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Instrumentation Framework for Molten Salt Reactors

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Reactor and Nuclear Systems Division
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ACRONYMS AND ABBREVIATIONS

ARE	Aircraft Reactor Experiment
cps	counts per second
CT	computed tomographic
DOE	US Department of Energy
DRACS	direct reactor auxiliary cooling system
EMAT	electromagnetic acoustic transducer
EMI	electromagnetic interference
FFTF	Fast Flux Test Facility
I&C	instrumentation and control
IR	infrared
JNT	Johnson noise thermometry
LWR	light water reactor
MSR	molten salt reactor
MEMS	microelectromechanical systems
MSRE	Molten Salt Reactor Experiment
NE	Office of Nuclear Energy
NPP	nuclear power plant
ORNL	Oak Ridge National Laboratory
PRBS	pseudo-random binary sequence
PWR	pressurized water reactor
RD&D	research, development, and demonstration
RTD	resistance temperature detector
RVACS	reactor vessel auxiliary cooling system
SBIR	small business innovation research
SPND	self-powered neutron detector
SSC	system, structure, and component
TRL	technology readiness level

ABSTRACT

This report provides an overview of the specialized instrumentation necessary to operate and maintain liquid-fueled molten salt reactors (MSRs). The report does not address nonspecialized industrial process control instrumentation, fissile material tracking instrumentation, or digital control/communication technologies. The report focuses on identifying MSR measurement technology gaps and recommending research, development, and demonstration (RD&D) activities to close the identified gaps.

Modern MSRs can rely on the instrumentation demonstrated during prior MSR development efforts. No fundamental technology gaps have been identified that would prevent operating or maintaining MSRs. However, improved instrumentation technology, combined with the integration of modern process modeling and simulation, could significantly improve the reliability and decrease the operating costs of future MSRs. The largest potential impact of new instrumentation technologies is in the integration of maintenance automation into reactor operations. Flow measurement has the largest technology hurdles remaining to enable deployment of robust systems. Also, the technology for reliable online fuel salt sample acquisition remains at a relatively low level of technology readiness.

1. INTRODUCTION

This report supports the US Department of Energy (DOE) Office of Nuclear Energy (NE) MSR campaign through

1. Describing instrumentation's role and performance requirements throughout an MSR's lifecycle,
2. Providing a structured MSR instrumentation technology and state-of-the-art reference, and
3. Identifying MSR instrumentation technology gaps and recommending RD&D to close the identified gaps.

This report describes the instrumentation that is anticipated to be employed to operate, maintain, inspect, refuel, construct, monitor, and eventually decommission future MSRs.

MSRs are thermally based nuclear power plants (NPPs); as such, a significant amount of information can be obtained from prior thermal power plants and existing nuclear facilities. In fact, much of an MSR's process instrumentation will be identical to that employed in other high-temperature systems, as most process instruments do not directly touch the process fluid. However, simply overlaying conventional light-water reactor (LWR) instrumentation performance requirements onto MSRs is inappropriate, as different reactor classes rely upon substantially different physical processes. The extensive, historic MSR development program also provides a substantial amount of information on MSR test reactor instrumentation [1,2,3,4]. However, due to the passing of five decades and the present emphasis on commercial deployment, future MSRs instrumentation will have considerable differences from predecessor facilities.

All MSRs will be both passively safe and resilient against disturbances. Their advantageous characteristics will significantly impact the performance requirements of much of the instrumentation and controls (I&C). Impacts include (1) avoiding the need for high-speed, safety-grade process monitoring due to the lack of rapidly progressing accidents, (2) increasing the need for automated intrusion monitoring to facilitate use of local law-enforcement personnel for plant security (enabled by the lack of accessible vital areas), and (3) adding requirements to inspect/monitor passive safety features to ensure that they continue to be able to perform their functions. The lower safety significance of individual MSR plant components will substantially decrease in-service inspection requirements. For example, the instrumentation required to assess flaws in the pressure retaining structures of LWRs will not be necessary in MSRs due to their independent, multi-layered containment structures.

The liquid nature of an MSR’s fuel while in service significantly alters the design and performance requirements of the plant’s I&C. Due to the fissile material’s mobility and lack of confinement within cladding, a substantially different approach to fissile inventory tracking will be required than that used for solid-fueled reactors. Also, while the fission process changes the composition of the fuel in both liquid- and solid-fueled reactors over time, liquid-fueled reactors distinctively afford the possibility of gradually, purposefully altering the fuel composition over time. This is done to decrease corrosiveness, improve heat transfer properties, or remove neutron absorbers. Therefore, instrumentation will be needed to measure the evolving fuel salt composition and to subsequently control the salt chemistry. Moreover, fuel salt composition can serve as a process history monitor. The fuel composition provides a confirmatory indication of average power level to calibrate or confirm the heat balance and/or reactor physics models, while the quantity of dissolved constituent elements from the container alloy provides evidence of corrosion progression. Therefore, components/instrumentation that provide access to the fuel salt will be a distinguishing aspect of MSR instrumentation. Since there will be a substantial amount of radioactivity outside the MSR’s core, both radionuclide and fissile material tracking instrumentation will be required to demonstrate that the materials remain within their intended boundaries.

Because economically competitive energy generation is the overall objective for MSR development, this framework emphasizes the economic aspects of instrumentation technology. Since staffing costs at NPPs are a significant component of the overall power cost, enabling staff reduction through automation is a key framework element in achieving this goal. Automation of in-containment activities is also especially important at MSRs due to their high local dose rates. MSRs lack the shielding inherently provided by the water coolant and thick reactor components of LWRs. Most modern MSR designs employ interior vessel shielding, which substantially reduces the in-containment dose rates. The very high local radiation level effectively prevents employing solid state electronics within an MSR’s biological shielding; long-handled tooling must be used for in-shielding manipulations. Simplifying the required set of measurements is also a key principle for this framework. For example, the heat balance pressurized water reactor (PWR) is typically performed on the secondary side of the primary heat exchanger, providing the required information with higher reliability and lower cost. The recommended instrumentation development set only includes those measurements judged necessary to enable reliable plant operation as opposed to supporting scientific discovery.

The low fuel salt pressure also substantially alters the design and performance requirements for the plant I&C. When compared to the mass of LWR components, the lower mass of components containing fuel salt and the lack of containment pressurization accident sequences significantly decreases the cost/difficulty of replacing system components. Consequently, all MSR components, including the reactor vessel, are intended for periodic replacement. The highly automated maintenance systems used to perform the replacements and the component health monitoring instrumentation must be substantially more advanced than those in prior NPPs. Moreover, wiring and process sampling lines can easily be passed through a low-pressure boundary, so MSRs can more easily interconnect with advanced signal processing electronics located outside their containment/shielding layers. The additional cabling and improved monitoring capabilities will facilitate using more advanced signal processing online, such as power signature analysis on pumps and valves, and neutron noise monitoring on flux monitoring systems. These features should provide increased confidence in the components’ useful life and should assist in avoiding unplanned shutdowns.

MSR designers can learn from decades of issues impacting previous LWR deployments. One key lesson learned from decades of LWR deployments is that it is difficult to assess the health of large concrete structures without embedded sensors. Another lesson learned is that replacing safety-grade cabling within containment is difficult and expensive, largely due to the required fire protection and penetrations through containment. Modern MSRs will use much less safety grade cabling than their predecessors, as they employ much less safety-significant instrumentation and equipment. Furthermore, higher dose rates within MSR shielding will require MSRs to use metal and ceramic power cabling, which is expected to have a lifetime exceeding those of the plant structures.

Instrumentation-specific elements of the MSR supply chain are included in the framework. Any MSR vendor must have an adequate component supply chain. Dedicated MSR instrumentation is not generally available, so general purpose and stand-off instrumentation will be required. Consequently, this framework briefly addresses the issues involved with employing general purpose instrumentation at MSRs and fabricating custom instrumentation from compatible components. Much of the customization is either in the selection of compatible materials or in technology selections to avoid instrument exposure to the harsh fuel salt environment.

Different MSR concepts exhibit substantial design diversity, and the framework discusses the differences in instrumentation performance requirements due to the variance. As in other reactor classes, integral primary systems restrict measurement access at MSRs. Chloride and fluoride salts create different chemical environments, requiring different material choices for salt-wetted components. Fast-spectrum reactors tend to have much higher power densities, making in-core instruments more difficult to implement. Thermal-spectrum MSRs have in-core materials and structures similar to those of high-temperature gas-cooled reactors, so guidance is available on useful in-core instruments.

This framework report begins with a topology-based description of the instrumentation required for each major plant area/function. The following section provides a functional description of the measurement requirements throughout an MSR lifecycle. The next sections address the nonoperational phases of the plant (e.g., maintenance and construction) and additional plant systems (waste handling, safeguards monitoring, etc.). The next section provides an overview of the technologies used to perform the measurements, followed by an assessment of MSR instrumentation maturity and availability, along with instrumentation development recommendations.

2. INSTRUMENTATION TOPOLOGY

An MSR's layout is based on its required functions. This chapter provides a layout-based, task-oriented description of fast- and thermal-spectrum MSR instrumentation. The rationale for performing each measurement is provided, along with the system description. This chapter groups the diverse topology options by their function. For example, different means of decay heat removal or reactivity control are considered together.

MSR layouts have substantial potential variation based on the design options selected. This description is restricted to the most common MSR design options. Less common variants, such as direct lead-cooled cores and/or externally moderated systems, are not included so that focus is maintained on the most likely reactors anticipated for development in the near- to mid-term. This report is limited to single fuel salt systems and does not include breeder blanket configurations, or any systems intended to create separated fissile material streams. Online chemical processing systems are not included, as they are not featured in leading design variants.

2.1 CORE REGION

The core is the region within the reactor vessel where nuclear criticality and the bulk of heat generation and radionuclide production occurs. The core regions differ substantially between fast and thermal spectrum MSRs. Most of the core in thermal spectrum MSRs consists of neutron moderator material, which defines flow channels for the fuel salt. A thermal spectrum core also contains moderator support structures. The core will be surrounded by additional moderator/reflector material to improve the neutron economy, which is then surrounded by a layer of neutron absorber material to minimize the neutron flux on the reactor vessel. Thermal spectrum MSRs generally will not require any in-core instrumentation for safety purposes. The Molten Salt Reactor Experiment (MSRE) did not incorporate any in-vessel instrumentation at all. However, in a commercial thermal-spectrum MSR, the core power distribution and temperature will likely be monitored as an indication of the health of the moderator material. Moderator materials can only withstand limited amounts of radiation damage and consequently will require periodic replacement. Maximizing the moderator replacement interval requires monitoring the accumulation of radiation damage. Additionally, fuel salt flow redistribution due to flow channel blockage can result in thermal striping within the core's outlet flow, which can damage the metallic salt container material. The core may also contain absorber-based control elements whose positions will likely be monitored to provide additional prognostic system information.

During normal operation, a fast spectrum MSR's core contains no materials other than the fuel salt and possibly sparging gas. Therefore, the core will not contain instrumentation. Fast-spectrum MSRs may employ fuel salt displacement shutdown rods or movable neutron reflectors (located near the core). The motion and position of these rods would be monitored ex-core. Fast-spectrum MSR cores will be contained within a neutron reflector/shielding structure to (1) improve neutron economy, (2) reduce radiation damage to the reactor vessel, and (3) reduce radiation levels outside the vessel. Performance of the shielding material can be measured most effectively by monitoring the radiation environment outside the reactor vessel. Accumulated radiation damage to the reactor vessel will most likely be monitored through the use of coupons. Interpreting online vessel strain/creep measurements would be complex, as the vessel material will toughen/embrittle with increasing neutron fluence. Consequently, coupon-based periodic assessment of vessel material properties will be the principal measurement to assess remaining useful life.

For fast and thermal MSRs, core outlet temperature will be monitored to ensure that container material limits are not exceeded. Similarly, core inlet temperature will be monitored to ensure that the fuel salt is not approaching any fissile material solubility limits. Both temperature measurements will be made using conventional flow inserted thermowells. The fuel salt composition will be monitored periodically in fast and thermal systems to (1) provide an integrated power production history, (2) assess the accumulation of corrosion products, (3) assess the salt redox condition, (which is the primary surrogate for corrosivity in any alkali-halide salt) and (4) ensure that the fuel salt thermophysical and/or thermochemical property limits have not been exceeded. Fuel salt volume/level will also be monitored to ensure that coolant salt in-leakage is not excessive and that any fuel addition has occurred as intended. Neutron flux will be measured ex-vessel as a rapid indication of reactivity change. Cross-correlated neutron noise from multiple ex-vessel neutron detectors will also be analyzed to assess fuel salt distribution variance (e.g., from flow blockages or vessel vibration).

2.2 PRIMARY HEAT TRANSPORT SYSTEM

The purpose of the primary heat transport system is to transfer fission heat from the core to the power system. The primary heat transport system includes multiple connected loops: fuel salt, primary coolant, optionally a secondary coolant, and power cycle fluid. Each loop must have a free surface to provide expansion volume and to allow fission gases from fuel salt to escape.

Both thermal and fast-spectrum MSRs can be configured as integral units in which the heat exchange from fuel salt to primary coolant salt is included within the reactor vessel, or they can be configured as loops in which the heat exchanger in a separate shell connected to the reactor vessel by piping. Because fuel salt is expensive, loop MSRs will have short interconnecting piping so that even-loop MSRs can share a common containment vessel/shell. In integral MSRs, the fuel pump impeller will be located within the reactor vessel, while in a loop system, the impeller will most likely be located on the hot leg to minimize the potential for cavitation. In either case, the pump power signature and rotational speed will be monitored to assess fuel flow rate and pressure drop across the core. Pump vibration may also be monitored to provide additional component health information.

The primary coolant loop will include high quality mass flow and temperature difference measurements to assess plant power production (perform primary heat balance). The primary or secondary coolant salt may also serve as a chemical trap for tritium produced in the core. Therefore, tritium content must be monitored. Salt redox will also be measured periodically to ensure that the salt has not become contaminated by environmental moisture. Coolant salt activity will be monitored to ensure that radionuclides are not leaking from the fuel salt through the primary heat exchanger.

2.3 COVER GAS SYSTEM

The cover gas system contains the only significant amounts of readily releasable radionuclides in an MSR, so monitoring its leak-tightness is a key measurement. The long-lived noble gas fission products must be removed from the fuel salt to avoid pressurization of the fuel salt boundary. Shorter lived gaseous fission products may also be removed from the fuel salt. Removing the shorter-lived fission products (1) reduces the number of fission products remaining in the core and thus potentially available as a core source term for accident release, and (2) increases the potential release amounts from the fission gas decay system. Short-lived fission products release substantial decay energy. If the energy is produced within the reactor vessel, the decay heat becomes part of the plant’s generated energy and will be transferred out through the power system. Otherwise, the decay energy must be dissipated by an auxiliary heat rejection mechanism.

The cover gas system will include several measurements, the most significant of which will determine whether radionuclides have leaked out of the cover gas system. The containment gas environment will be continuously monitored/filtered to observe any fission gas releases. Performance of the short-lived fission product decay heat rejection system must also be monitored. The measurements will include peak system temperature, temperature difference between hot and cold ends, as well as the mass flow of the coolant. Any leakage in the heat rejection system must also be detected.

MSRs will produce significant amounts of intermediate lifetime fission products and condensable vapors which may be designed to be deposited on replaceable mechanical filters or on cover gas system piping. Upon deposition, the condensate will accumulate and progressively plug the cover gas system piping and/or filters. Salt condensation within the cover gas system will be more pronounced for salts with high vapor pressures such as ZrF_4 or UCl_4. Therefore, pressure drops along the cover gas system piping and across any filter banks must be measured. Alternatively, the electrical load on the cover gas circulator can also be monitored. Salt condensate onto piping will likely be returned to the fuel salt melt mechanically using a scraping system. The force necessary to clean the piping walls will likely be measured to determine the amount and adherence of the condensate. Plugged filters will require replacement.

Once the high-activity fission products have decayed, the cover gas in most designs will transition to a separate containment area (analogous to the multiple bays of a hot cell chain). Longer lived fission products will likely be held up on activated charcoal beds that are intended for use for the life of the plant. These will be contained within piping that is submerged in cooling water. The progress of the fission gases through the charcoal beds will be observed using gamma spectroscopy, and any leakage of the charcoal beds must be monitored.

2.4 FUEL ADDITION/REMOVAL AND POLISHING SYSTEMS

The primary function of the fuel addition and/or removal systems is to maintain the reactor’s reactivity within operational bounds by adding or removing fuel salt. The frequency of fuel salt addition/removal will be determined by the amount of reactivity adjustment available via the control system. Daily additions/removals are anticipated to be typical. The system will also likely be used to adjust the fuel redox to compensate for burn-up (fission is oxidative) by adding fuel in a reducing chemical form. Fuel addition/removal will likely be performed using a common set of bypass piping that is part of the fuel polishing system rather than having multiple interconnections into the fuel salt boundary. The fuel salt polishing system consists largely of a high surface area mechanical filter, likely a nickel mesh, to promote deposition of suspended, undissolved fission and/or corrosion products. The fuel addition system will consist of a fuel salt melting pot interconnected to the polishing system piping with a valve. The fuel addition/removal system will include the means to measure temperature, pressure, differential pressure, and level, as well as leakage monitoring. Flow through the system will be driven by gas pressure or a sampling pump. Performance of the flow system’s active elements will be monitored using power signature analysis.

2.5 REACTOR CAVITY SYSTEMS

MSR reactor cavities will include several specialized systems, including (1) fuel salt sampling, (2) coupon retrieval, (3) component cooling, (4) trace heating, (5) leakage and pressure monitoring, and (6) component inspection.

The fuel salt sampling system periodically obtain representative samples of the fuel salt to be monitored for shifts in redox, build-up of corrosion products, as well as actinide and lanthanide concentrations. Salt samples were obtained at MSRE using a cable-driven dip-type sampling system. The system measurements will be the set of mechanical measurements necessary to insert and remove the sample container.

Material coupons provide the best evidence of the remaining life of materials in and near the core. The conservative material lifetime assumptions that would be necessary without in-situ measured material data provide strong incentive to employ material coupons to demonstrate actual material condition. The remaining life of graphite (thermal spectrum) and container materials will likely be monitored. Material coupons will be much easier to remove and emplace while the reactor is off line. Any reactor must be shut down periodically for maintenance. The number of coupons and their frequency of retrieval must be scheduled as part of the maintenance outages. Radiation-hardened, long-handled tooling will be used to remove and emplace material coupons.

Components that generate substantial heat within containment will require cooling, as will other instruments such as freeze valves and temperature-sensitive instruments. MSR containments cannot include substantial quantities of water, because if water is allowed to flash to steam, its potential to pressurize the containment would violate the low-pressure safety attribute. Consequently, cooling will likely be performed using chilled gas. The gas chilling and flow distribution system will employ conventional process measurement instrumentation such as temperature, pressure, and flow rate.

All salt-wetted systems must be electrically heated externally to prevent salt from freezing during initial startup or during extended outages. The trace heating system will likely consist of electrical resistance elements and thermal insulation on the surfaces of the components and power supplies located outside of containment. The systems will rely on temperature and power signature monitoring. The condition of resistive elements and cables under insulation can be monitored through measurement of resonant parameters or by time-domain reflectometry.

Leakage of radionuclides outside their intended locations is a key element of any MSR accident. Consequently, the environment outside each radionuclide barrier will be monitored for radionuclides. The freeze valve leak at MSRE was discovered using the containment atmosphere monitoring system. Similar systems would be anticipated to be employed today. The containment atmosphere would be blown through a filter bed located in a shielded enclosure. The gamma content of the filter and flowing gas will be monitored for fuel salt and/or cover gas leakage.

The containment environment would be maintained at a slightly negative pressure relative to the ambient environment. Consequently, a small bleed (to compensate for in-leakage) of containment atmosphere would be continuously removed through a heavily filtered line monitored for radionuclides. A larger containment venting system would be used prior to start-up to establish the containment pressure differential.

An MSR’s containment will also include an inspection system to provide evidence of the continued functionality of in-containment systems, structures, and components (SSCs). A typical task will be to monitor for leakage in flange connections. Radiation-hardened infrared (IR) imaging systems can be used for thermal signatures in critical junctions. Another task will be to observe the vibration spectrum of the pump and piping. Monitoring higher frequency changes in reactor power (neutron noise analysis) also can provide an indication of reactor system health.

2.6 DECAY HEAT REMOVAL SYSTEM

MSRs can employ either indirectly or directly coupled decay heat removal mechanisms. Indirectly coupled decay heat removal systems are referred to as *reactor vessel auxiliary cooling systems* (RVACSs). RVACSs function by passively transferring heat by radiation and convection from the exterior surface of the reactor vessel to a natural-draft–driven cooling system. Directly coupled decay heat removal systems are referred to as *direct reactor auxiliary cooling systems* (DRACSs), which function by inserting a natural circulation-driven decay heat removal loop directly into the fuel salt. In reactor configurations with substantial removal of short-lived fission products from the fuel salt, passive decay heat removal must also be provided for the off-gas system.

MSRs can reject decay heat to the environment with the fuel salt in the reactor vessel, or it can be rejected through passive draining of the fuel salt into subcritical drain tanks, typically using a freeze valve. Thermosiphons other natural circulation loops, as well as heat pipes, are all candidate mechanisms for transferring heat from the radionuclides to the environment. In any case, the instrumentation required to monitor the functionality of the passive decay heat removal systems would provide temperature distribution, total inventory monitoring, and system leakage monitoring.

Maintenance systems enable replacement of worn out components. MSR maintenance will likely be performed using remotely operated, long-handled, overhead tooling. Such maintenance systems must be able to grab and manipulate components and perform all necessary joining processes (welding, cutting, cleaning, etc.) [5,6]. Due to the extremely high radiation environment within containment, maintenance instrumentation will be visually guided using radiation-hardened overhead cameras. Maintenance systems will rely on force feedback from their driving elements and key matching to assess their grip condition. Radiation-hardened maintenance systems have been developed over the past few decades in support of other high-radiation activities. Overviews of modern radiation-hardened remote maintenance developments are provided in the technology maturity section of this report.

2.7 WASTE HANDLING

Waste handling for an MSR has both similarities and differences from that at other NPPs. In both cases, used filter materials will be highly radioactive and may require cooling for a limited period prior to longer term storage. However, as MSR filters can be directly exposed to fuel materials, they will require surveying for actinide content prior to release as part of the plant fissile material accountancy. Fuel salt samples may be returned to the reactor as part of the refueling system, or they may be separately assayed and packaged as small-volume fuel waste. Laboratory supplies and other contact-contaminated materials will largely enter the low-level waste stream as at any other NPP.

One key distinction of modern MSR designs is that fuel-salt–wetted components are typically not life-of-the-plant components in that they are designed to be replaced multiple times over the course of the plant's life. Fuel-salt–wetted components will have significant amounts of fission products plated onto and embedded into their surfaces. Moreover, container alloys will have been significantly activated while in use and may include surface contamination with actinide materials. Activation of nickel (^{59}Ni > 220 Ci/m^3) within the nickel-based alloys may (depending on the shielding design) result in the replaced vessel structural alloy being classified as "Greater than Class C waste" [7], which currently does not have a disposal path and would consequently need to be retained onsite indefinitely.

All the large, activated materials (e.g., reactor vessel and heat exchangers) produced at an MSR will likely be retained onsite until the end of the plant life, when a specialized decommissioning company can be employed to consolidate and package the waste. Consequently, the plant site will require a waste storage building with a shielded pit or wells and shielded mechanisms to transport components from the primary containment to the onsite waste facility. The transport mechanisms will require adequate instrumentation to survey for fissile materials, so the plant can perform its required fissile material accountancy. However, no other specialized instrumentation requirements are anticipated.

Both thermal and fast-spectrum reactors intend to reuse fuel salts indefinitely in future generations of reactors. Consequently, fuel salts only become waste upon the end of the use of MSRs as a reactor class.

2.8 CONTAINMENT INTERFACE SYSTEMS

Transferring items into and out of containment requires passing them through the sealed radionuclide containment boundary and biological shielding. The technology to automatically perform these types of transfers is well known and commercially available. The only distinction for an MSR is the possibility of having fissile materials accompany salt-wetted components (fuel salt heel left at the bottom of components or plated out fissile materials on surfaces), so the component transfer airlock system will require the capability to monitor and assess fissile material quantities in the presence of substantial background gamma radiation. Fissile material survey systems are conventionally used in fuel processing facilities. These systems are typically based on shielded gamma spectroscopy and are often augmented by neutron activation.

3. FUNCTIONAL DECOMPOSITION

3.1 INTRODUCTION

This section describes the functionality of I&C anticipated to be employed at an MSR throughout its lifecycle. The depth of the following analysis is limited by the early stage of MSR plant design and the diversity of potential MSR configurations at the time of publication. Technology-oriented I&C descriptions are provided in Section 4 of this document. Neither fully developed system layouts nor detailed functional analyses are available at this writing. Consequently, this section represents a best-effort evaluation based on required elements of MSR performance and issues identified at other NPPs.

This evaluation focuses on elements distinctive to MSRs, avoiding issues such as balance-of-plant monitoring common to any high-temperature power plant. Plant passive safety is a key feature that significantly changes instrumentation performance requirements. However, some aspects of operational instrumentation requirements remain speculative, as anticipated operational occurrences, design basis accidents, and beyond design basis events have yet to be defined for MSRs. Moreover, many aspects of MSR design and operations are sufficiently large departures from prior practice at NPPs, so only high-level requirements can be determined at this stage. Consider, for example, that melted fuel is the norm at an MSR.

Future MSRs will have much higher levels of automation compared with current generation NPPs, with accompanying increases in instrumentation. Increased automation has multiple driving forces:

1. Staffing costs must be reduced to achieve economic competitiveness,
2. Construction time must be reduced to achieve economic competitiveness,
3. Technology advancement has reduced automation costs and increased its capabilities,
4. High doses within biological shielding prevent staff access for manual actions, and
5. Plant security and safeguards can be improved by avoiding staff ingress (or egress).

3.2 CONSTRUCTION

A substantial portion of LWR lifecycle costs accrue during construction. I&C will play a substantially larger role in future NPP construction due to its role in decreasing costs through process automation, and the strong ties between I&C and automated operations and maintenance activities. Automation is anticipated to have substantial impacts on fabrication, module assembly, and site preparation. Much of construction costs result from the high staffing level during construction, as well as its extended duration. The very high levels of quality assurance required in conventional high-pressure, not fully passively safe nuclear plants, combined with prescriptive fabrication/construction requirements, also frequently result in substantial rework and consequent cost escalation. Functionally based SSC performance requirements, combined with MSR passive safety characteristics, are anticipated to substantially reduce the amount of rework required at MSRs. MSRs will employ modern construction methods, integrating factory fabrication and onsite module assembly with semi-autonomous site preparation. While small MSRs will consist of fewer modules, both large and small MSRs are anticipated to be largely factory fabricated from modules that are subsequently assembled onsite. Measurements are especially important to verify that component fabrication plans match the approved design and that the as-built components are within tolerance.

MSRs lack a developed supply chain, and specialty material and component vendors are often unfamiliar with the requirements of the nuclear power industry. Applying intelligent automation to manufacturing enables even single pieces to be precisely tailored to specific requirements. While the high degree of passive safety inherent in MSRs is anticipated to substantially reduce components’ safety significance, the economic imperative for high reliability and extended performance ensures that quality assurance will be a key point of emphasis in all MSR fabrication activities.

Earth moving and other site preparation activities are likely to remain only semiautonomous for the near- to mid-term due to the difficulty of accommodating natural variations in site materials. Remotely operated earth moving equipment relies on substantial amounts of sensing (global positioning system [GPS]) and communications technology. However, no aspect of site preparation technology appears to be distinctive to MSRs. Consequently, MSR site preparation technology advancement will follow that of other large-scale construction activities.

NPP lifetimes tend to substantially exceed the lifetimes of their components, so plants must be designed to accommodate repeated component replacement. An MSR's low fluid pressure means that none of its nuclear components will require thick or heavy structures. This significantly decreases the difficulty of component manipulation. However, salt-wetted and cover-gas contacting components are likely to have heavy surface contamination, significantly increasing manipulation, transport, and storage challenges. The environment within an MSR's biological shielding is likely to be too radioactive to permit staff access at any time following initial start-up. Radiation levels are likely to be sufficiently high to necessitate long handled tooling without solid-state electronics within the shielding. Consequently, all component replacement must be fully automated. Conceptually, once plant structures are in place, plant construction will then consist of 100% component emplacement and connection. Thus, a potential plant construction strategy is to first construct the remote maintenance system and then validate its performance by employing the maintenance equipment to assemble and connect plant components.

A lesson learned from existing LWRs is that long-term structural health monitoring, especially of concrete, is difficult without preinstalled instrumentation. Consequently, future MSRs will embed structural health monitoring instrumentation within all fixed structures during construction.

3.3 OPERATIONS

3.3.1 Steady-State Operation at Power

Power operation at an MSR begins with (1) generating thermal energy from fissions in the fuel salt, causing the temperature to rise, and then (2) transferring the thermal energy to an electric power generation system. Measurements necessary for power operation include the number of fissions occurring, the heat generation rate, and heat transfer from fuel salt to coolant salt. Other measurements that are taken during normal operations include reactivity control system monitoring, anomaly detection (see safety measurement section), component condition and performance measurements (see maintenance section) and the cover gas control system condition and performance assessment (see waste handling).

Fission power monitoring at an MSR is likely to closely parallel monitoring for measurements made at other types of NPPs. Ex-core neutron detectors would be employed to monitor the fission rate. Neutron detectors would be calibrated for overall power production by heat balance measurement, which would be performed by measuring the temperature rise and mass flow rate of coolant salt across the secondary coolant side of the primary heat exchangers. Longer term power generation calibration would be provided by composition evaluation (burn-up) of the fuel salt [8].

Coolant mass flow measurement and coolant temperature rise across the primary heat exchanger must be measured to determine the reactor's heat production rate. Reactor power could also be determined by measuring the fuel salt temperature rise across the core, along with its mass flow rate. However, fuel salt measurements are more difficult and expensive to implement than other types of measurements. In practice, the plant will monitor the fuel pump speed, which will provide an approximate indication of fuel salt mass flow rate and the fuel salt temperature change across the primary heat exchanger will be monitored as a confirmatory measurement. The heat balance measurements will be made on the coolant side of the primary heat exchanger.

Reactivity control system monitoring will depend on the specific technology employed. MSRs will only have sufficient excess reactivity to enable more rapid power maneuvering (load following) and to compensate for reactivity changes due to operations—increased reactivity for breeders or decreased reactivity for burners—prior to refueling. The reactivity control system may take the form of an absorber rod (thermal spectrum), an adjustable reflector (fast spectrum), or a fuel salt displacement system such as an in-core sparging system or a fuel displacement rod. In any case, the variables measured would be the position of the control element and the response of the reactor (neutron flux) to control changes. Small perturbations may be impressed onto the reactor power to enable evaluation of online reactor dynamics, much like the pseudo-random binary movements of the regulation rod were made at MSRE [9].

3.3.2 Power Level Transitions

MSRs are inherently load following. I&C systems will be employed to optimize the transition and to decrease the stress on components. Power level shifts will be monitored by ex-vessel neutron detectors. Pump speed and/or absorber or reflector-based control elements will be employed in an anticipatory control scheme. A key control system goal is to minimize the temperature swings on the high-temperature structural materials, as fatigue induced by thermal is one of the key lifetime limits. Reactor power will be monitored via external neutron detectors, along with control element position, for power level transitions.

3.3.3 Refueling

The amount of new fuel required will be determined by a combination of the integrated power generation history and the observed system’s reactivity. The system reactivity will be monitored by correlating the system’s temperature and the power production rate. Fuel will be added (burner) or removed (breeder) to maintain the desired power level at operating temperature. The functionality of the components and instrumentation to perform the fuel addition (removal) must also be monitored.

3.3.4 Start-Up

Monitoring an MSR’s approach to criticality will likely be performed by employing a high-sensitivity neutron detector and neutron source located within the core. An in-core high-sensitivity detector will likely be necessary due to the small signal size. For dilute fuel salts (i.e., MSRE) the approach to criticality can be performed by gradually adding fissile material to the fuel salt. This is not practical for fuel salts in which the actinide materials make up a substantial portion of the fuel salt. Also, some MSRs will only have small direct reactivity control mechanisms (reflectors, absorbers, or fuel displacement). Achieving a gradual reactivity addition approach to criticality may require a larger adjustment range capability. Another approach to achieving criticality would be to rely on negative temperature feedback. Fuel salt would be loaded into the core above operating temperature and maintained at an elevated temperature using external electrical heaters. The heating power would then be slowly reduced, and/or the primary coolant pump speed would gradually be increased until the reactor reaches criticality with the direct reactivity control mechanism at its least reactive position (to enable compensation for reactivity modeling errors). The measurements required to support startup once the reactor is filled include (1) neutron flux, (2) reactivity control position, (3) pump speed (fuel salt mass flow rate, if available), (4) external heater power, and (5) fuel salt temperature. Additionally, the fuel salt fill rate and the reactor fill level must be monitored prior to initiating criticality. MSRs have very high levels of passive safety to reactivity excursions, thus decreasing the performance requirements for start-up monitoring instrumentation. No damage would be anticipated from even inadvertent prompt criticality.

3.3.5 Shut-Down

MSRs can be driven to subcriticality by decreasing their reactivity directly (reflectors, absorbers, or fuel displacement), by removing fuel from the core (partial draining), by shifting the neutron spectrum to increase neutron absorption, or by reducing the heat rejection rate (negative thermal feedback). 10CFR50 Appendix A general design criterion 26 requires two independent means of bringing and holding the reactor subcritical. The measurement systems required to support the possible shutdown mechanisms are (1) neutron flux, (2) reactivity control position, (3) fuel level (if draining is employed as the control mechanism), and/or (4) fuel salt temperature (if thermal feedback is employed as a control mechanism). MSRs may also employ salt poisoning to bring the reactor semi-permanently subcritical, as poison removal is anticipated to require a substantial amount of fuel processing.

3.4 SAFETY

The MSR's high degree of passive safety substantially alters safety measurement requirements. Consequently, the major safety function of instrumentation is to detect and monitor the progression of accidents, including post-accident monitoring, and to monitor continued functionality and performance of passive safety features. For example, monitoring the temperature profile of a DRACS loop provides evidence that its salt is circulating as intended. Accident detection will begin with anomaly detection such as unplanned variations in core power distribution or coolant salt in-leakage. Thermal spectrum reactors may employ local power range monitors to assess power distribution within the core and thermocouples to measure core outlet temperature distribution. Fuel salt level measurement assures a lack of significant fuel salt out-leakage and coolant salt in-leakage. Salt presence within the guard vessel would indicate that the salt-wetted boundary has leaked. Gaseous radionuclides outside the fuel system boundary also indicate a fuel system leak. Detecting the presence of radionuclides where they are not intended—beyond salt boundaries—is a major safety function for MSRs. MSRs also need to verify the performance of their decay heat removal systems (likely measuring the temperature distribution around DRACS loops) and the integrity of their outer containment layers.

3.5 MAINTENANCE

Maintenance activities at MSRs will require extensive instrumentation. The radiation levels within their biological shielding will be much too high for staff access and often too high for solid-state electronics, even following shut-down and fuel-salt draining. In-vessel shielding has been proposed in several MSR design variants to ameliorate the extreme radiation dose rate. Therefore, measurements must be made remotely using cameras and long-handled tools, or electronics that are highly tolerant of radiation with local shielding may be employed for some tasks.

Component condition assessment is a major maintenance measurement task. This assessment will involve salt sampling to assess the amount of structural alloy dissolved into the salt. Ideally, corrosion of the container alloy would be directly measured, thus reducing salt sampling requirements. Also, retrieving material coupons for off-line condition assessment will be a significant maintenance instrumentation task. Inspection of components must also be automated at MSRs. Since the reactor vessel is thin walled, likely covered with insulation, and likely surrounded by a guard vessel, inspecting its condition will be challenging. The reactor's electrical components will employ power signature analysis to remotely assess their condition and performance.

Structural monitoring will be another maintenance instrumentation task. The MSR's structures may be life-of-the-plant systems. Instrumentation embedded during construction will allow for assessment of long-term structural health, assessing factors such as corrosion of embedded rebar and any changes to the concrete's pH.

MSR components will be designed for automated replacement. Much of the replacement hardware will likely be on overhead cranes with pneumatically operated long-handled tooling. Plant assembly and disassembly must be modeled all throughout the plant's design phases. As early as 1959, Oak Ridge National Laboratory (ORNL) demonstrated the process of replacing all components of a nonradioactive MSR using remotely operated long-shafted tooling [10]. While similar technology would be employed today, substantial advancement (see the instrumentation maturity section) has been made in supporting modeling and human-interface technologies.

Another MSR I&C objective would be to take sufficient measurements to allow for prediction of the remaining useful lives of components. While component failure is not likely to be safety significant, unplanned failure of components would result in an extended duration outage. The relative immaturity of MSR materials and components provides significant incentive for separate effects testing during development to enable development of signatures to indicate impending failure. Many of the failure modes may involve progressive degradation, so measurements of temperature histories and accumulated fast fluences are likely to be important in assessing the remaining lifetimes.

3.6 WASTE HANDLING

A key conceptual difference between liquid-fueled reactors and their solid-fueled counterparts is that the liquid fuel does not accumulate radiation damage. To the extent that its chemical composition can be maintained, fuel will not age or need to be replaced. MSR fuel salts inherently contain the fission products that do not escape during operations, as well as accumulated amounts of corrosion and environmental contamination products. For reactor designs that do not implement fission product removal, the fuel salt will eventually reach an equilibrium level of fission products as fission products burn out, transmuting into a gaseous or non-soluble form, and build in. For designs that provide for reconditioning the fuel salt and those with equilibrium fission product contents that result in acceptable thermophysical properties, the fuel salt would be usable in future generations of MSRs, so it would not become waste until MSRs cease to be an operating reactor class. As performance of fuel salt treatment systems is not certain, periodic measurements of fuel salt composition will be required.

Roughly 40% of fission products have a gaseous phase in their decay chains. Noble gases are not highly soluble in fuel salts, so much of the fission product burden will accumulate in an MSR's cover gas. This cover gas can either be kept mostly within the reactor vessel, allowing only the long-lived fission gases to escape, or it can be removed to prevent daughter fission products from accumulating in the fuel salt. Activated carbon beds have generally been proposed as decay hold-up tanks for fission gases. The carbon filter beds will eventually become filled, possibly at the end of plant life, and will need to be disposed of as highly active, moderate lifetime, Class A or Class B low-level waste. Loading and flow within the carbon beds will likely be indicated by a combination of gamma signatures and pressure drop across the bed.

MSR operation will result in several fuel salt and coupon samples that, while volumetrically small, will be highly active and will contain fissile material that must be tracked and disposed. MSRs will typically employ particulate filters to plate out undissolved fission products to prevent them from agglomerating into larger erosive particles. These filters will eventually reach capacity and will need to be replaced. The used filters will be highly radioactive and thermally hot. Differential pressure measurements across the filters are anticipated to be used as an indication to determine when the filters are full. Other filter fill sensing instrumentation includes close-proximity metal detectors for detecting ferromagnetic or electrically conductive filtrate.

Salt-wetted components will be removed from service upon reaching their end of life. Salt-wetted surfaces will be highly contaminated with fission products and possibly fissile materials. Components must be stored for partial decay, their fissile materials must be documented and tracked, and eventually the components must be consolidated and packaged for shipment to a long-term disposal site. For components with service lives substantially shorter than the plant's life, multiple copies will require storage, treatment, and disposal over the course of the plant's lifetime. Manipulation will likely be performed based upon visual guidance. Cameras, lighting systems, and mechanical manipulators will be the primary instrumentation employed to guide replacement.

3.7 SAFEGUARDS

Under 10CFR75, the United States agreed for its civilian nuclear power facilities to have fissile materials tracking that is sufficient to be compliant with the nonproliferation treaty and the additional protocol. Safeguards monitoring for MSRs will be much more complex than it has been for heterogeneous fuel reactors, as fissile material tracking is much more involved than counting fuel rods. However, the general principal is that diversion of fissile materials from their intended peaceful use must be rapidly and effectively monitored. Safeguards instrumentation will be described in other MSR campaign reports.

3.8 SECURITY

Security and safeguards costs will be substantially influenced by MSR design choices. Modern NPPs are likely to be either partially below grade with a substantial berm or fully below grade to improve their ability to withstand a large civilian aircraft impact, to reduce hostile access to the parts of the facility containing significant amounts of radionuclides, and to limit the required number of measurement points required to be monitored to demonstrate that fissile materials have not been removed. Passive safety frees MSRs from dependence on off-site electrical power or the non-nuclear balance-of-plant to reject decay heat. The net result of the improved inherent and engineered security features would be to meet the plant's security requirements as proposed by the Nuclear Energy Institute white paper, "Proposed Physical Security Requirements for Advanced Reactor Technologies" [11]. Instrumentation would then serve to detect and assess threats, up to and including the design basis threat, to support local law enforcement in neutralizing the threat.

Passive safety also substantially reduces regulated aspects of cybersecurity because hostile forces cannot cause a safety event to occur simply from controlling the plant's computer systems. Plant safety—including reactivity control, radionuclide confinement, and decay heat removal—is inherent and cannot be disabled by commanding the control system. Consequently, MSRs would be anticipated to employ commercial facility types and levels of cybersecurity to ensure that there is no damage to the plant or disruption in power production.

4. TECHNOLOGY DESCRIPTION

4.1 NEUTRON INSTRUMENTATION

Neutron flux measurements will be employed to serve as a high-speed indication of the reactor power to enable feedback control. Modern MSRs will be fully passively safe, so they will not have short-term safety measurements. Longer term reactor power will be assessed using a combination of heat balance measurements on the primary coolant and measurements of the evolution of the fuel salt composition performed off-line with fuel salt samples. Most neutron detection for MSRs will take place outside of the salt and can be performed using the same equipment employed at existing NPPs. The MSRE did not employ any in-core neutron detectors, but it may be useful for start-up to employ in-core, high sensitivity neutron detection, and thermal-spectrum MSRs may employ local power range monitors to characterize the power distribution within core.

Several neutron and gamma detection technologies are appropriate for the environment and operating characteristics of MSRs. Relevant details of these technologies are discussed below. Note that the upper temperature of ~750 °C in salt reactor cores is challenging to the deployment of any detector. No high-sensitivity neutron flux measurement technology is commercially available that functions at temperatures above 600 °C.

Nuclear instrumentation accomplishes multiple functions associated with a reactor. Sometimes a nuclear detector provides data useable for several purposes, whereas specialized detectors may be required for some operations. Each measurement application has specific performance requirements, as cataloged in Table 1.

Table 1. Neutron measurement requirements for salt reactors

Measurement function	**DETECTOR CHARACTERISTICS**						
	Sensitivity or detection efficiency	**Signal response time**	**Survivability in reactor environment**	**Device lifetime**	**Physical** (Note: fast spectrum reactors require larger detectors than thermal reactors.)	**In-vessel**	**Ex-vessel**
Count-rate data during approach to critical (first fuel start)	Pulse counting detector measures in counts per second (cps_ (typically less than 2 to over 1,000 cps)	200 µs	Very often the startup detector is movable. It is removed from the core before assent to power because it cannot tolerate high flux.	Indefinite lifetime if removed from the core during normal operation.	Small diameter for mounting to movable platform. Diameter 1–2 cm. Length 10–20 cm.	Neutron counts measured at initial fueling are essential to characterizing approach to critical. In-core measurement is usually preferred.	Ex-vessel startup measurements can be made if the source is placed near the wall proximally to the detector.
Count-rate data during startup (startup after initial fueling)	Measured in cps (typically less than 10 to 1,000 cps). Similar or identical to the detector used during initial fueling. However, extends to continuous range— 1×10^{6} n/cm^{2}-s.	500 µs	Very often the startup detector is movable. It is removed from the core before assent to power because it cannot tolerate high flux.	Indefinite lifetime if removed from the core during normal power operation.	Small diameter for mounting to movable platform. Diameter 1–2 cm. Length 10–20 cm.	Neutron counts for reactor startup measured after initial criticality characterization may be in-core or ex-core.	Ex-vessel startup measurements can be made if the source is placed near the wall in proximity to the detector.
Indicates rapid power level change (calibrated against thermal power measurement)	1×10^{7} to 1×10^{10} (n/cm^{2}-s)	1 ms	Survives for 10 years. Ex-vessel location is required with operating temperature of less than 200 °C	1.7×10^{19} nvt (10 full power years)	Large volume is not a problem	Not appropriate for MSRs	Can be 1–3 inches in diameter and up to length of vessel. Lower temperature of 200 °C is feasible.

Table 1. Neutron measurement requirements for salt reactors (continued)

Measurement function	**DETECTOR CHARACTERISTICS**						
	Sensitivity or detection efficiency	**Signal response time**	**Survivability in reactor environment**	**Device lifetime**	**Physical** (Note: fast spectrum reactors require larger detectors than thermal reactors.)	**In-vessel**	**Ex-vessel**
Confirm calculated core performance (spatial flux information)	1×10^{8} to 1×10^{13} (n/cm^{2}-s)	10 s	Survives for 10 years at 750 °C and in multi-component molten salt.	1.7×10^{22} nvt (10 full power years)	Smaller size may be needed to discriminate flux variations	Small number of detectors may be placed in regions of core	Likely ex-vessel placement will not provide detailed in-core spatial data.
Map core flux distribution (likely measurement only performed on test reactor to confirm predicted values.)	1×10^{10} to 1×10^{13} (n/cm^{2}-s)	100 s (rapid response not important)	Survives for test duration in reactor	1.7×10^{22} nvt (10 full power years)	Small size and movability needed to map axial distribution.	Only makes sense for in-core operation	N/A
Provide an indication of fuel, moderator, and coolant integrity	1×10^{8} to 1×10^{13} (n/cm^{2}-s)	1 s	Survives for 10 years	1.7×10^{22} nvt (10 full power years)	Small size may not be important	The premise is that the expected in-core flux/power distribution will not develop if all parts are not working properly	Could also be mounted ex-vessel
Identify loose parts and structural integrity	1×10^{8} to 1×10^{13} (n/cm^{2}-s)	100 μs (high frequency response necessary)	Survives for 10 years	1.7×10^{22} nvt (10 full power years)	Small size may not be important	Can be in core	Can be ex core

Table 2. Comparison of several neutron detectors

Neutron detector type	Advantage(s)/disadvantage(s)	Primary usage in MSRs
Ion chambers BF_3 gas	Can be used in pulse counting mode. Efficient conversion of neutrons to ionization. High radiation levels cause gas dissociation. Rapid burn-out and self-heating in high flux environment due to high neutron cross section.	The BF_3 ion chamber is useable for source (startup) range for pulse counting. Not for partial or full power operation.
Ion chambers ^{10}B lined	Can be used in pulse counting mode for startup and in current mode for higher flux levels. Rapid burn-out and self-heating in high flux environment.	Limited to lower power ranges because of high neutron cross section.
Ion chambers ^{3}He	Can be operated in any mode (ionization chamber, proportional, or Geiger-Mueller), depending on the anode voltage. Most efficient in converting neutrons to ionizations. Low reaction to gamma rays. Disadvantage is the unavailability and cost of ^{3}He. Rapid burn-out and self-heating in high flux environment due to high neutron cross section.	Initial fueling startup only.
Compensated ion chambers	Compensation is to reduce sensitivity to gamma rays—all ion chambers naturally respond to gamma rays. The typical compensated detector comprises two separate chambers, one sensitive to gammas and neutrons, the other sensitive to gammas only. Currents from each chamber are subtracted locally so that detector output is the difference current, which is the neutron response. Useful for intermediate range when gamma compensated.	Intermediate range neutron fluxes.
Fission chambers	Fission chambers are a type of ion chamber in which the reaction surface is coated with a thin layer of ^{235}U. Because the ^{235}U coating must be kept very thin due to limited fission product penetration distances, the chamber exhibits low detection efficiency. The fissionable material is consumed in the neutron flux. Some depletion mitigation is possible by including fertile material such as ^{238}U. Diameters of fission chambers are smaller than other ion chambers. Fission counters have the highest insensitivity to gamma rays. Larger pulse size generated by fission counters allows for locating preamplifier electronics further away from harsh environment.	Intermediate and power range neutron fluxes. Fission chambers many be used in-core or ex-vessel. When used in-core, they are made movable to extend the lifetime by removing them from high neutron flux regions.
Fast neutron detectors (applicable to fast spectrum MSRs)	The capture cross section of ^{10}B is reduced by 500 and ^{235}U by 1,100 with fast neutrons as compared to thermal neutrons. One method of detecting fast neutrons is to include moderation in the detector. However, larger detectors are generally employed instead.	Startup of fast spectrum MSRs. Thermalize and detect will generally be used ex-core for power range operation.
Self-powered neutron detectors (SPNDs)	Used effectively as in-core flux monitors for close to 50 years. Advantages are small size, low cost, and simple electronics required for measurement readout. Disadvantage is the delayed response and small signal size.	Excellent for core flux mapping.
Gamma flux detectors	Not suitable for startup or low power operation because of bias from background (fission-product decay) radiation. Only that fraction of the gamma flux which originates in prompt processes (capture and fission) varies with the power level; gamma radiation is also emitted by decay processes originating from fission products. Above the intermediate power level, gamma intensity becomes proportional to reactor power. Gamma detector design can be based on ionization or gamma heating.	Measurement of reactor power distribution in the 5–150 percent range.

Ionization chambers, which are gas-filled radiation detectors that can be designed to measure several types of ionizing radiation, use the principle that incident radiation ionizes the fill gas either directly or indirectly through a secondary reaction. The process causes charge separation between ions and electrons and liberates free electrons that are detected in a strong electric field established between cathode and anode. The quantity of collected charge is a measure of the incident radiation intensity. Since neutrons do not cause ionizations directly, a nuclide is added having a neutron cross section suitable for the maximum flux levels encountered. Isotopes such as ^{3}He and ^{10}B give ion chambers high-efficiency response to neutrons. For high flux (high power level) operation, another isotope with a small thermal neutron cross section must be used.

Ion chambers can be configured in several shapes, although the cylindrical type is most commonly used. The cylinder is the cathode, and a center-placed fine wire is the anode. Detector variations include the compensated ion-chamber detector, which rejects gamma response to permit monitoring neutron flux levels on a linear scale covering power operation from 1–150 percent. Power-range detectors are used for rapid reactor power control. The deployment of ion chambers for MSRs should be straightforward, as power range detectors will be mounted ex-core in relatively benign environments.

Chambers apply up to several thousand volts of polarization potential (a few hundred volts is typical) to achieve charge separation and subsequent detection of the associated radiation pulse. This process requires conductors suspended by electrical insulation. Insulators must not only withstand the high potential so as not to arc over, but they must also not develop leakage currents that contaminate the radiation-generated ionization signals. Insulators are used structurally to suspend internal voltage-bearing components and to pass the electrical signals across the metal/vacuum boundary. These insulators are fully exposed to the radiation environment. Temperatures outside the vessel’s insulation will be much lower than the upper bounds for commercially available ion chambers.

4.1.1 Fission Chambers

Fission chambers can monitor the neutron source flux-level on a linear scale during startup and on a wide-range, log-scale that covers 9–13 decades. Fission chambers which can be deployed in the reactor core or ex-vessel can be fixed position or movable chambers. Traverse movement through the reactor core allows flux mapping.

A fission chamber is an ionization chamber with an array of electrically conducting plates, each with a deposited layer of fissile uranium. The benefit of uranium fission in the detector is that the resulting fission products deposit orders of magnitude more energy per reaction than alpha particles produced in ^{3}He-filled or boron-lined ion chambers. These higher energy particles allow fission chambers to monitor small neutron fluxes in higher gamma environments because of pulse discrimination from other types of ion chambers.

Design and fabrication of neutron detectors suitable for the environments of an MSR present a challenge if located in the core region, chiefly because of the deleterious effects of high temperature over an extended period. High temperature has a large influence on detector components, including (1) reduction in insulation resistance of ceramic insulators, (2) generation of spurious discharges on ceramic insulator surfaces at high voltage (generating pulses indistinguishable from neutron pulses), (3) outgassing of the chamber’s metal body (contaminating the fill gas), and (4) weakening of electrode support structure, forcing wider electrode spacing than desired. However, locating the chambers in the ex-vessel region reduces the operating temperature to levels acceptable for currently existing technology.

Modes of operation for a fission chamber are pulse rate counting, Campbelling or mean-square voltage (MSV), and current mode. The chamber remains the same for operation in each of these modes with the electronics adjusted to accomplish the measurement.

4.1.2 Self-Powered Neutron Detectors

A self-powered neutron detector (SPND) is designed as a coaxial configuration of an inner electrode (emitter) made from a material chosen for its ability to respond to neutrons through radiative capture (e.g., Co, V, Rh, Pt, and Ag). This material emits either prompt or delayed electrons. The output signal of an SPND is the superposition of a delayed response (up to several minutes) and an instantaneous response. Therefore, the SPND is not suitable for applications that require instantaneous response, but rather for those uses in which a slower response is acceptable, such as flux mapping. The SPND is not suitable for startup range measurement because of its inadequate sensitivity and delayed time response.

SPNDs are commercially available for MSR power range fluxes and temperatures. The exterior sheath material for SPNDs will require custom specification for specific salt compatibility (e.g., Alloy N, nickel, SS316, or molybdenum).

4.1.3 Gamma Thermometers

Gamma thermometers, an alternative for power-range energy deposition monitoring, have close technical similarities to thermocouples and are thus quite likely to perform at the temperatures of an MSR core. Gamma thermometers are not as commonly deployed as SPNDs and would require a customization effort to develop a version suitable for an MSR.

Only that fraction of the reactor gamma flux which originates in prompt processes (capture and fission) varies with the power level; gamma radiation is also emitted by decay processes originating from fission products. Once in the intermediate power level, gamma intensity becomes proportional to reactor power.

Gamma thermometers are not suitable for startup or low-power operation because of the reactor's residual background (fission-product decay) radiation.

4.2 THERMOMETRY

Temperature is an essential variable to be measured in an MSR system, as in other nuclear reactors. The dominating factors for survival of temperature measurement instruments are (1) elevated temperature (over extended period), (2) potentially corrosive nature of the salt mixture, (3) transmutation of the elemental composition of the transduction and/or insulation component, and (4) mechanical vibrations of the thermowells due to high-velocity salt flow. The effect of high gamma radiation is minimal. Although resistance temperature detectors (RTDs) exhibit a low measurement uncertainty, which is always desirable, temperatures over 600 °C are out of the practical range of most RTDs. Among the remaining commercially available temperature measurement technologies, the thermocouple is the best overall choice for the temperature range in MSRs. Thermocouple technology is mature. There are, however, alternative temperature instrumentation technologies that may have specialized applications in various regions of an MSR. However, these alternative temperature measurements may have limited usefulness because of the simplicity and effectiveness of the thermocouple. As in other reactors, the temperature measurement elements are not generally in contact with the working fluid (i.e., salt). Instead, the sensing elements are inserted into thermowells or attached to the exterior surfaces of components.

4.2.1 Thermocouples

Type N thermocouples are a good choice for MSRs because they have low drift and decalibration up to 1,300 °C. Lowering drift and uncertainty further in type N thermocouples may be possible by specifying a higher grade device. This entails higher purity materials and more care in construction. The thermocouple bead cannot be immersed directly into a molten salt mixture due to the electrically conductive salt wicking up the wires and shorting out the measurement. A sheath is required surrounding the thermocouple, as well as a thermowell, to protect it from salt interaction. A body of research exists on thermocouple sheath materials, the selection of which is important because these materials can contribute to decalibration at high temperatures over extended periods.

As a secondary validation of calibration of the type N thermocouple, Au-Pt type thermocouples can be deployed at select locations near the type N thermocouples. Note that the Au-Pt thermocouple is subject to transmutation decalibration. Also, the Au-Pt thermocouple has upper temperature limitations because of differential expansion of internal components. A likely location for the secondary validation is in the low radiation environment of coolant salt loops.

The technology readiness level of type N thermocouples is fully commercialized (technology readiness level [TRL] 9). Type N thermocouples are available from numerous commercial sources. Au-Pt thermocouples are also available commercially but have had little industrial deployment.

4.2.2 Distributed Fiber-Optic Bragg Thermometry

Distributed fiber-optic Bragg thermometry uses a series of Bragg gratings along the core of a single-mode optical fiber. The primary advantages of distributed fiber-optic Bragg thermometry are its immunity to electromagnetic interference (EMI) and the deployment of many temperature sensing locations along a single fiber path. Another possible advantage is that the same optical path can be used as a distributed set of strain or vibration sensors for mechanical diagnosis.

Although the fiber-optic Bragg temperature measuring technique has some positive attributes, deployment in an MSR does not offer significant advantages over the low cost and low complexity of the thermocouple. Additionally, optical fibers in high gamma radiation fluxes may experience darkening. This darkening effect is ameliorated by the annealing effect of high temperatures. The fiber-optic Bragg thermometry technology is at high TRL and is commercially available.

4.2.3 Blackbody Radiation Temperature Measurement

The advantage of blackbody temperature measurement is that the temperature of an item under transparent liquid salt can be measured remotely, which is especially useful when a thermocouple or other forms of cabling cannot be run to the point of interest. A clear optical path over a range of wavelengths corresponding to the blackbody emission is required to determine temperature. Blackbody temperature measurement is used routinely in many industrial processes.

Non-fuel salts will generally be transparent. However, fuel salt mixtures are likely to be nearly opaque due to the presence of fission products. Because of increasing salt opaqueness in the core loop over time, it is not practical to use blackbody temperature measurements within the primary reactor system. However, coolant loops are possible applications because of their consistent transparency. An application of this technology would be to observe temperature profiles across a heat exchanger.

The TRL of blackbody temperature measurements is commercially available at TRL9. However, for the salt environment, additional engineering must be applied, which lowers the TRL to 4. Issues to overcome include (1) variable emissivity compensation, (2) design of optical widows that provide environmental isolation without becoming fogged by salt vapors, and (3) development of free-space or fiber coupling between sensors (or the imager) in a benign environment and a high temperature environment. Such engineering development is not insurmountable, but it is not commercially available.

4.2.4 Johnson Noise Thermometry

Johnson noise thermometry (JNT) is not a substitute for existing primary temperature measurements such as thermocouples. Rather, JNT provides a slow but low-uncertainty temperature value that is usable as a calibration reference for the thermocouple-generated signal. A functional configuration would be a JNT analyzer system operating in parallel with a traditional thermocouple signal processing system, both analyzing the same thermocouple signal to constantly calibrate the thermocouple’s output value. This configuration virtually eliminates drift in thermocouple readings while providing the rapid response expected of a traditional thermocouple system.

JNT is rated at is TRL3 or TRL4, so it is not yet available as a commercial product. One major impediment is JNT’s extreme susceptibility to electromagnetic interference. Also, cable distance between the thermocouple junction and preamplifier input stages is limited to several meters. This is because long cable runs reduce bandwidth and require longer integration time to achieve low-uncertainty temperature values. Auto-calibration and drift reduction offered by JNT technology have not yet been accepted by regulatory bodies.

4.2.5 Ultrasonic Guided Wave Temperature Measurement

A principal advantage of guided wave ultrasonic temperature measurement is that multiple zones can be incorporated over an extended waveguide length, much like that of the distributed fiberoptic Bragg thermometry. The average temperature measurement is determined over defined zones along the waveguide. A zone is demarcated by embedded reflection points (i.e., fiducial registrations that alter acoustic impedance) that are also used as calibration. The waveguide may be constructed of metal alloy or ceramic materials. If the waveguide is to be placed in the salt environment then the TRL is 5, and if it can be located within a thermowell, then the TRL is 6–7.

As is the case for optical temperature measurement, there may only be minor benefits to using a guided wave temperature measurement compared with multiple thermocouple deployment in MSRs. Selecting compatible materials is crucial, because the waveguide must not succumb to the chemical action of the salt mixture if it is submerged and in direct contact with the fluid. Otherwise, the waveguide must be contained in a sheath, much like a thermocouple. As with the distributed fiberoptic Bragg thermometry, an advantage of the waveguide is that it does not function as an electrical component, so it is immune to EMI and to a large extent, it is not subject to transmutation effects. It is conceivable that a thin-wire waveguide could be passed through the open core of a liquid fuel reactor to obtain a temperature profile along the active zones length. However, the same measurement may be accomplished using a string of thermocouples housed in a thermowell.

4.2.6 Noninvasive Free Liquid Ultrasonic Temperature Measurement

Noninvasive ultrasonic temperature measurement involves the same transducer deployment and reconstruction algorithm technology as employed by medical ultrasound and computed tomographic (CT) imaging. A series of timed ultrasonic signals from a spatially separated array is applied directly to the fluid medium (as opposed to a wire immersed within it) to generate a temperature/density profile from time-of-flight and attenuation data. The potential benefit is the ability to measure the temperature profile in a free volume like that of a CT scan. In the open volume of a homogeneous reactor, thermocouples can be used to measure core temperature profiles at low power levels. However, the presence of multiple extended thermowells in the core region may affect flow distribution, and it may also pose break-off vulnerability, so it would not survive full power range operation. Therefore, there may be an advantage to using an ultrasonic tomographic method to obtain volumetric temperature profiles. The TRL is 8 for CT technology, but it would only be 3 in this application because of the temperatures that ultrasonic transducers may experience, as well as the flow geometry. Research would be required to develop high-temperature transducers or low-distortion waveguides.

4.3 FLOW MEASUREMENT

Fuel-salt flow monitoring is useful for feeder lines that add or remove fuel salt associated with make-up and polishing operations. Direct measurement of the coolant salt's mass flow rate in secondary loops is generally more important because the reactor's heat balance is achieved using the flow rate on the coolant side of the primary heat exchanger.

Flow measurement technologies can be characterized as either penetrating or nonpenetrating based on the piping or tank boundary and whether the technology requires internal structures. It is most desirable for salt flow measurements to be nonintrusive to the piping. The addition of penetrations and internal piping structures results in complications such as (1) the possibility of internal parts breaking loose and being carried downstream, to causing blockage or impact damage, and (2) the need to match dissimilar parts in the thermal expansion coefficient or to make special engineering accommodations to prevent destructive stress development over the full 700 °C range. Possible metering techniques include ultrasonic, differential pressure, variable area (e.g., rotameters), and nuclear reactions such as neutron activation methods, which use the ongoing nuclear reactions as a driving function. Some of these techniques are summarized according to technology groups in Table 3, and more detailed descriptions are provided in the sections below.

4.3.1 Time-of-Flight Ultrasonic Flow Meter

Experience with a clamp-on time-of-flight ultrasonic flow meter at ORNL has shown reasonable results on water loops, but it has not yet been fully tested and characterized on a liquid-salt loop. Preliminary salt-loop results revealed that the stainless steel waveguides carry sufficient heat away from the loop piping to cool the salt, with a potential for solidification. For the ORNL loop, the flow meter was installed on a 1-inch schedule 40 Inconel pipe wrapped with trace heating and insulation. Increasing the trace-heat power applied in the waveguide vicinity and adjusting insulation was necessary to prevent overcooling of salt by the waveguides. Waveguides are required because the piezoelectric transducers' upper temperature limit of 200 °C is incompatible with the 700 °C piping. This technology is TRL8–9 because of its commercial availability, but it needs further testing and validation for operation on liquid salt piping. The time-of-flight ultrasonic flow meter is a viable technology for some piping in MSRs. However, it is likely not usable for totally submerged piping due to the temperature limit of the transducers. The stainless-steel waveguides introduce uncertainty (up to several percent error) in the flow measurement because of their attenuation, internal reflections, and wave velocity gradient that follows the temperature gradient along its length.

Additional development work could lead to improvements in the wave injector design, but more importantly, the development of high-temperature transducers could reduce or eliminate the problem altogether by eliminating the waveguides. Candidate high-temperature piezoelectric materials, as well as other transduction methods such as the electromagnetic acoustic transducer (EMAT), may be substituted for currently used transducers but not without redesign of signal processing algorithms and possibly transducer drive electronics. Research and development is required to create higher temperature transducers and to assess their radiation response.

Table 3. Comparison of flow meter technologies

Technology classification	Device type	Application to MSRs
Pressure-based meters	Venturi, orifice plate, Pitot tube, cone meter, drag, bluff body vortex, microelectro-mechanical systems (MEMS)	This flow measurement method, which is based on developing a pressure difference along the flow path, is most common. However, some embodiments require an internal structure to restrict flow, presenting the possibility for dislodgement and generation of loose parts, especially in highly corrosive environments. Flow is calculated from static differential pressure measurement, $Q_m = K\sqrt{\Delta P \cdot \rho}$, where K collects all the coefficients, P is pressure, and ρ is density. Alternative methods use vortex and other dynamic pressure measurements (e.g., vortex shedding). These methods also require internal structures.
Mechanical flow meters	Piston, nutating disk, turbine, paddle wheel	The basis of operation is displacement or momentum transfer. Mechanical flow meters require moving parts and attendant bearings. These methods are prone to jamming and tossing loose parts.
Mass flow meters	Thermal displacement (hot-wire anemometer), Coriolis	A hot-wire anemometer measures a fluid's capacity to carry heat away from a calibrated source. Several variations of the technique exist, including one with upstream and downstream temperature measurement with respect to a heater. The relationship for one with external heaters and sensors is $m^{0.8} = Kq/\left(C_p\left(T_w - T_f\right)\right)$. At 700 °C ambient, it may be difficult to further modulate the piping temperature. A Coriolis meter measures mass through motion mechanics. It is necessary for the fluid-bearing tubing to move or vibrate sufficiently to detect phase variations resulting from changes in angular momentum. Sufficiently flexible piping that can withstand 700 °C is not available.
Variable area meters	Rotameter	The basis of operation is drag force on a float positioned in a flow zone with a widening area in the direction of the flow. The balance point of forces can be calibrated as a scale, and flow rate can be measured by displacement from zero. However, large flows require large floats, so the method is not appropriate for large flows such as the main reactor flow loop. However, a side stream can be diverted for large flows for measurement by the variable area meter and a new calibration factor applied.
Optically based meters	Doppler shift, scatter	This is likely not feasible for fuel salt due to opaqueness. Optics methods require an optical window, which may be problematic in salt at 700 °C, even for coolant salt. Optics transducers (light source and detector) would need to be mounted far from high heat and radiation zones. Darkening of optical fibers by gamma dose would need to be addressed.

Table 3. Comparison of flow meter technologies (continued)

Technology classification	Device type	Application to MSRs
Acoustic meters	Ultrasonic Doppler, ultrasonic transit time	Both ultrasonic techniques of Doppler and transit time can be applied through the pipe wall, so no penetrations are required. However, the fluid must totally fill the pipe's inner volume. The Doppler method requires suspended particles in the fluid and its measurement and is corrupted by nonuniform distribution. The transit-time technique requires two transceivers and is not dependent on suspended particles. The latter method is suitable with the following caveat: *Ultrasonic transceivers typically deploy piezoelectric transducers, which have an upper usable temperature range much less than 700 °C salt temperature. A waveguide separating the transducer and the pipe wall reduces the transducers' temperature. Unfortunately, waveguides introduce reflection and attenuation anomalies, greatly increasing measurement uncertainty. High-temperature ultrasonic transducers are needed that mount directly to the pipe. This high-temperature sensor does not currently exist but may be realized by using either high temperature piezoelectric materials or EMAT devices.*
Magnetic-based	EM flowmeter	The EM flow meter is based on Faraday's law, $\mathcal{E} = -d\Phi_B/dt$. It requires an electrically conductive liquid plus two or more electrode-insulator piping penetrations. Measurement is unaffected by temperature, density, or viscosity of liquid. No pressure orifice is required.

4.3.2 Differential Pressure Flowmeters

Venturi-style flowmeters are a mainstay of industrial control, but they require a differential pressure measurement. The differential pressure method used in MSRE required impulse lines to locate the transducers away from temperature and radiation. Although impulse-line configuration is a well-known technology, it appears to be unavailable as a non-custom commercial item at the time of this writing. Impulse lines are discussed below in the pressure measurement section. Alternatively, directly mountable, diaphragm-type transducers may be developed using high-temperature materials.

Flow measurement techniques based on differential pressure measurement are useable for piping submerged in a high-temperature working fluid. Differential pressure flow measurement technology is TRL9 because it is used extensively in industry. However, the high-temperature impulse lines that were once readily available are now a special-order item. Design and manufacturing of impulse lines for MSRs will require engineering development and demonstration.

4.3.3 Cross-Correlation Methods

A thermal disturbance in the liquid flow stream, either externally introduced or naturally occurring, can be observed to calculate flow rate using cross-correlation algorithms. Algorithms identify statistical temperature variations traveling through a pipe. The basic concept is to measure the elapsed time for a thermal pattern to traverse a known distance from which velocity can be calculated. These methods can be designed so that features inside the piping are not required. However, the cross-correlation method may require large pulsed upstream power inputs to elevate the signal-to-noise ratio for a measurement. A variation of this technique looks for naturally occurring thermal patterns that propagate in the flow. Some research is needed to assess the limitations of this approach, especially at temperatures of 600–800 °C and for larger piping. Alternatively, stimulation by an upstream white-noise source, such as the pseudo-random binary sequence (PRBS), may also be useful to generate the cross spectral power density, from which the frequency response of flow dynamics can be generated. Spectral shift would indicate change of flow rate. The research would comprise modeling and simulation activities, as well as small-scale facility testing and confirmation.

4.3.4 Rotameters

Flow in the fluoride circuit of the Aircraft Reactor Experiment (ARE) was measured by a high-temperature rotameter. Such instruments are feasible for use in MSRs, but they could not be used to measure large flows because the floating element would be large and unmanageable. Hence, a side stream would be required to perform a large flow measurement. Rotameters are regularly used in industry and are commercially available (TRL9). However, they are not commercially available for high-temperature and molten salt applications. This meter can be adapted by using upgraded technology. Typically, the readout of a rotameter is by visual inspection. It would be necessary to develop a transducer-based readout of float position because of the high radiation field.

The primary coolant flow in PWRs can also employ the interaction of ^{16}O with fast neutrons to measure the primary coolant flow. Flowmeters based upon ^{16}O(n,p)^{16}N were developed by Westinghouse in the 1970s and early 1980s [12,13].These flowmeters function by tracking the spatial location of the decaying ^{16}N as it transported along the primary coolant piping. Activation flow measurement in fuel salts would require innovative shielding methods (likely gamma mirrors) to enable extraction of a useful signature from the extreme background. Fluoride coolant salts, however, will be activated within the primary heat exchanger. Flow measurement based upon coolant salt activation was demonstrated at MSRE [14].

Multiple decay gamma ray energies provide flow distribution information, which can increase the accuracy of the flow measurement. The differential attenuation of the two different energy gamma rays by the coolant itself and the coolant pipe wall enables mapping the flow distribution within the pipe. The higher energy gamma ray will have less self-attenuation within the coolant and near the pipe wall, so it will be less sensitive to flow distribution patterns within the pipe. In contrast, the lower energy gamma ray provides flow information that is more heavily biased towards flow on the side of the pipe closest to the detector. Having several gamma-ray detectors located in two rings around the pipe (one downstream of the other) enables augmenting the gamma ray correlation signal with flow distribution information, thus increasing the accuracy of the flow measurement.

Neutron activation flow meters are TRL8 for LWRs but they will require development for fluoride salt reactors, particularly development of radiation shielding.

4.4 PRESSURE MEASUREMENT

Pressure measurements in MSRs provide a variety of needed functions such as controlling cover gas pressure, measuring fission-gas buildup, and monitoring pump conditions (e.g., suction, head, and cavitation). Pressure measurement also leads to flow measurement (through differential pressure) and level measurement. With a few exceptions, pressure measurements are almost always made in the salt or at a location that may experience salt plating and at full temperature. Three pressure measurement techniques are useful for MSRs. These are discussed below.

4.4.1 Impulse Lines

Most pressure transducers and their associated electronics are sensitive to temperature, corrosion, and radiation. Because of this sensitivity, an intermediary fluid transmission line is often used to separate transduction and electronics from the harsh environment. The salt interface, which is a diaphragm at the distal end of an impulse line, must fully withstand the immediate environment. The impulse-line method was used in the MSRE and other high-temperature systems. Today, the commercial availability of 800 °C (usually NaK-filled) impulse lines is limited. Impulse-line technology is commercially available at TRL7–9, but it needs refreshing and re-commercialization before reactor designs can use it at 700 °C and higher in a molten salt environment. This option may be an opportunity to further improve the design of impulse line systems.

An impulse line is a small diameter tube that serves as a conduit transferring a pressure signal from a measurement point in the process to a measuring instrument. The name may have come about because *impulse* is defined as force over length of time, which describes the transference of pressure from one end of the line to the other. The typical impulse line is equipped with diaphragms at both ends to isolate the intermediate fluid for pressure measurements that must be remotely performed because of chemical contamination, temperature, or material compatibility.

Temperature compensation and drift must be addressed for practical installation. Because of nuclear transmutation effects, gas bubble formation can cause loss of calibration or complete loss of that impulse line's measurement capability and performance. Use of impulse lines was restricted in the MSRE to salt piping not connected with the core-fuel system because of the consequences of fuel precipitation in the event of diaphragm rupture and subsequent leak of NaK into the fuel loop. NaK will dissolve into chloride salts, making the salt more reducing. However, given the volume ratios between a capillary line and the fuel salt, the effects on a commercial scale reactor are anticipated to be minor.

4.4.2 Bubblers

Bubblers had been used to measure pressure and level in the MSRE. Bubblers are also used in many industrial processes (see ISO 18213 and other standards). As with the impulse line, the bubbler method permits placement of (nonhardened) transducers and electronics in low-temperature and low-radiation environments. The lack of an *in-situ* diaphragm and attendant salt compatibility concerns are an advantage of bubblers over impulse lines for pressure measurement.

Bubblers do not generate a continuous pressure signal. Rather, they generate a pressure signal with a series of superimposed pulses that must be averaged. Bubbler response times are therefore slow. Also, bubblers are constantly injecting gas into the system. Ultimately, this gas must be removed or controlled. MSRs, however, will also be generating large volumes of fission gasses, so a small volume of bubbler helium may not be significant. Failure modes include plugging of gas lines and damage to the in-vessel tip due to corrosion or deposition. In salt reactor applications, the bubbler gas would need to be preheated to prevent freezing of liquid salt. Gas bubblers are at TRL8 because of their long-term use in industry.

A triple-line bubbler has been investigated by researchers at Idaho National Laboratory [15]. The concept is that using two bubbler tubes at different known depths provides differential pressure measurement, allowing a convenient density calculation. A third bubbler tube with a smaller (capillary) diameter is introduced to correct for bubble buoyancy and surface tension effects. Tests with this approach show a reasonable 0.3% difference between measured and accepted true values.

Advanced signal processing can be applied to bubbler pressure measurements systems that also correct for temperature and density. Because bubbles generate discrete pulses, frequency content in the bubbling action can provide additional process information and diagnostics (e.g., determining tip fouling and corrosion). This form of analysis is open for research.

4.4.3 Direct Measurement Sensors

Eliminating impulse lines altogether and implementing a direct pressure measurement has performance and systemic advantages. Impulse lines have performance disadvantages such as slow response times and insensitivity, as well as compatibility issues, as previously discussed. These consequences have led to interest in developing high-temperature (electronic) transducers with internal pressure diaphragms. Silicon carbide and other ceramic materials show promise, but further research is needed. In many cases, direct measurement will be limited to accessible areas where usage is low and quick access to information is not required. TRL3–4 is the commercialization advancement of high-temperature, salt-compatible, direct pressure measurement transducers.

4.5 LEVEL MEASUREMENT

Fuel salt level measurements are needed in several locations: pump volutes and housings, core head space (if the reactor type has a void space), processing tanks, and storage tanks. Similarly, level measurements are needed for coolant salt such as that contained in intermediate thermal loops: pump volutes and storage tanks.

Recent experiences with guided microwaves indicate that it is an excellent candidate technology because it can be mounted in a vapor space above the liquid salt and would therefore be less susceptible to attack. Heated lance, bubbler, electrical point contact probes, and mechanical float methods are also feasible, with the caveat that probe materials are compatible with molten salt. Ultrasonic methods are potentially useful but may require more development than is reasonable since other more mature techniques are available. This is an engineering-economic judgement.

4.5.1 Guided-Wave Microwave

Microwave level measurements are TRL8 and are available from several manufacturers. The commercial instrument requires further adaptation for use in high-temperature salt systems because the sensor system can be installed well above the high-temperature measurement zone and connected by a hollow waveguide. Deploying a standpipe as part of the waveguide reduces liquid sloshing and extends the useable operating distance. There are several choices in configuring the microwave level gauge, depending on depth of the application.

One benefit of the guided microwave approach to level measurement is the non-contact nature of the measurement. However, the head-end of the microwave transceiver has an electrically insulating plug made of polytetrafluoroethylene, silicon, or aluminum ceramics. Salt vapors may deposit on the plug and shorten its life.

4.5.2 Bubbler

The bubbler level measurement method is fundamentally a pressure measurement in which level is determined by subtracting cover gas pressure from the average gas pressure that is required to produce bubbling. Using the differential pressure and the known mass of the liquid, the level can be calculated. The method is TRL8 and has the same drawbacks as the pressure bubbler described above.

4.5.3 Heated Lance

Heated lance level measurements are based on observing heat transfer through the wall of a probe to the surrounding liquid. Because heat transfer in gas is several magnitudes less than that of a liquid, a heat source and a thermocouple are paired to determine whether liquid is present. Higher temperatures indicate a lack of liquid because of lower gas conduction. This technology is mature at TRL9. The probe material must be compatible with the salt mixture.

4.5.4 Guided-Wave Ultrasonic

Free-space ultrasonic waves are highly influenced by the gas and vapor media through which they travel. Therefore using an acoustic time-of-flight distance method is not recommended for molten salt applications. The *guided-wave* ultrasonic method, in which the ultrasonic waves are propagated through a rod or tube, is more reliable. One such method was used at MSRE, where it only measured level whether the liquid level was above or below the probe end (that consisted of a small round plate). It is possible to build on the basic MSRE design and construct a more robust system capable of continuous level measurement.

Another level measurement method is the torsional guided-wave probe, which measures either the reflection or attenuation of a twisting motion launched in a probe blade in contact with the liquid media. Both ultrasonic methods (longitudinal or torsional) require design of a force-insensitive mount that penetrates the tank wall boundary. Because there are other commercially available level measurement methods, further development of the ultrasonic instruments for salt reactors is not recommended.

4.6 OTHER MEASUREMENT TECHNOLOGIES

4.6.1 Salt Chemistry

Knowledge of fuel-salt composition—impurities concentration, redox potential, and fissile concentration—is important for primary loop operation. As the fuel salt composition only varies slowly with time, the primary measurements of fuel salt composition are likely to be based on salt sampling and off-line evaluation.

Several control systems will be employed in the plant to maintain an optimal salt mixture over the life of the reactor. Fuel salt characteristics discussed below are pertinent to (1) corrosion, (2) particulate formation, and (3) redox potential.

*Corrosion***.** In well-controlled systems, corrosion is a slow process that can largely be monitored off-line by observing the quantities of the container alloy materials dissolved within the circulating salt. The corrosion monitoring technique employed at MSRE was to observe the amount of chromium dissolved in the fuel salt every few days. In a commercial reactor, it may be useful to more rapidly observe corrosion occurring as part of a capital asset preservation program. A potential method for this is to directly observe corrosion of a surrogate material.

*Particulate Formation***.** Fine particulate matter forms in fuel salt because some of the fission products are not soluble (i.e., they are noble with respect to the salt). Fissile materials (especially the actinide trifluorides) have limited solubilities that compete with fission products, and salt container elements have temperature and redox varying solubilities. Insoluble particulates can aggregate and form surface deposits. For materials such as noble fission products, plating out onto metal surfaces could result in a corrosion protection layer, whereas for others, such as fissile materials, plating out could result criticality at an unintended location. It would be useful to observe particulate generation at specific locations. Particle assessment in fuel salt would performed by the plugging filters (via pressure drop measurement) with precisely sized holes.

*Redox Potential***.** Measuring redox potential provides needed insight into the rate and degree of corrosive interaction between salt mixture and piping and vessels. The oxidative potential of fuel salt will increase in service (fission is oxidative), which will lead to increased corrosion potential. The time horizon for measuring redox potential is daily to weekly as opposed to every minute or second, as changes in the corrosion potential do not occur rapidly. Hence, sample-batch off-line measurements are possible. Measurement of redox potential in salt media is a major problem because of the difficulty to design a reference electrode with high stability, useful wetting characteristics, high mechanical resistance, and high accuracy. Reference electrodes with high stability over reasonable times would be useful even for laboratory measurements.

Alternatively, salt chemistry can be monitored using various spectroscopic methods, including gamma spectroscopy, laser-induced breakdown spectroscopy, mass spectroscopy, gas chromatography, optical absorption spectroscopy, UV spectroscopy, Raman spectroscopy and many others. In this approach, each spectroscopic method provides a range of information; a more complete information is obtained through spectral fusion of multiple techniques. This advanced monitoring capability can be accomplished through sampling the cover gas or through direct sampling of the fuel salt. Direct sampling of primary sodium was used in the Fast Flux Test Facility (FFTF) to enable mass spectroscopy measurements [16]. However, the technological maturity of the spectroscopic systems required significant labor for operation and data analysis, so its operation was later terminated. Technological advances in spectroscopy systems will enable its automation, as well as fully automated data sampling and analysis. Surface-enhanced Raman spectroscopy can be another technique for direct monitoring of salt compositional changes [17]. However, the optical sensing element requires access to the fuel salt, so it must be radiation hardened.

4.6.2 Piping and Vessel Cladding Integrity

Piping and vessel components containing the fuel salt may be clad with a material to withstand salt corrosion. This technique is analogous to employing a stainless steel liner on the interior of the low-alloy steel vessel at a PWR. The concept is that the piping material is selected primarily to provide structural integrity at operating temperature, e.g., 750 °C. Chemical compatibility with the salt is provided by the cladding layer. The cladding material may be loose, attached, or diffused into the substrate alloy. Thick cladding layers will not likely require online monitoring. However, thin, discrete layers will require assessment to ensure that they have not developed defects that enable the salt to bypass the cladding. Possible cladding integrity measurements include electrical resistance, acoustic (ultrasonic velocity and attenuation) monitoring, and thermal pulse evaluation. These techniques have not been sufficiently examined to determine whether they are suitable for thin cladding integrity monitoring.

4.6.3 Piping Corrosion Monitoring

One important function of a salt chemistry control system is to maintain the salt redox state to minimize corrosive effects on materials. Although salt chemistry measurements can provide evidence that the salt is well away from chemical conditions that would result in excessive corrosion or material deposition, it may be useful to include monitoring points that explicitly observe removal and deposition of materials by the salt. These monitoring points can be implemented as independent instruments having surrogate sacrificial components; alternatively, the monitoring can be made directly on actual piping or tank walls. Several technologies may be practical for in situ corrosion monitoring, including magnetic susceptibility measurement, ultrasonic time-of-flight or attenuation, electrical conductivity, and thermal conductivity.

As an adjunct to corrosion monitoring, regions deemed particularly susceptible to corrosion, or regions whose integrity is uniquely important, can be placed under cathodic protection in which an externally applied potential prevents local oxidation. Voltages used for such protection systems are low (usually less than two volts); however, the currents can be high, depending on the area protected and the conductivity of the media.

4.6.4 Structural Monitoring

Maintaining support structure integrity in MSRs is important, as in all nuclear power reactor plants. High radiation levels in MSRs make access to many reactor system structures impossible for human inspectors. For this reason, embedded sensors in concrete and other structures should be considered for long-term monitoring of structural integrity.

Typically, an initial baseline is established for steel tendons, steel reinforcement rods, and concrete structures. Subsequent monitoring tracks baseline deviation, which is expected to be a gradual change resulting from age-related degradation at the microstructural level (e.g., slow hydration, crystallization of amorphous constituents, and reactions between cement paste and aggregates). Embedded measurements can be based on one of several technologies: electrical impedance (e.g., built-in resistance wires), strain (displacement) measurement (e.g., built-in optical fiber), acoustic (e.g., built-in ultrasonic waveguides or transducers), and embedded failure indicators (e.g., fluorescent dye release capsules). Chemical detectors or sensory portions of a detector system may be implantable. The principal detection is for chloride ions.

4.6.5 Residual Fracture Toughness of Primary Containment Alloy

The primary radiation damage mechanism for nickel-based alloys at high temperature is loss of fracture toughness due to the build-up of helium at their grain boundaries. MSRE experienced this phenomenon. Subsequent MSR designs largely mitigated the issue by using internal shielding. Nevertheless, measurement of the loss of ductility of the reactor vessel will be a primary indication of the remaining useful life. Toughness measurement can be performed periodically using a coupons approach. Removal of coupons would need to be performed off-line using tooling that is highly tolerant to radiation. It would be beneficial to develop an efficient, cost-effective method to remove the coupon, transport the coupon, and perform the necessary mechanical measurements. Even more advantageous would be the ability to perform the analysis without having to remove a coupon.

A coupon removal system would consist of a coupon port holding apparatus, a robotic manipulation system, coupon transport, and a mechanical analysis laboratory that is remote from the reactor area. It may also be necessary to use machine vision for locating fasteners and other mechanical components.

Alternatively, nonlinear ultrasonic methods can provide useful information regarding the microstructural evolution of the alloy. However, industrial applications of these techniques are at their infancy. The primary challenge is the low signal-to-noise ratios of higher harmonics—which are typically an order of magnitude lower for the second harmonic—generated by the fundamental frequency. However, research shows a strong correlation among microstructural changes such dislocation density, precipitate nucleation, and growth of nucleation sites, and the nonlinearity parameter, β. These observations apply to microstructural changes due to thermal aging [18], as well as changes due to radiation embrittlement [19].

Deployment of this technology will most likely require highly radiation-resilient piezoelectric transducers or powerful EMAT devices.

4.6.6 Fissile Inventory of Removed Filters

Salt filters removed from service will require inspection to ascertain fissile material inventory to comply with required fissile materials accountancy rules. A simple method to assess fissile material quantity is neutron activation. This analysis is performed off-line using either compact neutron generators or isotopic neutron sources. Observation of the gamma spectrum is a direct map to the isotopic materials present. The challenge is to overcoming masking caused by the residual gamma field.

4.6.7 Primary Heat Exchanger Leak Status

In MSRs, series salt loops carry reactor-generated heat to power conversion subsystems. The first loop comprises the fuel salt, while the second comprises the primary coolant salt. A key safety principle is to contain the fuel salt in the reactor loop. To prevent leaks in the fuel's primary coolant heat exchanger from leading to radionuclide escape from the first containment layer, the coolant loop is maintained at a slightly higher pressure than the fuel loop, typically by being located at an elevation above the fuel salt. Pressure instrumentation and control systems measure salt pressure in both loops and continuously adjust argon gas pressure to maintain the correct ΔP. A second monitoring-only system would likely be implemented to verify functionality of the pressure control system. Pressure sensors can monitor either cover gas or liquid salt: the former is a more conventional sensor mounted in a head space, while the latter is either an impulse system or direct-mount-to-pipe sensor. The liquid salt measurement would capture the static and dynamic head of the salt.

Determining whether a loop-to-loop leak is occurring and the extent of such a leak can be accomplished by one of several methods discussed below. It is also conceivable that these methods are simultaneously executed to lower uncertainty.

> *Primary Salt Level*. Because salt in the second loop will flow into the first due to the controlled ΔP, fluid levels in the reactor system tanks will increase. Level measurement instrumentation can detect an unscheduled increase in fuel salt inventory. The resolving power of the level measurement instrumentation determines the minimum detectable leak.
>
> *Coolant Salt Cover Gas Flow Rate*. Loss of coolant loop salt volume requires injection of additional argon cover gas to maintain loop-to-loop ΔP. Monitoring gas flow rate and comparing it against a temperature-compensated model may permit detection of a small leak. The model completeness determines the minimum detectability.
>
> *Reactivity Decrease*. Core reactivity decreases as coolant salt dilutes fuel salt during a leak. Change in core reactivity could manifest as a change in output power level; however, reactor power feedback may adjust other available reactivity control features to maintain set-point power. Observation of control system parameters such as the set-point error signal may indicate that the fuel is becoming diluted faster than the expected rate due to burnup. Other factors such as burnup, temperature, and fuel salt flow rate also influence these control parameters. The sensitivity of the reactivity change method depends on the accuracy of models used in the design and operation of the control system. An adjunct to the reactivity measurement approach is to externally induce minute power oscillations through control rods or reflectors and measure the core transfer function. Changes in reactivity will show up in the terms of the transfer function. A technique of synchronous detection can be applied to the oscillations to improve the signal-to-noise ratio so that power oscillation amplitude is insignificant to reactor operation.

4.6.8 Radionuclide Inventory of Off-Gas System

The off-gas processing system removes radioactive gaseous fission/activation products such as krypton, xenon, and tritium from the head space above the fuel salt to prevent pressurizing the first containment layer. The off-gas system filters and retains these gaseous components so that the short half-life elements decay and the longer half-life elements are stored (see Table 4). Therefore, the filters will contain radionuclides with gaseous precursors, notably including isotopes such as ^{137}Cs. Observing the radionuclide progression through the off-gas system provides evidence of its continued correct operation. Ion chambers to measure gross activity can be deployed at the hot end closest to the reactor, while gamma spectroscopy can be used at the cool end to identify the concentration of specific radionuclides.

Table 4. Disposition of gaseous fission products

Fission product	Half-life	Disposition
^{125}Xe	16.9 hr	Decays in process
^{127}Xe	36.3 d	Decays in process
^{133}Xe	5.3 d	Decays in process
^{135}Xe	9.1 hr	Decays in process
^{136}Xe	2×10^{21} yr	Released
^{85}Kr	11 yr	Stored
^{3}H (Tritium)	12.3 yr	Stored

4.6.9 Primary Pump Status Including Cavitation

Reliable and continuous operation of salt pumps in fuel and coolant salt is a challenge because pumping components operate at over 700 °C in contact with a potentially corrosive media. Pump types used in MSR systems are either overhung or submerged (canned-rotor) pumps. For the overhung pump, the electric motor is remote from the pump impeller and volute; it remains relatively cool, as it is being cooled by gas or liquid. The drawback is that mechanical bearings and seals experience the full effect of operating temperature, as well as plating out of salt, if the bearings and seals are in a cover-gas region. The seal and bearing problem is solved by the canned rotor pump design with the drawback that motor electrical and magnetic parts must operate at 700 °C.

For either pump design type, knowing the real-time status of the motor and pump is essential for continued operation. Variable speed pumps will likely be used to accommodate a variety of power levels, including some degree of load following. The motors will require variable frequency drive. The drive electronics should be able to supply information on drive power, speed, and torque. In addition, acoustic data should be available via accelerometers and other transducers to detect imbalance conditions, failed components, blockage, and cavitation. These data sets can be analyzed to identify problems as they occur and to predict future failures. Pumping systems are designed to operate in pressure regions where cavitation is not possible. Consequently, cavitation monitoring is primarily of interest in pump testing. Cavitation occurs when molten salt is subjected to rapid pressure changes that cause cavity formation in the liquid where pressure is relatively low. The voids then implode and generate intense shock waves as higher pressures return. The shock waves behave as hammers on the metal or ceramic surfaces, causing destructive consequences. Cavitation is most likely to occur at the vanes of the impeller, which will result in pit formation. The traditional method of detecting cavitation is by acoustic monitoring. By monitoring the flow characteristics and the vibration spectrum, a unique cavitation signature can be established [20]. Frequencies are in the 100 Hz to 40 kHz range. Vibration and acoustic methods have been used commercially for decades and are TRL9. The challenge is to attach accelerometers to a surface over

700 °C. The attachment must remain secure with reasonably small attenuation and reflection, and the transducer must be fully functional at the operating temperature.

4.6.9.1 Power Signature Analysis

Power signature analysis can also be used to detect pump cavitation, flow blockages, and seal failures, as well as faults in the stator and rotor components. The method is based on using the motor as a sensor by monitoring the frequency spectrum of drive current. Minute variations in torque result in corresponding fluctuations in the drive current that can be observed in the frequency space. The challenge is to provide sufficient dynamic range to avoid saturating the input electronics with the fundamental drive current while being able to see the minute torque fluctuations. Typically, a 16-bit data acquisition system with 96 dB dynamic range is sufficient to detect most operational anomalies, including cavitation. Bearing and stator/rotor slot failures present as artifacts at specific frequencies. Detection of such failures are made by comparing actual drive current data with the baseline data using a variety of mathematical techniques. Cavitation causes an increase in energy consumption, along with an increase in noise level and distribution (uncorrelated with rotational dynamics) [21]. Research has been conducted regarding the use of current signature analysis to diagnose motor/pump problems (TRL7), but additional work is needed to generate similar data sets for molten salts of various elemental components.

4.6.10 Loose Parts Monitoring

Loose parts monitoring will use similar techniques to that used for LWRs. However, high radiation and temperature tolerance is required of the acoustic and vibration sensory devices. Piezoelectric transducers will not likely have the endurance at 700 °C: EMAT-based transducers will must be developed to withstand the temperature and radiation environment. Electronics can be remotely located in less severe conditions.

5. MSR INSTRUMENTATION MATURITY AND AVAILABILITY

5.1 INTRODUCTION

The United States successfully and reliably operated a molten salt test reactor in the 1960s, (as well as one in 1954), multiple MSR critical experiments, and about a dozen in-pile loops. These multiple demonstrations have established the basic viability of the technology. Consequently, contemporary instrumentation development and demonstration should focus on the differences between the technology available in the 1960s and today. Notable development issues include:

1. MSRE only demonstrated limited-term operations. Extensive, automated maintenance and component replacement will be required for a commercial plant. Structural material embrittlement and corrosion monitoring will be especially important, as these represent the lifetime-limiting phenomena for the fuel salt boundary. Health monitoring of the fuel salt pump and primary heat exchanger will also be key measurements. Long-term health monitoring of the semi-permanent concrete structures is also advisable and was not demonstrated with MSRE.
2. Instruments that depend on higher speed signal processing, such as ultrasonic flowmeters and radar level gauges, were unavailable in the 1960s. While earlier technologies continue to be viable, newer technologies can provide performance or reliability advantages.
3. MSRE relied on manual actions to perform all maintenance, inspection, and operational activities. The MSR remote maintenance facility did demonstrate remote replacement of all components (notably including the reactor vessel) in 1959 [10] by using a multi-camera system with long-handled tooling, which was entirely manually operated. To reduce staffing requirements, commercial plants will rely on automated systems employing control systems technology that were unavailable during the earlier MSR era.
4. MSRE was a less-than-10-MW_{th} reactor. Commercial scale operation will be substantially larger.
    a. Measurement access into larger systems has not been proven.
    b. Decay heat removal will have a higher safety significance in a larger system. Instrumentation to demonstrate the functionality of an MSR’s passive decay heat removal system(s) will need to be demonstrated.
5. MSRE was operated on a government-owned site, which provided plant security. Instrumentation to support access monitoring on commercial sites will be necessary.
6. Fissile materials tracking (safeguards) instrumentation was not specifically considered at MSRE.
7. An NRC license is required to operate any nuclear facility. Any safety-related instruments or measurements must meet 10CFR50 Appendix B quality assurance standards.
8. Fast-spectrum MSRs will have significantly higher power densities than MSRE, making any in-core instrumentation impractical.
9. MSRE was a thermal spectrum reactor. The cross sections for neutron interacting materials in sensors are much lower in a fast spectrum, necessitating larger flux monitors.
10. While the historic MSR program worked with instrumentation suppliers of the day to produce its instruments, little of that capability remains active.

5.2 MATURITY ASSESSMENT

The majority of instruments employed at an MSR would have performance requirements essentially identical to those for other *high temperature* industrial process plants and are consequently mature and commercially available. An MSR’s high degree of passive safety and lack of any known rapidly progressing accidents means that few instruments will be safety related. Based on these factors, standard industrial supply chains can be employed. Few instruments require contact with salt, so only a limited fraction will require specialized versions for an MSR. Also, heat balance measurements will likely be performed on the coolant salt, avoiding fuel salt contact and exposure to high radiation levels. This is similar to the PWR practice of performing the heat balance on the secondary side.

Most material degradation processes (corrosion, embrittlement, etc.) are slow if salt chemistry control is maintained, so inspection instrumentation does not require a rapid response and can employ samples examined off-line in a laboratory environment. For example, the stress-rupture characteristics of the structural alloy can be assessed using periodically extracted coupons, and fuel salt corrosion can be monitored by assessing the build-up of structural alloy constituent elements (e.g., chromium, iron, nickel) in the fuel salt. While online measurements of embrittlement and corrosion would help avoid accessing the salt and generating a highly radioactive waste stream, a plant could be reasonably operated without online measurements.

While the radiation environment within the biological shielding at an MSR will be quite high at up to ~10^6 R/h), similar environments exist in other nuclear facilities, and tooling that is extremely hardened by radiation has been developed to support those applications. Remote manipulation in extreme radiation environments is typically performed using long-handled tooling that is guided visually through multi-camera systems with long focal-length lenses. Notably, ITER's maintenance facilities [22, 23] are currently under development, and the Spallation Neutron Source's target manipulation facilities [24] were deployed in 2006, providing modern examples of remote maintenance capabilities with extreme radiation hardening. Equipment for use within the Hanford waste tanks provides another contemporary example of manipulators with extreme radiation hardening. ORNL's remote operations and maintenance demonstration facility was designed to develop experience in remote maintenance practices within high-radiation areas [25]. ORNL has also produced a number guidelines and overviews of remote maintenance technology [26,27,28].

5.3 DEVELOPMENT ISSUES

5.3.1 Maintenance automation and integration into operations

The MSRE employed physical mock-ups for maintenance planning and training. New reactor system development would primarily employ virtual mock-ups. Apart from high-speed computing and the resulting process simulation, the most significant maintenance technology development since the earlier MSR era is the development of extremely radiation hardened force feedback via power signature analysis of the drive motors in long-handled tooling. Providing force-feedback substantially improves manipulation dexterity.

Maintenance automation has not previously been incorporated into NPP operations to the extent that it must be incorporated into MSRs. Automated instrumentation replacement, including cable connection and routing, is not mature. While the basic elements of coupon retrieval technology are generally known, the technology for retrieving material coupons from MSRs—whether structural materials or moderator materials—requires consideration of MSR-specific phenomena, such as the potential for salt deposition on surfaces in the vapor space above the liquid, and high-speed automation to minimize any downtime.

5.3.2 Instrument Drift, Recalibration, and Aging

MSR designs are intended to operate for years between outages and for substantially longer than LWRs. Instruments drift over time, and some instruments may fail prematurely. Instrumentation recalibration intervals are often shorter than the planned operating times, thus necessitating online instrumentation replacement and/or recalibration; neither of these processes are currently mature.

5.3.3 Salt Sampling

First generation commercial MSRs will rely on fuel salt sampling for several functions, ranging from corrosion assessment to fissile material tracking. MSRE’s sampling mechanism was not sufficiently reliable for commercial operations [29]. In particular, its cable drive mechanism, which was required to operate through clamping seals, proved unreliable. A metering valve and side-stream salt sampling alternative configuration has not been demonstrated.

5.3.4 Online Corrosion Monitoring

Corrosion assessment at MSRE was performed by observing the build-up of structural alloy constituent materials in fuel salt that was periodically sampled. While this remains a valid measurement technique, a recent innovative technique has been proposed. This technique is based on an online measurement of the change in magnetic properties of the structural alloy in which chromium has been preferentially corroded from the material [30]. The proposed system builds on the corrosion measurement system developed and demonstrated by Tiefnig [31]. Having an online corrosion monitor would avoid the waste stream and mechanical challenges of a salt-sampling based system, and it appears to be reasonably achievable over the next few years. The least mature components of the proposed system have a TRL of 3 but could be advanced to at least a TRL6 within three years.

5.3.5 Online Redox Condition Measurement

Online salt redox condition assessment would be desirable because the dominant corrosion mechanism for halide salts is through oxidation. The redox condition at the MSRE was performed off-line through analyzing the ratio of U^{3+} to U^{4+} (via several techniques) contained within the fuel salt. Two of the proven off-line techniques are electrochemical and optical. Online electrochemical measurement of fuel salt properties would be very difficult, as this is a small-signal phenomenon that depends on wetting and diffusion processes that occur over time. Online optical measurement may be possible based on the absorption differences of disparate chemical species. However, providing optical access into the fuel salt will be challenging because of several issues: radiation darkening of the optical components, salt plate-out (fogging) onto nonwetted components, scum layer formation on salt-free surfaces, salt auto-scintillation, and salt darkening from the build-up of fission products. Overall, online optical measurements of fuel salt remain at a low TRL and appear to require extensive development to mature.

5.3.6 Flow Measurement

Low uncertainty measurement of coolant flow rates will be necessary to calculate the heat-balance at an MSR. An impulse-line coupled orifice flowmeter (Venturi-type) was demonstrated at MSRE. However, flowmeter inaccuracy was suspected as the primary cause for the variation between the planned (8.0 MW) and actual (7.34 MW) power output [32]. NaK-filled impulse lines are no longer commercially available as a non-custom item. Even custom fabrication capabilities are rare for MSR temperatures. The technology of the 1960s could be re-engineered with some modern touches such as temperature compensation and performance status determination. Ideally, the impulse lines could be dispensed with altogether by employing a radiation and high-temperature tolerant salt-compatible diaphragm for pressure measurement.

An activation-based flowmeter could also be employed on fluoride coolant salts, taking advantage of the neutron interaction properties of ^{19}F due to the delayed neutrons in the primary heat exchanger [33]. The components of activation flowmeters are mature. However, no specific system has been developed and demonstrated for MSRs. Chlorine does not have equivalent cross sections, so chloride salt reactors would not have an equivalent option.

Multi-path clamp-on ultrasonic flowmeters can be employed to measure coolant salt flow much in the same way as they have been used at PWRs. The primary technical challenge for employing the technology at MSRs is the higher salt temperature resulting in higher temperature of the electroacoustic transducers. Mechanical stand-offs, which are conventionally employed to reduce the temperature at the transducer, substantially reduce the signal level, increase signal-to-noise ratio, and increase uncertainty. All of these factors intensify the transduction challenge. Overall, clamp-on ultrasonic flowmeters for coolant salt are currently at a TRL level of 3–4, but they show potential for advancing to a commercial level of readiness over the next few years. Development of high-temperature and radiation-tolerant electro (or opto)-acoustic transducers to eliminate the need for standoffs would be a desirable but longer term, higher risk option.

5.3.7 Integral Configuration Measurement Access

Most modern MSR designs are configured as integral systems, or primary heat exchangers located within the reactor vessel. This approach minimizes the salt volume and the potential for leaks. As a result, integral configuration substantially reduces access to measure the fuel salt. Standpipes above the fuel salt may be possible, but direct fuel salt measurements will be difficult. A rotameter-type flowmeter that was plunged into salt from above was demonstrated at the ARE [34], and this type of instrument may be useful for off-line flow diagnostics. However, for high-power density reactors, no solid materials appear likely to withstand the in-core environment.

5.3.8 Radiation Tolerant Electronics

The in-containment radiation environment at MSRs would be well beyond what solid-state electronics systems could withstand. Instrumentation will rely on remote, well-shielded, or non-solid-state (i.e., vacuum tube) electronics. In-containment electronics would be difficult to diagnose, repair, or replace, so remote electronics are anticipated to be the dominant deployment configuration. An exception might be for specialized front-end signal amplifiers and repeaters that must be in close proximity to the process sensor.

5.3.9 Cover Gas Composition and Solids-Build Up Measurement

Residue was periodically removed from MSRE’s off-gas lines by mechanical swabbing. This type of mechanical brush- or scraper-based approach is likely still a viable, mature technology option. A few salts are of specific concern for plate-out in the off-gas system due to their higher vapor pressures. These salts include ZrF_4 and UCl_4. Higher vapor pressure salts that do not have a liquid phase (such as ZrF_4) are especially problematic. The ARE employed a “snow trap” [35] to capture its ZrF_4 off gas. The technology underlying mechanical removal of salt deposits on piping is mature, but it is unproven in the specific environment of an MSR. Technology demonstration would be appropriate to develop a specific commercial version.

5.3.10 Start-Up Flux Monitoring

Neutron flux monitoring will generally be performed ex-vessel at MSRs using readily available commercial technology. Additional modeling will be required to assess whether start-up flux monitoring can be performed ex-vessel given the much smaller number of neutrons available during source-range operation. Initial start-up flux monitoring would be performed either with a high-sensitivity flux monitor that is either mechanically withdrawn or allowed to burn out after start-up is complete. The MSRE employed a near ex-vessel flux monitor that was withdrawn following start-up. For a low power density reactor, the high sensitivity flux monitoring system might survive for a useful period in the core following start up. However, no instrumentation would survive a high power density core.

5.3.11 Power Profile Measurement

Measurement of the in-core power profile would indicate core structural integrity, because obstructed flow in graphite-moderated MSRs would directly affect neutron flux and power levels due to local thermal feedback. The power profile would also indicate fuel salt penetrating into the graphite due to the local change in the reactor spectrum (fuel-to-moderator ratio) and the resultant power profile shift. Power profile measurement would likely be made using SPNDs or ion-chamber strings. A high-temperature gamma thermometer string could be a more reliable, albeit less mature, alternative measurement technology since SPNDs are small-signal, delayed-output devices, and ion chambers have poor reliability at high temperatures. Gamma thermometers are commercially available, but they are not offered in a high-temperature configuration. The underlying technologies for gamma thermometers are thermocouples combined with radiative and conductive heat transfer. Consequently, a high-temperature gamma thermometer string suitable for use at MSRs appears possible, but this would require development and demonstration.

5.3.12 Fuel Salt Leakage Assessment

Fuel salt leakage instrumentation is not yet demonstrated in relevant conditions at MSRs. The most likely leakage scenario at an MSR is for the higher-pressure coolant salt to leak into the fuel salt via the primary heat exchanger. Substantial in-leakage of coolant salt could be observed by level measurement (i.e., volume) of either fuel or coolant salt. More sensitive measurement to detect small leaks would be desirable. The unanticipated presence of radionuclides within the next layer of containment (guard vessel or DRACS salt loops) would provide evidence of containment leakage. MSRE’s freeze valve leakage was observed based on detecting radioactive vapors within containment [36]. While the technology for detecting radionuclides within a gaseous environment is mature, the ability to localize and characterize the leak in a high radiation background is less mature. Since radionuclides escaping from beyond a barrier would be an accident, the plant would be required to shut down until the source of the leakage could be determined, corrected, and the severity assessed. Therefore, developing effective remote inspection technology for portions of the containment layers that are not readily observable is of high value.

5.4 SUPPLY CHAIN ISSUES

Because no commercial MSR has ever been constructed, and even the test reactors were developed at least 50 years in the past, no specialized MSR instrument vendors exist. Given the lower safety significance of the measurements due to the plant’s high degree of passive safety, the lack of a dedicated supplier base appears to be less significant. However, even conventional high-temperature instrumentation suppliers are largely unaware of the specific requirements of MSRs since there is no market. Development of common instrumentation performance requirements would help prospective vendors develop instruments for the potential future market.

6. CONCLUSIONS

Most instrumentation at MSRs will not contact liquid salt. The high degree of MSR passive-safety substantially reduces the number of safety-related instruments, and it completely eliminates the need for rapidly responding safety-related instrumentation. Much of the remaining safety-related instrumentation provides assurance that safety-related SSCs continue to be able to perform their functions, performs post-accident condition monitoring, or provides control room habitability monitoring.

High-temperature, radiation-tolerant commercial-grade instrumentation from other industrial processes can be widely employed at MSRs. MSR customized instrumentation technologies have been demonstrated to be adequate to operate MSR test reactors at prior molten salt test reactors for in- and ex-pile salt loops, and for multiple specialized testing rigs. Instrumentation advancement needs to be focused on technology improvements to enable high-reliability, cost-effective, long-lived, commercial-scale plant operation.

Operations and maintenance automation was not a focus of the large, historic MSR development program. The greatest potential enhancement to MSRs is in the new instrumentation technologies for maintenance automation that can be integrated into reactor operations. Modeling and simulation of maintenance and waste handling activities will be especially important to ensure reliable, long-term operations.

A prioritized list of MSR instrumentation development activities from the body of the report is provided below:

1. Integration of maintenance planning and waste handling into reactor point designs to enable support for instrumentation development,
2. Online salt and material coupon removal tooling,
3. Instrumentation and cabling replacement tooling,
4. Tooling for inspection of areas that are not readily observable,
5. Online corrosion monitor development,
6. High-temperature, salt-compatible gamma-thermometer development,
7. Coolant salt ultrasonic flowmeter development,
8. Fissile materials tracking planning to enable instrumentation evaluation,
9. Fluoride salt activation flowmeter development, and
10. Online redox measurement capability development.

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