

Neutron-Detection Materials and Structures Enabled by Photopolymerisation: Converter Loading, Light Collection and Discrimination

Separating neutron conversion, scintillation, optical transport and background rejection in printed detectors

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Abstract

Additive manufacturing can place neutron-conversion materials and scintillating volumes into geometries that are difficult to machine, but the response of a neutron detector depends on more than converter loading. A neutron must interact in the converter, reaction products must deposit useful energy in the scintillating region, generated photons must reach the photosensor, and the event must be discriminated from gamma-ray and other backgrounds. This review treats those stages separately and focuses on photopolymerisation-compatible routes while using adjacent additive-manufacturing evidence when it defines the detector physics. Fast-cured organic scintillator formulations have demonstrated neutron-gamma pulse-shape discrimination; boron-loaded fast-cured plastics demonstrate thermal-neutron-sensitive chemistry; and 3D-printed lithium-6-containing scintillator structures illustrate how spatially designed converter distributions can support event discrimination. The engineering conclusion is that converter mass fraction alone is an inadequate optimisation variable. Required reporting should connect isotope, chemical form, particle size, spatial distribution, optical attenuation, scintillation yield, event-selection method, neutron spectrum, gamma background and geometry.

Keywords: neutron detection; photopolymer; scintillator; lithium-6; boron-10; pulse-shape discrimination; light collection; additive manufacturing

1. Significance and scope

Neutron detection in polymer-based systems usually requires a conversion or scattering mechanism plus an optical or electrical readout. Thermal neutrons are commonly addressed with high-capture-cross-section nuclides such as ^6Li or ^{10}B , whereas fast-neutron detection can exploit proton recoils in hydrogenous scintillators and pulse-shape discrimination. Photopolymerisation offers geometric control, but geometry cannot compensate for an unbalanced converter-scintillator-optics system.

ER-424 owns neutron-converter loading, capture geometry, light collection, discrimination and system efficiency; ER-423 separately owns scintillator-intrinsic optical response and fast-timing qualification.

2. Converter loading is not detector efficiency

Adding more converter increases the probability of neutron interaction only until other terms begin to dominate. Converter particles can scatter or absorb scintillation light, interfere with cure, sediment during printing and place reaction products too far from the scintillating phase. For particulate converters, particle size and spatial distribution therefore matter as much as nominal mass fraction.

The relevant chain is neutron capture or recoil $\rightarrow$ charged-particle energy deposition $\rightarrow$ scintillation $\rightarrow$ photon transport $\rightarrow$ sensor detection $\rightarrow$ event classification. A material claim attached to only one stage should not be promoted to a detector-efficiency claim.

3. Photocurable and fast-cured scintillator evidence

Frandsen and co-workers demonstrated photocurable organic scintillators capable of neutron-gamma pulse-shape discrimination under 405 nm curing conditions [1]. Ruland and Febraro subsequently reported a boron-loaded fast-cured plastic organic scintillator with measurable thermal-neutron capture light output [2]. Together, these studies establish that fast-curing chemistry can support both discrimination-oriented organic scintillation and converter-loaded neutron sensitivity.

The processing window remains formulation-specific. Boron-bearing species, lithium salts or particles may alter absorption, viscosity, polymerisation kinetics and optical clarity. Cure characterisation must therefore be repeated after converter addition rather than inherited from the base scintillator.

4. Geometry as a detection variable

Barr and co-workers reported a neutron-sensitive detector using 3D-printed scintillators containing ^6LiF and combined the printed sensor with a time-resolving camera and event-discrimination algorithm [3]. Although their fabrication route was fused deposition rather than photopolymerisation, the detector architecture is directly informative: converter placement, scintillation transport and event morphology can be co-designed.

For photopolymerisation, similar geometric freedom could be used to control converter-rich and optically clear regions, create channels for light collection or construct repeated cells. Such concepts must be evaluated against printing resolution, interfacial optical losses and the escape ranges of charged reaction products. Geometric complexity is useful only when it improves a measured detector metric.

5. Background discrimination and calibration

Neutron detection is generally performed in the presence of gamma rays and other backgrounds. Pulse-shape discrimination, spatial topology, coincidence, timing or energy cuts can all contribute to classification. Reported neutron efficiency therefore depends on the event definition. A detector that rejects background aggressively can show excellent purity while losing true neutron events.

Qualification should include the neutron energy spectrum, source geometry, moderation state, gamma background, acquisition threshold and discrimination algorithm. Efficiency, false-positive rate and energy-dependent response should be separated. A single count-rate increase in a neutron field is not sufficient evidence of neutron-specific detection.

Qualification axis	Required evidence	Failure if omitted
Converter identity	Nuclide/compound, enrichment where applicable, particle size, loading and spatial distribution	Capture probability cannot be related to a defined converter state
Capture geometry	Detector thickness, converter distribution and neutron spectrum/energy stated or modelled	Higher loading may be credited with efficiency that actually arises from geometry or spectrum
Light collection	Scintillation/secondary light path, transparency/scattering, surface state and photosensor coupling	Capture events may occur without producing a detectable optical signal
Discrimination	Gamma field, energy window, PSD/acquisition method and decision threshold reported	Neutron response can be confused with gamma sensitivity or acquisition settings
System efficiency	Absolute or relative efficiency, calibration/reference detector, background and ageing state reported at device level	A resin or converter loading can be incorrectly labelled as detector efficiency

Table 1. Domain-specific qualification matrix for photopolymer-enabled neutron-detection structures.

6. Device-level verification

6.1 Thermal-neutron and fast-neutron detection are physically different problems

Thermal-neutron detection usually relies on a capture nuclide such as ^6Li or ^{10}B that converts the neutron into energetic charged particles, whereas fast-neutron detection in organic scintillators is commonly dominated by proton recoil. A formulation intended to do both must therefore preserve two response channels and still discriminate them from gamma interactions. The capture-nuclide concentration, its chemical form and spatial distribution affect thermal-neutron efficiency, while hydrogen content and scintillation kinetics govern much of the fast-neutron response. Reporting only total neutron count rate conceals these distinctions and prevents transfer between spectra.

6.2 Capture loading creates a coupled efficiency–light-transport problem

Adding a neutron-converter species increases capture probability only if the reaction products deposit useful energy in the scintillating phase and the resulting light can be collected. High loading can reduce optical transmission, disturb cure, change density and create non-uniform response. Doležal and co-workers demonstrated a fast-cured boron-loaded organic scintillator with thermal-neutron sensitivity, but the result also illustrates why capture response must be calibrated in electron-equivalent light output rather than inferred from boron content alone [2]. The engineering optimum is therefore not the maximum converter fraction; it is the loading and geometry that maximise useful detection probability at acceptable optical and discrimination performance.

6.3 Photocurable formulations can support PSD, but cure chemistry participates in the detector physics

Kim and co-workers demonstrated 3D-printable PVT-based photocurable scintillators with neutron/gamma pulse-shape discrimination and additional sensitivity routes using lithium- and boron-containing components [4]. Chandler and co-workers separately showed that fluorescent dopants influence the vat-photopolymerisation working curve [5]. Together these results show that detector formulation and print process cannot be optimised sequentially. Initiator absorption, fluor absorption and cure-limiting dyes shape the optical field used to manufacture the detector, while the cured network composition determines scintillation transfer and PSD. The required design object is the combined resin–exposure–geometry state.

6.4 Segmentation changes both spatial resolution and calibration burden

Printed arrays and pixelated detectors can exploit additive manufacturing to integrate optical separators, alignment features and complex channel geometries. Recent work on photocurable pixelated scintillator arrays demonstrates the manufacturing advantage and the ability to retain per-pixel neutron/gamma discrimination [6]. The penalty is that every pixel can acquire a different optical path, coupling efficiency or threshold. Array qualification therefore requires channel-by-channel gain or light-output calibration, cross-talk measurement and dimensional inspection. A detector that performs well as a monolithic coupon should not be assumed to preserve the same PSD figure of merit after segmentation.

6.5 Discrimination metrics must be tied to energy window and acquisition chain

PSD figure of merit is not a universal material constant. It depends on deposited-energy range, integration windows, photosensor, electronics, thresholding and pulse-processing method. Light yield is similarly geometry- and readout-dependent. For cross-study comparison, the energy or electron-equivalent window and the calculation method should be reported with the value. Detector-level neutron efficiency should additionally state the source spectrum, moderation and geometry. Without those conditions, apparent improvements in PSD or efficiency can arise from acquisition choices rather than from the printed material.

6.6 Charged-particle escape length couples capture chemistry to microstructure

For converter-loaded materials, neutron capture is only the first step. The reaction products must deposit sufficient energy in or near the scintillating phase. If converter particles or domains are too large, a fraction of the charged-particle energy can be lost within a non-scintillating converter grain; if they are too sparsely distributed, capture efficiency falls. Fine dispersion can improve energy transfer but may increase optical scattering or interfere with cure. This creates a microstructural optimisation problem in which converter-domain size, spatial distribution and optical transparency all matter. The correct characterisation therefore includes converter morphology and dispersion, not only bulk weight fraction. Monte Carlo transport can help interpret the trade-off, but the model should use measured geometry and composition and should be validated against a calibrated neutron spectrum.

6.7 Detector efficiency is a system metric, not a resin property

Intrinsic detection efficiency depends on interaction probability and event-selection criteria, while absolute efficiency additionally includes source geometry, moderation, solid angle, thresholds and dead time. A printed neutron-sensitive resin can therefore be compared meaningfully only when the measurement geometry and analysis chain are reported. For imaging systems, spatial resolution and cross-talk may matter as much as total efficiency. For safeguards or mixed-field monitoring, gamma rejection at the operating threshold can dominate practical performance. Qualification should therefore define the detector mission first and then select the appropriate combination of efficiency, PSD, light yield, spatial resolution and timing metrics. This prevents a high capture count under one laboratory configuration from being misrepresented as a generally superior neutron detector.

7. Minimum qualification framework

The minimum material description should include converter isotope and enrichment, chemical form, loading basis, particle size, density and spatial distribution; scintillator chemistry; cure and post-cure; and optical attenuation. Detector reporting should add geometry, photosensor and coupling, neutron field, gamma background, threshold, discrimination method and uncertainty.

Useful staged measurements are: cure response versus converter loading; transmission or attenuation length; gamma-only response; neutron-only or neutron-dominant calibration; mixed-field discrimination; and repeated measurements after ageing or radiation exposure. These controls allow failures to be assigned to conversion, scintillation, optical transport or classification rather than hidden inside a single “efficiency” number.

8. Engineering conclusions

Photopolymerisation can contribute to neutron-detector design by enabling fast-cured scintillating materials and spatially engineered converter architectures. The optimisation target is not maximum converter fraction. It is the product of interaction probability, useful energy deposition, scintillation efficiency, light collection and background discrimination under a defined neutron spectrum. A credible printed detector therefore needs coupled materials, optical and event-level qualification.

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Competing interest

Juan Segurola is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and related additive-manufacturing technologies. This review is an engineering analysis and does not constitute a product-performance claim or a device qualification.