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Electromagnetic Pulse Interference and Compatibility of In-core and Ex-core Reactor Instrumentation (A Technical Memorandum)

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Abstract: The measurement channel of a fission reactor extends beyond its neutron or temperature sensor. Its MI (mineral-insulated) cable, vessel penetration, under-vessel transition, grounding arrangement, receiver, power supply, and logic all contribute to the validity of the indicated value. This memorandum examines EMI (electromagnetic interference), EMC (electromagnetic compatibility), and EMP (electromagnetic pulse) for SPNDs (self-powered neutron detectors), thermocouples, LPRMs (local power range monitors), WRNMs (wide-range neutron monitors), and ex-core channels. The central engineering conclusion is that passive sensors and metal sheaths reduce some coupling but do not establish channel immunity. A plant-specific, end-to-end assessment must address conducted and radiated coupling, shared references, transient recovery, and failures common to redundant channels [1-5].

Key words: EMP (electromagnetic pulse), EMC (electromagnetic compatibility), EMI (electromagnetic interference), in-core instrumentation, ex-core neutron monitoring, SPNDs (self-powered neutron detectors), LPRMs (local power range monitors), WRNM (wide-range neutron monitoring), mineral-insulated cables, signal integrity.

1. Scope and Terminology

EMI (electromagnetic interference) denotes unwanted electromagnetic energy that changes a measured signal or the behavior of its electronics. EMC (electromagnetic compatibility) denotes the ability to function in the specified electromagnetic environment while maintaining acceptable emissions and immunity. EMP (electromagnetic pulse) denotes a short, intense electromagnetic transient. An external high-altitude nuclear EMP is one scenario; lightning, switching, electrostatic discharge, and local pulsed equipment create other transient environments with different waveforms and coupling paths. These phenomena should not be assigned one universal test level [1, 3, 4].

"HITC" is interpreted here as a high-temperature in-core thermocouple channel. "Singles" is interpreted as signals or signal leads. Equipment-specific meanings, safety classification, detector placement, grounding, and test levels require the applicable plant drawings and design basis. The discussion addresses electromagnetic signal integrity, not detector radiation qualification or the full reactor safety analysis. See Fig. 1, where the image illustrates EMP, EMI, and EMC across a reactor measurement channel, from in-core and ex-core detectors through MI signal cables to the instrumentation cabinet.

2. Physical Coupling from Core to Cabinet

The in-core detector is immersed in an intense neutron and gamma field, yet much electromagnetic pickup enters outside the active detector region. A typical path includes an MI coaxial or multi-conductor segment, vessel penetration, under-vessel cable or

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connector, transition to flexible cable, junction box, and remote electronics. Current can couple capacitively between adjacent conductors, inductively through loop area, conductively through shared grounds and power, or by fields entering an enclosure or discontinuous shield. NRC (Nuclear Regulatory Commission) research explicitly identifies conducted susceptibility along interconnecting signal lines as a concern for safety-related I&C [2].

An intact metallic MI sheath offers electrostatic shielding, environmental containment, and a defined return or reference path according to design. It is not an ideal shield at all frequencies. It's transfer impedance, seams and terminations, bend damage, corrosion, moisture barriers, and how the sheath bonds to structures affect performance. A cable may pass a room-temperature continuity test yet develop elevated leakage or intermittent contact under thermal, vibratory, or wet conditions. Radiation-induced currents and insulation degradation can further complicate the low-level signal baseline; they should be separated analytically from EMI rather than labeled as the same mechanism. See Fig. 2, where the image illustrates capacitive, inductive, conducted, and radiated interference along the reactor measurement path from the in-core detector through MI cables to the instrumentation cabinet.

2.1 Common Mode and Differential Mode

Common-mode disturbance raises a conductor pair or coaxial assembly relative to the receiving cabinet. Finite receiver rejection, asymmetry, and imperfect shield termination convert some of that disturbance into differential voltage or current. Differential-mode disturbance is coupled directly between measured conductors. A transient can also saturate an input amplifier or analog-to-digital converter without permanently damaging it. Recovery time then becomes a safety-relevant performance measure, particularly where monitoring supports a trip or protective action. Input filtering must be designed against the channel's required bandwidth and response time; indiscriminate filtering can suppress a real event. See Fig. 3.

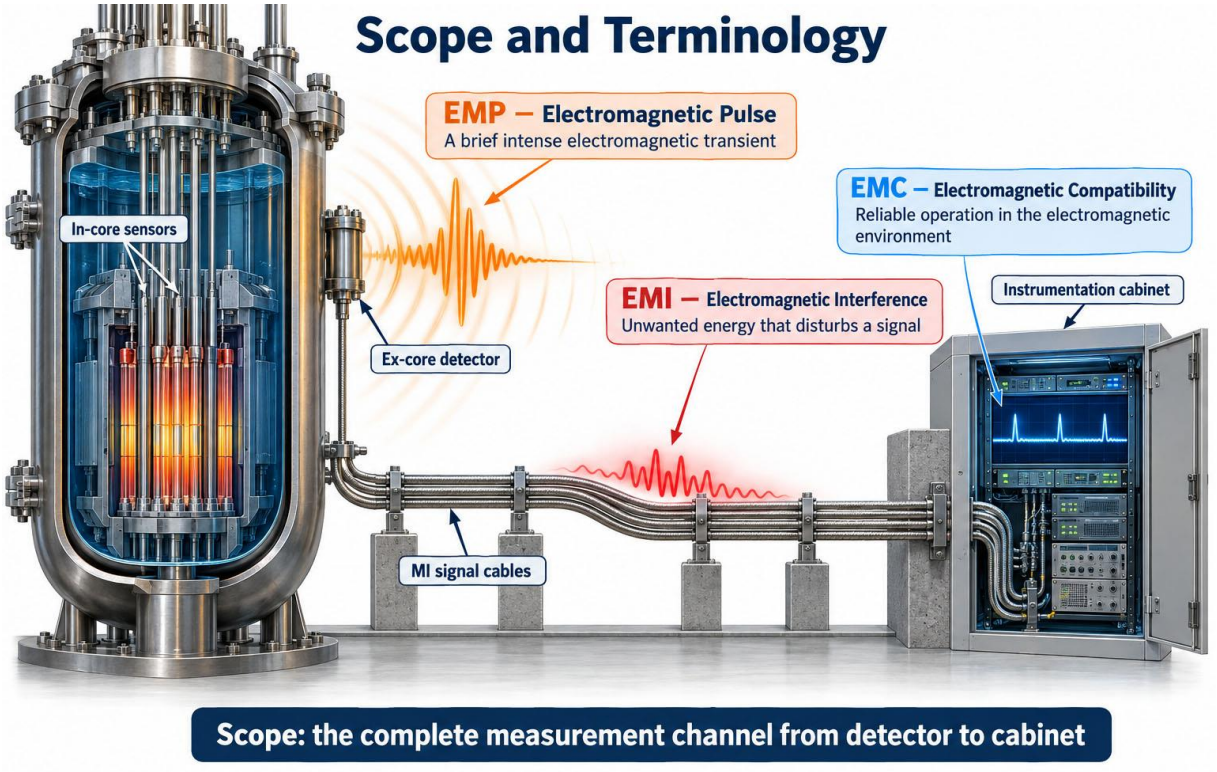


Fig. 1 EMP, EMI, and EMC in reactor instrumentation from core to cabine.
(Source: AI generated image by authors)

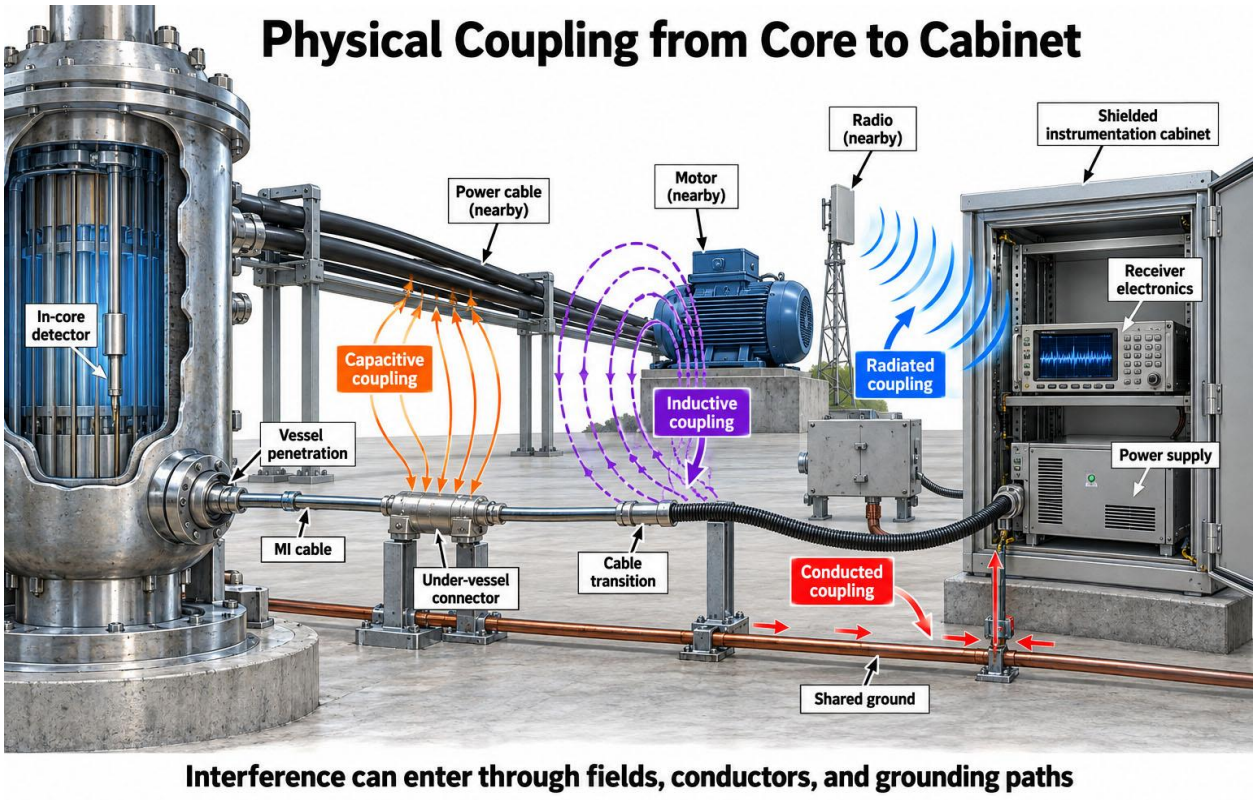


Fig. 2 Electromagnetic coupling paths from reactor core to instrumentation cabinet.
(Source: AI generated image by authors)

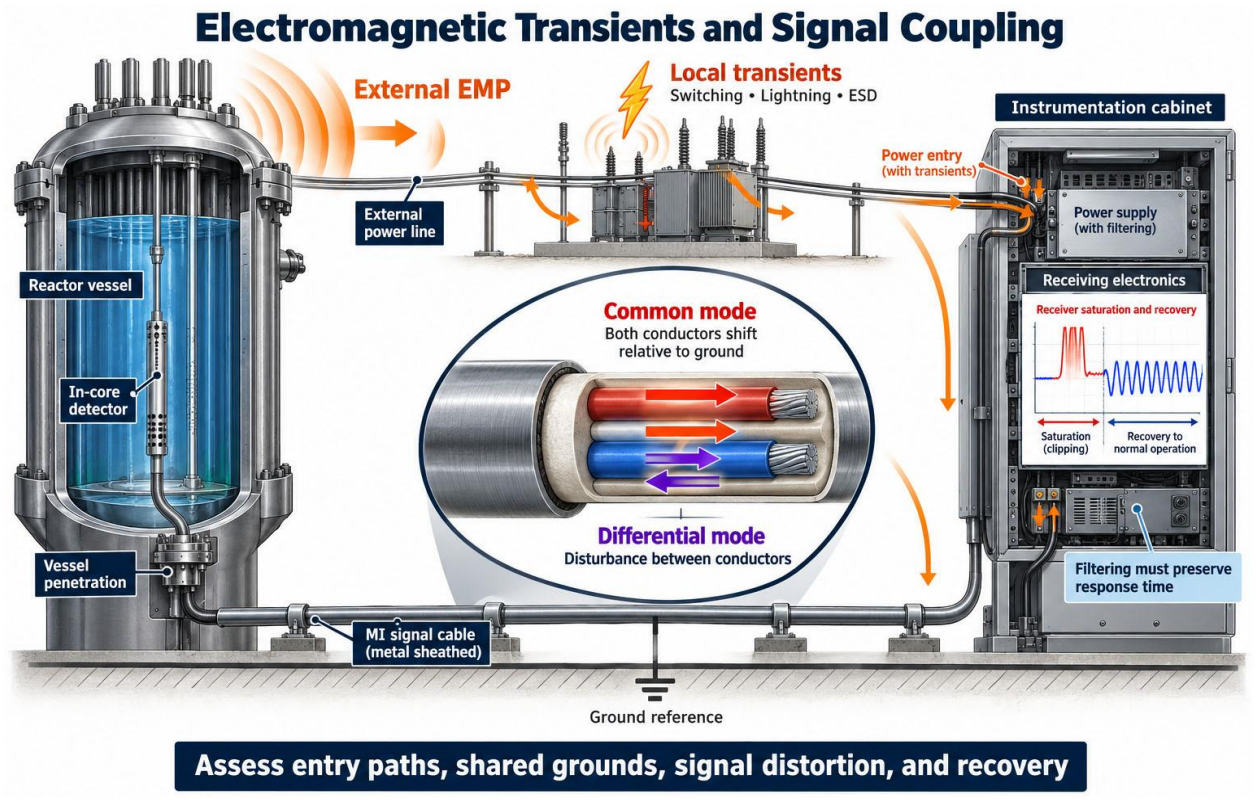


Fig. 3 EMP and local transients in reactor instrumentation: Common-mode and differential-mode coupling.
(Source: AI generated image by authors)

2.2 External EMP and Local Transients

For a high-altitude EMP, entry through long external conductors, power systems, communications, and structural paths can dominate; the core vessel and containment provide shielding but do not justify assuming immunity for a complete instrument channel. Sandia tested secondary coupling onto nuclear plant instrumentation cables in early-time HEMP configurations [4]. A plant analysis should trace primary entry, cable-to-cable transfer, cabinet susceptibility, power supply upset, and the potential simultaneous loss or misreading of multiple channels. Local switching and lightning can be assessed separately with their own credible waveforms and locations. See Fig. 3.

3. Instrument-Specific Behavior

SPNDs (self-powered neutron detectors), thermocouples, LPRMs (local power range monitors), and WRNMs (wide-range neutron monitors) respond differently to electromagnetic interference because they measure different signal types and use different processing methods.

Each channel requires suitable shielding, grounding, filtering, and verification to maintain measurement accuracy and the required response time.

3.1 Rhodium and Vanadium SPNDs

A Rh (Rhodium) or V (Vanadium) SPND produces a small electrical current through neutron-induced processes. The IAEA describes delayed emitter response associated with Rh and V activation and a coaxial lead to the current meter [5]. Hence an abrupt electrical excursion is not equivalent to an abrupt change in the delayed neutron component. Cable-generated background and gamma contributions, emitter depletion, insulation leakage, and receiver offset also need separate treatment. Compare a suspected event with spatially adjacent detectors, independent neutron channels, and the known dynamic response before attributing it to flux.

The current receiver should be assessed for input bias, shielding, leakage, common-mode range, surge withstand, overload recovery, and channel diagnostics. Background-compensation conductors, if provided, require matched routing and their own continuity and leakage evaluation. A compensating lead does not automatically cancel an EMP-induced transient: the two paths can differ in impedance and exposure.

3.2 Thermocouples and HITC

A thermocouple develops a small voltage at the junction of dissimilar metals. The channel includes extension materials, transition junctions, cold-junction compensation, and an input configured for either an isolated or grounded sensing junction. A spurious junction or sheath-to-conductor contact can cause an error that resembles a real temperature shift. Ground loops and common-mode voltages matter especially where a grounded junction or shared structural reference is used. Differential sensing, controlled reference practice, and suitable filtering must be demonstrated for the actual arrangement rather than specified generically.

3.3 LPRM and WRNM

An LPRM in the BWR context is a fission-chamber channel, not a Rh/V SPND. Signal levels, counting or current processing, cable impedance, and preamplifier placement determine susceptibility. Interference may appear as false counts, baseline shifts, power oscillation, or a receiver fault. WRNM spans multiple decades of neutron level; low-count conditions and range or processing transitions deserve separate tests. A design-specific review should establish whether a WRNM detector is in-core or ex-core and which channel functions are safety related. Electromagnetic performance must be evaluated at the

detector, cable, receiver, and derived indication or trip output.

4. Ex-core Instruments and Under-vessel Interfaces

Ex-core neutron channels are outside the reactor vessel and typically have a different radiation and electromagnetic environment from in-core channels. Long cable runs, nearby power equipment, cabinet penetrations, and grounding transitions can control their susceptibility. The outer detector may be physically remote from a disturbing source while its signal lead or receiver shares a raceway or ground reference with that source. Channel-by-channel route drawings and field measurements are therefore more useful than assumptions based on detector location alone.

For an in-core assembly, the under-vessel region is a critical interface. It may contain the pressure-boundary penetration, MI-to-flexible cable transition, connectors, strain relief, supports, moisture seals, and densely routed independent channels. A discontinuity in sheath bonding or a compromised connector can convert a shielded in-core path into a sensitive pickup point. Temperature, coolant leakage, condensation, vibration, maintenance handling, and irradiation history should be considered alongside electrical measurements. Connections must preserve the qualified pressure-boundary and environmental functions; an EMC modification cannot bypass those requirements.

4.1 Grounding and Separation Principles

A single-point or multipoint shield bond is not universally correct. The choice depends on frequency, sheath function, safety isolation, plant grounding topology, and the vendor's qualified interface. Document which metal sheath, drain, signal return, and enclosure is bonded at each end; distinguish intentional bonds from accidental ones. Control loop area, route low-level signals away from high-energy conductors where feasible, and maintain the applicable separation and independence of redundant safety divisions. NRC RG 1.75 addresses independence of electrical systems; the electromagnetic assessment of safety-related I&C is addressed by RG 1.180 [1, 6].

A common cabinet ground, shared power supply, or shared cable tray may defeat apparent detector redundancy under a fast disturbance. Conversely, unnecessary isolation or a floating sheath can create high common-mode voltage, unreliable surge return, or a personnel hazard. Every proposed bond, filter, isolator, or surge device should be checked against channel accuracy, timing, leakage, environmental qualification, and fault behavior. The regulatory status and adopted revision of any guidance must be confirmed for the licensing basis of the specific plant.

See Fig. 4, where the image shows ex-core detectors and in-core instruments connected to the instrumentation cabinet through shielded cables and under-vessel interfaces.

It highlights vessel penetrations, sealed connectors, MI cable transitions, moisture barriers, grounding, and separate channel routes that help preserve signal integrity. See Table 1 for more granular descriptions as well, where the table compares reactor instruments and signal paths according to their measurements and main electromagnetic compatibility concerns. It identifies current errors in Rh/V SPNDs, voltage errors in thermocouples, signal distortion in LPRMs and WRNMs, and interference along ex-core cable runs. It also highlights under-vessel connectors and MI cable transitions, where shielding, moisture protection, insulation resistance, and grounding affect signal integrity.

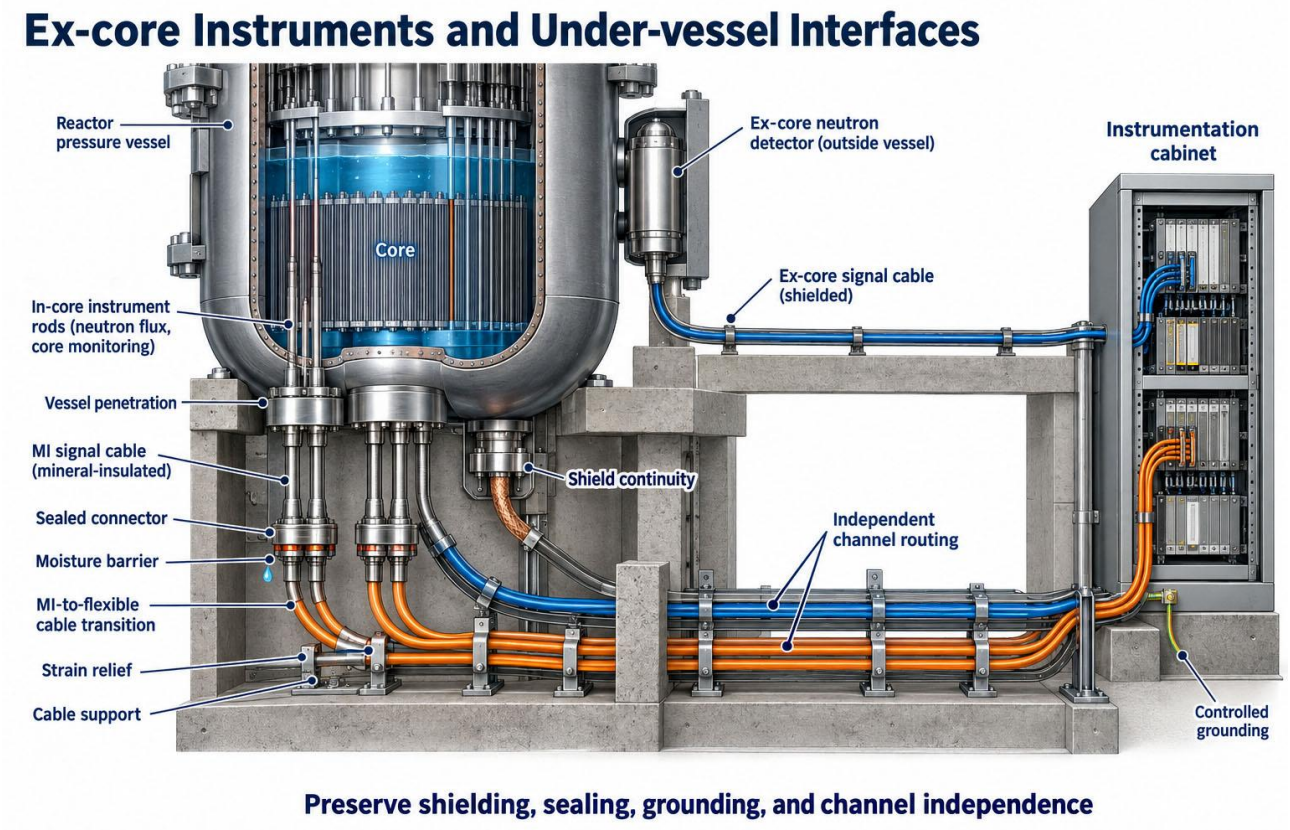


Fig. 4 Ex-Core instrumentation and under-vessel signal interfaces.
(Source: AI generated image by authors)

Table 1 Reactor instrumentation and signal paths: Measurements and principal EMC concerns.

Instrument or path	Measurement and principal EMC concern
Rh or V SPND	A rhodium or vanadium *self-powered neutron detector* produces a small current. Leakage, cable-generated background current, or coupled noise can bias the reading; a sharp transient can overload the current-measurement electronics. Rh and V also have different delayed responses to a real flux change, which must be distinguished from an electrical spike. (nucleus.iaea.org)
HITC/thermocouple channel	If by HITC you mean a high-temperature in-core thermocouple, the measured quantity is a small thermoelectric voltage. A ground loop, an unintended junction at a transition, or coupled common-mode voltage can appear as a temperature error. The exact arrangement matters: a two-wire isolated junction and a grounded junction need different input treatment.
LPRM	A local power range monitor uses an in-core fission chamber, rather than a Rh/V SPND. Cable pickup or a receiver upset can distort its neutron-rate signal or create a false excursion. The assessment must cover the chamber, coaxial path, preamplifier/input, and downstream power calculation together.
WRNM	Wide-range neutron monitoring spans very different signal levels and processing modes. Susceptibility should be checked in each operating range, particularly around range transitions and during low-count operation; the detector's physical location and cable route are design specific.
Ex-core neutron channels	These detectors sit outside the core and may use long runs to remote electronics. Nearby power equipment, cabinet wiring, and cable transitions can therefore be more consequential than direct pickup at the detector.
Under-vessel MI cables and signal leads	The under-vessel region concentrates penetrations, connectors, cable bends, supports, and transitions from MI to other cable types. Each transition deserves attention for shield continuity, moisture intrusion, insulation resistance, and unintended sheath-to-ground connections.

Table 2 EMC verification stages, required evidence, and acceptance criteria for reactor instrumentation.

Stage	Evidence to retain	Acceptance question
Channel map	Schematics, cable schedule, penetration and bond drawings	Where can energy enter or pass between divisions?
Baseline	Signal noise, leakage, insulation resistance, background current	What is normal across operating states?
Disturbance tests	Conducted, radiated, surge and power-port results	Does the channel remain within its function limit?
Recovery	Waveforms, logs, alarm/trip timing	Does valid indication return in the allowed time?

5. Qualification and Verification Program

A credible EMC demonstration begins with a functional requirement for each measurement, including permissible error, false alarm probability or criterion, trip response, availability, and recovery after a disturbance. It then characterizes the environment at the installed location rather than applying an arbitrary generic exposure. NRC NUREG/CR-6431 addresses operating envelopes and test criteria for EMI/RFI and surge withstand [3]. Canadian reactor design guidance explicitly calls for electromagnetic conditions affecting equipment and cables and limits on conducted and radiated emissions [7]. See Table 2, where the table outlines four stages for verifying electromagnetic compatibility: mapping the measurement channel, establishing normal signal behavior, testing disturbances, and assessing recovery. For each stage, it identifies the evidence to retain and the acceptance question used to determine whether the channel maintains its required function and restores valid indication within the allowed time.

Testing should include representative cable length, routing, shield terminations, enclosure, receiver input, power supply, and realistic loads. Apply disturbances at accessible interfaces using approved test procedures and controlled injection levels; do not inject transients into an operating plant instrument without an authorized plant test plan. Observe raw detector input where feasible, processed indication, alarm and trip output, diagnostic flags, and adjacent channels. Assess sensor operating states such as startup, low-count monitoring, full-power flux, and thermal transients.

Credible degraded states include a high-resistance shield connection, insulation leakage, connector moisture, and one failed channel, if consistent with the plant design basis. Acceptance must cover measurement error and recovery, not only absence of hardware damage. Correlated errors matter: a disturbance that causes two channels to agree on the same false value may evade simple voting logic. Any test of a safety channel must preserve plant technical specifications and approved maintenance controls.

5.1 Separating Electromagnetic from Physical Phenomena

Review the timing and spatial pattern of an anomaly. A simultaneous spike across dissimilar detectors and cabinet diagnostics may point to common electrical coupling. A gradual Rh/V SPND response, consistent ex-core neutron indication, and process-variable agreement may support a true flux change. These are diagnostic inferences, not proof. Preserve high-rate waveforms and event logs to test alternative explanations, including cable leakage, sensor failure, actual process change, and software or power-supply upset.

6. Conclusions and Design Actions

The relevant unit of EMC analysis is the complete measurement channel. In-core location and a metallic MI cable do not guarantee that a Rh/V SPND, thermocouple, LPRM, or WRNM will produce a trustworthy indication under EMI or an EMP. The transition under the vessel, long ex-core routes, cabinet input, power supply, and shared grounding can determine the result. Channel-specific performance limits and a documented electromagnetic environment are prerequisites to a meaningful qualification claim.

For a new design or modification, first issue an end-to-end signal-path and grounding drawing for every instrument type. Next identify safety functions and

credible electromagnetic sources, characterize the installed cable and cabinet configuration, and establish pass/fail criteria for accuracy, false action, missed action, and recovery. Verify with integrated tests that preserve qualified cable, penetration, and division boundaries. Finally, retain the baseline and test evidence so that future connector repairs, rerouting, and electronics changes trigger a focused EMC reassessment.

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