ASSESSMENT OF SENSOR TECHNOLOGIES FOR ADVANCED REACTORS

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ABSTRACT

This paper provides an assessment of sensor technologies and a determination of measurement needs for advanced reactors (AdvRx). It is a summary of a study performed to provide the technical basis for identifying and prioritizing research targets within the instrumentation and control (I&C) Technology Area under the Department of Energy's (DOE's) Advanced Reactor Technology (ART) program.

The study covered two broad reactor technology categories: *High Temperature Reactors* and *Fast Reactors*. The scope of "High temperature reactors" included Gen IV reactors whose coolant exit temperatures exceed ≈650 °C and are moderated (as opposed to fast reactors). To bound the scope for fast reactors, this report reviewed relevant operating experience from US-operated Sodium Fast Reactor (SFR) and relevant test experience from the Fast Flux Test Facility (FFTF).

For high temperature reactors the study showed that in many cases instrumentation have performed reasonably well in research and demonstration reactors. However, even in cases where the technology is "mature" (such as thermocouples), HTGRs can benefit from improved technologies. Current HTGR instrumentation is generally based on decades-old technology and adapting newer technologies could provide significant advantages.

For sodium fast reactors, the study found that several key research needs arise around (1) radiation-tolerant sensor design for in-vessel or in-core applications, where possible non-invasive sensing approaches for key parameters that minimize the need to deploy sensors in-vessel, (2) approaches to exfiltrating data from in-vessel sensors while minimizing penetrations, (3) calibration of sensors in-situ, and (4) optimizing sensor placements to maximize the information content while minimizing the number of sensors needed.

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1 INTRODUCTION

Sensors and measurement technologies provide information on processes, support operations and provide indications of component health. They are crucial to plant operations and to commercialization of advanced reactors (AdvRx). In 2016, the Department of Energy's (DOE's) Advanced Reactor Technology (ART) program sponsored a study by a team from three national laboratories − Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL) and Pacific Northwest National Laboratory (PNNL) – to provide an assessment of sensor technologies and a determination of measurement needs for advanced reactors (AdvRx). This paper is a summary of that assessment. The full report [1] provides the technical basis for identifying and prioritizing research targets within the instrumentation and control (I&C) Technology Area under DOE's ART program and contributes to the design and implementation of AdvRx concepts.

The study was organized under two broad categories: **High Temperature Reactors** and **Fast Reactors**. The scope of "High temperature reactors" included Gen IV reactors whose coolant exit temperatures exceed ≈650 °C and are moderated (as opposed to fast reactors). We included in this category gas-cooled reactors that have been built and operated throughout the world to date – including those that use carbon dioxide (CO_2) or Helium (He) as coolant – and the molten salt reactor. With regard to fast reactors, there are several reactor years of experience with several technology variants (including sodium fast reactors and other fast reactors such as the LBFR). In particular, several experimental, prototype and demonstration units have been designed and operated in several countries, including France, India, Japan, USSR/Russia, UK, and the United States. To bound the scope, the study reviewed relevant operating experience from US-operated Sodium Fast Reactor (SFR) and relevant test experience from the Fast Flux Test Facility (FFTF).

2 HIGH TEMPERATURE REACTORS

2.1 General Characteristics

The inherent safety of HTGRs (including high-quality ceramic-coated particle (TRISO) fuel, single-phase inert coolant (helium), a post-shutdown decay heat removal feature that is consistent with TRISO fuel temperature design limits, a combination of core low-power density, large size and heat capacity, high thermal conductivity, and large fuel thermal margins resulting in very slow progressions of postulated core heat-up accidents) argues for less sensor redundancy compared to LWRs. The much larger time allowance for accident response provided by an HTGR allows human-based action to be highly effective in performing correct safety functions. However, even though HTGRs do not need as much redundancy in instrumentation as other reactor designs, the higher temperatures of an HTGR cause more rapid aging of the sensor materials and thus necessitate the use of more durable materials. Instrumentation system components become commercially unavailable with time as suppliers change and upgrade their products. "HTGR instrumentation systems are more likely than LWRs to rely on standard industrial safety-grade control electronics because the reactor inherent passive safety relaxes the system performance requirements … HTGRs are anticipated to be able to make much more extensive use of digital system improvements as they become technologically available, resulting in a higher net instrumentation system reliability than is typical at an LWR" [8]. Another challenge they face is the relatively large mechanical shift between the core and the vessel caused by the differential coefficient of thermal expansion (CTE) between the graphite moderator and the metal pressure vessel. Basically, the motion of the core causes too much stress to allow for instruments to be used anywhere but the top and bottom of the core. Access to the hot inner annulus of annular primary piping is also restricted by the mechanical shifting of the inner piping as the reactor heats up. Figure 1 is a schematic showing instrumentation and control systems in a typical HTGR.

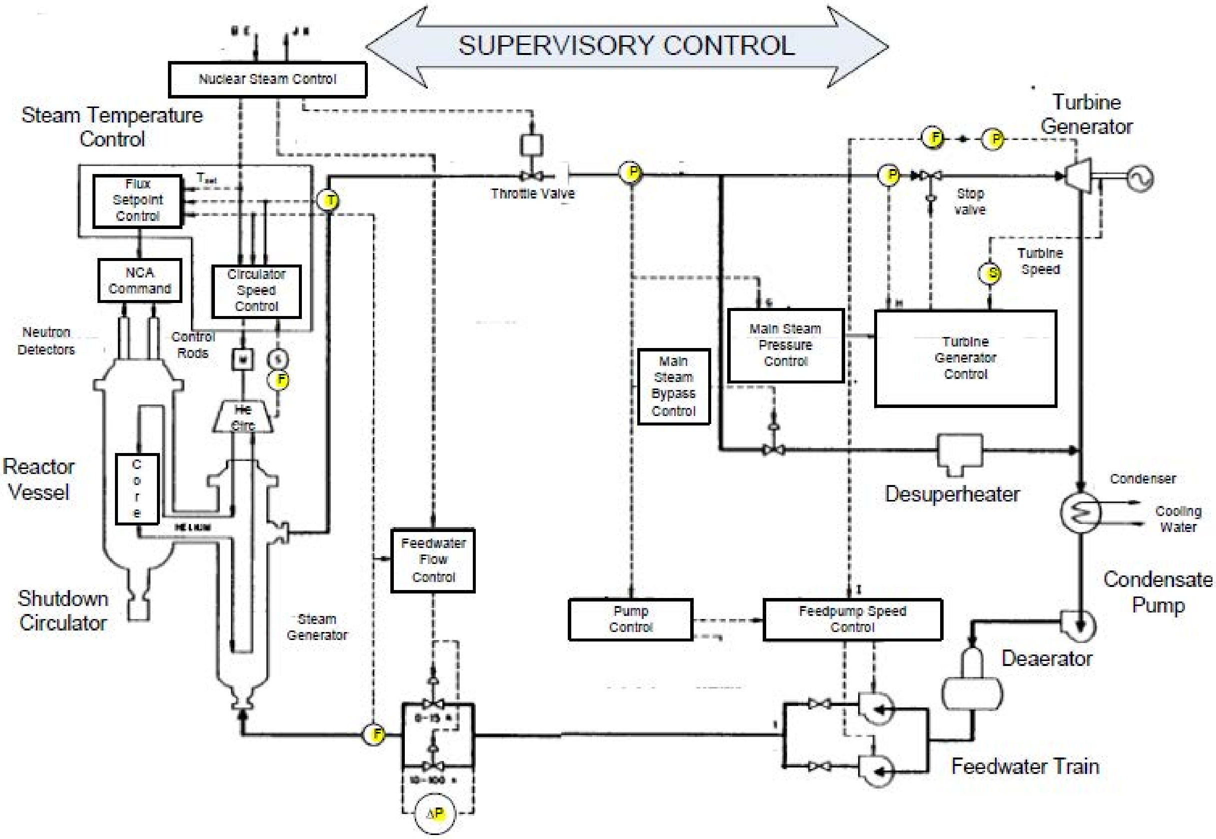

Fig. 1. Typical control system layout and instrumentation for an HTGR plant (F, flow sensor; P, pressure; ΔP, differential pressure; S, circulator/turbine speed) [Ref 9]

2.2 State of the Art of Sensor Technologies for HTGRs

References [2-9] were used to compile Table 1, which provides a summary of the state-of-the-art of sensor technologies for HTGRs. Note that some accuracy and/or range information is missing in a few cases, this is because such information could not be found from the literature reviewed.

Table 1 Summary of information for available sensors in HTGRs [**Error! Bookmark not defined.-Error! Bookmark not defined.**]

Sensor	Sensor Type	Reactor	Location	Range	Accuracy	Comments
Temperature	Chromel-Alumel thermocouple	Peach Bottom	Fuel element, vessel metal, and reactor coolant	0-538 °C	±2.2 °C	
	Tungsten-rhenium thermocouple	Peach Bottom	Fuel elements	0-1310 °C	N/A	
	Acoustic Thermocouple	Peach Bottom	Fuel spines	N/A	N/A	In-core measurement during start-up

Sensor	**Sensor Type**	**Reactor**	**Location**	**Range**	**Accuracy**	**Comments**
	Geminol-P & Geminol N type thermocouples	FSV HTTR	Pre-stressed concrete reactor vessel	0-1093 °C	±2.2 °C	
	Chromel-Constantan	FSV	Circulator and core support structure	0-538 °C (In use)	±1.7 °C	Measure the circulator and core support structure
	K-type (NiCr-NiAl)	HTR-10	Inlet and outlet of steam generator	At least up to 800 °C	±1.5 °C ($0 \le T \le 375$°C) or ± 0.4% T (375 °C $\le T \le$ 800°C).	
Pressure	Safety-grade class 1E pressure transmitters	HTTR	Inside the primary coolant at the inlet and outlet of reactor vessel	N/A	N/A	Will also measure flow in order to find differential pressure
Flow	Core differential pressure to monitor gas flow Gas circulator differential pressure	HTTR	Core inlet and outlet At the circulator location	0-4 MPa 0-4.8 MPa	N/A Not available	Used to monitor flow; used as a safety parameter To measure primary gas flow rate
Neutron Flux	Fission Chambers or Boron-lined proportional counters	FSV	Sensor well and structure around the core	Temperatures up to 800 °C	N/A	Work from start up to full power.
		HTTR	Top of permanent reflector	Up to 600 °C Flux up to 10^7 n/cm^2-s	N/A	Designed for 10^{-8} to 30% rated power
	Compensated DC ionization chambers	Peach Bottom	In-core sensor well	Eight decades down from 500% power	N/A	For intermediate or log power range
		FSV	In-core sensor well	10 decades with a log count reading up to (~2 × 10^5 neutrons/cm^2-s)	N/A	
	Uncompensated ionization chamber	HTTR	Outside of the pressure vessel	0-150 % power	The sensitivity of the detector was measured to be 4.7 × 10^{-12} A/nv	Power range of 0.1 to 120 % Linear Power Range
Moisture	Electrolytic hygrometer moisture detector	Peach Bottom	Outlet helium stream from Steam generator	Full scale from 0 to 1000 parts per million by volume	±5%	

Sensor	Sensor Type	Reactor	Location	Range	Accuracy	Comments
	Rhodium-plated mirror	FSV	Primary Coolant	Sample will range between 66-121 °C.	Mirror temperature can be controlled to better than ±0.6 °C	Two modes: Indicating and trip mode
	MMY170	HTR-10	Outlet of helium blower	-100 – 20 °C	±2 °C	
Stress and Strain	Strain Gauges	Peach Bottom	Vessel internal and exterior structure	N/A	N/A	Measured in start-up to prove design, and periodically after that
		FSV	Various locations in structure	Some can measure up to 3000 micro-strain	The vibrating-wire strain gauges have a resolution of 0.1 micro-strain	Several types found in the facility

N/A: Not available.
FSV = Fort St. Vrain; HTTR = High Temperature Test Reactor; HTR = High Temperature Reactor.

2.3 Summary of Findings for High Temperature Reactor Instrumentation

The following are some of the issues that were identified with regard to high temperature reactor instrumentation:

a) For pebble bed reactors, no temperature sensors are currently available to measure the pebble temperature distribution in the core directly. Temperatures of the surrounding graphite structure and the structural metal components are measured using thermocouples. These include top reflector, core surrounding reflector, hot gas cell, bottom plate, bottom carbon bricks, fuel discharge tube, radiation channel, and the cylindrical core vessel.

b) The drift in thermocouples is unacceptable at the high (operating) temperature and radiation environment. There is a need for less-drift-prone sensors. Precious metal thermocouples are generally accurate, but tend to have too high a neutron cross-section for use in areas with significant neutron flux.

c) The Johnson Noise Thermometer (JNT) [1], while arguably the "holy grail" of temperature measurement if fully developed, currently suffers from significant susceptibility to electromagnetic interference (EMI) because of the minute voltages it produces. To date, Johnson noise thermometry is best employed for online periodic recalibration of mature temperature sensors such as RTDs.

d) In-core temperatures and radiation fluxes are well beyond what any available semiconductor could handle in a pebble bed reactor.

e) Significant issues with implementing ultrasonic-guided wave thermometry [1] are (1) the challenge of transmitting the ultrasonic-guided wave through the primary pressure boundary and (2) the fact that it is not immune from drift. The high temperatures and high radiation flux of an HTGR will affect the mechanical properties of the waveguide over time and transmute its composition, shifting the recorded temperature.

f) Issues with implementing distributed fiber-optic Bragg thermometry is susceptibility to photo-bleaching in high radiation, high temperature environments.

g) Flow measurement in liquid salt has been problematic. Work is currently proceeding on ultrasonic, time-of-flight methods for measuring flow velocity. High temperature is the challenge from two perspectives: (1) the ultrasonic transducers fail at the elevated salt temperatures and therefore must be isolated from the process via waveguides, and (2) the waveguides act as efficient heat sinks that cool the salt flow piping, which can lead to salt freeze. There are work arounds to the heat sinking dilemma; however, other flow measurement technologies need investigation such as thermal pulse. Additionally, the development of ultrasonic transducers that fully operate at 750 °C is needed.

h) Work is needed on high-temperature fission chambers that would allow location within the reactor core. Such chambers are not commercially available.

i) Tritium measurement historically has been measured using an off-line process. A better solution is to deploy an in-process, near real-time sensing technology to track tritium production. Such technology is not currently available.

The study suggested the following list of sensor development needs for high temperature reactors:

*Rugged, accurate thermocouples for high temperature measurement in high radiation***:**
Au–Pt thermocouples can achieve precision of approximately ±10 mK at temperatures up to 1000 °C and offer one of the best promises for precision temperature measurements at high temperatures in a high radiation environment. However, the stability and durability of mechanically rugged, metal-sheathed, mineral-insulated versions of the Au–Pt thermocouple have not yet sufficiently been demonstrated for long-term application to safety-important measurements.

Calibration of temperature sensors for high temperature and radiation environments:
Johnson noise thermometry is theoretically the ultimate in temperature measurement, since it depends on fundamental (noise) properties rather than on materials properties. In practice however, because of the extremely small signals involved, electromagnetic interference noise pickup is particularly problematic and understanding and compensating for any shifts in the cable properties is required for a successful long-term implementation.

Direct, accurate pressure measurements:
Direct, accurate pressure measurement in high temperature environments is important in high temperature gas reactors for improved performance. Using a closed-pore ceramic sensor body (e.g., SiCN) is a new method to find the differential pressure in the system. Thick and thin films of SiCN can withstand high temperatures with the added advantage that it can be molded to any shape. The sensor body can serve as a strain gauge with a nonporous sensor body employed as a reference leg. Because the ceramic element and electrical wiring pads are directly exposed to the primary fluid, avoiding shorting the electrical leads becomes a significant technical issue. Methods of reliably solving this is important to its application in high temperature reactors.

Mass flow rate:
There is a need to provide a better measure of mass flow rate in high temperature gas-cooled reactors.
Current methods rely on measuring differential pressure across the compressor.

Neutron Flux measurement at high temperatures:
No suitable neutron flux measurement sensor is commercially available that functions at temperatures above 550 °C. HGTRs run at temperatures much above this. However previous programs have developed

fission chambers that can function up to 800 °C, but these detectors are not yet commercially available. The issue with reliable operation of fission chambers at high temperature stems from the metallic deposits, which arise from the evaporation of contaminants from the structural alloy that form across the electrical insulator between the central node and wall, shorting out the chamber. To overcome the temperature vulnerability of fission chambers, low-outgassing structural materials and high-temperature-tolerant sealing materials and methods need to be devised.

In Situ Corrosion Monitoring in Liquid Salt Cooled and Other Nuclear Reactors:
There is a need for instrumentation deployable directly in coolant process piping that measures the progression of corrosion. Development of a direct measurement instrument is complicated by the high process temperatures and the corrosive nature of chloride and fluoride salts. An innovative measurement device is needed that accurately and quantitatively tracks the progress of material removal.

High-Radiation and High-Temperature Tolerant Solid-State Electronics:
High temperature and gamma radiation are the killers of modern electronics. Advancements to greatly improve several solid-state electronics technologies can be adapted for the survivability of electronics for advanced reactor systems such as remote robotic equipment. It is feasible to develop the required combination of circuit fabrication methods (process and device selection), proper circuit topology selection (topologies that are tolerant of temperature and radiation effects), rad-hard-by-design (RHBD) techniques for custom chip design, and proper packaging including significant shielding for field deployment in advanced reactor environments.

3 FAST REACTORS

3.1 General Requirements for Sensor Technology Advances in Fast Reactors

3.1.1 Sensor Reliability and Compatibility

A number of sensor advances have occurred recently that may be applicable to meet the measurement needs for fast reactors. While each sensor technology may need a different type of adaptation for use in FRs, a common thread among all of these technologies is the need for improved reliability. Sensors for in-vessel temperature, flow, and pressure measurements will likely need improved reliability to meet the long lifetimes associated with many advanced reactor designs. The sensors for in-vessel temperature, flow, and pressure measurements are typically deployed in challenging environmental conditions in sodium with high temperatures and neutron and gamma fluxes. Advanced reactors could benefit from improved compatibility of the sensor with these types of environments.

3.1.2 Distributed and Integrated Path Length Sensing

Most reactor sensor systems are point sensors that provide measurements at specific spatial locations within the plant. Reactor parameter profiles are commonly estimated using discrete sensing points, such as multiple-temperature sensors positioned to estimate primary reactor outlet temperatures. A preferred method is direct-profile measurements using distributed or integrated path length sensing.

3.1.3 Drift-free Sensor Systems

Many sensing techniques are susceptible to signal drift. Time-dependent drift is a common problem in thermocouples, which estimate temperature based on changes in junction voltage. Drift in thermocouples is induced by metallurgical changes in the junction electrode (e.g., oxidation, depletion, contamination, strain) caused by aging and radiation exposure for example.

3.2 Summary of Findings for Sodium Fast Reactor Instrumentation

For sodium fast reactors, the study found that several key research needs arise around (1) radiation-tolerant sensor design for in-vessel or in-core applications, where possible non-invasive sensing approaches for key parameters that minimize the need to deploy sensors in-vessel, (2) approaches to exfiltrating data from in-vessel sensors while minimizing penetrations, (3) calibration of sensors in-situ, and (4) optimizing sensor placements to maximize the information content while minimizing the number of sensors needed. Where possible, sensors may be useful for providing sensitivity to multiple parameters. With this in mind, the following are some critical sensor applications that will require addressing:

1. Optical measurements of temperature are likely to be valuable in test reactors and perhaps in first-of-a-kind (FOAK) commercial reactors. The technical challenges associated with the application of optical sensors in advanced reactors include the provision of optical access ports for fiber optics and standoff optical sensors, the development of radiation and high temperature tolerant optical materials and fiber optic components for in-vessel devices, and the opaque properties of liquid metal coolants.

2. The technical challenges with the application of passive and active acoustic monitors in advanced reactors include the need for radiation and high temperature tolerant acoustic sensor materials and low frequency (<500 kHz) sensor fabrication. Other challenges include efficient probe design and calibration difficulties. Addressing these challenges is likely to have impacts encompassing a number of measurement needs, including acoustic emission monitors for Loose Parts Monitoring (LPM), acoustic monitoring of voids, leak detection, active component monitoring, and noninvasive high-fidelity process monitoring applications in advanced reactors.

3. Non-destructive evaluation (NDE) for primary systems in advanced reactors will be concerned mostly with detecting cracking (especially incipient cracking) in hard-to-access components and in regions that are readily accessible to probes deployed in-sodium. In-situ monitoring addresses concerns with hidden cracking in components likely to be of safety significance, where detection may be possible mid-cycle without shutting the reactor down or draining sodium from the primary system. Deploying and using these sensors are likely to be of most value in test reactors ((enabling testing the sensor technology itself, generating data for updating codes, and potentially creating the technical bases for regulatory relief from periodic in-service inspection (ISI) on these components), with limited deployment in commercial units (only at locations considered risk-significant). The technical challenges with in situ nondestructive evaluations in the primary systems of advanced reactors include the development of radiation and high temperature tolerant sensor materials (acoustic, electromagnetic and optical). Aspects that should be considered include probe design for in-situ monitoring, field fabrication techniques (for integrating sensor technology with the component), and calibration to address aging concerns. Leveraging lessons learned from under-sodium viewing (USV) for immersion probe design may provide a path forward. This effort addresses the challenges in monitoring hard-to-replace passive component monitoring for advanced reactors.

4. The technical challenges associated with power sensors (e.g., fission chambers) include the development of radiation and high temperature tolerant materials and sensor design. Conventional sensors quickly burn out in the harsh in-core environment. Cherenkov gas or radiation-induced luminescence detectors might be possible solutions for in-vessel power monitoring. This effort addresses clear monitoring challenges and gaps in advanced SFR designs.

5. As the deployment of greater numbers of sensors inside the vessel (and in other critical components) increases, there will be a need for increased amounts of cabling for power and sensor measurement extraction. For in-vessel sensors, this may lead to a need for additional vessel penetrations that may not always be feasible. Recently technologies have been proposed for

wireless (EM and acoustic) communication that may provide a mechanism for powering and exchanging information between sensors. Technical challenges here would involve acoustic wave propagation characteristics in liquid Na, electronics survivability, protocols, etc.

6. The use of robotics, visualization, and augmented reality technologies for refueling and for in-service inspection is regarded as a means to minimize the human error element of maintenance operations and to speed up maintenance, contributing to improved capacity factor, safety, and reduced staffing. Application of under sodium viewing technology could be an integral component to these technologies.
7. *In situ* serviceability and high reliability of the primary system flowrate measurement sensor is considered to be of great importance for SFR pool-type plants. This is highlighted by the experience at EBR-II [10].
8. The measurement of material degradation via acoustic methods in select locations is considered a high priority. This would include weld locations where differing structural materials interface and stress concentration points operating near or at the greatest system temperature.

As in the case of high temperature reactors, the study also suggested the following list of sensor development needs for sodium fast reactors:

In-situ ultrasonic non-destructive evaluation (NDE) for inspection and monitoring of hard-to-replace components
Conventional ISI is technically challenging (in-coolant) and costly when dealing with hard-to-access components in-vessel. Existing sensors are not compatible with requirements for SFRs.

Sodium flowmeter with high reliability/serviceability:
There is a need for development of sodium flow meter with high reliability and serviceability. Operating experience with EBR-II flowmeters indicated difficulty in servicing, creating a reliability problem.

Sodium level measurements:
SFR technology can benefit greatly from the development of a standoff non-contact technique for real-time measurement of sodium level (non-insertion sensor). The sensor (perhaps based on radio frequency (RF) techniques) should be immune to factors that limit the use of optical sensors (e.g., harsh environment, optical opacity, size, etc.).

In-service tubing integrity evaluation:
Passive components such as steam generators are difficult and expensive to replace and in-situ nondestructive evaluation of such components will increase reliability and inform proactive maintenance, repair, or replacement.

In-situ detection of dissolved hydrogen in sodium of secondary sodium loop:
There is a need for a reliable, in-situ hydrogen sensor capable of detecting water/steam leak of steam generators before catastrophic steam generator tubing failure and minimize corrosion and heat transfer surface fouling develop.

4 CONCLUSIONS

This paper has provided a summary of the DOE-sponsored sensor technologies assessment study for advanced reactors. The study focused on high temperature (gas) reactors and (sodium) fast reactors. For high temperature reactors the study found that in many cases HTGR instrumentation have performed reasonably well in research and demonstration reactors. However, even in cases where the technology is “mature” such as thermocouples, HTGRs can benefit from improved technologies (e.g., to eliminate drift at high temperatures). Current HTGR instrumentation is generally based on decades-old technology and adapting newer technologies could provide significant advantages. For example, advancements in several solid-state electronics technologies can be adapted to greatly improve the survivability of electronics for advanced reactor systems such as remote robotic equipment. The reliability and survivability of sensor technology for molten salt reactors is less mature because of relatively much less experience with this type of reactor. For fast reactors, the study found that several key research needs arise around (1) radiation-tolerant sensor design for in-vessel or in-core applications, where possible non-invasive sensing approaches for key parameters that minimize the need to deploy sensors in-vessel, (2) approaches to exfiltrating data from in-vessel sensors while minimizing penetrations, (3) calibration of sensors in-situ, and (4) optimizing sensor placements to maximize the information content while minimizing the number of sensors needed. Where possible, sensors may be useful for providing sensitivity to multiple parameters.

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