

Accelerated Ageing and Life-Claim Validity for Printed Photopolymers: Acceleration Factors in a Material Whose State Is Still Evolving

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Statement of Significance

Accelerated ageing of a printed photopolymer contains a confound that is easy to miss: the elevated temperature, radiation or humidity intended to accelerate degradation can also continue cure, relax residual state, change free volume or alter transport. A specimen can therefore become stiffer or stronger during an ageing exposure even while another degradation process is occurring. ER-170 does not review the degradation mechanisms themselves; those remain in ER-072 and neighbouring reviews. It asks the narrower qualification question: **when does an accelerated exposure preserve enough mechanism and material state that an acceleration factor or service-life claim is defensible?** The controlled VPP ageing corpus shows that post-cure history, water state, geometry, temperature and recovery protocol can move the measured endpoint independently of degradation [1-6]. It also establishes that one laboratory hour cannot be converted into service time merely because a property changes faster at elevated severity [1]. A valid acceleration model requires a frozen initial state, mechanism equivalence across severities, an unchanged failure mode, an appropriate transport regime and uncertainty sufficient for the intended life claim.

Keywords: accelerated ageing; vat photopolymerisation; VPP; service life; acceleration factor; Arrhenius; post-cure; State 0; mechanism equivalence; lifetime extrapolation; hydrothermal ageing; weathering; qualification

Abstract

Printed photopolymers can continue to evolve after nominal printing and post-cure. Heat can advance residual reaction or physical ageing while simultaneously accelerating oxidation, hydrolysis, diffusion, extraction or damage. Water can temporarily plasticise a network, and subsequent drying can partly restore a measured property. Geometry changes diffusion length and oxygen access. These couplings make conventional accelerated-life inference hazardous when the accelerated exposure changes the state or dominant mechanism that it is intended to accelerate.

This review defines the validity conditions for accelerated ageing and life claims in printed photopolymers. It distinguishes screening acceleration from validated lifetime extrapolation and places the frozen initial material state, severity ladder, chemical signatures, transport regime, crack/failure morphology, property ranking, geometry and recovery protocol inside the acceleration model. Controlled VPP evidence shows that environmental response depends on resin chemistry and post-cure history [2], that water-induced and physical ageing can move properties in different directions [3], that hydrothermal severity can produce irreversible cracking and property loss [4], and that UV post-cure can change the initial mechanical state before ageing begins [5]. The established ER-072 framework further requires more than one severity level and mechanism-equivalent evidence before Arrhenius or dose-based extrapolation is attempted [1]. No universal acceleration factor, lifetime, activation energy or retained-property threshold is proposed.

1. Scope and ownership

ER-170 owns one engineering question: whether stressed laboratory data may be used to infer a time-dependent service claim for a printed photopolymer. It does not own oxidation, hydrolysis, water uptake, chemical resistance, fatigue or creep mechanisms. It does not replace exposure standards. It does not prescribe a universal durability test.

The article begins only after a candidate material and use environment have been defined. Its output is not a degradation mechanism; its output is a decision about the validity and limits of an acceleration model.

The central distinction is between **screening acceleration** and **life-claim acceleration**. Screening deliberately makes change happen faster to rank formulations, expose failure modes or identify sensitive variables. It may be useful even when the accelerated condition is not service-equivalent. Life-claim acceleration is stricter: it asserts a quantitative or bounded relation between accelerated time and service time. That relation requires evidence that the accelerated exposure has not changed the mechanism, state or failure criterion that governs service.

2. The post-cure confound

A printed photopolymer can enter an ageing test with residual reactive functionality, a non-equilibrated free-volume state, residual stress, incomplete solvent removal, spatial conversion gradients or a post-cure history that has not reached a stable baseline. Elevated temperature or further radiation can move those variables during the test.

The controlled ageing corpus explicitly warns that modulus or strength can rise through continued cure or physical ageing rather than through improved durability [1]. Menargues et al. demonstrate that UV post-curing changes the initial state in a resin-dependent way and can trade mechanical gains against shrinkage or stress evolution [5]. The starting state must therefore be frozen before an ageing clock acquires meaning.

If an accelerated exposure both advances cure and accelerates degradation, the measured property can represent the net of two opposing processes. A stable or increasing tensile modulus is then not proof that degradation is absent. Conversely, an initially adverse change can partly recover after conditioning. Life inference based on a single endpoint becomes structurally ambiguous.

3. State 0 is part of the acceleration model

ER-072 defines a defensible state sequence from stored resin through printed and post-cured baseline to exposed and recovered states [1]. ER-170 adopts only the inference consequence: the life model must name the initial state from which time is counted.

A valid State 0 record should include the material version and lot, printer and build orientation, exposure settings, washing/extraction history, post-cure spectrum and thermal history, conditioning, geometry and the measured properties relevant to the intended claim. Where residual conversion or network state can still change, the baseline should include an appropriate chemical or thermo-mechanical indicator.

Without State 0, two laboratories can run the same nominal ageing protocol on specimens that are at different positions in their post-cure trajectory. The difference will appear as an ageing effect even when the exposure chamber is perfectly reproducible.

4. Why temperature acceleration can change the mechanism

Temperature is commonly used to accelerate polymer ageing, but it changes more than reaction rate. It can move a material across or closer to its glass transition, change oxygen and water transport, change equilibrium sorption, accelerate evaporation or extraction, alter stress relaxation and activate reactions that are negligible at service temperature [1].

The controlled corpus therefore states that a single Arrhenius extrapolation is invalid when mechanism or state changes across the temperature range [1]. This is not a rejection of Arrhenius kinetics; it is a requirement that the process represented by the fitted rate constant remains the same process across the fitted range.

For printed photopolymers, the post-cure confound makes this especially important. An elevated-temperature condition may accelerate degradation while simultaneously increasing conversion or relieving residual stress. Hedayati et al. provide a controlled example in which high-temperature storage changes the chemical, dimensional and mechanical state of a photopolymer feedstock before printing [7]. A fitted slope can therefore combine several processes whose relative weights change with temperature.

5. Mechanism equivalence before time equivalence

Time equivalence follows only after mechanism equivalence has been established. ER-072 proposes comparison of chemical signatures, transport regime, crack morphology and property ranking across more than one severity before Arrhenius or dose-based extrapolation [1]. ER-170 turns that principle into a gate.

At minimum, an acceleration series should ask whether the same chemical products appear, whether the same failure location and crack morphology dominate, whether the same property hierarchy is retained and whether the transport regime remains comparable. If a new oxidation product, phase change, extraction mode, brittle crack path or surface-limited transport state appears only at the high-severity condition, that condition is not automatically a faster representation of service.

A changed mechanism does not make the experiment useless. It remains a screening or abuse condition. What fails is the conversion of its time scale into service time.

6. More than one severity level is required

One accelerated condition plus one control cannot establish a general acceleration law. At least a severity ladder is needed to determine whether response trends are continuous, whether the same mechanism persists and whether a model parameter is stable over the intended range.

The number and spacing of severities depend on the mechanism. Temperature, humidity, radiant exposure, chemical concentration and cycling amplitude are not interchangeable axes. When multiple stressors interact, a one-factor acceleration may not represent the combined service condition.

The purpose of multiple severity levels is not merely statistical. It is mechanistic: the experiment must reveal where the assumed acceleration relation stops being valid.

7. Property trajectories, not first-versus-last comparisons

A two-point retention number hides non-monotonic behaviour. A photopolymer can stiffen early through continued cure and then embrittle; a water-exposed material can soften rapidly and partially recover; a coating can retain bulk tensile properties while developing surface oxidation or cracks.

Schwarz et al. show that water-induced and physical ageing can move mechanical state in different ways [3]. Nugraha et al. show that hydrothermal severity and time can produce persistent cracking and major property loss in a printed bio-based photopolymer [4]. These examples support trajectory-based observation rather than universal numerical transfer.

For life modelling, the measured trajectory should include the failure criterion or property relevant to service. A lifetime inferred from colour drift cannot automatically become a mechanical lifetime, and a tensile-retention curve cannot automatically become a leak, fracture or optical-service claim.

8. Reversible and irreversible change

Immediate aged state and recovered state answer different questions. Water or another penetrant can depress modulus and glass-transition behaviour without permanent network damage; drying can restore part of the response. Aggressive drying, however, can itself anneal or further cure the network [1].

ER-170 therefore requires the recovery protocol to be part of the model whenever reversibility matters. A service claim for a wet-use device may legitimately use the equilibrium-wet state. A component exposed intermittently to solvent may need both exposed and recovered states. The choice must follow the service question rather than convenience.

A recovered property near baseline is evidence only for that property under the declared recovery procedure. It does not prove that chemical structure, fracture behaviour or future life has been restored.

9. Geometry and transport scaling

Acceleration models often use small coupons because they are convenient and statistically efficient. Geometry, however, changes surface-to-volume ratio, oxygen access, diffusion length, heat transfer and stress concentration. A thin coupon can equilibrate with water or oxygen long before a thick component reaches the same internal state.

The controlled ageing framework therefore treats geometry, thickness, orientation and exposed surface as part of transferability [1]. An accelerated condition that becomes diffusion-limited in a thick part but reaction-limited in a thin coupon cannot be related by one time multiplier without a transport model.

The same caution applies to lattices, enclosed channels, filled systems and layered assemblies. A service-life factor belongs to a represented geometry class, not automatically to a resin name.

10. Weathering and radiant acceleration

Laboratory light exposure must be described by spectrum, irradiance or radiant exposure, specimen temperature, chamber temperature, humidity or wet cycle, oxygen condition and geometry [1]. Calendar hours alone are not a radiation dose.

Zareanshahraki et al. demonstrate that weathering response is chemistry- and post-cure-specific in tested VPP systems [2]. Wallach et al. likewise show that a defined accelerated-weathering protocol can shift colour and translucency in printed orthodontic materials without establishing a universal mechanical or service-life endpoint [8]. ER-072 concludes that post-cure and weathering must be evaluated as an interacting system rather than reduced to a universal best post-cure [1]. That conclusion illustrates the discipline ER-170 requires: an acceleration factor cannot bridge conditions that were not experimentally connected.

ISO 4892-2 and ISO 4892-3 define laboratory light-source exposure methods [S1,S2]. They do not assign a universal VPP service life [1].

11. Hydrothermal acceleration

Increasing water temperature can accelerate sorption, diffusion, hydrolysis, extraction and crack development, but it can also change equilibrium uptake and the relative importance of reaction versus transport. The observed response must therefore be separated into immediate wet state, recovered state and irreversible chemical or structural evidence.

Nugraha et al. provide a controlled VPP example with long-term hydrothermal exposure at multiple temperatures [4]. Ariyo et al. distinguish continuous immersion from wet-dry cycling in an SLA wood-polymer composite [6]. These studies show why exposure mode is part of the mechanism; they do not establish a universal temperature acceleration factor.

ISO 62 and ISO 175 provide useful water-absorption and liquid-exposure method frameworks [S3,S4]. They are measurement/exposure standards, not lifetime-conversion standards.

12. Cycling is not equivalent to steady exposure

Thermocycling, wet-dry cycling and on-off radiation introduce repeated transitions, not merely a higher average severity. Interfaces can accumulate damage, residual stresses can reverse or relax, and diffusion fronts can repeatedly advance and retreat.

Kaynak Ozturk et al. show an application-specific thermocycling effect on the colour state of a printed dental assembly [9]. The result demonstrates that repeated thermal cycling can alter an observed endpoint, while also showing that adjacent layers and assembly state can dominate the apparent response. It does not provide a general cycle-to-year conversion.

When service itself is cyclic, a cycle-based claim may be appropriate, but the amplitude, dwell, transition rate, environment and failure criterion must be represented.

13. Acceleration-factor models

An acceleration factor is meaningful only for a declared response and a validated domain. In an Arrhenius-type model, a rate relation may be fitted to temperature when one dominant thermally activated mechanism remains valid across the range. The fitted parameter is not automatically transferable to another resin, geometry, humidity state or failure criterion.

Dose-based acceleration faces an analogous constraint: increasing radiant exposure rate can change oxygen inhibition, heating, penetration and photochemistry. Concentration-based acceleration can alter swelling or phase state. Mechanical-stress acceleration can change failure mode.

ER-170 therefore treats every acceleration factor as a conditional model with an evidence domain. Extrapolation beyond that domain requires a mechanistic justification or new validation data.

14. Statistical uncertainty and censored life data

Even a mechanism-valid acceleration experiment can support a weak life claim if variability is ignored. Specimen-to-specimen scatter, build position, lot, orientation and measurement uncertainty should be retained in the model. Failure-time data may be censored when specimens survive the test duration; treating those observations as exact failures or simply discarding them biases the result.

The statistical architecture should match the claim. A conservative lower-bound life statement, a median-life model and a probability-of-failure statement are different outputs. ER-170 does not prescribe one universal statistical model, because the correct model depends on the failure definition and data structure.

What is mandatory is that uncertainty in the accelerated data propagates into uncertainty in the service inference. A point estimate without a validity range is not a qualified life claim.

15. Validation against an intermediate condition

A powerful check is to reserve an intermediate severity or duration that is not used to fit the model and test whether the predicted state agrees with observation. Where feasible, service-like exposures should also be included as anchors even if they are too slow to reach failure during the development programme.

Prediction failure at the intermediate condition is evidence that the chosen model, mechanism assumption or State 0 definition is incomplete. Passing one intermediate check does not prove universal validity, but it is stronger than an unchallenged fit to the same data used for model construction.

Bridging after formulation, printer, post-cure or geometry changes should use the same logic: demonstrate that the new state lies inside the model's validity domain before carrying forward the acceleration factor.

16. Claim classes and permissible language

ER-170 separates four claim classes.

Screening claim: condition A produced faster or larger change than condition B under the tested protocol. No service-time conversion is implied.

Retention claim: a declared property remained within an acceptance criterion after a specified exposure. This is bounded to that exposure and state.

Acceleration-model claim: a validated relation links severity to response rate over a defined domain with mechanism equivalence demonstrated.

Service-life claim: the acceleration model is connected to a declared service environment, geometry, initial state, failure criterion and uncertainty rule.

Moving from one class to the next requires additional evidence. Language should not silently promote a screening result into a lifetime claim.

17. Requalification triggers

An existing acceleration model should be challenged after changes that can move State 0, mechanism or transport. These include formulation or stabiliser changes, different printer exposure, changed post-cure, thickness or orientation changes, new pigments/fillers, changed surface condition, altered service humidity or temperature, and changes in the failure criterion.

The required bridge can be focused if evidence shows that the changed system preserves the relevant mechanism and model parameters. If the change introduces a new state or failure mode, the previous factor is not automatically portable.

No universal percentage-change threshold is proposed. Requalification follows causal sensitivity, not administrative magnitude.

18. Conclusions

Accelerated ageing becomes a life test only when acceleration preserves the mechanism and the material state needed for the intended service inference. Printed photopolymers make this requirement unusually important because the accelerated condition can continue cure, change free volume, alter transport or relax residual state at the same time that it accelerates degradation.

The controlled VPP corpus establishes the essential safeguards: freeze State 0; separate continued cure from degradation; measure trajectories rather than endpoints; distinguish immediate and recovered states; represent geometry and transport; use more than one severity; compare chemical signatures, crack morphology and property ranking; and reject a simple time conversion when the failure mechanism changes [1]. Existing exposure standards provide controlled laboratory methods but not universal VPP service-life assignments [S1-S4].

No universal acceleration factor follows from resin identity alone. A defensible factor belongs to a declared formulation, process, initial state, geometry, exposure axis, failure criterion and uncertainty range. Where those conditions are not demonstrated, accelerated testing remains valuable for screening and qualification, but it must not be translated into unsupported service years.

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Standards

[S1] ISO 4892-2:2013/Amd 1:2021. Plastics - Methods of exposure to laboratory light sources - Part 2: Xenon-arc lamps.

[S2] ISO 4892-3:2024. Plastics - Methods of exposure to laboratory light sources - Part 3: Fluorescent UV lamps.

[S3] ISO 62:2008. Plastics - Determination of water absorption.

[S4] ISO 175:2010. Plastics - Methods of test for the determination of the effects of immersion in liquid chemicals.

Related Engineering Review boundaries

- ER-072 retains environmental-ageing and degradation-mechanism ownership.
- ER-039 and ER-069 retain time-dependent deformation and fatigue/damage mechanics.
- ER-041 retains chemical-resistance and solvent-uptake qualification.
- ER-170 owns only the validity and limits of accelerated-life inference across those mechanism domains.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. The paper is an engineering review and qualification framework, not an independent product comparison. No proprietary formulation, product ranking or universal operating window is provided.

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Data availability

No new experimental dataset was generated for this review.