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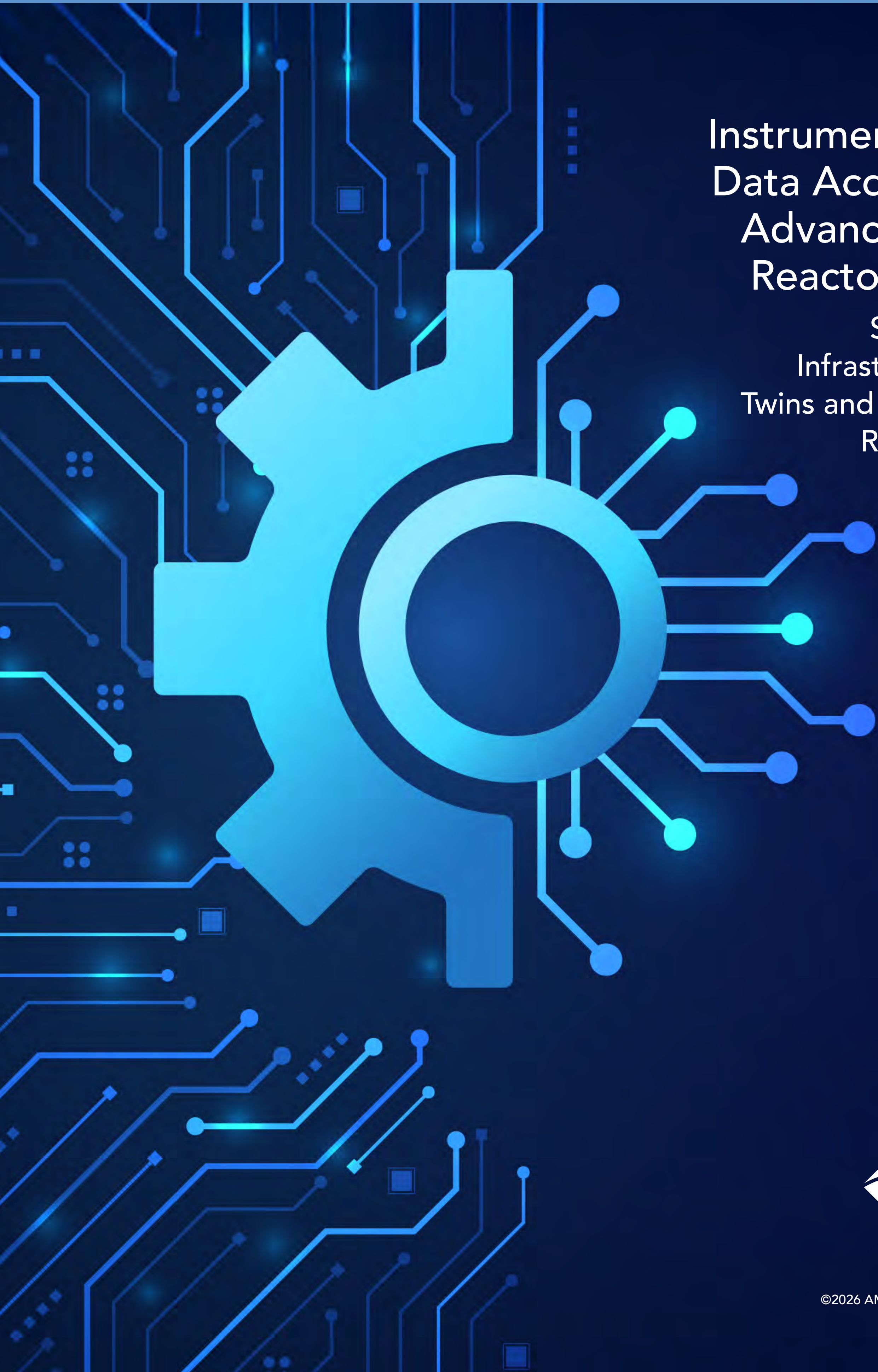

Instrumentation and Data Acquisition for Advanced Nuclear Reactor Programs

Supporting Test Infrastructure, Digital Twins and Demonstration Reactor Systems

United Electronic Industries
AMETEK

Instrumentation and Data Acquisition for Advanced Nuclear Reactor Programs

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Executive Summary

Nuclear energy is entering a period of renewed innovation driven by advanced reactor technologies, demonstration reactor programs, and increasing global investment in carbon-free baseload energy systems. Governments, utilities, national laboratories, and private reactor developers are pursuing new reactor designs intended to improve safety, reduce construction complexity, and enable more flexible deployment of nuclear power.

Unlike conventional nuclear plants that benefit from decades of operating experience and standardized designs, many advanced reactor technologies require extensive experimental validation before commercial deployment. Reactor developers must collect high-fidelity engineering data across multiple physical domains including thermal hydraulics, neutronics, structural behavior, and control system performance.

These activities frequently rely on large engineering test environments including thermal-hydraulic loops, hardware-in-the-loop systems, digital twin validation platforms, and integrated system testbeds. Advanced reactor development programs therefore create substantial demand for flexible, scalable instrumentation architectures capable of supporting large sensor counts, synchronized measurements, and distributed data acquisition.

Instrumentation and data acquisition (DAQ) systems play a critical role in enabling these activities by providing deterministic timing, synchronized measurement, and integration of diverse sensor technologies across complex experimental facilities.

This paper examines the role of modern data acquisition platforms in supporting advanced reactor development programs and the engineering infrastructure required to bring next-generation nuclear technologies from concept to commercial deployment.

The Changing Nuclear Energy Landscape

Modern nuclear energy development is often described using terminology that mixes reactor technology with plant size or deployment strategy. In practice, two distinct classifications exist:

- Reactor technology class
- Reactor form factor

Reactor technology describes the underlying reactor physics and thermal-hydraulic design of the system. The reactor form factor describes the scale, manufacturing strategy, and deployment model of the reactor.

Understanding this distinction helps clarify the engineering infrastructure required to support reactor development programs, including instrumentation and measurement systems.

Generation IV Reactor Technologies

The **Generation IV International Forum (GIF)**, an international research collaboration launched by the **U.S. Department of Energy** and partner nations, identified six advanced reactor technologies intended to improve sustainability, safety, proliferation resistance, and economic performance.

Generation IV Reactor Type	Primary Coolant	Key Characteristics
The nuclear industry commonly categorizes reactors into three broad-size classes.	Liquid sodium	Fast neutron spectrum with potential closed fuel cycle
Lead-Cooled Fast Reactor (LFR)	Lead or lead-bismuth	High operating temperature and passive safety potential
Gas-Cooled Fast Reactor (GFR)	Helium	High power density fast spectrum reactor
Very High Temperature Reactor (VHTR)	Helium	High outlet temperatures suitable for industrial heat applications
Supercritical Water Reactor (SCWR)	Supercritical water	High-efficiency design using water coolant
Molten Salt Reactor (MSR)	Molten salt	Liquid fuel options and strong passive safety characteristics

Reactor Form Factors: Traditional Reactors, SMRs, and Microreactors

Separate from reactor technology class is reactor form factor, which describes the scale and deployment model of a reactor system.

The nuclear industry commonly categorizes reactors into three broad-size classes.

Reactor Category	Typical Electrical Output	Description
Traditional Large Reactors (Gen III / III+)	~900–1600 MWe	Conventional utility-scale nuclear power plants
Small Modular Reactors (SMRs)	~50–300 MWe	Modular reactors designed for factory fabrication and scalable deployment
Microreactors	~1–20 MWe	Very small reactors designed for remote power or specialized applications

SMRs emphasize modular construction and factory fabrication to reduce construction complexity and enable incremental deployment of nuclear generating capacity.

Microreactors represent an even smaller form factor intended for remote communities, industrial facilities, defense installations, or emergency power applications.

The term 'advanced reactor' is often used in industry discussions as an umbrella term that can include both Generation IV technologies and certain modern light water reactor designs. For example, several light water small modular reactors (SMRs) are sometimes described as advanced reactors because they incorporate modular construction approaches, enhanced safety systems, or new deployment models, even though their underlying reactor physics is based on traditional light water technology rather than Generation IV concepts.

Understanding how these terms are used helps clarify discussions surrounding reactor development programs and the supporting engineering infrastructure required to bring these systems to deployment.

Why Advanced Reactor Development Often Requires Expanded Instrumentation

Conventional Generation II and Generation III nuclear plants benefit from decades of operational experience, established design practices, and mature instrumentation architectures. These plants operate within well-understood regulatory frameworks and rely on proven plant configurations refined through years of deployment.

Advanced reactor programs often involve new coolant technologies, alternative fuel cycles, different neutron spectra, higher operating temperatures, and novel materials. Because many of these technologies have not yet been commercially deployed, reactor developers must perform extensive engineering validation before full-scale implementation.

This expanded instrumentation demand should not be interpreted as a limitation of traditional nuclear plants. Instead, it reflects the earlier stage of technical maturity associated with many advanced reactor programs.

Validation activities frequently occur in specialized engineering environments such as:

- Thermal-hydraulic test loops
- Integrated system testbeds
- Component testing laboratories

These facilities may contain hundreds or thousands of sensors distributed across multiple subsystems. Coordinating these measurements requires scalable, synchronized data acquisition infrastructure.

Instrumentation Challenges in Advanced Reactor Development

Advanced reactor development programs require the collection of synchronized measurements across multiple engineering domains, including thermal-hydraulics, structural behavior, and control system performance. Experimental facilities supporting these programs may include thermal-hydraulic loops, component test rigs, materials testing systems, and hardware-in-the-loop control environments operating simultaneously.

Instrumentation deployed in these facilities typically includes sensors such as:

- Thermocouples
- RTDs
- Strain gauges
- Vibration sensors
- Pressure and flow sensors
- Neutron flux monitors

These sensors are often deployed across large experimental systems that span multiple physical areas of a facility. Measurements may be collected from piping systems, structural test rigs, control cabinets, and equipment racks located throughout the test environment.

In addition to supporting large numbers of sensors, instrumentation platforms must operate reliably in demanding industrial environments. Reactor test facilities may expose measurement hardware to electromagnetic interference from power electronics, mechanical vibration from pumps and rotating equipment, elevated temperatures near thermal-hydraulic systems, and electrical noise generated by high-power heaters and control systems.

Together, these conditions create significant challenges for instrumentation infrastructure. Measurement systems must support **high channel density, precise time alignment between measurements, and reliable operation in rugged industrial environments** while remaining flexible enough to support evolving experimental facilities.

These constraints have increasingly driven the adoption of **rugged, distributed data acquisition architectures** in advanced reactor development programs.

The Increasing Role of Distributed Data Acquisition

Distributed data acquisition (DAQ) architectures address many of the instrumentation challenges present in advanced reactor development environments by placing acquisition hardware close to the sensors being measured while connecting measurement nodes through high-speed communication networks.

In many reactor test facilities, instrumentation may be deployed across large experimental loops, control cabinets, and subsystem test rigs located throughout a facility. Locating acquisition hardware near these measurement points reduces long sensor cable runs, improves signal integrity, and simplifies instrumentation deployment.

Distributed architectures also allow instrumentation capacity to scale as experimental facilities evolve. Additional acquisition nodes can be deployed near new test systems or subsystems without requiring major changes to the overall measurement infrastructure.

Accurate timing is essential when correlating measurements collected across multiple subsystems. Modern distributed DAQ platforms frequently use **IEEE-1588 Precision Time Protocol (PTP)** to synchronize clocks across networked measurement systems, allowing sensor data collected from different locations to be aligned with high precision.

In addition to PTP synchronization, emerging industrial networking technologies such as **Time Sensitive Networking (TSN)** enable deterministic Ethernet communication while maintaining precise time synchronization across distributed devices. TSN networks leverage PTP as a common time reference while supporting predictable, high-speed communication across distributed measurement systems.

By combining rugged acquisition hardware with synchronized networking technologies, distributed DAQ architecture enables reliable, scalable instrumentation across the complex experimental facilities used to support advanced reactor development programs.

Distributed DAQ Architecture for Reactor Test Facility

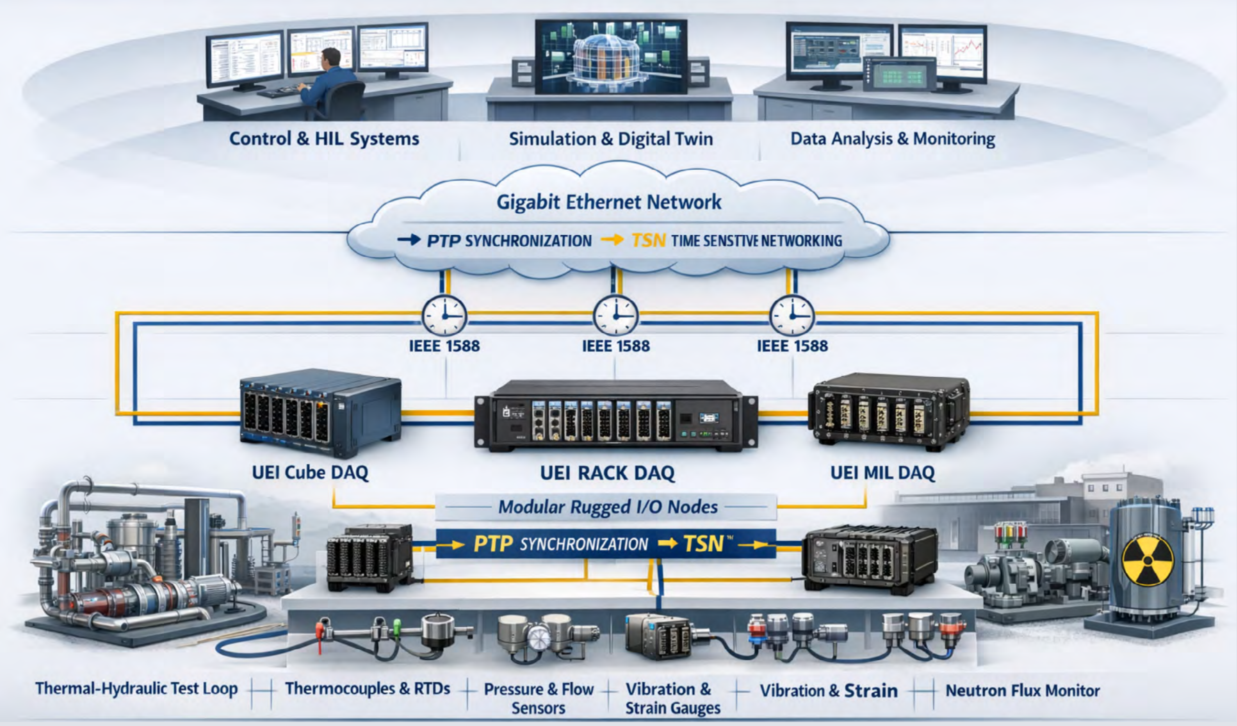

Figure 1. Example distributed data acquisition architecture showing acquisition nodes located near test assets and synchronized over Ethernet/PTP to a central engineering server.

The Role of Data Acquisition in Advanced Reactor Engineering

Instrumentation systems typically follow a layered architecture connecting physical measurements to engineering analysis tools.

The instrumentation stack generally includes the following layers:

- Sensors—Devices that measure physical phenomena such as temperature, pressure, vibration, neutron flux, and strain
- Signal Conditioning—Electronics that amplify, filter, and convert raw sensor outputs into formats suitable for digital acquisition
- Data Acquisition Systems—Platforms that digitize signals, synchronize measurements across channels, and transmit engineering data
- Control Systems—Real-time systems that process measurement data to regulate equipment and plant systems

- Engineering Analytics / Digital Twins—Modeling and analysis environments that use measured data to validate system models and evaluate performance

Within this architecture, DAQ systems provide the bridge between physical instrumentation and engineering analytics environments.

Advanced Reactor Development & Testing Ecosystem

Figure 2. The nuclear instrumentation stack connecting sensors and signal conditioning to DAQ, control systems, and engineering analytics / digital twin environments.

Applications in Reactor Development Programs

DAQ systems support a wide range of engineering environments used in advanced reactor development.

Thermal-Hydraulic Test Loops

Thermal-hydraulic loop facilities simulate coolant flow and heat transfer behavior under representative operating conditions. These systems require dense instrumentation for temperature, pressure, flow, vibration, and materials response.

Hardware-in-the-Loop Validation

Hardware-in-the-loop environments allow reactor control systems to be tested using real control hardware connected to physics-based simulation models. These facilities require deterministic timing and synchronized measurement of control signals and plant responses.

Digital Twin Validation

Digital twin models are increasingly used to simulate plant behavior, analyze performance, and refine predictive simulations. These models require high-quality engineering data for validation.

Reactor Component Testing

Critical components such as pumps, valves, heat exchangers, and instrumentation packages are often tested in specialized facilities requiring flexible instrumentation architectures.

Demonstration Reactor Programs

Integrated system testbeds and demonstration reactors rely on instrumentation infrastructure to monitor reactor performance, validate engineering models, and support operational analysis.

Advanced Reactor Development Ecosystem

The broader engineering ecosystem supporting advanced reactor programs extends from individual component testing through integrated system demonstration.

Instrumentation and DAQ systems support each stage of this ecosystem by providing engineering visibility and synchronized measurement data across experimental facilities.

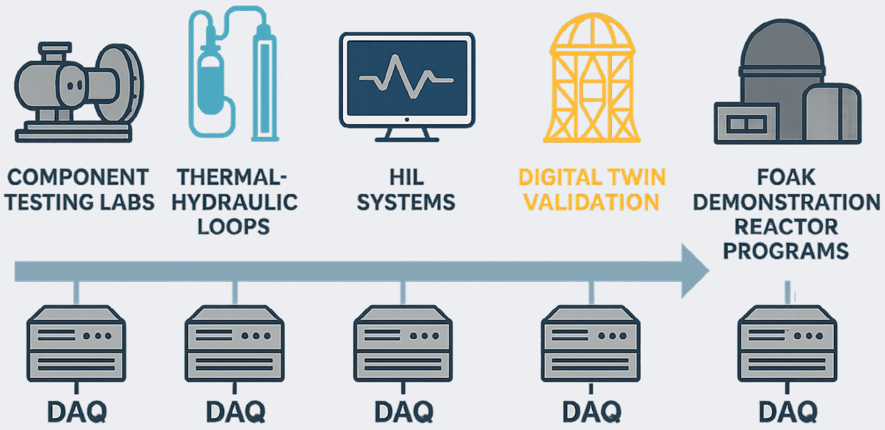
Advanced Reactor Development Ecosystem

Figure 3. Advanced reactor development ecosystem showing the progression from component testing labs through thermal-hydraulic loops, HIL systems, digital twin validation, and FOAK demonstration reactor programs, with DAQ supporting each stage.

FOAK vs NOAK Reactor Programs

Instrumentation requirements evolve as reactor programs mature.

First-of-a-Kind (FOAK)

FOAK deployments represent the first operational implementation of a reactor design. These systems require extensive engineering validation and flexible instrumentation capable of supporting evolving test requirements.

FOAK programs frequently emphasize:

- Flexible sensor integration
- High channel counts
- Distributed measurement architectures
- Documentation supporting licensing and validation activities

Nth-of-a-Kind (NOAK)

As reactor designs mature and move toward broader deployment, instrumentation architectures become more standardized and increasingly focused on operational monitoring, diagnostics, and long-term reliability.

Documentation developed during FOAK programs—such as calibration reports, EMC evidence, and cybersecurity artifacts—can help streamline subsequent deployments.

Regulatory Expectations for Non-Safety Instrumentation

Even when instrumentation systems are not classified as safety-related equipment, reactor developers typically expect alignment with regulatory frameworks and industry practices, including:

- NRC Regulatory Guide 1.180—Electromagnetic compatibility
- 10 CFR 73.54—Cybersecurity programs
- 10 CFR 50.49—Environmental qualification considerations
- Regulatory Guide 1.100—Seismic considerations
- 10 CFR 50.59—Plant modification processes

Appendix A provides an alignment matrix describing how UEI DAQ platforms address common regulatory expectations for non-safety instrumentation systems.

UEI Data Acquisition Architecture

United Electronic Industries develops modular data acquisition platforms designed for industrial and mission critical environments. These capabilities align well with the distributed experimental facilities commonly used in advanced reactor development programs.

Because reactor test facilities frequently involve vibration, electrical noise, and temperature variation, instrumentation platforms must provide reliable operation in demanding industrial environments while maintaining precise measurement performance.

UEI data acquisition platforms support integration with thermocouples, RTDs, strain gauges, vibration sensors, pressure transducers, and other instrumentation sources. Distributed architectures allow acquisition nodes to be deployed near experimental equipment while maintaining synchronized measurements using technologies such as IEEE 1588 Precision Time Protocol (PTP).

In addition, UEI platforms support Time Sensitive Networking (TSN), enabling deterministic Ethernet communication with precise time synchronization across distributed measurement systems.

This combination of rugged hardware design, flexible sensor integration, and synchronized networking capabilities makes modular DAQ architectures well suited for reactor test facilities, experimental loops, and engineering validation environments supporting advanced reactor programs.

Modular DAQ platforms such as those developed by UEI are increasingly being evaluated for use in reactor test facilities, experimental loops, and engineering validation environments supporting advanced reactor programs.

Typical DAQ Capabilities for Reactor Test Facilities

Typical instrumentation platforms supporting advanced reactor programs may include:

- 32–500+ measurement channels
- Thermocouple, RTD, strain, vibration, and pressure inputs
- IEEE-1588-time synchronization
- Distributed acquisition nodes connected via Ethernet
- Deterministic timing for HIL and simulation environments

Lifecycle Support and Long-Term Availability

Nuclear programs often span multiple decades, making lifecycle stability a critical consideration when selecting instrumentation platforms.

Instrumentation vendors supporting nuclear engineering environments must provide:

- Long hardware lifecycle availability
- Predictable product obsolescence policies
- Long-term repair support
- Transparent lifecycle costs
- Reliability
- Integration flexibility
- Cybersecurity alignment
- Suitability for specialized test environments

Conclusion

Advanced reactor development depends on reliable instrumentation capable of collecting synchronized engineering data across multiple domains.

Modular data acquisition architectures enable flexible sensor integration, deterministic timing, and scalable deployment across experimental facilities. These capabilities make modern DAQ platforms an important enabling technology for next-generation nuclear reactor programs.

About the Author

Todd VanGilder is the Nuclear Business Development Manager for United Electronic Industries (UEI). His work focuses on advanced reactor programs including Generation IV systems, microreactors, and demonstration reactor initiatives. He works with reactor developers, national laboratories, and utilities to align modular data acquisition architectures with the engineering and regulatory expectations of modern nuclear energy programs.

Appendix A

NRC Alignment Matrix for Non-Safety DAQ Systems

Requirement Area	NRC / Industry Expectation	Implications for FOAK/NOAK	UEI Alignment (Artifacts)	Status / Gaps & Mitigations
EMC/EMI	RG 1.180 EMC practices; plants commonly apply EPRI TR 102323 methods to control emissions/immunity for equipment installed near safety systems.	Provide EMC evidence for installation; ensure no adverse interference with safety cabinets or protection racks.	CE EMC; FCC Part 15B compliance; MIL STD 461 methods recognized in NRC RG 1.180; installation/grounding guidance.	Compliant for typical baselines; where close to safety equipment, propose EPRI style tests or on site EMC verification as mitigation.
Cybersecurity	10 CFR 73.54 with RG 5.71 / NEI 08 09: owner cyber program governs zoning, CDA identification, and defensive architecture.	Classify DAQ within site zones; evaluate potential CDA interactions; document services/ports/logging	Cyber ready chassis with TPM/secure boot options; NIST 800 213 aligned device level controls; port/services inventory and hardening worksheet supporting 10 CFR 73.54 site cyber programs.	Cyber ready chassis with TPM/secure boot options; NIST 800 213 aligned device level controls; port/services inventory and hardening worksheet supporting 10 CFR 73.54 site cyber programs.
Environmental (EQ)	10 CFR 50.49 applies if failure could prevent safety functions in harsh environments; mild areas are outside §50.49 scope.	Install DAQ in a mild environment; document location and thermal/EMI constraints in as built.	Commercial: −40...+70 °C, 3 g vib / 50 g shock; MIL: IP66, 5 g vib / 100 g shock, designed for MIL STD 810.	Compliant for mild areas; rugged UEI hardware can be qualified for harsher zones if required, with formal test
Seismic	RG 1.100 (IEEE 344 / ASME QME 1) is for safety related equipment; non safety typically relies on anchorage and cabinet assessments.	Provide mounting/anchorage data; justify non safety classification and functional independence.	Shock/vibe robustness data; mounting guidance; cabinet integration notes.	Generally compliant; UEI's rugged hardware tolerates significant shock and vibration, and full seismic qualification or cabinet level testing can be performed if a site requests Category II–equivalent behavior. Compliant tailor a 50.59 input sheet
50.59 / Changes	Licensee screens modifications using RG 1.187 and 10 CFR 50.59.	Provide interface description, failure effects, timing/sync behavior, and power/grounding.	Complete documentation package (interface/failure modes; timing report; power/EMC notes).	Compliant tailor a 50.59 input sheet per site.
Data Integrity & Timing	Traceable calibration and synchronized measurements (PTP and/or IRIG B) when data informs models or operations	FOAK emphasizes high fidelity, time aligned data; NOAK favors a repeatable timing topology.	ISO/IEC 17025 calibration availability; IEEE 1588 PTP; deterministic scan performance.	Compliant; UEI natively supports common plant timing protocols— including IRIG B, IEEE 1588/PTP, and NTP—and can integrate with the site's preferred time source once identified.
Quality Management & Regulatory Compliance	ISO 9001 QMS; CE/FCC EMC; RoHS/REACH/WEEE declarations; ITAR as needed.	Used by owners for procurement, acceptance, and material compliance.	Certificat bundle avalable (ISO 9001, CE/FCC, RoHS/REACH/WEEE, ITAR).	Compliant—include certificate pack with proposal/submittal.
Lifecycle & Obsolescence	Stable long-term availability and predictable supplier support across multi-year plant programs.	Ensure lifecycle visibility and sustain hardware across multi-year deployments.	Lifecycle statements; change-control; redesign or form-fit-function replacement options; 10-year post-EOL support.	UEI products typically remain available for long lifecycles with infrequent EOL events.

* Not classified or credited as safety I&C equipment for reactor shutdown or accident-mitigation functions.

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