EMERGING AND EXISTING SENSING TECHNOLOGIES FOR SMALL MODULAR REACTORS AND ADVANCED REACTORS

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ABSTRACT

The development of small modular reactors (SMRs) and Generation-IV advanced reactor designs represents a promising future for nuclear energy. These next-generation reactors can support new applications for nuclear energy like hydrogen production, industrial heat generation, and water desalination in addition to electricity generation. Furthermore, SMRs and advanced reactors enable load-following operations, offer improved passive safety features, support lengthened refueling cycles, and provide spent fuel management capabilities. To date, there are no SMRs operating or under construction in the United States, but commercial operation of the first integral Pressurized Water Reactor (iPWR) SMR is expected by the mid-2020s with Generation-IV advanced reactors to follow a decade or two later. To facilitate the development and deployment of SMRs and advanced reactors, key instrumentation and control (I&C) system challenges must be addressed and existing nuclear grade I&C sensors will need to be adapted or new sensors developed. For example, traditional measurement techniques and maintenance strategies used in the current generation of light water reactors (LWRs) will be challenged by the inherent design characteristics of the iPWR. For Generation-IV reactors, conventional I&C sensors will not withstand prolonged exposure to the harsh environmental conditions of advanced reactors (e.g. elevated temperatures, corrosive coolants, increased radiation). This paper discusses the challenges associated with making primary system process measurements in next-generation reactors and includes a summary of work performed to evaluate existing and emerging sensor technologies for these systems. As importantly, the paper presents the initial test results of a prototype temperature sensor developed by Analysis and Measurement Services Corporation (AMS) for use in SMRs and advanced reactors.

Key Words: Small Modular Reactors, Advanced Reactors, Instrumentation, Nuclear Power Plants

1 INTRODUCTION

Small modular reactors (SMRs) and Generation-IV advanced reactors are being developed around the world to provide clean sustainable electricity and offer new applications for nuclear energy. These reactors offer inherent design safety features, extended refueling cycles, load-following capabilities, and increased proliferation resistance relative to conventional light water reactors (LWRs). In addition, SMRs provide greater site flexibility and reduced construction cost compared to large-scale plants operating today. However, the fundamental design characteristics of both SMRs and advanced reactors introduce key challenges to instrumentation and control (I&C) sensors that must be addressed in order to realize the benefits of these reactors.

Important to the safe and efficient operation of any nuclear power plant (NPP) is the measurement of primary system process conditions (e.g. temperature, pressure, level, and flow). For a conventional plant with primary system loops, these measurements are relatively straightforward, because the sensor technologies for measuring process conditions in a circular pipe are well established. However, for an integral Pressurized Water Reactor (iPWR) SMR with limited space for sensors and no primary loops, it becomes considerably more challenging to obtain accurate process measurements using current nuclear grade sensor technology. In addition, time-based I&C maintenance activities such as sensor calibrations in conventional NPPs are typically performed during a plant outage every 18 to 24 months. However, for SMRs and advanced reactors capable of operating at elevated temperatures for years at a time, existing nuclear grade sensors will drift and require maintenance. Therefore, I&C sensors for these reactors must be sufficiently robust to withstand the anticipated operating conditions and in-situ testable to verify the static and dynamic performance of the sensor for the duration of the operating cycle. Furthermore, online calibration monitoring and in-situ response time testing capabilities shall be designed into SMR and advanced reactor instrumentation to allow automated maintenance of the sensors.

This paper summarizes the collective work performed by engineers of Analysis and Measurement Services Corporation (AMS) as part of a Small Business Innovation Research (SBIR) Phase II project with grants from the United States Department of Energy (DOE).

2 SMRS AND ADVANCED REACTORS

Interest has grown in SMRs and advanced reactor technologies recently, and a number of SMR and advanced reactor designs are under development or under construction around the world. In 2012, DOE called for applications from the industry to support the development of U.S. LWR SMR designs. Four applications were made from Westinghouse, Babcock & Wilcox (B&W) mPower, Holtec, and NuScale. The first round of funding was awarded to the B&W mPower design to be developed by Bechtel and the Tennessee Valley Authority (TVA). A second grant was made to NuScale Power to support design development and NRC certification and licensing of its 50 MWe SMR. In fact, NuScale has recently submitted the first ever design certification application (DCA) to the U.S. Nuclear Regulatory Commission (NRC). The first NuScale plant will be built at a site located in the Idaho National Laboratory (INL) complex and is expected to begin commercial operation in 2026 [1]. In addition, DOE awarded contracts to X-Energy to develop its helium-cooled modular pebble-bed reactor and Southern Company to explore and demonstrate advanced reactor technologies, working with TerraPower and the Oak Ridge National Laboratory (ORNL) [2]. A list of SMR and advanced reactor designs from the U.S. is provided in Table I. There is also great interest in SMRs and advanced reactors outside the United States to satisfy the need for flexible power generation in less-developed countries and to replace existing aging fossil plants. There are a number of reactor types currently at various development stages, and some are already being utilized for commercial power generation. A list of SMRs and advanced reactor designs from around the world is provided in Table II. It should be noted that these tables do not encompass all SMRs and advanced reactor designs.

Table I. SMRs and Advanced Reactors in the United States

Reactor	Company	Reactor Type	Coolant	MWe
NuScale	NuScale Power	iPWR	Light Water	50
mPower	BWX Technologies	iPWR	Light Water	180
W-SMR	Westinghouse	iPWR	Light Water	225
SMR-160	Holtec	PWR	Light Water	160
Xe-100	X-Energy	Very High-Temperature Reactor (VHTR)	Helium	50
EM^2	General Atomics	Gas-Cooled Fast Reactor (GFR)	Helium	265
PRISM	GE Hitachi	Sodium-Cooled Fast Reactor (SFR)	Sodium	311
TWR	TerraPower	Sodium-Cooled Fast Reactor (SFR)	Sodium	600
LFTR	Flibe Energy	Molten Salt Reactor (MSR)	FLiBe	250
G4M	Gen4 Energy	Lead-Cooled Fast Reactor (LFR)	Lead-Bismuth	25

Table II. SMRs and Advanced Reactors Around the World

Reactor	Country	Reactor Type	Coolant	MWe
CAREM-25	Argentina	iPWR	Light Water	27
ACP-100	China	iPWR	Light Water	100
HTR-PM	China	VHTR	Helium	211
CEFR	China	SFR	Sodium	20
PFBR-500	India	SFR	Sodium	500
HTTR (Prototype)	Japan	Gas-Cooled	Helium	30 (MWt)
SMART	Korea	iPWR	Light Water	100
KLT-40S	Russia	PWR	Light Water	35
RITM-200	Russia	iPWR	Light Water	50
BREST-300	Russia	LFR	Lead	300

3 EXISTING I&C SENSORS

For any SMR or advanced reactor design, the accurate and timely measurement of key process parameters is essential to the safe and efficient operation of the plant during normal, transient, and design basis events. Conventional I&C sensors used in currently operating LWRs are primarily analog technologies with well-understood performance characteristics and failure mechanisms. Although it can be argued that this equipment is progressing towards obsolescence, these sensors continue to satisfy the operational requirements of the existing fleet. Table III provides a summary of existing I&C sensor technology used for primary system variables in LWRs [3-6]. The tale shows the process variable that each sensor measures, type of sensor, typical number of each sensor type in a nuclear power plant, measurement uncertainty, and dynamic response characteristics.

Table III. Characteristics of I&C Sensors in Current Generation of LWRs

<table>
<tr><th>Measurand</th><th>Process Sensor</th><th>Quantity</th><th>Range</th><th>Uncertainty</th><th>Response Time</th></tr>
<tr><td rowspan="2">Temperature</td><td>RTD</td><td>16-32</td><td>< 400ºC</td><td>± 0.2 ºC</td><td>2.0-8.0s</td></tr>
<tr><td>Thermocouple</td><td>50-60</td><td>> 900 ºC</td><td>± 2 ºC</td><td>< 3.0s</td></tr>
<tr><td>Pressure</td><td>Electromechanical Transmitter</td><td rowspan="3">> 200</td><td rowspan="3">0-3000 psi</td><td rowspan="3">± 1.25%</td><td rowspan="3">< 2.0s</td></tr>
<tr><td>Level</td><td rowspan="2">Differential Pressure Transmitter</td></tr>
<tr><td>Flow</td></tr>
</table>

For a large-scale PWR, there are typically 16-32 resistance temperature detectors (RTDs) in the reactor coolant system to measure the primary system temperature. These RTDs also provide input to the plant protection system to shut down the reactor in case of an undesirable process transient and are periodically tested (every 18 to 24 months) to verify their response time and calibration. Relative to thermocouples, RTDs have excellent long-term stability and high accuracy at normal PWR operating conditions. In a typical PWR, three single or dual-element RTDs are installed in the hot leg piping (located in the same plane and 120º apart from one another), and one or two RTDs are installed in the cold leg piping after the reactor coolant pump. For core exit temperature measurements, thermocouples are commonly used over RTDs because of their resilience to flow-induced vibration, high measurement range, and installation flexibility. Core exit thermocouples are only used for monitoring purposes and do not provide input to the plant control or protection systems. Therefore, they do not have to be as accurate as RTDs. Typically, between 50 and 60 core exit thermocouples are found in a PWR. These sensors are not normally tested for calibration or response time but their insulation resistance (IR) is periodically checked.

Pressure transmitters in nuclear plants are electromechanical systems that convert pressure to an electrical signal. When pressure is applied to the system, the elastic sensing element (e.g. diaphragm, bellows, etc.) is displaced, and this displacement is detected by a capacitance cell, strain gauge, force motor, or other mechanisms and thereby converted to an electrical signal (typically 4-20 mA). A plant has hundreds of pressure and differential pressure transmitters that are used to measure important parameters such as pressurizer pressure, steam generator level, and reactor coolant system flow. Many of these pressure transmitters provide input to the plant protection system and are periodically maintained to verify performance. This performance verification may be accomplished using either conventional hands-on methods that require plant technicians to perform calibration and response time testing activities in the field during a plant outage or online monitoring (OLM) techniques that can be applied while the plant is operating. In addition, OLM can be used to monitor pressure sensing line response degradation that may result from blockages or voids.

4 EMERGING I&C SENSORS

Although there is operating experience with advanced reactor coolants, existing nuclear grade I&C sensors may not withstand prolonged exposure to the harsh conditions expected in next-generation reactors. For example, at higher temperatures (above 600ºC), RTDs become susceptible to metal ion contamination of the platinum wire sensing element which affects the purity of the platinum element, and ultimately, the electrical characteristics of the RTD. This contamination effect is irreversible and results in sensor drift [7]. Frequent sensor maintenance or replacement to combat increased calibration drift is not practical for advanced reactors operating for extended periods and not feasible for SMRs with limited space for hands-on maintenance activities. Therefore, there exists a need for new I&C sensors for SMRs and advanced reactors that can satisfy the operating and design characteristics of these reactors. Currently, researchers from national and international laboratories, universities, and commercial organizations are working to develop sensors for measurement of process variables in SMRs and advanced reactors. The following are notable examples of candidate sensor technologies currently under development and commercial products that may be suitable for deployment.

4.1 Johnson Noise Thermometer

Johnson Noise is intrinsic electrical noise in a circuit due to thermal fluctuation and is generated as a result of the thermal agitation of charge carriers within an electrical conductor. The motion of charge carriers (electrons) is proportional to absolute temperature, and temperature measurements derived from Johnson Noise are inherently drift free. The major challenge facing Johnson Noise thermometry is its high sensitivity to electromagnetic noise. Although this technology was demonstrated for in-core temperature measurements over forty years ago, commercialization of Johnson Noise thermometry is still pending [8]. A Johnson Noise thermometer is basically made of an RTD whose open circuit voltage which is very small is measured with a sophisticated set of amplifiers and conditioned with advanced electronic filters and subsequently converted to temperature via a well-known equation.

4.2 Fiber Optics

An optical fiber may be used to transmit sensor signals or the fiber itself may be used as a sensor to measure temperature, pressure, level, flow, strain, and other parameters. If the optical fiber is the transducer, the measurement variable may modulate intensity, wavelength, phase, or transit time of the light in the fiber. A basic fiber optic sensor system requires a light source and a detector to function. Fiber optic sensors are attractive alternatives to traditional sensor systems, because they are nonconductive, electrically passive, and inherently immune to electromagnetic or radio frequency interference. In addition, fiber optic sensors have high bandwidth, good resolution and accuracy, and excellent long-term stability. Multiple sensors can be incorporated into a lightweight fiber to enable specialized applications including embedded structural monitoring. Although it is true that fiber optics are vulnerable to radiation darkening, there are some commercially available radiation-resistant fibers in addition to prototype fiber optic probes under development specifically for nuclear power reactor applications. Two examples of such sensors are identified in the following paragraphs.

4.2.1 Chiral Photonics

Chiral Photonics has developed pressure and temperature sensors based on chiral fiber gratings that can operate in harsh environments. Laboratory testing of the temperature sensor was conducted by Chiral Photonics to determine the drift of the sensor. According to the manufacturer, after being exposed to a constant temperature of 900ºC for 1400 hours, the thermal drift was calculated to be 0.0005 ºC/hr. (linear fit). The pressure sensor is capable of operating at temperatures up to 700ºC. It was tested from 1 atmosphere (14.7 PSI) to 12,000 PSI with excellent resolution (1 PSI), repeatability, and negligible hysteresis [9]. The authors of this paper have not independently verified these characteristics.

4.2.2 LUNA

LUNA has developed a prototype pressure sensor with built-in temperature compensation for nuclear reactors. The sensor has a measurement range of 0-500 PSI and can operate up to 800ºC. It was tested at the Ohio State University Laboratory Reactor (450 kW) and exhibited minimal radiation sensitivity according to Luna. The sensor was developed to support future high-temperature gas-cooled reactors. In addition, LUNA is also currently developing radiation-insensitive fiber optic temperature sensors [10].

4.3 Ultrasonic Temperature Sensor

Ultrasound waves are inaudible sound waves at frequencies greater than 20 kHz. Ultrasonic devices are used for sensing applications in many fields. In fact, in the nuclear industry, ultrasonic transit time flow measurements have been used by many NPPs in support of power uprates. In particular, the ultrasonic transit time flow measurement method has been used to reduce uncertainty in feedwater flow measurements which is an important parameter for NPP heat balance calculations. However, ultrasonic sensor readings are not typically used for any control or protection action in nuclear power plants. Rather, they are used to monitor flow and overcome the inherent uncertainty of the existing Venturi flow sensors that can become clogged over time as the plant is operating and measure inaccurate flow rates.

Ultrasonic thermometry has the potential to satisfy the temperature measurement requirements of high-temperature gas-cooled advanced reactors and SMRs. In the 1960s, ultrasonic pulse techniques were used for the study of the transport properties of gases to measure temperatures above 10,000°C [11]. Although ultrasonic measurements typically rely on piezoelectric or magnetostrictive materials that tend to degrade over time when subjected to high temperatures and radiation, candidate transducer materials like aluminum nitride have been identified that may be considered for in-core use or near-core applications [12].

It is expected that the core outlet temperatures of gas-cooled advanced reactors will exceed 800°C during normal operation. At the outlet, local temperatures will deviate significantly from the average bulk fluid temperature. This is due to non-uniform heat-up in the core resulting in flow stratification effects which greatly challenge accurate temperature measurement. The non-uniformities of the coolant temperatures and flows in the lower plenum and into the hot leg at any measurement plane can vary significantly (spatially). In addition, flow may exhibit temporal instabilities (i.e. swirling and shifting with time) which will require measurements at multiple locations and specialized analysis techniques [13].

Researchers at INL have been designing an ultrasonic temperature sensor that could be used for high-temperature measurements in advanced reactors or SMRs. Since the speed at which sound travels through a material is dependent on the temperature of the material, the temperature of the probe may be determined by introducing an acoustic pulse to the sensor and measuring the resulting time delay of echoes. In addition, if multiple acoustic discontinuities are introduced within the probe, measurements may be obtained at multiple points to provide a temperature profile along the length of the probe [14]. This technology will become a strong candidate for deployment in high-temperature advanced reactors and SMRs as transducer material research and development (R&D) continues to progress.

4.4 Other Emerging Sensors

Table IV below provides a list of additional emerging sensor technologies. These technologies represent a small sample of the sensors being developed around the world for deployment in the next generation of reactors. Although many of these concepts are very promising, it is important for sensor developers to understand the many aspects of sensor performance in an operating plant as well as the nuclear qualification process in order to supply robust products to the industry and support the deployment of SMRs and advanced reactors.

Table IV. Examples of Emerging Sensor Technologies

Sensor	Development Status	Key Attributes	Potential Shortcomings
In-Pile Thermocouples	Developed at INL, Used at the Advanced Test Reactor	Highly accurate, first principles temperature measurement.	Requires processing and integration of noise signals.
Silicon Carbide Piezo-resistive Pressure Sensor	Developed by NASA and others	Works in high temperatures and harsh environments.	Reduced sensitivity in radiation.
Thermo-acoustic Sensor	Developed by Penn State University in Collaboration with INL	Self-powered system, potential for extremely low measurement uncertainty (±0.01°C)	Requires further development
High-Definition Fiber Optic Strain and Temperature Sensor	Commercial Product: LUNA	High-resolution measurements along fiber (up to 50m), low profile (for embedding within structures), EMI/EMC immune, corrosion proof.	Requires complex data processing, low maximum temperature (220°C), radiation darkening.
Multi-Point Temperature Sensor	Commercial Product: Emerson	Up to 60 independent measurement points, utilizes existing temperature sensor technologies (RTD, thermocouple)	Potential for common cause failure, potential for common mode drift
Sapphire Sensor	Commercial Product: Emerson	Extremely high temperature range: Up to 1800ºC	Short sensor lifetime (< 24 months)
Liquid Level Multi-Point Sensor	Commercial Product: Delta-M	Up to 6-point level measurements, fast response time (< 1 sec), High operating temperature (458°C)	Small insertion length of probe (< 120 inches)
High-Temperature Sensor	Commercial Product: Stoneridge	Wide range: -40ºC to 900ºC	Relatively large response time: Up to 10s
Johnson Noise Thermometer	Prototype System: Metrosol	Inherently drift free	Net yet deployable

4.5 Digital Sensors

The I&C sensors used in currently operating Generation-II LWR NPPS are primarily analog technologies that are steadily progressing towards obsolescence. Emerging sensors that utilize digital components and processing can provide significant benefits over analog-based equipment in terms of performance, reliability, and maintainability. However, the nuclear power industry in the United States has been slow to adopt digital technology, especially in safety-related systems, as a result of regulatory concerns regarding potential common-cause failures (CCFs) of equipment with embedded digital devices including smart sensors [15]. Therefore, emerging digital sensors including Johnson Noise thermometers, fiber optic sensors, and ultrasonic sensors will need to consider potential CCF concerns in order to be viable options for use in safety-related nuclear applications.

5 AMS SENSOR TESTING AND DEVELOPMENT

This section presents work performed by the authors as part of an SBIR Phase II project granted by DOE to evaluate new I&C sensors capable of meeting SMR and advanced reactor measurement needs and provide a smart sensor system for next-generation reactors. In support of this R&D, a light water flow loop was constructed at the AMS laboratory and instrumented with various nuclear and commercial grade temperature, pressure, and flow sensors. The loop is intended to simulate the dynamic conditions of an SMR in terms of natural circulation flow versus forced flow and to serve as a test bed for new sensors. The flow loop and associated systems are shown in Figure 1. The sensors that are being developed or evaluated at AMS are described below.

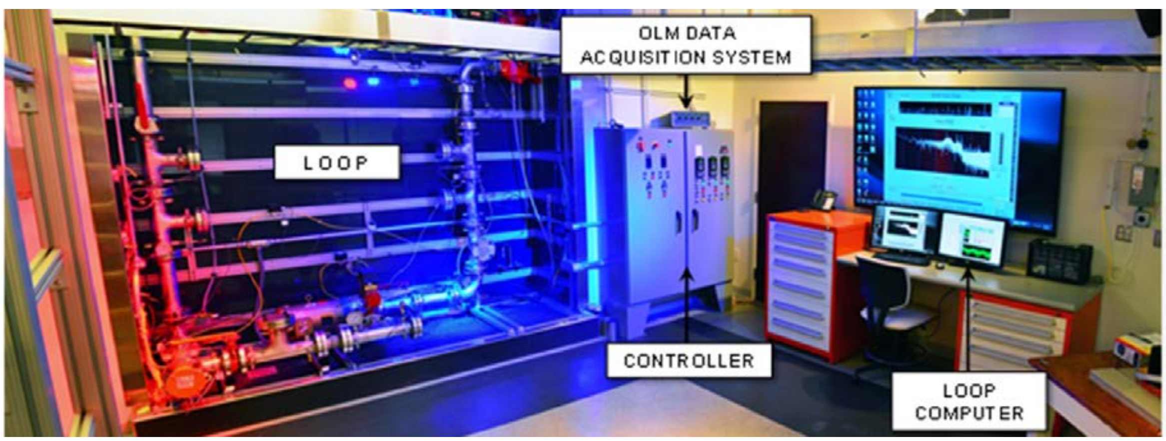

Figure 1. AMS Flow Loop Test Facility

5.1 Wireless Sensor Submergence Evaluation

Wireless sensors and technologies for SMRs must be capable of long-term, reliable operation under adverse conditions. Successful implementation of wireless sensors in SMRs enables cost and space savings in cabling and associated conduits, junction boxes, penetrations, cabinets, cable trays, and connectors. Existing industrial wireless networks (e.g. ISA100.11a and WirelessHART) are readily deployable for many plant applications to improve site efficiency via low power, low data rate wireless communication. However, for deployment in SMRs, wireless sensors must be capable of submerged operation and signal transmission and resilient to interference with other networks sharing the same frequency spectrum. In addition, the nuclear industry requires robust cybersecurity measures to ensure secure wireless communication of plant data.

AMS set up a small network (5 nodes) of WirelessHART devices to determine the feasibility of deploying existing industrial wireless networks in next-generation reactors. WirelessHART is a global IEC-approved standard (IEC 62591) for wireless sensor communication in the 2.4 GHz ISM frequency band. WirelessHART is the most recent revision of the HART (Highway Addressable Remote Transducer) Protocol and is widely used for control and monitoring applications in other industries.

Outside of the nuclear power industry, reliable and robust wireless technologies are becoming more prevalent in industrial applications for improving plant operations and efficiency. Existing wireless technology is capable of operating over long distances at high data rates with low power consumption when transmitting through air. However, if wireless sensors are deployed in SMRs and advanced reactors, it is possible that the sensors will be submerged and transmitting signals through water or some media other than air. Wireless I&C sensors in SMRs and advanced reactors must be able to communicate process measurement data to the gateway receiver consistently and reliably through these media.

To evaluate the performance of WirelessHART signal transmission through water, laboratory experiments were performed on a wireless temperature transmitter using a 55-gallon container of water. During these tests, the transmitter and gateway were isolated from other wireless devices (i.e. Wi-Fi, Bluetooth, ZigBee, Z-Wave, etc.) and placed in a Gigahertz Transverse Electromagnetic (GTEM) cell at the AMS laboratory. A vector signal analyzer (National Instruments PXIe-5646R) was used to monitor the WirelessHART frequency spectrum (2.4 GHz ISM band). Using the WirelessHART software, AMS engineers were able to confirm that the test setup was isolated from other wireless networks and monitor communication between the gateway and the wireless transmitter. As specified by IEEE 802.15.4, the 2.4 GHz ISM band is divided into 16 non-overlapping frequency channels. During these tests, the WirelessHART devices communicated on 15 of the 16 available channels in a pseudo-random channel hopping sequence. The plot in Figure 2 (taken from a screenshot of the vector signal analyzer) clearly shows these 15 individual channels that span from 2.4000 GHz to 2.4835 GHz

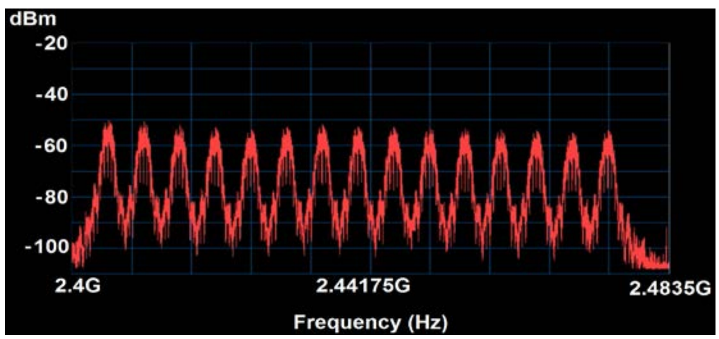

Figure 2. WirelessHART Channels on 2.4 GHz ISM Band

Once the WirelessHART network communication was established and signal isolation confirmed, a comparison was conducted on the performance of the 2-device (i.e. transmitter and gateway only) WirelessHART network while both devices were in air and again when only the transmitter was submerged in water. For this testing, the transmitter was configured for a "burst rate" of 8.000 seconds. The burst rate is the interval in which a WirelessHART field device updates its measurement data to the gateway. When both devices were in air, the average burst rate of the transmitter was 8.000 ± 0.2 seconds, and the network reliability was maintained at 100% (as indicated by the WirelessHART gateway). When the transmitter was submerged approximately six inches below the surface of the water, it immediately began to lose communication. The average burst rate of the submerged transmitter steadily increased above the configured rate of 8.000 seconds, and the device classification changed from "Live" to "Stale," indicating that the transmitter had missed several consecutive updates to the gateway. After 10 minutes of submergence, the device classification changed again from "Stale" to "Unreachable," indicating that the device may be considered offline. Once the device has been classified as "Unreachable," it will not resume communication with the gateway upon resurfacing. The newly-resurfaced transmitter must begin the secured network joining process to reestablish communication. This joining process takes several minutes. Any measurement data collected by the device during submergence, resurfacing, and rejoining is lost completely.

Based on the result of the field and laboratory tests, it would be reasonable to suggest that WirelessHART is not feasible for submerged SMR applications. However, it should be noted that the laboratory test was repeated using the stripline conductor of the GTEM cell acting as an antenna for the WirelessHART signal. With this revised setup, the submerged transmitter was capable of successful communication with the gateway without increased average burst rates or decreased network reliability. Therefore, to realize the benefit of wireless technologies for submerged or potentially submerged field devices, plants must incorporate an antenna system to boost the strength of electromagnetic waves through water. A distributed antenna system such as a leaky coaxial cable (also known as a "radiating cable") could be a suitable low-cost option for SMR designers to consider incorporating in the plant infrastructure for wireless device communication.

5.2 Adapting Existing Sensing Technologies for SMR Applications

Existing nuclear-grade sensors can be repurposed to infer or estimate additional process parameters. For example, a temperature sensor can be used to provide discrete level indication or primary flow estimation via analysis of the thermal response of the sensor. This concept was demonstrated on the AMS flow loop to determine pressurizer level and primary system flow rate.

5.2.1 Thermal Level Sensor

In order to determine pressurizer level, three identical thermocouples were installed along the height of the AMS flow loop pressurizer as show in Figure 3. Thermocouple response data was collected on all three thermocouples via the Loop Current Step Response (LCSR) test which is used periodically in NPPs for response time testing of reactor coolant system I&C sensors. During the LCSR test, a small electric current is passed through the temperature sensor lead wires to elevate its temperature above the ambient. When the current is removed from the circuit, the resulting thermal response is analyzed to obtain the response time. The response time of a thermocouple is dependent on its mass, heat capacity, surface area, and the local heat transfer coefficient. For identical thermocouples, the mass, heat capacity, and surface areas are essentially equal (minor discrepancies associated with manufacture are negligible here). Therefore, the response of the thermocouple is dominated by the local heat transfer coefficient. Since the heat transfer coefficient of water is much larger than that of air, the response time of the submerged thermocouples (middle and bottom) must be significantly less than the response time of the exposed thermocouple (top). It is evident in the plot that two thermocouples are submerged in water and one thermocouple is exposed to air. The pressurizer water level is between the submerged middle thermocouple and the exposed top thermocouple. Resolution of level measurement using thermocouple response is dependent on the number of thermocouples used and the distance between them.

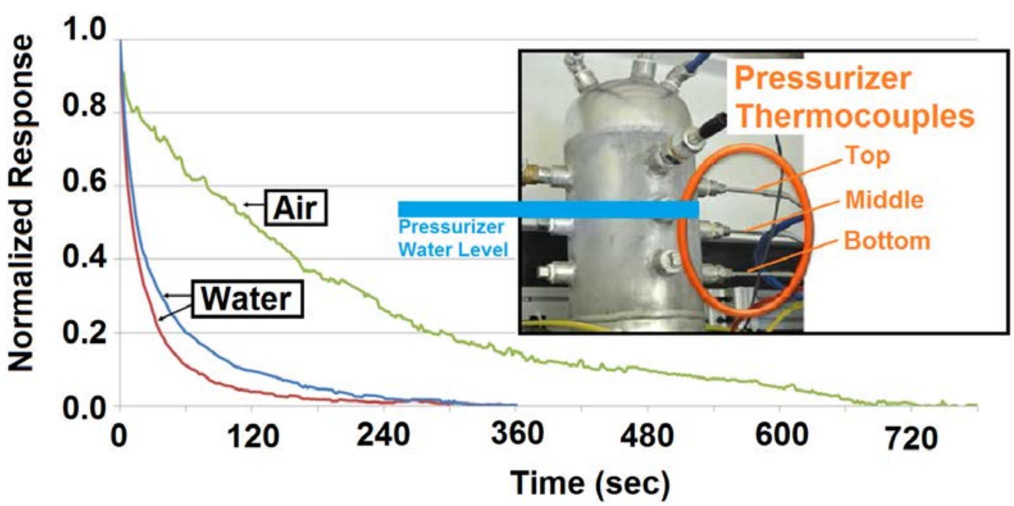

Figure 3. Normalized Thermal Response

5.2.2 Thermal Flow Sensor

Similarly, if the thermocouple being subjected to the LCSR test method maintains submergence (i.e. the local heat transfer coefficient does not change due to a multi-phase environment), then this same phenomenon can be applied to estimate primary system flow. Using a thermocouple installed in the hot leg piping of the AMS flow loop, response data via the LCSR test method was collected to evaluate a thermocouple's sensitivity to changes in flow. As expected, the response time of the thermocouple decreased with increasing flow rate as shown in Table V. However, the response sensitivity was low and the repeatability of the test was inconsistent. Although the feasibility of this concept for flow measurement is poor, it may still be useful for flow confirmation.

Table V. Thermocouple Response Times at Various Flow Rates

Flow Rate (Gal/min)	Response Time (sec)
4	7.30
33	6.75
68	5.73

5.3 AMS Triple Temperature Sensor

AMS holds a patent for a multi-element temperature sensor that incorporates two standard thermocouples and one RTD within the same probe and is referred to as the AMS Triple Temperature Sensor (TTS). It was designed to provide sufficient diversity and redundancy of measurements and facilitate enhanced sensor diagnostics such as calibration stability, in-situ response time testability, and in-situ calibration testability. Three Type-K TTS probes and two Type-N TTS probes were manufactured for testing and analysis in support of this R&D. Preliminary response time tests of the Type-K TTS probes have been conducted. Using the standard plunge test method for temperature sensors, the TTS elements were subjected to a step change in temperature, plunging from hot flowing air into cool flowing water. The response times of each element were obtained via a first-order analysis commensurate to standard practice in the industry. An example of the response time results for one of the TTS probes is shown in Figure 4. Currently, AMS is conducting thermal aging experiments of the TTS probes in order to characterize its calibration stability.

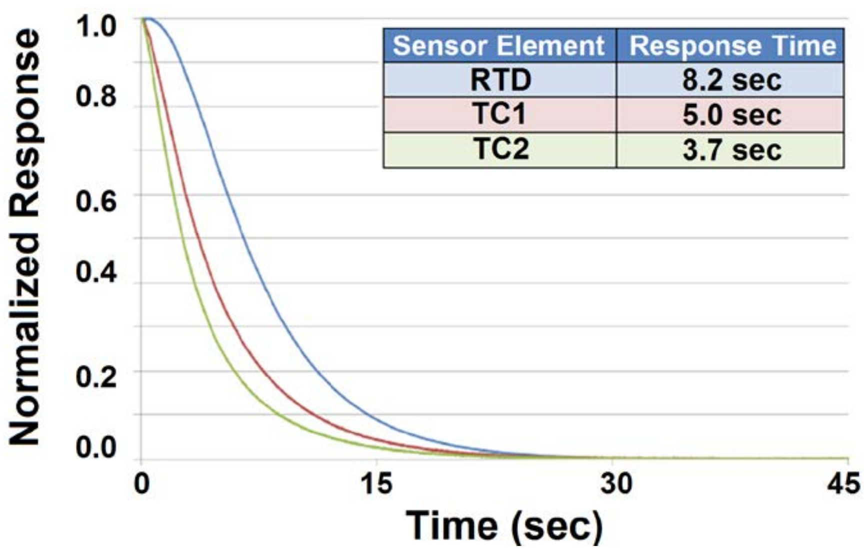

Figure 4. Plunge Test Data and Response Time Results for TTS Probe

6 CONCLUSIONS

There are many sensor technologies and concepts on the horizon and in the marketplace that may one day serve as viable options for I&C in SMRs and advanced reactors. Emerging sensors are capable of high accuracy measurements, good calibration stability, and wide measurement ranges. However, existing I&C sensors are much simpler, their operating principles are well understood, and their maintenance practices are well known. As these next-generation reactor designs progress, it is important for designers to communicate with the industry, academia, and laboratory communities about the specific requirements and challenges associated with measurement of key process parameters.

7 ACKNOWLEDGMENTS

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