

Dielectric, Ferroelectric, Piezoelectric and Magnetically Functional 3D Materials: Loading, Alignment, Poling, Field Response and Device Qualification

A State-Resolved Framework for Polar, Electromechanical, Permanent-Magnet, Soft-Magnetic and Field-Responsive Functions

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ER-158 · Engineering Review · Version 0.2 · 8 September 2026

Statement of Significance

Dielectric, ferroelectric, piezoelectric and magnetic additive-manufacturing materials are often grouped as *functional* or *smart*, although they answer different physical questions. Relative permittivity does not prove low dielectric loss or adequate breakdown strength. A polarization–electric-field loop does not by itself prove switchable ferroelectric polarization. A local piezoresponse image does not establish the force, charge, voltage, displacement, bandwidth or lifetime of a finished transducer. Magnetic-powder content does not specify whether a component is a permanent magnet, a low-loss soft-magnetic core, a superparamagnetic tracer or a field-responsive elastomer. This review creates an auditable chain from the intended device function through constituent identity, connectivity, loading, dispersion, print history, debinding or curing, densification, electrodes, poling, magnetization, ageing and system-level verification. It explains where additive manufacture creates genuine value—graded composition, local orientation, architected connectivity, integrated cavities and spatially programmed fields—and where it creates new failure modes. The public 3Dresyns portfolio is used only to map candidate material families and a declared BTO-filled photopolymer route; manufacturer statements are not substituted for independent material or device evidence. The qualifying object is the final material–process–geometry–field–electrode–test system in its delivered state.

Abstract

Nano- and micron-scale dielectric, ferroelectric, piezoelectric and magnetic phases can enable additively manufactured capacitive structures, radio-frequency elements, sensors, actuators, ultrasonic transducers, energy harvesters, permanent magnets, flux guides and magnetically responsive devices. Their value is conditional. High-permittivity particles can raise viscosity, scatter curing light, sediment, concentrate electric field and increase loss. Ferroelectric or piezoelectric ceramics can require debinding, sintering, electrode firing and high-field poling; retained polymer composites can remain printable but dilute active-phase connectivity and transfer stress inefficiently. Permanent-magnet powders can increase melt viscosity, nozzle wear, density gradients and demagnetizing-field sensitivity; field alignment can improve a selected axis only if particle torque exceeds viscous and frictional resistance without pulling the deposit out of place. Soft-magnetic and magnetically responsive systems require different loops, frequencies, field amplitudes, geometries and acceptance metrics from hard magnets. This qualitative engineering review separates dielectric storage and loss, ferroelectric switching, piezoelectric transduction, permanent-magnet energy delivery, soft-magnetic flux transport and field-responsive motion. It establishes state-resolved requirements, route-specific invalidation gates, measurement records and change-control logic. Primary studies are treated as bounded demonstrations rather than transferable recipes. An applied example compares candidate routes for a removable condition-monitoring module that needs a poled vibration sensor, controlled electrical insulation and a shaped magnetic attachment field. The example shows why these functions are best allocated to independently verifiable zones. The review concludes that composition is only an input: function emerges from phase state, connectivity, orientation, interfaces, activation history, geometry and the device boundary.

Keywords: *additive manufacturing; dielectric; permittivity; dielectric loss; ferroelectric; polarization; piezoelectric; poling; barium titanate; PZT; PVDF; permanent magnet; NdFeB; ferrite; soft magnet; magnetic alignment; anisotropy; qualification*

1. Purpose, scope and governing distinctions

This paper makes electrically polar, electromechanically active and magnetic nano/micron materials selectable as industrial systems. It has eight objectives. First, it distinguishes six functions that are often collapsed under *functional material*. Second, it identifies the state variables that connect received powder or polymer to a usable response. Third, it compares retained composite, printed green ceramic, densified ceramic, bonded magnet, consolidated magnetic alloy and hybrid routes without creating a universal ranking. Fourth, it explains loading, connectivity, orientation, poling and magnetization as separate operations. Fifth, it defines process-specific no-go gates. Sixth, it establishes measurement records that preserve frequency, field, temperature, direction, geometry and uncertainty. Seventh, it demonstrates selection with a worked component-scale 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 dielectric, ferroelectric, piezoelectric and magnetic-function evidence for applying that framework.

Electrical conduction, electrostatic-control, electromagnetic-shielding and thermal-transport functions are owned by ER-157, and optical, photonic, luminescent and radiation functions by ER-159; this review does not reopen those domains.

ISO/ASTM 52900 provides the vocabulary and process categories for additive manufacturing (AM) [1]. ISO/ASTM 52920 addresses qualification principles for industrial AM processes and production sites [2], and ISO/ASTM 52927 organizes main characteristics and corresponding test methods [3]. Those standards anchor the manufacturing system; they do not turn a chemical name into a functional specification. Two photopolymers containing barium titanate (BTO) can differ in particle size, phase, surface treatment, loading basis, dispersion, cure state, porosity, electrode geometry and frequency response. Two bonded neodymium–iron–boron (NdFeB) magnets can differ in powder grade, easy-axis distribution, density, magnetizing field, shape and service temperature. Category equivalence is not functional equivalence.

Six distinctions govern the review. A **dielectric** is evaluated through complex permittivity, loss, conductivity, electric strength and application geometry over declared frequency, field, temperature and humidity. A **ferroelectric** adds reversible spontaneous-polarization states; its evidence must separate switching from leakage, dielectric displacement and electrode artefact. A **piezoelectric** couples electrical and mechanical variables; its coefficients are tensorial, boundary-dependent and incomplete without electrodes, poling direction, frequency and device loading. A **permanent or hard magnet** is evaluated through demagnetization behaviour, remanence, coercivity, energy product, temperature stability and external field in the intended geometry. A **soft magnet** is evaluated through permeability, hysteresis and dynamic losses under a declared waveform and frequency. A **field-responsive composite** uses magnetic force or torque to move, stiffen or reconfigure a structure and is judged by the controlled motion or mechanical response, not simply by magnetization.

The scope covers component-scale retained polymer composites, photoactive suspensions, extrusion filaments or pellets, direct-ink-writing (DIW) inks, jetted or patterned materials, green ceramics transformed by debinding and sintering, polymer-bonded magnets, magnetically assisted deposition and hybrid assemblies. Representative polar phases include BTO, barium-strontium titanate, lead zirconate titanate (PZT), related lead-free electroceramics and poly(vinylidene fluoride) (PVDF) or PVDF-trifluoroethylene (PVDF-TrFE). Representative magnetic phases include ferrites, magnetite and related iron oxides, NdFeB, samarium–iron–nitrogen systems and soft-magnetic metals or ferrites. The public 3Dresyns nano/micron page lists BTO, PZT, barium ferrite, iron oxides, NdFeB and related candidates [14]. Its BTO-filled photopolymer page declares a retained, high-permittivity photopolymer route and explicitly states that performance depends on printing, geometry, frequency and post-processing [15]. Both sources are manufacturer declarations, not independent validation.

Concrete, cement, geopolymers, regolith and macroscopic construction deposition are excluded. The paper does not prescribe universal filler fractions, cure doses, sintering cycles, poling fields, magnetizing fields, dielectric limits, piezoelectric coefficients, coercivities or safety controls. Those values belong to a named formulation, device, test method, population, uncertainty and jurisdiction. Direct laser consolidation of dense magnets and soft-magnetic alloys is included only as a route boundary because its metallurgical mechanisms are treated in the metal-process papers of this series.

2. Begin with a device function, not a material adjective

“High-k”, “ferroelectric”, “piezoelectric” and “magnetic” are not complete requirements. A requirement states the desired input–output relationship, geometry, direction, environment, duration, uncertainty and failure consequence. It also identifies the comparator. A higher relative permittivity can shrink one resonator while increasing loss or field concentration. A larger piezoelectric charge coefficient can be irrelevant if stiffness, voltage coefficient, coupling, bandwidth or electrode reliability governs the device. A stronger powder can produce a weaker external field if the printed part is porous or magnetized in an unfavourable shape.

For a dielectric component, the requirement declares whether the design needs capacitance, energy storage, electrical insulation, impedance control, wave slowing, resonance or field shaping. It specifies the frequency band, electric-field amplitude and waveform, temperature, humidity, electrode configuration, thickness, tolerable loss, leakage and breakdown risk. IEC 62631-2-1:2018 covers relative permittivity and dissipation-factor measurements of solid insulating materials from 0.1 Hz to 10 MHz [4]. ASTM D150-22 provides AC loss and permittivity methods for solid insulation [5]. Neither method automatically describes microwave operation, a patterned electrode or a three-dimensional resonator; the method and fixture must match the decision.

Dielectric strength is a destructive statistical outcome, not simply a material constant. ASTM D149-25 requires the voltage application, rate, specimen conditioning, surrounding medium, electrodes and failure criterion to be specified, and warns that test results seldom transfer directly to the application without functional evidence [6]. AM voids, layer interfaces, sharp corners, embedded particles, residual solvent and surface contamination can create field-enhancement paths absent from a polished moulded plaque.

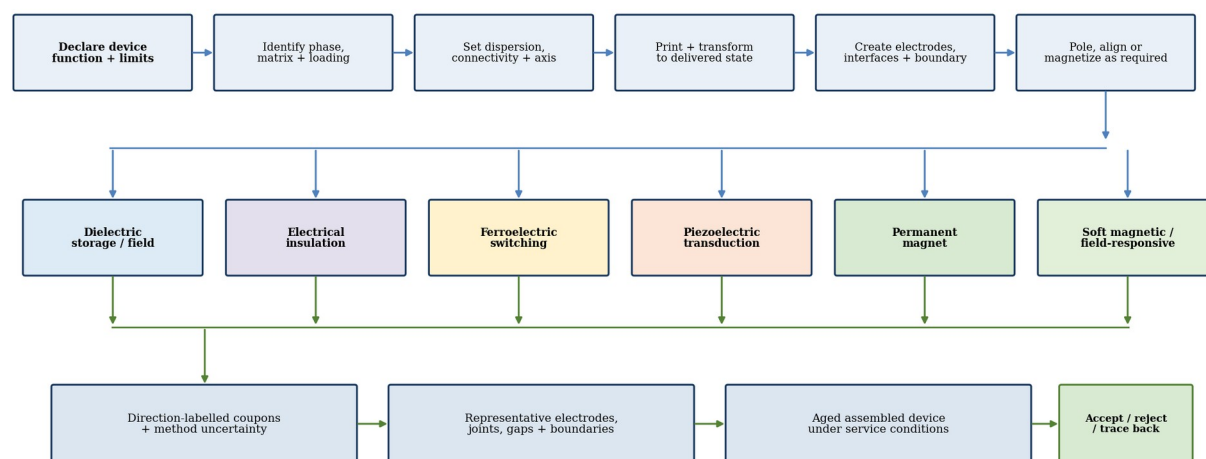
For a ferroelectric element, the requirement states whether switchable polarization, non-volatile state, tunable permittivity, pyroelectric response or electromechanical coupling is actually used. A device that merely uses high permittivity does not need ferroelectric switching. The voltage waveform, cycle rate, allowed imprint, fatigue, leakage, retention, temperature window and electrode stack are specified. A visually open hysteresis loop is insufficient when conduction and dielectric loss can contribute charge.

For a piezoelectric sensor, actuator, transducer or harvester, the requirement defines mechanical mode, preload, stress or strain axis, electrical boundary, bandwidth, resonance, signal-to-noise ratio, source and load impedance, displacement or force, temperature and service cycles. IEC TS 61994-5:2023 provides current terminology for piezoelectric sensors [11], and IEC 63041-3:2026 supplies guidance for physical piezoelectric sensors [12]. A reported coefficient on a small coupon is one part of that chain, not a device qualification.

For magnetic function, the requirement first chooses the class. A hard magnet supplies an external field or torque and must retain magnetization against opposing fields and temperature. A soft magnet carries time-varying flux with acceptably low loss. A superparamagnetic or field-responsive inclusion can provide force, heating, contrast or motion without behaving as a permanent magnet. IEC 60404-1:2016 with its 2025 amendment classifies magnetic materials [7]. IEC 60404-4 addresses DC measurement of magnetically soft materials in defined closed magnetic circuits [8]. IEC 60404-5:2015 addresses demagnetization curves and recoil behaviour of permanent-magnet materials [9], while IEC 60404-18:2025 covers open-circuit permanent-magnet measurements using superconducting-magnet methods and demagnetizing-field correction [10]. The standards demonstrate why “magnetic strength” is not one number.

Table 1. Six functions that require different evidence

Function	Primary outputs	Mandatory descriptors	Device-level closure	Invalid substitution
Dielectric storage or field shaping	Complex relative permittivity, loss tangent, conductivity, capacitance or resonant response	Frequency; field amplitude; temperature; humidity; direction; electrode/fixture; thickness; density; uncertainty	Capacitance, impedance, field distribution, heating or resonance in final geometry	Powder permittivity or one low-frequency value
Electrical insulation	Leakage, volume/surface resistivity, partial-discharge behaviour or breakdown distribution	Waveform; ramp; electrode edge; medium; thickness; conditioning; failure criterion; population	Margin to field hot spots, interfaces, contamination and ageing in the assembly	Calling a high-k composite an insulator without breakdown evidence
Ferroelectric switching	Switchable/remanent polarization, coercive field, retention, fatigue and imprint	Waveform; rate; leakage subtraction; electrode area; temperature; cycle history; polarization direction	Reversible state and endurance in the actual electrode stack	An open charge–field loop alone
Piezoelectric transduction	Charge/voltage coefficient, coupling, impedance, force, displacement, sensitivity or harvested power	Mode; tensor indices; poling; electrode; preload; frequency; mechanical/electrical load; direction; uncertainty	Calibrated sensor, actuator or transducer response over service conditions	Local piezoresponse or unqualified open-circuit voltage
Permanent-magnet function	Demagnetization curve, remanence, coercivity, energy product and stray-field map	Internal/external field; temperature; orientation; shape/demagnetizing correction; magnetizing history; density	Target field, force or torque with assembled air gaps and tolerances	Filler fraction or saturation magnetization alone
Soft-magnetic or field-responsive function	Permeability/loss loop, force, torque, displacement, stiffness or heating	Frequency; waveform; field amplitude/gradient; direction; temperature; mechanical boundary; cycle rate	Flux, loss, motion or force in the complete magnetic circuit or mechanism	A DC attraction demonstration



Function emerges from phase state, connectivity, orientation, interfaces, activation history and the device boundary.

Figure 1. State-resolved chain from functional requirement to accepted polar or magnetic device.

The chain is intentionally reversible. A weak piezoelectric output is not corrected first by increasing ceramic fraction. The failure may lie in incomplete poling, a compliant interface, electrode resistance, wrong mechanical mode or an impedance mismatch. An incorrect magnetic field is not corrected first by adding NdFeB; part density, magnetization direction, air gap and demagnetizing geometry may dominate. Root-cause work moves backward through device, activation, interfaces, transformation, build, formulation and received material.

3. Material identity and the states that must not be conflated

Functional identity begins before formulation. A material record contains composition, crystal or polymer phase, dopants, stoichiometry, particle-size distribution, morphology, specific surface, agglomeration, surface treatment, moisture, contamination, lot and storage history. ISO/TR 13014 links physico-chemical characterization of engineered nanoscale materials to toxicological assessment [13]; it is a useful prompt for identity and exposure-relevant attributes, not a declaration that one characterization set proves functional performance or safety. A label such as BTO, PZT, ferrite or NdFeB does not close those attributes. Particle size can change dispersion and curing while grain size after sintering controls a different physical scale. Weight fraction cannot be compared with volume fraction without density and porosity. Nominal formulation fraction is not the local active-phase fraction after settling, filtration, drying or binder loss.

At least eight states are separated. The **received state** is the powder, polymer, dispersion or compound as supplied. The **formulated state** includes matrix, dispersant, binder, photoinitiator, plasticizer and solvent. The **printable state** includes temperature, shear history, residence time and sedimentation age. The **as-shaped state** may be a cured composite, a solvent-bearing deposit or a green ceramic. The **transformed state** follows post-cure, drying, debinding, sintering, annealing or infiltration. The **interfaced state** includes electrodes, leads, adhesives, magnetic return paths and mechanical contacts. The **activated state** follows poling or magnetization. The **conditioned service state** includes humidity, temperature, preload, bias and ageing. A property measured in one state cannot be silently assigned to another.

BTO illustrates the problem. In a retained photopolymer composite, ceramic particles remain separated by an organic matrix unless loading and microstructure create other connectivity. The composite can be shaped directly and may provide useful effective permittivity, but it is not equivalent to a dense, sintered BTO ceramic. In a lithography-derived ceramic route, the printed object is a green body; polymer removal and sintering change mass, dimensions, porosity, grains and phase state before electrodes and poling. Smirnov and co-workers demonstrated this full chain for SLA-shaped BTO, including sintering, metallization and poling [20]. Their result supports feasibility for their material and process; it does not convert every BTO-filled resin into a piezoceramic.

PZT adds composition and lead control. Its electromechanical response depends on zirconium/titanium ratio, dopants, calcination and sintering history, phase distribution, grain structure, density, electrodes and poling. A lead-containing powder or green body also creates occupational and waste obligations distinct from a lead-free BTO route. Liu and co-workers demonstrated DLP fabrication of a specified PZT-based system with composition and structure optimization [25]. That evidence is bounded to their chemistry and transformation history.

PVDF and PVDF-TrFE add polymer polymorphism. Polar beta- or related phases, chain orientation, crystallinity, thermal history and mechanical drawing can determine response. Printing can create or destroy the relevant phase. Frick and co-workers demonstrated volumetric printing of PVDF-TrFE-containing films whose response was associated with the printed microstructure [23]. Song and co-workers later demonstrated process-sensitive PVDF devices produced by extrusion [24]. These studies show that “contains PVDF” is not a functional state.

Magnetic powders require an equally detailed identity. A ferrite can be hard or soft depending on composition and microstructure. Iron oxide can be magnetite, maghemite or another oxide with different moment, coercivity and chemistry. An NdFeB grade can be isotropic or anisotropic and can include coatings, rare-earth substitutions and thermal-stability differences. Particle oxidation reduces useful phase and can change safety and interfacial behaviour. In bonded magnets, the matrix fixes particle positions but dilutes magnetic volume and limits service temperature. In consolidated magnets, the thermal cycle can alter grains and phases. Jaćimović and co-workers showed that laser processing of NdFeB changed phase and microstructure while producing a dense net-shape magnet [36]; it is a metallurgical route, not a direct benchmark for a bonded composite.

4. Dielectric response: permittivity, loss and breakdown are coupled but not interchangeable

Complex relative permittivity can be written as a storage component and a loss component. Their ratio is often expressed as loss tangent. Both depend on frequency, temperature, field amplitude, moisture and microstructure. Interfacial polarization can make a heterogeneous composite appear strongly polarizable at low frequency while conductivity and electrode effects inflate loss. At radio frequency (RF) or microwave frequency, different polarization mechanisms and fixture errors dominate. Reporting “dielectric constant” without frequency and loss is therefore insufficient.

A particulate composite is not a weighted average of neat matrix and neat powder values. Local field distribution depends on contrast between phases, particle shape, orientation, interfaces, aggregation, porosity and connectivity. Newnham, Skinner and Cross established connectivity notation for piezoelectric and pyroelectric composites [18]. The same topology discipline is useful for dielectrics: isolated particles in a continuous matrix, connected ceramic networks, laminates and porous ceramics distribute field differently. A higher nominal loading can raise effective permittivity while also increasing particle contact, voids, leakage, optical scattering and process variability.

Castles and co-workers demonstrated microwave characterization of printed BTO/ABS composites [16]. Wu, Isakov and Grant fabricated BTO-containing filaments for fused-deposition printing and measured their dielectric response [17]. These primary studies are evidence that printed polymer–ceramic dielectrics can be engineered and measured. They are not transferable recipes because BTO grade, polymer, loading, porosity, specimen architecture and frequency differ. Their more general lesson is that printing and test direction remain part of the effective dielectric.

The public 3Dresyns HP1 BTO70 page declares a retained BTO-filled photopolymer with typical relative permittivity of 8–9 and loss tangent below 0.04 at 10–20 GHz, while warning that printing, geometry, frequency and post-processing affect performance [15]. Those values can define a candidate-screening hypothesis, not an accepted specification. A receiving programme would verify formulation identity, loading basis, coupon geometry, cure state, frequency fixture, calibration, direction, lot variability and uncertainty. It would then test the intended resonator, capacitor or field-shaping component.

Dielectric loss becomes heat. A resonator, antenna substrate or high-field insulator can fail thermally even when its room-temperature small-signal permittivity meets target. The qualification test therefore monitors temperature and drift at application power. If the electric field is nonuniform, the hottest or most highly stressed local region may be a layer boundary, particle-rich sedimented face, electrode edge or trapped void rather than the nominal bulk.

Breakdown strength usually decreases with defect size, stressed volume and test duration. AM geometries can include corners, supports, layer seams and internal surfaces that are absent from standard coupons. A thin, polished test plaque may be useful for process control but cannot qualify an internal channel beside a conductor. Direct inspection can be supplemented by validated process controls, representative

witnesses, non-destructive evaluation and proof testing where direct access is impossible; impossibility of direct inspection does not eliminate the need for verified evidence.

5. Ferroelectric switching: a loop is an experiment, not a verdict

Ferroelectric materials possess polarization states that can be reoriented by an electric field within a suitable temperature and time domain. In a practical device, the measured current also contains linear dielectric displacement, loss, leakage, charge injection, electrode polarization and parasitic capacitance. Integrating all current during a field sweep can produce a rounded or open loop even when switchable polarization is weak. The report therefore distinguishes **total measured charge, switchable polarization, remanent state, coercive field, leakage** and **non-switching background**.

A defensible switching record declares electrode material and area, specimen thickness, waveform, field amplitude, ramp rate or pulse width, cycle history, temperature, delay, leakage method and uncertainty. Saturation should be demonstrated without confusing electrical breakdown with switching. Pulse sequences that compare switching and non-switching responses can help separate components, but they also rely on repeatable leakage and relaxation. No single subtraction protocol is universally valid for heterogeneous printed composites.

Retained polymer–ceramic composites often experience an unfavourable field partition. A low-permittivity polymer matrix can carry a disproportionate local field while a high-permittivity ceramic particle experiences less of the applied field. Particle interfaces, voids and poor electrodes further distort the field. Increasing ceramic fraction can improve coupling but narrow processability and electrical-strength windows. A measured composite loop must not be described as the powder’s intrinsic loop.

Dense printed electroceramics face a different chain. The green geometry survives only if debinding avoids internal pressure and cracking. Sintering must establish phase, grains and density without unacceptable distortion or volatilization. Electrode firing or deposition must produce stable contact. Poling or switching then acts on this transformed object. Smirnov et al. [20] and Liu et al. [25] show why shape formation is only an early state in an electroceramic process.

Porosity is not automatically a defect or a benefit. Menne and co-workers used DIW of capillary suspensions to create hierarchically porous BTO and reported an enhanced energy-harvesting figure of merit for their architecture [21]. The mechanism combined material, connectivity and geometry. A porous design can reduce permittivity, stiffness or acoustic impedance in ways that benefit one figure of merit while reducing charge, strength or breakdown performance elsewhere. The correct comparison is the accepted device output per constrained volume, mass, load and lifetime—not the largest isolated coefficient.

Ferroelectric ageing includes fatigue, imprint, depolarization, retention loss, leakage growth and electrode degradation. Cycling must use the application waveform and temperature. A memory-like switching device, a tunable RF element and a poled piezoelectric sensor stress domains differently. They cannot share one endurance statement.

6. Piezoelectric transduction: tensor, poling, boundary and device

Piezoelectric response connects electrical displacement and mechanical stress, or strain and electric field. Coefficients carry indices because direction matters. A longitudinal coefficient, transverse coefficient and shear coefficient do not describe the same experiment. The sign and magnitude also depend on axis convention and poling direction. A result without a specimen coordinate system is incomplete.

The commonly reported charge coefficient does not alone determine sensor or harvester output. Voltage sensitivity depends on permittivity as well as charge response. Actuator displacement depends on field, geometry, mechanical constraint and nonlinear behaviour. Electromechanical coupling depends on stored and converted energy under a stated mode. Mechanical quality factor and dielectric loss affect resonant devices. Acoustic impedance, matching layers and backing determine an ultrasonic transducer. The engineering requirement selects the figures of merit before material comparison.

Poling is a manufacturing operation. Its record includes waveform or DC field, temperature, duration, medium, ramp, current limit, electrode configuration, cooling under field and rest time. Field should be expressed through the active thickness, with local field concentration considered. Poling can be incomplete in a thick or heterogeneous composite, can break down at pores, or can relax with temperature and time. A later machining, soldering, sterilization or high-temperature step can depole the component.

Cui and co-workers printed piezoelectric architectures with designed anisotropy and directional response [19]. Their work demonstrates that geometry can transform the effective tensor response beyond a conventional monolithic shape. Sharma and co-workers later combined designed truss topology with additive manufacture of particulate-epoxy piezoelectric structures [22]. These studies validate architecture as a design variable; they do not permit a topology result to be transferred to another constituent system, scale or loading.

Smirnov et al. demonstrated SLA-shaped and subsequently sintered, electroded and poled BTO [20]. Frick et al. demonstrated a volumetrically printed PVDF-TrFE-containing route [23]. Liu et al. demonstrated a PZT-based DLP route [25]. The material systems occupy different positions: flexible retained polymer, retained particulate composite, dense lead-free ceramic and dense lead-containing ceramic. Comparing one reported coefficient across them ignores stiffness, voltage coefficient, bandwidth, processing burden, lead control, geometry, electrodes and device response.

Local piezoresponse-force microscopy can map electromechanical contrast and domains, but a local amplitude can include electrostatic contributions and does not establish a macroscopic device coefficient. A Berlincourt-type quasi-static reading, resonance method, laser-vibrometry displacement and calibrated charge measurement also probe different boundaries. Correlation among structure, coupon response and finished device is stronger than any single technique.

7. Magnetic response: hard, soft and field-responsive systems

Hard and soft magnetic materials solve opposing problems. A permanent magnet seeks high remanence and resistance to demagnetization while delivering useful energy in an external circuit. A soft magnet seeks high, controlled permeability with low coercivity and low dynamic loss. A filler that is attractive to a handheld magnet is not thereby suitable for either device class.

For a hard magnet, the second-quadrant demagnetization curve, intrinsic coercivity, remanence and maximum energy product are measured with demagnetizing-field correction and temperature control. The final external field depends on magnet shape, magnetization vector, air gap, neighbouring ferromagnetic materials and assembly tolerances. Open-circuit field maps and force or torque tests complement material loops. IEC 60404-5 [9] and IEC 60404-18 [10] make the measurement geometry explicit.

Li and co-workers demonstrated large-area extrusion of polymer-bonded NdFeB magnets from a specified high-loading compound [26]. Huber and co-workers demonstrated end-user material extrusion of polymer-bonded rare-earth magnets and three-dimensional field scanning [27], then demonstrated spatial variation of magnetic-compound fraction for a predefined stray field [28]. These studies show that AM can shape both geometry and material distribution. Their values remain tied to powder, matrix, density, toolpath and magnetization history.

Binder jetting offers another bonded-magnet route. Paranthaman and co-workers demonstrated binder-jet fabrication of NdFeB bonded magnets [29]. Photopolymerization provides higher-resolution shapes at different loading and matrix constraints; Huber and co-workers compared stereolithography, fused-filament and selective-laser-sintered polymer-bonded NdFeB systems [30]. Route selection should compare accepted field per cell cycle, density, feature size, debinding or infiltration burden, magnetization access, mechanical integrity and service temperature—not process name alone.

Anisotropic powder adds an alignment gate. Suppan and co-workers placed a magnetic field near an extrusion nozzle and found substantial alignment for one ferrite compound but not for a Sm–Fe–N compound under the available conditions [31]. Sonnleitner and co-workers also examined printing of polymer-bonded anisotropic magnets in an external field [32], and Gandha and co-workers demonstrated anisotropic Sm–Fe–N nylon bonded magnets [33]. The general mechanism is a competition among magnetic torque, viscous resistance, particle interactions, residence time and field gradient. A strong gradient can pull material toward the magnet instead of simply rotating particles.

Kim and co-workers printed ferromagnetic domains in soft materials to program fast, untethered transformations [34]. Here the qualifying output is motion under a specified applied field, mechanical load and cycle history. Permanent-magnet metrics alone do not close the device. Kokkinis, Schaffner and Studart used magnetically assisted multimaterial printing to program particle orientation in composites [35]. Their work shows that magnetic fields can be manufacturing tools even when the final function is not magnetic. Alignment process and delivered function must be labelled separately.

For a soft-magnetic component, static permeability is not enough. Hysteresis, eddy-current and anomalous losses depend on waveform, frequency, peak induction, electrical resistivity, lamination or segmentation, porosity and stress. A polymer-bonded soft-magnetic composite can reduce eddy currents while diluting flux-carrying phase. A dense laser-processed alloy can carry more flux while requiring deliberate geometry to control eddy currents and residual-stress effects. These routes should be evaluated in the intended core and winding assembly.

Superparamagnetic nanoparticles and magnetite-filled soft composites occupy another class. Their response can be useful for local heating, magnetic force, imaging or reconfiguration, but aggregation, oxidation, field gradient, frequency and thermal boundary are decisive. A zero-remanence objective is different from a permanent-magnet objective. The material name *iron oxide* cannot select the class.

Table 2. Representative families, opportunities and invalidation gates

Material or architecture	Functional opportunity	Coupled processing risks	State that must be qualified	Early no-go gate
BTO or related high-permittivity oxide in retained polymer	Printed dielectric, RF field shaping, capacitive element; possible polar response	Viscosity, sedimentation, cure scattering, voids, field partition, loss and brittleness	Fully cured and conditioned composite with final electrodes, direction and frequency	Required loss, breakdown or print stability cannot coexist with target permittivity
Sintered BTO or lead-free electroceramic	Dense dielectric or poled piezoceramic with architected geometry	Green fragility, debinding cracks, shrinkage, phase/grain drift, electrode and poling failure	Sintered, electroded, poled and aged component	Geometry cannot be debound/sintered uniformly or critical internal surfaces cannot be verified
PZT-based transformed ceramic	High electromechanical response and mature transducer concepts	Lead exposure/waste, cure attenuation, volatilization, composition control, depoling	Composition-verified, dense, electroded and poled final device	Lead controls or lifecycle obligations cannot be closed; transformation leaves unstable phase/porosity
PVDF or PVDF-TrFE route	Flexible or conformal sensing, actuation or harvesting	Non-polar phase, thermal-history sensitivity, creep, humidity, electrode strain and depoling	Phase-identified, oriented/poled as required, electroded device under load	Printing does not create or preserve required polar phase and macroscopic response
Ferrite or rare-earth bonded hard magnet	Complex shape, graded fraction or locally controlled easy axis	High viscosity, porosity, particle pull, oxidation, nozzle wear, binder temperature limit	Magnetized final geometry with corrected loop and stray-field/force map	Available field cannot align/magnetize the part or required field cannot survive temperature and opposing load
Soft-magnetic or magnetically responsive composite	Flux guide, low-eddy-current core, force-driven motion or tunable stiffness	Dilution, hysteresis loss, field-gradient nonuniformity, heating, fatigue and particle migration	Complete magnetic circuit or mechanism at waveform, field, temperature and cycle	Coupon attraction or static permeability cannot predict device loss, motion or stability

8. Loading, connectivity, dispersion and orientation

Loading should be recorded by mass and volume, with constituent densities and uncertainty. Functional comparisons on weight fraction alone can mislead when ceramic, metal and polymer densities differ widely. The local fraction after printing may differ from the batch fraction because of sedimentation, filter retention, particle migration, solvent evaporation or segregation across a nozzle.

Connectivity determines which phase carries electric field, stress, flux and heat. Isolated ceramic particles in a polymer form a 0–3-type active architecture; a connected ceramic scaffold infiltrated by polymer creates a different path. Laminates, fibres and lattices create other directional connectivities. Newnham et al. [18] provided the enduring notation that makes these differences explicit. AM expands the architecture space but also increases the number of interfaces requiring verification.

Dispersion is not synonymous with deagglomeration to the smallest possible unit. The target state depends on mechanism. Large agglomerates can clog or scatter light and create weak spots. Excessive milling can change particle surface, contamination, crystal structure or magnetic properties. A dispersant can improve rheology while insulating particle contacts or altering cure. The control plan therefore uses physically relevant proxies: particle-size distribution after mixing, microscopy, rheology, optical working curve, sedimentation profile, local composition and functional response across the vat or cartridge hold time.

Orientation can be created by shear, electric field, magnetic field, gravity, recoating and toolpath. Platelets, rods, polymer chains and anisotropic magnetic particles respond differently. Orientation that benefits one axis can harm another. An extrusion road can align PVDF chains or magnetic particles along flow while layer rotation averages or spatially programs the effect. Cure can freeze orientation; sintering can reduce or transform it; post-print magnetization can align magnetic domains without rotating particle easy axes.

Field alignment must distinguish **particle rotation during shaping, domain switching or poling after shaping, and bulk magnetization of a hard-magnetic part**. They use different fields and mechanisms. A modest field may rotate magnetically responsive platelets in a low-viscosity ink yet be unable to magnetize a high-coercivity NdFeB component. A high electric field can pole a piezoceramic after sintering but would cause breakdown in the uncured suspension. Recording only “field-assisted” is inadequate.

9. Route selection: retained composites, transformed ceramics and magnetic architectures

Retained composites avoid debinding and sintering, preserve polymer toughness or flexibility and allow direct manufacture around inserts. Their main limitation is dilution and field or stress partition between phases. They are attractive when moderate effective permittivity, flexible sensing, distributed low-force actuation or bonded-magnet geometry matters more than dense-ceramic or dense-magnet performance.

Transformed ceramic routes use printing to shape a green body and thermal processing to create the functional ceramic. They can approach high active-phase connectivity and temperature capability, but shrinkage, cracking, warpage, phase evolution, electrode access and brittle reliability dominate. The printer does not deliver the final device; it delivers a precursor whose genealogy must remain linked.

Directly printed functional polymers can eliminate a ceramic transformation but require phase control. PVDF-based extrusion, solution, photoactive and volumetric routes differ in solvent, crystallization, drawing, cure and poling. They should not be grouped by polymer acronym alone.

Bonded-magnet routes include material extrusion, vat photopolymerization, binder jetting and powder-bed fusion of polymer–magnet compounds. They trade density and thermal ceiling for shape, local composition and lower transformation burden. Dense magnetic-metal routes can improve magnetic volume and temperature capability but introduce melting, oxidation, phase and cracking risks. Field-assisted printing adds local orientation but also cell hardware, calibration and force-gradient control.

Hybrid manufacture is often strongest. A high-permittivity retained insert can be printed separately from a poled sintered ceramic; a polymer-bonded magnet can be press-fit behind it; patterned electrodes and a metallic return path can be added by controlled secondary operations. Additive manufacture still supplies geometric integration, but each functional zone can be processed and tested under its own optimum conditions.

Table 3. Route-level benefits, limitations and qualification focus

Route	Main benefit	Principal limitation or hidden burden	Qualification focus
Retained filled photopolymer or thermoplastic	Direct shaping, moderate-temperature processing, local dielectric or magnetic function, possible multimaterial integration	Optical/rheological window, sedimentation, phase dilution, anisotropy, voids, matrix ageing and limited temperature	Lot/hold-time composition; cure or thermal history; direction-resolved dielectric/magnetic response; final interfaces
Printed green electroceramic followed by debinding/sintering	High active-phase fraction, dense ceramic function and architected pores or tensors	Multi-stage shrinkage, cracking, phase/grain drift, brittle handling, electrodes and poling	Green genealogy; thermal mass loss; density/phase/grains; dimensions; electrodes; poling; device response
Directly printed polar polymer	Flexible and conformal function without ceramic sintering	Phase/orientation sensitivity, lower stiffness, creep, environmental drift and electrode strain	Crystalline phase; orientation; poling state; viscoelastic boundary; calibrated device sensitivity and ageing
Polymer-bonded hard magnet	Complex shape, graded loading, local easy-axis or field design, material efficiency	Lower magnetic volume, porosity, viscosity, wear, oxidation and binder temperature ceiling	Density; corrected loops; magnetizing/alignment history; three-dimensional field/force map; thermal demagnetization
Dense or soft-magnetic metal/ceramic route	Higher flux or energy capability and service temperature	Metallurgical transformation, residual stress, phase loss, eddy currents, brittle or corrosion risk	Phase/microstructure; corrected static and dynamic loops; loss under waveform; geometry and cooling in magnetic circuit
Hybrid modular assembly	Allocate dielectric, piezoelectric and magnetic functions to independently optimized zones	More interfaces, tolerance stack, joining, inspection and supply-chain records	Interface adhesion/contact; electrical isolation; magnetic air gap; replaceability; assembled-device test

10. Vat photopolymerization and the green-to-functional transformation

Vat photopolymerization can resolve complex dielectric or piezoelectric geometries, but high-index particles alter the optical process. Cure depth and lateral growth depend on wavelength, absorption, scattering, particle size and refractive-index contrast as well as photoinitiator and dose. Sedimentation changes the local solid fraction over time. A working curve generated on fresh, shallow material may not represent a warm, repeatedly recoated production vat.

Retained composites and transformed ceramics require different process endpoints. For a retained BTO photopolymer, exposure and post-cure establish the final polymer network around the ceramic. Excessive cure can change shrinkage, stress and dielectric loss; insufficient cure can leave extractable species and creep. Cleaning can remove surface resin or drive solvent into pores. The final coupon needs the same build orientation, wash, dry and post-cure as the part.

For a ceramic route, the cured polymer is temporary. High solids can improve green density and reduce shrinkage while reducing cure depth and recoating ability. Debinding must provide paths for decomposition products without exceeding the strength of the porous skeleton. Thick regions, closed cavities and abrupt section changes create internal gradients. Sintering then changes grain size, phase, porosity and dimensions. An excellent green print can fail before becoming an electroceramic.

Smirnov et al. [20] documented the coupling among powder size, paste loading, 465-nm SLA cure, sintering, density and post-poling properties for BTO. Liu et al. [25] showed a DLP PZT route in which precursor selection and doping affected printability and final response. These studies support route feasibility and also show why wavelength, composition and thermal history cannot be removed from the claim.

Electrode accessibility should be designed before printing. A complex internal surface may be printable and sinterable but impossible to metallize uniformly, contact, pole or inspect. Sacrificial conductors, co-firing and conformal deposition can expand access but each creates compatibility risks. Geometry is acceptable when required material can be recovered and critical features can be verified by direct inspection or a validated qualification strategy.

Volumetric printing can create polar-polymer microstructures without conventional layer interfaces. Frick et al. [23] demonstrated a specific PVDF-TrFE-containing photoactive system. The industrial questions include resin stability, optical dose field, feature-to-feature phase uniformity, scale, electrode integration and repeatability. A fast exposure is not equivalent to a qualified cell cycle.

11. Material extrusion, DIW, jetting and field-assisted deposition

Material extrusion imposes thermal and shear histories. In high-permittivity filaments, ceramic loading raises melt viscosity and can create brittle filament, poor road fusion and nozzle wear. In PVDF systems, temperature, cooling, drawing and shear can alter crystalline phase and orientation. In bonded magnets, high powder loading raises torque and pressure while road voids reduce density and remanence. Diameter, moisture, residence time, nozzle condition, flow calibration and toolpath belong to the functional record.

Castles et al. [16] and Wu et al. [17] demonstrated printed dielectric composites; Li et al. [26] and Huber et al. [27,28] demonstrated bonded permanent magnets. The common lesson is that road architecture changes the effective path. A dielectric specimen can be anisotropic because of voids and particle orientation. An isotropic magnetic powder can produce an approximately isotropic local material yet the final stray field still depends on part shape and magnetization.

DIW separates formulation rheology from melt processing and can carry high solids. Shape retention needs yield stress and rapid recovery; extrusion needs manageable pressure and stable flow. Binders and rheology modifiers can insulate particles, alter sintering residue or reduce active fraction. Drying creates gradients and cracks. Menne et al. [21] used these variables deliberately to form porous BTO architectures; their route demonstrates controlled porosity, not a universal instruction to maximize it.

Jetting imposes particle-to-nozzle, viscosity, surface-tension and drying limits. Drop spacing and substrate wetting control line or voxel geometry. Coffee-ring flow and repeated passes can segregate particles. Fine high-permittivity or magnetic powders increase agglomeration and exposure concerns. A printed pixel pattern is not yet an electrode-ready, activated functional device.

Field-assisted deposition can program orientation or magnetic domains. Kokkinis et al. [35] demonstrated local particle orientation during multimaterial printing, and Suppan et al. [31] demonstrated that available alignment conditions worked differently for two magnet compounds. The field is therefore a process variable with a spatial map, calibration, direction, gradient, temperature and timing—not an accessory setting.

Kim et al. [34] printed ferromagnetic domains in soft structures for programmed motion. Such a route requires synchronized material deposition and magnetization encoding. Qualification measures commanded versus actual motion, blocked force, hysteresis, repeatability, thermal response, fatigue and sensitivity to field-position error. An impressive free-motion video is a mechanism demonstration, not an industrial acceptance test.

12. Electrodes, poling, magnetization and interfaces

Electrodes define the electrical boundary and can dominate performance. Material, thickness, roughness, porosity, adhesion, cure or firing temperature, diffusion and edge geometry are recorded. A compliant electrode can preserve a flexible sensor but change strain transfer. A stiff electrode can clamp a thin piezoelectric layer. Contact resistance and parasitic capacitance affect impedance and signal. Electrode area must correspond to the active geometry used to calculate coefficients.

Poling occurs after the active phase and electrodes are ready unless the route deliberately creates a polar state during printing. The field distribution is simulated or bounded when permittivity is heterogeneous. Current is monitored to distinguish polarization from leakage and

incipient breakdown. Cooling under field, short-circuit ageing and stabilization time can affect the measured state. The qualified poling recipe is part-specific when thickness, topology or electrode spacing changes.

Magnetization is distinct from alignment. An isotropic bonded magnet can be shaped first and magnetized in a pulse field. An anisotropic particle needs its easy axis oriented during or after shaping before magnetization can exploit that anisotropy. A locally programmed magnet can require a multi-axis magnetizing fixture or encoded domains. The achievable field must exceed the requirement throughout the part without causing unacceptable heating, force or fixture saturation.

Demagnetizing effects are geometric. A short, wide magnet along its magnetization axis can operate at a different internal field from a long magnet of the same material. Cutting a specimen for a magnetometer changes shape and may change the inferred internal field. The report therefore keeps material-loop measurements, corrected internal fields and final stray-field maps linked but separate.

Mechanical interfaces control piezoelectric stress transfer and magnetic air gaps. Adhesive thickness and modulus can attenuate a sensor. A small gap can reduce magnetic holding force or encoder field. Thermal expansion can preload or debond an electroceramic. Assembly torque, surface preparation, cure and inspection belong in the device genealogy.

13. Measurement architecture and uncertainty

Every measurement begins with a specimen drawing and state label. The drawing includes dimensions, build direction, toolpath, local composition, electrodes, poling or magnetization axis, support-removal surfaces and test contacts. The state label identifies cure, drying, sintering, conditioning, bias and cycle history. Replicates span independent material lots, formulations, builds and positions rather than repeated instrument readings on one specimen.

Dielectric testing reports complex response over the application frequency and field domain. Guarding, open/short/load or resonator calibration, electrode fringing, fixture de-embedding and specimen thickness uncertainty are treated explicitly. A low-frequency parallel-plate result cannot qualify a microwave resonator. Temperature rise and field dependence are measured when power or nonlinearity matters.

Breakdown testing records the population and censoring. A single highest value is not a design allowable. The tested electrode geometry and stressed area/volume are retained. Failure surfaces are examined to distinguish bulk puncture, interface flashover, electrode-edge initiation and pre-existing voids. The application uses a guard band based on its geometry, environment and consequence.

Ferroelectric testing preserves raw voltage and current waveforms. Leakage is measured independently. Switching and non-switching sequences, frequency variation and temperature dependence help test whether the loop represents polarization reversal. Remanence and coercive field are not reported without waveform and cycling state. Local imaging is correlated with macroscopic charge and device response.

Piezoelectric testing names coefficient, indices, sign convention, preload and frequency. Direct-effect charge measurement, converse-effect displacement, impedance resonance and device calibration are not treated as interchangeable. Fixtures are checked for compliance, clamping, cable motion and triboelectric noise. Sensor sensitivity is verified against a traceable mechanical reference; actuator displacement is measured under declared load; harvested power is measured into an optimized and a specified practical load.

Magnetic testing separates intrinsic or material quantities from device quantities. Hysteresis loops declare maximum field, rate, temperature, specimen shape and demagnetizing correction. Hard magnets receive second-quadrant curves and recoil information where relevant. Soft magnets receive dynamic loops and loss separation at application waveform and frequency. Field maps declare probe calibration, orientation, coordinate frame, spacing and environmental magnetic background. Holding force declares counterface material, finish, thickness, gap, alignment and pull direction.

Uncertainty includes instrument calibration, geometry, electrodes or probes, fixture correction, within-build variability and between-lot/build variability. When an inverse field or material model is used, model form, regularization, boundary conditions and non-uniqueness are part of uncertainty. Huber et al. demonstrated both magnetic field scanning [27] and inference of graded compound distribution from external field data [28]; their work also illustrates why external measurements alone may not uniquely recover internal state.

14. Environmental ageing, safety and lifecycle boundaries

Polar and magnetic functions drift under temperature, humidity, bias, stress and time. Polymer matrices absorb moisture, creep and soften. Interfaces debond. Electrodes corrode or migrate. Ferroelectric domains age, fatigue or depole. Permanent magnets lose remanence or coercivity with temperature and opposing field. Soft-magnetic losses change with stress and microstructure. Field-responsive elastomers fatigue and can retain residual deformation.

Qualification chooses stressors from service. A piezoelectric sensor is cycled under representative preload and spectrum while output and impedance are monitored. A dielectric RF component is power-cycled while resonance, loss and temperature are tracked. A hard magnet is tested at temperature and worst opposing field, then mapped after thermal and mechanical shock. A soft-magnetic core is operated under actual waveform, duty cycle and cooling. End-of-test measurements alone may miss intermittent depoling, microcracking or heating.

Lead-containing PZT creates a distinct control boundary. NIOSH identifies occupational exposure limits and health effects for lead and notes that its recommendation applies to lead compounds as lead [38]. A jurisdiction-specific assessment must cover receiving, weighing, mixing, green machining, debinding emissions, kiln maintenance, grinding, waste and contaminated surfaces. A bound finished ceramic

does not erase upstream exposure and end-of-life obligations. Lead-free composition is an important selection benefit only when it also satisfies the required function and its own process hazards are controlled.

Nano/micron powders are task-dependent exposure sources. NIOSH recommends prevention-through-design and ventilated containment for handling engineered nanomaterials, particularly during weighing, transfer and mixing [37]. Its nanotechnology guidance consolidates engineering-control, sampling and safe-work resources [39]. These official sources support hazard recognition; they do not declare every listed powder equally hazardous or provide one universal control set.

Magnetic powders add attraction, pinch, contamination and equipment risks. Fine reactive metals can oxidize or burn; strong magnetizing fields can accelerate loose parts and affect implants or instruments. High-voltage poling and dielectric-breakdown tests require interlocks, current limiting, discharge verification and guarded fixtures. Debinding adds decomposition products; sintering can involve controlled atmospheres and volatile constituents. Route selection compares the entire safe cell, not only the material response.

Critical-material efficiency belongs to the lifecycle analysis. Bonded and additively shaped magnets can reduce machining waste or place rare-earth material selectively, but lower magnetic volume may require more component volume. Repairability, separation of magnetic material from polymer, powder recovery, oxidation and recycling yield should be measured rather than assumed. A sustainability claim needs a defined comparator and system boundary.

15. Applied example: removable condition-monitoring module

Consider a removable module for a sealed industrial gearbox. It must attach reproducibly to a steel inspection pad without drilling, detect a vibration band through a piezoelectric element, maintain electrical insulation between electrodes and housing, survive oil mist and thermal cycling, and reproduce its magnetic holding force and sensor calibration after repeated installation. The design envelope does not require a universal multifunctional material. It requires three controlled functional paths: mechanical vibration into an active element; charge from that element into a shielded electrical interface; and magnetic flux through a defined attachment circuit.

The first candidate is a single BTO-filled photopolymer body described as dielectric, ferroelectric and piezoelectric, with dispersed magnetic powder added for attachment. It is rejected at the concept gate unless evidence shows that both fillers can coexist without unacceptable cure scattering, sedimentation, viscosity, voids, field concentration, magnetic dilution and mechanical damping. Even if it prints, one material couples every change to all three functions and makes root-cause isolation difficult.

The second architecture uses a retained BTO-filled photopolymer as an insulating, dimensionally integrated carrier; a separately printed or conventionally produced poled piezoelectric insert; and a polymer-bonded magnet in a rear pocket against a ferromagnetic return piece. The public 3Dresyns HP1 BTO70 page can nominate the dielectric carrier as a candidate, using its manufacturer-declared RF values only as a screening input [15]. The carrier then receives independent dielectric, loss, breakdown and environmental tests. The active insert is selected among PVDF/PVDF-TrFE, retained BTO composite, sintered BTO and PZT only after bandwidth, sensitivity, stiffness, temperature, lead and assembly constraints are quantified. The magnet is selected by holding-force and field-map requirements, not powder label.

The third architecture prints a green BTO sensor/carrier monolith and transforms it to a sintered, electroded and poled ceramic, with a bonded magnet attached later. It offers a direct ceramic vibration path and complex electrode geometry, but must pass debinding, sintering distortion, brittle attachment, electrode access and impact gates. It is attractive if the transformed geometry supplies a measurable advantage over an inserted conventional element; otherwise the extra transformation risk has no compensating value.

For illustration, suppose the device specification prioritizes calibration stability, replaceability and moderate temperature over minimum part count. The modular second architecture survives the initial screen because each function has an independent test and replacement path. A lead-free BTO or PVDF-based sensor route remains preferred if it meets sensitivity and temperature; PZT remains conditional on a documented performance need and closed lead controls. A ferrite bonded magnet may be sufficient if holding force and temperature margin pass; NdFeB is retained only if volume or field constraints require it.

The route is not accepted on coupons alone. The dielectric carrier is tested after full cure and oil/thermal ageing. The piezo insert is calibrated after bonding because adhesive modulus and thickness change stress transfer. The magnetic circuit is mapped and pull-tested with the actual steel counterface, coating, gap and temperature. The assembled module is installed repeatedly, and calibration drift, attachment position, cable strain and sealing are measured as one system.

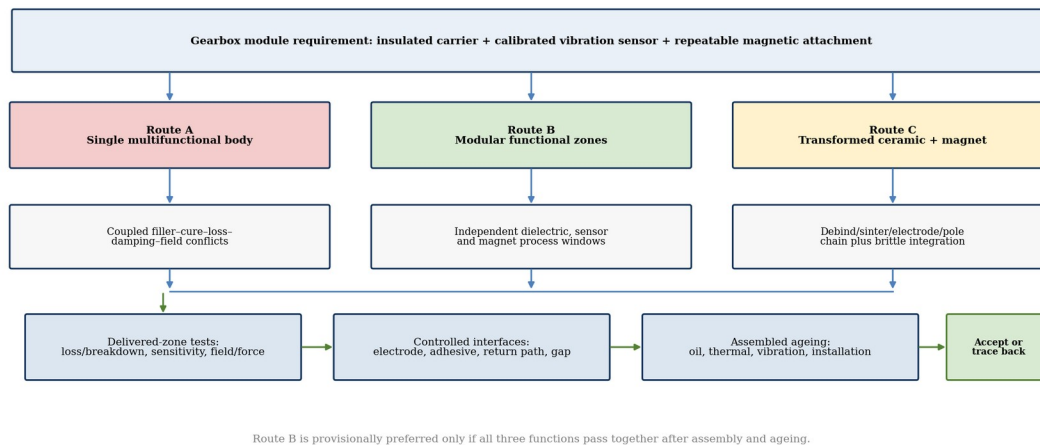


Figure 2. Gate logic for allocating dielectric, piezoelectric and magnetic functions in the removable module.

This example demonstrates a general principle. Multimaterial integration is valuable when it makes conflicting physics inspectable and change-controlled. A reduction in part count is not automatically a reduction in risk. The most integrated route is selected only when it offers a verified device advantage that exceeds its coupled process burden.

16. Qualification genealogy and change control

A qualified product links nine records. The **requirement record** defines function, input, output, geometry, direction, environment, comparator and guard-banded limit. The **material record** identifies phase, composition, particle, surface, matrix, lot and storage. The **formulation record** captures mass and volume fractions, mixing, dispersion, rheology, stability and hold time. The **build record** captures equipment, optics/nozzle, layer, toolpath, position, temperature and any field map. The **transformation record** captures cure, wash, dry, debind, sinter and anneal. The **interface record** captures electrodes, leads, adhesive, magnetic return path, gaps and preload. The **activation record** captures poling, alignment and magnetization. The **test record** preserves methods, raw data, uncertainty, failures and ageing. The **disposition record** links accepted products and deviations to authorized evidence.

Change control follows physics. A new BTO supplier, particle distribution, surface treatment, dispersant or matrix can change rheology, optical cure, field partition and loss. A new PZT composition or sintering setter can change phase, volatilization, density and poling. A new PVDF lot or cooling profile can change crystalline phase. A new NdFeB powder, coating or magnetizing fixture can change coercivity, orientation and field. Software and toolpath changes can alter local loading, voids and direction.

Reference coupons accompany production but do not replace the product. A dielectric plaque cannot detect an electrode-edge defect in the device. A piezoelectric disc cannot detect adhesive stress-transfer loss. A magnetic cube cannot detect the assembled air gap. Witnesses are placed across build position and time and are tied to device tests through validated correlations.

Table 4. Minimum linked evidence for industrial qualification

Record	Controlled content	Required functional evidence	Change that reopens qualification
Requirement and architecture	Function, mode, direction, waveform/frequency, field, load, environment, comparator and limit	Approved allocation of dielectric, polar, piezoelectric and magnetic paths with no-go criteria	New device geometry, load, frequency, field, temperature, air gap or failure consequence
Material and formulation	Phase/composition, particle/nanoform, surface, matrix, lot, mass/volume fraction, mixing and stability	Identity, local fraction, dispersion/orientation proxies, rheology, optical/thermal window and safety controls	Supplier, grade, dopant, coating, fraction, dispersant, sequence, ageing or storage
Build and transformation	Machine, nozzle/optics, path, layer, position, cure, drying, debinding, sintering and annealing	Dimensions, density/porosity, phase, grains, defects and direction-labelled functional coupons	Hardware, software, field fixture, geometry, exposure, thermal profile or atmosphere
Interface and activation	Electrodes, leads, adhesive, return path, air gap, preload, alignment, poling and magnetization	Contact/adhesion, field distribution, activation uniformity and representative subassembly response	Electrode, adhesive, surface, gap, fixture, field, temperature, time or assembly sequence
Test, ageing and disposition	Raw waveforms, drawings, method, conditioning, uncertainty, population, failures and authorized limits	Initial/aged coupon, subcomponent and complete-device conformity with traceable disposition	Fixture, laboratory, conditioning, cycle spectrum, cleaning, repair or service boundary

Statistical control selects causal signals. Useful variables include slurry viscosity after a defined shear history, cure working curve, sedimentation profile, deposited mass, green density, debinding mass-loss signature, sintered density and phase, electrode resistance, poling current, resonance impedance, dielectric loss at sentinel frequencies, magnetizing pulse, field-map residual and holding force. A mean value can remain stable while spatial variability or tails worsen; acceptance monitors distribution and guard bands.

No model replaces validation. Effective-medium, finite-element, micromagnetic, acoustic and inverse-field models can screen architecture and define sensitive variables. Their inputs, meshing, boundary conditions and calibration domain are controlled. A model is revalidated when material, geometry or interface leaves that domain.

17. Discussion, route trade-offs and conclusions

The principal advantage of functional-material AM is not that any filler can be printed. It is that geometry, connectivity, composition and orientation can be designed together. High-permittivity regions can be placed where electric field is useful. Piezoelectric architecture can

redirect effective response. Permanent-magnet fraction or easy axis can be spatially programmed. Magnetic force can drive a printed soft mechanism. Internal cavities, matching structures and return paths can be integrated.

Every advantage has a coupled loss. Higher ceramic loading can improve effective response while degrading cure, flow, strength and breakdown. Sintering can restore active-phase connectivity while adding shrinkage and brittle risk. Alignment can improve one axis while increasing process complexity and nonuniform force. Rare-earth magnets can reduce volume while raising oxidation, critical-material and magnetization burdens. PZT can provide strong electromechanical performance while adding lead control and lifecycle obligations. Flexible PVDF-based routes can simplify integration while making phase, creep and temperature central.

The literature demonstrates mechanisms, not universal rankings. Castles et al. [16] and Wu et al. [17] show printable dielectrics; Cui et al. [19], Smirnov et al. [20], Menne et al. [21], Sharma et al. [22], Frick et al. [23] and Liu et al. [25] show different paths to polar or piezoelectric function. Li et al. [26], Huber et al. [27,28,30], Paranthaman et al. [29], Suppan et al. [31], Sonnleitner et al. [32], Gandha et al. [33], Kim et al. [34], Kokkinis et al. [35] and Jaćimović et al. [36] show different magnetic shaping, alignment, programming and consolidation routes. Their values cannot be pooled because their material states and device boundaries differ.

Eight conclusions follow.

- **Function precedes composition.** Permittivity, switching, transduction, hard-magnetic energy, soft-magnetic loss and field-driven motion require different inputs, outputs and tests.
- **The delivered state is the unit of comparison.** Received powder, printable feedstock, green body, cured composite, sintered ceramic, electroded part, poled element and magnetized assembly are not interchangeable states.
- **Loading is not connectivity.** Mass fraction alone cannot describe electric-field partition, stress transfer, ceramic paths, magnetic volume or voids; local volume fraction and architecture are required.
- **Orientation, poling and magnetization are distinct.** Particle rotation, domain activation and final magnetization use different fields, temperatures, times and acceptance evidence.
- **A favourable coupon cannot close a device.** Electrodes, adhesive, preload, magnetic air gap, return path, waveform, frequency and ageing can dominate the finished response.
- **Lead-free is a system decision.** Avoiding PZT can reduce a major hazard and lifecycle burden, but the alternative must still meet function and have its own process controls; PZT use requires a documented need and closed controls.
- **Hybrid modularity can outperform maximum integration.** Separating dielectric, piezoelectric and magnetic zones can improve process windows, inspection, replacement and root-cause control even when it increases part count.
- **Qualification preserves causality.** Requirement, material, formulation, build, transformation, interface, activation, test and disposition records must remain linked through change control.

The selection framework is designed to expose invalid assumptions before they are hidden behind *high-k*, *ferroelectric*, *piezoelectric*, *magnetic* or a favourable isolated number. A route is technically credible only when the mechanism survives formulation and printing, the required activation reaches the full geometry, interfaces transmit the intended field or stress, uncertainty fits the decision, and the aged assembled device still performs its declared function.

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