

Cryogenic Compatibility of Dissimilar-Material Photopolymer Assemblies: Interfaces, Seals, Microcracking and Leak Integrity

Qualifying bonded and sealed assemblies by thermo-mechanical mismatch, damage connectivity and leak response across cryogenic cycles

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Abstract

Cryogenic service changes both polymer constitutive response and the stresses generated at dissimilar-material interfaces. A photopolymer bonded to a metal, fibre composite, glass or elastomer can experience large differential contraction, local embrittlement and interfacial shear during cool-down. The engineering failure is often not a simple strength loss: distributed matrix microcracks can connect into a leak path, a seal can lose contact pressure, or an adhesive interface can remain apparently intact while permeability increases. Recent cryogenic-composite work shows that intrinsic molecular permeation and damage-assisted leakage must be separated experimentally. ER-384 therefore qualifies the assembly, not the bulk resin alone. Temperature history, joint geometry, thermal-expansion mismatch, crack density, leak rate and post-cycle mechanical integrity are linked in one evidence chain, with acceptance tied to the declared fluid, pressure and cycle envelope. [1-3]

Keywords: cryogenic; photopolymer assembly; thermal mismatch; microcracking; seal; leakage; permeability

1. Assembly state dominates cryogenic risk

Cryogenic compatibility is assessed on the joined assembly because differential thermal contraction creates stresses that do not exist in isolated material coupons. Metals, glasses, fibre composites, elastomers and cured photopolymers can have markedly different contraction and stiffness changes during cool-down. The same resin can therefore pass a bulk coupon test and fail at a bonded edge or seal land.

2. Distinguish intrinsic permeation from damage-assisted leakage

Recent composite-tank studies separate molecular permeation through an intact matrix from leakage through connected crack networks. [1-3] This distinction is essential for printed photopolymer assemblies: a gradual permeation change suggests transport through the material or interface, whereas abrupt leakage after cycling can indicate crack connectivity or seal loss.

Table 1. Cryogenic failure pathways in dissimilar assemblies.

Pathway	Diagnostic signal	Most relevant control
thermal-mismatch microcracking	cycle-dependent crack density or acoustic events	joint geometry and contraction mismatch
interface debonding	localized opening or shear failure at bond line	surface preparation and adhesive thickness
seal contact loss	reversible leak increase at low temperature	compression, modulus and groove geometry
bulk permeation	steady flux without visible damage	material thickness, gas species and temperature

3. Cooling path and dwell matter

Cryogenic cooling does not simply make an epoxy 'more brittle'; it changes modulus, yield behaviour, residual stress and the size of the plastic zone at a crack tip. Experiments on cryogenic epoxy systems have shown that temperature-dependent toughness can increase while the plastic zone contracts sharply, illustrating why one scalar room-temperature toughness value cannot predict crack evolution in an assembly. The relevant state includes temperature, cooling rate, prior thermal cycles and constraint from adjoining materials. [1-4]

Cooling rate itself can change damage. In-situ cryogenic studies of carbon-fibre/epoxy have reported more extensive microstructural damage under slow cooling than under thermal shock in the tested system, despite intuition that faster cooling must always be worse. This reinforces the need to reproduce the actual mission or process thermal path rather than qualify only at the final temperature. [3,5]

A qualification cycle records cooling rate, minimum temperature, dwell, warming rate and any pressure load. Rapid gradients can introduce transient stresses beyond those predicted from equilibrium contraction, while long dwell can change seal relaxation and gas transport. The cycle profile is therefore part of the qualified state.

4. Leak measurement must be paired with damage inspection

Permeation and leakage must remain separate observables. Koord et al. directly distinguished molecular permeability from crack-mediated leakage in composite materials and showed that biaxial loading could create through-thickness crack networks; a clay-based barrier reduced helium flux by more than eighty-fold under their steady-state conditions. These numerical values cannot be transferred to printed photopolymer assemblies, but the experiment demonstrates why gas transport must be measured both before and after mechanically relevant cryogenic damage. [1-3]

Helium screening can be useful because of sensitivity and handling, but hydrogen or the actual cryogen may differ in solubility and diffusivity. Any surrogate correlation should be demonstrated for the material state in question. Leak testing should also be tied to crack inspection, because a rising leak rate can mark connectivity of a crack network rather than a uniform increase in matrix permeability. [1,2]

A leak-rate increase without structural inspection cannot distinguish seal motion from matrix cracking. Conversely, microscopy alone cannot determine whether cracks form a connected flow path. ER-384 pairs a quantified leak method with pre/post crack or interface inspection at selected cycle counts. [2,3]

5. Representative geometry before full assembly

Testing proceeds from material pairs to representative joints, then to the actual pressure boundary or sealed geometry. Bond-line thickness, fillets, corners and fastener or insert constraints are retained because these features determine local stress concentrations.

Table 2. Cryogenic qualification gates.

Gate	Pass evidence	Reason for failure
contraction compatibility	repeatable dimensions and no progressive crack growth	thermal mismatch drives accumulating damage
interface integrity	retained joint strength and no debond path	bond line becomes primary failure plane
leak integrity	bounded leak/permeation at temperature and after cycling	connected damage or seal relaxation exceeds requirement
recovery	post-warm properties and dimensions remain functional	irreversible damage persists after thermal recovery

6. Qualification envelope

Acceptance limits should separate permeability from leakage. Permeability through an intact polymer is often a continuous material property, whereas leakage through connected cracks is a damage state. A permissible molecular flux does not imply tolerance of a through-thickness crack path, and the measurement method should be capable of distinguishing the two. [1-5]

Cryogenic dimensional change should be measured on each constituent where possible. Published CTE values for nominal material families may not represent a specific printed and post-cured network. Direct dilatometry or calibrated displacement measurements reduce uncertainty in interface-stress modelling. [1-5]

Bondline thickness is another controlled variable. Very thin adhesive layers can generate high constraint, whereas thicker compliant layers may accommodate mismatch but increase creep or permeation path length. The manufactured bondline should therefore be measured and included in the qualification state. [1-5]

Thermal ageing before cryogenic testing should be avoided unless it is part of service, because additional post-cure can change Tg, modulus and residual stress. If a specimen must be dried or conditioned, the procedure should be identical across comparison groups and documented as part of the starting state. [1-5]

Leak tests should use a defined pressure differential and dwell long enough to separate system background from specimen transport. Chamber seals and fixtures should be characterised with blanks, especially at cryogenic temperature where fixture contraction can create apparent specimen leakage. [1-5]

For repeated-use hardware, a pass after the final cycle does not reveal the approach to failure. Trending crack density, leak rate and interface opening across cycle blocks provides a margin and supports maintenance or retirement criteria. [1-5]

A representative subcomponent should include the actual joint geometry, local thickness transitions and fastening or bonding constraint. This is the stage where coupon-derived constitutive and permeability models are tested against assembly behaviour before full-system qualification. [1-5]

No generic cryogenic compatibility label is assigned. The accepted envelope names material pair, joint or seal design, fluid or tracer gas, pressure, temperature range, cycle profile and maximum allowed leak or property drift. Changes to any of those state variables trigger targeted requalification. Scope boundary: ER-384 owns cryogenic dissimilar-material interfaces, seals, microcracking and leak integrity. Sustained high-pressure permeation, creep and rapid-decompression damage belong to ER-385, while subsea water uptake, hydrostatic exposure, biofouling and fatigue belong to ER-386. Pressure magnitude alone does not make evidence transferable between these service regimes.

7. Metrology for cracks, interfaces and leaks

Crack density, interface opening and leak rate should be measured through thermal-cycle blocks. A practical sequence is baseline leak/permeation, cooling and dwell, leak test at temperature where feasible, warm-up, microscopy or CT, and repetition. The warm measurement alone can miss cracks that close after recovery, while a cold leak test without imaging cannot identify the path. [1-3]

Dissimilar-material joints require local strain measurement at the bondline or seal because global contraction does not reveal constraint. Digital image correlation at accessible surfaces, embedded fibre sensors or calibrated finite-element strain fields can help identify where CTE mismatch concentrates deformation. Seal preload should be recorded because thermal contraction can either reduce contact pressure or over-compress the sealing element depending on joint architecture. [1-3]

Leak testing defines tracer gas, pressure differential, temperature, stabilization time and instrument detection limit. Crack observations define field of view and whether isolated surface cracks, through-thickness cracks and interface separations are distinguished. These two datasets are aligned by cycle count so that crack connectivity can be related to transport.

Mechanical re-testing after cryogenic cycles is interpreted with caution because room-temperature strength can partially recover even after leak pathways have formed. Retained strength therefore cannot replace low-temperature leak evidence for a pressure-boundary application.

8. Design-of-experiments for dissimilar interfaces

Interface qualification should include fracture mode as well as nominal bond strength. A joint that retains peak strength after cryogenic cycling may nevertheless move from cohesive to interfacial failure, indicating reduced robustness. Fractography and crack-path mapping therefore belong in the acceptance evidence when dissimilar materials or primers are involved. [1-5]

Seal behaviour should be evaluated through preload retention. Elastomeric or compliant seals may stiffen strongly at low temperature, while surrounding photopolymer and metal parts contract differently. Measuring leak rate together with closure displacement or contact force allows loss of sealing to be distinguished from bulk permeation through an otherwise intact assembly. [1-5]

Thermal-cycle block size should be chosen to reveal the shape of damage accumulation. Inspection only at the final cycle count cannot distinguish early saturation from progressive crack multiplication. Intermediate checks at logarithmically or mechanistically chosen intervals provide enough information to decide whether lifetime extrapolation is justified. [1-5]

Geometric scale affects constraint. A small bonded coupon can relieve mismatch by edge deformation, while a large closed ring or tank-like section can accumulate higher biaxial stress. Representative curvature and constraint should therefore be introduced before the full assembly stage. [1-5]

The uncertainty budget must include gas-flow calibration, background leak, temperature measurement, crack-detection threshold and specimen-to-specimen variability. Near a leak acceptance threshold, background subtraction and chamber permeation can be as important as material scatter. [1-5]

The major evidence gap remains direct cryogenic testing of printed photopolymer assemblies rather than conventional epoxies and fibre composites. Existing cryogenic composite evidence defines credible failure mechanisms and test architecture, but acceptance values for VPP parts require material-specific data at the actual printed and post-cured state. [1-5]

A design-of-experiments matrix should vary temperature minimum, number of cycles, cooling rate and mechanical load separately before testing their interactions. For linerless or bonded assemblies, biaxial stress is particularly important because uniaxial coupons may not generate the crack connectivity responsible for leakage. The qualification endpoint is therefore not simply 'no visible crack' but a bounded leak/permeation rate together with retained structural margin. [1-3]

Transfer from composite-tank data to printed photopolymers must be explicit and limited. The shared mechanisms are CTE mismatch, cryogenic modulus change, matrix cracking and damage-assisted transport; fibre architecture, cure chemistry and crack morphology are different. Evidence from cryogenic composites is therefore used to define tests and failure logic, not to assign acceptance values to VPP materials. [1-5]

Table 3. Variables to separate in cryogenic interface studies.

Variable pair	Reason to separate
material pair vs joint geometry	identifies whether mismatch or stress concentration dominates
cooling rate vs minimum temperature	separates transient gradient stress from equilibrium contraction
pressure load vs thermal cycle	distinguishes mechanical opening from purely thermal cracking
seal compression vs seal material	prevents geometry loss from being misdiagnosed as material embrittlement

A reduced test matrix can be used, but each accepted simplification is linked to the specific failure mechanism it preserves. This prevents coupon convenience from becoming an unspoken surrogate for the full assembly.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-384 contains no comparative recommendation between commercial products.

Data availability

ER-384 is a literature-based engineering review; no new experimental dataset was generated.