

Leak Testing and Seal Qualification of Vat-Printed Fluidic Components: Through-Defects, Interfaces, Pressure Decay and Bulk-Permeation Boundaries

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Statement of Significance

A fluidic component can fail containment even when its bulk photopolymer has low molecular permeability. Liquid or gas may escape through a printing defect, a partially cleared microchannel wall, a bonded cover, a connector, a threaded fitting, a gasket contact, an embedded insert or a crack generated during pressure cycling. Conversely, a leak-free short pressure hold does not establish low long-term permeation through the polymer. This review separates bulk transport from discrete leakage and develops a measurement architecture for vat-printed microfluidic chips, manifolds, connectors, seals and pressure-bearing prototypes. The central engineering requirement is to report where the leak path exists, how the pressure or tracer method interrogates it, and whether the test object is rigid, deformable, reusable or ageing-sensitive.

Keywords: vat photopolymerisation; leak testing; leak rate; pressure decay; burst pressure; sealing; microfluidics; gasket; connector; interface; SLA; DLP; LCD

Abstract

Vat photopolymerisation can fabricate monolithic microfluidic channels, integrated covers, valves, connectors and complex flow paths, but fluidic success cannot be inferred from printability or dimensional accuracy alone. Published SLA and DLP studies report pressure-driven flow, pressure-to-failure tests, leak-free bonded interfaces, reusable connector burst-pressure measurements and, in a recent hydraulic-fitting comparison, failure of printed components to achieve application-level leak tightness despite acceptable dimensional tolerances. This Engineering Review establishes a state-based qualification framework for leak testing and sealing of vat-printed photopolymers. It distinguishes molecular permeation through the bulk network from through-defect, crack, interface, connector and seal leakage; separates proof, leak-rate and burst tests; and requires reporting of pressure differential, medium, temperature, hold time, trapped volume, compliance, connection hardware and failure location. ASTM E2930-26 is identified as a current pressure-decay method anchor for rigid vessels, while ISO 20484:2017 and ISO 20485:2017 provide leak-testing vocabulary and tracer-gas method context. 3Dresyns microfluidic materials, its Microfluidics IFU and the Self-Heal Seal additive family are included only as manufacturer implementation examples. No leak rate, pressure rating, self-sealing efficiency or service life is inferred from product positioning.

1. Scope and boundaries

ER-89 addresses containment integrity of printed fluidic components after fabrication and assembly. The test object may be a monolithic SLA/DLP/LCD chip, an enclosed channel, a bonded open-channel device, a modular connector, a threaded fitting, a manifold, a gasketed joint or an encapsulated volume. The review

focuses on leak-path definition, pressure/tracer measurement, interface and seal state, failure localisation, reusability and ageing transfer.

The scope is deliberately separated from neighbouring Engineering Reviews. ER-54 treats molecular diffusion, sorption and bulk gas permeability through the polymer network. ER-24 discusses pneumatic soft-actuator device performance, where leakage is one device-level failure mode. ER-43 addresses multimaterial interfaces broadly, and ER-41 addresses chemical resistance and solvent uptake. ER-89 is restricted to containment and leak-test evidence. A reported pressure loss is not automatically a material-permeability measurement, and a permeability coefficient is not a substitute for whole-device leak testing.

2. Five physically different loss routes

A measured loss of pressure, mass or tracer concentration can originate from different physical routes. The distinction matters because the corrective action is different. Bulk permeation is controlled by sorption and diffusion through the network; a pinhole or under-cured wall is a geometric discontinuity; an interface leak depends on adhesion, contact pressure and surface state; a connector leak depends on tolerances, compliance and reuse; and crack leakage can emerge only after mechanical or environmental history.

Table 1. Leakage and transport routes that must not be conflated

Route	Physical origin	Best first discriminator
Bulk molecular permeation	Transport through apparently continuous polymer over time.	Thickness dependence + gas/liquid identity + long-time flux; compare with ER-54 permeability methods.
Through-defect / pinhole	Void, incomplete wall, trapped uncured region, print defect or post-processing damage.	Localisation by dye/bubble/tracer/inspection; abrupt rather than thickness-scaled path.
Bonded-interface leak	Incomplete wetting/bonding, contamination, cure mismatch, residual stress or delamination.	Interface-specific pressure/tracer test plus post-test microscopy.
Connector / gasket leak	Insufficient compression, tolerance mismatch, rigid abrasion, swelling or surface damage.	Leak/burst test across repeated connect-disconnect cycles; inspect contact surfaces.
Crack / fatigue leak	Pressure cycling, notch, brittle wall, environmental stress or ageing creates a new path.	Cycle-resolved leak test with inspection before/after failure.

3. Evidence from vat-printed microfluidic systems

The available literature demonstrates that leak integrity is an experimentally measurable outcome rather than a generic property of “SLA resin”. Sagot et al. [1] integrated coverslips and other components during stereolithographic printing and increased internal pressure until leakage appeared or external tubing detached, explicitly treating pressure resistance as an interface/device endpoint. Bucciarelli et al. [2] printed DLP microfluidic structures, sealed a proof-of-concept device to a PDMS membrane after plasma treatment and reported successful leakage testing over one week. Subirada et al. [3] fabricated microfluidic devices by moulding, open-channel assembly and monolithic printing and demonstrated pressure-driven flow after process optimisation.

More recent modular-connector work is especially useful because it separates initial sealing from reusability. Zhang et al. [4] measured bursting pressure after repeated insertions: rigid PEGDA connectors lost sealing capacity after a small number of reuse cycles, whereas a more compliant commercial soft resin maintained substantially higher sealing pressures through repeated reconnection. The study also showed that a compliant custom resin could lose sealing over time because of swelling. This is direct evidence that connector

geometry, modulus, abrasion and fluid uptake interact and that a single first-use pressure test is insufficient for reusable devices.

4. A leak-free print is a three-state problem: geometry, material and interface

For enclosed channels, print physics determine whether a nominal wall is actually continuous. Excess exposure can block a channel while inadequate exposure or poor drainage can produce thin or discontinuous walls. Ong et al. [8] explicitly classified three outcomes for enclosed channels: blocked channels, leaky channels and leak-free perfusable channels. Xu et al. [6] independently addressed residual-resin over-curing and clogging in transparent microchannels using in-situ transfer vat photopolymerization. The manufacturing window is therefore not one-dimensional: both over-cure and under-integrity can reject the part. The Xu et al. result is used here as channel-fabrication evidence, not as a quantified leak-rate result.

The interface state is equally important. Carrell et al. [5] demonstrated covalent sealing strategies between SLA-printed methacrylate parts and PDMS, while Sagot et al. [1] showed that embedded glass and other components require controlled interfacial processing. The existence of a strong bulk resin does not remove the need for interface-specific qualification.

5. Pressure-hold, pressure-decay and burst tests answer different questions

Table 2. Common containment tests and their interpretation

Test	Primary output	Important limitation
Pressure hold / no visible leak	Pass/fail containment over specified pressure and time.	Detection limit may be undefined; does not quantify small leak rate.
Pressure decay	Pressure change over time; may be converted to mass/leak rate for a controlled rigid volume.	Temperature drift, dead volume and compliance can mimic leakage; ASTM E2930-26 excludes deformable vessels.
Burst / pressure-to-leak	Pressure at first leakage, connector release or structural failure.	Destructive or near-destructive; not a steady service leak rate.
Tracer-gas test	Tracer-specific leak detection/localisation and potentially quantified leak rate.	Requires calibrated detector/reference leak and gas-specific method control.
Liquid dye / bubble localisation	Visible path confirmation.	Usually qualitative/semi-quantitative and dependent on surface tension, pressure and observation threshold.
Flow balance	Difference between inlet and outlet flow under a declared pressure state.	Pump/controller uncertainty, compliance and evaporation must be controlled.

6. Pressure-decay metrology requires thermal and compliance control

ASTM E2930-26 [S1] describes a pressure-decay practice for determining leakage rate of a vessel under positive pressure by combining measured pressure, temperature, time and the ideal-gas relation. It requires the test to be designed so that the total pressure change remains limited relative to the starting pressure and explicitly states that the method does not apply to deformable vessels. These restrictions are highly relevant to VPP. A rigid microfluidic manifold may be a plausible test object; an elastomeric chamber, flexible gasketed assembly or soft actuator can change internal volume under pressure and confound the apparent leak rate.

For small printed volumes, temperature stability becomes especially important because a small gas-temperature change can generate a pressure change comparable with the leakage signal. Tubing compliance, trapped liquid, regulator hysteresis, connector motion and post-cure thermal relaxation can add further artefacts. A pressure-decay report should therefore include the total test volume, specimen and tubing

compliance assumptions, temperature measurement location, stabilization time, starting pressure, pressure differential, acquisition interval and blank-system loss.

7. Tracer gas and localisation

ISO 20484:2017 [S2] defines leak-testing terminology and ISO 20485:2017 [S3] describes tracer-gas leak-testing techniques. Both remain published as of 27 August 2026, with their most recent systematic review closed (ISO stage 90.60). These standards are useful method anchors, not VPP-specific acceptance criteria. A tracer-gas method can distinguish a discrete leak path from slower background effects when detector sensitivity, calibration and test geometry are controlled. ISO 20486:2017 [S4] provides calibration methods for reference gas leaks, remains published as of 27 August 2026 with its most recent systematic review closed (ISO stage 90.60), and is relevant when quantified detector response must be traceable.

For VPP qualification, tracer-gas testing is most useful when the expected leak is below the visual liquid-leak threshold, when the part is intended for gas/vacuum service, or when the leak location must be distinguished from bulk permeation. The selected gas must not be assumed to reproduce the long-term permeability of another service fluid; leak detection and material transport remain different questions.

8. Bonded covers, embedded windows and multimaterial boundaries

Bonded microfluidic devices introduce at least two interfaces: the bonded perimeter and any local embedded feature. Surface chemistry, washing residue, post-cure state, roughness and differential thermal/mechanical response can all influence integrity. Pressure qualification should therefore use the final assembled state, not an unbonded material coupon. Where the device includes glass, PDMS, elastomeric membranes or embedded electronics, the test should record the exact surface treatment and cure chronology because a nominally identical geometry can produce a different interface state.

Sagot et al. [1] reported pressure resistance of glass-integrated stereolithographic chips. This is a process-specific demonstration, not a universal pressure rating for SLA interfaces.

9. Reusable connectors and seals need cycle-resolved qualification

A seal that passes once may not pass after repeated assembly. Reusable connectors experience abrasion, local yielding, creep and contamination. Elastomeric or hydrogel-like contact materials may also swell in the service fluid. The modular-connector study [4] shows both mechanisms directly: rigid PEGDA lost sealing after reuse, whereas a softer resin improved repeated sealing; a custom compliant formulation was limited by time-dependent swelling. The correct unit of qualification is therefore the connector/seal system across the intended number of cycles and exposure duration.

Table 3. Variables required for reusable seal qualification

Variable	Why it matters	Recommended record
Contact geometry / tolerance	Controls interference, compression and stress concentration.	Nominal dimensions + measured critical diameters/gaps.
Material state	Modulus, cure state and swelling alter contact pressure.	Post-cure, conditioning medium/time, temperature.
Assembly cycle count	Abrasion and plastic/viscoelastic set accumulate.	Leak or burst result versus cycle number.
Service fluid	Can swell, plasticise or chemically attack the seal.	Fluid identity, concentration, temperature and exposure time.
Pressure history	Proof pressure and cyclic load can create cracks or permanent set.	Operating, proof and burst pressure sequence.

Variable	Why it matters	Recommended record
Failure location	Distinguishes seal, interface, wall or fitting failure.	Visual/tracer localisation and post-test inspection.

10. Hydraulic fittings illustrate the transfer limit from dimensional accuracy

Backiel et al. [7] compared FDM and SLA hydraulic fittings and found that dimensional agreement alone did not establish pressure-service suitability. In their stated test configuration, the printed fittings failed to achieve the leak-tightness of the brass reference and structural failure occurred during tightening at low pressure. The result should not be generalized to all SLA resins or fitting designs, but it is a strong demonstration of the evidence boundary: a thread can be dimensionally credible yet fail the combined seal, contact-stress and structural requirement.

For engineering release, thread form, sealing strategy, torque, mating material and pressure medium must therefore be qualified together. A VPP resin datasheet cannot supply a universal pressure rating for every printed fitting geometry.

11. 3Dresyns implementation boundary

The controlled 3Dresyns web corpus contains a dedicated Microfluidics collection [M1] and Microfluidics IFU [M2]. The collection explicitly states that fluidic performance depends on internal geometry control, printer tuning, viscosity, cleaning and post-processing, especially for thin enclosed channels. Ultra-low-viscosity MF grades, including MF T-ULV1 Clear [M4], are positioned to improve microchannel evacuation and feature definition. These are manufacturer implementation statements and do not establish leak rate or pressure rating.

The 3D-ADD Self-Heal Seal family [M3] is positioned for flexible barrier, encapsulation, gasket/O-ring and leakage-mitigation applications, including manufacturer claims of self-sealing behaviour for superficial cuts and micro-leak paths. ER-89 does not accept those descriptions as independent evidence of a quantified self-sealing efficiency, pressure-decay result, burst pressure or service life. They define a legitimate qualification question: compare the final printed/sealed state against an unmodified control under a declared leak method, pressure, fluid, temperature, cycle count and ageing history.

12. Minimum qualification architecture

- Define the containment function and maximum intended pressure differential before selecting the test.
- Distinguish rigid monolithic walls, bonded covers, connectors, gasketed joints and flexible chambers as separate test-object classes.
- Record printer, resin batch/state, build orientation, layer thickness, exposure/post-cure, cleaning and channel-clearing procedure.
- Measure the critical wall, channel, connector or gasket dimensions that control the suspected leak path.
- Run a blank-system test for tubing, fittings, regulator, pressure sensor and measurement volume.
- Select pressure hold, pressure decay, burst, tracer gas or liquid-localisation method according to the required detection limit and specimen compliance.
- Record test medium, temperature, starting pressure, pressure differential, hold time, sampling interval and detection threshold.
- Localise the failure path whenever possible; do not report only a global pressure loss.
- For reusable assemblies, repeat the leak endpoint through the intended connection/disconnection cycle count.
- For service in water, solvents, heat or UV, repeat the leak test after representative conditioning and ageing.

- Keep bulk permeation testing separate when long-term molecular transport through intact walls is also relevant.

13. Failure-mode and discrimination matrix

Table 4. Common leak observations and discriminating evidence

Observation	Competing explanations	Discriminating evidence
Immediate liquid leak at low pressure	Open defect; poor bond; connector mismatch; crack.	Dye/tracer localisation + microscopy + dimensional check.
Slow pressure decay, no visible leak	Small discrete leak; temperature drift; tubing loss; bulk permeation.	Blank correction + temperature control + tracer localisation + thickness/time dependence.
Passes once, fails after reuse	Abrasion; creep/set; swelling; connector damage.	Cycle-resolved leak test + contact-surface inspection + dimensional change.
Passes water, fails gas	Gas-sensitive discrete path; different wetting; bulk gas transport.	Tracer-gas localisation + separate permeability test if needed.
Leak begins after ageing	Environmental stress crack; interface degradation; swelling/shrinkage; fatigue.	Pre/post microscopy, mass/dimensions and repeated leak test.
Pressure drop only in soft chamber	True leak or elastic/viscoelastic volume change.	Independent volume/compliance characterization; avoid rigid-vessel pressure-decay assumptions.
Channel blocked rather than leaking	Overcure or trapped resin.	Flow/visual patency test; exposure/channel-clearing investigation.
Threaded fitting leaks despite good dimensions	Seal design, torque/contact stress, surface damage or material fracture.	Torque-controlled assembly + failure localisation + structural inspection.

14. Research and standardisation priorities

- round-robin leak testing of rigid VPP microfluidic components using controlled pressure-decay and tracer-gas methods;
- detection-limit studies that separate test-system background loss from printed-part leakage at microfluidic volumes;
- paired leak-rate and bulk-permeability studies on identical resins and wall thicknesses to quantify when each mechanism dominates;
- cycle-resolved connector and gasket studies spanning rigidity, toughness, swelling and surface wear;
- pressure-cycling studies that detect the transition from intact wall to crack-mediated leakage;
- interface-specific studies for printed resin-glass, resin-PDMS and multimaterial resin-resin bonds;
- ageing-conditioned leak qualification after water, solvents, UV, heat and sterilisation where applicable;
- reporting standards for failure location, pressure medium, temperature, test volume, sensor accuracy and specimen compliance.

15. Conclusions

Leak tightness is a device-state property, not a generic attribute of a photopolymer. Vat printing introduces possible leak paths through walls, interfaces, connectors, seals and cracks, while the polymer itself can also transport molecules by permeation. These mechanisms require different measurements and should not be collapsed into one “barrier” or “waterproof” claim.

The strongest qualification sequence defines the intended containment function, identifies the likely path class, uses a method with a stated detection limit and pressure/temperature history, localises failure, and repeats the endpoint after reuse or ageing when relevant. Pressure-decay testing can quantify rigid sealed volumes when thermal stability and system compliance are controlled; tracer-gas methods can extend

sensitivity and localisation; burst testing characterises margin rather than steady leakage. Flexible devices require additional care because deformation itself changes pressure and volume.

For 3Dresyns, the Microfluidics portfolio, Microfluidics IFU and Self-Heal Seal product family define legitimate implementation routes and qualification targets, but they do not substitute for leak-rate evidence. ER-89 therefore converts the existing industrial application space into a defensible test architecture while preserving the boundary between manufacturer positioning and independent scientific validation.

Limitations

The independent literature spans microfluidic chips, modular connectors, bonded interfaces and hydraulic fittings with different resins, printers, fluids and pressure scales. Numerical pressure or leak-rate values are therefore not pooled and should not be transferred between devices. ASTM E2930-26 is a method anchor for rigid pressure-decay objects and explicitly excludes deformable vessels. ISO leak-testing documents are general non-destructive-testing standards, not VPP-specific acceptance criteria. The review does not prescribe a universal proof pressure, burst factor or allowable leak rate; those remain application-specific.

Author contributions

Juan Seguro: conceptualisation, industrial problem definition, literature synthesis, leak-test and seal-qualification framework, writing and critical review.

Competing interests

The author is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. Manufacturer documentation is included only as implementation context and is separated from independent scientific evidence.

Data availability

No new experimental dataset was generated for this review. Scientific statements derive from the cited literature and standards; manufacturer examples derive from controlled 3Dresyns documentation.

Company information

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