A nominally AO-resistant coating can fail through pinholes, cracks, edges or poor conformity over printed texture. NASA durability studies show that defect density and substrate roughness strongly affect protection. [3] Coating qualification therefore includes intentionally challenging edges and representative surface texture, not only flat witness films.

4. Ground simulators and beam relevance

AO sources differ in particle energy, flux, directionality and collateral plasma or ultraviolet exposure. A valid report records how fluence was measured and whether the simulator produces damage morphology comparable with accepted space-exposure references. Ground exposure can rank candidates, but an erosion yield becomes mission evidence only when source relevance is established.

5. Printed geometry creates shadowing and edge amplification

Barrier qualification should search for local breach rather than average coating thickness. Pinholes, cracks induced by CTE mismatch and incomplete coverage at layer valleys can create highly localised attack fronts. Cross-sectional microscopy after exposure is needed to determine whether mass retention reflects a genuinely intact barrier or a small damaged area that has not yet propagated. [2,3,6]

For self-protecting chemistries, formation of an inorganic surface layer may reduce erosion with dose. That behaviour must be distinguished from simple sacrificial recession by tracking composition and thickness over fluence. A coating or resin that passivates under one AO spectrum may not do so under another if the formation and removal rates of the protective layer differ. [1,5]

Recessed features, overhangs and cavities do not receive the same directional AO exposure as open faces. Conversely, edges and protrusions can lose functional dimension rapidly. ER-382 therefore maps the intended orientation of critical surfaces and reports local recession at geometry features that control fit, sealing or optical performance.

Table 2. AO qualification decisions.

Decision	Minimum evidence	Reject when
uncoated substrate use	erosion yield plus local recession at representative surface state	critical geometry is consumed inside the mission fluence
coating acceptance	coating continuity, defect challenge and post-exposure adhesion	undercutting or defect-driven attack dominates
simulator transfer	fluence calibration and morphology comparison	source energy or collateral exposure changes the mechanism

6. Boundary with ER-381 and ER-383

ER-382 owns AO erosion and AO-protection evidence. ER-381 owns the integrated LEO mission envelope, while ER-383 owns UV/vacuum/thermal combined ageing. AO data can feed those reviews but should not be stretched into a complete orbital qualification on its own.

7. Qualification statement

The accepted output is a fluence-bounded surface durability claim with stated surface preparation, AO source, local recession limits and coating-defect tolerance. No universal AO-resistant classification is assigned across print states or missions.

8. Measurement uncertainty in erosion yield

A failure map should distinguish uniform recession, local pitting, coating breach and undercutting. Uniform recession supports a surface-reaction model; isolated pits implicate defects or heterogeneous chemistry; undercutting beneath a barrier indicates that local breach can propagate laterally. These modes have different scaling implications, so averaging them into one erosion yield can produce a misleading lifetime estimate. [1-6]

Surface roughness deserves explicit tracking because it can feed back into subsequent exposure. Increasing area and local incidence angles can change apparent erosion rate, while roughness can also alter optical scatter or aerodynamic drag before bulk dimensions become unacceptable. Profilometry should therefore use the same spatial scale and filtering parameters before and after exposure. [1-6]

Coating adhesion should be challenged after thermal cycling as well as AO exposure. An oxide barrier that survives a room-temperature beam may crack or delaminate after repeated CTE mismatch. Combined thermal/AO sequences are therefore appropriate when a coated photopolymer is intended for LEO, even though ER-382 retains ownership of the AO erosion mechanism and ER-383 owns combined-environment ageing logic. [1-6]

Part geometry should include intentionally difficult features in the qualification article: a recess, an edge, a convex radius and at least one surface orientation representative of the print. This converts coating conformity and AO line-of-sight effects from qualitative concerns into measurable design variables. [1-6]

An uncertainty-controlled erosion result should report initial mass and area, fluence uncertainty, reference-material response, balance resolution, post-exposure cleaning or handling, and the method used to convert mass loss to recession. Filled or multilayer materials require the density assumption to be stated explicitly. [1-6]

The major evidence gap is direct AO testing of commercial VPP networks and their coatings across realistic printed topographies. Until such data exist, results from polyimides, thermoplastics and coated printed substrates should be used to design conservative tests rather than to assign a universal erosion coefficient to photopolymer parts. [1-6]

The qualification envelope should be expressed in fluence and retained function, not only exposure duration. At minimum it should include erosion yield or recession, roughness, coating continuity, mass change and the property that matters for the component, such as optical transmission, dielectric strength or flexural integrity. Geometry-specific witness features should be included because flat coupons under-represent coverage failures at corners and recesses. [1-6]

Transfer from a ground facility to LEO should be treated as a model with uncertainty. Facility chemistry, flux acceleration and specimen temperature contribute uncertainty independently of measurement scatter. A conservative decision rule is to require mechanism agreement—surface chemistry, morphology and recession mode—before using an accelerated erosion rate to estimate mission life. [3-6]

Erosion yield inherits uncertainty from mass loss, exposed area, density and fluence. For textured prints, the projected area and the true reactive area differ, so the chosen area convention is stated explicitly and used consistently. Profilometry adds its own uncertainty from datum choice and surface roughness.

Where contamination deposits mass during the same exposure, a mass-only erosion estimate can be biased low. Surface recession or chemistry and witness data provide an independent check. Disagreement between methods is investigated rather than averaged.

9. Minimum reporting set for AO qualification

The minimum report should record the unexposed surface area used for erosion calculations and how rough printed surfaces were treated. Projected area and true area can differ substantially; the chosen convention should remain consistent across specimens and reference materials. [1-6]

Mass-loss measurements should include handling blanks because very small erosion signals can be comparable to moisture desorption, fingerprints or cleaning residues. Drying and conditioning before weighing should be standardised, particularly for hygroscopic photopolymers. [1-6]

Coating thickness should be measured at representative topographic locations rather than reported as one nominal deposition value. Valleys, sidewalls and downward-facing features can receive less material than flat witness coupons, and these are often the locations where barrier breach begins. [1-6]

If a coating fails locally, the decision should consider whether erosion remains self-limiting or exposes an expanding substrate area. A small stable pinhole can be acceptable in one function but catastrophic in an optical or dimensionally critical surface. The acceptance rule therefore needs a geometry- and function-specific defect criterion. [1-6]

Mechanical testing after AO exposure should target the surface-sensitive mode expected in service. Flexure, fatigue or crack initiation can be more sensitive to a damaged skin than bulk tensile modulus. The test geometry should place the exposed surface on the critical stress side when evaluating that risk. [1-6]

For optical surfaces, roughness and haze should be tracked with erosion because nanometre-to-micrometre texturing can degrade function before measurable structural recession occurs. Surface-function metrics can therefore define a shorter service life than mass-loss models. [1-6]

A final transfer statement should specify whether the evidence supports screening, comparative ranking or mission-life prediction. Most ground AO studies support the first two unless the facility has demonstrated species, energy and flux equivalence for the intended extrapolation. [1-6]

Table 3. ER-382 reporting requirements.

Category	Required information
AO source	generation method, mean/representative energy if known, flux, cumulative fluence and uniformity
surface state	print texture, finishing, coating stack, thickness and defect condition
erosion response	mass loss, recession or both, area convention and uncertainty
coating response	adhesion, pinholes/cracks, edge condition and evidence of undercutting
geometry relevance	orientation, shadowing and critical feature dimensions

These records allow later ERs to combine AO evidence with UV, thermal and contamination evidence without silently changing the surface or exposure definition.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-382 contains no comparative recommendation between commercial products.

Data availability

ER-382 is a literature-based engineering review; no new experimental dataset was generated.