

Adaptive, Soft and Application-Specific 3D Resins: 4D and Shape-Memory, Self-Healing, Hydrogel, Silicone-Like, Foam, Microfluidic, High-Security and Process-Specialty Systems

A State-Resolved Framework for Activation, Recovery, Repair, Hydration, Softness, Cellular Structure, Fluidic Function, Authentication and Process Compatibility

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Statement of Significance

Adaptive and application-specific photopolymers are frequently selected by names that compress a complete mechanism into one adjective: 4D, shape-memory, self-healing, silicone-like, hydrogel, foam, microfluidic, secure or hot-printable. Those labels do not specify the state in which function exists, the stimulus that creates it, the energy and time required, the extent of recovery, the loss accumulated across cycles, the geometry that enables transport, or the readout that proves performance. A soft printed coupon is not a seal; a swollen gel is not its dry precursor; a repaired cut is not proof of fatigue-life restoration; a closed channel in computer-aided design is not an open, clean flow path; a fluorescent marker is not an authentication system; and a heated resin is not transferable to a room-temperature printer. This review replaces family labels with a state-resolved functional specification. It connects formulation, printer, geometry, washing, post-cure, conditioning, activation, recovery, ageing, inspection and change control. Public 3Dresyns pages are treated only as manufacturer-declared candidate taxonomies and validation boundaries, never as independent proof. The resulting framework identifies when one functional resin is defensible, when a modular assembly is safer, and when a conventional elastomer, hydrogel, foam, microfabrication or security technology should remain the primary route.

Abstract

Specialised vat-photopolymerization systems can be designed to move, recover a memorised shape, repair damage, operate as soft elastomers, swell as hydrogels, expand into cellular solids, form enclosed fluidic networks, carry authentication features or process unusually viscous feedstocks. Their apparent diversity conceals a shared engineering problem: the useful response emerges only after a sequence of transformations and is strongly coupled to geometry, transport, network mobility and process history. This qualitative engineering review defines the functional evidence required for eight resin families without transferring vendor specifications or research-paper values across systems. Shape-memory is separated into programming, fixation, storage, activation, recovery and cyclic drift. Self-healing is separated from repair, welding and reprocessing, and is quantified by the recovery of several failure-relevant properties rather than visual closure. Silicone-like photopolymers are distinguished from chemically verified silicones; hydrogels are evaluated in their equilibrated medium and transient hydration states; and true cellular foams are distinguished from architected lattices and unfoamed soft solids. Microfluidic qualification connects optical overcure, cleaning access, surface condition, pressure, leakage and analytical compatibility. Security function begins with a threat model and a controlled challenge–response decision. Hot and viscous lithography are treated as different process architectures, not merely warmer exposure recipes. An applied case compares three routes for an authenticated, serviceable soft microfluidic maintenance cartridge used in an industrial analyser. The decision rejects an unverified all-in-one material, provisionally retains a modular printed route and preserves a conventional comparator. Across all families, the qualifying object is the aged material–process–geometry–interface system in its declared functional state.

Keywords: vat photopolymerization; adaptive resin; 4D printing; shape-memory polymer; self-healing; dynamic covalent network; silicone-like elastomer; hydrogel; cellular foam; microfluidics; physical unclonable function; security marker; hot lithography; rheology; qualification

1. Purpose, scope and governing distinctions

This paper makes adaptive, soft and application-specific photopolymer systems selectable as industrial component routes. It has ten objectives. First, it defines function as a measured transition between declared states rather than as a resin label. Second, it separates shape-memory programming, fixation, recovery and repeatability. Third, it distinguishes autonomous self-healing from assisted repair, thermal welding and full reprocessing. Fourth, it defines the mechanical evidence needed for soft and silicone-like components. Fifth, it places hydrogel geometry and mechanics in the actual hydration medium and time history. Sixth, it separates true cellular material from architected porosity and merely soft polymer. Seventh, it converts microfluidic resolution into a functional channel, cleaning and pressure problem. Eighth, it converts a marker into an authentication system through a threat model and readout. Ninth, it treats heated or highly viscous vat photopolymerization (VPP) as a controlled material–machine process. Tenth, it demonstrates a route decision and defines linked qualification evidence.

ISO/ASTM 52900 supplies additive-manufacturing (AM) vocabulary and process categories [1]. ISO/ASTM 52920 addresses qualification principles for industrial AM processes and production sites [2], while ISO/ASTM 52927 links main AM characteristics to corresponding test methods [3]. These standards establish a production-system foundation. They do not establish that a stimulus response,

repair mechanism, hydration state, soft interface, cell morphology, microchannel, security response or heated feedstock is transferable between formulations, printers or geometries.

Eight distinctions govern the review. **Adaptive** means that a controlled input changes a measurable output; it does not imply that the change is reversible, useful or durable. **Shape-memory** means that a permanent network and a switching mechanism permit programming and later recovery; it is not equivalent to any temperature-dependent deformation. **Self-healing** means restoration through a material mechanism after damage; **repair** may require added material, pressure, heat, solvent or an operator. **Silicone-like** describes a mechanical or tactile target unless polysiloxane chemistry is independently established. **Hydrogel** denotes a crosslinked network containing a substantial liquid phase in service, so the dry print is an intermediate. **Foam** requires a cellular phase morphology; an open lattice is architected porosity, not a material foam. **Microfluidic** denotes controlled fluid operation in small channels, not simply a transparent print containing holes. **High-security** requires attack-aware authentication performance; visibility under a lamp alone is a marker observation.

The scope covers component-scale stereolithography (SLA), digital light processing (DLP), masked stereolithography or liquid-crystal-display printing (LCD/MSLA), projection microstereolithography, two-photon polymerization where it supplies relevant evidence, and closely related heated or specialised VPP variants. It includes washing, drying, photo/thermal post-cure, hydration, activation, repair, foaming, assembly and ageing. It covers industrial research, functional prototyping and qualified production routes only where application-specific evidence is available.

Concrete, cement, geopolymers, regolith, building-scale deposition and other macroscopic high-volume construction applications are excluded. Implantable, therapeutic, diagnostic, food-contact, child-safety and protective-equipment claims are also outside this review. A hydrogel, soft resin or microfluidic candidate is not biocompatible because its family is used in biomedical research. A security pigment does not satisfy document, identity or regulated-product controls without the applicable governance. Product and regulatory standards remain mandatory beyond this framework.

2. Specify the function as a complete state transition

A functional requirement has five elements: an initial state, a controlled input, a transition path, a measurable output and an acceptance window. The initial state includes temperature, humidity or immersion medium, prior load, prior activation, age and storage time. The input includes magnitude, rate, duration, spatial distribution and allowable contact conditions. The output includes response amplitude, response time, residual error, energy, leakage or readout confidence. The acceptance window includes both success and prohibited side effects. Without all five, the word *responsive* is not an engineering requirement.

The component then passes through a causal chain: received feedstock; conditioned liquid; printer and vat history; green geometry; wash and dry state; photo/thermal post-cure; assembly; functional conditioning; programming or activation; recovery or readout; service cycling; ageing; and final verification. Some families add a transformation. A hydrogel is hydrated and equilibrated. A foam is expanded and stabilised. A dynamic network is brought into contact and healed. A security feature is enrolled before it can be authenticated. The transformation is part of manufacturing or service and consumes tolerance, time and yield.

The delivered state must be named. A hydrogel can be delivered dry, partially hydrated or equilibrated; each choice changes package, dimension and start-up. A shape-memory part can be delivered in its permanent or programmed temporary shape. A self-repairing component can be delivered with an on-site repair protocol or returned to a controlled facility. A security feature can be delivered unenrolled, enrolled in a database or matched to a reader. A hot-lithography component is delivered only after its heated resin history and cooling/post-cure transformation are complete.

Table 1. Functional families, state transitions and minimum decision evidence

Family	Defining transition	Useful outputs	Conditions that remain attached	Invalid substitution
4D / shape-memory	Program permanent shape into a stable temporary state; apply declared stimulus; recover	Fixity, recovery, response time, force/work, residual strain, cyclic drift	Geometry, orientation, programming strain, stimulus field, temperature/rate, load, post-cure, cycle count	One photograph before and after heating
Self-healing / repairable	Create controlled damage; reunite interface under a declared protocol; retest	Recovered strength, toughness, fatigue, seal or electrical function; healing time and repeatability	Damage type/size, contact pressure, temperature, catalyst, atmosphere, rest time, prior cycles	Visual crack closure or recovered strength alone
Soft / silicone-like	Load, unload, dwell and age a compliant component	Modulus curve, hysteresis, set, stress relaxation, tear/fatigue, seal force, adhesion	Strain rate, temperature, thickness, notch, orientation, post-cure, fluid exposure, cycles	Shore hardness or elongation at break alone
Hydrogel	Hydrate or exchange medium; reach a controlled transient or equilibrium state	Swelling tensor, hydrated modulus, transport, actuation, mass balance, dimensional drift	Medium chemistry, pH, ionic strength, temperature, exchange history, crosslink state, time	Dry dimensions or dry tensile data
Cellular foam	Generate and stabilise gas-filled cells, or retain a preformed cellular phase	Density, cell distribution, compression curve, energy absorption, set, airflow, ageing	Expansion chemistry, thermal profile, skin/core, direction, specimen size, humidity, cycles	Lattice density or soft-solid hardness
Microfluidic	Build, clear and operate connected channels under a defined fluidic protocol	Open-channel yield, pressure–flow response, leakage, dead volume, optical/chemical baseline, carryover	Dose history, channel orientation, cleaning access, fluid, pressure, surface state, reader	Pixel size, CAD channel size or transparency alone
High-security	Enrol feature; apply challenge; acquire response; decide authentic/reject under attack	False acceptance/rejection, uniqueness, reproducibility, detectability, ageing and tamper evidence	Threat model, reader, illumination, algorithm, database, environment, operator, attack set	Fluorescence, colour change or hidden pattern alone
Viscous / hot lithography	Heat or actively recoat feedstock; expose within coupled thermal/rheological window; cool and post-cure	Stable recoat, cure, separation, dimension, property and cell throughput	Full viscosity curve, residence time, inhibitor, temperature field, recoater, exposure, cooling	One room-temperature viscosity or warmer vat setting

The route is deliberately reversible. Declare the initial and delivered states; define stimulus, load, fluid, challenge or thermal process; identify material, printer, geometry, interfaces and mandatory transformations; measure the conditioned baseline; activate, repair, hydrate, foam, flow, authenticate or hot-process under controlled conditions; quantify response, loss, side effects and uncertainty; repeat across lots, builds, positions and cycles; age in the credible service sequence; then retest the final function. A slow actuator is traced through heat and mass transfer, geometry, switching transition, cure state and formulation. A leaking channel is traced through overcure, wash access, wall defects, connector load and conditioning. A failed security read is separated into feature degradation, illumination drift, focus, algorithm threshold and attack. A manufacturing label is never allowed to absorb these distinct causes. The outcome is to accept, modularise, redesign or reject the route with a traceable rationale.

3. Network architecture, mobility and competing clocks

All families depend on a network that must first become printable and then remain mobile enough—or contain a second mechanism—to perform its function. The permanent network supplies shape retention and insolubility. Switching segments, reversible bonds, physical associations, liquid-filled pores, phase-separated domains, expandable inclusions or embedded markers supply additional behaviour. The same crosslinks that preserve print fidelity can suppress segment motion, swelling, healing or foaming. The same mobility that enables response can increase creep, extractables, permeability or dimensional drift.

At least four clocks compete. The **reaction clock** determines when gelation and conversion occur. The **transport clock** governs heat, solvent, water, reactant and gas movement. The **relaxation clock** governs chain rearrangement, stress decay and interface interpenetration. The **degradation clock** governs oxidation, hydrolysis, photobleaching, bond scission, additive loss and fatigue. Function is reproducible only when their ordering is controlled. For example, a self-healing interface must gain sufficient contact and mobility before oxidation or unwanted cure immobilises it. A foam must expand before gas escapes and must stabilise before collapse. A microchannel must be cleared before residual resin advances. A shape-memory part must fix before load is removed and recover before thermal damage accumulates.

The liquid formulation is not the final network. Its identity includes oligomers or prepolymers, reactive diluents, crosslinkers, photoinitiators, absorbers, inhibitors, catalysts, dyes, pigments, particles, surfactants, water, blowing species and contamination. Lot, shelf age, container headspace, mixing, filtration, thermal history and reclaimed-vat fraction can change the working response. A functional additive may absorb the printing wavelength, change viscosity, partition to the surface or migrate during ageing. Therefore a marker or dynamic agent is not qualified independently from the base resin.

Conversion is spatial. Transparent, thin coupons post-cured from both sides can differ from pigmented walls, thick seals, enclosed channels and shadowed interfaces. Similar conversion can still conceal different crosslink topology, dangling chains, phase morphology, free volume and residual stress. The engineering record therefore joins a process proxy—dose, temperature, mass plateau or spectroscopy where justified—to a functional result in representative geometry. A proxy cannot replace the functional test until correlation and control limits are established.

Dynamic covalent bonds illustrate the central conflict. They can allow topology rearrangement, interfacial rebonding or reprocessing, but their activation can also permit stress relaxation under service load. Yu et al. demonstrated a printable photoelastomer in which thiol–ene photopolymerization created the part while disulfide metathesis enabled thermally assisted healing [28]. The same study showed direct competition between photocuring and healing chemistry. Fang et al. later demonstrated that dynamic-bond-enabled topological reconfiguration can contribute to unusually strong and tough printed elastomers [30]. These are mechanism demonstrations, not universal property values. Any lipoate- or disulfide-containing candidate must independently close cure speed, dark stability, service creep, oxidation, healing protocol and recovered function.

4. 4D and shape-memory systems: program, fix, store, recover

Four-dimensional printing is a manufacturing and programming concept, not a material class. A printed object changes geometry or function over time under a stimulus. The change may arise from shape memory, differential swelling, liquid-crystal ordering, phase transition, residual-stress release, magnetic or photothermal actuation, or another mechanism. Calling every delayed deformation “4D” conceals whether the response is designed, repeatable and useful.

A thermally activated shape-memory polymer normally contains a permanent network and a switching phase. Programming brings the material into a mobile state, deforms it, fixes the temporary shape by crossing or changing the switch, removes load and stores the programmed object. Recovery reactivates mobility so the permanent network drives the object toward its memorised geometry. Ge et al. demonstrated multimaterial printed shape-memory polymers with tailorable transitions and spatial response [25]. Alam et al. demonstrated thermoresponsive structures printed by DLP and quantified geometry-dependent recovery [26]. These studies establish design possibilities but also show that recovery depends on composition, geometry and protocol.

At least six outputs are required. **Shape fixity** measures how much of the imposed temporary deformation remains after unloading. **Shape recovery** measures how much returns toward the permanent state. **Response time** is defined at a stated fraction of recovery and under a characterised stimulus field. **Recovery force or work** is measured when the part must act against load. **Residual strain and drift** quantify incomplete return across cycles. **Failure mode** records cracking, delamination, plastic deformation, stress relaxation or loss of response. A high recovery ratio without useful force can fail an actuator requirement; high force with poor geometric recovery can fail a deployment requirement.

Temperature cannot be reduced to “heat applied”. The specimen temperature, ramp, spatial gradient, dwell, heat-transfer medium and allowed overshoot are part of the stimulus. Thin open lattices can respond faster than thick solid walls because thermal diffusion distances

differ. Water immersion and hot air at the same nominal temperature create different heat-transfer and chemical conditions. The transition measured on a small dynamic-mechanical specimen does not ensure that the full component reaches the required state uniformly.

Programming is a manufacturing operation. Maximum strain, strain rate, bending radius, fixture contact, temperature, cooling rate and load-removal sequence determine stored stress and damage. Programming near a notch can create microcracks that are hidden in the temporary state. Fixtures need calibration and traceability where geometry is critical. A programmed component also needs a storage-life study: creep, physical ageing, temperature excursions and humidity can relax the temporary shape before intended deployment.

Geometry and material must be designed together. Hinges concentrate strain; lattices distribute it but introduce build-direction and defect sensitivity; multimaterial gradients can guide motion but add interfaces. Finite-element models require state-dependent constitutive data, not one room-temperature elastic modulus. Contact, self-collision, gravity and payload affect the recovered state. A recovered free shape does not prove loaded function.

The 3Dresyns 4D page states that response depends on formulation version, printer, geometry, orientation, post-cure and activation cycles, and positions the systems for research and advanced prototyping [17]. This is an appropriate manufacturer boundary. It does not supply a universal activation temperature, response time or life. Candidate-specific claims are accepted only after the permanent and programmed states, stimulus, load and cycle population are tested.

Shape-memory and high-security functions can overlap without being equivalent. Zhang et al. printed submicron shape-memory structures whose deformation and recovery altered structural colour and revealed information [27]. The study demonstrates a coupled optical-mechanical mechanism. It does not establish resistance to copying, reader variation or environmental attack. When used for authentication, shape recovery becomes one element of a challenge-response protocol and must meet the security evidence in Section 10.

5. Self-healing, assisted repair and reversible-network claims

Self-healing claims must identify agency. **Autonomous healing** proceeds under service conditions without an external intervention beyond bringing damaged surfaces into their natural state. **Stimulus-assisted healing** requires heat, light, moisture, pressure or another controlled input. **Repair** adds an external patch, resin, solvent or operator action. **Thermal welding** joins compatible surfaces through heat and pressure. **Reprocessing** reshapes bulk material and is not proof that an in-service crack will heal. These routes have different detection, downtime, equipment and validation burdens.

Damage is also specific. A clean razor cut offers intimate surfaces and little contamination; fatigue cracks contain damaged process zones and may not close; abrasion removes material; a puncture creates plastic deformation; chemical cracking changes the network; and delamination may expose incompatible surfaces. Healing performance from one artificial cut cannot be transferred to another damage mechanism. The protocol records crack size and location, surface age, contamination, contact pressure, stimulus, time, atmosphere and prior cycles.

Visual closure is only a screen. At minimum, the repaired population is compared with virgin, damaged-unrepaired and protocol-only controls. Several properties are recovered: strength, strain at failure, fracture or tear resistance, stiffness, hysteresis and the component function that actually matters. A seal requires recovered leakage and compression behaviour. A conductor or dielectric requires electrical retest. A microfluidic wall requires pressure, leakage, surface and carryover checks. Recovery ratios retain the property, specimen geometry and failure location; one ratio cannot stand for the entire component.

Yu et al. used thiol and disulfide groups to combine photopolymerization with disulfide-metathesis healing in a soft printed system [28]. Their bounded experimental protocol included controlled cuts, contact, temperature and time, and revealed a cure-healing composition trade-off. The transferable lesson is not the reported recovery of that formulation; it is that dynamic-site concentration, network mobility and processing compete and must be jointly optimised. A base resin modified with a repair additive can lose cure depth, green strength or service stability before it gains useful healing.

The 3Dresyns self-heal collection describes formulation additives rather than ready-to-print resins and makes the response dependent on base resin, loading and repair conditions [21]. That distinction is essential. A glycerol-lipoate, polyethylene-glycol-lipoate or other disulfide-bearing candidate can be treated as a formulation route, but its number of functional groups, flexible segment, hydrophilicity, viscosity and network participation change cure and final behaviour. A multifunctional lipoate may increase network cohesion while a flexible or hydrophilic route may favour mobility or water interaction; neither tendency is a qualified outcome without measured composition, conversion, mechanics, healing and ageing.

Healing conditions can conflict with service. A temperature high enough for exchange may unload a seal, activate shape memory, soften an adhesive or damage a fluidic analyte. Pressure needed for contact may be unavailable inside a closed crack. Catalyst or residual monomer may migrate. Repeated exchange may accumulate creep or oxidation. Therefore the repair protocol includes detection, access, cleaning, alignment, fixture, activation, cooling, inspection, return-to-service and a maximum number of cycles.

The strongest industrial use case is often maintainability rather than autonomous immortality. A component designed with visible damage zones, replaceable soft inserts and a controlled repair fixture can produce a more reliable outcome than a monolithic self-healing claim. The decision metric is restored component function per full maintenance cycle, including inspection and rejected repairs, not the most favourable coupon recovery.

6. Soft, elastomeric and silicone-like photopolymers

Softness is not one scalar. Initial modulus, tangent modulus at working strain, nonlinear response, hysteresis, stress relaxation, compression set, tension set, tear propagation, fatigue, friction, tack and surface damage can lead to different selections. Shore hardness is an indentation response influenced by method and thickness; it is not a substitute for a full stress-strain and time-dependent record. ISO 37 covers tensile stress-strain properties for vulcanized and thermoplastic rubbers [4], ISO 34-1 covers tear strength [5], ISO 815-1 covers

compression set [6], ISO 3384-1 covers compression stress relaxation [7], and ISO 48-2 covers IRHD hardness [8]. Applicability to a particular printed photopolymer and specimen must be justified rather than assumed from the word “rubber”.

“Silicone-like” must remain literal. It can describe a target combination of feel, compliance, rebound or transparency. It does not prove a polysiloxane backbone, the surface energy of a silicone, gas permeability, thermal stability, chemical inertness, biocompatibility or regulatory history. The 3Dresyns silicone-like collection explicitly organises photopolymer candidates by soft mechanical behaviour [19]. Supplier family placement is useful for screening, but chemistry and application performance require independent evidence.

Wallin et al. demonstrated printable silicone double networks in which a photocurable thiol–ene network formed the shape and a condensation network developed final mechanical behaviour and bonding [29]. The work shows how orthogonal reactions can separate printability from final softness and toughness. It also exposes additional states: green network, developing secondary network, final interface and aged assembly. A claimed “silicone” route using a different chemistry cannot inherit these results.

Fang et al. demonstrated that dynamic covalent topology, hierarchical hydrogen bonding, phase separation and interpenetration can jointly produce high strength and toughness in a printed elastomer [30]. The mechanism counters the idea that all soft VPP polymers must be weak, but it does not erase rate, temperature, notch and ageing sensitivity. High tensile strength can coexist with inappropriate compression set or surface friction for a seal. Maximum strain at break can coexist with crack growth under a smaller repeated strain.

For seals and valves, the acceptance variable is retained contact or closing force through time, temperature and fluid exposure. Compression set quantifies residual deformation after a defined compression and recovery [6]; stress relaxation measures force decay under fixed deformation [7]. These answer different questions. A gasket can show modest permanent set yet lose too much force during service. A valve membrane can survive a tensile test and fail by flexural fatigue, swelling or sticking.

Tear and defect tolerance are central because printed soft parts contain support scars, layer-boundary variation and sharp internal transitions. Test specimens reproduce critical notch direction, surface and print orientation. Fatigue uses the component strain range, mean strain, frequency, waveform and temperature. Hysteretic self-heating is measured when cycling is rapid. Fluid ageing is followed by tests in the wet state and after a defined recovery, because plasticisation and extraction can move performance in opposite directions.

Soft-to-rigid interfaces need their own qualification. Co-printing, overprinting, adhesive bonding, mechanical interlocks and inserts create different failure paths. Bulk elongation does not predict interfacial fracture. Ageing can change modulus mismatch and peel stress. Interface specimens include edge geometry and surface preparation from production, and the complete assembly is cycled under representative bending, pressure and temperature.

7. Hydrogels: the liquid-filled state is the product

A hydrogel is a crosslinked network whose useful state contains a liquid phase. The dry or partially cured print is usually an intermediate. On hydration, solvent uptake changes mass, dimension, refractive index, modulus, diffusion, surface chemistry and residual species. The delivered-state decision—dry, pre-equilibrated or packaged in medium—therefore governs dimensions, shelf life, contamination and start-up.

Swelling is a tensor in a constrained printed geometry, not only a bulk mass ratio. Crosslink density, conversion gradient, orientation, feature thickness and constraint can cause anisotropic change. Thin ribs equilibrate faster than thick hubs; a channel wall swells from two sides while an embedded region may hydrate slowly. Differential swelling can intentionally actuate a device or unintentionally warp it. Dimensions are recorded against medium, temperature and time until a stated equilibrium criterion or operational transient is reached.

Han et al. used projection microstereolithography to print temperature-responsive PNIPAAm hydrogels and showed that resin composition and manufacturing parameters affected deformation [31]. Alketbi et al. studied how PEGDA photopolymerization affected printed hydrogel structure and swelling [32]. The bounded lesson is that optical cure, network structure and swelling are coupled. Reported transition temperatures, resolution or swelling ratios remain formulation- and geometry-specific.

The medium is a formulation component in service. Water source, pH, ionic strength, buffer species, organic fraction, dissolved gas, biocide and contaminants can change equilibrium and kinetics. Medium exchange can extract soluble species or introduce ions. A hydrogel qualified in deionized water is not automatically qualified in cleaning solution, salt solution or process fluid. The qualification record includes medium preparation and renewal, volume-to-part ratio, agitation and evaporation control.

Hydrated mechanics require fixtures that prevent evaporation and damage. Compression, tension, oscillatory response, fracture and friction can all matter. Apparent modulus changes with strain, rate, temperature and equilibration. A swelling ratio cannot predict load capacity. For a hydrogel valve or actuator, pressure–flow behaviour and response time are measured in the assembled channel. For an optical element, transmission, scattering and dimensional stability are measured through medium changes and cycles.

Transport creates both function and risk. A hydrogel membrane may permit selective diffusion, but selectivity, flux, lag, binding and fouling depend on solute, concentration and state. Leachables from incomplete cure or photoinitiator products can contaminate an analytical system. Washing until a mass plateau does not prove analytical cleanliness. Blank response, extractables or application-specific interference are measured at the sensitivity of the intended instrument.

The 3Dresyns hydrogel collection treats dry printing, hydration, swelling and hydrated function as separate considerations [18]. It supplies a candidate taxonomy, not evidence for diagnostic, implantable or biological use. This review confines the industrial claim to controlled research, sensing, flow control or soft-device functions for which chemical, mechanical and analytical compatibility are directly tested.

Hydrogel failure includes dehydration, over-swelling, syneresis, cracking, delamination, fouling, hydrolysis, oxidation, microbial contamination and response drift. Package water loss and sterilisation or disinfection—if required—can dominate. A long-lived device needs water-activity control, medium compatibility and a replacement strategy. A disposable element needs shelf and activation windows and a waste plan. “Water-based” is not a safety or sustainability conclusion.

8. Foam, cellular solid, architected lattice and soft solid

Three structures must not be conflated. A **material foam** contains gas cells within a polymer matrix and has a cell-size, cell-shape, connectivity and density distribution. An **architected lattice** contains designed voids resolved by the manufacturing process. An **unfoamed soft solid** can feel foam-like but lacks a gas-cell morphology. They can share low apparent stiffness but respond differently to compression, airflow, tear, ageing and defects.

True printed foam may be created by physical or chemical blowing, expandable microspheres, emulsion templates, phase separation or a preformed cellular feedstock. Each route has a gas-generation or pore-formation clock and a stabilization clock. Temperature, pressure, viscosity, network mobility, surface tension, diffusion and geometry determine whether cells nucleate, grow, coalesce, collapse or create a dense skin. The green printed geometry can expand anisotropically and lose dimensional accuracy.

The 3Dresyns foam collection explicitly distinguishes thermal expansion of a blowing-agent-containing formulation from directly printed foam-like architecture and notes that a standard photopolymer does not expand by itself [20]. This is a useful manufacturer boundary. It does not supply a transferable expansion ratio, cell morphology or service life.

Gao et al. demonstrated a VPP route that used thermally responsive network rearrangement, expandable microspheres and subsequent reactions to balance green-part fidelity, expansion and soft-foam mechanics [33]. Their result illustrates why the thermal profile, dynamic bonds, gas-retaining shell, diluent and post-cure must be treated as one transformation. It does not establish that another resin or geometry will expand uniformly.

ISO 1856 specifies compression-set methods for flexible cellular materials [9], and ISO 3386-1 addresses compression stress-strain characteristics of low-density flexible cellular materials [10]. ISO 2440 covers accelerated ageing tests for flexible and rigid cellular polymeric materials [11]. Method applicability, density range, specimen skin and geometry remain attached. An architected lattice may need different structural tests even when its macroscopic curve resembles foam.

Table 2. Measurement architecture for soft, adaptive and transformed states

Decision	Baseline and transformed states	Primary outputs	Population and geometry	Frequent hidden failure
Shape-memory deployment	Permanent, programmed, stored, activated and recovered	Fixity, recovery, time, force/work, residual strain, damage	Multiple lots/builds; hinges, lattices and maximum-thickness zones; loaded cycles	Thermal gradient produces partial recovery or cracks a hinge
Healing / repair	Virgin, damaged, protocol-only, repaired and re-aged	Strength, tear/fracture, fatigue, leak/electrical function and repeat cycles	Controlled damage plus production defects and contaminated interfaces	Crack closes optically but toughness or fatigue remains poor
Soft seal / valve	Initial, compressed/cycled, fluid-aged and recovered	Nonlinear mechanics, force relaxation, set, tear, hysteresis and leak	Critical surface, notch and print orientations; assembled contact	Contact force decays although hardness and tensile strength pass
Hydrogel element	Dry, transient hydration, equilibrium, medium-exchanged and dehydrated	Mass/dimensional swelling, hydrated mechanics, transport, optics and drift	Thin and thick features; constrained interfaces; full flow cell	Unequal hydration warps geometry or releases interferents
Cellular foam	Green, expanded, stabilised, cycled and aged	Density/cell map, compression curve, set, energy absorption and airflow	Skin/core and directions; minimum/maximum section; full component	Local cell collapse, dense skin or expansion gradient
Microfluidic device	As-built, cleaned, post-cured, wetted, pressured and aged	Open yield, channel metrology, pressure-flow, leak, blank and carryover	Worst roof dose, bends, junctions, long channels and connectors	Channel appears open but retains resin or adsorbs analyte
Security feature	Manufactured, enrolled, challenged, environmentally aged and attacked	Signal distribution, false decisions, uniqueness, reproducibility and tamper response	Lots, build positions, readers, operators and attack samples	Reader drift or a copied deterministic pattern defeats decision
Hot / viscous VPP	Received, heated/resident, recoated, exposed, separated, cooled and cured	Rheology, dark stability, cure, force, dimension, final mechanics and yield	Vat locations, dwell extremes, thermal edges and representative cross-sections	Viscosity is acceptable but premature reaction or poor cooling shifts state

Foam acceptance requires density and cell maps rather than one mean. Micro-computed tomography, section imaging or another qualified method can map cell size, closed/open fraction and defects, but resolution and sampling limits are reported. Mechanical tests retain skin condition, direction, strain rate, compression level and recovery time. Cushioning or energy-absorption claims require repeated impact or compression under the actual temperature and rate. Acoustic and thermal-insulation claims require their own methods; low density is not proof.

The transformation yield is counted. A printed green part that later expands outside tolerance, cracks, sticks to a fixture or develops a density gradient is a failed part even if printing succeeded. Throughput is accepted components per complete print-clean-expand-stabilise-inspect cycle. Architected lattices can be preferable when deterministic pores, local reinforcement or cleanability matter; conventional cut foam can be preferable when volume, cost and mature ageing data dominate.

9. Microfluidic resins: an open channel is only the first gate

Microfluidic manufacture couples optics, transport, surface chemistry and assembly. The smallest nominal pixel or laser spot does not define an enclosed channel. The channel roof receives exposure while previously built transparent layers transmit additional light into nominal voids. Resin trapped inside a cavity can cure, thicken walls or block the path. Xu et al. demonstrated in-situ transfer VPP to control overcure in small transparent channels [34], and Luo et al. demonstrated dose- and zone-controlled exposure to manage accumulated irradiance [35]. Their route-specific feature sizes are not printer-independent specifications; they establish accumulated dose as a causal variable.

The design record separates positive-feature resolution, negative-feature resolution and enclosed-channel yield. It maps channel height, width, length, bends, junctions, roof thickness, orientation, distance from the window, neighbouring exposures and drain/vent paths. A

short straight calibration channel cannot qualify a long serpentine network. The worst location is often where a thin roof, long optical history and poor drainage coincide.

Cleaning is part of geometry. Uncured resin must have an exit path and a driving mechanism. Flush pressure, solvent, temperature, time, direction and cycles are controlled. Excess pressure can deform a green roof or drive resin into a dead zone. A clear outlet does not prove that all surfaces are clean. Mass balance, coloured or fluorescent tracer studies, imaging, blank analysis or destructive cross-sections may be needed. The cleaning solvent can swell the network, extract species or leave residue; drying and post-cure can then shrink or distort the channel.

ISO 22916 specifies interoperability requirements for dimensions, connections and initial microfluidic-device classification [12]. It supports interface discipline but does not qualify the printed material or flow function. The current published 2022 edition remains the normative reference while a revision is under development. Connection geometry, seal material, insertion force, dead volume and leak path are tested as an assembly.

Fluidic function includes pressure–flow response, burst or proof pressure where justified, leakage, valve response, mixing or separation performance, dead volume, residence-time distribution, gas permeability, bubble nucleation and carryover. Laminar flow does not make surface effects irrelevant. Wettability, roughness, adsorption, swelling, extractables and photobleaching can alter analytical baselines. Transparent appearance does not prove optical transmission or low autofluorescence at the measurement wavelengths.

The 3Dresyns microfluidics collection organises candidate resins by viscosity, rigidity and internal-feature priority and explicitly conditions results on printer calibration, exposure, cleaning, post-processing and geometry [23]. Its grade table is manufacturer-declared navigation; none of its values are transferred here. Candidate selection begins with channel accessibility and fluid compatibility, then tests relative resolution in the specific printer and state.

For industrial analytical use, chemical compatibility is not enough. The device blank, drift, adsorption, recovery after a high-concentration sample, cleaning carryover and background fluorescence are measured against the instrument's limit. If a soft valve, hydrogel gate or repaired wall is added, the full fluidic sequence is repeated after cycling and ageing. A component can pass pressure and fail analysis.

Microfluidic qualification is especially sensitive to population bias. Reporting the best open channel hides blockage yield and cleaning failures. Build maps retain every device, including censored and blocked parts. The production metric is accepted fluidic devices per complete cell cycle, with channel opening, cleaning and functional test included.

10. High-security resins, markers and challenge–response systems

A security material has no meaningful level without a threat model. The threat model states the protected asset, attacker access, equipment, knowledge, time, budget and acceptable consequences. It distinguishes casual visual imitation, high-resolution copying, chemical removal, feature transplantation, reader spoofing, database compromise and insider substitution. A marker designed for rapid public verification answers a different threat from a covert forensic feature.

Security features can be **overt**, visible without a tool; **covert**, requiring a controlled reader or stimulus; **forensic**, requiring laboratory analysis; or **machine-authenticated**, producing a response evaluated by an algorithm. A feature can combine levels. More effects do not automatically increase security: too many readers, thresholds and procedures can reduce reliability or reveal the mechanism. Defence in depth uses independent mechanisms and controlled information, not merely multiple colours.

The 3Dresyns high-security collection and security-ink portfolio describe visible, ultraviolet, infrared, phosphorescent, magnetic, conductive, reactive and other candidate effects, including custom systems [22,41]. These pages establish a manufacturer-declared design space. They do not demonstrate unclonability, reader performance or resistance to a specified attack. Exact formulation, distribution and enrolment controls may themselves be sensitive and should not be disclosed in an open engineering review.

A deterministic printed logo can be copied if its geometry and response are observable. A physical unclonable function (PUF) instead uses manufacturing randomness to create a feature that is easy to measure but impractical to reproduce within the decision tolerance. Randomness alone is insufficient. The enrolled response must be unique between parts and reproducible for the same part across readers, angles, temperatures, ageing and contamination. Random-fractal PUF research has demonstrated attack-aware optical authentication concepts [39], but every production embodiment needs its own distributions and threat tests.

The decision chain is: manufacture; inspect; enrol; securely bind identifier and response; issue; challenge; acquire; preprocess; compare; accept/reject; log; revoke or re-enrol. Each link can fail. The material can fade, the reader can drift, the algorithm can overfit, the database can be altered, and an operator can use the wrong illumination. False-acceptance and false-rejection rates are reported with confidence bounds for the enrolled population and attack set. A threshold chosen after viewing the test data is not independent validation.

Stimuli-responsive structural colour illustrates both opportunity and risk. Zhang et al. demonstrated shape-memory microstructures that hide and reveal optical information [27]. The response can support a physical challenge, but activation temperature, viewing geometry, recovery, fatigue and environmental stability become security variables. A counterfeit may imitate the visible state without reproducing the response path; conversely, an unstable genuine feature may be rejected. The authentication protocol therefore evaluates the trajectory or multi-channel response where it adds discriminating power.

Security formulation creates manufacturing conflicts. Fluorescent dyes, absorbers and particles can change cure depth, lateral growth, viscosity, sedimentation and final mechanics. High marker loading can improve signal while making the feature easier to analyse or degrading print fidelity. Deore et al. demonstrated that polymerization-induced phase separation can drive functional phases toward a surface or retain them in gradients depending on gelation, diffusion and crosslinking [40]. For security design, this means that nominal marker loading does not prove local distribution or signal stability. Reactive tamper indicators must not respond to legitimate cleaning, humidity or packaging. Magnetic or conductive fillers can create equipment and electrical hazards. The secure feature is qualified as material, geometry, reader and algorithm together.

Change control is stricter than for a decorative colour. A pigment lot, resin refractive index, printer optical field, post-cure, surface finish, reader firmware or algorithm update can shift the response distribution. Changes require bridging studies and, where needed, re-enrolment. Reference artefacts monitor reader drift. Access to master formulations, digital files, enrolment keys and rejected security parts is controlled. Disposal prevents harvesting of genuine features.

11. Viscous and hot lithography as a process-specialty system

High-viscosity and high-temperature VPP are not ordinary exposure settings. Conventional bottom-up processes require resin to replenish a narrow gap and the cured layer to separate from a window. Highly viscous feedstocks slow levelling and amplify pressure and drag. Heating can lower viscosity but changes diffusion, reaction rate, inhibitor consumption, sedimentation, phase behaviour, shrinkage and separation. Active recoaters, rollers, films or scanning zones create different shear and residence histories.

ISO 3219-1 defines rheological terms and symbols [13], and ISO 3219-2 gives general principles for rotational and oscillatory rheometry [14]. A single viscosity at one shear rate and temperature is inadequate. The process record includes viscosity versus shear rate and temperature, time dependence, yield or thixotropic behaviour where present, oscillatory response where useful, thermal cycling, filler settling and a history that represents conditioning, pumping, recoating and idle residence.

Weng et al. demonstrated a linear-scan VPP system that isolated curing and detachment zones to process ultra-high-viscosity resins [36]. The transferable lesson is architectural: machine design can change the allowable rheological window. The reported viscosity and properties cannot be transferred to a passive-recoat printer. Meenakshisundaram et al. developed thermal and rheological characterisation to select high-temperature VPP conditions without triggering unwanted thermal polymerization [37]. Sameni et al. showed, in two bounded mixtures, that the effect of vat temperature depended on mixture design and the relation between process temperature and network formation [38]. Together these studies establish dark thermal stability and composition-specific response as independent gates, not assumptions from a short warm print.

The 3Dresyns viscous and hot-lithography page describes elevated-temperature processing for high-viscosity or highly filled systems and conditions use on rheology, thermal stability, reactivity and equipment [24]. It is a candidate-route declaration. A heated vat does not qualify resin recirculation, hot surfaces, vapour control or temperature uniformity.

The process window has at least six coupled bounds. The lower temperature bound is set by recoat and separation. The upper temperature bound is set by dark reaction, volatilization, additive stability and equipment. The residence-time bound limits thermal history. The exposure bound must gel the layer without unacceptable lateral growth or exotherm. The mechanical bound limits forces on green features. The cooling/post-cure bound controls crystallization, stress, secondary reaction and dimension. A valid set point lies inside all six with uncertainty and spatial uniformity.

Safety changes with temperature. Vapour generation, skin burn, heated spill, runaway reaction and cleaning compatibility require assessment. Resin transfer and maintenance may expose workers to hotter, less viscous liquid. NIOSH's desktop VPP guidance addresses resin handling, printing, cleaning and post-processing controls [16]; industrial heated systems require additional task-specific hazard analysis, ventilation verification, temperature interlocks and emergency procedures.

Process economics include warm-up, thermal conditioning, idle loss, cleaning, rejected thermally aged resin, energy, recoater maintenance and cooling. A high-performance material is not advantageous if the complete cell produces fewer accepted components or an unstable vat history. The comparison is against other VPP architectures and conventional moulding, machining, casting or extrusion routes.

12. Multi-objective conflicts and modular design

Every functional route spends part of the same design budget. Mobility assists shape recovery, healing and sometimes toughness, but can increase creep and permeability. High crosslink density improves shape retention and print fidelity but can suppress healing, swelling and foaming. Hydrophilic segments enable hydration but can increase water uptake and extractables elsewhere. Optical absorbers improve depth control but can reduce transparency or security signal. Fillers can improve marker response or mechanics while increasing viscosity, sedimentation and scattering.

The all-in-one functional resin is therefore a high-burden hypothesis. It may remove joints and enable compact geometry, but one formulation must close every mechanism and every interaction. A modular assembly allocates rigid channels, soft seals, responsive elements and security features to different zones. It adds interfaces, but those interfaces can be inspectable, replaceable and individually qualified. The correct route is the one with the smallest unresolved coupled risk, not the fewest material names.

Table 3. Candidate route patterns, credible advantages and decisive no-go gates

Route pattern	Credible advantage	Coupled burdens	Decisive evidence	No-go condition
Monolithic multifunctional photopolymer	Maximum integration; no bonded internal interface	One network must print, clean, remain dimensionally stable and deliver every adaptive, soft, fluidic or security function	Worst-state conversion plus complete aged component response under all stimuli and fluids	Any critical function relies on a family label, best coupon or inaccessible internal state
Two-stage or dynamic network	Printability separated from final network development; repair or reconfiguration possible	Secondary reaction, exotherm, ageing, creep, activation access and irreversible drift	State mapping, reaction completion, dimensional change, loaded cycles and repaired-function distribution	Functional activation overlaps service and causes unacceptable relaxation or damage
Modular rigid body plus soft/responsive insert	Each zone uses a narrower material window; replaceable wear element	Seal, adhesion, alignment, dead volume, tolerance and assembly labour	Interface ageing, leak, force retention, replacement repeatability and full-system test	Interface cannot be inspected, replaced or kept inside its strain/chemical window
Printed body plus enrolled security feature	Authentication bound to component geometry and genealogy	Marker affects cure; enrolment, reader, database and attack testing required	Uniqueness/reproducibility distributions, environmental drift and red-team attack set	Deterministic response is copyable or genuine population cannot meet false-decision limits

Route pattern	Credible advantage	Coupled burdens	Decisive evidence	No-go condition
Hot or active-recoat VPP	Access to viscous, highly filled or higher-performance chemistry	Thermal residence, dark reaction, shear, equipment and lower cell flexibility	Full rheology–temperature–time map, spatial thermal control and accepted-cell throughput	Stable overlap of recoat, cure, separation and dark stability cannot be demonstrated
Conventional material with printed secondary feature	Mature seal, foam, microfluidic or security route retained; AM used only where it adds geometry	Joining, alignment and extra part genealogy	Qualified primary component plus interface and secondary-feature function	Printed primary structure adds no verified benefit sufficient for its qualification burden

Modularity is not automatically safer. A hydrogel insert can dry at an interface; a soft seal can roll; an adhesive can inhibit a dynamic surface; a security coating can delaminate; and a conventional connector can add dead volume. Modular design succeeds only when failure modes become observable and controllable. The complete assembly remains the acceptance object.

The selection order is exclusionary. First remove routes that cannot reach or verify the delivered state. Then remove those whose stimulus conflicts with service, whose channels cannot be cleaned, whose soft interface cannot retain load, whose foam transformation cannot hold tolerance, whose security response cannot be enrolled, or whose heated process lacks a stable window. Only surviving routes are compared for throughput, cost, maintenance and sustainability.

13. Measurement architecture, populations and uncertainty

Each result begins with a requirement, drawing, state label and test plan. The drawing identifies build orientation, layer/exposure relation, supported surfaces, maximum/minimum section, hinges, notches, enclosed paths, drain holes, soft interfaces, foam skin, marker zone and post-cure access. The state label records resin lot, formulation version, vat history, build file, printer, wash, dry, post-cure, hydration, programming, foaming, enrolment, repair and ageing.

Replicates span independent lots, builds and build positions. Repeated readings on one specimen estimate instrument repeatability, not production variation. Adaptive cycles are not treated as independent specimens. Censored failures—blocked channels, broken hinges, unhealed interfaces and unreadable markers—remain in the yield and reliability record. Excluding them would condition results on survival.

Soft mechanics retain specimen method, thickness, surface, orientation, strain rate, temperature and conditioning [4–8]. Compression set and stress relaxation are not merged [6,7]. Foam tests retain density, skin and direction [9–11]. Hydrogel measurements retain medium and equilibration. Shape-memory results retain programming and activation protocols. Healing results retain damage and contact. Microfluidic results retain pressure, fluid, cleaning and optical history. Security results retain reader and threshold. Hot-lithography results retain complete rheological and thermal history [13,14].

Response time is defined against an observable threshold, not by video impression. A shape actuator might use time to 90% recovered angle under load; a hydrogel valve might use time to reach a declared flow reduction; a security response might use acquisition-to-decision latency. Spatial uniformity is measured where partial response matters. Recovery and drift are measured after a fixed rest condition.

Uncertainty includes calibration, thickness, temperature, humidity, medium composition, pressure, flow, force, displacement, optical intensity/spectrum, camera position, reader electronics, algorithm threshold, operator, lot, build and position. Acceptance uses a predeclared guard band. A result whose uncertainty crosses a limit is not converted to a pass through rounding or selective repeats.

Reference controls are causal. A formulation without a dynamic group tests the healing contribution. A nonresponsive network tests shape recovery. A solid specimen without blowing species tests foam transformation. An open channel tests surface compatibility separately from enclosed-channel cleanability. A known genuine and known attack artefact monitor a security reader. A room-temperature or low-viscosity route tests whether heating provides an actual production advantage.

Correlation can reduce routine testing only after it is demonstrated. A spectroscopy or dose proxy may predict response within one controlled formulation and geometry range. Viscosity may predict recoat within one machine. Fluorescent intensity may monitor marker concentration. None remains valid after unbridged material, printer, post-cure or geometry changes. Sentinel tests are chosen because they lead failure, not because they are easy.

14. Ageing, safety and lifecycle boundaries

Functional materials often fail by drift before fracture. Shape-memory transition and recovery force can change; healing slows; a seal relaxes; a hydrogel loses water; foam cells collapse; channel surfaces foul; fluorescence fades; a reader threshold moves; or hot-stored resin advances in reaction. Ageing endpoints therefore include the functional distribution, not only retained tensile strength.

ISO 188 covers accelerated heat ageing of rubber-like materials [15], while ISO 2440 covers accelerated ageing of cellular polymeric materials [11]. These methods support controlled comparison where applicable but do not predict universal service life. Acceleration is rejected when temperature changes mechanism, crosses a switching transition, dehydrates a hydrogel, activates repair chemistry, expands a foam or drives a different dark reaction.

Service sequences are reproduced in causal order. A soft microvalve may see compression, process fluid, cleaning, drying and thermal storage. A shape-memory lock may be programmed, stored under load and activated once after humidity exposure. A security marker may see abrasion, sunlight, solvent wipe and multiple readers. Combined exposures can be more damaging than isolated tests. Recovery periods are controlled because reversible plasticisation and irreversible degradation lead to different decisions.

Occupational hazards are formulation- and task-specific. Liquid resin can cause skin or eye exposure; wash solvent can add flammability and inhalation risk; powders and pigments can become airborne; hydrogels can support contamination; foaming can release gas or create pressure; repair can heat or volatilize material; and security additives may require restricted handling. NIOSH guidance provides control concepts for desktop VPP resin handling and post-processing [16], not a declaration that a particular functional or heated system is safe.

The hierarchy of controls is applied to mixing, printing, washing, activation and maintenance: eliminate unnecessary open handling; use closed transfer, enclosure and local exhaust; verify temperature, pressure and ventilation interlocks; establish cleaning and spill procedures; then select personal protective equipment. Heating, UV sources, lasers, pressure and reader illumination add physical hazards. Safety data and exposure assessments remain tied to exact formulation and jurisdiction.

Lifecycle comparison uses a declared functional unit, such as accepted cartridges over a service interval or deployed actuators per maintenance cycle. It includes resin and vat losses, solvent, water conditioning, thermal energy, failed programming, foam expansion rejects, destructive fluidic tests, marker enrolment rejects, reader infrastructure, repair yield and end-of-life separation. A self-healing label does not establish lower impact if repair consumes energy, fails unpredictably or prevents recycling. A modular replaceable seal can outperform a nominally durable monolith when it extends the primary body's life.

Sensitive security waste is a special boundary. Rejected genuine markers, enrolment data, formulation masters and digital keys require controlled destruction or revocation. Reuse and recycling routes must not release authentic features into uncontrolled channels. Scientific transparency about mechanisms must be balanced with operational secrecy about keys, thresholds and production distributions.

15. Applied example: authenticated soft microfluidic maintenance cartridge

15.1 Requirement, delivered state and failure boundaries

The illustrative component is a replaceable maintenance cartridge for an industrial liquid analyser. It contains a clear rigid flow body, two low-volume channels, a flexible diaphragm valve, a compressed perimeter seal and an authentication feature used to reject unknown cartridges before an automated cleaning cycle. The instrument is not medical or diagnostic. It handles a declared set of process and cleaning fluids at owner-defined temperature and pressure. The cartridge must arrive dry and clean, wet predictably, avoid unacceptable blank or carryover, maintain valve closure and seal force, and remain identifiable after storage and handling.

The owner's specification lists: channel envelope and allowable pressure–flow range; maximum leak and dead volume; valve opening/closing pressure; seal force retention; allowed fluid absorption and dimensional drift; optical baseline at the reader wavelengths; cleanability and dry-back; number of fluidic and valve cycles; storage environment and life; permitted security reader and decision limits; and disposal. No numerical limit in this example is universal.

Critical failures are: roof overcure or residual resin that blocks a channel; extractable material that shifts the analytical blank; soft-valve creep that changes flow; seal relaxation that leaks; swelling that distorts a connector; security false rejection after cleaning; counterfeit acceptance; repair activation that contaminates the fluid path; and an inaccessible interface whose condition cannot be inspected. The output sheet records delivered state, candidate routes, mandatory transformations, no-go gates, evidence gaps and final rationale.

15.2 Three candidate routes

Route A: monolithic multifunctional print. A single nominally clear, soft-tough, chemically resistant, self-healing and security-marked resin forms channels, diaphragm, seal and authentication feature. Integration is attractive, but the mechanical requirements conflict: channel roofs need dimensional stiffness while the diaphragm and seal need controlled compliance and low relaxation. Marker additives may change optical cure. Dynamic mobility may help repair while increasing creep or chemical transport. The route is rejected at screening unless one formulation closes every local state, including clean enclosed channels, long-term seal force, valve fatigue, analytical blank and attack-aware authentication. No such evidence is assumed.

Route B: modular printed cartridge. A rigid clear VPP body contains the channels; a separately printed or conventionally formed soft diaphragm/seal insert is mechanically retained in an inspectable seat; and a security feature is placed outside the wetted path in a protected, reader-accessible zone. The marker is enrolled after final cure and assembly. Any repairable chemistry is confined to the replaceable soft insert and is not activated in the fluidic path. This route is provisionally retained because functions are separated and the soft element can be replaced, but it must pass interface, dead-volume, valve, leakage, blank and security tests after the full ageing sequence.

Route C: conventional primary cartridge with printed secondary feature. A moulded or machined transparent body uses an established elastomer seal and a conventional security label or embedded feature; AM is limited to a low-volume mixing insert or development fixture. This route loses some geometric integration and may require tooling, but it preserves mature material data and remains the default if the printed rigid body cannot meet channel yield, cleanliness or throughput. It is not treated as a failure of AM; it is the controlled comparator.

15.3 Evidence programme and decision

The rigid-body study maps enclosed-channel yield across length, height, roof thickness, orientation and build position. It records every blocked or incompletely cleaned specimen. Pressure–flow, local/total leakage and optical blank are measured after washing, post-cure, wetting, fluid exposure and dry-back. Sacrificial geometries verify internal cure and cleaning. Connection dimensions follow an interface record informed by ISO 22916 [12].

The soft insert is characterised in tension, tear, compression set and compression relaxation using justified methods [4–7], then in the assembled valve and seal. The population spans material lots, print orientations if printed, post-cure positions and fluid ageing. Valve opening/closing, hysteresis, leak and fatigue are measured. A nominal hardness is retained only as a process screen. If repair is considered, controlled damage and a facility repair protocol are added; the repaired insert must recover leak, force and fatigue, not merely tensile strength.

The security programme begins with a threat model for casual substitution and commercially capable copying. It keeps the feature outside the fluid path. Genuine cartridges are enrolled across lots and build positions; known negatives, imitations, transplanted genuine fragments and environmentally aged samples form the attack set. Readers are challenged across allowed angle, distance, temperature and operator variation. Decision thresholds are frozen before confirmation testing. Reader reference artefacts detect drift.

Assembly qualification then applies storage, vibration/handling, declared fluids, cleaning and valve cycles in the real order. It repeats channel, leak, valve, blank and authentication endpoints with guard bands. The primary metric is accepted cartridges per complete manufacture–clean–assemble–enrol–test cycle. Rework and rejected enrolments remain in the denominator.

Route A is rejected because its integration does not compensate for unclosed coupling between stiffness, softness, dynamic mobility, optical cure and security. Route B remains provisional because it makes wetted, soft and security zones independently measurable. Route C remains approved as the comparator and production fallback. Route B can be selected only when its accepted-cell throughput and functional evidence demonstrate a benefit large enough to justify its added qualification and assembly control.

16. Qualification genealogy and change control

The qualification record is a linked evidence system, not a folder of certificates. It permits any accepted component to be traced from function through measurement to formulation and process, and any drift to be traced back from failure. At least eight linked records are maintained.

Table 4. Minimum linked records for adaptive and application-specific resin systems

Record	Minimum contents	Release question	Change trigger
Functional-requirement record	Initial/delivered states; stimulus, fluid, load, challenge; output; limits; prohibited effects; service sequence	Is the claimed function measurable and complete?	Duty, environment, reader, fluid, cycle or acceptance change
Material and formulation genealogy	Supplier, lot, version, composition ranges, additive/marker identity, storage, mixing, reclaimed fraction and safety data	Is the exact functional feedstock controlled?	Supplier/lot rule, component, loading, pigment, catalyst, inhibitor or storage change
Printer, vat and thermal genealogy	Machine/configuration, optics, calibration, build file, vat history, temperature field, recoater, residence and maintenance	Was the qualified material–machine state reproduced?	Printer, optics, firmware, vat, temperature, recoater, exposure or maintenance change
Transformation record	Wash/dry/post-cure; hydration; programming; healing; foaming; assembly; enrolment; fixtures and operators	Did every mandatory state transition remain inside its window?	Solvent, chamber, medium, fixture, thermal profile, repair or enrolment change
Geometry and interface record	CAD/revision, orientation, supports, feature map, soft/rigid joints, channels, foam skin, marker zone and inspection access	Does the tested evidence represent the released component?	Wall, channel, hinge, cell, interface, marker position, support or scaling change
Measurement and uncertainty record	Methods/editions, equipment, calibration, raw data, populations, censoring, uncertainty and guard bands	Do results demonstrate the requirement without selective reporting?	Method, fixture, lab, sample plan, analysis, threshold or uncertainty change
Ageing, attack and failure record	Service-sequence exposures, functional retests, security attacks, failure analysis, repair and disposition	Does function survive credible service and attack?	New failure, contaminant, environment, threat, maintenance or lifetime change
Release and monitoring record	Approved ranges, no-go gates, accepted-cell yield, sentinel tests, control limits, deviations and owner	Is routine production demonstrably inside the qualified state?	Trend, outlier, drift, deviation, complaint, supplier notice or software change

Changes are classified by causal reach rather than administrative name. A colourant change can affect cure and a security response. A softer formulation can alter channel roof stability. A new wash can change swelling, blank and adhesion. A firmware update can change dose accumulation. A reader update can change false decisions. Each change receives an impact map across all linked records and a predeclared bridging plan.

Bridging evidence is asymmetric. Similar initial tensile properties do not bridge healing, fatigue, hydrogel swelling or security. Similar viscosity does not bridge dark stability or exposure. Similar fluorescence does not bridge uniqueness or reader threshold. The burden is largest when the change affects a functional mechanism or a poorly observed internal state. Retained samples and digital/raw data support retrospective analysis.

Production monitoring focuses on leading causal variables: conditioned viscosity and thermal history; working-curve or exposure sentinel; green/worst-section transformation proxy; soft-element force or relaxation sentinel; channel-opening and blank tests; foam density/cell sentinel; shape or healing response witness; and security reference response. Control limits derive from qualified populations. Passing a convenient sentinel does not override a failed functional test.

17. Discussion and conclusions

Adaptive and application-specific resins do not form a residual category outside “real” engineering materials. They expose, more clearly than conventional rigid resins, that material function is a trajectory. Printing creates only one state. Programming, hydration, healing, foaming, fluid operation, authentication or heated processing creates another, and ageing may move it again. A defensible selection names every state and measures the transitions that matter.

The scientific opportunity is genuine. Printed network architecture can spatially organise switching behaviour; dynamic bonds can support repair or topology rearrangement; double networks can decouple shape formation from soft mechanics; hydration can generate transport and actuation; controlled expansion can create local cellular structure; dose management can produce complex enclosed fluidics; and material–geometry responses can support authentication. Primary studies [25–40] demonstrate these mechanisms in bounded systems. They do not make a commercial label, value or recipe transferable.

The industrial obstacle is rarely the absence of a remarkable first response. It is the coexistence of response with manufacturability, geometric accuracy, retained load, clean surfaces, environmental stability, population yield, inspectability and change control. A functional gain that requires an uncontrolled stimulus, inaccessible cleaning, unmeasured drift or an unverifiable internal state is not a production advantage.

Seven conclusions follow.

- **Function belongs to a declared state transition.** Initial state, input, path, output and acceptance window must be specified together.
- **Shape-memory requires programming and loaded cyclic evidence.** A heated before/after image does not establish fixity, recovery force, storage stability or durability.
- **Healing is property- and damage-specific.** Visual closure and recovered tensile strength cannot stand for tear, fatigue, leakage, electrical or service restoration.
- **Softness, hydration and cellularity are different architectures.** Silicone-like is not verified silicone; a dry hydrogel is not the delivered wet component; and a lattice is not a foam.
- **Microfluidic and security labels begin, rather than end, qualification.** A channel must be open, clean and functional; a marker must operate within an enrolled, attack-aware decision system.
- **Hot or viscous lithography is a coupled machine–material process.** Rheology, residence, dark stability, recoat, exposure, separation, cooling and safety require one overlapping window.
- **Modular routes often reduce unobservable coupling.** They are preferred only when interfaces remain inspectable and the aged assembly passes every guarded functional endpoint.

The practical selection rule is to work backwards from the final observable failure. Define what must move, seal, recover, heal, swell, compress, flow, authenticate or survive; identify the state and interface where failure would appear; and require evidence that represents that state. Then retain only routes whose transformations can be controlled and verified across production populations. This approach cannot guarantee a correct selection. It is designed to expose invalid assumptions before they are hidden behind an adaptive label, an exceptional coupon, a nominal printer resolution or a response measured in the wrong state.

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