

High-Pressure Service of Printed Photopolymers: Compression, Permeation, Creep, Sealing and Decompression Damage

Separating hydrostatic compression from gas sorption, viscoelastic deformation and decompression-driven internal damage

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Abstract

High-pressure qualification of printed photopolymers is governed by more than compressive strength. Pressurised gases and liquids can sorb into the network, alter free volume, diffuse across seals or walls, and generate internal damage when pressure is released faster than dissolved gas can escape. Sustained pressure also loads joints and seals for long periods, making creep and contact-pressure relaxation relevant even when peak stress is modest. Rapid gas decompression studies in elastomers show that pressure level, temperature, gas composition and decompression rate can strongly influence blistering and cracking, while current oil-and-gas standards separate thermoplastic, elastomer, thermoset and composite qualification routes. ER-385 converts these mechanisms into a staged test plan that distinguishes compression, permeation, creep, sealing loss and decompression damage. [1-4]

Keywords: high pressure; photopolymer; gas permeation; creep; seal; rapid gas decompression; decompression damage

1. Pressure service creates coupled transport and mechanics

A printed polymer under pressure experiences hydrostatic stress, deviatoric stress around geometry changes, molecular sorption and time-dependent deformation. If gas dissolves in the network, decompression can create internal supersaturation. These mechanisms are tested separately before they are combined.

2. Start with compression and creep, not burst alone

Hydrostatic pressure changes both polymer mechanics and gas transport. Under high-pressure gas, free-volume reduction can lower diffusion and permeability even while the stored gas concentration increases. A polyethylene study to 90 MPa found decreasing diffusion coefficient and permeability coefficient with increasing pressure, attributed to hydrostatic shrinkage of free volume. The result is material-specific, but it warns against extrapolating low-pressure permeability linearly to service pressure. [1-6]

Compression and creep should be measured under pressure and temperature together. A sealing interface can pass a short proof test but lose contact stress during dwell through viscoelastic relaxation. Conversely, pressure can temporarily increase apparent stiffness while accelerating damage at voids or interfaces. The qualification record should therefore include loading rate, pressure dwell, decompression schedule, temperature and post-exposure recovery time before mechanical re-test. [1-5]

Short-term burst or compression tests identify gross strength but do not establish dimensional stability under sustained service. Creep of a wall, thread or seal land can reduce preload and change local stress. ER-385 therefore includes dwell under pressure with dimensional or seal-force tracking at the service temperature.

Table 1. High-pressure mechanisms and discriminating tests.

Mechanism	Test action	Key observable
elastic/hydrostatic compression	step pressure up and down	reversible strain and dimensional recovery
pressure-assisted creep	sustained pressure dwell	time-dependent strain or contact loss
gas permeation	steady pressure gradient with intact specimen	flux or pressure-decay rate
rapid gas decompression	controlled saturation followed by defined depressurisation	blistering, internal cracks, volume change

3. Permeation is species and temperature dependent

Permeation data should report the gas species, upstream and downstream pressure, specimen thickness, exposed area and whether steady state was reached. Solubility and diffusivity can respond differently to pressure and temperature, so a single permeability coefficient without state information is not portable. If a multilayer barrier or coating is used, edge leakage and defects must be excluded or measured separately. [1-6]

For printed photopolymers, internal porosity and layer interfaces can create parallel transport paths that are absent in a homogeneous film. Pressure cycling can open or close those paths reversibly before permanent cracking occurs. Gravimetry, pressure-decay tests and microscopy should be combined to distinguish molecular permeation from defect-assisted leakage. [1-5]

Gas transport depends on solubility and diffusivity, both of which vary with polymer network state, gas species and temperature. Barrier performance therefore cannot be transferred from one gas to another without evidence. Current gas-barrier reviews reinforce that crosslink density, fillers and morphology all influence transport. [5]

4. Decompression rate is a controlled variable

Rapid gas decompression is a coupled diffusion-fracture event. Gas dissolved under pressure can nucleate cavities during depressurisation when local supersaturation rises faster than gas can diffuse out. The critical variable is therefore not only peak pressure but decompression rate, prior saturation time, temperature and specimen thickness. Thick sections can retain steeper concentration gradients and should not be qualified from thin coupons alone. [1,2,4]

Inspection immediately after decompression should search for internal damage even when the surface appears intact. Micro-CT, sectioning or ultrasonic methods can reveal cavities and cracks, while repeated pressure cycles determine whether subcritical damage accumulates. A specimen that reseals elastically after one cycle may still have lost fatigue margin. [2,4,5]

Rapid gas decompression work shows that saturation pressure, temperature, gas composition and release rate affect damage severity. [4] The decompression profile is therefore specified as tightly as the maximum pressure. A specimen that survives slow venting is not automatically qualified for emergency blow-down.

5. Standards define useful boundaries, not universal pass values

A useful pressure-screening matrix begins with low-rate compression and creep at ambient pressure, then repeats the same measurements after pressure conditioning. This separates intrinsic nonlinear viscoelasticity from exposure-induced change. Where gas service is intended, specimens should be conditioned to defined saturation fractions rather than an arbitrary dwell time, because thick walls and low-diffusivity networks may remain far from equilibrium. [1-6]

Seal interfaces require contact-pressure margin. If a printed seat relaxes under compressive load, leak tightness can be lost long before gross structural failure. Compression-set or force-relaxation measurements on the actual seal/seat pair therefore complement bulk resin creep data. Surface finish and print orientation at the seat should be controlled because roughness and layer steps can alter local contact. [1-6]

Pressure cycling can also pump fluid into small defects. A void or imperfect bond that is benign under static compression may accumulate gas or liquid during repeated pressure changes and become a crack nucleus. Periodic imaging after cycle blocks is preferable to inspecting only after final failure because it reveals whether damage nucleates gradually or abruptly. [1-6]

Permeation measurements should be normalised to thickness only when transport is one-dimensional and the material is homogeneous. Complex printed walls, ribs, lattices or internal skins can violate that assumption. In such cases a component-level leak-rate measurement is often more defensible than converting the result into a nominal bulk permeability coefficient. [1-6]

For safety-critical service, acceptance should include a residual-strength or residual-leak test after the full environmental sequence. Passing at peak pressure once does not show that the component retains margin after dwell, cycling and decompression. The residual test should be defined prospectively so it cannot be weakened after observing degradation. [1-6]

A pressure rating should therefore be treated as an assembly qualification, not a resin datasheet property. Material, cure state, wall thickness, geometry, fittings, seals, fluid, temperature and pressure history all contribute to the qualified claim. Any change that alters one of those controlling variables requires a documented bridging rationale or requalification. [1-6]

The ISO 23936 family separates thermoplastics, elastomers, thermosets and fibre-reinforced composites because exposure modes and failure mechanisms differ. [1-3] ER-385 uses that separation to choose evidence but does not import an acceptance threshold that is not applicable to the printed part or its end-use code.

Table 2. Service-envelope decisions.

Decision	Evidence needed	Requalification trigger
maximum operating pressure	elastic response plus margin to damage onset	geometry, cure state or temperature change
pressure dwell duration	creep/contact-force history	longer hold or higher duty cycle
venting/decompression procedure	RGD challenge at declared gas and rate	faster blow-down or different gas mixture
seal or barrier claim	permeation/leak evidence at service state	surface finish, seal design or barrier change

6. Outcome

Qualification is a pressure-temperature-time-gas envelope. Compression strength alone is insufficient, and rapid decompression resistance is not inferred from steady-state permeation. Scope boundary: ER-385 owns sustained high-pressure gas or liquid transport, creep, sealing and decompression damage. Cryogenic interface mismatch and leak integrity belong to ER-384; seawater-conditioned hydrostatic service and fatigue belong to ER-386; chemically aggressive process exposure and barrier failure belong to ER-389.

7. Internal damage inspection after decompression

Internal-damage inspection should be selected according to feature size. Micro-CT can resolve cavities and cracks in many printed polymers, but dense fillers or thick sections can reduce contrast; sectioning or acoustic methods may be needed as complementary techniques. The detection limit should be recorded so that 'no damage observed' has a quantitative meaning. [1-6]

Creep under pressure should be measured both during loading and after unloading. Permanent strain, delayed recovery and seal-force loss can have different time constants. A component that recovers dimensions after hours may still have experienced unacceptable leakage during the pressure dwell. [1-6]

Temperature-pressure coupling should be tested because gas solubility, diffusivity and polymer relaxation all change with temperature. Qualification at room temperature alone is not transferable to hot process service or cold gas storage. At minimum, the intended temperature extrema should be represented at the pressure states that produce the largest transport or mechanical risk. [1-6]

Pressure-media compatibility can evolve with absorbed concentration. A gas that is chemically inert can still plasticise the network or alter free volume, while a liquid can extract residual species. Post-exposure spectroscopy or mass balance can identify whether a mechanical change is purely physical or accompanied by chemical modification. [1-6]

Cycle sequencing matters when a component alternates pressure and ambient storage. Diffusion during the low-pressure interval can partially reset the concentration field, changing decompression severity on the next cycle. Test frequency should therefore reflect service rather than compressing cycles arbitrarily. [1-6]

Statistical qualification should include multiple specimens because internal defect populations are stochastic. A single thick printed wall with no decompression damage does not define a safe process window. Replicate data allow the interaction between pressure history and manufacturing variability to be bounded. [1-6]

The final decision should state whether the evidence supports material screening, a component-specific operating envelope or a pressure design allowable. Those are different claims and require progressively stronger geometry, replication and lifetime evidence. [1-6]

Rapid gas decompression can create subsurface blisters or cracks that are not visible externally. Sectioning, micro-CT or another internal inspection method is therefore used on representative specimens when the service gas and pressure create meaningful sorption. Surface appearance alone is insufficient to clear a decompression challenge.

The inspection threshold is tied to function. Small isolated cavities may be tolerable in a non-sealing bulk component but unacceptable in a thin pressure wall or threaded seal land where they reduce remaining ligament or create a leak path.

8. Minimum high-pressure reporting set

Pressure-vessel qualification should distinguish proof, endurance and damage-detection tests. A proof pressure establishes short-term structural margin; a dwell test probes creep, permeation and seal relaxation; cycling probes fatigue and defect growth; and rapid decompression challenges gas-saturated regions. Combining these objectives into one pressure ramp can miss the mechanism most relevant to service. [1-6]

Fluid purity and composition should be controlled because plasticisation and swelling can be species dependent. For gas service, trace condensables or lubricants may alter interfaces; for liquid service, absorbed solvent can change T_g and creep. The exposure medium should therefore be defined chemically rather than only by a commodity name. [1-6]

Pressure history should be logged continuously at the specimen, not only as commanded setpoints. Valve dynamics and compressibility can create decompression transients much faster than the programmed ramp, which matters directly for cavitation and rapid-gas-decompression damage. [1-6]

A component with threads, sharp internal corners or bonded fittings should be represented by a subcomponent test because hydrostatic stress in a smooth coupon does not reproduce local triaxiality. Micro-CT before and after pressure blocks can establish whether defects nucleate preferentially at these features. [1-6]

Acceptance criteria should separate reversible swelling or compression from permanent damage. Dimensions and mass should be measured after a defined recovery interval, while leakage and internal damage can require immediate post-decompression inspection. Both time points are useful because some pressure effects relax while cracks do not. [1-6]

The evidence gap is direct high-pressure cycling and decompression data for crosslinked VPP networks over realistic wall thicknesses. Existing elastomer, thermoplastic and gas-barrier literature should guide mechanism selection and test severity, but not be used to assign unverified service pressures to printed photopolymer parts. [1-6]

The qualification envelope should be multidimensional: gas or liquid species, pressure, temperature, dwell, decompression rate, cycle count and mechanical preload. Acceptance should include leak/permeation, dimensional stability, creep or seal force and an internal-damage criterion. Standards provide useful test architecture, but acceptance limits must be tied to the actual component and consequence of failure. [1-5]

Requalification is required when geometry changes alter diffusion length or stress triaxiality. A small coupon and a thick pressure boundary can experience different saturation times and decompression damage even at the same nominal pressure. Scaling should therefore use transport time and stress state, not pressure alone. [1-6]

Table 3. ER-385 reporting set.

Block	Required record
pressure history	pressurisation rate, maximum pressure, dwell, cycle count and depressurisation profile
fluid/gas state	species, composition, temperature and humidity or condensable content where relevant
specimen state	print orientation, wall thickness, cure, porosity-sensitive geometry and seal configuration
response	strain/creep, permeation or leak rate, dimensional recovery and internal damage inspection
acceptance boundary	maximum pressure, dwell and venting rate for the tested state

Because gas sorption is time dependent, saturation history is included whenever decompression resistance is claimed. A specimen exposed briefly at pressure is not equivalent to one allowed to approach sorption equilibrium.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-385 contains no comparative recommendation between commercial products.

Data availability

ER-385 is a literature-based engineering review; no new experimental dataset was generated.