Journal of Energy and Power Engineering 20 (2026) 58-65
doi: 10.17265/1934-8975/2026.02.003

Core Instrumentation and Monitoring Architecture for High-Temperature Gas-Cooled Small Modular Reactors: Safety, Routine Operation, TRISO Fuel Surveillance, Digital I&C, Artificial Intelligence, and Digital Twins

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Abstract: HTGR-SMRs (high-temperature gas-cooled small modular reactors) combine coated-particle fuel, graphite moderation, helium cooling, high outlet temperature, and passive decay-heat removal. These attributes substantially change the instrumentation problem relative to light-water reactors. The principal safety variables are not water level and departure from nucleate boiling, but reactivity, three-dimensional power distribution, peak TRISO (tri-structural isotropic) fuel temperature, helium inventory and flow, graphite and vessel temperatures, coolant chemistry, air or water ingress, fission-product transport, and continued availability of passive heat-rejection paths. This paper develops a technology-informed instrumentation and monitoring architecture for prismatic-block and pebble-bed HTGR-SMRs intended for civilian grid, defense, or space-related missions. It connects measured variables to routine control, reactor protection, post-accident monitoring, fuel qualification, probabilistic risk assessment, and safety-analysis acceptance criteria. The paper recommends independent safety, control, diagnostic, radiation-monitoring, and advisory analytics layers; discusses digital common-cause failure, cybersecurity, human factors, and environmental qualification; and defines an appropriate role for artificial intelligence and digital twins. A licensing traceability matrix is proposed so that every credited initial condition, trip function, operator action, and accident-analysis acceptance criterion is supported by qualified instrumentation or a conservative analytical basis. The resulting framework is suitable for early system requirements, a phenomena identification and ranking process, and preparation of a technology-inclusive safety analysis report.

Key words: High-temperature gas-cooled reactor, small modular reactor, TRISO, reactor protection system, helium coolant, digital instrumentation and control, artificial intelligence, digital twin, Chapter 15 safety analysis, advanced reactor licensing.

1. Introduction

HTGR-SMR (high-temperature gas-cooled small modular reactor) concepts are attractive for electricity generation, industrial heat, hydrogen production, remote installations, defense energy resilience, and selected space-power missions. Their safety case normally rests on low power density, high graphite heat capacity, a large negative temperature coefficient, chemically inert helium, high-integrity TRISO-coated fuel particles, and passive heat transfer from the core to the reactor vessel and ultimate heat sink. Instrumentation must demonstrate that these favorable characteristics remain available during startup, normal operation, anticipated operational occurrences, design-basis events, and risk-significant beyond-design-basis sequences.

The phrase "NRC (Nuclear Regulatory Commission) Part 15" is sometimes used informally, but the relevant concept is normally Chapter 15, "Transient and Accident Analysis", of a safety analysis report or the

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corresponding Standard Review Plan material. There is no standalone reactor-safety regulation called NRC Part 15. For an advanced non-light-water reactor, the event set, safety functions, safety classification, and defense-in-depth evaluation should be developed through the applicable licensing framework, including RGs (Regulatory Guides) 1.232 and 1.233 and the ARCAP (Advanced Reactor Content of Application Project) guidance [1-3]. NRC licensing applies directly to a commercial civilian facility under its jurisdiction. A Department of Energy, Department of Defense, or space mission reactor may be governed by a different authorization authority; nevertheless, the measurement principles and defense-in-depth architecture presented here remain technically useful.

Instrumentation requirements must therefore be derived, not copied from a LWR (Light Water Reactor). The derivation begins with licensing-basis events, required safety functions, mechanistic source-term assumptions, TRISO fuel performance limits, thermal-fluid phenomena, human actions, and PRA importance. The output is a measurement-to-action chain with specified range, accuracy, response time, reliability, independence, qualification, surveillance, calibration, and uncertainty.

2. Safety Functions and Measurement Philosophy

The monitoring design should demonstrate five fundamental safety functions: control of reactivity; removal of heat from the fuel during operation and after shutdown; retention of radioactive material within the TRISO particles and subsequent barriers; preservation of geometry and heat-transfer paths; and provision of information needed for reliable operator action. These functions lead to the measurement objectives summarized in Table 1.

A measurement credited in the safety analysis must be treated differently from a useful diagnostic. Its sensing element, signal conditioning, logic, power supply, communication path, display, actuation interface, calibration, and setpoint calculation all belong to the credited chain. Conversely, a non-safety diagnostic may improve availability without being required to meet a safety acceptance criterion. This separation prevents useful analytics from unintentionally becoming unqualified safety dependencies.

3. Layered Instrumentation and Control Architecture

A defensible design separates the RPS (reactor protection system), engineered safety-feature actuation, post-accident monitoring, plant control, equipment protection, condition monitoring, and advanced analytics. Physical, electrical, functional, and communication independence should be commensurate with the safety classification and common-cause-failure evaluation. Four measurement divisions with two-out-of-four voting are a reasonable starting concept, but the final channel count and voting logic must follow reliability analysis, spurious-actuation consequences, maintenance strategy, and PRA results.

Table 1 Safety objectives and associated measurement functions.

Safety objective	Measured or inferred variables	Primary use
Reactivity control	Neutron flux, reactor period, control-element position, shutdown margin	Startup supervision, trip, shutdown confirmation
Fuel temperature control	Core inlet/outlet temperature, reflector/vessel temperature, power, flow, validated peak-fuel-temperature estimate	Operating margin and accident acceptance
Core cooling	Helium pressure, mass flow, core differential pressure, circulator status	Protection against loss of flow or inventory
Barrier integrity	Coolant activity, delayed neutrons, gamma spectra, particulate activity	TRISO failure and source-term surveillance
Chemical protection	H2O, O2, N2, H2, CO, CO2, CH4, helium purity	Water/air ingress and graphite oxidation
Passive heat rejection	Vessel/cavity temperatures, RCCS flow and inventory, ultimate heat-sink status	Post-trip and post-accident heat removal

Table 2 Layered instrumentation and control architecture.

Architecture layer	Functions	Key design attributes
Safety-related protection	Trip reactor; actuate isolation or required safety features	Deterministic, fail-safe, redundant, testable, qualified and independent
Post-accident monitoring	Confirm shutdown, cooling, barrier status and radiological conditions	Accident range, long-duration power, harsh-environment qualification
Plant control	Power maneuvering, helium inventory/flow control, Brayton coordination	Stable control, bumpless transfer, isolated from protection
Equipment protection	Turbine/compressor overspeed, vibration, bearing and generator protection	Fast local action; reactor independently detects loss of heat sink
Diagnostic monitoring	Leak, chemistry, vibration, loose parts, aging and calibration surveillance	High information content; maintainable and trendable
AI/digital twin	Anomaly detection, margin estimation, predictive maintenance and decision support	Advisory, bounded, validated, explainable, read-only to safety systems

The safety platform should implement deterministic execution, channelized self-test, bypass and inoperable-status indication, manual initiation, qualified priority logic, sequence-of-events recording, and controlled interfaces. Diversity may be achieved through different sensing principles, processors, software, actuation paths, or a limited hardwired backup. The objective is not diversity for its own sake, but mitigation of credible common-cause failures that could defeat a required safety function. NRC digital I&C guidance identifies independence, single-failure tolerance, setpoints, environmental qualification, software verification and validation, electromagnetic compatibility, and configuration control as central review topics [4, 5].

4. Nuclear and Core-Power Instrumentation

4.1 Source, Intermediate, and Power Ranges

Continuous neutron coverage is required from subcritical fuel loading through full power. Source-range channels may use fission chambers, helium-3 proportional counters, or boron-lined detectors with pulse-counting and mean-square-voltage processing. They should support fuel-loading surveillance, source verification, startup permissives, multiplication monitoring, and protection against an excessive startup rate. Intermediate- and power-range functions may use wide-range fission chambers, compensated ion chambers, or qualified high-temperature ex-core detectors. Overlap between ranges must prevent a blind region and must be demonstrated under expected gamma background and temperature conditions.

Candidate protection variables include high neutron flux, short reactor period, excessive rate of power increase, flux-to-flow or power-to-flow mismatch, and disagreement among redundant channels. The required response time depends on the fastest credible reactivity event. Setpoints must include sensor error, calibration drift, signal-processing delay, analytical uncertainty, and the margin between the trip and the applicable safety limit.

4.2 Three-Dimensional Power and Shutdown Margin

Total power alone does not establish local fuel margin. A core surveillance system should reconstruct axial and radial power, power-peaking factors, burnup, control-element shadowing, bypass-flow effects, and uncertainty. In a prismatic reactor, replaceable reflector channels can host selected neutron, gamma, and temperature sensors without placing fragile devices directly in fuel compacts. In a pebble-bed reactor, the design will generally rely more heavily on ex-core neutron measurements, pebble circulation and loading records, outlet-temperature mapping, burnup measurement, and a validated online core model.

Every shutdown device requires continuous position indication, independent fully inserted indication, insertion-time testing, drive-current monitoring, and failure-to-insert alarms. If a reserve shutdown system releases absorber spheres or another independent poison, instrumentation should confirm material availability, release-path readiness, initiation, and final delivery. Online shutdown-margin calculations should use measured temperature, element position, burnup, and conservative nuclear-data and modeling uncertainty.

5. Thermal, Helium, and Passive-Heat-Removal Monitoring

5.1 Fuel-Temperature Margin

Peak TRISO fuel temperature is a central safety variable, but direct measurement in every compact or pebble is impractical. The plant should combine diverse direct thermal measurements with validated physics-based inference. Required inputs include neutron power, decay heat, helium inlet and outlet temperatures, core flow, reflector temperatures, vessel temperatures, heat-exchanger conditions, and the spatial power solution. Direct measurements should be located to bound hot-channel behavior and detect flow maldistribution. Mineral-insulated Type N or qualified noble-metal thermocouples are candidate technologies; optical or sapphire sensors may supplement surveillance where radiation, temperature, routing, and long-term drift are demonstrated.

The protection system should not depend solely on an AI (artificial intelligence) or digital-twin estimate of fuel temperature. At least one directly measured surrogate—such as limiting outlet, reflector, or vessel temperature—should produce protective action early enough to preserve the analyzed fuel-temperature margin. The analytical estimate should report both the best estimate and a conservative upper bound incorporating model-form, parameter, calibration, and measurement uncertainty.

5.2 Helium Inventory, Flow, and Heat Transport

Primary-system monitoring should include reactor inlet and outlet pressure, core differential pressure, mass flow, circulator speed and electrical load, hot- and cold-duct conditions, heat-exchanger differential pressure, helium makeup and purification flow, isolation-valve position, and inventory balance. No single flow technology should be assumed adequate until tested at representative pressure, temperature, radiation, geometry, and gas purity. Differential-pressure measurements, circulator performance maps, ultrasonic methods, and primary heat-balance calculations can provide diverse estimates.

Potential trip inputs include low or high primary pressure, low core flow, high outlet temperature, excessive power-to-flow ratio, multiple circulator trips, and loss of heat sink. Protection logic should distinguish sensor failure from a real transient without delaying required action. Sensor taps and impulse paths must be arranged to minimize plugging, thermal-gradient error, leakage, and common routing vulnerability.

5.3 Reactor Cavity Cooling and Post-Accident Monitoring

Passive decay-heat removal does not eliminate the need for monitoring. The RCCS (reactor cavity cooling system) should measure vessel temperature at multiple elevations and azimuths, cavity temperature and pressure, cooling-panel inlet/outlet temperature, natural-circulation airflow or water flow, water inventory where applicable, isolation-damper status, structural concrete temperature, and ultimate heat-sink availability. Post-accident channels must survive the temperature, radiation, humidity, seismic loading, pressure, and mission duration associated with the bounding depressurized loss-of-forced-cooling event. Displays should enable operators to confirm subcriticality, core cooling, heat-sink performance, pressure-boundary condition, and radiological release without relying on the normal plant network.

6. Coolant Chemistry, Ingress, and Fuel-Integrity Monitoring

6.1 Helium Chemistry and Graphite Protection

Although helium is inert, impurities are not. Water, oxygen, nitrogen, hydrogen, carbon monoxide, carbon dioxide, methane, hydrocarbons, and particulates affect graphite oxidation, carbon transport, metallic corrosion, fouling, activity transport, and component life. A helium chemistry system should combine continuous high-sensitivity moisture and oxygen measurements with gas chromatography, mass spectrometry, laser absorption, or periodic laboratory confirmation. Sampling locations and transport delays must be justified because a bulk purification-stream sample may not identify a localized ingress event quickly enough.

6.2 Water and Air Ingress

Water ingress may be indicated by a rapid moisture increase, hydrogen and carbon-monoxide generation, steam-generator inventory imbalance, primary pressure change, reactivity response, and drainage-system level. Air ingress may be indicated by oxygen and nitrogen, carbon monoxide and dioxide, cavity pressure, depressurization, natural-circulation flow reversal, graphite temperature, and particulate activity. Diverse measurements are important because each signal can be delayed or ambiguous. Confirmed ingress should initiate the analyzed combination of trip, isolation, shutdown, purification, cooldown, or operator action.

6.3 TRISO Fuel Integrity and Source Term

Fuel integrity should be monitored through primary-coolant gross gamma activity, gamma spectroscopy, delayed-neutron detection where applicable, particulate and dust activity, purification-system activity, plate-out surveillance, and building or effluent radiation monitoring. Trends in krypton, xenon, iodine, cesium, and selected activation products can distinguish expected heavy-metal contamination from progressive coated-particle failure. Alarm and action levels should be linked to fuel-performance and mechanistic-source-term assumptions rather than treated only as chemistry limits. NUREG-2246 provides a structured advanced-reactor fuel-qualification framework, while NRC TRISO phenomena work emphasizes the relationship among manufacturing quality, fuel temperature, release, transport, and retention [6, 7].

7. Power Conversion and Balance-of-Plant Monitoring

A direct or indirect Brayton cycle is normally non-safety-related, but its failures can initiate reactor transients. Monitoring should include turbine and compressor inlet/outlet temperature and pressure, pressure ratio, shaft speed, overspeed, bearing temperature, vibration, axial displacement, generator load, recuperator differential pressure and effectiveness, bypass and inventory-control valve positions, surge or stall indication, seal leakage, lubrication parameters where applicable, and heat-sink availability. Local high-speed equipment protection can trip the turbomachine, but the RPS must independently recognize the associated loss of cooling or heat sink.

Structural and condition monitoring should cover reactor-vessel temperature and strain, circulator vibration, acoustic emission, loose parts, support movement, seismic acceleration, pressure-boundary leakage, insulation performance, and fatigue or creep usage. Replaceable surveillance specimens should address graphite dimensional change and oxidation, vessel and internal materials, insulation, and representative sensor materials. These programs provide the evidence needed to manage aging and confirm that qualified analytical assumptions remain valid throughout life.

8. Minimum Protection and Accident-Monitoring Functions

The final trip set must be derived from event selection and safety analysis. Table 3 provides a technically reasonable starting set; it is not a prescriptive licensing list. Some signals may serve as alarms, permissives, or diverse indications rather than independent trips, depending on response time, reliability, and consequence analysis.

Post-accident monitoring should be independent enough to confirm that automatic action occurred and that the plant is moving toward a stable end state. Accident-range design values, sensor saturation behavior, power duration, data retention, display availability, and recovery from failed channels should be specified. For remote or reduced-staff operation, the design must also establish which indications remain locally available and which remote functions, if any, are permitted without creating a safety or cybersecurity dependency.

9. Chapter 15 and Licensing Traceability

The most useful requirements artifact is a living traceability matrix linking each licensing-basis event to a safety function, monitored variable, credited instrument, trip or operator action, analytical assumption, and acceptance criterion. Table 4 illustrates this approach. The completed matrix should include anticipated operational occurrences, design-basis events, high-consequence beyond-design-basis events, and risk-significant sequences identified through PRA and defense-in-depth evaluation.

For each row, the safety analysis must define the initial condition, uncertainty treatment, time response, equipment availability, single failures, operator action time, and environmental conditions. Instrument setpoints should be analytically connected to safety limits using a documented methodology. Surveillance and calibration intervals should be justified by drift, failure data, channel-check capability, and allowable out-of-service time. The application should clearly identify which systems are safety-related, non-safety-related with special treatment, or conventional non-safety systems under the selected advanced-reactor methodology [1-3].

10. Artificial Intelligence and Digital Twins

AI and digital twins can add substantial operational value by reconstructing three-dimensional power, estimating peak fuel temperature, detecting sensor drift, diagnosing helium leaks, forecasting turbomachinery degradation, assessing graphite condition, and prioritizing maintenance. Their licensing role must be deliberately bounded. At initial deployment, the prudent position is that AI supplements but does not replace qualified sensing, deterministic protection logic, or required operator indications.

A credible digital twin requires a verified physics basis, documented data pedigree, version and configuration control, validation against integral and separate-effects tests, uncertainty quantification, sensitivity analysis, out-of-domain detection, missing-data behavior, and independent monitoring of model health. Outputs should distinguish measured values from inferred quantities and display uncertainty and data-quality flags. Any model update must pass regression tests and controlled approval before operational use.

The AI platform should receive one-way or strongly controlled data from safety systems and should not have uncontrolled write access to reactor protection, engineered safety features, or credited setpoints. Cybersecurity must cover model files, training data, software supply chain, remote maintenance, time synchronization, and adversarial or corrupted inputs. NRC cybersecurity requirements and RG 5.71 emphasize protection of digital systems associated with safety, security, and emergency preparedness functions [8]. Human-system interfaces and automation should be developed under a structured human-factors program so operators understand system authority, uncertainty, failure modes, and required manual actions [9].

11. Qualification, Testing, and Lifecycle Surveillance

Instrumentation must be demonstrated across its full lifecycle. Qualification should address normal and accident temperature, pressure, radiation, humidity, vibration, seismic loading, electromagnetic and radio-frequency interference, electrical transients, fire exposure, aging, and maintenance conditions. For high-temperature sensors, drift and calibration stability can dominate short-term accuracy. Representative irradiation and thermal cycling are therefore as important as initial calibration.

Table 3 Candidate protection and accident-monitoring functions.

Function or signal	Potential protective response	Principal hazard addressed
High neutron flux/short period	Rapid reactor trip	Reactivity insertion
High core outlet or limiting reflector temperature	Trip and heat-removal alignment	Loss of thermal margin
Low core flow/high power-to-flow ratio	Trip; circulator or bypass action	Loss of forced cooling
Low or high primary helium pressure	Trip and isolation as analyzed	Depressurization or overpressure
Multiple circulator trip/loss of heat sink	Reactor trip	Heat-removal degradation
Confirmed excessive moisture or water ingress	Trip, isolate source, purification/cooldown actions	Reactivity and graphite oxidation
Air ingress/cavity-pressure anomaly	Isolation and accident response	Graphite oxidation and activity release
Control-element withdrawal or position anomaly	Trip or inhibit motion; diverse shutdown	Reactivity-control failure
Manual trip/diverse backup actuation	Direct shutdown	Operator response and common-cause mitigation

Table 4 Illustrative Chapter 15 licensing traceability matrix.

Licensing-basis event	Key credited indication	Protective or mitigating action	Acceptance focus
Control-element withdrawal	Flux, period, element position	Trip and inhibit withdrawal	Fuel temperature and shutdown margin
Loss of forced cooling	Flow, delta-P, outlet temperature, circulator status	Trip; establish analyzed passive path	Peak TRISO temperature
Primary depressurization	Helium pressure and inventory	Trip/isolate; passive cooling	Coolable geometry and barrier retention
Water ingress	Moisture, H2, CO, pressure/inventory balance	Trip and isolate ingress source	Reactivity, oxidation and source term
Air ingress	O2/N2, CO/CO2, cavity pressure, temperatures	Isolation and accident management	Graphite oxidation and release
Loss of heat sink	Brayton/secondary conditions; primary temperature	Trip and passive heat rejection	Decay-heat removal
TRISO degradation	Coolant gamma spectrum, delayed neutron/particulate	Alarm, power reduction or shutdown	Fuel/source-term assumptions

The verification program should include separate-effects sensor tests, integral system tests, response-time measurements, channel calibration, environmental and seismic qualification, software verification and validation, failure-injection testing, independence and communication-failure testing, common-cause-failure evaluation, integrated control-room validation, and periodic surveillance. Online monitoring may extend calibration intervals only when the method, uncertainty, fault-detection coverage, and acceptance thresholds are validated. The design should also permit replacement of detectors exposed to the highest fluence without compromising the pressure boundary or requiring excessive dose.

Technology demonstration should proceed from sensor coupon and irradiation tests to prototypical helium loops, electrically heated core simulators, critical or zero-power testing where authorized, and integrated startup testing. Test acceptance criteria should be written from the licensing traceability matrix so that test evidence directly closes safety-analysis and qualification requirements.

12. Recommended Baseline Instrumentation Package

For conceptual design and procurement planning, the following five packages should be established as top-level plant systems:

- Wide-range nuclear instrumentation, control-element monitoring, reactor protection, and diverse shutdown actuation.
- Core thermal-margin monitoring, including outlet-

temperature mapping, reflector/vessel measurements, three-dimensional power reconstruction, and conservative peak-fuel-temperature estimation.

- Primary helium inventory, pressure, flow, differential pressure, circulator, purification, chemistry, and air/water-ingress monitoring.
- TRISO fuel-integrity, primary-coolant activity, particulate/plate-out surveillance, area radiation, and effluent monitoring.
- RCCS, reactor-vessel, cavity, ultimate heat-sink, and qualified post-accident monitoring.

These packages should be supported by an independent plant-control system, turbomachinery protection, structural and equipment-condition monitoring, a qualified human-system interface, and a segregated AI/digital-twin environment. Detailed sensor counts and locations cannot be fixed before the core form, power level, primary-system geometry, accident set, required response time, replaceability strategy, and PRA are defined.

13. Conclusions

An HTGR-SMR requires a measurement architecture centered on reactivity, spatial power, TRISO fuel temperature, helium cooling, graphite chemistry, barrier integrity, and passive heat rejection. Conventional neutron and process instrumentation remain essential, but they must be complemented by coolant chemistry, fission-product surveillance, accident-range thermal monitoring, and validated model-based estimates. The safety case should neither assume that inherent features eliminate instrumentation nor allow sophisticated analytics to obscure the need for independent, qualified protection.

The central licensing recommendation is to create a requirement trace from every selected event and acceptance criterion to a measured variable, qualified channel, protective action, surveillance test, and uncertainty allowance. This approach aligns core instrumentation with Chapter 15 accident analysis, fuel qualification, PRA, defense in depth, digital I&C review, and human factors. AI and digital twins can then be added as high-value advisory layers without weakening deterministic safety functions. Early use of this framework will reduce redesign risk and provide a coherent basis for sensor development, test-facility planning, manufacturing specifications, licensing engagement, and eventual operating technical specifications.

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