

# Dielectric Breakdown and Insulation Ageing in Printed Photopolymers: Defects, Field Concentration, Temperature and Moisture

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## Abstract

Printed photopolymers can function as electrical insulators only when their dielectric state is qualified as a manufactured and aged system rather than inferred from nominal resin chemistry. This review separates short-time breakdown from service ageing and examines how voids, incomplete cure, interlayer interfaces, surface contamination, electrodes, thickness, temperature and moisture reshape the local electric field and failure path. Standard dielectric-strength measurements are treated as protocol-bound observables, not intrinsic constants. A non-compensatory qualification architecture is proposed that combines geometry and defect inspection, resistive and dielectric measurements, breakdown statistics, environmental conditioning and post-failure examination. The central conclusion is that high initial breakdown strength does not establish insulation reliability unless the printed state, field distribution and ageing history are jointly controlled.

**Keywords:** dielectric breakdown; electrical insulation; photopolymers; defects; field concentration; temperature; moisture; ageing; qualification; additive manufacturing

## 1. Significance and scope

Dielectric failure in a printed photopolymer is a coupled event involving material chemistry, geometry, field distribution and history. A nominally insulating resin may contain cure gradients, pores, interlayer interfaces, support scars, retained contaminants or moisture-sensitive domains after printing. ASTM D149 and IEC 60243-1 explicitly frame dielectric-strength testing around specified specimen and test conditions [1,2]. ER-263 therefore treats breakdown strength as a conditional engineering measurand and owns the qualification of printed photopolymer insulation under electrical, thermal and environmental stress. It does not own capacitive sensing, conductive-network design or complete device-level battery qualification.

### 1.1 Corpus boundary

Published incumbents are retained explicitly: ER-07 covers electrically functional photopolymer resins; ER-27 conversion metrology and spatial cure heterogeneity; ER-72 hydrothermal conditioning; ER-157 conductive-functional material architectures; ER-158 dielectric materials and field response; ER-170 accelerated ageing and life-claim validity; ER-181 post-cure process engineering; ER-184 competing defect mechanisms; ER-206 process-history effects; ER-231 statistical size effects, Weibull analysis and defect populations; and ER-240 related qualification architecture. ER-261 retains conductors and resistive elements, ER-262 capacitive-sensor calibration below destructive breakdown, ER-264 electrochemical electrodes, and ER-265 integrated battery components. ER-263 owns destructive insulation failure and pre-failure ageing of printed dielectric structures. Forward ER identifiers are scope boundaries only and provide no evidentiary authority.

## 2. Breakdown is local, not nominal

The applied voltage divided by nominal thickness is not necessarily the maximum electric field. Electrode edges, sharp corners, pores, inclusions, poorly bonded interfaces and thickness variation can concentrate field locally. A printed lattice or thin wall may therefore fail at a geometric or process-generated defect even when bulk dielectric spectroscopy appears acceptable. This distinction is especially important in additive manufacturing because the same CAD geometry can produce different local thickness and surface states after orientation, support removal and post-cure.

## 3. Printed-state defects and cure heterogeneity

Vat-photopolymerised dielectric composites demonstrate that filler loading, dispersion and matrix-to-filler bonding affect both printability and dielectric response [3]. For insulation qualification, the concern extends beyond designed filler: trapped gas, agglomerates, under-cured regions and layer boundaries can create permittivity and conductivity contrasts that distort field lines. The acceptance object must therefore be the finished printed and post-processed state. Density, optical appearance or nominal conversion alone cannot prove the absence of electrically critical defects.

## 4. Temperature and moisture

Temperature changes carrier mobility, segmental motion, leakage and dielectric loss; moisture adds a highly polar phase and can increase conductivity or promote interfacial processes. Evidence from epoxy mould compounds shows that wet/dry condition, temperature and test frequency can materially alter breakdown behaviour [4]. IEC 60505 accordingly treats electrical insulation ageing as potentially multifactorial, including electrical, thermal, mechanical and environmental stresses [5]. For printed photopolymers, humidity conditioning and thermal history should therefore be part of the declared test state whenever service exposure makes them credible.

## 5. Short-time strength versus ageing

A short-time ramp-to-breakdown test answers a different question from whether an insulation system survives repeated or prolonged stress. High initial dielectric strength can coexist with ageing driven by heat, moisture, partial discharge, surface tracking, contamination or cyclic mechanical damage. Qualification should separate baseline strength, proof or endurance testing where applicable, and environmental ageing. Data from one mode should not be substituted for another. In particular, a single dry-room breakdown value should not be promoted to a service-life claim.

## 6. Measurement architecture

A defensible programme begins with dimensional metrology and defect inspection, then measures volume or surface resistive properties where relevant, dielectric response over the intended frequency/temperature range, and finally destructive breakdown on specimens representative of the final geometry. IEC 62631-3-1 provides a general DC method for volume resistance and volume resistivity [6]. Breakdown reporting should include electrode geometry, specimen thickness, conditioning, surrounding medium, voltage waveform, ramp rate, failure criterion and number of specimens. Failure locations should be mapped back to manufacturing features.

## 7. Statistical treatment

Breakdown is a stochastic extreme-event property. Mean voltage alone can hide a broad weak-tail distribution caused by sparse defects. Report individual values and a justified distributional analysis, with specimen count and censoring rules declared before testing. If a Weibull model is used, its fit and confidence intervals should be shown rather than reporting only a characteristic strength. A process change that raises the mean but worsens the lower tail may reduce real insulation margin.

## 8. Non-compensatory qualification matrix

No weighted score should allow a high dry dielectric strength to compensate for failure after moisture, a defect population, or an unacceptable weak tail.

| Gate                         | Required evidence                                            | Failure meaning                           |
|------------------------------|--------------------------------------------------------------|-------------------------------------------|
| G1 Printed state             | Thickness/orientation, cure and post-cure, defect inspection | Test object is not defined                |
| G2 Baseline electrical state | Resistivity/dielectric data under declared conditions        | Leakage or polarization state unbounded   |
| G3 Breakdown                 | Protocol-defined destructive test with specimen-level data   | No supported insulation strength          |
| G4 Environment               | Temperature/moisture conditioning representative of use      | Service transfer unsupported              |
| G5 Ageing                    | Electrical/thermal/environmental history where relevant      | Initial strength mistaken for durability  |
| G6 Failure analysis          | Location and morphology linked to geometry/process           | Root cause and change control remain open |

## 9. Minimum reporting set

Report resin and lot, formulation state if modified, printer and wavelength, build orientation, layer thickness, support strategy, wash and post-cure, specimen dimensions, electrode material and geometry, conditioning temperature and humidity, surrounding medium, voltage waveform and frequency, ramp or dwell protocol, leakage-current or trip criterion, specimen count, every breakdown result, failure location, visual or microscopic post-failure observations and any statistical model. When comparing builds, report whether geometry, cure and conditioning were held constant.

## 10. Knowledge boundary

The available evidence supports a qualification architecture, not universal voltage limits or acceleration factors. Photopolymer chemistry, fillers, conversion, thickness and geometry vary too widely for a single dielectric-strength or humidity derating value. The most defensible engineering rule is therefore state-specific: establish the printed baseline, deliberately stress the mechanisms that can change that state, and require the weakest relevant gate to remain acceptable.

## 11. Conclusions

Printed photopolymers should be qualified as electrical insulation systems, not as datasheet resins. Breakdown is governed by the highest local field and the weakest local material state. Defects, temperature and moisture can each shift that state, while ageing can create failure pathways that are absent in a short baseline test. A credible release decision therefore combines manufactured-state evidence, protocol-controlled electrical measurements, environmental conditioning, statistics and failure analysis. Initial strength is necessary but not sufficient evidence of insulation reliability.

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