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Abstract

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Keywords

Small Modular Reactors, Prognostics Health Management, Advanced Reactors, Reliability, Passive Components

Disciplines

Energy Systems

Comments

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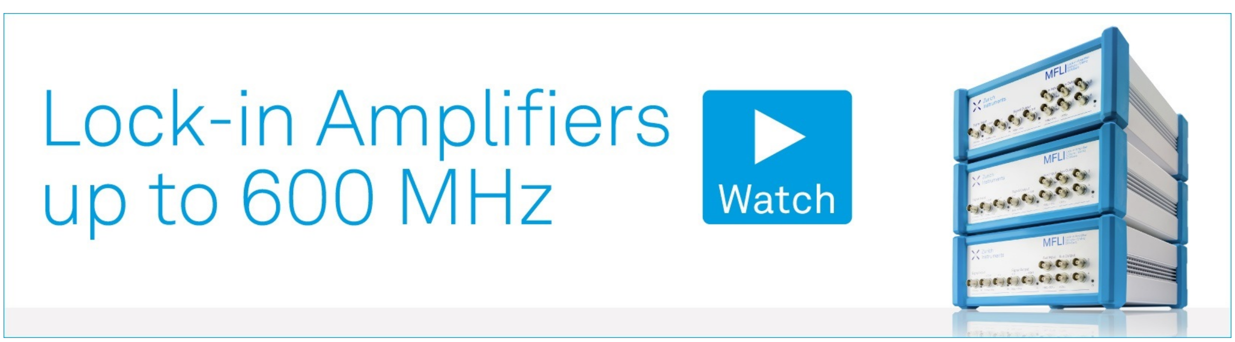

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Research Gaps and Technology Needs in Development of PHM for Passive AdvSMR Components

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Abstract. Advanced small modular reactors (AdvSMRs), which are based on modularization of advanced reactor concepts, may provide a longer-term alternative to traditional light-water reactors and near-term small modular reactors (SMRs), which are based on integral pressurized water reactor (iPWR) concepts. SMRs are challenged economically because of losses in economy of scale; thus, there is increased motivation to reduce the controllable operations and maintenance costs through automation technologies including prognostics health management (PHM) systems. In this regard, PHM systems have the potential to play a vital role in supporting the deployment of AdvSMRs and face several unique challenges with respect to implementation for passive AdvSMR components. This paper presents a summary of a research gaps and technical needs assessment performed for implementation of PHM for passive AdvSMR components.

Keywords: Small Modular Reactors; Prognostics Health Management, Advanced Reactors, Reliability, Passive Components
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INTRODUCTION

Nuclear energy currently contributes approximately 20% of baseload electrical needs in the United States and is considered a reliable generation source to meet future electricity needs. Sustainable nuclear power to promote energy security is a key national energy priority. The development of deployable small modular reactors (SMRs) is expected to support this priority by diversifying the available nuclear power alternatives for the country, and enhance U.S. economic competitiveness by ensuring a domestic capability to supply demonstrated reactor technology to a growing global market for clean and affordable energy sources.

Several concepts for SMRs have been proposed [1, 2] with integral pressurized water reactor (iPWR) concepts the current front-runner for near-term licensing and deployment. Advanced small modular reactors (AdvSMRs), which are based on modularization of advanced reactor concepts using non-light-water reactor (LWR) coolants such as liquid metal, helium, or liquid salt may provide a longer-term alternative to LWRs and iPWRs.

The economics of small reactors (including AdvSMRs) will be impacted by the reduced economy-of-scale savings when compared to traditional LWRs, although the modular nature of such reactors can be advantageous in presenting lower initial capital costs. In addition, the controllable day-to-day costs of AdvSMRs are expected to be dominated by operations and maintenance (O&M) costs, and achieving the full benefits of AdvSMR deployment requires a new paradigm for plant design and management. In particular, degradation in passive components, if not addressed in a timely fashion, is likely to result in unplanned plant shutdowns. Thus, PHM of passive components in AdvSMRs can play a key role in enabling the economic deployment of AdvSMRs.

This paper provides a summary of a recent technical needs and research gap assessment documented in a technical report [3]. Research gaps and technical needs are identified based on a requirements analysis for PHM of AdvSMR passive components and a PHM state-of-the-art assessment relevant to AdvSMR passive components. The following sections summarize the requirements analysis and PHM state-of-the-art assessment and present the research gaps and technical needs to address these gaps.

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REQUIREMENTS ANALYSIS

AdvSMRs will be based on advanced reactor concepts, such as those promoted by the Generation IV International Forum to help focus international resources and efforts to establish the feasibility and performance of future generation reactors [4, 5]. Improvements in safety and reliability, sustainability, proliferation resistance, and economics are among the key goals of the Generation IV efforts. Some key factors of AdvSMRs that will impact PHM systems for passive components include i) the operating environment, ii) O&M, iii) concepts of operation, iv) materials degradation performance, v) past operating experiences, vi) balance-of-plant, and vii) refueling intervals. A brief discussion of these factors as they relate to AdvSMRs is provided in [3]. For instance, one of the factors of AdvSMRs that will influence the implementation of PHM systems for passive components is the coupling of AdvSMR systems to multiple product streams (illustrated in Fig. 1).

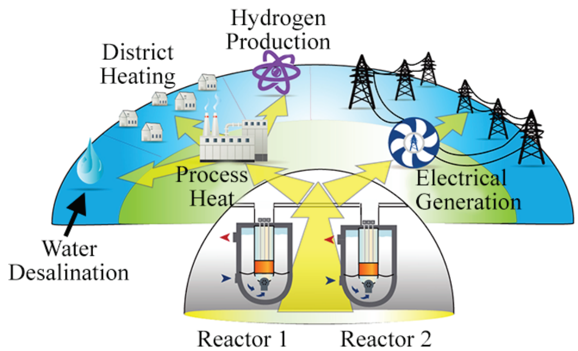

FIGURE 1. AdvSMR Deployment Concept Illustrating Multiple Generation Missions.

These factors, in addition to the need to interface with the plant supervisory control system and to conform to codes, standards, and regulatory requirements, drive the requirements of PHM systems for passive components in AdvSMRs, as depicted in Fig. 2. Based on this, a requirements analysis for the application of PHM to AdvSMRs has been performed, identifying six requirements to date [3]:

1. Sensors and instrumentation for condition assessment of passive components
2. Fusion of measurement data from diverse sources
3. Address coupling between components or systems, and across modules
4. Incorporation of lifecycle prognostics
5. Integration with risk monitors for real-time risk assessment
6. Interface with plant supervisory control system

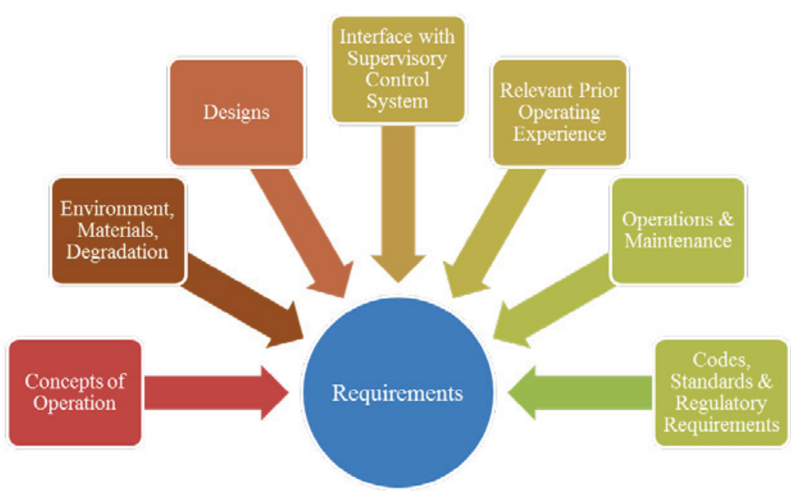

FIGURE 2. Factors driving the requirements for PHM systems of passive components in AdvSMRs.

Sensors and instrumentation for condition assessment of passive components refer to the technologies needed to perform the measurements in harsh AdvSMR environments. The next three requirements imply a need for prognostic algorithms with significant versatility. These general requirements are identified to address practical needs and desires associated with forecasting the state of passive components under the influence of time varying and uncertain future load conditions that result from O&M and concepts of operations protocols that call for load reallocation to relieve stresses on degraded components and to respond to dynamic product stream demand. In addition, the ability to use and combine multiple types of measurements (i.e., stressor, condition, local, global, online, and offline) for component forecasting is desirable to achieve greater efficiency and enhanced performance. Finally, a framework for lifecycle prognostics will enable use of both stressor and condition-based prognostics and the updating of model parameters to transition across multiple stages of degradation and to adjust to load changes.

PHM STATE-OF-THE-ART

Some basic elements of a PHM system for passive components in AdvSMRs are diagramed in Fig. 3. With respect to measurements, measurements relevant to PHM of passive components in nuclear power plants can be generally classified as local NDE measurements (e.g., ultrasound), stressor/environmental measurements (e.g., temperature, neutron flux, pressure, chemistry variables), and global condition measurements (e.g., vibration monitors, neutron noise). Local NDE measurements are usually performed through periodic inspections, when the reactor is off-line, while many stressor/environmental measurements and global condition measurements are collected continuously during reactor operation. As practiced in the field, these technologies are sensitive only to macro degradation, but trends point toward the availability of fieldable NDE technologies in the future that can detect degradation evolution in materials before cracks or significant material loss occurs. Another likely trend is the integration of structural health monitoring (SHM) tools and concepts from other industries into nuclear power facilities. An example includes distributed fiber optic sensors for measurements of temperature, stress, etc. A basic challenge to the deployment of existing and future technologies in AdvSMRs is the harsh operating environment.

An overview of diagnostics and prognostics is provided in [6]. Several approaches to diagnostics and prognostics are potentially available. Research towards addressing issues such as data fusion for diagnostics, prognostic models, lifecycle prognostics, uncertainty quantification, and prognostics in coupled systems, is ongoing. It is likely that ongoing research in these areas will require adaptation to address issues specific to AdvSMR passive component applications. With respect to data fusion for diagnostics, most efforts have focused on the fusion being performed at the signal level, using similar forms of measurements (for instance, image data), with less effort being expended on fusing dissimilar forms (such as fusing image data with time-series measurements). These latter efforts have tended to focus on fusing information at a higher level after the measurement data has been processed and a diagnostic result obtained from each of the measurement sources. These techniques are largely data-driven and require data sets from known sources to determine the parameters of the fusion algorithm. Fusion using physics-based models, although not as widespread, has also been investigated.

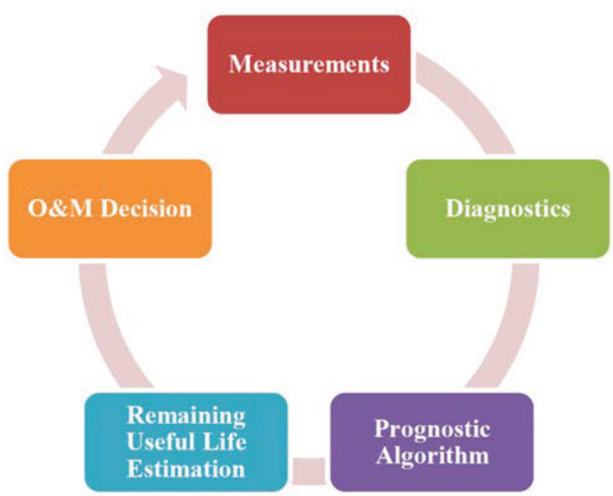

FIGURE 3. Depiction of the Multiple Components of a PHM System for Passive AdvSMR Components.

Numerous state prediction techniques exist for potential application to passive components in AdvSMRs, many of them based on data-driven or probabilistic models of damage progression. Physics-of-failure models are increasingly gaining popularity for applications in electronics, batteries, and machinery prognostics. Limited failure rate data or information related to many passive components in AdvSMRs will motivate the use of physics-of-failure models over historical data-driven models for many applications. Simple models exist for many forms of relevant degradation such as Paris' Law for fatigue and Norton's Law for thermal creep. However, these models contain empirically derived constants that may not be fully known over the range of relevant operating conditions in AdvSMRs. Tracking algorithms (i.e., Kalman filtering, extended Kalman filtering, and particle filtering) provide a convenient framework for incorporating the latest information from measurements and facilitating the propagation of uncertainty to failure. Coupling the particle filter technique with physics-of-failure models for degradation modes can provide a versatile means for estimating the remaining useful life (RUL) of AdvSMR passive components.

RESEARCH GAPS AND TECHNICAL NEEDS TO ADDRESS GAPS

This section presents technical gaps associated with requirements previously presented and based on the current status of PHM systems for AdvSMR passive components. For several requirements, many of the gaps are associated with applying existing techniques or methodologies to AdvSMR components. Several gaps for each of the identified requirement are briefly highlighted below and are more fully discussed in [3].

Requirement 1: Sensors and Instrumentation for Condition Assessment of Passive Components –

- Characterization of performance and survivability of sensors in AdvSMR environments
- Accurate determination of component condition from one or more measurement signals
- Adequate characterization of baseline material condition (pre-service)
- Characterizing the reliability of new and unconventional sensors developed for AdvSMR environments

Requirement 2: Fusion of Measurement Data from Diverse Sources –

- Integration of different types of data (for instance, image data and time-series data), and integrating distributed sensor information to assess component health
- Algorithms for robust, automated spatial and temporal co-registration of data, and accounting for differing levels of uncertainty in the different measurements with a focus on material condition estimation
- Algorithms for solving inverse problems for assessing component condition, quantifying the uncertainty in the resulting solution
- Availability and applicability of accurate models for passive component prognostics that capture the degradation accumulation process under different stressor conditions
- Ability to incorporate global and local condition indices within the framework of prognostics for RUL estimation of the component

Requirement 3: Address coupling between components or systems, and across modules –

- Ability to quantify and propagate uncertainty in coupled systems
- Development of prognostic approaches for uncertain or unknown future loading conditions

Requirement 4: Incorporation of lifecycle prognostics –

- Accounting for uncertainty across the transitions in models over the lifecycle of a passive AdvSMR component
- Transitioning from stressor-based to condition-based (or vice-versa) prognostic models in a seamless fashion
- Transitioning between different degradation rate models and combining multiple degradation models

Requirement 5: Integration with Risk Monitors for Real-time Risk Assessment –

- Representation of passive components in risk monitors
- Incorporation of real-time estimates of passive component probability-of-failure distributions into so-called enhanced risk monitors (ERM) [7]

Requirement 6: PHM Architectures and Interface with Plant Supervisory Control System –

- Defining optimal interfaces between PHM and Supervisory Control System
- Development of suitable PHM architectures for AdvSMR passive component applications

Technical Needs to Address Research Gaps

Several technical needs have been identified to address many of the gaps for each requirement listed above. Some of these technical needs are cross cutting because they impact multiple requirements. A brief discussion of each technical need follows:

Quantification of Uncertainty

Quantification of uncertainties and their incorporation into prognostic algorithms is vital to determine the confidence bounds in RUL estimates. A number of sources of uncertainty exist when attempting to calculate RUL estimates for nuclear structural materials. These include:

- Stochastic variations in macro- and microstructure of the material
- Unknown material fabrication history
- Variability and uncertainty in stressor severity (past and future)
- Measurement noise, both in the monitoring of stressor levels as well as in the nondestructive evaluation of material degradation state
- Uncertainties in the models that relate stressor levels, current material degradation state, and future degradation material states
- Uncertainty in the damage index threshold for failure.

Verification and Validation (V&V)

Approaches for effective V&V that demonstrate applicability of the proposed approaches to problems specific to AdvSMRs will be needed. Experimental approaches to V&V will be challenged by the need to ensure a close match with anticipated operational (harsh) environments. On the other hand, information generated in other environments may suffer from limited relevance. Simulation tools that model AdvSMR environments may provide a way of performing limited validation of proposed PHM systems.

A potential approach to addressing the V&V challenge is to leverage ongoing research on materials degradation in environments that mimic anticipated AdvSMR environments, both domestically as well as internationally. This leveraging could take multiple forms, and include sharing of data, models, and instrumenting experimental facilities to acquire data from realistic environments that could be used to validate the proposed PHM tools.

Quantitative NDE Analysis Tools

Several forms of degradation relevant to passive AdvSMR components (e.g., forms of embrittlement and creep) can progress to advanced stages without appreciable signs of cracking or material loss. Several NDE techniques are sensitive to the microstructural evolution of degradation. Quantitative correlations of measurement outputs (e.g., ultrasonic velocity, ultrasonic nonlinear parameter) to the inputs of physics-of-failure models for prognostics will be needed. For example, to implement Norton's Law for secondary creep, strain or strain rate values might be inferred from measurements of ultrasonic velocity or the ultrasonic nonlinear parameter (assuming strain cannot be measured directly). The development of such quantitative relationships addresses gaps in achieving reliable diagnostics with one or more measurements.

Physics-of-Failure Models

Physics-of-failure models do not exist for several forms of passive component degradation in AdvSMRs. The development of such models addresses a fundamental technical gap in achieving lifecycle prognostics as well as PHM for interconnected systems. In each case, the availability of such a model or models would help improve the accuracy of the RUL estimation. Physics-of-failure models may contain several parameters or coefficients that must be determined over different ranges of loading conditions for different materials. Multi-scale models may be needed to better quantify the changes in microstructure at all scales. In addition, it may be possible to have coupled forms of degradation; for instance, a weld joint undergoing corrosion while also undergoing thermal creep degradation.

Sensors for Degradation Monitoring in Harsh Environments

On-line monitoring capability of passive components in AdvSMRs will be important because of reduced opportunities for off-line inspections in many AdvSMR designs. As a consequence of the harsh operating environments of AdvSMRs, there is a need to either develop or demonstrate measurement sensors in anticipated AdvSMR environments. Beyond the survivability of sensors, there are issues associated with survivability of cabling and other associated instrumentation also located in the harsh environment to enable sensor deployment. The calibration of all sensors during reactor operation will be very important to successful AdvSMR operation.

Lifecycle Prognostics

Lifecycle prognostics methodologies will need to enable transitioning between models across the lifecycle of the component with different models being more or less appropriate during different stages of degradation. Specific needs include accounting for uncertainty across the transitions, transitioning from stressor-based to condition-based (or vice-versa) in a seamless fashion, transitioning between different degradation rate models, and combining multiple degradation models.

PHM Architectures and Integration with Plant Supervisory Control Systems

Deployment of PHM for systems, structures, and components in nuclear power plants will likely require the use of architectures (i.e., a software product or suite of products that integrates the necessary analyses for complete PHM). This broad definition includes condition monitoring, fault detection, and diagnostics in addition to prognostics. An existing software framework may be leveraged to develop a full PHM system with reduced development time and cost. Several commercial architectures for PHM systems are summarized [8]. The applicability of any of these (or other architectures) to AdvSMR passive component applications requires further evaluation. It is likely that modifications to the architecture will be necessary to address specific operational requirements for AdvSMRs. In particular, the ability to manage real-time measurements from a number of local and global sensors for process measurement and component condition assessment, the integration of prognostic results with operational risk monitors and plant supervisory control algorithms, and the incorporation of third-party prognostic algorithms will need to be assessed. The ability to scale the data management and analysis as more sensors or modules are brought on line will also be important. Finally, the ability to incorporate life-cycle prognostics concepts within these architectures will be needed. An important aspect of this integration with plant supervisory systems will be the ability to integrate the results of the PHM system with risk monitors to provide real-time assessments of risk and component reliability due to component condition, as well as operational decisions given current component condition [7].

CONCLUSIONS

Advanced small modular reactors (AdvSMRs) using non-light-water reactor coolants can offer potential advantages over more conventional reactor technologies in the areas of safety and reliability, sustainability, affordability, functionality, and proliferation resistance. A potential challenge is ensuring that degradation in all passive components is well-managed. Prognostics and health monitoring (PHM) can provide a mechanism for AdvSMRs to address this challenge and maximize safety, operational lifetimes, and plant reliability while minimizing maintenance demands. PHM, which encompasses sensors and instrumentation for condition monitoring, diagnostics techniques for assessment of degradation state, and prognostics algorithms for RUL estimation, can potentially provide greater awareness of in-vessel and in-containment component and system conditions and play an important role in reducing operation and maintenance costs and staffing needs. This paper provides a summary of a recent technical needs and research gap assessment for PHM of AdvSMR passive components, which is documented in a technical report [3]. In many cases, underlying methodologies or techniques exist to address the technical needs but will require adaptation and tailoring to AdvSMR passive component applications.

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REFERENCES

1. M. M. Abu-Khader, Progr. Nucl. Energ. 51, 225-235 (2009).
2. D. T. Ingersoll, Progr. Nucl. Energ. 51 (4-5), 589-603 (2009).
3. R. M. Meyer, J. B. Coble, E. H. Hirt, P. Ramuhalli, M. R. Mitchell, D. W. Wootan, E. J. Berglin, L. J. Bond and J. Henager C.H, "Technical Needs for Prototypic Prognostic Technique Demonstration for Advanced Small Modular Reactor Passive Components," PNNL-22488 Rev. 0, SMR/ICHMI/PNNL/TR-2013/01, Pacific Northwest National Laboratory, Richland, Washington, 2013.
4. NERAC, "A Technology Roadmap for Generation IV Nuclear Energy Systems - Ten Nations Preparing Today for Tomorrow's Energy Needs," GIF-002-00, U.S. DOE Nuclear Energy Research Advisory Committee (NERAC) and the Generation IV International Forum (GIF), Washington, D.C., 2002.
5. T. Abram and S. Ion, Energy Policy 36 (12), 4323-4330 (2008).
6. J. B. Coble, P. Ramuhalli, L. J. Bond, J. W. Hines and B. R. Upadhyaya, "Prognostics and Health Management in Nuclear Power Plants: A Review of Technologies and Applications," PNNL-21515, Pacific Northwest National Laboratory, Richland, Washington, 2012.
7. J. B. Coble, G. A. Coles, P. Ramuhalli, R. M. Meyer, E. J. Berglin, D. W. Wootan and M. R. Mitchell, "Technical Needs for Enhancing Risk Monitors with Equipment Condition Assessment for Advanced Small Modular Reactors," PNNL-22377 Rev. 0; SMR/ICHMI/PNNL/TR-2013/02, Pacific Northwest National Laboratory, Richland, Washington, 2013.
8. N. Lybeck, B. Pham, M. Tawfik, J. B. Coble, R. M. Meyer, P. Ramuhalli and L. J. Bond, "Lifecycle Prognostics Architecture for Selected High-Cost Active Components," INL/EXT-11-22915, Rev. 0, Idaho National Laboratory, Idaho Falls, Idaho, 2011.