IMPACT OF PASSIVE SAFETY ON FHR INSTRUMENTATION SYSTEM DESIGN AND CLASSIFICATION

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ABSTRACT

Fluoride-salt-cooled high-temperature reactors (FHRs) will rely more extensively on passive safety than earlier reactor classes. 10CFR50 Appendix A, "General Design Criteria for Nuclear Power Plants," establishes minimum design requirements to provide reasonable assurance of adequate safety. 10CFR50.69, "Risk-Informed Categorization and Treatment of Structures, Systems and Components for Nuclear Power Reactors," provides guidance on how the safety significance of systems, structures, and components (SSCs) should be reflected in their regulatory treatment. The Nuclear Energy Institute (NEI) has provided "10 CFR 50.69 SSC Categorization Guideline" (NEI-00-04) that factors in probabilistic risk assessment (PRA) model insights, as well as deterministic insights, through an integrated decision-making panel. Employing the PRA to inform deterministic requirements enables an appropriately balanced, technically sound categorization to be established.

No FHR design concept currently has an adequate PRA or set of design basis accidents to enable establishing the safety classification of its SSCs. While all SSCs used to comply with the general design criteria (GDCs) will be safety related, the intent is to limit the instrumentation risk significance through effective design and reliance on inherent passive safety characteristics. For example, FHRs have no safety-significant temperature threshold phenomena, thus enabling the primary and reserve reactivity control systems required by GDC 26 to be passively, thermally triggered at temperatures well below those for which core or primary coolant boundary damage would occur. Moreover, the passive thermal triggering of the primary and reserve shutdown systems may relegate the control rod drive motors to the control system, substantially decreasing the amount of safety-significant wiring needed. Similarly, FHR decay heat removal systems are intended to be running continuously to minimize the amount of safety-significant instrumentation needed to initiate operation of systems and components important to safety as required in GDC 20. This paper provides an overview of the design process employed to develop a pre-conceptual FHR instrumentation architecture intended to lower plant capital and operational costs by minimizing reliance on expensive, safety-related, safety-significant instrumentation through the use of inherent passive features of FHRs.

Key Words: FHR, instrumentation, classification

1 BACKGROUND

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.

Nuclear reactors have three primary safety functions: 1) control the reactivity, 2) cool the fuel, and 3) prevent the release of radionuclides. The primary safety functions form the basis for a NPP's principal design criteria. The principal design criteria establish the necessary design, fabrication, construction, testing, and performance requirements for structures, systems, and components (SSCs) important to safety. 10CFR50 Appendix A, "General Design Criteria for Nuclear Power Plants," establishes the minimum requirements that must be met to obtain permission to operate an NPP in the United States. The differences between the requirements to perform safety functions at FHRs and light-water-cooled reactors (LWRs) provide the basis for the distinctive elements of FHR SSCs.

LWRs employ two measures to demonstrate achievement of the quantitative health objectives derived from the U.S. Nuclear Regulatory Commission's (NRC's) safety policy goals [1]. The first of these, the large release frequency (or large early release frequency), is directly applicable to FHRs. The second measure (core damage frequency) could be employed at FHRs, as fuel damage is required to release radionuclides (other than tritium) into the environment. Core damage provides an indication of increasing probability of releasing radionuclides into the environment. For LWRs the fuel cladding is the most vulnerable barrier in the series of barriers preventing radionuclide release. In contrast, FHR fuel is highly thermally robust, and FHRs lack threshold phenomena in their temperature or heat transfer that would lead to fuel damage. For FHRs the reactor vessel is the most vulnerable radionuclide containment layer. Employing reactor vessel failure frequency as the second measure to demonstrate achievement of the quantitative health objectives maintains alignment with the LWR regulatory approach. An FHR's guard vessel, employed to keep the fuel and decay heat removal heat exchangers covered with coolant salt even in the event of reactor vessel failure, provides defense-in-depth to ensure that the substitution is conservative.

FHRs have hundreds of degrees of margin to either fuel damage or coolant boiling. FHRs are low-pressure systems and consequently lack mechanisms to cause dispersion of radionuclides in the case of accidents that breach containment layers. Consequently, FHRs will have a thinner primary coolant boundary and containment walls. While the melting point of the primary containment alloy is hundreds of degrees above normal operating temperature, the combination of time, elevated temperature, and stress could result in unacceptable mechanical distortion (creep) when operated substantially beyond design conditions. It should be noted that mechanical distortion beyond that prevented by the guard vessel would be required to cause ductile failure (loss of radionuclide containment or uncovering decay heat removal heat exchangers) of the reactor vessel under hydrostatic load. FHRs have substantially lower power density than LWRs and a substantial thermal mass in the reactor vessel, resulting in much slower accident progression rates. Further, the radionuclide release source term for FHRs as a result of defective or damaged fuel is much lower than that of an LWR due to the strong radionuclide retention by the primary coolant.

The containment and vessel size cost dependence will be much less for FHRs than high-pressure systems. Consequently, FHRs will likely have larger containments and vessels than equivalent power LWRs. The additional space will enable simplified maintenance, decreased dose to the vessel, as well an increase in the amount of coolant above the core in-vessel. FHRs will require a separate external missile shield, as their low-pressure radionuclide containment layers will not withstand high external loads. Locating the reactor partially below grade will provide the majority of the impact shielding. However, to minimize excavation costs, FHRs will be partially above grade. The above-grade portion of the nuclear island will be covered with a soil berm to provide impact shielding.

The normal operations radiation environment within containment will be more severe in FHRs than in LWRs due to the larger amount of short half-life (< 30 seconds) activation products at FHRs. Fluorine-19 has significant neutron cross sections for radioactive capture, proton, and alpha emission, all of which result in energetic gamma rays. Moreover, the thinner primary coolant boundary walls will provide less gamma shielding. FHRs, thus, will need to include additional gamma-ray shielding between the primary coolant and sensitive electronics. Also, any near-containment environments intended for human occupancy during operation will require gamma shielding.

FHRs will generate substantially more tritium than LWRs due to neutron interactions in the primary coolant. At high temperatures, tritium rapidly permeates through structural alloys. Consequently, an FHR's containment gas cleanup system will need to include tritium trapping. Also, tritium stripping from the primary coolant as well as blocking from transport through the primary-to-intermediate heat exchanger will likely be required.

No FHR yet has a complete design. To the extent possible, the discussion presented in this paper is kept at a high level and would pertain to any FHR. The advanced high-temperature reactor (AHTR) is employed as an example when more specific information is required [2].

2 INTRODUCTION

As with any NPP, the overall function of an FHR's instrumentation system is to provide the information necessary to safely and effectively 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, accident progression monitoring, and post-accident condition monitoring.

While the primary safety requirements of all nuclear reactors are the same, the characteristics of FHRs are different from LWRs. Consequently, the requirements for particular SSCs and their safety significance will be markedly different between the reactor classes. FHRs lack the threshold events corresponding to reactor power and/or heat transfer (e.g., departure from nucleate boiling, pellet-clad interaction, boiling stability, etc.) that are characteristic of large LWRs. On the other hand, the decay heat removal systems for FHRs are much more vulnerable to loss of functionality by freezing than those of LWRs.

This paper focuses on the impact of FHR characteristics on its instrumentation system design and classification. Specific FHR instrumentation technology requirements derive from their performance requirements. For example, the required accuracy and response time of the primary loop temperature and mass flow measurement arise from the necessity of knowing the thermal power generation rate to facilitate efficient power cycle operation, provide assurance of core cooling, and enable calibration of the neutron-based power measurements. The United States has a compliance-based, deterministic nuclear power regulatory system. The regulations provide the acceptance criteria for the plant design. Experience with LWRs provides guidance on the aspects of nuclear power instrumentation that have proven to be expensive and/or burdensome.

FHRs feature full passive safety and, thus, do not require active response over any time period for even beyond-design-basis events with nontrivial probabilities (e.g., apart from meteorite strikes, acts of war, etc.) to prevent reactor vessel failure or large radionuclide release. However, ensuring that safety-related SSCs remain capable of performing their functions is a safety-related activity performed by the instrumentation. Also, an FHR's instrumentation may provide information necessary to prevent fuel damage during non-power activities (e.g., to prevent fuel-handling machines from mechanically damaging fuel assemblies). A key distinction arising directly from the lack of required active response is that the instrumentation does not provide information necessary to perform actions necessary to comply with the general design criteria (GDCs). Specifically, instrumentation is not required to directly support protection functions.

FHRs will seek to employ their passive safety features to comply with safety regulations in the most transparent, cost-effective manner possible. A key element to the FHR strategy to decrease the cost of compliance is to use the existing NRC licensing framework and not to depend upon making conceptual changes to the safety arguments that would require deviations from established precedent, thereby minimizing licensing risk. The combination of the inherent FHR safety characteristics along with the conceptual underpinnings of existing licensing requirements on fundamental safety concepts enables FHRs to avoid requiring exceptions to established regulatory principles. Nevertheless, the specific wordings of NRC's regulations are based upon ensuring the safety of large LWRs. Consequently, the licensing of FHRs will be facilitated by NRC's ongoing process to develop technology-neutral GDCs and eventually FHR-specific design review guidance.

FHR anticipated operational occurrences (AOOs), design basis accidents (DBAs), and beyond design basis accidents have not yet been established, nor has a design specific probabilistic risk assessment (PRA) been developed. Consequently, specific instrumentation performance and environmental tolerance requirements are not yet possible. However, the general plant layout and basic mechanical configuration of the AHTR have been developed. An early phase FHR instrumentation system description is, thus, now possible, although it will require updating as the reactor concept matures and the accident performance requirements are analyzed.

Qualification of instrumentation for application in a nuclear safety system is both expensive and time-consuming. Minimizing the amount of specialized, safety-significant instrumentation in first-of-a-kind power plants is also important due to the lack of a preexisting supplier base. Lacking an existing market, commercial instrumentation suppliers typically cannot justify the expense of developing and maintaining qualified, specialized instrumentation products. Digital instrumentation with its characteristic internal complexity has proven challenging to introduce into LWR safety systems largely due to the necessity of providing high assurance of its correct operation. The self-diagnostics and on-line monitoring provided by high-quality, industrial-grade digital instrumentation enable it to be both more reliable (albeit less provably so) and substantially less expensive than dedicated nuclear-safety-grade instrumentation. The complexity challenge of digital instrumentation and control (I&C) continues to be a significant issue at NPPs. The application of high-quality digital systems (that lack complete proof of correctness) in all other safety-significant industries has resulted in substantially improved safety performance. Consequently, FHRs will seek to employ high-quality industrial instrumentation where their passive safety enables decreasing the required level-of-proof of correct operation.

Installing, and eventually replacing, control cables at NPPs is expensive. Cables cross construction module boundaries and, thus, have to be installed in situ. Moreover, cables are buried within fire protection materials, preventing easy access. Consequently, a strong economic incentive exists to minimize the amount of control cable. LWRs traditionally have employed point-to-point wiring between safety-related instruments and instrument racks located outside of containment. Modern LWR designs have largely transitioned to safety-grade digital networks to minimize the amount of safety-grade wiring. FHRs will continue the wiring reduction trend and will introduce additional communication techniques and technologies to further reduce costs. Technologies such as all ceramic and metal optical fibers to avoid the long-term aging of organic insulators, wireless, and communications over power leads are anticipated to be more broadly deployed at FHRs both due to general technology advancement and the relaxed requirements enabled through passive safety and slowly progressing accidents.

This paper is organized to first describe the risk-informed instrumentation aspects of the SSC categorization process and then the instrumentation required to comply with specific GDCs. Next, the instrumentation's role in accommodating AOOs and DBAs (NUREG-0800 Chapter 15) and in responding to severe accidents (NUREG-0800 Chapter 19) is then described. The paper concludes with an overview of the major development issues that need to be resolved to create a licensable instrumentation architecture for FHRs.

3 EVALUATION

3.1 Categorization

An FHR's reactivity control systems, decay heat removal systems, and radionuclide containment boundaries will be composed of safety-related SSCs that perform safety-significant functions. At FHRs all of these primary safety functions are intended to be performed passively, without requiring operator or active system intervention at any time. The principal safety-related function of FHR instrumentation is to monitor the condition of the SSCs that perform safety functions. For example, the reserve negative reactivity insertion system in the AHTR design employs inert gas accumulators to drive poison salt into the reactor inlet plenum in the event of a large over-temperature accident. Instrumentation will be employed to monitor the accumulator pressure, as the system will not function properly without adequate driving pressure. The pressure monitoring instrumentation classification, thus, hinges on the safety significance of the pressure monitoring function.

10CFR50.69, "Risk-Informed Categorization and Treatment of Structures, Systems and Components for Nuclear Power Reactors," subdivides SSCs into four categories.

- RISC-1—SSCs that are safety related and perform safety-significant functions.
- RISC-2—SSCs that are non-safety related and perform safety-significant functions.
- RISC-3—SSCs that are safety related and perform low safety-significant functions.
- RISC-4—SSCs that are non-safety related and perform low safety-significant functions.

10CFR50.69 defines a safety significant function as one whose degradation or loss could result in a significant adverse effect on defense-in-depth, safety margin, or risk. A key FHR design objective is to avoid requiring the instrumentation to provide information necessary to perform safety-significant functions as all FHR safety-significant functions are to be performed passively.

Applying 10CFR50.69 begins with developing a plant-specific PRA. As even a high-level PRA is not yet available for the FHRs, no definitive SSC classification can yet be made. All of the instrumentation classification discussed in this paper remains at an engineering estimate level of maturity and is intended to assist in the design development process rather than to support any licensing action.

The functional importance of SSCs is determined by evaluating the plant responses to initiating events (internal and external). A comprehensive set of initiating events for FHRs is not yet available, nor is a plant master logic diagram. However, a preconceptual plant layout for the AHTR has been developed, and the general plant response to postulated initiating events has been preliminarily assessed.

3.2 GDC Compliance

The introduction of 10CFR50 Appendix A indicates that the GDCs are intended to be generally applicable to different types of NPPs to provide guidance in establishing the principal design criteria for other reactor classes. Several of the LWR GDCs include instrumentation and/or measurements. The text of GDCs that call for measurements is provided next along with the anticipated FHR approach to compliance.

Criterion 13—Instrumentation and Control.

Instrumentation shall be provided to monitor variables and systems over their anticipated ranges for normal operation, for anticipated operational occurrences, and for accident conditions as appropriate to assure adequate safety, including those variables and systems that can affect the fission process, the integrity of the reactor core, the reactor coolant pressure boundary, and the containment and its associated systems. Appropriate controls shall be provided to maintain these variables and systems within prescribed operating ranges.

FHRs will include instrumentation to measure the plant processes and systems. However, FHRs will monitor different variables from LWRs to ensure adequate safety due to the different reactor properties. FHRs are not significantly vulnerable to fuel temperatures or power distributions, and an increase in primary coolant temperature is only significant to the extent it results in accelerated vessel creep. Thus, upon initial consideration, few, if any, of the normally monitored LWR variables appear to be safety significant. On the other hand, an FHR's passive safety is dependent on the functionality of its passive decay heat removal loops in the event that its non-safety-related active primary and maintenance cooling systems fail. Moreover, decay heat removal loops have a number of potential failure modes ranging from stalling out the flow by inadvertently leaving the trace heating running on the loop cold leg to causing loop vulnerability to hydraulic shock by allowing a frozen plug to form in the surge tank. Consequently, instrumentation will be employed to monitor the functionality of the decay heat removal loops. Development of an FHR PRA with sufficient depth to include the different failure modes of the plant safety features thus remains a significant development task.

Criterion 20—Protection system functions.

The protection system shall be designed (1) to initiate automatically the operation of appropriate systems including the reactivity control systems, to assure that specified acceptable fuel design limits are not exceeded as a result of anticipated operational occurrences and (2) to sense accident conditions and to initiate the operation of systems and components important to safety.

An FHR's protection system will be both safety related and safety significant. However, an FHR's means to sense accident conditions and initiate the operation of systems and components important to safety are passive. The melt point triggers in an FHR's negative reactivity insertion systems both sense accident conditions and initiate system operation. Thus, while the melt point triggers will sense the accident conditions, they may not be considered part of the instrumentation system.

Criterion 24—Separation of protection and control systems.

The protection system shall be separated from control systems to the extent that failure of any single control system component or channel, or failure or removal from service of any single protection system component or channel which is common to the control and protection systems leaves intact a system satisfying all reliability, redundancy, and independence requirements of the protection system. Interconnection of the protection and control systems shall be limited so as to assure that safety is not significantly impaired.

Operation of an FHR's protection system does not involve instrumentation channels, as both its sensing and actuation are passive. Monitoring the accumulator gas pressure in the reserve shutdown system enables monitoring the operability of a key aspect of the protection system. The accumulator pressure will be provided by gas bottles, to avoid dependence on an active system while in operation. While the plant operators can rapidly insert large amounts of negative reactivity into the core separately from the passive protection systems, no operator actions are credited to achieve or maintain a safe shutdown condition as no instrumentation is credited to provide them with information necessary to determine when to scram the plant. The passive protection system also needs to maintain passive safety when subjected to incorrect operator or control system actions such as withdrawing control elements at the maximum possible rate. Thus, FHRs achieve compliance with GDC 24 largely by avoiding instrumentation in the protection system.

3.3 AOOs and Postulated Accidents

An FHR's instrumentation system informs the plant operators and control system that an adverse condition exists or is developing, thereby enabling active response. The primary purpose for most of an FHR's instrumentation is to support effective reactor operation. However, the NRC's "Policy Statement on the Regulation of Advanced Reactors" [3] includes an objective of having "sufficient instrumentation to allow for more diagnosis and management before reaching safety systems challenge and/or exposure of vital equipment to adverse conditions." FHRs will, thus, tend to feature more extensive monitoring than LWRs. These measurements, while not specifically required to comply with the GDCs, support increased situational awareness.

A primary function of the instrumentation system is to enable the plant's operators to maintain situational awareness. Understanding the current plant conditions enables the operators and plant active systems to take mitigating actions to reduce the impact of accidents and transients. For example, the plant staff or control system can bring the maintenance cooling system on-line (including starting the local diesel generators) in the event of loss of offsite power to avoid challenging the safety-grade decay heat removal systems. Maintaining situational awareness also enables the plant staff or active systems to minimize the impact of control system or operator errors. Adequate plant instrumentation is key to enabling observing changes in plant state in response to control actions. While accident progression is slow at FHRs, sensing accident conditions early enables more effective response that minimizes the stress on the plant SSCs.

A key element in FHR instrumentation system design is developing a sufficient set of instruments to enable effectively diagnosing the full set of AOOs and DBAs. Recognizing that an AOO has occurred, enabling the plant operators to prevent further degradation towards a DBA, is a safety-related action. However, such accident mitigation would only be safety significant if failure to perform the mitigation function has a significant adverse impact on defense-in-depth, safety margin, or risk. A plant-specific PRA will be required to establish whether the mitigating actions are safety significant. However, a central design tenant of FHRs is that the primary safety functions are all to be performed passively. Thus, AOO response would be performed with safety-related non-safety-significant instrumentation.

While both LWRs and FHRs are thermal power plants and, consequently, will have conceptually similar process measurement requirements, the configuration of an FHR's instrumentation architecture will more closely resemble that of the safety-significant, high-value, non-nuclear process control industry. FHRs have adequate, fully passive negative reactivity insertion and decay heat removal responses that cannot be disabled by operator or active system actions. Thus, most of an FHR's instrumentation is not required to comply with safety requirements but instead primarily serves to support effective reactor operation. The design intent is that FHR operator actions may be safety related but will not be safety significant. The lower safety significance of most FHR instruments may allow FHRs to employ nontraditional network technologies and architectures. For example, wireless and communication over power lines may have larger roles at FHRs due to the decreased requirements for provability of correctness for lower safety-significance systems.

A significant portion of the FHR instrumentation design effort is to develop instruments capable of monitoring accident and/or transient conditions. The distinctive aspects of an FHR enable different measurement techniques. The low-pressure, transparent coolant enables measurements to be made optically from above the coolant pool. For example, a single control rod drop would only cause a small change in reactor power but may be observable visually through optical elements located in the upper plenum. Additionally, the more plentiful gamma rays emitted as a result of ^{19}F neutron interactions facilitate standoff measurements of physical processes such as reactor power or primary coolant flow. Other AOOs such as small heat exchanger tube leaks (which would be inward) could be observed through monitoring activation products in the primary coolant or change in coolant inventory. The plant control system would be relied upon to shut down the plant if significant leaks were to occur. The plant I&C system would, thus, be relied upon to perform a safety-related activity. Deterministic accident progression evaluation as well as a plant-specific PRA would be required to assess the safety-significance of the control system actions.

FHRs will also include instruments to accommodate plant aspects that do not have a direct correspondence at LWRs. For example, FHRs (unlike LWRs) operate in the structural alloy creep temperature regime. Monitoring (or periodically assessing) the reactor vessel creep provides direct evidence that the vessel is not approaching failure.

Anticipated transient without scram will not be an especially challenging transient for FHRs as the large upper plenum provides ample gas volume to avoid the potential to pressurize the system and a large thermal excursion would inherently scram the reactor. A single thermal transient would result in a minor (likely undetectable) increase in the vessel creep. Similarly, the pressure spike that would result from an intermediate-to-power-cycle heat exchanger tube rupture accident would be mitigated by rupture disks along the intermediate loop.

3.4 Severe Accidents

The principal role for an FHR's instrumentation system in the prevention or mitigation of severe accidents is to monitor the status of the SSCs responsible for the principal reactor safety functions as well as those providing an alternate means to perform safety functions. The instrumentation system is responsible to provide the plant staff information on the core reactivity, the decay heat removal status, and the integrity of the radionuclide barriers. The instrumentation system also provides the information necessary to engage active alternate means to cool the core. For example, the instrumentation system monitors the condition of both the primary and maintenance cooling systems to assist the plant staff to either start the non-safety cooling systems or to make repairs. In a post-severe accident environment, the instrumentation system is also responsible to track the location of radionuclides that have escaped from the core as well as the core thermal and structural status.

Much of the instrumentation challenge in a LWR post-severe accident environment results from the consequences of severe core melt (e.g., steam, hydrogen explosion potential, pressure-driven radionuclide release from the primary coolant boundary). As a low-pressure system with highly thermally robust fuel, FHRs lack equivalent accident phenomena. FHRs, consequently, will not be able to draw extensively from the existing experience with severe accidents at LWRs. FHRs do not yet have a consensus set of severe accidents. However, early stage evaluation of accident progression and post-accident environment conditions can be performed by postulating non-causal failures of safety-significant SSCs. For example, substantial fuel damage (from a bad fuel batch) would release radionuclides into the fuel structure. Much of the fission gases released in a fuel damage accident would emerge into the upper plenum. If the primary coolant boundary were also to fail, the next layer of containment would become contaminated. Similarly, if the thin-walled reactor vessel were to rupture, the primary coolant level would lower to fill the space between the reactor vessel and the guard vessel. Also, a large civilian plane impact could substantially damage a single (due to the wide spacing between the mechanically robust chimneys) decay heat removal system.

A key element of the severe accident instrumentation requirements is component survival in the post-accident environment. However, the post-severe accident environment at an FHR will be less severe than at an LWR. An FHR's low-pressure primary coolant means that FHRs lack an equivalent environmental tolerance requirement of the hot steam exposure of LWRs following a coolant line rupture. Also, the post-severe accident radiation environment within containment may be lower than the normal operation environment, as the short-lived ^{19}F activation products will have died away within a few minutes after the reactor becomes subcritical. Only escaping fission gasses would significantly increase the in-containment dose away from the primary coolant boundary in the event of fuel damage accompanied by primary coolant boundary failure. The normal instrumentation shielding would continue to shield against gamma rays from radionuclides within the primary coolant boundary. FHRs also employ a thermally insulated primary coolant boundary minimizing containment heat-up and the consequent thermal challenge to instrumentation. The ability of FHRs to employ diverse communication pathways (wireless and communication over the power lines) due to the lower safety classification of the communications increases the probability of maintaining situational awareness in a post-severe accident environment when any particular communications pathway may become degraded.

4 DEVELOPMENT NEEDS

FHR instrumentation system design and classification has three primary development needs: (1) system evaluation tools, (2) licensing framework, and (3) sensors for the salt environment. Developing and validating system evaluation tools are key to enabling FHRs to develop defensible system performance requirements. FHRs require development of accident initiators and a master logic diagram to enable modeling of accident sequences and assessing component performance requirements. Also, an FHR class-specific (and eventually a plant-specific) PRA is necessary to enable applying risk-based insights into the design and evaluation process. Developing a more complete AHTR plant model that includes a full set of the specialized components and systems is the leading task in developing the PRA.

Instrumentation system design for FHRs would benefit substantially from the development of a technology neutral licensing framework for advanced reactors with substantial passive safety features. The function of FHR instrumentation necessary to comply with the GDCs is substantially different from LWR practice. Obtaining the NRC's guidance on acceptable means to comply with the safety principles underlying the existing LWR-focused GDCs through the use of passive safety features would reduce the uncertainty surrounding licensing in the United States. An FHR-specific license application review plan would also be a substantial aid to FHR development as the review plan would enable plant designers to minimize the uncertainty about the acceptability of specific plant design features.

An FHR's passive safety generally decreases the performance requirements of its instrumentation system. FHRs will have an extensive set of safety-related, non-safety-significant instrumentation. Understanding the current plant conditions enables the operators and plant active systems to take actions to prevent accidents from challenging the safety systems. The status of the safety-related, safety-significant SSCs can largely be determined using established measurement technologies. However, development and validation of FHR-specific sensors would be useful to validate that control and safety actions have occurred as intended. For example, the ability to optically access the upper plenum environment and thereby directly observe the core, vessel internals, and interior surface of the reactor vessel enables direct observation of the core coolability and the core criticality (Cerenkov glow). Significant aspects of the technology necessary to provide the optical access remain unproven.

5 CONCLUSIONS

FHRs have strong inherent safety characteristics that enable FHR designs to be developed that passively perform their principal safety functions over any time frame. However, substantial development remains in all aspects of the FHR design. FHRs currently lack the PRA necessary to apply risk-informed insights to instrumentation classification. Also, FHRs do not have validated system performance evaluation tools that would enable confidently evaluating accident progression.

FHRs, like LWRs, are thermal power plants and will, consequently, measure the same process variables to operate the plants. The instrumentation performance requirements for FHRs, however, will be substantially different from LWRs due to the different characteristics of the plants. FHRs do not have any safety-significant threshold phenomena in their heat transfer or temperature characteristics. An FHR's reactivity control systems, decay heat removal systems, and radionuclide containment boundaries will be composed of safety-related SSCs that perform safety-significant functions. FHRs will also have a significant set of safety-related, non-safety-significant instrumentation to effectively operate the plant. However, all of an FHR's primary safety functions are intended to be performed passively, without requiring operator or active system intervention at any time. The full passive safety shifts the primary function of the instrumentation from providing the information necessary to take safety actions to monitoring the status of passive safety systems and the function of the process monitoring from ensuring adequate safety (GDC compliance) to providing sufficient information to take mitigating actions prior to challenging safety systems (achieving advanced reactor safety goals).

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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