

Fire Behaviour, Smoke and Toxic-Effluent Assessment of Printed Photopolymer Systems: Test Scale and Material State

Keeping ignition, heat release, smoke obscuration and effluent chemistry tied to the specimen state and fire scenario that produced them

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Abstract

Fire behaviour is not a single material property. Ignition time, heat-release rate, mass-loss rate, smoke production and toxic-effluent composition depend on imposed heat flux, ventilation, specimen thickness, orientation, backing, surface area and the actual cured formulation. Printed photopolymers add internal voids and anisotropic geometry, while additive-manufacturing studies show that geometry, porosity and composition can affect ignition and heat-release behaviour relative to conventionally produced specimens [6,7]. Bench-scale cone calorimetry is valuable for heat release and dynamic smoke, while single-chamber smoke testing and FTIR effluent analysis answer different questions. ER-390 therefore requires the fire scenario and specimen state to accompany every result and prohibits direct conversion of a bench-scale ranking into a full-product fire-safety claim. It also separates finished-material fire response from manufacturing fire prevention, which remains outside this review. [1-5]

Keywords: fire behaviour; photopolymer; cone calorimeter; smoke; toxic effluent; FTIR; reaction to fire

1. Fire response belongs to a test scenario

Heat release, ignition, smoke and toxic effluent are not intrinsic constants independent of geometry. ISO 5660-1 specifies controlled irradiance and oxygen-consumption calorimetry for heat-release rate and dynamic smoke, while ASTM E1354 provides a closely related oxygen-consumption framework. [1,2] Results are therefore reported with heat flux, orientation, specimen thickness, backing and ignition conditions.

2. Printed geometry and composition can change burning behaviour

Additive-manufacturing studies show that object geometry, internal spacing, porosity and material composition can change ignition and heat-release behaviour relative to conventionally produced specimens [6,7]. A recent SLA study reports a multi-scale porous design enabling in-situ alpha-ZrP growth in flame-retardant SLA-printed photopolymers [8]. These studies do not establish quantitative transfer to every VPP formulation; they establish that printed architecture and composition are variables that cannot be assumed fire-neutral. A cast plaque is therefore not automatically representative of a thin-walled or cellular printed part. Post-cure is retained as a controlled specimen-state variable, but ER-390 does not claim that a particular post-cure schedule changes fire response without direct evidence.

Table 1. Fire metrics answer different engineering questions.

Metric	Primary question	Do not infer
time to sustained ignition	how readily the specimen ignites under stated irradiance	full-scale ignition probability in all scenarios
peak and total heat release	rate and amount of combustion energy in the bench test	flame spread or compartment outcome without model/scale bridge
smoke optical density	obscuration produced in the specified apparatus	toxic potency of the smoke
effluent species/yields	which toxic gases are produced under the test condition	whole-product tenability without scenario integration

3. Smoke obscuration and toxicity are separate measurements

ISO 5659 measures optical density in a single-chamber configuration, whereas ISO 19702 provides FTIR methods for gases such as CO, CO₂, HCN, HCl and other fire-effluent species. [3,4] A low-smoke result does not establish low toxicity, and gas yields from one ventilation condition are not treated as universal.

4. Ventilation and heat flux alter decomposition chemistry

Polymer-fire studies using cone calorimetry coupled with FTIR show that toxic-effluent interpretation depends on the burning condition. [5] ER-390 therefore links gas concentrations or yields to the fire model, heat flux and ventilation state that generated them.

5. Scale transfer requires an explicit bridge

Bench-scale data are excellent for material comparison and fire modelling inputs, but geometry, flame spread, pooling, dripping and enclosure ventilation emerge at larger scale. A product-level claim requires either a relevant larger-scale test or a validated model/standard pathway. Ranking from the cone calorimeter is not itself that bridge.

Table 2. ER-390 qualification record.

Record	Why it is mandatory	Typical omission that invalidates comparison
specimen state	captures print, cure, thickness and orientation effects	comparing printed and cast specimens as equivalent
thermal exposure	defines imposed heat flux and ignition condition	reporting HRR without irradiance
smoke method	distinguishes dynamic smoke from chamber optical density	mixing incompatible smoke metrics
effluent method	ties species data to FTIR sampling and fire condition	toxicity claim from smoke density alone
scale statement	limits what bench data can support	product fire rating inferred from coupon ranking

6. Scope boundary with manufacturing safety

ER-390 covers fire, smoke and toxic-effluent response of finished materials and parts. Reactive-process safety, storage fire prevention and emergency controls during manufacture remain owned by ER-176 and are not replaced by these finished-material tests.

7. Qualification decision boundary

The accepted result is a scenario-specific fire-response dataset with material state, scale and measurement method fully declared. It may support product fire engineering, but it is not a universal flammability or toxicity label.

8. Replicates, conditioning and specimen variability

Additively manufactured parts can differ from conventionally produced plaques in build-related porosity and internal geometry [6,7]. Fire testing therefore records specimen mass, thickness, orientation and conditioning and uses enough replicates to determine whether ignition or peak heat-release variability is associated with manufacturing scatter. Outliers are investigated for voids, warpage or surface defects rather than discarded without cause.

Post-cure and ageing history are fixed as controlled specimen-state descriptors. ER-390 does not assume a particular fire-response effect from those variables without direct evidence; the requirement is that the tested material state be reproducible and explicitly identified.

9. Minimum fire-response reporting set

Table 3. ER-390 reporting set.

Block	Required report
specimen	printed/cast state, orientation, thickness, mass, cure and conditioning
fire exposure	apparatus, irradiance, ignition, orientation, backing and ventilation condition
thermal response	time to ignition, HRR metrics, total heat release and mass-loss behaviour
smoke/effluent	optical method plus gas-analysis method and species/yields where measured
scale statement	explicit limit on transfer from coupon/bench data to product or compartment behaviour

This record supports later fire engineering without implying that one small-scale method can replace the others. Heat release, smoke obscuration and toxic-effluent chemistry remain separate evidence streams that are combined only within a declared hazard model.

10. Coupled interpretation of heat release, smoke and effluent

A fire-response dataset becomes engineering evidence only when the measured channels are interpreted together without collapsing them into one score. Time to ignition describes the imposed thermal challenge needed to establish sustained flaming under the selected configuration; heat-release rate describes the energy-release history; mass loss constrains the rate at which condensed material is converted into gases, droplets or residue; smoke obscuration describes optical attenuation; and gas analysis identifies selected effluent species. None of these channels is a substitute for the others. A formulation can reduce peak heat release while increasing smoke, or delay ignition while producing a different effluent profile after ignition. ER-390 therefore treats each channel as a separate measurand linked by a common specimen and fire-scenario record. The integrated interpretation asks which mechanism changed, when it changed, and whether that change is relevant to the intended product scenario. [1-5]

11. Architecture, surface area and thermal feedback in printed parts

Printed geometry creates a transfer problem that is absent from a homogeneous plaque. AM experiments show that internal spacing, porosity and object geometry can change burning or heat-release behaviour [6,7]. Those results are not quantitatively transferable to every photopolymer, but they justify recording which geometric features a coupon does and does not represent. A qualification programme can therefore use a hierarchy: first a controlled material coupon for repeatable comparison, then a geometry-representative specimen when architecture is expected to alter heating or volatile escape, and finally the relevant product-scale method when flame spread, enclosure effects or installed configuration control the hazard. The bridge between levels must be demonstrated rather than assumed. [1,2,6,7]

12. Failure modes and acceptance logic

A useful fire qualification does not end with a ranking. It defines failure modes that would invalidate a transfer claim. Examples include early structural collapse that changes exposed area, sustained flaming after removal of the external ignition source when the application requires self-extinguishing behaviour, smoke production that exceeds the optical criterion of the product standard, or an effluent profile that introduces a species not represented in the screening configuration. The acceptance rule should therefore be written before testing and

should identify which metric is controlling, which metrics are supporting, and which observations trigger escalation to a larger-scale test. Replicate dispersion is part of the decision: a mean value that passes while individual printed specimens fail for different geometric reasons is evidence of an uncontrolled process, not a robust qualification. ER-390 therefore links fire acceptance to both the response distribution and the integrity of the manufacturing state record.

13. Qualification envelope and requalification triggers

Fire evidence is valid only inside the tested formulation, print architecture, specimen conditioning and test configuration. Experimental AM studies show that composition, flame-retardant distribution, porosity and geometry can change ignition or heat-release behaviour [6,7], while recent SLA work reports a multi-scale porous flame-retardant photopolymer design with in-situ alpha-ZrP growth [8]. ER-390 therefore treats changes in those demonstrated variable classes as potential requalification triggers. Cure history remains a controlled state descriptor and should trigger re-test when the producer cannot demonstrate equivalence; this review does not assert a universal fire-response effect for every post-cure change. Administrative changes with demonstrated material equivalence need not trigger a new programme. The resulting record is a scenario-specific qualification envelope, not a permanent material label.

14. Test-matrix design for isolating material-state effects

A qualification campaign should vary one controlling factor at a time where practical and use factorial combinations only when interaction is the question. A useful minimum matrix holds formulation and geometry constant while comparing post-cure states, then holds cure state constant while comparing representative geometries. If pigment, filler or flame-retardant loading changes, that change is treated as a new material state rather than pooled with the baseline. The matrix should include at least one reference material or internal control measured under the same instrument configuration so that day-to-day apparatus drift is not confused with formulation change. For cone-calorimeter work, imposed heat flux, ignition mode, specimen backing and orientation remain fixed inside a comparison set; for smoke or FTIR measurements, chamber or sampling configuration remains fixed. Cross-method comparisons are interpreted mechanistically rather than numerically equated because the methods observe different response functions. [1-5]

15. Data reduction, uncertainty and anomalous specimens

Fire data are time histories before they are summary numbers. Peak heat-release rate, total heat release, time to ignition, smoke-production rate and gas peaks should therefore retain the underlying curves or time-resolved data where possible. A single peak can be sensitive to filtering, sampling frequency and transient collapse. ER-390 recommends recording the data-reduction rule, baseline correction and any smoothing used, then retaining the raw signal sufficient to reproduce the reported metric. An anomalous specimen should be investigated against mass, thickness, voids, cure history and visible burning mode. If exclusion is justified, the reason and both pre- and post-exclusion summaries should be retained. This converts variability from an inconvenience into evidence about manufacturing control.

16. Engineering use of the resulting evidence

The final output is not a generic 'fire rating'. It is a structured evidence package that can feed a product-specific fire assessment. The package states which material state was tested, which scenarios were represented, which scenarios remain untested, and which response channels control the decision. It can support material down-selection, trigger reformulation, define a product-scale escalation test or supply input to a validated fire model. It cannot by itself establish compliance with a product standard whose geometry, installation or end-use configuration differs. This explicit use statement is important because it prevents bench-scale evidence from being detached from the boundary conditions that make it meaningful.

17. Scenario matrix and acceptance hierarchy

A useful fire-qualification plan separates three levels of acceptance. Level 1 is specimen validity: conditioning, dimensions, mass and mounting must satisfy the chosen method. Level 2 is response validity: ignition, heat-release, smoke and effluent signals must be internally consistent and free of instrument or handling artefact. Level 3 is engineering acceptance: the measured response must fall inside limits defined for the intended use. These levels should not be collapsed. A specimen can be method-valid yet unacceptable for service, and a product can meet one heat-release criterion while failing smoke or toxic-effluent criteria. The acceptance matrix should therefore list each response variable, the applicable method, the limit or decision rule, the uncertainty allowance and the action triggered by failure. Where no normative limit exists, the report should state that the result is comparative or exploratory rather than compliant. This hierarchy prevents a single favourable metric from being used as a surrogate for the whole fire response. [1-5]

18. Requalification after formulation or process change

Fire behaviour can change after modifications that appear minor in ordinary mechanical qualification. AM fire studies demonstrate sensitivity to material composition, flame-retardant content or distribution, porosity and geometric spacing [6,7], and recent SLA work reports a multi-scale porous flame-retardant photopolymer design with in-situ alpha-ZrP growth [8]. ER-390 therefore treats changes in these evidenced variable classes as potential requalification triggers rather than clerical formulation changes. Wall architecture and internal porosity are included because they directly change the tested geometry; cure history and residual processing state are retained as controlled descriptors whose equivalence must be demonstrated rather than assumed. A change-control record should identify the altered variable, compare the new state with the qualified state and justify whether bridging data are sufficient. Where equivalence cannot be defended, direct re-test is the conservative default. The decision should be recorded before testing so that a favourable result is not used retrospectively to redefine which changes were significant.

19. Minimal decision record

The final qualification record should be concise enough to audit without the raw laboratory notebook. It should identify the exact material revision, build and post-cure state; the specimen geometry and conditioning; the fire methods and instrument settings; the primary time-resolved outputs; the summary metrics and their uncertainty; the acceptance limits; all exclusions or anomalous specimens; and the resulting engineering disposition. It should also state which end-use scenarios are not represented. This record is the bridge between laboratory evidence and product governance. Without it, later users cannot tell whether a reported fire result belongs to the same material state or to a superseded one, and a technically sound experiment can become unusable evidence.

20. Limitations and research priorities

The strongest limitation is transfer from controlled specimen tests to printed products with complex geometry and installation. Research priorities are therefore paired-material studies that vary only print state or architecture, simultaneous heat-release/smoke/effluent measurement on the same specimens, and bridge studies from coupon to representative product geometry. Particular value would come from reporting the full time-resolved response together with post-test residue and failure morphology, because these data help distinguish dilution of a peak from a genuine change in decomposition pathway. Interlaboratory comparisons should include a common reference material and a common printed state so that apparatus and specimen effects can be separated. Until such evidence exists, ER-390 supports scenario-specific qualification envelopes rather than universal fire rankings for photopolymer families. [1-5]

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L.; ER-390 contains no comparative recommendation between commercial products.

Data availability

ER-390 is a literature-based engineering review; no new experimental dataset was generated.