

Optical, Photonic, Luminescent, High-Refractive-Index and Radiation-Functional 3D Materials: Scattering, Attenuation, Spectral Response and Qualification

A State-Resolved Framework for Transmission, Refraction, Emission, Detection, Attenuation and Optical Ageing

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Statement of Significance

Optical and radiation-functional additive-manufacturing materials are routinely described by attractive but incomplete labels: transparent, high-index, fluorescent, scintillating, radiopaque or shielding. None identifies the measurement boundary that determines whether a printed component works. A transparent plaque can fail as a lens because surface figure, birefringence or internal index gradients distort the wavefront. A bright fluorophore can fail in a thick part because excitation is screened, emission is reabsorbed or oxygen and cure dose alter the emitting state. A dense high-atomic-number filler can increase calculated attenuation while porosity, segregation, streaming paths or an unsuitable neutron interaction reduce component effectiveness. This review establishes an auditable chain from wavelength-, energy- and geometry-resolved requirements through constituent identity, dispersion, print exposure, transformation, interfaces, ageing and final-system verification. It separates transmission from haze, index from optical power, photoluminescence from scintillation, and calculated attenuation from measured shielding. Public 3Dresyns information is used only to map candidate material families and one manufacturer-declared plastic-scintillator route; it is not treated as independent evidence. The qualifying object is the conditioned material–process–geometry–spectrum–detector system, not the filler name or an isolated coupon.

Abstract

Additive manufacture can shape fused silica, transparent polymers, high-refractive-index nanocomposites, gradient-index structures, photonic crystals, fluorescent and quantum-dot architectures, scintillators, radiation collimators and mixed-field attenuators. The same interactions that create function also constrain manufacturing. Absorbers and high-index particles reshape the cure field; fluorophores and quantum dots can compete with photoinitiators; interfaces scatter; residual stress creates birefringence; polishing changes both dimensions and optical loss; scintillation output depends on energy deposition, transport, coupling and detector response; high-Z loading can increase photon attenuation while viscosity, voids and spectral hardening change the delivered component. This qualitative engineering review defines six distinct functions—transmission, refractive or diffractive control, luminescent conversion, scintillation detection, photon attenuation and neutron attenuation—and links each to appropriate evidence. It develops route-specific invalidation gates for vat photopolymerization, two-photon polymerization, direct ink writing, material extrusion and green-to-glass or ceramic transformations. It also defines spectral measurement records, uncertainty, accelerated ageing and change control. An applied example compares monolithic and modular routes for a compact X-ray inspection head containing a collimator, scintillator, light guide, optical isolator and protective housing. The analysis shows why independently optimized and verifiable zones usually outperform a nominally multifunctional body. The review concludes that optical or radiation function is a system response: composition enables it, but state, spatial distribution, interfaces, geometry, source and detector determine whether it survives qualification.

Keywords: *additive manufacturing; transparent materials; haze; refractive index; gradient index; photonic crystal; fluorescence; quantum dots; scintillator; X-ray; gamma attenuation; neutron shielding; tungsten; boron carbide; spectral response; optical ageing; qualification*

1. Purpose, scope and governing distinctions

This paper makes optical, photonic, luminescent and radiation-functional nano/micron materials selectable as industrial component systems. It has eight objectives. First, it separates functions that are often hidden beneath the words *transparent*, *optical* or *shielding*. Second, it identifies the material and process states that connect a powder, dye, quantum dot or dense filler to a delivered response. Third, it explains absorption, scattering, refraction, emission and ionizing-radiation interaction without turning screening equations into universal predictors. Fourth, it compares retained-polymer, printed-green-body, transformed-glass or ceramic and hybrid routes. Fifth, it defines no-go gates for each route. Sixth, it establishes wavelength-, energy-, direction-, geometry- and detector-resolved measurement records. Seventh, it demonstrates selection through a component-scale industrial example. Eighth, it defines a linked qualification genealogy and change-control system.

Corpus-level additive-manufacturing technology selection is inherited from ER-139; this review owns only optical, photonic, luminescent and radiation-function evidence for applying that framework.

Electrical conduction, electrostatic-control, electromagnetic-shielding and thermal-transport functions are owned by ER-157, while dielectric, ferroelectric, piezoelectric and magnetic functions are owned by ER-158; this review does not reopen those domains.

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], and ISO/ASTM 52927 links main AM characteristics to test methods [3]. These standards anchor manufacturing language and quality-system expectations, but they do not make two nominally transparent resins optically equivalent or two tungsten-filled objects equally attenuating. Function depends on the tested state and system boundary.

Six distinctions govern the review. **Transmission** is the fraction of incident radiation reaching a defined acceptance aperture or integrating sphere; it must be separated into spectral, directional, specular and diffuse components when the use requires that separation. **Refractive or diffractive control** concerns phase, optical path, wavefront, dispersion and surface or voxel geometry, not simply visual clarity. **Photoluminescent conversion** uses optical excitation and must report excitation, emission, quantum yield or efficiency, concentration, thickness and ageing. **Scintillation** converts ionizing-radiation energy into detectable light and adds energy deposition, light yield, decay, afterglow, radiation damage, coupling and readout. **Photon attenuation** covers X-ray or gamma interactions over a declared energy spectrum and geometry. **Neutron attenuation** involves energy-dependent scattering and capture and cannot be inferred from photon density or atomic number alone.

The scope covers component-scale transparent and translucent polymers, silica and glass routes, filled photopolymers, two-photon-polymerized (2PP) micro-optics, direct-ink-written (DIW) structures, fluorescent, rare-earth and quantum-dot systems, plastic and inorganic scintillators, radiopaque markers, radiotransparent structures, high-Z photon attenuators and hydrogenous or neutron-absorbing composites. The public 3Dresyns nano/micron page maps candidate silica, glass, rare-earth, quantum-dot, fluorescent, scintillator, high-refractive-index and high-Z families [14]. Its PSci PPO page declares a photopolymer containing wavelength-shifting species for plastic-scintillator development and notes formulation–printing–geometry dependencies [15]. These are manufacturer declarations, not independent proof of a component specification.

Concrete, cement, geopolymers, regolith, building envelopes and other macroscopic construction or high-volume civil applications are excluded. The paper does not prescribe universal filler fractions, optical doses, polishing sequences, attenuation thicknesses, occupational limits or acceptance values. It does not authorize use in medical diagnosis, radiotherapy, nuclear safety, critical shielding or personnel protection. Those applications require the relevant regulated design controls, qualified specialists, calibrated facilities and jurisdiction-specific approval.

2. Begin with the interaction and decision, not a material adjective

“Clear” is a visual observation, not an optical specification. A transmission requirement states wavelength band, incidence angle, polarization where relevant, source numerical aperture, accepted output angle, path length, surface condition, temperature, humidity and permissible image or power degradation. ISO 13468-1:2019 measures total luminous transmittance of substantially transparent, colourless plastics under defined conditions; its scope does not automatically cover fluorescent plastics, strongly scattering materials or arbitrary three-dimensional optics [4]. ISO 14782:2021 addresses haze for transparent plastics [5]. These methods are useful only when the specimen and decision match their scopes. A low-haze plaque at visible wavelengths does not qualify a near-infrared waveguide, an ultraviolet window or a curved lens.

A refractive requirement identifies wavelength-dependent refractive index, dispersion, homogeneity, birefringence, optical-path difference, wavefront error, surface figure, roughness and environmental range. ISO 489:2022 provides methods for refractive index of plastics [6], but the designer must still declare whether the part is isotropic, oriented, graded or absorbing and whether the result represents bulk material, a printed road, a voxelized microstructure or an assembled optic. A high refractive index can shrink an optical element or increase phase delay; it can also increase Fresnel reflection and particle–matrix scattering if interfaces are not controlled.

Colour and appearance require a measurement condition rather than a colour word. ISO/CIE 11664-4:2019 defines CIE 1976 L*a*b* colour space calculations [7]. Illuminant, observer, geometry, backing and fluorescence condition remain part of the record. A colour difference measured with one instrument geometry can miss angular scattering or metamerism that matters in use.

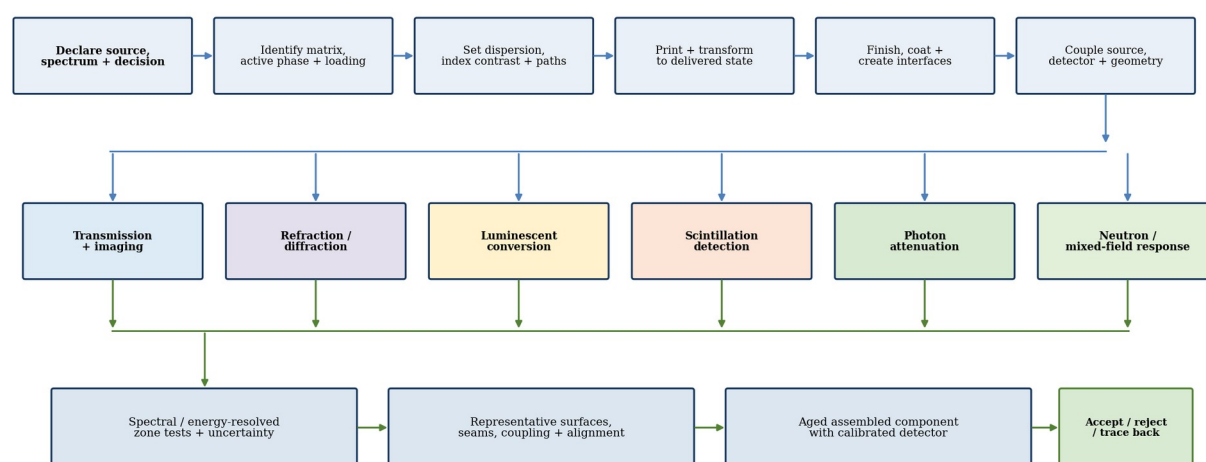
A luminescent requirement declares excitation spectrum, emission spectrum, absorbed-photon basis, absolute or relative quantum efficiency, lifetime, concentration, thickness, temperature, oxygen and ageing. IEC 62607-3-1:2014 describes measurement of quantum efficiency for luminescent nanomaterials [8]. IEC TS 62607-3-5:2026 addresses efficiency of quantum-dot light-conversion films by luminance-meter methods [9]. Neither standard turns an uncharacterized printed three-dimensional body into a qualified emitter; self-absorption, waveguiding, surface escape and local cure environment can make the body different from a film.

A scintillation requirement begins with radiation type and spectrum, deposited energy, geometry and readout. It specifies light output or photoelectron yield, spectral match, decay time, afterglow, timing or energy resolution, spatial resolution, dose rate, accumulated dose, temperature and acceptable background. IEC 62372:2021 covers measurement of light output and intrinsic resolution of housed scintillators [10]. A powder’s photoluminescence under ultraviolet excitation is not evidence of scintillation under X-rays, gamma rays, neutrons or charged particles.

An attenuation requirement names the radiation field and the protected or imaged quantity. Photon requirements include energy spectrum, beam geometry, narrow- or broad-beam condition, field size, build-up, permitted transmission and secondary-radiation concerns. Neutron requirements include source spectrum, moderation, scattering, capture products and downstream dose or detector response. NIST’s XCOM database provides photon cross sections and mass attenuation coefficients for elements, compounds and mixtures over a broad energy range [13]. It is a calculation resource, not a substitute for density, composition and geometry measurements on a printed component.

Table 1. Six functions and the evidence that closes each decision

Function	Primary outputs	Mandatory descriptors	Component-level closure	Invalid substitution
Transmission and imaging	Spectral total/specular/diffuse transmittance, haze, modulation transfer or image quality	Wavelength; path length; incidence; aperture; surface state; polarization; temperature; uncertainty	Power or image delivered through final geometry after conditioning	Visual clarity or one plaque value
Refractive, diffractive or photonic control	Index and dispersion, wavefront, phase, focal response, bandgap, insertion loss	Wavelength; direction; polarization; voxel/surface geometry; homogeneity; alignment	Optical function in the assembled path with tolerances and interfaces	Nominal filler index or CAD geometry
Photoluminescent conversion	Excitation/emission spectra, quantum yield or efficiency, lifetime, colour, stability	Absorbed-photon basis; concentration; thickness; atmosphere; temperature; ageing	Emitted flux/spectrum from the final body under the real excitation field	Brightness photograph or dye identity
Scintillation detection	Light or photoelectron yield, decay, afterglow, energy/timing/spatial response	Radiation type/energy; dose rate; geometry; optical coupling; detector; electronics; temperature	Calibrated detector response and background after accumulated dose	UV photoluminescence or scintillator loading
Photon attenuation or collimation	Spectral transmission, attenuation, scatter, penetration and spatial response	Composition; density; energy spectrum; beam/build-up geometry; path map; uncertainty	Measured field or image through the final component	XCOM value, atomic number or mass alone
Neutron moderation, capture or attenuation	Energy-dependent transmission, capture, secondary fields and detector/dose response	Neutron spectrum; hydrogen/absorber content; thickness; geometry; secondary radiation	Calibrated downstream response in representative mixed field	Photon attenuation or bulk density alone



Function emerges from material state, spatial distribution, surfaces, geometry, spectrum, source and detector.

Figure 1. State-resolved chain from spectral or radiation requirement to an accepted component.

This chain is reversible for root-cause work. Low detector signal does not first justify more scintillator. The deficit may arise from insufficient energy deposition, concentration quenching, self-absorption, surface escape, a spectral mismatch, an air gap or electronic saturation. Excess X-ray leakage does not first justify a thicker CAD wall. It may arise from density loss, a seam, material segregation, an oblique streaming path or beam hardening. Diagnosis moves backward from system response to interface, conditioned part, transformation, build, formulation and received material.

3. Material identity and states that must not be conflated

Material identity includes composition, stoichiometry, crystal or amorphous phase, dopants, impurity profile, particle-size distribution, morphology, surface chemistry, agglomeration, moisture, optical constants, density, lot and storage history. ISO/TR 13014:2012 links physicochemical characterization of engineered nanoscale materials to toxicological assessment [12]. It is a useful prompt for identity and exposure-relevant attributes, not a claim that one characterization set proves optical function or safety.

At least nine states are separated. The **received state** is the neat resin, powder, dye, phosphor, quantum dot, glass precursor or compounded pellet. The **formulated state** includes matrix, solvent, binder, photoinitiator, inhibitor, dispersant, stabilizer and active loading. The **printable state** adds temperature, shear history, residence time, oxygen, humidity and sedimentation age. The **as-shaped state** may be a cured polymer, solvent-bearing deposit or green body. The **transformed state** follows post-cure, drying, debinding, sintering, annealing, pyrolysis or infiltration. The **finished optical state** includes grinding, polishing, coating, blackening and cleaned surfaces. The **interfaced state** includes adhesive, optical couplant, reflector, cladding, detector and housing. The **irradiated or excited state** depends on source spectrum, intensity, dose rate and accumulated dose. The **conditioned service state** includes heat, humidity, mechanical load, cleaning and ageing. A property in one state cannot be silently assigned to another.

For transparent nanocomposites, particle size alone is insufficient. Scattering depends on size relative to wavelength, refractive-index contrast, agglomerate size, volume fraction, spatial correlation, shape and absorption. A nanoscale primary particle can become an optically damaging micron-scale aggregate. Matching the particle and matrix refractive indices at one wavelength and temperature does

not ensure a match over a band or after cure shrinkage. Orange Kedem et al. demonstrated that near index matching can enable additively manufactured solid diffractive optical elements [23]; the result supports a design mechanism, not a universal formulation recipe.

For fused-silica or glass routes, the printed state may be an organic nanocomposite whose optical function emerges only after debinding and sintering. Kotz et al. demonstrated transparent fused silica from a printed silica nanocomposite [19] and later extended two-photon processing to transparent fused-silica microstructures [20]. The evidence establishes route feasibility while also exposing the state transition: polymer content, green density, shrinkage, hydroxyl or impurity content, bubbles and surface finish determine whether the transformed object approaches glass-like performance.

For luminescent systems, chemical identity and environment are inseparable. A dye, carbon quantum dot (CQD), perovskite quantum dot or rare-earth ion can change absorption, emission, lifetime and stability with aggregation, ligand loss, oxygen, water, acidity, radicals, cure temperature and matrix polarity. Plé et al. demonstrated photopolymer-confined CQDs for fluorescent two- and three-dimensional printing [29]. Jeon et al. demonstrated direct-ink-written perovskite-quantum-dot/polymer architectures [28]. Both are bounded demonstrations. Neither proves that an arbitrary commercial quantum dot will survive another resin, wavelength, heat history or service environment.

For scintillators, distinguish the activator-bearing phase, the binder or matrix, porosity, optical transport and detector interface. Dosovitskiy et al. printed a complex inorganic green body and transformed it to a polycrystalline scintillator [32]. Weber et al. additively manufactured a segmented plastic-scintillator detector with integrated architecture [33]. Elattar et al. reported a water-stable cadmium-doped perovskite/polymer composite for high-flux X-ray scintillation [34]. These studies occupy different states and system boundaries; light yield, spatial response and stability cannot be compared by material label alone.

For attenuation, nominal weight fraction is not local areal density. The record distinguishes mass fraction, volume fraction, bulk density, void fraction, wall thickness and the integral of density along each relevant ray. High-Z particles can settle or be filtered by a nozzle. Tungsten powder can form dense metal through one route or a lower-density composite through another. Boron carbide can capture neutrons but its dispersion, hydrogenous matrix, neutron spectrum and secondary products matter. Composition enables interaction; the delivered path distribution determines performance.

4. Transmission, absorption, scattering and haze

Spectral transmittance is a system ratio, not a single adjective. The measurement records incident spectral irradiance or flux, detector spectral responsivity, aperture and collection geometry, specimen thickness, incidence, polarization, temperature and surface condition. Total transmittance collected by an integrating sphere can remain high while image-forming specular transmittance falls because forward scatter broadens the angular distribution. Conversely, a narrow-aperture instrument can report low transmission for a diffuser designed to redirect rather than absorb light.

Absorption and scattering must be separated where the decision depends on their causes. Absorbed power becomes heat, photochemistry or luminescence. Scattered power may remain useful, become veiling glare or escape the detector. Reflectance closes the energy balance only when angular and spectral collection are adequate. Fluorescence can violate a simple same-wavelength balance because absorbed photons are re-emitted at other wavelengths and with less than unity quantum efficiency.

The relation $T = I/I_0 = \exp(-\mu x)$ is useful as a screening model for a homogeneous, non-emitting medium under defined collection geometry. It is not automatically valid for a printed part with Fresnel losses, multiple scattering, anisotropic roads, fluorescent conversion, an absorbing gradient or a detector with broad spectral response. Even when an apparent attenuation coefficient is fitted, the report states the wavelength, path range and model residuals. Extrapolating a coefficient from a thin coupon to a thick component can fail if aggregation, self-absorption or detector dynamic range changes.

Haze measures wide-angle light redistribution under a specified method; it is not surface roughness, opacity or wavefront error. Layer stair-stepping and partially fused roads can add directional scatter. Particle aggregates and pores add volume scatter. A polishing operation can reduce surface scatter while exposing filler, creating subsurface damage or changing dimensions. The qualification plan therefore measures an as-printed state when that is the delivered state and a finished state when polishing or coating is mandatory.

Transparent photopolymers can yellow or change index during post-cure. Cure conversion, photoinitiator fragments and oxygen inhibition vary with depth. A thick lens or window can therefore have a spectral gradient even when a thin witness coupon appears clear. The process study maps exposure, post-cure wavelength, temperature, atmosphere and time to spectral transmission and index. The production record retains resin age, vat exposure history and thermal history.

Cho et al. reported a transparent block-copolymer resin designed to combine impact resistance and low haze through photopolymerization-induced microphase separation [25]. Olikagu et al. developed sulfur-rich photopolymer systems for plastic optics and high-index applications [26]. These studies show that polymer chemistry and cured morphology can be deliberately designed; they do not establish identical haze, toughness or index after another machine, geometry or cure schedule.

An optical-path map is often more informative than one mean value. It samples centre, edge, build direction, thick-to-thin transitions and regions near supports or drainage openings. For imaging components, modulation-transfer function, point-spread function, stray light or wavefront may reveal defects that total transmittance misses. Acceptance follows the intended decision: power delivery, image contrast, beam shape, colour fidelity or visual appearance.

5. Refractive index, dispersion, birefringence and gradient-index function

Refractive index is reported as $(n(\lambda, T))$, with polarization and direction when anisotropy is possible. The real part governs phase velocity; the imaginary part relates to absorption. Dispersion controls chromatic focal shift and group delay. A single catalogue index at the sodium

D line is not adequate for a broadband visible, ultraviolet or near-infrared optic. Temperature and moisture can change both matrix and particle indices, so an index-matched nanocomposite can become mismatched in service.

AM creates four index mechanisms. **Composition** changes constituent polarizability. **Density and porosity** change effective optical path and scattering. **Molecular or particle orientation** produces anisotropy. **Spatial programming** creates a gradient-index (GRIN) or discrete phase profile. These mechanisms can coexist and must be distinguished experimentally. An intended compositional GRIN can be confounded by an unintended cure-conversion gradient.

Gissibl et al. demonstrated ultracompact multi-lens objectives by two-photon direct laser writing [21]. Ocier et al. used direct laser writing to create volumetric GRIN lenses and waveguides [22]. Those studies show the value of voxel-scale three-dimensional control. Industrial transfer requires calibrated voxel dimensions, field-dependent shrinkage, stage and optical distortions, resin-lot response, post-exposure drift and surface or interface losses. The CAD surface is not automatically the optical surface.

High-index particles or sulfur-rich networks can increase phase delay per unit thickness. The benefit is conditional on absorption and scatter across the band. For a particulate composite, effective-medium models are screening tools whose assumptions about particle size, distribution and interface must be tested. When the feature size approaches wavelength, a homogenized index can cease to describe the device; the structure may behave as a photonic or diffractive medium.

Residual stress creates birefringence in otherwise isotropic polymers and glass. Layered cure, support restraint, thermal gradients, wash swelling and assembly preload can leave a spatial retardance field. A component for polarization-sensitive imaging or waveguiding therefore receives polarized transmission or retardance mapping after final mounting. Annealing can reduce stress but change dimensions, surface figure or luminescent chemistry.

Index measurement on a cut coupon can destroy the very gradient or orientation being qualified. Non-destructive refractometry, interferometry, ellipsometry, optical coherence or inverse wavefront methods may be needed. Their spatial resolution and inverse-model assumptions belong to the uncertainty statement. A reference coupon remains useful for material state; it does not replace the part-level optical-path measurement.

6. Surface figure, diffractive and photonic architecture, and waveguides

An optical component succeeds through both material and geometry. Surface figure determines low-spatial-frequency wavefront error; roughness and voxel texture contribute scatter; edge definition affects diffraction; internal seams and support scars create stray-light paths. The drawing therefore separates mechanical datum, optical clear aperture, functional microstructure, finish allowance and prohibited-support regions.

For conventional refractive optics, printing may reduce assembly count or create freeform surfaces, but finishing can dominate the cell cycle. Grinding and polishing remove stair steps and subsurface defects while changing curvature and thickness. A process that prints quickly but requires manual optical finishing may have lower accepted throughput than a slower route with a near-net optical surface. Coatings add adhesion, stress, spectral shift and environmental durability requirements.

For diffractive optical elements, local height or index encodes phase. Quantization, voxel convolution, shrinkage and surface rounding change diffraction efficiency and unwanted orders. Near index matching can suppress internal scatter while preserving a designed phase difference through geometry [23]. Acceptance measures efficiency into specified orders, wavefront or point-spread response and stray light across wavelength, incidence and polarization—not only profilometry.

Photonic crystals use periodic structure at a scale comparable with wavelength. Zhang et al. demonstrated printed titania photonic crystals with a complete bandgap across the visible spectrum [24]. The demonstration connects material index, lattice geometry, shrinkage and disorder. Industrial replication requires control of lattice constant, fill fraction, defects, orientation, transformed phase, surface termination and spectral measurement. A CAD-perfect lattice with random missing struts can close mechanically yet fail photonic function.

Waveguides require core-cladding contrast, modal geometry, bend radius, surface and volume loss, launch conditions and connector interfaces. A visually clear printed channel can have unacceptable propagation loss. A high-index core without stable cladding may leak or become multimode. Coupling loss is reported separately from propagation loss, and cut-back or equivalent methods preserve the launch condition. Bends, crossings, splitters and printed transitions are measured in their actual orientations.

Two-photon polymerization can create submicrometre or micrometre optical structures, and multi-focus exposure can raise writing throughput. Geng et al. demonstrated ultrafast multi-focus three-dimensional nanofabrication [31]. Parallelization introduces field non-uniformity, focus-to-focus calibration and synchronization questions. Throughput is accepted optical elements per controlled cycle, including development, drying, inspection and any coating—not voxels per second.

Surface contamination is an optical variable. Unreacted resin, polishing slurry, fingerprints and cleaning residue can change scatter, fluorescence and coating adhesion. Cleaning validation specifies chemistry, ultrasonic or mechanical energy, drying and inspection. For internal channels, access and drainage are part of the optical design because trapped liquid can alter index or become a radiation-sensitive contaminant.

7. Photoluminescent, quantum-dot, rare-earth and photoresponsive systems

Photoluminescence begins with an excitation–emission relationship, not a pigment name. The record includes absorption or excitation spectrum, emission spectrum, quantum yield or efficiency, lifetime, concentration, matrix, oxygen, temperature, thickness and measurement geometry. Emitted intensity alone is ambiguous unless excitation absorbed by the specimen and detector response are known.

Concentration creates competing effects. More emitters can increase absorbed excitation but also promote aggregation, non-radiative transfer, self-absorption and inner-filter effects. In a thick printed body, the excitation field decays with depth and emission may be reabsorbed before escape. Apparent brightness can peak at a loading below the maximum chemically dispersible fraction. Optimization therefore uses the delivered geometry and intended observation or collection direction.

Ruiz et al. demonstrated a fluorescent 3D-printing material whose optical properties could be tuned [27]. Plé et al. demonstrated CQDs formed and confined in a photopolymer for two- and three-dimensional fluorescent applications [29]. Szukalski et al. demonstrated additively manufactured active optical components using photoresponsive molecules for dynamic light modulation [30]. The examples span passive emission, in-situ photochemistry and reversible response; they should not be pooled into one “fluorescent resin” class.

Quantum dots add size- and surface-dependent emission, ligand chemistry and environmental sensitivity. Their absorption can compete with the photoinitiator at the printing wavelength. Radicals, heat or light can damage ligands or create traps. Perovskite quantum dots can be especially sensitive to moisture, polar solvents and ion migration. Jeon et al. used a polymer architecture and DIW to print luminescent perovskite quantum-dot structures [28]. The route avoids assuming compatibility with a vat-photopolymerization spectrum; its evidence remains formulation- and geometry-specific.

Rare-earth emitters can offer narrow bands, long lifetimes or upconversion, but concentration quenching, host phonons, phase and local symmetry matter. A rare-earth powder dispersed in polymer does not inherit the optical efficiency of a dense crystal or glass. Scattering and interface loss can dominate. Upconversion claims declare excitation irradiance because nonlinear response at a high laboratory irradiance may not be useful under the intended source.

Photochromic, thermochromic or photomechanical systems require a cycle definition. Contrast, switching time, fatigue, recovery, temperature cross-sensitivity and residual state are measured. Dynamic modulation is accepted at the system level because illumination intensity and heat transfer change with geometry. “Reversible” is bounded by cycle count, residual change and service conditions.

Table 2. Candidate material families, opportunities and invalidation gates

Family	Credible component-scale opportunity	State variables that control function	Early no-go gates
Transparent polymer or block-copolymer network	Freeform window, lens, fluidic optic, protective cover	Conversion, absorber fragments, stress, water uptake, surface figure, ageing	Band transmission or haze fails after full cure/conditioning; polish cannot recover figure
Silica/glass nanocomposite transformed to glass	Heat-stable micro-optic, channel, fused-silica component	Solids, green uniformity, debinding, sintering shrinkage, bubbles, hydroxyl/impurity, finish	Cracks, closed-pore/bubble population or shrinkage variation cannot meet optical path
High-index particle or sulfur-rich composite	Thin phase element, compact refractive/diffractive optic	Index spectrum, contrast, dispersion, absorption, aggregation, cure field	Required index gain is offset by scatter, absorption, reflection or cure loss
Quantum-dot, fluorescent or rare-earth composite	Encoded marker, converter, sensor, display or spectral element	Excitation overlap, quantum efficiency, loading, self-absorption, oxygen/moisture, photobleaching	Print light damages emitter or emitter prevents cure; thick-part output is non-uniform/unstable
Plastic or inorganic scintillator	Detector segment, shaped light collector, component-scale sensor	Energy deposition, intrinsic yield, transparency, reflector/couplant, decay, afterglow, dose damage	UV emission is uncorrelated with ionizing-radiation response; coupling or background defeats signal
High-Z or neutron-active composite/metal	Collimator, radiopaque marker, local shield or mixed-field attenuator	Composition, density, segregation, ray-path thickness, spectrum, build-up, secondary radiation	Void/seam streaming or spectral response fails; occupational/process controls are unavailable

8. Scintillation and ionizing-radiation detection

Scintillation is a coupled energy-conversion chain: incident radiation deposits energy; the material creates electronic excitations; energy migrates to emitting centres; photons propagate through the body; surfaces and reflectors redirect them; a detector converts collected light to charge; electronics estimate event time, energy or position. Each stage can limit response. A luminescence spectrum is necessary for spectral matching but does not quantify the complete chain.

Intrinsic material descriptors include light yield under a defined particle or photon energy, emission spectrum, decay components, afterglow, non-proportionality, density and effective atomic composition. Component descriptors add geometry, optical attenuation length, surface state, reflector, optical isolation, couplant and detector coverage. System descriptors add gain, noise, threshold, saturation, timing extraction and calibration. Reports state whether “light output” means photons per energy deposited, photoelectrons at the sensor or an instrument channel value.

Plastic scintillators commonly combine a polymer matrix, primary fluor and wavelength shifter. Polymerization and printing can change oxygen content, fluor distribution, transparency and surface state. The public 3Dresyns PSci PPO page declares a PPO/POPOP-containing photopolymer route and explicitly presents loading, printability, optical coupling and geometry as development variables [15]. This supports candidate screening only. Independent qualification requires radiation-specific response, extraction, ageing and lot/build repeatability.

Weber et al. demonstrated an additively manufactured segmented plastic-scintillator detector for particle tracking and calorimetry [33]. Its importance is architectural: additive manufacture can integrate segmentation and optically isolating features that would otherwise require assembly. It does not imply that any printed scintillator achieves the same yield or cross-talk. Acceptance separates segment response, cross-talk, uniformity, timing and system calibration.

Inorganic scintillators can provide higher density or different stopping power and emission kinetics but often require crystalline order, activator control and optical transport. Dosovitskiy et al. demonstrated a printed complex inorganic polycrystalline scintillator after transformation [32]. Grain boundaries and pores can scatter scintillation light even when X-ray absorption is strong. Elattar et al. demonstrated a printed perovskite/polymer composite for high-flux X-ray scintillation [34]. Cadmium content and perovskite chemistry create occupational and lifecycle obligations alongside optical stability.

Energy resolution is not inferred from brightness alone. It includes photon statistics, non-proportional response, collection non-uniformity, detector gain and electronics. Spatial resolution can improve with small segments or collimation while collected light falls. Timing can improve with a fast component while slow afterglow still affects high-rate operation. The requirement resolves these trade-offs before material selection.

Radiation damage testing uses the relevant particle, energy, dose rate, total dose, atmosphere and recovery interval. Optical bleaching or darkening measured immediately after exposure can differ after thermal or temporal recovery. A dose stated without specimen temperature and oxygen may be incomplete for polymers. The acceptance record contains pre-exposure baseline, in-situ or post-exposure measurement time and retained performance.

9. Photon attenuation, radiopacity, collimation and neutron interaction

For a homogeneous narrow photon beam, the screening relation $I(E)/I_0(E) = \exp[-\mu(E)x]$ links energy-dependent linear attenuation coefficient and path length. For a mixture, XCOM can supply mass attenuation inputs based on declared composition [13]. The printed component adds actual density, voids, segregation, surface geometry and spectral weighting. Broad beams add scattered build-up. Polychromatic beams harden as lower-energy photons are preferentially removed. A single “attenuation percentage” without spectrum and geometry is not portable.

Radiopacity, collimation and shielding are different decisions. A radiopaque marker needs contrast relative to its surroundings under an imaging protocol. A collimator must control angular acceptance, penetration and septal geometry. A local shield reduces a specified downstream field, often under broad-beam conditions. A radiotransparent structure must minimize attenuation and artefact across a band. Higher attenuation is not universally better: detector housings, patient supports, radomes or beam windows may require the opposite.

Gear et al. measured attenuation properties of additively manufactured tungsten for gamma-camera collimation [35]. Fujii et al. evaluated a pure-tungsten collimator made by additive manufacture for an astatine-211 radionuclide-therapy research context [36]. These examples show why metal density, geometry and imaging response must be measured together. They do not authorize a collimator for clinical use without the applicable regulated validation.

Streaming paths dominate some failures. A nominal wall thickness can be bypassed by layer pores, a seam, a fastener hole or an oblique line through a lattice. The design therefore uses a ray-path or transport map over relevant source positions and angles, then verifies representative hot paths. Dimensional inspection alone cannot close attenuation if density varies spatially.

Neutrons interact differently from photons. Hydrogenous phases can moderate fast neutrons; boron-containing phases can capture thermalized neutrons; high-Z constituents that attenuate photons may be ineffective or introduce secondary fields for a neutron problem. Wu et al. investigated 3D-printed boron-carbide/polyether ether ketone composites for neutron shielding [37]. Arslonova et al. developed lead-free printable composites for mixed photon and neutron attenuation [38]. Their reported formulations are demonstrations tied to source spectra, processing and test geometries, not universal thickness tables.

Mixed fields require coupled evaluation. Adding boron carbide can alter viscosity and void formation while a high-Z oxide alters photon interaction and density. The same filler distribution can improve one energy range and degrade another. Capture gamma rays or scattered radiation can move the protection problem downstream. Final acceptance uses the relevant detector or dose quantity at the protected location, with background and secondary contributions characterized.

The unit of useful attenuation is not mass fraction but verified reduction per constrained component, including weight, thickness, envelope, cost, inspectability and lifecycle. A lighter composite can be preferable to denser metal when integration removes gaps; dense metal can be preferable when composite thickness or ageing is unacceptable. The comparator is explicit.

10. Vat photopolymerization and wavelength–function conflicts

Vat photopolymerization uses light to create geometry, while many optical additives also absorb, scatter or emit light. This makes the functional additive part of the exposure system. The working curve is therefore formulation-, wavelength-, temperature-, layer-, vat-history- and geometry-specific. A neat-resin exposure does not qualify a filled or fluorescent variant.

High-index particles scatter according to index contrast, size and aggregation. Absorbing dyes reduce penetration. Fluorophores can shift energy away from the initiator or emit into another initiator band. Quantum dots can absorb the projector spectrum and change during exposure. Scintillator fluors can undergo oxygen quenching or cure-induced chemical changes. The process study measures cure depth and lateral growth together with post-cure spectrum and functional response.

Exposure has lower and upper functional bounds. Below the lower bound, insufficient network conversion causes swelling, leachables, creep or weak features. Above the upper bound, excess dose can broaden geometry, yellow the polymer, bleach an emitter or create stress. The optimal dose for geometry may not maximize optical response. A feasible process window exists only where geometry, conversion, spectral performance and cleaning all pass simultaneously.

Layer interfaces can become optical interfaces. Refractive-index or conversion differences, trapped oxygen and incomplete bonding create scatter. Tilting or orienting the part may move interfaces relative to the optical path but can change support scars and cure geometry. Build orientation is therefore selected against an optical-path map, not only mechanical support volume.

Wash and post-cure are state transformations. Solvent can extract fluor, swell the network, alter surface roughness or leave residue. Post-cure can improve conversion while shifting emission or index. A mandatory dark rest, oxygen exclusion or staged cure becomes part of the recipe only after evidence. The release test uses the same waiting interval after cure because continuing dark reaction or physical ageing can move the result.

Ruiz et al., Plé et al. and Cho et al. demonstrate different strategies for functional photopolymers [25,27,29]. Their chemistries and optical mechanisms are not interchangeable. A transfer study begins by reproducing the published material state and measurement boundary, then tests the intended machine and geometry. Literature feasibility is not a production allowable.

11. Two-photon polymerization, DIW, extrusion and transformed glass routes

Two-photon polymerization confines reaction near the focal volume and enables freeform micro-optics, waveguides and photonic structures. The voxel depends on objective numerical aperture, pulse energy and duration, repetition rate, scan speed, resin threshold, refractive mismatch and aberration with depth. Development and drying change geometry. Gissibl et al., Ocier et al. and Geng et al. show capabilities ranging from micro-objectives to GRIN structures and parallelized nanofabrication [21,22,31]. A production control tracks laser power at the specimen, optical alignment, objective condition, field position and resin response.

For nanoparticle-loaded 2PP, particles alter focus, scattering and local heat. Kotz et al. demonstrated a nanocomposite route transformed to fused silica [20]. Debinding and sintering shrink the microstructure; anisotropic or feature-size-dependent shrinkage changes optical design. The pre-compensation model is validated across orientation, field and feature density. A single scale factor is rejected when residuals show spatial dependence.

DIW can carry high solids or environmentally sensitive emitters without requiring the same vat cure penetration. Rheology must permit extrusion, shape retention and inter-road fusion. Solvent evaporation can drive coffee-ring segregation, skin formation and cracks. For quantum dots, nozzle residence, shear and atmosphere may alter dispersion or ligands. Jeon et al. demonstrated DIW luminescent perovskite-quantum-dot architectures [28]; industrial adoption still requires lot stability, moisture control, interlayer optical uniformity and final-device testing.

Material extrusion can shape transparent or radiation-active thermoplastics, but roads, welds and voids alter optical and attenuation paths. For transparent components, inter-road interfaces scatter. Thermal history can yellow polymer or degrade fluor. For high-Z or boron-carbide composites, loading raises viscosity, pressure and nozzle wear and can create density gradients. Wu et al. [37] and Arslonova et al. [38] support feasibility for radiation-functional composites while also showing that formulation and processing are coupled.

Green-to-glass processing separates shaping from final optical material. Kotz et al. [19] demonstrated a fused-silica route, and Colton et al. later investigated geometry-dependent outcomes in low-temperature, sinterless three-dimensional nanoprinted glass [39]. The relevant chain includes green solids, organic removal or chemical conversion, gas escape, shrinkage, cracking, surface finish and impurity. Thick and thin regions can transform differently. Closed cavities require an exit strategy for solvent and decomposition products.

Table 3. Route-level advantages, limitations and process gates

Route	Credible advantage	Coupled limitations	Qualification focus
Vat photopolymerization	Complex component-scale transparent, fluorescent or filled geometry; integrated channels and segmentation	Additive–initiator spectral competition; scattering; sedimentation; cure gradient; wash and post-cure drift	Formulation-specific working window; spatial spectrum/index map; leachables; ageing
Two-photon polymerization	Micro-optics, waveguides, GRIN and photonic lattices with three-dimensional voxel control	Small field; depth aberration; long write/development cycle; shrinkage; fragile features	Voxel/field calibration; wavefront or spectral function; development and transformation reproducibility
Direct ink writing or jetting	High solids, multimaterial placement and mild-temperature deposition	Rheology, nozzle filtering, drying segregation, road interfaces, atmosphere sensitivity	Local composition; density; optical continuity; geometry-dependent drying; nozzle/process genealogy
Material extrusion	Robust thermoplastic matrix, larger parts, high-Z or neutron-active loading	Road voids, weld scatter, thermal degradation, pressure, wear and segregation	Ray-path density map; road orientation; spectrum-specific attenuation; ageing and fire/heat boundary
Printed green body transformed to glass/ceramic	Final inorganic optical or scintillating phase; heat and radiation resistance	Debinding/conversion gas paths; shrinkage; cracks; grains/pores; finish demand	Phase, density, bubble/pore field, dimensional compensation, transmission/light transport after finish
Hybrid modular assembly	Each optical, scintillating and attenuating zone can use its best route and be replaced	Interfaces, alignment, couplant, tolerance stack, contamination and assembly work	Interface loss; alignment; field leakage; detector coupling; assembled ageing and calibration

12. Interfaces, coupling, coatings, reflectors and detector boundaries

Interfaces determine how much of an intrinsic response reaches the system. At an optical interface, index mismatch creates reflection and can trap light by total internal reflection. Surface roughness redistributes angles. An adhesive can yellow, fluoresce, absorb radiation or change thickness under temperature. An air bubble in a couplant can dominate a high-quality scintillator.

Optical coupling is specified by material, index spectrum, thickness, cure, application method, bubble criterion and ageing. Coupling a scintillator to a photodiode, silicon photomultiplier or camera changes collection and spectral match. A detector's photon-detection efficiency and window transmission are wavelength dependent. The qualified quantity is photoelectrons, charge, calibrated signal or imaging response at the selected boundary—not emitted photons inferred from a supplier sheet.

Reflectors and optical isolators serve different functions. A diffuse or specular reflector can return escaping light and improve collection. An absorbing separator can reduce cross-talk while sacrificing some light. A white scatterer, metal foil, black coating or printed opaque wall has its own thickness, adhesion, fluorescence and radiation stability. Segmented detectors measure both within-segment uniformity and neighbour cross-talk.

Cladding sets waveguide confinement. A printed core with an air boundary may guide well until a housing or adhesive contacts it. A conformal cladding can protect the mode but adds deposition and inspection. Bend and connector losses are measured after assembly. Mechanical tolerance that closes a housing can still move a fibre or detector enough to change response.

Coatings can provide antireflection, filtering, barrier, reflection or blackening. They may also add stress, pinholes, delamination and radiation sensitivity. The coating process is qualified on the actual printed surface chemistry and roughness. A coating developed for polished glass cannot be assumed to adhere to a washed photopolymer or porous transformed body.

Collimator interfaces include seams, fasteners and contact between attenuating segments. A thin gap can become a streaming path. Overlaps, labyrinth joints or locally denser inserts can control leakage, but their geometry must be verified. Assembly inspection combines dimensional metrology with a radiation scan because an apparently closed seam can have insufficient areal density.

Cleaning and handling are controlled through the final interface. Optical surfaces receive particle and residue limits. High-Z or toxic fillers require contamination control. Reusable assemblies define decontamination chemistry and its effect on transmission, coating and seals. If a part cannot be cleaned without moving its calibrated response, reuse is not accepted.

13. Measurement architecture and uncertainty

Every result begins with a specimen drawing, state label and measurement model. The drawing identifies build direction, optical path, clear aperture, surface finish, local composition, detector or probe position and datum. The state label records cure, drying, debinding, sintering, annealing, polishing, coating, coupling, conditioning and irradiation history. Replicates span independent material lots, formulations, builds and build positions rather than repeated readings on one coupon.

Transmission reports wavelength grid or bandwidth, source stability, reference path, detector linearity, stray light, aperture and sphere geometry. Total, diffuse and specular components are kept separate when relevant. Thickness and surface reflectance are not silently absorbed into a “material coefficient”. If fluorescence reaches the detector, filters or time resolution separate transmitted excitation from emitted light.

Index and wavefront measurements record wavelength, temperature, direction and polarization. For GRIN components, spatial resolution and reconstruction model are reported. Surface profilometry, interferometry and optical imaging are connected by common datums. A good surface-height map does not prove index homogeneity; a good index coupon does not prove assembled wavefront.

Luminescence measurements correct for excitation power, absorbed fraction, detector response and geometry. Absolute integrating-sphere methods state reabsorption and sample-holder corrections. Lifetime analysis preserves the instrument response and fitting model. Quantum efficiency or yield is not reported with more significant figures than the uncertainty supports. Colour coordinates include illuminant/observer and whether fluorescence was excited.

Scintillation measurements state radiation source, energy, distance, collimation, rate, dead time, accumulated dose and background. The chain from scintillator to detector and electronics is calibrated or explicitly treated as a relative system result. Energy spectra retain calibration peaks, resolution definition and fitting. Timing retains trigger and time-walk correction. Spatial response retains source spot, collimator and reconstruction.

Photon attenuation measurements distinguish narrow-beam material characterization from broad-beam component protection. Incident and transmitted spectra are preferred when beam hardening matters. Detectors are checked for pile-up, scatter and energy dependence. Areal density and path length are measured along the tested ray. XCOM inputs and mixture rules are retained with version and composition, then compared with the measured component rather than reported as validation by themselves [13].

Neutron measurements state source spectrum, moderator, distance, detector response and secondary-radiation sensitivity. Monte Carlo or deterministic transport can guide design; code, nuclear data, geometry, variance reduction and validation cases belong to the record. Simulation disagreement is not hidden by renormalizing a curve without physical justification.

Measurement uncertainty includes calibration, repeatability, geometry, thickness, density, temperature, source stability, detector nonlinearity, spectral correction, fitting and between-lot/build variability. A pass/fail guard band is defined before testing. When a result lies inside the uncertainty interval around a limit, it is not converted to a pass by extra decimal places.

14. Optical ageing, radiation damage, safety and lifecycle boundaries

Optical performance can drift without visible mechanical failure. Heat and humidity change polymer water content, index and dimensions. Ultraviolet or blue light can yellow a matrix or bleach an emitter. Oxygen can quench luminescence or accelerate oxidation. Ionizing radiation can darken, crosslink or chain-scission polymers and create colour centres in inorganic materials. Thermal cycling can debond coatings and couplants. The ageing plan selects stressors from the real service and cleaning environment.

ISO 4892-1:2024 provides general guidance for laboratory light-source exposure of plastics [11]. Laboratory exposure supports comparative degradation studies but does not, by itself, predict a universal service lifetime. Spectrum, irradiance, black-panel or specimen temperature, moisture cycle and specimen state must be reported. Functional measurements are taken before, during when needed, and after exposure with a defined recovery interval.

Accelerated tests are rejected when the acceleration changes mechanism. Raising temperature can cross a glass transition, melt a crystalline phase or accelerate oxygen diffusion differently. Increasing photon flux can saturate a photoresponse or create multiphoton chemistry. Raising dose rate can change radical recombination. The report justifies the acceleration model and verifies that degradation signatures remain representative.

Nano/micron powders require task-specific exposure assessment. NIOSH guidance for handling nanomaterials emphasizes hazard identification, exposure assessment and a hierarchy of controls [16]. Wet resin does not eliminate exposure: weighing, mixing, spills, sanding, polishing, filter changes and waste handling can release particles or contaminated liquid. Local exhaust, enclosure, closed transfer, housekeeping, training and verified protective equipment are selected through a formal assessment.

Lead and cadmium deserve explicit controls when candidate chemistries contain them. NIOSH identifies serious health hazards from workplace lead exposure and recommends prevention through the hierarchy of controls [17]. The NIOSH Pocket Guide treats cadmium dust as a potential occupational carcinogen and identifies respiratory and kidney targets [18]. A “lead-free” marketing label does not prove the remaining formulation is benign; every constituent, reaction product and task is assessed. Substitution is preferred where functional and lifecycle requirements can be met.

Radiation-source operation is outside ordinary material handling. X-ray, gamma and neutron testing requires authorized facilities, calibrated instruments, controlled areas, interlocks, training and applicable dose-management procedures. A printed attenuator is never used as personnel protection solely because a calculation or one coupon test passed. Safety relies on the facility’s validated engineered controls and regulatory programme.

Lifecycle records include incoming active material, residual monomer or solvent, powder recovery, contaminated consumables, polishing slurry, failed parts, irradiated parts, recycling and disposal. A composition that performs well but cannot be safely manufactured, inspected, cleaned or disposed of is not an industrially viable route. Supply continuity and restricted-substance obligations are design inputs.

15. Applied example: compact X-ray inspection head

15.1 Requirement and functional decomposition

Consider a compact industrial X-ray inspection head for small manufactured components. It is not a medical or personnel-protection device. The head must define a narrow field of view, convert transmitted X-rays to light, deliver that light to a photosensor, suppress optical cross-talk and stray X-rays, protect the optical path from shop contamination and retain calibration after thermal cycles and vibration. Envelope and mass are constrained, and the detector module must be replaceable.

The initial concept proposes one printed “multifunctional” body containing high-Z filler near the aperture, scintillating filler behind it, transparent material between scintillator and detector and black pigment around the optical path. That concept is attractive in CAD and weak in qualification. The high-Z filler scatters or absorbs print light and raises viscosity. The scintillator requires optical clarity and spectral compatibility. The black absorber can inhibit cure or contaminate the guide. The transparent zone needs low scatter and controlled index. A single exposure and post-cure cannot be presumed optimal for all four chemistries.

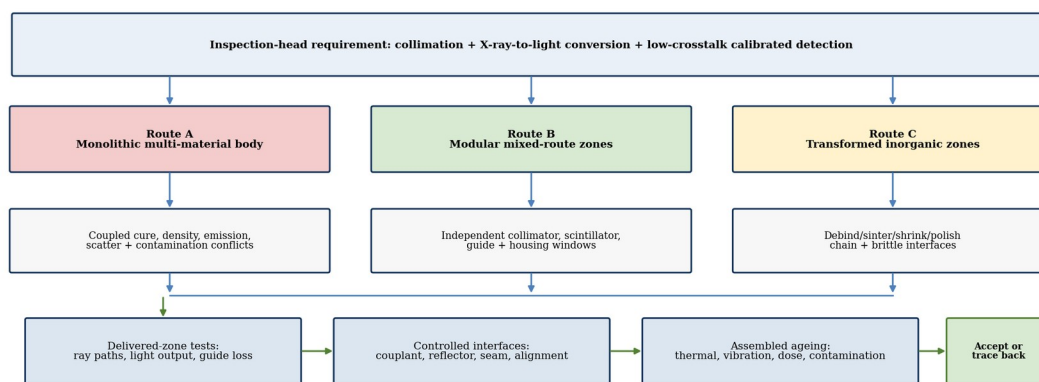
The system is therefore decomposed into five zones. **Z1**, a collimator or aperture, controls X-ray angular acceptance and penetration. **Z2**, a scintillator, converts the transmitted spectrum to light. **Z3**, a light guide or direct couplant, controls collection and spectral delivery. **Z4**, an optical separator/reflector, suppresses cross-talk and redirects useful light. **Z5**, a mechanically protective housing, maintains alignment without creating an unwanted attenuation or fluorescence path. Each zone has its own measurable output and interfaces.

15.2 Candidate routes and invalidation gates

Route A retains the monolithic filled-photopolymer concept. It proceeds only if a multi-material platform prevents cross-contamination, each formulation has an overlapping print/process window, interfaces bond without optical or radiation leakage, and the full assembly can be inspected. A coupon from each vat is insufficient because spatial registration and interface history govern the result. The route is rejected early if the collimator formulation cannot reach required areal density without voids or if scintillator output falls after the common post-cure.

Route B is modular: an additively manufactured tungsten or high-Z collimator, a separately printed or conventionally supplied scintillator segment, a transparent printed or machined light guide, a controlled reflector/black separator and a polymer housing. This route adds interfaces and assembly but lets each zone use its best process. Gear et al. and Fujii et al. support the feasibility of AM tungsten collimation as bounded demonstrations [35,36]. Weber et al. supports printed detector segmentation [33]. Route B is provisionally preferred because failures can be localized and modules replaced.

Route C transforms printed green bodies to inorganic zones: a dense metal or ceramic collimator and an inorganic scintillator, with a glass micro-optic. It can offer temperature or radiation stability but adds debinding, sintering, shrinkage, brittle handling, polishing and joining. Kotz et al. and Dosovitskiy et al. demonstrate relevant transformation mechanisms [19,32]. Route C survives only if dimensional compensation, optical transport and interface stress meet the envelope and throughput requirement.



Route B is provisionally preferred only if every zone and the calibrated assembly pass after ageing.

Figure 2. Applied selection logic for a modular compact X-ray inspection head.

15.3 Evidence plan and decision logic

The collimator receives composition and density verification, X-ray computed tomography or equivalent void/path inspection where suitable, dimensional metrology and an energy-resolved penetration and spatial-response scan. The test includes off-axis positions that challenge seams and minimum septa. XCOM supports initial thickness and material screening [13], while measured response closes the decision.

The scintillator receives excitation/emission characterization only as a diagnostic, followed by X-ray-specific light output, uniformity, afterglow and accumulated-dose response. The selected photosensor is included in the system test. The guide receives spectral transmission, scatter or propagation loss and alignment sensitivity. The reflector/separators receives reflectance or absorption and cross-talk testing. The housing receives dimensional and environmental testing and is screened for unintended attenuation or fluorescence.

Interface experiments vary couplant thickness, bubble population, reflector contact, detector pressure and alignment within drawing tolerances. The assembled calibration maps source position and energy or thickness standard to detector response. Background, stray radiation, cross-talk and thermal drift are measured. A guard band separates process capability from the minimum functional limit.

Route B is selected only if every zone and the assembled head pass. Its advantage is not assumed from modularity; the interface burden is tested. Route A can replace it if the monolithic process demonstrates equal or better accepted-system throughput, calibration stability and traceability. Route C can replace it if radiation or thermal life justifies its longer transformation chain. The selection record therefore remains provisional until ageing and independent builds close.

The example produces a reusable output sheet: required source/detector state; zone functions; candidate routes; mandatory transformations; invalidation gates; safety constraints; evidence gaps; surviving route; rejected-route rationale; measurement uncertainty; and change triggers. It converts “print a radiation detector” into auditable decisions.

16. Qualification genealogy and change control

Qualification links material, formulation, machine, software, geometry, finishing, interfaces, source and detector. A convenient genealogy uses eight connected records rather than one generic material certificate.

Table 4. Minimum linked records for optical and radiation-functional qualification

Record	Controlled content	Evidence retained	Change trigger
R1 — Requirement and system boundary	Function; source spectrum/energy; incidence; detector; geometry; environment; failure consequence; acceptance and guard band	Approved requirement, optical/radiation model, comparator and uncertainty plan	Source, detector, geometry, environment or acceptance change
R2 — Constituent identity and safety	Matrix; active phase; dopant/ligand; particle distribution; surface; optical constants; density; lot; SDS and exposure assessment	Certificates plus independent identity checks and task controls	Supplier, lot family, phase, surface treatment, restricted substance or storage change
R3 — Formulation and printable state	Loading basis; dispersant/initiator; solvent; mixing; filtration; oxygen/moisture; viscosity/rheology; residence and sedimentation	Batch genealogy, in-process checks and retained samples	Composition, mixing energy/order, filter, ageing time or environmental window change
R4 — Build and transformation	Machine; wavelength/power; dose or heat/shear; orientation; support; wash; cure; dry; debind; sinter; anneal; compensation	Signed build file, calibrated settings, sensor logs and transformation profile	Hardware, optics/nozzle, software, parameter, geometry family or post-process change
R5 — Finish and spatial state	Density/porosity; composition map; surface figure/roughness; polish; coating; blackening; dimensional/ray-path map	Metrology, spectroscopy, microscopy/CT as applicable, defect disposition	Finish, coating, path thickness, feature scale or defect population change
R6 — Zone-level functional test	Transmission/index/wavefront; emission/lifetime; scintillation; attenuation or neutron response	Raw spectra/events/images, calibration, method, uncertainty and replicate hierarchy	Instrument/method, wavelength/energy, specimen state or statistical basis change
R7 — Interface and assembled-system test	Couplant, reflector, cladding, detector, seams, alignment, electronics and calibration	Interface inspection, assembled optical/radiation response, cross-talk and background	Couplant/coating, detector, joint, tolerance, firmware or calibration model change

Record	Controlled content	Evidence retained	Change trigger
R8 — Ageing, release and field feedback	Light/radiation dose; heat/humidity; cleaning; vibration; retained function; serial/lot release; failure analysis	Ageing curves, release certificate, deviations and trace-back	New exposure, service interval, drift, failure mode, repair or reuse cycle

Change classification follows causal reach. An editorial drawing correction with no geometry effect can be documented without requalification. Changing fluor supplier, quantum-dot ligand, high-Z particle distribution, photoinitiator, exposure wavelength, nozzle, post-cure, sintering furnace, polishing route, detector window or couplant can move function and requires impact assessment. A change to part thickness or aperture angle can affect both optical and radiation response even when material is unchanged.

A family qualification defines its allowed domain. Feature size, optical path, local thickness, loading, build orientation, field position and post-process range are bounded. A new geometry outside that domain is not accepted by resemblance. Worst cases are evidence-based: longest optical path, smallest aperture, thickest transformation section, most difficult drainage, minimum attenuating path, maximum surface-area-to-volume ratio or highest accumulated dose may be different parts.

Statistical control preserves independent levels. Instrument repeats estimate measurement noise; multiple locations estimate spatial non-uniformity; multiple parts estimate within-build variability; builds estimate process reproducibility; lots estimate incoming-material effects. Pooling all readings as independent replicates understates uncertainty. Acceptance evidence names the level relevant to release.

Calibration is itself controlled configuration. Spectral-response corrections, X-ray energy calibration, neutron detector response, image reconstruction and background subtraction have versions and validity intervals. Changing electronics or software can move the result without changing the printed part. The release genealogy connects material serial number to the calibration used for its decision.

17. Discussion, route trade-offs and conclusions

The central finding is that optical and radiation-functional AM selection is a problem of interacting fields and states. The print field—light, heat, shear or solvent—creates geometry while interacting with the same constituents chosen to absorb, scatter, emit or attenuate. Post-processing then changes density, chemistry, stress and surfaces. Finally, the source and detector define which portion of the response is useful. There is no context-free ranking of material families or AM categories.

Transparent retained polymers offer rapid freeform geometry and integration but remain sensitive to conversion, stress, water, yellowing and surface finish. Transformed silica or glass can provide a more stable inorganic state but demands controlled organic removal, shrinkage and finishing. High-index nanocomposites or sulfur-rich networks can reduce optical thickness but add reflection, dispersion, absorption and process-window constraints. Two-photon routes offer exceptional spatial control while field size, development, transformation and calibration limit accepted throughput.

Luminescent materials create value when AM controls concentration, spatial encoding, light extraction or integrated sensing. Their limitation is that brightness photographs conceal excitation absorption, self-absorption, detector response and ageing. Quantum dots and perovskites expand spectral design while adding ligand, moisture, solvent and occupational considerations. Rare-earth phases can offer spectral specificity but do not bypass scattering or host effects.

Scintillators and attenuators demonstrate why the delivered system matters most. A scintillator with high intrinsic output can perform poorly through bad coupling or opaque grain boundaries. A high-Z object with favourable XCOM inputs can leak through pores or seams. Neutron shielding cannot be selected from photon attenuation. Additive manufacture creates genuine value through shaped collimation, segmentation, graded paths, integrated reflectors and reduced gaps only when those features can be inspected and measured.

The applied example supports modular allocation as the default starting hypothesis, not a universal rule. Separate zones allow incompatible chemistries and post-processes to be optimized and replaced. They also introduce coupling, alignment and seam risks. A monolithic part becomes preferable only after demonstrating an overlapping manufacturing window, local-material fidelity, inspectable interfaces and stable assembled response. The decision is based on accepted systems per complete cell cycle and service interval, not part count or printing speed.

Nine conclusions follow.

- **Function must be named before material.** Transmission, phase control, luminescence, scintillation, photon attenuation and neutron attenuation require different inputs, methods and acceptance evidence.
- **The qualifying object is the conditioned source–component–detector system.** Powder, neat resin, thin coupon, green body and polished assembled component are distinct states.
- **“Transparent” is incomplete.** Spectral total and directional transmission, haze, wavefront, surface figure, polarization and path length are selected according to the decision.
- **Refractive-index benefit requires spectral and interface closure.** A higher index is useful only when absorption, scattering, reflection, dispersion, stress and environmental drift remain acceptable.
- **Luminescence is not scintillation.** Optical excitation data cannot substitute for ionizing-radiation response, light transport, detector coupling, timing, background and dose ageing.
- **Attenuation calculations are screening inputs.** Composition-dependent databases and exponential models must be joined to measured density, geometry, build-up and final-component testing.
- **Photon and neutron problems remain distinct.** Mixed-field designs require energy-resolved interaction, moderation/capture and secondary-radiation assessment.
- **Geometry is acceptable only when required material can be recovered and critical optical or radiation paths can be verified by direct inspection or a validated qualification strategy.** Printability alone is insufficient.
- **Change control includes the measurement chain.** Constituent, formulation, exposure, transformation, finish, interface, source, detector, calibration and software changes can all invalidate prior evidence.

The framework is designed to expose invalid assumptions before they are hidden behind a category name, a vivid emission image, a nominal refractive index or a calculated attenuation percentage. Its practical output is a traceable decision: the selected route, its surviving process window, the evidence still missing, the reasons alternatives failed, and the conditions under which the decision must be revisited.

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