Prognostics Health Management for Advanced Small Modular Reactor Passive Components

Ryan M. Meyer[1], Pradeep Ramuhalli[2], Jamie B. Coble[3], Mark R. Mitchell[4], David W. Wootan[5], Evelyn H. Hirt[6], Eric J. Berglin[7], Leonard J. Bond[8] and Chuck H. Henager, Jr.[9]

[1,2,4,5,6,7,9]*Pacific Northwest National Laboratory, Richland, WA, 99354, USA*

Ryan.Meyer@pnnl.gov
Pradeep.Ramuhalli@pnnl.gov
M.R.Mitchell@pnnl.gov
David.Wootan@pnnl.gov
Evelyn.Hirt@pnnl.gov
Eric.Berglin@pnnl.gov
Chuck.Henager@pnnl.gov

[3]*University of Tennessee, Knoxville, Knoxville, TN, 37996, USA*

jcoble1@utk.edu

[8]*Iowa State University, Ames, IA, 50011, USA*

bondlj@iastate.edu

ABSTRACT

In the United States, sustainable nuclear power to promote energy security is a key national energy priority. Advanced small modular reactors (AdvSMR), which are based on modularization of advanced reactor concepts using non-light-water reactor (LWR) coolants such as liquid metal, helium, or molten salt, may provide a longer-term alternative to more conventional LWR-based concepts. The economics of AdvSMRs will be impacted by the reduced economy-of-scale savings when compared to traditional LWRs and the controllable day-to-day costs of AdvSMRs are expected to be dominated by operations and maintenance costs. Therefore, achieving the full benefits of AdvSMR deployment requires a new paradigm for plant design and management. In this context, prognostic health management of passive components in AdvSMRs can play a key role in enabling the economic deployment of AdvSMRs. This paper discusses features of AdvSMR systems that are likely to influence PHM implementation for passive components and discusses some requirements based on those features. Further, a brief overview of the state-of-the-art in PHM relevant to AdvSMR passive components is provided followed by an illustration of prognostics for passive AdvSMR components.

1. 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 (Abu-Khader, 2009; Ingersol, 2009) 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.

Components in nuclear power plants can be classified as active or passive. Passive components refer to those structures or components in a nuclear power plant that are functional without a power source. Examples of passive components include pipes, vessels, tanks, cables, etc. This is in contrast with active components which include pumps, valves, motors, etc. While proper maintenance of both active and passive components is important in the operation of nuclear power plants, the degradation in passive components, in particular, 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.

A recent technical report describes several of the requirements for performing PHM of passive AdvSMR requirements and outlines several research gaps and technical needs to address these gaps (Meyer, Coble, Hirt, Ramuhalli, Mitchell, Wootan, Berglin, Bond, & Henager, 2013). This paper discusses features of AdvSMR systems that are likely to influence PHM implementation (Section 2) for passive components and discusses some requirements based on those features (Section 3). Further, a brief overview of the state-of-the-art in PHM relevant to AdvSMR passive components is provided (Section 4) followed by an illustration of prognostics for passive AdvSMR components (Section 5). Finally, some brief discussions and concluding remarks are provided in Section 6.

2. ADVANCED SMALL MODULAR REACTORS

The evolution of nuclear power generating technology is organized by categorizing systems as Generation (Gen) I, II, III, III+, and IV technologies. Gen I includes the earliest prototype reactors while most commercial LWRs in operation today are considered Gen II technologies. Gen III and III+ reactors represent improvements over Gen II technologies with respect to increased reliance on passive safety mechanisms, increased use of digital instrumentation and control, and increased monitoring instrumentation. Gen IV represents a more significant leap in terms of technology advancements and concepts within Gen IV have expected deployments dates beyond 2030. The Gen IV International Forum (GIF) was created to help focus international resources and efforts to establish the feasibility and performance of future generation reactors. Improvements in safety and reliability, sustainability, proliferation resistance, and economics are among the key goals of the GIF efforts. AdvSMRs will be based on Gen IV concepts, such as those promoted by the GIF. Candidate technologies promoted by the GIF include (NERAC, 2002; Abram & Ion, 2008):

- Sodium Fast Reactors (SFRs)
- Very High Temperature Reactors (VHTRs)
- Gas-Cooled Fast Reactors (GFRs)
- Lead-Cooled Fast Reactors (LFRs)
- Molten Salt Reactors (MSRs)
- Supercritical Water-Cooled Reactors (SWCRs)

Like all nuclear reactors, heat is removed from the core in Gen IV reactors by a reactor coolant system that transfers the heat to a system of heat exchangers for power conversion. A depiction of a SFR in Figure 1 serves to illustrate many of the components that are basic to many nuclear power systems. In the case of the SFR, the primary sodium coolant and reactor core are contained within a reactor vessel. Penetrations in the reactor vessel allow the insertion and removal of control rods to manage the fission chain reaction. Pumps circulate the sodium through the reactor core and a secondary sodium loop transfers heat from a heat exchanger located in the reactor vessel to the steam generator. In the steam generator, heat is transferred from the sodium to water which is converted to steam. The steam is then converted to electricity through the turbine generator system.

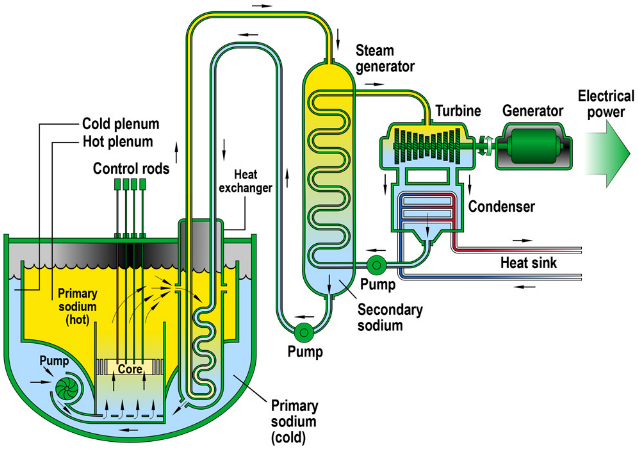

Figure 1. Depiction of a pool-type Sodium Fast Reactor.

There are many possible variations on the system discussed above for Gen IV technologies, including loop versus pool type designs for the primary systems or the elimination of the secondary heat exchange loop. In the case of gas-cooled reactor systems, it may even be possible to couple the primary coolant (i.e., He) directly to the gas turbine. In essence, the higher operating temperatures and exotic coolants of Gen IV systems enable many system configurations that cannot be realized with conventional technologies to achieve improved efficiencies. The following subsections briefly summarize features that will be generally applicable to AdvSMR systems and how these features will impact PHM system deployment for passive components.

2.1. Operating Environment and Materials Degradation

Passive components in AdvSMRs will be subject to relatively harsh operating environments in comparison to LWRs. This includes higher temperatures, fast neutron fluxes, and corrosive coolant conditions. Materials for advanced nuclear reactor applications generally consider radiation damage resistance, environmental stability, and high-temperature capability as paramount (Yvon & Carre, 2009; Zinkle & Busby, 2009). Volumetric swelling and dimensional stability, embrittlement, stress corrosion cracking, irradiation and thermal creep, and corrosion are critical materials degradation issues. Welds are problematic in nuclear structures as preferred sites for environmental degradation and stress-assisted degradation processes. Compatibility issues arise with regard to liquid metal coolants for liquid metal fast reactors (LFRs and SFRs) when metals and alloys in flowing coolant experience unwanted chemical reactions or leaching. In addition to driving the degradation issues, the harsh operating environment will negatively impact the performance of sensors for health monitoring and constrain their deployment.

2.2. Operations and Maintenance

Staffing and control room requirements have been identified as a significant technical and policy issue for multi-module SMR installations (Cetiner, Fugate, Kisner, & Wood, 2012). Key issues include determining appropriate staffing levels and how many units may be operated from a single control room. PHM systems can play an important role in reducing O&M costs and staffing needs by providing greater awareness of component and system conditions. In this case, to mitigate impending failure of a critical passive component of one module, the power level of that module may be decreased to reduce stresses and slow down the failure mechanisms. The power level of other modules may also be increased to compensate for the decrease in power to the first module. In this case, the role of a PHM system may be to determine appropriate stressor levels to achieve a desired remaining useful life (RUL). Also, compensation introduces coupling between modules and uncertainty that needs to be considered in the PHM implementation.

2.3. Concepts of Operation

In order to balance overall electricity generation and to meet fluctuating electrical demands, AdvSMRs may operate in a load-following mode, where the output of one or more reactor modules is adjusted (and thereby the electrical output of the plant). This type of operation has been studied for iPWR reactor designs (Hines, Upadhyaya, Doster, Edwards, Lewis, Turinsky, & Coble, 2011). Alternatively, electricity generation can be adjusted by using surplus heat for a secondary application. AdvSMRs may be required to operate in tandem with variable sources of renewable energy and/or supply electricity and process heat for industrial applications. One of the objectives of the Next Generation Nuclear Plant (NGNP) was to demonstrate cogeneration of electricity and hydrogen using high-temperature process heat (Southworth, MacDonald, Harrell, Shaber, Park, Holbrook, & Petti, 2003). Concepts for large-scale nuclear geothermal energy storage, shale oil extraction via nuclear and renewable energy, and symbiotic nuclear and renewable energy systems for electricity generation and hydrogen production have also been proposed (Haratyk & Forsberg, 2011; Forsberg, 2012; Forsberg, Lee, Kulhanek, & Driscoll, 2012). A key characteristic of many of these concepts is that they facilitate matching a constant nuclear energy source with variable electricity demand by distributing the nuclear production over multiple product streams (see Figure 2). In such scenarios, the distribution of load over components in the product streams will be subject to daily and seasonal load variations. Similar to the O&M, this introduces coupling and uncertainties that need to be considered in the PHM implementation.

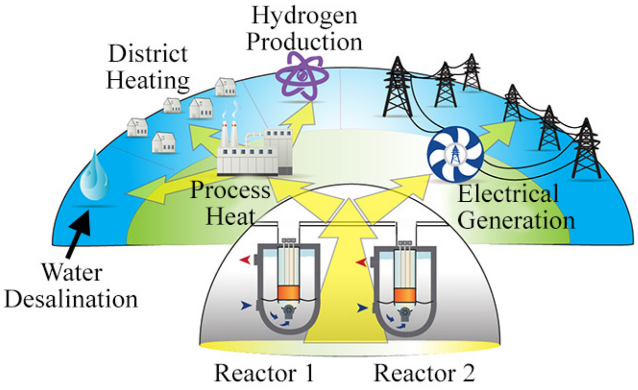

Figure 2. AdvSMR deployment concept illustrating multiple generation missions.

2.4. Refueling Schedules

Several advanced reactor concepts are intended to operate for extended periods between outages. For LWRs, outages are scheduled every 18–24 months for refueling but several advanced reactor concepts are intended to operate with much longer periods between refueling. The Toshiba 4S concept, for instance, is designed to operate up to 30 years without refueling (Tsuboi, Arie, Ueda, Grenci, & Yacout, 2012). The SSTAR is another advanced reactor concept with targeted operation periods of 15 to 30 years between refueling activities (Smith, Halsey, Brown, Sienicki, Moisseytsev, & Wade, 2008). Several other reactor concepts such as the liquid fuel MSRs and pebble bed-type VHTRs may have the capability to refuel while operating. Thus, it will be important that PHM systems for AdvSMRs are capable of utilizing data obtained from on-line measurements as well as data collected during outages.

3. PROGNOSTIC HEALTH MONITORING REQUIREMENTS

Based on AdvSMR features such as those discussed in Section 2, a requirements analysis for the application of PHM to AdvSMRs has been performed, identifying several important requirements to date (Meyer et al., 2013):

3.1. Sensors and Instrumentation for Condition Assessment of Passive Components

Because opportunities to perform inspections and maintenance of passive components when the plant is off-line will be limited in many designs, there is a need to monitor risk-significant passive components during plant operation for degradation. In addition, there is a need to monitor the stressors (time at temperature, fluence, mechanical loads, etc.) that are expected to contribute to degradation of these components. Requirements for sensors and instrumentation (whether for on-line or off-line condition assessment or for stressor monitoring) include:

- Ability to tolerate the harsh operating conditions in AdvSMRs.
- High sensitivity, to ensure that reliable measurements from earlier stages of degradation are possible.
- Capability to quantify the amount of degradation from the measurements.

3.2. Fusion of Measurement Data from Diverse Sources

Accessibility to some AdvSMR components may be restricted, particularly in pool-type reactors in which many of the primary system components will be submersed in coolant. Additionally, for concepts with infrequent refueling outages, opportunities to access components for periodic off-line inspection will be reduced. The fusion of data obtained from both online and offline measurements may enhance the performance of prognostics relative to relying on either type of measurement alone.

3.3. Address Coupling Between Components or Systems, and Across Modules

Compensating O&M strategies and concepts of operation that seek to distribute the output over multiple product streams will result in coupling effects between components, systems, and modules. This is likely to result in changing or time-varying load conditions that will introduce uncertainty in future stressor profiles.

3.4. Incorporation of Lifecycle Prognostics

An effective PHM system for AdvSMRs should be able to adapt or adjust its prognostics methodology to where the component or degradation is in its lifecycle. This helps to ensure accurate and timely determination of RUL based on the available information. Part of this requirement is determining the appropriate degradation models and updating these models in response to changes in operating conditions. Further, it will be necessary to transition between stressor-based prognostics and condition-based prognostics depending on the available data.

3.5. Integration with Risk Monitors for Real-time Risk Assessment

Given that it will likely be impractical to monitor or assess every component, a risk assessment will need to be performed to determine risk-significant components to ensure the highest return on investment. Such a risk assessment is in line with current practice for safety-significant components using risk-informed in-service inspection (RI-ISI). Also, the PHM system will be required to feed-back information on component condition and estimated RUL to the plant supervisory control algorithm for decision-making on O&M to manage and mitigate the impact of detected degradation. This feedback will have to flow through real-time risk monitors (Coble et al., 2013) that assess the risk associated with continued operation using the degraded component and contrast it with other options such as reactor-runbacks and shifting loads to other modules.

3.6. Interface with Plant Supervisory Control System

As already discussed, with compensating O&M strategies in a modular plant the potential exists to shift the power-generating burden among the units and/or modules to ensure component availability until the next scheduled maintenance opportunity. To accomplish this, PHM systems for passive components will require interfacing with the plant supervisory control system for AdvSMRs, to both obtain real-time information on operating conditions as well as feedback information that the control systems may use to adjust operating conditions to ensure a certain RUL.

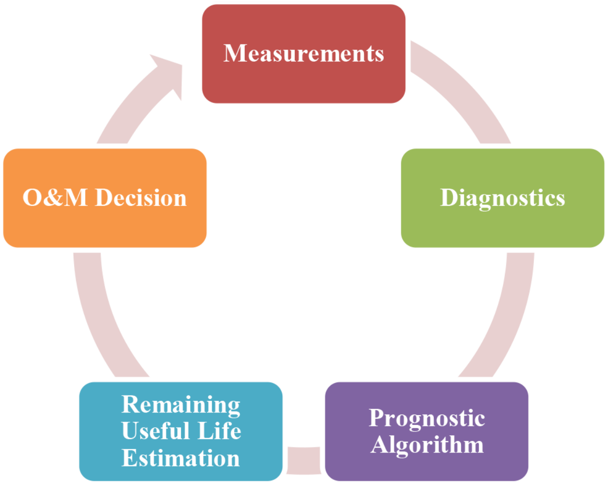

Figure 3. Depiction of the multiple components of a PHM system for passive AdvSMR components.

4. RELEVANT PHM STATE-OF-THE-ART OVERVIEW

A PHM system of AdvSMR passive components will consist of several elements, as depicted in Figure 3. This section contains a brief overview of the state-of-the-art for PHM relevant passive AdvSMR components by considering these elements. The overview provided here is an abbreviated version of a state-of-the-art assessment provided in Meyer et al. (2013).

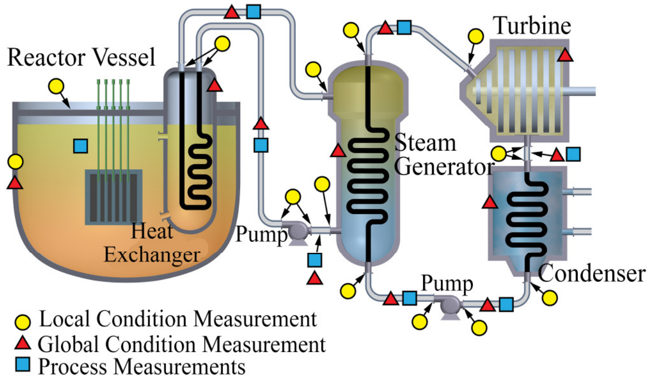

Figure 4. Conceptualization of candidate measurements and sensor locations for monitoring passive component degradation in AdvSMRs.

4.1. Measurements

Many different types of measurements can potentially be implemented in AdvSMRs to sample degradation and to input into prognostic models. Measurements can be categorized as local condition, global condition, and process/environmental measurements. Figure 4 illustrates several candidate measurements and sensor locations for monitoring passive component degradation in AdvSMRs. Local condition measurements refer to local nondestructive examination (NDE) measurements typically including various ultrasonic, eddy current, and visual testing techniques. These NDE measurements are currently limited to being performed while the reactor is off-line due to the operating environment. Although this limits the frequency at which these measurements can be performed, NDE measurements are generally more direct and descriptive than global condition or process/environmental measurements.

Global condition monitoring has also been deployed to monitor the status of passive components in nuclear reactors. As the name implies, these measurements relate to the overall health of a component or system and do not necessarily contain information about the nature of the fault or its precise location. Global condition measurements are sensitive to fairly advanced degradation such as cracks or the existence of loose parts. Although the measurements are less descriptive than local NDE measurements, global condition measurements are performed during reactor operation, and thus can be performed with greater frequency. In addition, global condition measurements can be used to monitor components that are not accessible to local NDE measurements due to physical access limitations. Examples of global condition monitoring methods in nuclear reactors include vibration analysis, neutron noise analysis, and acoustic emission. Guided ultrasonic wave techniques are also emerging in the nuclear power industry and have the potential to merge some of the benefits of global measurements (i.e., long range sampling) and local measurements (i.e., descriptiveness).

In addition to condition measurements, passive component health may indirectly be inferred from process/environmental measurements. These typically include measurements of temperature, flow rate, pressure, neutron flux, and coolant chemistry variables. Process/environmental conditions can be both contributors to passive component degradation and indicators of passive component degradation. In the former case, they represent stressors, and in the latter case, they are condition indicators. Like global condition measurements, process/environmental measurements are generally less descriptive or direct than local NDE measurements, but they are performed during reactor operation and can be performed with greater frequency.

4.2. Measurements in Harsh Environments

Multiple concepts exist for performing process/environmental and NDE measurements on-line at high temperatures and research in these technologies is ongoing. Examples of such efforts are provided by Ball, Holcomb, and Cetiner (2012) for measurements of temperature and neutron flux including gold-platinum (Au-Pt) thermocouples, Johnson Noise Thermometers (JNT), and high temperature fission chambers. In addition, there are several fiber optic and ultrasound based concepts for measuring temperature and pressure parameters. On the NDE side, there are efforts to develop piezoelectric based technologies for applications in SFRs (Bond, Griffin, Posakony, Harris, & Baldwin, 2012) and LFRs by Kažys, Voleisis, and Voleisiene (2008). A significant issue includes understanding how many proposed sensor types will hold-up to significant radiation fluxes and research efforts to address this gap with respect to in-pile instrumentation applications is ongoing (Rempe et al. 2011).

4.3. Diagnostics and Prognostics

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 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 with less effort being expended on fusing dissimilar forms. Techniques for the latter efforts 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.

Several 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 being considered. 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. Applicable models exist for many forms of relevant degradation such as Paris' Law for fatigue and Norton's Law for thermal creep. 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 RUL of AdvSMR passive components.

5. ILLUSTRATION–PROGNOSTICS FOR ADVSMR PASSIVES

The PF technique is adequately described in the literature, including several tutorials for implementation (Arulampalam, Maskell, Gordon, & Clapp, 2002; An, Choi, & Kim, 2012). An application of PF to forecast mechanical fatigue degradation in passive components in LWRs is described by Ramuhalli, Bond, Griffin, Dixit, and Henager Jr. (2010). Here, we provide a simple illustration of the PF technique to predict the failure of AdvSMR components due to thermal creep. Additional functionality and complexity can then be demonstrated by stepwise expansions and modifications to this simple illustration.

The forecasting of thermal creep damage in He gas turbine blades fabricated from a Ni-based superalloy has recently been investigated by Baraldi, Mangili, and Zio (2012) using an ensemble of empirical models to improve performance. Here, Norton's Law is used with the PF technique to predict the RUL of AdvSMR passive components. To generate a sequence of states, Norton's Law [eq. (1)], is written as a state transition model:

$$\varepsilon_{k+1} = A\sigma^{n}\left(t_{k+1} - t_{k}\right) + \varepsilon_{k}. \qquad (1)$$

Norton's Law parameters for 316L stainless steel weld material provided in Nassour, Bose, and Spinelli (2001) are used for the initial demonstration presented here assuming a temperature of T = 700°C. For now, the Norton's Law parameters are assumed to be Gaussian distributed variables and the values from Nassour et al. (2001) are interpreted as mean values although other distributions for these variables can be accommodated. The values of these parameters are provided in Table 1, along with assumed standard deviations.

Norton's Law is also used to generate simulated NDE measurement data. In this case, the model is developed in anticipation of accelerated aging studies that will provide data to validate the model illustrated here and potentially other models. The measurement uncertainties are assumed to have a Gaussian distribution. In this case, the uncertainty in the NDE measurements is assumed to be 0.1% of creep strain and the failure criterion is 3% creep strain. The actual failure time for these conditions according to Norton's Law is 10.8 hrs. The NDE measurements are simulated to be performed with a periodicity of 1 hr. This selection was made to approximate the relative frequency that offline NDE measurements may be performed on an AdvSMR, assuming the failure time in the accelerated studies is correlated with a plant lifetime.

Failure projections are included in Figures 5 through 7, for NDE measurements performed at 0 and 1 hours; 0, 1, and 2 hours; and 0, 1, 2, 3, and 4 hours. The distributions of RUL for each scenario are shown in Figures 8 through 10. The results were generated using a sample of 5000 particles.

Table 1. Summary of parameters and variables used in Norton's Law model to forecast thermal creep failure.

Parameter	Value (mean)	Std. Dev.
n	9.05	3.33%
A	2.93×10^{-22} $(\mathrm{N\ m}^{-2})^{-n}$ h^{-1}	10%
σ	125 MPa	---

6. CONCLUSIONS AND DISCUSSIONS

PHM for passive components in AdvSMRs can play a key role in facilitating the deployment of AdvSMRs by minimizing controllable day-to-day costs associated with plant O&M. Although potential concepts and designs for AdvSMRs vary significantly, there are some general features that can help define the requirements of a PHM system for passive components. Degradation may be sampled in AdvSMRs through online and offline measurements. A PHM system is likely to be most effective if prognostics algorithms can use both types of measurements.

A basic illustration is provided of a prognostics method based on the PF technique for predicting passive component failure due to thermal creep degradation. The illustration simulates sampling of creep degradation with offline NDE measurements. The illustration only represents the start of prognostic algorithm development as additional functionality to address many the requirements in Section 3 will need to be demonstrated. The approach is to alternately add functionality and demonstrate that added functionality with accelerated aging studies.

ACKNOWLEDGMENT

The work described in this report was sponsored by the Small Modular Reactor Research and Development Program of the U.S. Department of Energy (DOE) Office of Nuclear Energy and performed at Pacific Northwest National Laboratory (PNNL). PNNL is a multi-program national laboratory operated by Battelle Memorial Institute for the U.S. DOE under Contract DE-AC05-76RL01830.

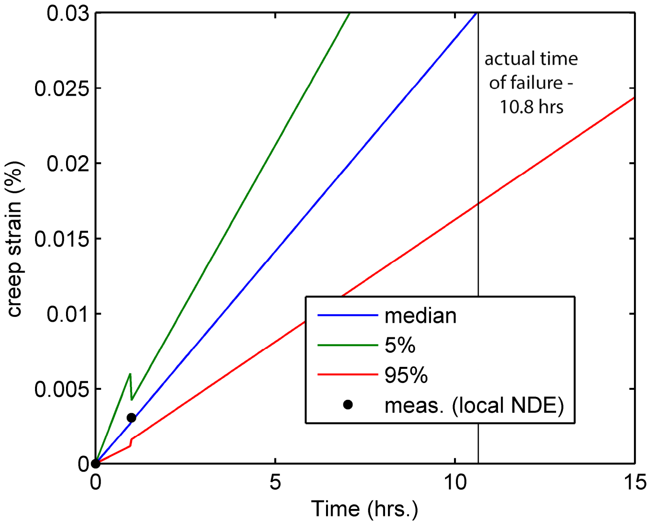

Figure 5. Failure projection for thermal creep based NDE measurements at 0 and 1 hours.

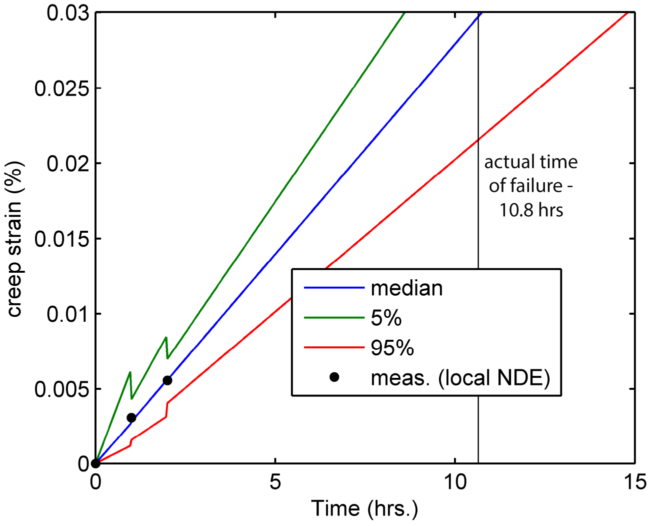

Figure 6. Failure projection for thermal creep-based NDE measurements at 0, 1, and 2 hours.

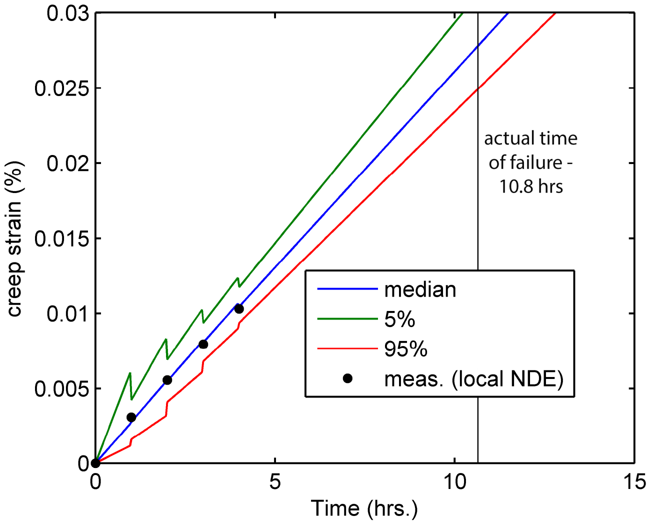

Figure 7. Failure projection for thermal creep-based NDE measurements at 0, 1, 2, 3, and 4 hours.

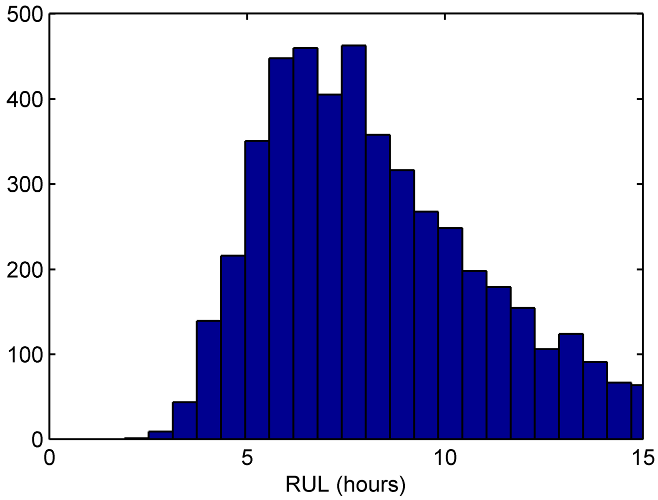

Figure 8. RUL distribution for NDE measurements performed at 0 and 1 hours (see Figure 6).

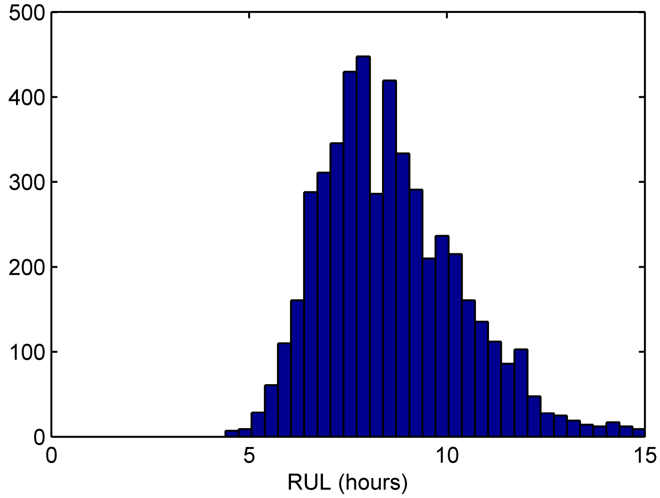

Figure 9. RUL distribution for NDE measurements performed at 0, 1, and 2 hours (see Figure 7).

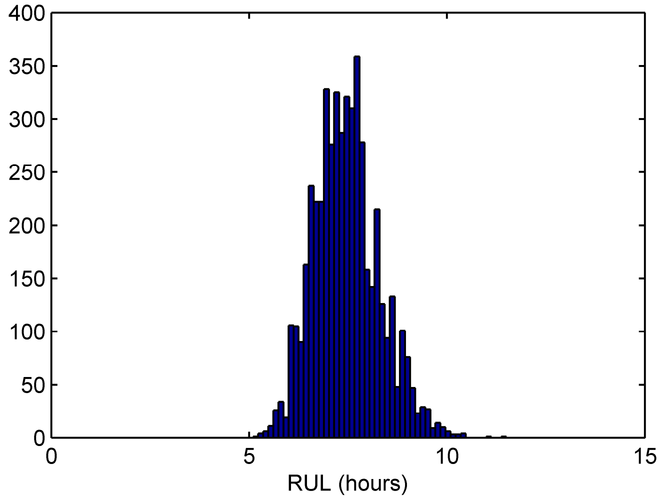

Figure 10. RUL distribution for NDE measurements performed at 0, 1, 2, 3, and 4 hours (see Figure 8).

REFERENCES

Abu-Khader, M. M. (2009). Recent advances in nuclear power: A review. *Progress in Nuclear Energy*, vol. 51, pp. 225-235. doi:10.1016/j.pnucene.2008.05.001.

Abram, T., & Ion, S. (2008). Generation-IV nuclear power: A review of the state of the science. *Energy Policy*, vol. 36 (12), pp. 4323-4330. doi:10.1016/j.enpol.2008. 09.059.

An, D., Choi, J.-H., & Kim, N. H. (2012). A tutorial for model-based prognostics algorithms based on Matlab code. *Annual Conference of Prognostics and Health Management Society 2012*, September 23-27, Minneapolis, MN. http://www.phmsociety.org/sites/ phmsociety.org/files/phm_submission/2012/phmc_12_ 122.pdf.

Arulampalam, M. S., Maskell, S., Gordon, N., & Clapp, T. (2002). A tutorial on particle filters for online nonlinear/non-Gaussian Bayesian tracking. *IEEE Transactions on Signal Processing*, vol. 50 (2), pp. 174-188. doi:10.1109/78.978374.

Ball, S. J., Holcomb, D. E. & Cetiner, S. M. (2012). *HTGR measurements and instrumentation systems.* ORNL/TM-2012/107, Oak Ridge, TN: Oak Ridge National Laboratory.

Baraldi, P., Mangili, F., & Zio, E. (2012). Ensemble of bootstrapped models for the prediction of the remaining useful life of a creeping turbine blade. *IEEE International Conference on Prognostics and Health Management: Enhancing Safety, Efficiency, Availability, and Effectiveness of Systems Through PHM Technology and Application (PHM 2012)* (pp. 1-8), June 18-21, Denver, CO. doi: 10.1109/ICPHM.2012.6299506.

Bond, L. J., Griffin, J. W., Posakony, G. J., Harris, R. V. & Baldwin, D. L. (2012). Materials issues in high temperature ultrasonic transducers for under-sodium viewing. *Proceedings of 38th Annual Review of Progress in Quantitative Nondestructive Evaluation* (pp. 1617–1624), July 17-22, 2011, Burlington, VT. doi: 10.1063/1.4716407.

Cetiner, S. M., Fugate, D. L., Kisner, R. A., & Wood, R. T. (2012). *Functional requirements for supervisory control of advanced small modular reactors.* SMR/ICHMI/ORNL/TR-2013/03, Oak Ridge, TN: Oak Ridge National Laboratory.

Coble, J. B., Coles, G. A., Ramuhalli, P., Meyer, R. M., Berglin, E. J., Wootan, D. W. & Mitchell, M. R (2013). *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, Richland, WA: Pacific Northwest National Laboratory.

Forsberg, C. (2012). A nuclear wind/solar oil-shale system for variable electricity and liquid fuels production. *Proceedings of 2012 International Congress on Advances in National Power Plants (ICAPP '12)* (pp. 2758-2765), June 24-28, Chicago, IL.

Forsberg, C. W., Lee, Y., Kulhanek, M., & Driscoll, M. J. (2012). Gigawatt-year nuclear-geothermal energy storage for light-water and high-temperature reactors. *Proceedings of 2012 International Congress on Advances in National Power Plants (ICAPP '12)* (pp. 2728-2737), June 24-28, Chicago, IL.

Haratyk, G., & Forsberg, C. W. (2011). Nuclear-renewables energy system for hydrogen and electricity production. *Nuclear Technology*, vol. 178 (1), pp. 66-82 http://epubs.ans.org/download/?a=13548.

Hines, J. W., Upadhyaya, B. R., Doster, J. M., Edwards, R. M., Lewis, K. D., Turinsky, P., & Coble, J. (2011). *Advanced instrumentation and control methods for small and medium reactors with IRIS Demonstration.*

Report No. DE-FG07-07ID14895/UTNE/2011-3, Knoxville, TN: The University of Tennessee. doi:10.2172/1015813.

Ingersoll, D. T. (2009). Deliberately small reactors and the second nuclear era. *Progress in Nuclear Energy*, vol. 51 (4-5), pp. 589-603. doi:10.1016/j.pnucene. 2009.01.003.

Kazys, R., Voleisis, A. & Voleisiene, B. (2008). High temperature ultrasonic transducers: Review. *Ultragarsas* (*Ultrasound*), vol. 63 (2), pp. 7-17.

Meyer, R. M., Coble, J. B., Hirt, E. H., Ramuhalli, P., Mitchell, M. R., Wootan, D. W., Berglin, E. J., Bond, L. J., & Henager Jr., C. H. (2013). *Technical needs for prototypic prognostic technique demonstration for advanced small modular reactor passive components*. PNNL-22488 Rev. 0, SMR/ICHMI/PNNL/TR-2013/01, Richland, WA: Pacific Northwest National Laboratory.

Nassour, A., Bose, W. W., & Spinelli, D. (2001). Creep properties of austenitic stainless-steel weld metals. *Journal of Materials Engineering and Performance*, vol. 10 (6), pp. 693-698. doi:10.1361/105994901770344566.

NERAC. (2002). *A technology roadmap for generation iv nuclear energy systems - ten nations preparing today for tomorrow's energy needs*. GIF-002-00, Washington, DC: U.S. DOE Nuclear Energy Research Advisory Committee (NERAC) and the Generation IV International Forum (GIF). http://www.osti.gov/energycitations/servlets/purl/859029-304XRr/.

Ramuhalli, P., Bond, L. J., Griffin, J. W., Dixit, M., & Henager, C. H., Jr. (2010). A Bayesian prognostic algorithm for assessing remaining useful life of nuclear power components. *7th International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human-Machine Interface Technologies (NPIC&HMIT 2010)* (pp. 875-886, vol. 2), November 7-11, Las Vegas, NV.

Rempe, J. L., MacLean, H., Schley, R., Hurley, D., Daw, J., Taylor, S., Smith, J., Svoboda, J., Kotter, D., Knudson, D., Guers, M., Wilkins, S. C. & Bond, L. J. (2011). Strategy for developing new in-pile instrumentation to support fuel cycle research and development. INL/EXT-10-19149, Idaho Falls, ID: Idaho National Laboratory.

Smith, C. F., Halsey, W. G., Brown, N. W., Sienicki, J. J., Moisseytsev, A., & Wade, D. C. (2008). SSTAR: The US lead-cooled fast reactor (LFR). *Journal of Nuclear Materials*, vol. 376 (3), pp. 255-259. doi:10.1016/j.jnucmat.2008.02.049.

Southworth, F. H., MacDonald, P. E., Harrell, D. J., Shaber, E. L., Park, C. V., Holbrook, M. R., & Petti, D. A. (2003). The next generation nuclear plant (NGNP) project. *Global 2003: Atoms for Prosperity: Updating Eisenhowers Global Vision for Nuclear Energy* (pp. 276-287), November 16-20, New Orleans, LA. http://www.inl.gov/technicalpublications/Documents/2761729.pdf.

Tsuboi, Y., Arie, K., Ueda, N., Grenci, T., & Yacout, A. M. (2012). Design of the 4S reactor. *Nuclear Technology*, vol. 178 (2), pp. 201-217.

Yvon, P., & Carre, F. (2009). Structural materials challenges for advanced reactor systems. *Journal of Nuclear Materials*, vol. 385 (2), pp. 217-222. doi:10.1016/j.jnucmat.2008.11.026.

Zinkle, S. J., & Busby, J. T. (2009). Structural materials for fission & fusion energy. *Materials Today*, vol. 12 (11), pp. 12-19. doi:10.1016/s1369-7021(09)70294-9.