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Incorporating Equipment Condition Assessment in Risk Monitors for Advanced Small Modular Reactors

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Advanced small modular reactors (AdvSMRs) can complement the current fleet of large light-water reactors in the USA for baseload and peak demand power production and process heat applications (e.g., water desalination, shale oil extraction, hydrogen production). The day-to-day costs of AdvSMRs are expected to be dominated by operations and maintenance (O&M); however, the effect of diverse operating missions and unit modularity on O&M is not fully understood. These costs could potentially be reduced by optimized scheduling, with risk-informed scheduling of maintenance, repair, and replacement of equipment. Currently, most nuclear power plants (NPPs) have a “living” probabilistic risk assessment (PRA), which reflects the as-operated, as-modified plant and combine event probabilities with population-based probability of failure (POF) for key components. “Risk monitors” extend the PRA by incorporating the actual and dynamic plant configuration (equipment availability, operating regime, environmental conditions, etc.) into risk assessment. In fact, PRAs are more integrated into plant management in today’s NPPs than at any other time in the history of nuclear power. However, population-based POF curves are still used to populate fault trees; this approach neglects the time-varying condition of equipment that is relied on during standard and non-standard configurations. Equipment condition monitoring techniques can be used to estimate the component POF. Incorporating this unit-specific estimate of POF in the risk monitor can provide a more accurate estimate of risk in different operating and maintenance configurations. This enhanced risk assessment will be especially important for AdvSMRs that have advanced component designs, which do not have an available operating history to draw from, and often use passive design features, which present challenges to PRA. This paper presents the requirements and technical gaps for developing a framework to integrate unit-specific estimates of POF into risk monitors, resulting in enhanced risk monitors that support optimized operation and maintenance of AdvSMRs.

1. Introduction

Advanced small modular reactors (AdvSMRs) can contribute to safe, sustainable, and carbon-neutral energy production. However, the economics of AdvSMRs suffer from the loss of economy-of-scale for both construction and operation. This is, in part, alleviated by the economy-of-replication that is gained by building many identical units with components that can be constructed in factories and transported to the plant site. However, operations and maintenance (O&M) costs may drive the economics of AdvSMR deployment; these costs could potentially be reduced through optimized scheduling of both module and plant-wide O&M activities. Integrated health monitoring of key active systems, structures, and components (SSCs) will be necessary to support enhanced O&M scheduling.

The characteristics of proposed AdvSMR designs present many challenges to evaluating the health of significant plant components. Harsh operating conditions, including high temperatures, corrosive coolant materials, and a fast neutron flux for certain designs, will be a characteristic of all AdvSMR concepts. Further, many designs will allow fewer opportunities to perform inspection and maintenance activities due to longer periods of operation between refueling outages. In addition, AdvSMRs may be sited in remote locations with minimal staffing availability. AdvSMRs will also deviate from conventional light-water reactors (LWRs) due to the potential for diverse missions (such as desalination of water, production of process or district heat, and hydrogen production, in addition to the production of electricity), potential for

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load following applications, and greater reliance on passive safety systems. The economics of AdvSMRs will rely, in part, on maintaining high plant availability. This need emphasizes the importance of optimized maintenance scheduling to minimize unplanned outages and outage duration, increase plant availability, and ensure the affordability of AdvSMR operation. Risk-based approaches to inspection optimization have shown significant cost savings over traditional, time-based inspection (Medina et al., 2011). The ability to perform accurate assessment of the condition of key active components and to assess the real-time risk of operating with degraded components will support optimized O&M planning.

Risk monitors are designed to provide a point-in-time estimate of the system risk given the current plant configuration (equipment availability, operational regime, environmental conditions, etc.). However, current risk monitors are limited in that they do not take into account unit-specific normal, abnormal, and deteriorating states of plant equipment. Current risk monitors are built on probabilistic risk assessment (PRA). PRA systematically combines the event probability and probability of failure (POF) for key components to determine the hazard probability for subsystems and the overall system (Wu and Apostolakis, 1992). Standard NPP PRA uses a static estimate of event probability and failure probability. A more accurate and realistic risk assessment can be made by using estimates of the actual component POF based on equipment condition assessment. These enhanced risk monitors (ERMs) have the potential to enable real-time decisions about stress relief for susceptible equipment while supporting effective operations, outage, and maintenance planning.

This paper describes the initial work in identifying the technical barriers to developing and deploying enhanced risk monitors. Section 2 introduces advanced small modular reactors and highlights some key features that motivate the use of enhanced risk monitors for operation and maintenance planning. Section 3 summarizes probabilistic risk assessment and its derivative, risk monitors. Equipment condition assessment, which will be integrated with risk monitors to provide enhanced risk monitors, is described in Section 4. The envisioned enhanced risk monitor and gaps in the technical basis are outlined in Section 5. Section 6 summarizes the discussion and outlines future work to fully develop enhanced risk monitors.

2. Advanced Small Modular Reactors

AdvSMR designs are distinguished from other nuclear plant designs by non-light–water coolants, deliberately small size, and potential modular operation. Leading AdvSMR designs are based on advanced reactor concepts, which have been prioritized by the Generation IV International Forum (GIF) (Abram and Ion, 2008). An outcome of GIF was the identification of six advanced reactor concepts to focus future R&D efforts. The six concepts include Liquid Sodium Fast Reactors (SFRs), Molten Salt Reactors (MSRs), Lead- (or Lead-Bismuth-) Cooled Fast Reactors (LFRs), Gas-Cooled Reactors (GCRs), Very High Temperature Gas Reactors (VHTRs), and Super Critical Water Reactors (SCWRs). With the exception of SFRs and VHTRs, limited experience has been accumulated with respect to operation of advanced reactors (VHTRs receive credit for experience gained from operation of high-temperature gas reactors [HTGRs]). The available operating experience has been reviewed to identify common issues in active component degradation for advanced reactors. For instance, intrusion of oil, water, and other contaminants into the coolant system has been a problem at HTGR plants. The use of water-lubricated bearings in helium circulators at Fort St. Vrain led to moisture intrusion, which contributed to corrosion in an otherwise non-corrosive environment. Oil leakage through the compressor at Peach Bottom 1 resulted in approximately 100 kg of oil in the reactor (Beck et al., 2010). Additionally, both mechanical and electromagnetic sodium pumps have experienced problems in SFRs (Guidez et al., 2008). Some of these issues will be resolved in AdvSMR designs (e.g., moisture intrusion through water-lubricated bearings may be avoided by using magnetic bearings); however, some issues may be common. Many AdvSMR designs employ control rods similar to those seen in existing LWRs [e.g., PRISM (Triplett et al., 2012), SMFR (Chang et al., 2007), SC-MHR (Shenoy et al., 2012)]. Advanced reactors have encountered problems related to control rods, particularly mechanical jamming of the rods that precluded both gravity and forced insertion (Beck et al., 2010). These known issues are likely to drive monitoring and maintenance requirements in AdvSMRs, at least initially.

Small modular reactors (SMRs) generally include reactors with electric output of ~350 MWe or less (this cutoff varies somewhat but is substantially less than full-size plant output of 700 MWe or more) (Ingersoll, 2009). These reactors are designed to incorporate multiple modules (which may or may not have shared components and structures) at a single location, comprising a full "plant." SMR operation differs fundamentally from large plants because the output of individual modules may be varied for load-following or peak demand power generation or to compensate for reduced output at other modules. Additionally, SMRs are being considered for dual-use, where process heat would be used for both electricity generation and another purpose such as hydrogen production or water desalination.

Taken together, the particular eccentricities of advanced reactors and small modular reactors provide unique challenges and needs for control and O&M planning for AdvSMRs. Several features of AdvSMR designs increase the need for accurate characterization of the real-time risk during operation and maintenance activities. AdvSMR design features that motivate the use of enhanced risk monitors include:

- Reduced accessibility, possibly due to pool-type designs with submersed components, sealed systems to improve proliferation resistance, or remote siting;
- Reduced redundancy of active components and systems, possibly due to greater reliance on passive systems;
- Potential multi-modular operation, which may introduce interconnections or dependencies between SSCs in reactor modules and generation blocks (multiple reactor modules connected to common balance-of-plant (BOP) systems, such as the power blocks proposed for the PRISM reactor);
- New operating regimes, including potential load-following and peak-demand power generation;
- Potential use for applications beyond electricity production (e.g., water desalination, hydrogen production, process heat applications); and
- Longer periods between inspection opportunities due to longer operating cycles and reduced O&M staff.

The lifecycle economics of AdvSMRs are expected to be dominated by O&M costs; these costs could potentially be reduced by risk-informed scheduling of maintenance, repair, and replacement of equipment. Probabilistic risk assessment and risk monitors have been employed in nuclear plants to monitor and manage the risk associated with different plant configurations.

3. Probabilistic Risk Assessment and Risk Monitors

Probabilistic risk assessment (PRA) (also called probabilistic safety assessment – PSA) gained favor in the nuclear power industry following the Reactor Safety Study commissioned by the U.S. Nuclear Regulatory Commission (NRC) and the accident at Three Mile Island. PRA has several uses in NPPs; main applications include (1) evaluating the adequacy of design and procedures, (2) optimizing operational activities, and (3) supporting regulations (Lederman et a., 1996). In the past decades, PRA has become an important part of nuclear plant management and the defense-in-depth regulatory framework. PRA analyses use static estimates of event and failure probabilities (Martorell et al., 2010); these estimates are typically based on historic failure rates across the nuclear fleet, plant-specific failure rates, and engineering judgment. More recently, time-based POF values have been incorporated in so-called living PRAs (Arjas and Holmberg, 1995). These time-based POF values are derived from operating experience and traditional reliability analysis; they are not specific to the operating component.

Traditionally, three levels of PRA, designated by the type of risk being assessed, have been considered for NPPs (NRC, 2012). Level I PRA evaluates the frequency of accidents that lead to core damage; Level II PRA, the frequency of radioactive release from the NPP; and Level III, the consequences to the public and environment outside the NPP due to radioactive releases. In the context of AdvSMRs, new measures of risk may be needed to accurately quantify the risks to a reactor module, the plant as a whole, and the public. To support the economic goals of AdvSMRs and optimized O&M planning, the plant (or module) unavailability may be an appropriate risk measure. An accurate view of the potential effects of different plant/module configurations on the ability to meet production needs will support longer operating cycles between outages and improve the ability to meet production demands across the entire plant.

AdvSMR designs feature advanced component designs (e.g., magnetic pumps and bearings) in order to increase safety, enhance the ability to withstand harsh environments, and improve plant availability and generation. Operating experience and well-developed models of component performance may not be available for these new designs, especially for the estimation of failure probabilities in the potentially harsh environment of an AdvSMR. This makes equipment condition assessment and integration with risk monitors even more important to provide an accurate, online assessment of risk associated with normal O&M activities.

4. Equipment Condition Assessment

Equipment condition assessment (ECA) has been an active area of research for several decades. Several reviews of ECA research and developments are available [e.g., (Schwabacher, 2005; Schwabacher and Goebel, 2007; Hines et al., 2008)]. Kothamasu et al. (2006) reviews approaches to system health monitoring and prognostics, including specific applications to vibration monitoring of rotating equipment, gearboxes, and bearings. EPRI extended their existing Preventative Maintenance Basis Database (PMBD) to include an assessment of the applicability of prognostics to various systems and components in power generating systems (EPRI, 2009); this assessment includes a list of potential measurements for assessing component and system degradation. A recent review by Coble et al. (2012) summarizes the state of the art in equipment monitoring, fault detection, diagnostics, and prognostics for conventional NPP components and systems. While AdvSMRs will likely employ some advanced component designs (e.g., magnetic pumps and bearings), work on conventional component designs forms a basis for developing similar monitoring capabilities for these new designs. ECA systems—also referred to as predictive maintenance, prognostics and health management, health monitoring, etc.—typically detect and diagnose faults and estimate the remaining useful life of a system or component, but this approach can be modified and extended to instead provide the instantaneous POF distribution or the POF over some specified time window.

Active components in NPPs include those components whose parts must move in order to fulfill their operational goals; these components typically include pumps, motors, generators, sensors, control rod drive, etc. For these components, prognostic and health management (PHM) systems can capitalize on the information already collected by the plant I&C system: temperature, flow, pressure, etc. Pump health may be estimated using discharge pressure and flow; valve operation could be monitored through the changes in flow as the valve position setpoint is changed; and sensor calibration can be monitored and diagnosed by using the data those sensors are collecting. Additional measurements may be useful or necessary to develop more robust and accurate prognostic models for some active components. Pumps and motors can be monitored through vibration measurements; in fact, reactor coolant pumps and casing are commonly monitored through the reactor coolant pump vibration monitoring system (RCPVMS) (Koo and Kim, 2000). However, these systems do not currently support automated, online analysis of the vibration data to detect and diagnose abnormal conditions. Motors, such as those used for motor-operated valves, can be monitored through multiple features, such as input current and voltage, active power, motor position measures, and applied forces. Many of these additional measurements, such as vibration, motor position, or electrical signatures, may largely be obtained autonomously, online, and unobtrusively.

Advanced SMRs will likely rely on passive mechanisms to achieve safety and security goals. This may include reliance on thermal convection or gravity for coolant circulation and/or decay heat removal through natural processes. However, a number of active components (e.g., coolant pumps, compressors in circulators, etc.) are needed for reliable operation. AdvSMR designs are expected to feature advanced component designs in order to increase safety, enhance the ability to withstand harsh environments, and improve plant availability and generation. Operating experience and well-developed models of component performance may not be available for these new designs, especially for the estimation of failure probabilities in the potentially harsh environment of an AdvSMR.

Equipment condition assessment can compensate for the relative lack of historic failure rates for components in AdvSMRs. Incorporating this information into risk monitors, resulting in enhanced risk monitors, will provide a stronger basis for risk-informed control and O&M planning. The following section briefly describes the proposed enhanced risk monitor and identifies the technical gaps in the current risk monitor approach.

5. Enhanced Risk Monitors

Risk monitors are designed to provide a point-in-time estimate of the system risk given the current plant configuration (equipment availability, operational regime, environmental conditions, etc.). However, current risk monitors are limited in that they do not take into account plant-specific normal, abnormal, and deteriorating states of active components and systems. The ability to incorporate unit-specific estimates of the probability of failure, by utilizing real-time or near-real-time condition knowledge of the equipment into operational risk monitors, has the potential to enable real-time decisions about stress relief for susceptible equipment while supporting effective maintenance planning.

Enhanced risk monitors that incorporate real-time estimates of the condition of active SSCs are expected to improve the safety, economics, and availability of AdvSMRs. Enhanced risk monitors will support the economic goals of AdvSMRs by providing a tool for optimizing operations and maintenance activities.

5.1 Technical Gaps

Risk monitors and equipment condition assessment have both been widely studied, both for the nuclear industry and in other areas. However, these two fields have not yet been combined to provide an online, real-time assessment of risk. Several gaps exist between the current PRA and risk monitor framework and the proposed enhanced risk monitor, including:

- *Evaluation and development of equipment condition assessment for key AdvSMR components* – Equipment condition assessment can compensate for the lack of reliability data for AdvSMR systems and components. Significant work has been done in development of equipment condition assessment and prognostics for conventional SSCs, in both nuclear and non-nuclear applications. The developed condition indicators and models need to be evaluated for application to AdvSMR components and environments to assess their efficacy. If the existing models are not sufficient, new approaches to equipment condition assessment may be needed (e.g., for advanced component designs or convention components operating in new regimes).

- *Integration of online equipment condition assessment* – No risk monitor or PRA framework was found that incorporates or proposes to incorporate an estimate of the probability of failure of specific active SSCs in a specific plant or module.
- *Application to multiple, interdependent modules* – Existing dynamic and living PRA frameworks focus on conventional single-module reactors. The implications of including multiple modules in a single plant, including potential system dependencies and the effect of physical proximity during external events such as earthquakes, fire, or flooding, will need to be investigated.
- *Consideration of common mode failures* – Common cause failure is addressed by traditional PRA for similar components or systems in a single reactor unit. However, multi-modular AdvSMRs will also need to account for the possibility of common cause failures for components across modules.
- *Development of accident scenarios* – Severe accident scenarios and the associated event and fault trees are well developed for LWRs, but scenarios in AdvSMRs may include a fundamentally different set of initiating events due to the differences in design and operation. Even for common initiating events, the sequence of events leading to undesired consequences may differ significantly for AdvSMRs.
- *Integration of variable plant loads* – Accident sequences and/or success criteria may change as the operating load rises and falls. AdvSMR modules are expected to exhibit dynamic loads as a result of load-following, balancing output across modules, and balancing power production with other missions. The possible effects of varying loads on the risk assessment need to be better understood and quantified.
- *Definition of risk measures for AdvSMRS* – New measures of risk may be needed to accurately quantify the risks for AdvSMRs, including for a reactor module, the plant as a whole, and to the public. Economic risks may also be of interest, such as the probability (risk) of plant or module downtime. An accurate view of the potential effects of different plant/module configurations on the ability to continue generating power will support longer operating cycles between outages and improve the ability to meet power generation demands across the entire plant.
- *Integration of online risk assessment with O&M planning* – The goal of the enhanced risk monitor is to support and inform optimized operations and maintenance planning. As the enhanced risk monitor is developed, future application to supervisory control and planning algorithms will be considered.
- *Run-time requirements* –The ERM is envisioned as a tool to use in real-time or near-real-time to support operations and maintenance planning.

Research to address these technical needs will support the development of enhanced risk monitors for AdvSMRs. Future work will also investigate incorporating online, real-time risk assessment into plant control and O&M planning.

6. Summary

Advanced small modular reactors are being considered for power generation and process heat applications. AdvSMRs can support non-baseload energy production (e.g., load following or peak demand generation), dual mission deployment (e.g., water desalination, shale oil extraction, hydrogen production), and remote siting. However, these plants do not enjoy the economy-of-scale that makes large plants economically competitive. Advanced health management techniques for key components, such as risk-informed O&M planning, may improve the economics of AdvSMRs by reducing O&M costs and increasing plant availability, which may be key for successful deployment in the future. Current risk monitors use average historic, population-based POF values to evaluate the risk of different plant configurations. This approach neglects the unit-to-unit variance and change over time that may be due to manufacturing variation, operational history, or operating environment. Additionally, the failure rates for AdvSMR components may not be well understood due to the harsh internal environments, use of advanced component designs, and interdependence between modules. Online equipment condition assessment can provide unit-specific estimates of component failure rates to provide a more accurate risk evaluation, which can then be used for risk-informed O&M planning and plant control.

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