FHR PROCESS INSTRUMENTS

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ABSTRACT

Fluoride-salt-cooled High-temperature Reactors (FHRs) are entering into early phase engineering development. Initial candidate technologies have been identified to measure all of the required process variables. The purpose of this paper is to describe the proposed measurement techniques in sufficient detail to enable assessment of the proposed instrumentation suite and to support development of the component technologies. This paper builds upon the instrumentation chapter of the recently published FHR technology development roadmap [1].

Locating instruments outside of the intense core radiation and high-temperature fluoride salt environment significantly decreases their environmental tolerance requirements. Under operating conditions, FHR primary coolant salt is a transparent low-vapor-pressure liquid. Consequently, FHRs can employ standoff optical measurements from above the salt pool to assess in-vessel conditions. For example, the core outlet temperature can be measured by observing the fuel's blackbody emission. Similarly, the intensity of the core's Cerenkov glow indicates the fission power level. Short-lived activation of the primary coolant provides another means for standoff measurements of process variables. The primary coolant flow and neutron flux can be measured using gamma spectroscopy along the primary coolant piping.

FHR operation entails a number of process measurements. Reactor thermal power and core reactivity are the most significant variables for process control. Thermal power can be determined by measuring the primary coolant mass flow rate and temperature rise across the core. The leading candidate technologies for primary coolant temperature measurement are Au-Pt thermocouples and Johnson noise thermometry. Clamp-on ultrasonic flow measurement, that includes high-temperature-tolerant standoffs, is a potential coolant flow measurement technique. Also, the salt redox condition will be monitored as an indicator of its corrosiveness. Both electrochemical techniques and optical spectroscopy are candidate fluoride salt redox measurement methods. Coolant-level measurement can be performed using radar-level gauges located in standpipes above the reactor vessel.

While substantial technical development remains for most of the instruments, industrially compatible instruments based upon proven technology can be reasonably extrapolated from the current state of the art.

Key Words: FHR, instrumentation, measurement

1 INTRODUCTION

Fluoride-salt-cooled High-temperature Reactors (FHRs) are a class of nuclear power plants (NPPs) that features low-pressure liquid fluoride salt cooling, high-temperature-tolerant ceramic fuel, fully passive decay heat rejection, and a high-temperature power cycle. FHRs have the potential to economically and reliably produce large quantities of electricity and high-temperature process heat while maintaining full passive safety. As with any NPP, the overall function of an FHR's instrumentation system is to provide the information necessary to safely and efficiently operate the plant over its entire lifetime under the full range of conditions it may experience. Measurements include process conditions (both online and during outages), component health, and accident progression monitoring.

FHRs, like light-water-cooled reactors (LWRs), produce thermal energy. Consequently, the process measurements at an FHR will be conceptually similar to those at an LWR. However, the performance requirements for an FHR's instrumentation system arise from its functional requirements, which in turn derive from the plant's physical characteristics and potential accident scenarios. The instrumentation performance requirements of LWRs do not directly apply to FHRs as the different characteristics result in different demands. Understanding potential FHR accidents including their initiating events and the resultant plant conditions is necessary to perform a full-scope instrumentation system design. An FHR's power cycle would employ the same measurements as any other high-temperature thermal power plant. This article is limited to the distinctive aspects of an FHR's instrumentation system.

As a rule, safety-related instrumentation should be simplified to the extent possible to provide the highest possible assurance of reliable, safe operation while minimizing equipment qualification challenges. The more complex, higher-speed signal processing is made possible by modern electronics; however, it frequently enables both improved performance and increased probability of correct operation (or failure to a safe state). FHR instrumentation systems will more broadly rely on standard, industrial-grade, high-quality control electronics than LWR systems because the reactor's inherent passive safety reduces the active safety response requirements. Use of industrial-grade components, instead of the bespoken production common for LWR safety system electronics, changes the system design and obsolescence paradigms.

FHRs feature a low-pressure primary system, moderate power density, a high-temperature-tolerant ceramic core, a large thermal margin to fuel damage, no primary coolant phase-change accidents, strong negative reactivity thermal feedback, fully passive decay heat rejection, and inherently slow accident progression scenarios. On the other hand, an FHR's decay heat removal system is vulnerable to freezing, and FHRs generate substantially more tritium than LWRs. As such, FHRs will require different measurement capabilities to support safety actions than would an LWR. The differences will inevitably be reflected in the instrumentation system architecture. While general design principles such as high quality, diversity, and defense-in-depth remain requirements for any reactor, the lack of a pressure differential to disperse radionuclides and the much larger time and temperature margins inherently afforded by an FHR to respond to any accident may, in addition to altering the instrumentation, affect the allocation of responsibility for safety response from equipment to operator or even to a remote expert.

NRC's guidance on reflecting risk significance into safety evaluation of NPPs remains at a high level. "Risk-informed categorization and treatment of structures, systems and components for nuclear power reactors," 10CFR50.69, was adopted in 2004. The regulatory guidance document, *A Proposed Risk Management Regulatory Framework*, NUREG 2150, was published in 2012. More specific guidance on how to acceptably reflect passive safety and risk significance into an NPP's instrumentation architecture is not yet available.

An operating nuclear reactor's core is an extremely hostile radiation environment. An FHR's high temperature and liquid fluoride salt environment substantially increase the environmental tolerance challenges. FHRs, however, are low-pressure reactors and will have an inert-gas-filled upper plenum facilitating optical access to the core. Also, ^{19}F's neutron interaction daughter products (^{20}F, ^{16}N, and ^{19}O) all have short half-lives (< 30 seconds) and emit energetic gamma rays during their decay. Monitoring the gamma ray emission provides an additional, non-contact means to monitor process variables. Reactor start-up is much more difficult to measure remotely due to the much lower neutron and gamma fluxes. Consequently, the current design intent is to employ in-core start-up instrumentation that is withdrawn prior to the reactor reaching full power.

An FHR's containment environment will also be challenging for electronics and the plant staff. At power, the energetic gamma rays, originating in the primary coolant, that facilitate process measurements will prevent staff access and degrade local electronics. The containment environment outside of the primary coolant boundary will be filled with inert gas and will likely be contaminated with beryllium fluoride dust, necessitating breathing gear for even offline human entry. Instrumentation maintenance will be facilitated by locating electronics either outside of the inert containment in locations shielded from the primary coolant gamma rays or in areas that can be robotically accessed. Telepresence-based maintenance will have substantially greater prominence in future NPPs due to the advancement of the technology. Additionally, many electronic components are now sufficiently inexpensive that they can be treated as consumables. For example, it is now common practice to employ inexpensive digital video cameras in hot cells that are replaced as needed (often every shift).

This paper is organized to first describe the set of measurements anticipated at FHRs. Specific sensors to implement the measurements are then presented. FHR development issues and challenges are then discussed. Finally, conclusions are drawn about FHR instrumentation.

2 MEASUREMENTS

A number of measurements will be performed at FHRs as part of normal plant operations. While conceptually similar measurements are performed for other reactor classes, the distinctive aspects of FHRs result in different measurements.

2.1 Core Coolability

Maintaining coolable core geometry is a reactor safety function. In other power reactor classes the status of coolant flow through the core is inferred from indirect measurements. Observation of core coolability is a significant reactor class advantage as accidents as diverse as the Fermi-1 inlet nozzle blockage (sodium fast reactor [SFR]) and the Three Mile Island Unit 2 (LWR) feedwater shutoff would be much less likely if the reactor core were under constant visual surveillance. Providing and maintaining the optical access into the reactor vessel, and possibly even to the lower plenum, will be the principal technology challenge for enabling continuous core coolability surveillance. Observing the core also allows continuous monitoring of the degree to which the fuel mechanical distortion impedes coolant flow and in-vessel structural vibrations.

2.2 Reactivity

Measuring the core reactivity is a safety function. The core reactivity is required to be monitored whenever the core contains fuel. The core reactivity is the rate of change in the reactor power. As such the instrumentation for measuring the reactivity and the reactor power are closely related with the exception that the reactor power integrates the local power over the entire core, under the assumption that the shape of the reactor power does not shift rapidly. Consequently, overall core reactivity is typically inferred from local measurements of the rate of change of core power.

Measuring the reactivity while the core is subcritical or during start-up requires much more sensitive instrumentation than measurements at higher power. The specific measurement sensitivity required while the plant is shut down is determined by the combination of the required measurement response time, the start-up source strength, and how far below criticality is required to be monitored. Start-up range flux monitoring is likely to be performed using a high-sensitivity fission chamber. As the reactor power transitions from start-up into the intermediate and power ranges, the neutron flux becomes much larger and more prominent. The core will produce an intense Cerenkov glow in the primary coolant, the intensity of which is proportional to the reactor power. The potential for monitoring the power range reactivity using remote optical detectors may avoid any requirement for high-temperature-tolerant, salt-compatible, power range flux monitors.

2.3 Reactor Power

Reactor power is monitored as a safety indication and to enable optimal operation of the power cycle. Measuring the temperature rise of the coolant along with its mass flow rate is the most common method for determining the reactor power in other reactor classes. A heat-balance-based power monitoring system will also be employed at FHRs. Thus, accurate coolant temperature and mass flow remain key measurements at FHRs. Accurate primary coolant temperature and mass flow rates, however, have significant technical challenges. The temperature distribution within the primary coolant may be both non-uniform and time varying. Most mass flow rate instruments are vulnerable to transducer degradation and inaccuracy due to non-well-characterized flow distributions.

Primary coolant activation can be employed at FHRs as an integrated, albeit delayed, indication of reactor power. FHRs have three different short-lived activation products (^{16}N, ^{20}F, and ^{19}O), each with different gamma-ray emission energies, production cross sections, and decay constants enabling cross checking the measurements. FHRs, consequently, will employ activation-based power monitoring more extensively than has been common practice at LWRs, as the sole useful water activation product, ^{16}N, production rate at LWRs is somewhat burnup dependent. (The ^{16}O(n,p)^{16}N reaction has a minimum energy threshold of nearly 10 MeV; ^{239}Pu thermal fissions produce more higher energy neutrons than ^{235}U fissions.)

2.4 Fuel Leakage

Fuel leakage will be monitored by a combination of cover gas activity monitoring and gamma monitoring of the primary coolant. At likely FHR fuel operating temperatures, the carbon matrix surrounding the fuel will act as a filter to fission product release and only the noble gases would be anticipated to be substantially released upon particle failure.

Circulating radionuclides within the primary coolant would be a potential source of maintenance worker dose and would have a higher probability of release into the environment than those retained in the fuel. The required sensitivity of the fuel leakage monitoring has not yet been determined. However, given the higher probability for radionuclide dispersal from an LWR coolant loop, due to the higher pressure, the FHR circulating activity limits will likely be higher than those permitted for LWRs.

2.5 Primary Coolant Boundary Integrity

Monitoring the integrity of the primary coolant boundary supports both safety requirements and long-term plant health. The primary coolant boundary could leak above the coolant level because of a vessel head gasket failure. Leakage would tend to be inward as the upper vessel upper plenum will be at slightly lower pressure than the containment. Note this is distinctly different from high-pressure reactors in that primary coolant boundary leaks do not provide a pathway for radionuclide egress. A small head gasket leak would be detectable by increased amounts of impurities in the cover gas cleanup system as the lower purity containment atmosphere enters the reactor vessel. Larger amounts of gasket leakage would be detectable by the pressure rise in the reactor vessel upper plenum.

The coolant boundary could also leak in the primary-to-intermediate heat exchanger. Again, the leakage direction would be inwards. Small leaks would be detectable by the activation of the intermediate coolant elements in the primary coolant. Larger leaks would be detectable by the rise in the in-vessel coolant level. The safety significance of heat exchanger tube leakage is distinctly different from that at LWRs, and as such, leaks would add coolant to the system and would not provide a pathway for radionuclides to exit because of the inflow.

The primary coolant boundary could also fail due to rupture of the external loop piping. Rupture of the external loop piping would lower the reactor vessel coolant level to the low edge of the piping exit level and would be detected through the in-vessel level sensors as well as the change in the pump and heat transfer performance. Large ruptures of the reactor vessel could lower the vessel coolant level until the space between the reactor vessel and the guard vessel fills with coolant. Small leaks of the reactor vessel would self-plug as the primary coolant salt solidifies in the lower temperature external atmosphere. Distortion (creep) of the reactor vessel would be a primary indicator of vessel aging and would be monitored optically from above the salt.

2.6 Decay Heat Removal Functionality

Safety-grade decay heat removal at FHRs is provided through their multiple, redundant direct reactor auxiliary cooling systems (DRACSs). Monitoring the functionality of each DRACS system will be a safety-related activity. A DRACS system is vulnerable to failure through freezing (plugging), leaking, and improper thermal profile development (preventing natural circulation flow). Also, the DRACS external salt-to-air heat exchanger is vulnerable to external events such as flooding or aircraft impact. The DRACS loops will include both level measurement in their surge tank and thermal profile measurement around the loop. Because loop flow is due to natural circulation, thermal profile measurement also provides flow indication. An alternate DRACS flow measurement technique would be to transiently heat the loop piping at a low point and observe the propagation of the thermal pulse around the loop.

2.7 Tritium Release

Tritium contamination will be monitored as multiple locations within the plant as tritium is the only radionuclide with significant potential for release into the environment. Tritium traps will also be included in all of the containment gas cleanup systems. Tritium contamination monitoring of the intermediate coolant will also be performed, as tritium leaking from the primary-to-intermediate heat exchanger is a potential radionuclide release pathway if the primary coolant tritium stripping system were to fail.

2.8 Coolant Redox Condition

Monitoring the coolant redox condition at FHRs is an important indicator for coolant corrosiveness. Fluoride salts containing electronegative impurities can be highly corrosive. Effectively, all primary coolant boundary corrosion at FHRs will result from oxidation of the boundary metal atoms into a soluble metal fluoride. Measuring the salt redox condition as well as the concentration of the circulating structural metal fluorides provides assurance that substantial corrosion is not occurring.

2.9 Refueling

All of the mechanical manipulations required for refueling are intended to be visually confirmed from above the salt pool. Views of the vessel interior and the positioning of the refueling equipment will be provided to the control system through relay optics located above the surface of the pool.

3 SENSORS

Sensor selection at FHRs remains preliminary. Many sensors at FHRs will be identical to their counterparts at other reactors and thermal power plants. Conventional technologies such as scintillators for gamma-ray measurements or base metal thermocouples for temperature measurements are not included in the paper. Substantial development effort remains for a number of the FHR customized measurement systems. Alternate sensors and measurement methods may be recommended as development progresses. However, initial candidate sensors have been identified to perform all of the as-yet-identified measurements at FHRs.

3.1 Visual

Visual access at FHRs will rely on customized versions of classical optical elements (mirrors, windows, lenses, cameras, etc.). Element customization is necessary for the components to perform within the FHR environment. The reactor vessel head will be at an elevated temperature, necessitating high-temperature elements. The optical alignment of the components will change as the core heats up, requiring compensation of the field of view. Also, the salt surface will ripple as the salt flows, distorting under-salt images. The distortion will have to be removed computationally to enable accurate imaging of immersed components. Salt vapor will evaporate from the pool surface. The vapor will condense into an opaque polycrystalline film on cool surfaces above the pool. Any in-vessel optical components will, thus, need to be heated or mechanically cleaned. Radiation dose to transparent components can cause them to darken. Window and lens materials will need to be selected for radiation tolerance. Also, all cameras (and other detection system electronics) will need to be remotely located from the primary coolant to minimize the radiation dose.

3.2 Flow

The two leading candidate fluoride-salt flow measurement techniques are ultrasonic transit time measurement and activation-based flow measurement. Ultrasonic transit time flow measurement will function largely as at LWRs with the exception of the requirement for more increased thermal buffering of the thermally sensitive piezoelectric transceiver elements. Also, the higher containment radiation environment at FHRs may limit the lifetime of the piezoelectric elements. Further, the sensor electronics may require increased shielding from the gamma rays emitted by the coolant (preferably by locating the sensor electronics outside of containment in a shielded enclosure).

Once the reactor is at power, measuring the propagation of the activity within the flow will provide an indication of the flow properties. Activity propagation based flow measurement does not require direct contact with the salt or elevated temperature and, thus, appears to be a preferred at-power flow measurement technique. Activation-based flow measurement is also performed at LWRs. These flowmeters function by tracking the spatial location of the decaying ^{16}N as it is transported along the primary coolant piping. Flowmeters based upon $^{16}O(n,p)^{16}N$ were developed by Westinghouse in the 1970s and early 1980s [2,3]. The principal issue limiting the accuracy for the ^{16}N decay-based measurement scheme in pressurized water reactors (PWRs) is the low intensity of the emitted gamma rays.

FHRs, in contrast, will produce more plentiful gamma rays due to the larger neutron interaction cross sections. The ^{19}F of an FHR's primary coolant has two separate activation reactions that yield useful decay gamma rays – $^{19}F(n,\alpha)^{16}N$ and $^{19}F(n,\gamma)^{20}F$. Nitrogen-16 has a 7.13 second half-life and emits a 6.123 MeV gamma ray with an intensity of 67% during its decay. Nitrogen-16 also emits a 7.115 MeV gamma ray with 4.9% intensity. Fluorine-20 has a half-life of 11.163 seconds and emits a gamma ray of 1.634 MeV with an intensity of over 99.99% during its decay. Complicating the measurement somewhat is the $^{19}F(n,p)^{19}O$ reaction, which yields a 1.36 MeV gamma ray (~50% yield) but has a longer half-life (~27 s), decreasing its usefulness for flow measurement.

The different absorption probability of the different gamma-ray energies provides information on the flow distribution, 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 by the pipe wall and will thus be less sensitive to flow distribution patterns within the pipe. The lower energy gamma ray, in contrast, provides flow information 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) thus enables augmenting the gamma-ray correlation signal with flow distribution information, increasing the accuracy of the flow measurement.

3.3 Neutron Flux

Neutron flux sensors at FHRs are required to support both start-up and power range operation. High-temperature fission chambers can provide high-sensitivity neutron flux measurement. High-sensitivity, high-temperature-tolerant fission chambers have been developed in support of sodium-cooled fast reactors (SFRs). SFRs, however, operate at somewhat lower temperature than FHRs. As such, the maximum temperature of commercially available fission chambers is 550°C, or roughly 150°C below the planned operating temperature of first-generation FHRs. Less optimally, a current generation fission chamber could be located in an insulated thimble near the reactor core. The sensor would be actively cooled and withdrawn upon the reactor achieving criticality when less sensitive flux measurements become useful.

At power, an FHR's core will produce an intense Cerenkov glow in the primary coolant. Cerenkov detectors monitor the light emitted as charged particles (energetic electrons) traveling faster than photons in the primary coolant slow down. The light emission is strongly peaked in the ultraviolet region and decreases in intensity roughly linearly with increasing wavelength. Cerenkov light detection relies upon the same measurement technologies as other optically based measurements. Additionally, at low reactor power, a significant fraction of the Cerenkov photons are due to beta decays of fission products and thus do not represent the current reactor power.

3.4 Temperature

Temperature measurement at FHRs serves two primary functions: (1) demonstrating proper heat transfer in the core and (2) supporting the heat balance measurements to assess the reactor power. Fuel and component temperatures at FHRs can be determined by observing their blackbody emissions. The thermal emission from the core and structures will also be optically monitored using similar optical elements as with other optically based measurements.

Accurate heat balance measurements require accurate thermometry. The high temperature of FHRs causes their temperature transducing elements to degrade over time. Two different thermometry techniques appear especially useful for FHR primary heat balance measurements. Both Johnson noise thermometry (JNT) and gold-platinum thermocouples offer the potential for high-stability temperature measurements at FHRs.

The pure element (99.999%), non-letter-designated gold-platinum (Au-Pt) thermocouple can achieve precision of approximately ±10 mK at temperatures up to 1000°C [4]. The Au-Pt thermocouple is markedly superior to conventional platinum-rhodium alloy thermocouples in terms of stability, homogeneity, and sensitivity (about double a Type S) and, thus, is a preferred option for ex-vessel temperature measurement. However, the stability and durability of mechanically rugged, metal-sheathed, mineral-insulated versions of the Au-Pt thermocouple have yet to be demonstrated sufficiently for immediate application to important measurements at NPPs. In particular, the coefficients of thermal expansion (CTEs) of gold and platinum are sufficiently different such that the hot junction mechanical interconnection needs to be flexible to avoid stressing the elements.

JNT is a first-principles representation of temperature. The impact of the mechanically and chemically induced changes in resistance temperature detector (RTD) electrical resistance with time at high temperature can be avoided by basing the measurement on a fundamental property of temperature. JNT results from the vibration of the electronic field surrounding atoms as they thermally vibrate. Since temperature is merely a convenient representation of the mean kinetic energy of an atomic ensemble, measurement of these electronic vibrations yields the absolute temperature.

JNT has three significant sources of potential measurement error that can be reduced in significance by proper design and implementation: (1) electromagnetic noise pickup, (2) amplifier drift, and (3) cable roll off. JNT is a small signal phenomenon requiring good grounding and shielding as well as high-stability, high-gain signal amplification. Electromagnetic noise pickup can be compensated for somewhat by applying digital signal processing to reject undesired signals. In addition, JNT relies on high gain (~10^6) wide-bandwidth signal amplification. If the amplifier gain shifts over time or with electronics temperature, the JNT would provide an incorrect RTD recalibration. Consequently, the amplifier gain characteristics need to be verified either online or by periodic maintenance. Finally, the intervening cabling between the sensor and the first-stage signal amplification will cause the higher frequency components of the wideband JNT signal to roll off, restricting the allowed upper measurement frequency. Understanding and compensating for any shifts in the cable properties are required for a successful long-term implementation.

3.5 Coolant Redox Condition and Cleanliness

Monitoring the redox condition of the fluoride salts is equivalent to the coolant chemistry monitoring programs of LWRs in that its primary purpose is to ensure that the correct chemical environment is maintained to minimize corrosion. Coolant chemistry monitoring is also important to ensure that significant amounts of neutron poisons have not been inadvertently introduced into the primary coolant (and compensated for by control element withdrawal) as having significant amounts of neutron absorbers in the primary coolant would result in an unacceptably large positive void coefficient.

Electrochemically based measurements are the most commonly used technique to assess the redox condition of molten fluorides. A general electrical and mechanical configuration for voltammetry-based redox measurements in FLiBe was demonstrated in the molten salt reactor program in the 1970s [5]. Additionally, optical absorption spectroscopy was demonstrated as a means to evaluate the redox condition of dissolved species in FLiBe [6]. Overall, the general framework for redox and impurity monitoring in the FHR primary coolant has been demonstrated. However, few of the engineering details such as the system durability or sensitivity have been determined.

3.6 Liquid Level

Several different liquid level measurement technologies are possible at FHRs. Radar level gauges, bubbler-type level gauges, and heated lance-type level measurements are all possible technologies. Radar level gauges have the advantage of not requiring contact with the primary coolant, but they have not been demonstrated for long-term use over liquid salts. Heated lance-type gauges provide only a limited precision of measurement but are robust and proven.

3.7 Pressure

Pressure measurements at FHRs are used primarily as a monitor of structure or component performance. For example, monitoring the primary coolant pump inlet and outlet pressure provides a measure of the pump performance. In addition, observing the change in the pressure drop across heat exchangers provides an indication of fouling progression and/or blockage development. Differential pressure measurement across a flow obstruction such as a Venturi orifice is also an aspect of a potential flowmeter. The most likely pressure measurement technique to be used at FHRs is classical diaphragm deflection-based pressure measurement. As with LWRs, the measurement electronics would need to be separated from the primary coolant environment by the use of impulse lines. Sodium-potassium eutectic-based impulse lines are currently commercially available and appear to be technically suitable for FHR implementation. A nickel diaphragm interface between the salt and NaK eutectic would be suitable to minimize corrosion vulnerability of the measurement.

Gas-filled, bubbler-type pressure gauges are also possible. In a bubbler pressure gauge, the gas pressure necessary to cause a small flow (bubbles) of gas into the primary coolant salt is monitored. As inert gases only have small solubility into the salt, the pressure at both ends of the gas line is approximately equal.

4 DEVELOPMENT ISSUES AND CHALLENGES

The details of the instrumentation implementation are deeply intertwined with the details of the plant's structures, systems, and components. Several anticipated instruments, such as those that would support the coolant cleanup system, cannot yet be specified, as the systems that they monitor remain largely undefined.

FHR instrumentation will rely extensively on the transparent nature of the coolant to enable optically based process instrumentation. Optically based instrumentation is not in common use in the nuclear industry. Consequently, more extensive unanticipated implementation hurdles may exist than with more conventional technologies. Instrumentation test and validation facilities remain to be developed. Molten salt test facilities will need to be built to support the overall reactor development effort. Instrumentation validation will be a significant element of the purpose for the test facilities.

Increased levels of automation are being implemented throughout the process control industries to lower staffing costs. FHRs will require more extensive instrumentation than has been common practice at existing plants to enable automated systems to perform functions with less operator oversight. Adequate planning needs to take place in early phase development to enable adequate amounts of measurement and communication to support the larger amounts of automation.

5 CONCLUSIONS

FHRs are high-temperature, thermal NPPs, and most of the measurements are closely related to those of previous generations of NPPs. The transparent nature of the coolant and the short-lived activation products of ^{19}F will enable many of the required process instruments to be made outside of the core and fluoride salt environment. No fundamental instrumentation hurdles have been identified that would prevent FHR operation. However, significant amounts of development remain for measurements systems that are already envisioned. As FHR plant designs become more detailed, additional measurement requirements will almost certainly arise. While most of the measurements are also likely to involve conventional process instrumentation, more complete plant designs are necessary to fully assess the required instrumentation suite.

6 ACKNOWLEDGMENTS

This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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