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Technical Needs for Prototypic Prognostic Technique Demonstration for Advanced Small Modular Reactor Passive Components

RM Meyer
JB Coble
EH Hirt
P Ramuhalli
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DW Wootan
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CH Henager, Jr.

May 2013

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Pacific Northwest National Laboratory
Richland, Washington 99352

(a) Iowa State University
Ames, Iowa 50011

Executive Summary

A key national energy priority to promote energy security is sustainable nuclear power. 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. Advanced small modular reactors (AdvSMRs) using non-light-water reactor coolants such as liquid metal, helium, or liquid salt are promising mid- to long-term options being explored for added functionality and affordability in future reliable nuclear power deployment. AdvSMRs can offer potential advantages over more conventional technologies in the areas of safety and reliability, sustainability, affordability, functionality, and proliferation resistance. However, a number of technical challenges will need to be addressed before AdvSMRs are ready for deployment, given their potential for remote deployment with minimal staffing, longer operating cycles between planned re-fueling and maintenance outages, and support for multiple energy applications. In addition, AdvSMRs (like SMRs based on more conventional light-water reactor technologies) will have reduced economy-of-scale savings when compared to current generation light-water reactors (LWRs). Issues related to AdvSMR deployment can be addressed through cross-cutting RD&D involving instrumentation, controls, and human-machine interface (ICHMI) technologies. Specifically, diagnostics and prognostics technologies provide a mechanism for improving safety and reliability of AdvSMRs through integrated health management of passive components. This report identifies activities and develops an outline of a research plan to address the high-priority technical needs for demonstrating prototypic prognostic techniques to manage degradation of passive AdvSMR components.

Concepts for AdvSMRs span a wide range of design maturity, specificity, and concepts of operation, including multi-unit, multi-product-stream generating stations. Key to the development and deployment of AdvSMRs will be the ability to ensure safe and affordable operation of these reactor designs. AdvSMR designs generally place more emphasis on passive systems to assure safety. However, degradation in all passive components will need to be well-managed to maximize safety, operational lifetimes, and plant reliability while minimizing maintenance demands, if reduced economies-of-scale are to be overcome. Traditional approaches such as periodic in-service nondestructive inspections are likely to have limited applicability to AdvSMRs, given the expectation of longer operating periods and potential difficulties with inspection access to critical components. Advanced instrumentation and control (I&C) technologies can provide a mechanism for achieving these goals. However, the significant technology and environmental differences between AdvSMRs and conventional LWRs and the potential for modularized deployment result in unique challenges and needs for advanced ICHMI applications in AdvSMRs.

One component of advanced ICHMI for managing degradation in passive components is related to health and condition assessment technologies such as prognostic health management (PHM) systems. These systems can potentially contribute to the affordability of AdvSMRs by providing greater awareness of in-vessel and in-containment component and system conditions. In turn, such increased awareness can help inform operation and maintenance (O&M) decisions to target maintenance activities that reduce risks associated with safety and investment protection through a greater understanding of precise plant component conditions and margins to failure. Figure S.1 shows an overview of the different elements in a typical PHM system. Keys to effective PHM are the ability to detect incipient failure through increased monitoring of both the component under test as well as the environmental stressors that affect the component, application of advanced in-situ diagnostics tools for degradation severity assessment, and estimation of remaining service life (also often referred to as remaining useful life (RUL)) through the use of prognostic tools. Available information from AdvSMR design concepts, expected operational characteristics, and relevant operating experience may be used to both define requirements for the various elements of the PHM system, as well as bound estimates of RUL with high confidence. Interfaces with plant supervisory control systems ensure that the information about component RUL and system conditions are utilized as a basis for planning maintenance activities. In particular, the ability to estimate remaining life provides a basis for determining whether continued safe operation (over some pre-determined interval) is possible, or whether operating conditions need to be changed to limit further degradation growth until a convenient maintenance opportunity presents itself.

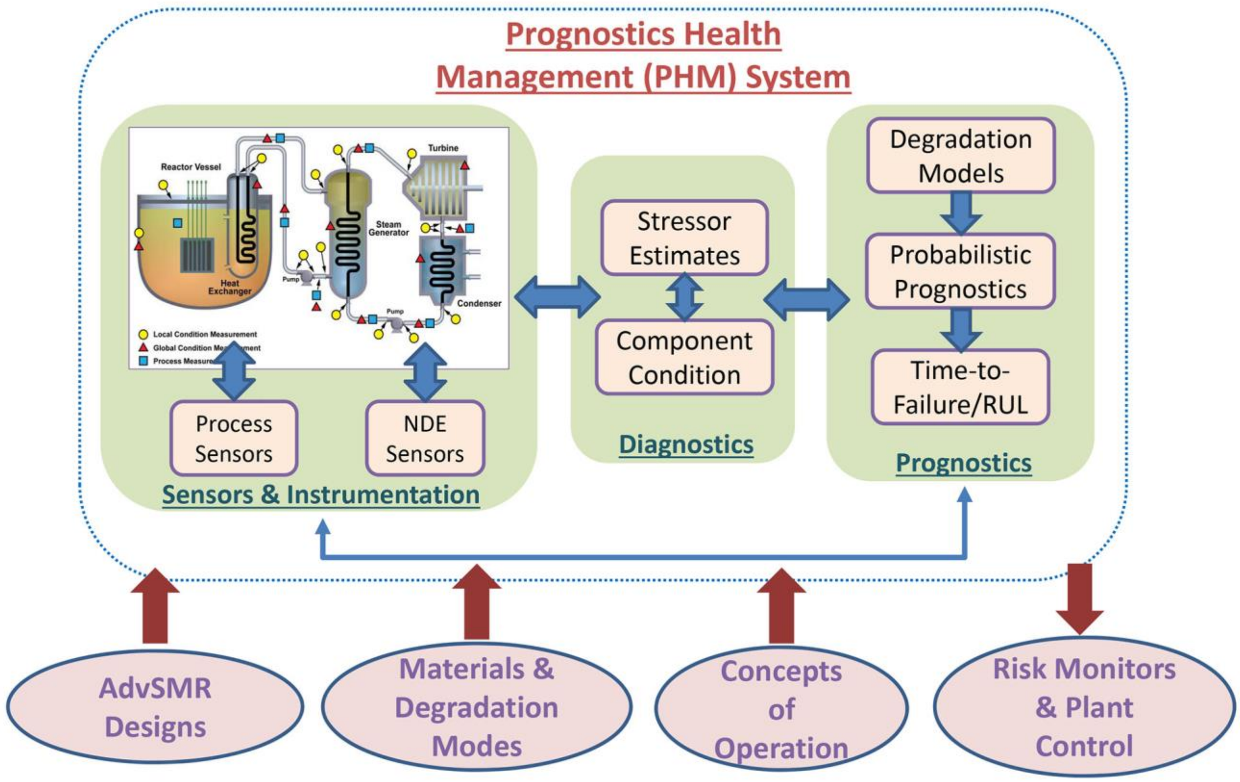

Figure S.1. Overview of a typical Prognostics Health Management (PHM) System

In general, requirements for a PHM system for passive AdvSMR components are driven by many factors such as those illustrated in Figure S.2. This report documents a number of requirements for PHM of passive safety systems in AdvSMRs. These requirements were derived from relevant operating experience of several deployed advanced reactors, expected operational characteristics of proposed AdvSMR concepts, and current approaches to diagnostics and prognostics. Available operating experience of advanced reactors was used to identify passive components (e.g., heat exchangers, pipes and welds) that may be subject to degradation, materials likely to be used for these components, and potential modes of degradation of these components. This information helps in assessing measurement needs for PHM systems, as well as defining functional requirements of PHM systems. An assessment of current state-of-the-art approaches to measurements, sensors and instrumentation, diagnostics and prognostics is also documented. This assessment, combined with the requirements, was used to identify technical gaps in the development, assessment, and deployment of PHM systems for AdvSMRs. This assessment of technical gaps was based on the evaluation of available literature to date.

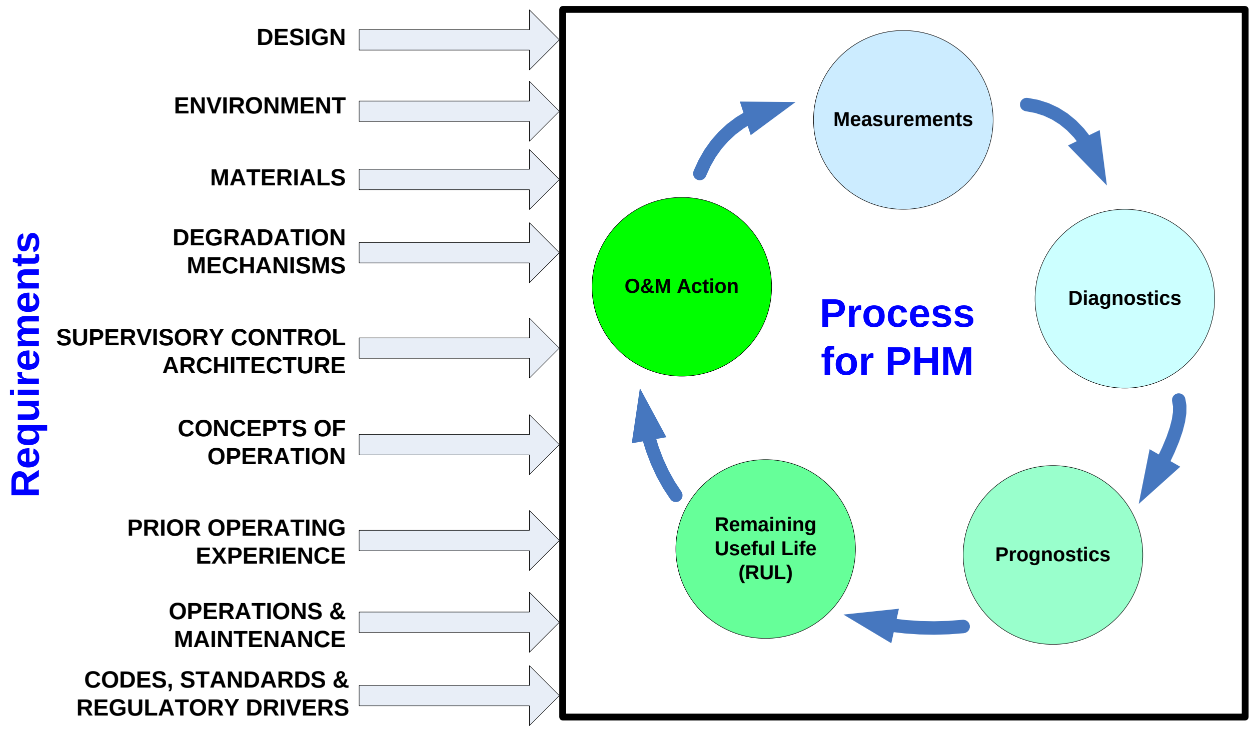

Figure S.2. Example of Requirements that Factor into PHM Systems and Processes

Functional requirements for PHM systems in AdvSMRs identified through this analysis covered all elements of PHM systems, from sensors and instrumentation for measurement of component condition indicators to analysis methods for performing diagnostic assessments of component health, and prognostic methods for RUL estimation. The expected operational concepts of AdvSMRs drove requirements for sensors tolerant to harsh environments, lifecycle prognostic tools capable of transitioning between different methods based on available information, and prognostic tools that account for coupling between components or systems in multi-module AdvSMR plants. Integration of PHM with risk monitors as well as the plant supervisory control system will be critical to ensuring that PHM systems help drive informed operational and maintenance decisions.

The health of a passive component or system may be inferred from measurements of the contributors (such as temperature, stress, and neutron fluence) to degradation, and their effects (such as material microstructural changes) on the materials. The assessment of state-of-the-art in diagnostics and prognostics indicated that health assessments of AdvSMR passive components may be performed using stressor measurements (such as time-at-temperature, flow, pressure, and fluence), global condition measurements (such as vibration) using a number of sensors distributed over the component or system, and nondestructive examination (NDE) measurements (such as ultrasonics) that are sensitive to localized changes in structural materials. Similarly, a number of prognostic methods may be available for computing remaining useful life based on either stressor or component condition, such as population reliability-based methods, methods that analyze trends in available data (data-driven methods), and methods that use physics-of-failure models. In the latter two cases, the information used to assess RUL could be either stressor history, or component condition. Methods for data fusion will likely play a role in PHM systems at several stages. For diagnostics (i.e., determining the current condition of the component), measurements (possibly from multiple measurement types) at the local level and global level may be integrated in a meaningful manner to derive a condition index. For prognostics, information about the current state (which may be represented by a condition index computed from one or more measurements) may need to be fused in a meaningful manner with stressor measurements (such as temperature and fluence) to estimate RUL.

Despite significant research in sensors and instrumentation (for nondestructive evaluation and stressors), diagnostics, data fusion, and prognostics, a number of technical gaps currently limit the applicability of PHM systems to AdvSMRs. The assessment using available literature of the state of the art in PHM systems indicated that there is a need for sensors that are tolerant to harsh environments (especially the higher temperatures and neutron fluences expected in AdvSMRs) while maintaining the sensitivity to incipient degradation in passive components. Gaps also exist in the availability (and applicability) of efficient and accurate algorithms for measurement analysis to determine component condition in near real-time; data fusion methods that can integrate local, global, and stressor data to determine a condition index for the component or system; models of degradation accumulation (especially physics-of-failure models with appropriate loading conditions) that are accurate over the component and degradation lifecycle; and prognostic methods that are able to transition between different models based on the available information. There is also limited work in the area of PHM systems that address cross-system fault propagation in coupled systems (such as multi-module AdvSMRs). While the available information is a function of the application domain, there is a clear gap here with respect to the use of PHM for AdvSMRs, where models of system coupling for interconnected systems are generally not yet available. Underlying all of these gaps is the need to account for uncertainty (due to factors such as sensor noise, environmental noise, and model approximations) at all levels. Methods for quantification of uncertainty in the diagnostic and prognostic stages, as well as propagating uncertainty in RUL estimates to risk metrics and the plant supervisory control system will be necessary if the estimates of remaining lifetimes are to be used as a basis for driving maintenance activities and operational decisions.

This report incorporates a research plan outline for addressing several of the research gaps and technical needs in developing and deploying a PHM system for passive components in AdvSMRs. The objective of this research plan is to demonstrate a prototypic prognostics technology to manage degradation of passive AdvSMR components. Greater efficiency in achieving this objective can be gained through judicious selection of materials and degradation modes that are relevant to proposed AdvSMR concepts, and for which significant knowledge already exists.

A generic design with multiple AdvSMR reactor modules connected to a common balance-of-plant (BOP) will be assumed to provide for future integration between the outcomes of this research and ongoing research within the AdvSMR R&D program into enhanced risk monitors and plant supervisory control algorithms. A general PHM system hierarchy for AdvSMRs provides the basis for the organization of the research plan and schedule of research activities. The interface between the PHM and supervisory control systems is anticipated to occur at higher levels of the PHM system hierarchy (i.e., component level and above) and have a greater influence on how PHM is performed at these levels. However, the uncertainty regarding the interface will have the least impact on PHM at the local level.

Thus, a logical approach to organizing the research was to start at the bottom of the hierarchy at the local level and to work up the hierarchy. Therefore, this research plan was developed only to address tasks related to the local, component, and system (multiple interconnected components to perform a given function) levels in a phased manner. This leaves open an opportunity to address module and site levels later.

The research activities to address the high priority technical needs are divided into multiple phases with each phase associated with a level of the hierarchy. Specifically the research plan consists of three phases that will focus on: (1) developing and validating prognostic algorithms using localized NDE and stressor measurements; (2) developing and validating PHM at the component level, and (3) integrating local and component level prognostics to perform PHM of a system. In each case, prototypic degradation modes (such as high-temperature creep or creep-fatigue) will be selected for the demonstration of the prognostics methodology. These selections will be made based on multiple constraints including the analysis performed in this document, ready access to laboratory-scale facilities for materials testing and measurement, and potential synergies with other national laboratory and university partners.

Acknowledgements

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Acronyms and Abbreviations

ADNA	Accelerator Driven Neutron Application Corporation
AFRL	Air Force Research Laboratory
AHTR	advanced high temperature reactor
AlN	aluminum nitride
ARE	Aircraft Reactor Experiment
ASME	American Society for Materials and Engineering
AdvSMR	advanced small modular reactors
AVR	Arbeitsgemeinschaft Versuchsreaktor (German reactor) or Working Group Test Reactor
bcc	body centered cubic
BOP	balance of plant
BWR	boiling water reactor
CDF	core damage frequency
CI	condition index
CRDM	control rod drive mechanism
DBTT	ductile-to-brittle transition temperature
DFR	Dounreay Fast Reactor
DOE	U.S. Department of Energy
EBR-II	Experimental Breeder Reactor II
EM	electromagnetic
EMAT	electromagnetic acoustic transducer
ERM	enhanced risk monitor
F/M	ferritic/martensitic
FBTR	Fast Breeder Test Reactor
FCP	false call probability
FFTF	Fast Flux Test Facility
FMS	fatigue monitoring system
FSV	Fort St. Vrain
GFR	gas-cooled fast reactor
GIF	Generation IV International Forum
HTGR	high-temperature gas-cooled reactor
HTR-10	High Temperature Reactor
HTTR	High Temperature Test Reactor
I&C	instrumentation and control
IASCC	irradiation-assisted stress corrosion cracking
IAEA	International Atomic Energy Agency

IGSCC	intergranular stress corrosion cracking
IHX	intermediate heat exchanger
IMM	interacting multiple model
IPPE	Institute of Physics and Power Engineering
iPWR	integral pressurized water reactor
IThEMS	International Thorium Energy and Molten Salt Technology Company
JNT	Johnson Noise Thermometry
KALLA	Karlsruhe Lead Laboratory
Kr	krypton
LBE	lead-bismuth eutectic
LFR	lead- (or lead-bismuth-) cooled fast reactor
LFTR	liquid fluoride thorium reactor
LMR	liquid metal reactor
LOCA	loss-of-coolant accident
LWR	light-water reactor
MARS	Microfuel Molten Salt Cooled Reactor of Low Power
MBN	magnetic Barkhausen noise
MGET	multireflecting guided wave energy trapping
MPa	megapascal
MSR	molten salt reactor
MSRE	Molten Salt Reactor Experiment
MsSs	magnetostrictive sensors
MWth	megawatt thermal
NDE	nondestructive examination
NGNP	Next Generation Nuclear Plant
NITI	A.P. Aleksandrov Scientific Research Technological Institute
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NS	nuclear submarine
O&M	operations and maintenance
ODS	oxide-dispersion strengthened
ORNL	DOE Oak Ridge National Laboratory
Pb	lead
PCHE	printed circuit board heat exchangers
PFM	phase field modeling
PFR	Prototype Fast Reactor
PHI	physical health index
PHM	prognostics health management

PHWR	pressurized heavy water reactor
POD	probability of detection
PRA	probabilistic risk assessment
PRISM	Power Reactor Innovative Small Module
PWR	pressurized water reactor
PZT	piezoelectric
QMN	Quantitative Micro-Nano
RAPID	Refueling by All Pins, Integral Design
RF	radiofrequency
RI-ISI	risk-informed in-service inspection
RPV	reactor pressure vessel
RTD	resistance temperature detector
RUL	remaining useful life
SCC	stress corrosion cracking
SCWR	supercritical water-cooled reactors
SFR	sodium-cooled fast reactor
SHI	synthetic health index
SHM	structural health monitoring
SmAHTR	small modular advanced high temperature reactor
SSTAR	small secure transportable autonomous reactor
TWR	traveling-wave reactor
UQ	uncertainty quantification
V&V	verification and validation
VHTR	very-high-temperature reactor
WAMSR	waste annihilating molten salt reactor
Xe	xenon

Contents

Figures

Tables

1.0 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. These reactors can present lower capital costs than large reactors, allow for incremental additions to power generation capacity, and support multiple energy applications (e.g., process heat, or operate in tandem with variable sources of renewable energy (Forsberg 2012; Forsberg et al. 2012)). Additionally, SMRs can be introduced through phased construction of modules at a plant site to incrementally achieve a large-scale power park. Consequently, commitment of the full investment for a large plant would not be required up front and concurrent revenue generation would be facilitated throughout later phases of construction and commissioning.

Several concepts for SMRs have been proposed (Abu-Khader 2009; Ingersoll 2009), with integral pressurized water reactor (iPWR) concepts the current front-runner for licensing and deployment. Advanced small modular reactors (AdvSMR), which are based on modularization of advanced reactor concepts using non-light-water reactors (LWRs) coolants such as liquid metal, helium, or liquid salt, may provide a longer-term alternative to LWRs and iPWRs. AdvSMRs generally place more emphasis on passive systems to assure safety. It is anticipated that AdvSMRs can provide advantages over more conventional technologies in the areas of safety and reliability, sustainability, and proliferation resistance. Advanced SMR concepts span a wide range of design maturity, specificity, and concepts of operation, including multi-unit, multi-product-stream generating stations.

Key to the development and deployment of AdvSMRs will be the ability to ensure safe and affordable operation of these reactor designs. 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 (such as cracking, creep or creep-fatigue damage) in passive components, if not addressed in a timely fashion, is likely to result in unplanned plant shutdowns. This is especially important for generally inaccessible passive components and key passive safety system components (such as heat exchanger tubing, primary boundary components, and reactor internals) (O'Donnell et al. 2008). Thus, degradation in all passive components will need to be monitored and well-managed to maximize safety, operational lifetimes, and plant reliability while minimizing maintenance demands, if reduced economies-of-scale are to be overcome. Traditional approaches such as periodic in-service nondestructive inspections are likely to have limited applicability to AdvSMRs, given the expectation of longer operating periods and potential difficulties with inspection access to critical components because of compact designs and submersion of primary-circuit components in pool-type designs. Advanced instrumentation and control (I&C) technologies provide a mechanism for achieving affordability, safety, and reliability of AdvSMRs. Diagnostics and prognostics technologies provide a mechanism for integrated health management of passive components. In particular, health and condition assessment technologies such as prognostic health management (PHM) systems can potentially ensure affordability of AdvSMRs by providing greater awareness of in-vessel and in-containment component and system conditions, thereby:

1. relieving the cost and labor burden of currently required periodic surveillance and in-service inspection (generally during refueling outages),
2. reducing safety and investment protection risks due to a greater understanding of precise plant component conditions and margins to failure,
3. informing O&M decisions to target maintenance activities during refueling outages,
4. supporting a science-based justification for extended plant lifetime by ensuring reliable component operation while avoiding unnecessary component replacement, and
5. supporting extension of operating intervals.

Wider integration of plant condition and lifetime estimates with the plant control systems to mitigate degradation growth has potential to increase (or at least maximize) estimated lifetimes and minimize maintenance demands.

1.1 Diagnostics, Prognostics, and Health Management

While several concepts for prognostic health management exist, they all have certain elements in common. PHM systems encompass several elements including: (1) sensors for performing measurements of both process parameters as well as indicators of degradation; (2) diagnostics algorithms that use the sensor measurements to estimate the condition of the component; (3) prognostics algorithms to calculate the remaining service life of the component with degradation; and (4) interfaces to decision and control systems that are used to make O&M decisions. Keys to effective prognostic health management are the ability to detect incipient failure through increased monitoring, application of advanced in-situ diagnostics tools for degradation severity assessment, and estimation of remaining service life (also often referred to as remaining useful life [RUL]) through the use of prognostic tools (Coble et al. 2012b). The health of a passive component or system may be inferred from measurements of the contributors (such as temperature, stress, and neutron fluence) to degradation, and their effects (such as material microstructural changes) on the materials. Traditional approaches to detect degradation in passive safety systems are based on periodic in-service nondestructive inspection methods (such as those used in current LWRs) during re-fueling or other planned outages (Bond and Doctor 2007). Operating cycles of AdvSMRs, the time between re-fueling or other planned outages, are anticipated to be much longer than the current 1.5–2 years typical for LWR reactors, with some estimates of 20–30 year single-core lifetimes for some reactor concepts (Ingersoll 2009; Tsuboi et al. 2012). In addition, compact designs and submersion of key primary-circuit components, create unique access challenges. Thus, periodic in-service inspections are likely to have limited applicability to AdvSMRs. Approaches that supplement traditional ISI methods using on-line monitoring with in-situ sensors may therefore be necessary, and may also serve as a means to compensate for a relative lack of understanding of long-term structural material behavior in potentially harsh in-vessel environments.

An important related issue is the ability to estimate remaining service life for passive components using a prognostic methodology. Well-founded estimates of remaining lifetimes are necessary as a basis for planning maintenance activities. In particular, the ability to estimate remaining life provides a basis for determining whether continued safe operation (over some pre-determined interval) is possible, whether operating conditions need to be changed to limit further degradation growth (Hines 2009), and whether other mitigation or repair actions are required.

1.2 Objectives and Approach

This report identifies a number of requirements for prognostics health management of passive systems in AdvSMRs, documents technical gaps in establishing a prototypical prognostic methodology for this purpose, and describes a preliminary research plan for addressing these technical gaps. AdvSMRs span multiple concepts; therefore a technology- and design-neutral approach is taken, with the focus being on characteristics that are likely to be common to all or several AdvSMR concepts.

An evaluation of available literature is used to identify proposed concepts for AdvSMRs along with likely operational characteristics. Available operating experience of advanced reactors is used in identifying passive components that may be subject to degradation, materials likely to be used for these components, and potential modes of degradation of these components. This information helps in assessing measurement needs for PHM systems, as well as defining functional requirements of PHM systems. An assessment of current state-of-the-art approaches to measurements, sensors and instrumentation, diagnostics and prognostics is also documented. This state-of-the-art evaluation, combined with the requirements, may be used to identify technical gaps and research needs in the development, evaluation, and deployment of PHM systems for AdvSMRs.

A preliminary research plan to address high-priority research needs for the deployment of PHM systems to AdvSMRs is described, with the objective being the demonstration of prototypic prognostics technology for passive components in AdvSMRs. Greater efficiency in achieving this objective can be gained through judicious selection of materials and degradation modes that are relevant to proposed AdvSMR concepts, and for which significant knowledge already exists. These selections were made based on multiple constraints including the analysis performed in this document, ready access to laboratory-scale facilities for materials testing and measurement, and potential synergies with other national laboratory and university partners.

1.3 Organization of Report

Section 2.0 describes an overview of advanced reactors and AdvSMRs. Included in this section is a discussion of expected operational characteristics that are likely to present unique challenges to implementation of advanced diagnostic and prognostic technologies for passive component degradation management, and therefore drive the requirements for PHM. This is followed, in Section 3.0, by a description of functional requirements for PHM. Section 4.0 presents a state-of-the-art assessment of diagnostic and prognostic technologies for materials and passive components. This is followed by an assessment of the research gaps and technical needs in realizing PHM (Section 5.0) and a preliminary research plan to demonstrate key PHM concepts related to AdvSMR passive components and to address high-priority gaps (Section 6.0). Section 7.0 summarizes the findings and briefly describes the next steps. Finally, references are contained in Section 8.0.

A set of appendices are also included that provide supplemental detail about different elements discussed in this document. These include details on advanced reactor concepts evaluated for this analysis (Appendices A–G), and details on sensors for health monitoring of passive structures in extreme environments (Appendix H).

2.0 Advanced Small Modular Reactors

Small modular reactors (SMRs) are generally defined as those having electrical output less than ~300 MW, and are designed to be modular. Advanced SMRs (AdvSMRs) refer to a specific class of SMRs and are based on modularization of advanced reactor concepts. SMRs (whether light-water cooled or based on advanced reactor concepts) are designed to incorporate multiple modules (which may or may not have shared components and structures) at a single location, comprising a full “plant” (Figure 2.1). The specific features of advanced reactors concepts and modularized deployment provide unique challenges and needs for advanced instrumentation, control, and human-machine interface (ICHMI) applications in AdvSMRs. The following sections provide an overview of AdvSMRs by introducing several advanced reactor concepts and then discussing several general features of AdvSMR deployment.

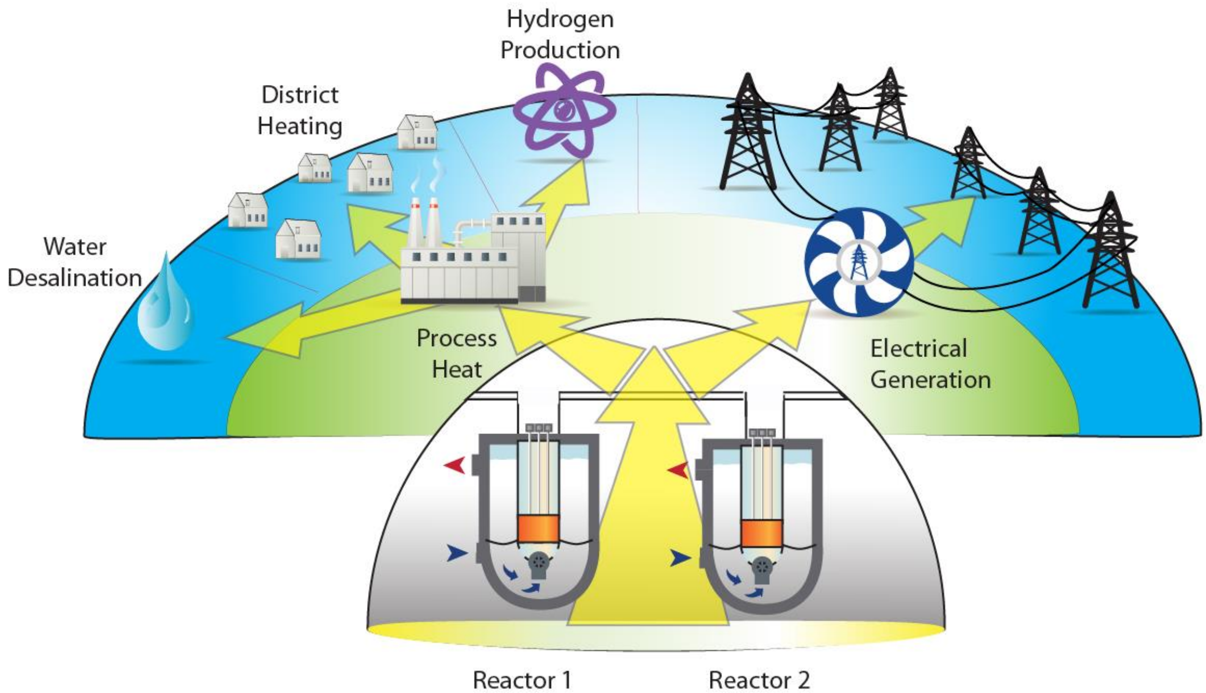


Figure 2.1. Illustration of AdvSMR Modules Used for Cogeneration of Electricity and Process Heat for a Variety of Possible Applications

2.1 Advanced Reactor Concepts

AdvSMRs are based on advanced reactor concepts with potential deployment several decades away. The Generation IV International Forum (GIF) identified six key advanced nuclear power generating technologies to help focus future international resources and efforts to establish the feasibility and performance of future generation reactors (expected deployment beyond 2030). Candidate technologies proposed by the GIF include (NERAC 2002; Abram and Ion 2008):

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

The Generation IV technology roadmap outlines the goals for future nuclear energy generation systems, which include improvements in safety and reliability, sustainability, proliferation resistance, and economics. Many of the Generation IV concepts target alternative missions such as the generation of process heat, heat for water desalinization, or heat for hydrogen production. In addition, coupling with advanced electricity production cycles such as He-Brayton, supercritical CO_2-Brayton, and supercritical-water-Rankine cycle is a priority of Generation IV systems (NERAC 2002). A brief table is provided to summarize operating bounds for the advanced reactor technologies selected by the GIF (see Table 2.1). The different reactor concepts are briefly described next, with detailed descriptions provided in Appendices A–E.

Table 2.1. Summary of Advanced Reactor Concepts Parameters

Concept	Outlet Temperature	Pressures	Neutron Spectrum	Average Power Density
SFR[a]	530°–550°C	Atmosphere	Fast	350 MWth/m^3
VHTR[a]	900°–1000°C	1–10 MPa	Thermal	6–10 MWth/m^3
LFR[b]	~550°C (near term) 750°–800°C (far term)	Atmosphere	Fast	---
MSR[c]	700°–850°C	Atmosphere	Thermal and Epithermal	22 MWth/m^3
GFR[a]	up to 850°C	5–9 MPa	Fast	100 MWth/m^3
SCWR[d]	510°C	25 MPa	Thermal or Fast	100 MWth/m^3

(a) From Abram and Ion (2008)
(b) See Appendix A
(c) See Appendix B
(d) See Appendix C

2.1.1 Sodium Fast Reactors (SFRs)

The sodium-cooled fast reactor (SFR) features very high core power densities, high reactor outlet temperatures, low system pressure (atmospheric), and a fast neutron spectrum. An advantage of sodium coolant is its relatively high heat capacity, which enables very efficient heat transfer from the core. However, internal core and reactor vessel components are exposed to a significant fast neutron flux. While sodium has the advantage that it does not corrode steel components, it does react chemically with air and water so the design of SFR components must take this into consideration.

The primary coolant system can either be arranged in a pool layout (a common approach, where all primary system components are housed in a single vessel), or in a compact loop layout. Several domestic SFR designs (e.g., Power Reactor Innovative Small Module [PRISM], traveling-wave reactor [TWR]) use a pool-type reactor vessel design containing the reactor core, primary heat exchanger, and mechanical or electromagnetic (EM) pumps. An inert cover gas system is required to maintain sodium purity and to prevent the sodium from reacting with moisture in the air. In general, penetrations into the reactor vessel occur at the top of the vessel. Further information regarding modularized SFR concepts is provided in Appendix D.

2.1.2 Very-High-Temperature Gas Reactors (VHTRs)

The very-high-temperature gas reactor (VHTR) is an evolution of high-temperature gas-cooled reactor (HTGR) technology. VHTRs are distinguished by the intent to operate at greater temperatures (up to 1000°C) to facilitate hydrogen production, creating significantly greater materials challenges. The main characteristics of VHTRs include the use of helium gas for coolant, use of graphite for major core and in-vessel components, low power density, high operating temperature, use of coated fuel particles, and reliance on passive mechanisms for heat removal in the event of a loss-of-coolant accident (LOCA). These design characteristics help maintain the integrity of the fuel and prevent the release of radioactive materials in the event of severe accidents. Another significant advantage of the helium gas reactor designs is that they enable direct coupling to He-Brayton energy conversion cycles.

Two major VHTR design variants include the pebble bed and prismatic block reactors. In the pebble bed reactors, coated fuel particles are embedded in spherical graphite pebbles, which circulate through the core. Reactivity is controlled through the distribution of pebbles loaded with fuel and absorber materials. This reactor concept enables on-line refueling as individual pebbles can be removed from the core and fresh pebbles added continuously. In prismatic block reactors, the coated fuel particles are embedded in a graphite matrix that is formed into prismatic blocks, so that the reactor must be shut down for refueling and control rods are employed for reactivity control. Appendix E contains further information about VHTR concepts.

2.1.3 Lead- (or Lead-Bismuth-) Cooled Fast Reactors (LFRs)

The LFR system features a high reactor outlet temperature, high power density core, low system pressure, and a fast neutron spectrum. The liquid metal coolant, either lead (Pb) or lead/bismuth eutectic (LBE) can utilize natural convection for heat removal or can be pumped, depending on core power requirements. Some LFR designs, like the SSTAR (small, secure, transportable, autonomous reactor) for small grids or developing countries, use a factory-built “battery” or “cassette” design and are optimized for power generation over long periods of time (10–30 years) without refueling.

Potential issues with lead-cooled technologies arise from the need to avoid solidification of the coolant, which can render the reactor inoperable. Lead is the heaviest of all proposed advanced coolants, making it expensive to pump. Additionally, corrosion of structural materials can occur as a consequence of the coolant chemistry. Inhibiting corrosion requires the ability to carefully control the oxygen level in the coolant. Further information regarding LFR concepts is provided in Appendix A.

2.1.4 Molten Salt Reactors (MSRs)

The MSR features moderate to high power density, high reactor outlet temperatures, low system pressure, and in some variants a fluid-fueled core where the molten salt coolant contains dissolved fuel that allows for refueling without reactor shutdown. This reactor type can be designed to operate with either a thermal or fast neutron spectrum and has the unique characteristic that very high fuel burn-up can potentially be achieved because fuel performance in the fluid-fueled concepts is not limited by fuel cladding strength and ductility considerations. Other designs (e.g., advanced high temperature reactor [AHTR], Microfuel Molten Salt Cooled Reactor of Low Power (MARS), small modular advanced high temperature reactor [SmAHTR]) use molten-salt as the coolant combined with a more conventional solid fuel approach. MSRs can be used for electricity generation, actinide burning, and hydrogen and fissile fuel production. MSR concepts typically employ a mixture of lithium and fluoride salts as coolant. The salt mixture can be highly corrosive if impurity levels are too high. Additional information about MSR concepts may be found in Appendix B.

2.1.5 Gas Fast Reactors (GFRs)

The main characteristics of gas fast reactors include operation with a fast neutron spectrum, robust refractory fuel, high operating temperature, use of helium gas coolant, and potential to couple directly with He-Brayton power conversion cycles. To enable a fast neutron spectrum, the GFR does not include graphite moderators. The relatively poor heat-transfer properties of a gas coolant place severe requirements on fuel and cladding components to survive extreme temperatures. This contrasts with VHTR and HTGR concepts in which the presence of large graphite masses provides a large thermal inertia to limit heating rates in the event of an accident. Additional information about GFR concepts may be found in Appendix E.

2.1.6 Supercritical Water-Cooled Reactors (SCWRs)

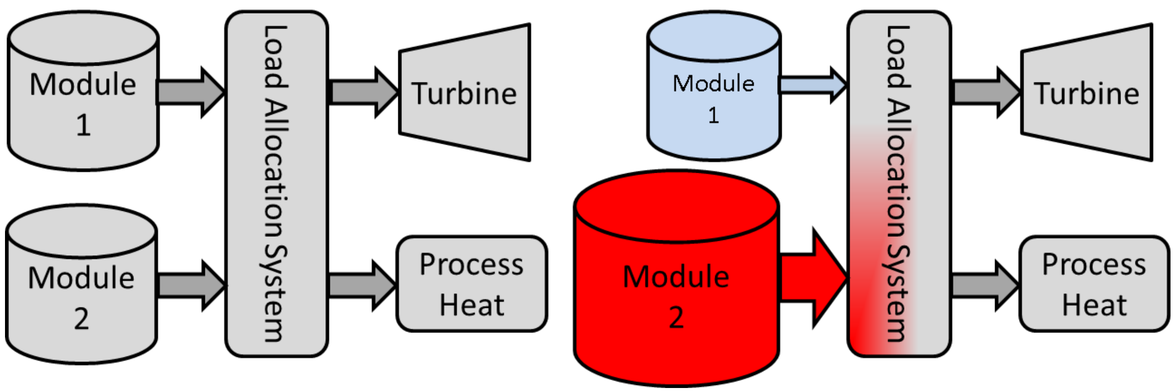
The SCWR is a water-cooled reactor that operates above the thermodynamic critical point of water. The reactor operates at much higher temperatures and pressures than LWRs, resulting in higher operating efficiencies when compared to current LWRs (44% compared to 32% in current LWRs). These reactors can be designed to operate with either a thermal or fast-neutron spectrum, providing flexibility in deployment and generation options. Additionally, the energy conversion technology associated with the secondary side of the reactor plant has been fully developed and commercialized by the coal power industry over the last several decades. The SCWR eliminates several major components, such as steam dryers, recirculation pumps, and steam generators. For additional information on SCWR concepts, the reader is referred to Appendix C.

2.2 Advanced Small Modular Reactor Characteristics

This subsection discusses several characteristics of AdvSMRs that are expected to be relevant to the design and implementation of PHM systems. These characteristics are applicable to multiple advanced reactor concepts, and are determined from consideration of likely scenarios for AdvSMR operations and maintenance, concepts of operation, balance-of-plant configurations, materials and materials degradation, and refueling intervals.

2.2.1 Operations and Maintenance (O&M)

Staffing and control room requirements have been identified as a significant technical and policy issue for multi-module SMR installations (Cetiner et al. 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. This concept is illustrated in Figure 2.2 with color shading and symbol sizes emphasizing an increase or decrease in output from a given module in a two-module system.

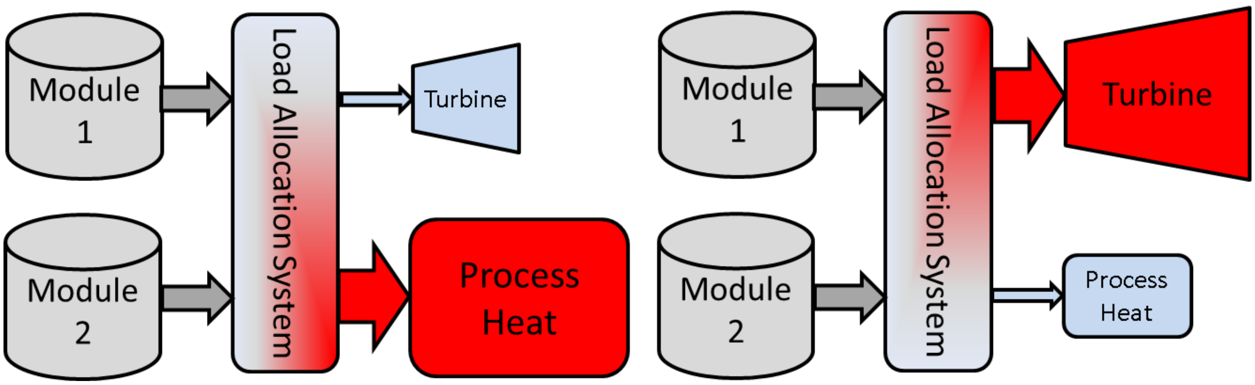


Note: Light blue shading represents a decreased load, while red shading represents increased loading.

Figure 2.2. Illustration of Uneven Load Redistribution among Modules to Compensate for Loss of Load Tolerance in Module 1

2.2.2 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 et al. 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 et al. 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 and Forsberg 2011; Forsberg 2012; Forsberg et al. 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. In such scenarios, the distribution of load over balance-of-plant (BOP) components will be subject to daily and seasonal load variations. Redistribution of load to and from the generation of electricity and process heat is depicted in Figure 2.3.



NOTE: In this figure, the product stream to which the load is shifted to is emphasized with red color and enlarged symbols. The product stream to which the load is shifted from is emphasized using light blue color and smaller symbols.

Figure 2.3. Depiction of Changing Load Allocation between Electricity and Process Heat Product Streams

2.2.3 Advanced Reactor Materials and Degradation

Materials for advanced nuclear reactor applications generally consider radiation damage resistance, environmental stability, and high-temperature capability as paramount (Yvon and Carre 2009; Zinkle and Busby 2009). Volumetric swelling and dimensional stability, embrittlement, stress corrosion cracking, irradiation and thermal creep, and corrosion are critical materials degradation issues. To this list can be added weldability and compatibility 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.

Table 2.2 is a list of potential materials for a number of advanced reactors. Some descriptive information as to their advantages and disadvantages are provided. In many cases, additional data is required to fully appreciate each material’s potential as a nuclear material. The GFR and VHTR both require improved oxidation and strength at elevated temperatures, approaching 1000°C for accident scenarios, but desiring operation at 800°C and higher. Studies have shown that Ni-based alloys, such is Inconel 617 and Haynes 230, have oxidation and strength limitations above 800°C and cannot be used above 850°C (Hittner et al. 2011; Buckthorpe and Genot 2012; Hittner et al. 2012). This is due to both oxidation degradation as well as loss of strength due to thermal creep. GFR and VHTR designs call for graphite core internals and an outstanding issue for graphite is that new validation data are required because the loss of previous manufacturers means that the graphite is synthesized differently than in the past. Many advanced reactor designs incorporate advanced materials listed in Table 2.2, but more conservative designs use existing LMR or pressurized water reactor (PWR) steels (Hittner et al. 2012). This can be either due to cost impacts or to a lack of large forging experience.

Table 2.2. Candidate Materials and Considerations

Material Type and Examples	Reactor Designs Considered	Potential Uses	Description of Advantages (A), Disadvantages (DA), and Likely Degradation Modes (DE)[(a)]
Ferritic/Martensitic (F/M) Steels • Mod 9Cr-1Mo • HT-9 • F82H • T91 • RAFM or Eurofer97	• VHTR • SFR • GFR • LFR	• RPV • Fuel cladding • Core internals	**A** High-temperature creep strength Radiation damage tolerance **DA** Limited to T < 825K (550°C) Incomplete liquid metal corrosion data **DE** Oxidation/corrosion (liquid metal) Fracture toughness/embrittlement Creep/irradiation creep
ODS F/M Steels • MA957 • 14YWT • Aermet (nanostructured precipitation steel)	• VHTR • SFR • GFR • LFR	• RPV • Fuel cladding • Core internals	**A** High-temperature creep strength further improved Radiation damage tolerance further improved Increased utility to T < 1175K (900°C) **DA** Reduced liquid metal corrosion resistance and lack of data Reduced fracture toughness Stability of dispersion or precipitate **DE** Oxidation/corrosion (liquid metal) Fracture toughness/embrittlement Phase stability and property decrease
Ceramics/Composites • C/C • C/SiC • SiC/SiC	• VHTR • GFR	• Core internals • Fuel cladding • Heat exchanger	**A** High-temperature strength much improved Radiation damage tolerance increased Increased utility to T < 1375K (1100°C) **DA** Incomplete radiation damage data Incomplete liquid metal corrosion data Low starting fracture toughness Low thermal conductivity **DE** Fracture toughness/embrittlement Creep/irradiation creep of fibers
Ni-base Superalloys • Hastelloy X and XR • Udimet 720 • Inconel 617 • Haynes 230	• VHTR • GFR	• Heat exchanger	**A** High-temperature strength and oxidation **DA** Incomplete radiation damage data Incomplete corrosion data **DE** Creep and oxidation

(a) It is understood that advantages and disadvantages are relative to either existing LWR or PWR materials or to other advanced materials. These are relative considerations.

LMR materials choices revolve around liquid metal compatibility for the most part and high-temperature properties in the 500°C to 650°C range (Furukawa et al. 2009). Here, the 12-Cr steels perform well with sodium where lower Cr-content steels, such as a 2.25Cr-1Mo steel, exhibits strength degradation in flowing sodium because of decarburization. Newer ODS ferritic steels exhibit some loss of Ni but no strength degradation and are currently being studied for LMR fuel cladding (Furukawa et al. 2009).

2.2.4 Balance of Plant

As previously noted, coupling with advanced electricity production cycles such as He-Brayton, supercritical CO_2-Brayton, and supercritical water-Rankine cycle is a priority of Generation IV systems. The characteristics of AdvSMRs when coupled with one of these production cycles bring both new challenges as well as opportunities for the deployment of new technologies. The balance of plant is a large contributor to the cost of a plant and closed-cycle gas turbines are potentially more simple, compact, and less expensive than turbine generators based on steam cycles, facilitating shorter construction periods and reactor modularity (Dostal 2004). He-Brayton cycles require an outlet core temperature near 900°C to achieve attractive efficiencies. No et al. (2007) provides an overview of Brayton cycle work performed in Germany and Japan applicable to HTGR systems. One of the design challenges noted for helium turbines versus air or steam turbines is operation at high pressure with a low pressure ratio. Further, it is noted that helium turbines have a shorter blade height and greater number of blades and that the horizontal orientation is preferable to vertical orientation.

Coutsouradis et al. (1978) review superalloys in comparison to other alloys for several high-technology applications. With respect to aircraft turbine engines, a challenge has been to maintain ductility and resistance to creep. The application to helium turbines for HTGRs and LFRs was also considered. For HTGRs, it is noted that impurities in the He coolant can lead to degradation of austenitic stainless steels and superalloys through surface reactions with elements in the alloy that lead to oxidation, and result in surface cracking. The gas/metal reactions cause significant reduction in stress capability, especially in the 700°C–900°C range where superalloys would be used. As HTGR environments become more “dry,” they become more reducing and carburization becomes a greater concern. Several failure analyses of turbojet engine blades have been reported in the literature (Park et al. 2002; Mazur et al. 2005; Kargarnejad and Djavanroodi 2012). Failures were attributed to either thermal creep, fatigue, or a mixture of creep/fatigue.

The supercritical CO_2 cycles have more moderate temperature requirements in the 500°C to 700°C range. The principal advantage of a supercritical CO_2-Brayton cycle compared to a He-Brayton cycle is reduced compression work, resulting in reduced turbine and compressor stages and system simplification. Supercritical CO_2 cycles are highly recuperative, motivating the minimization of heat exchanger size and cost. Thus, printed circuit board heat exchangers (PCHE) for supercritical CO_2 cycles have been the subject of investigation by some (Hejzlar et al. 2006).

2.2.5 Refueling Intervals

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 operated up to 30 years without refueling (Tsuboi et al. 2012). The SSTAR is another advanced reactor concept with targeted operation periods of 15 to 30 years between refueling activities (Smith et al. 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.

2.3 Relevant Operating Experience

Advanced reactor concepts have been constructed and operated worldwide, and associated operating experience is documented in numerous publications. The operating experiences of several advanced reactor concepts are summarized in Appendix G, along with information on the specific reactors from which this experience is derived. It is likely that lessons learned from the construction and operation of advanced reactors will also be relevant to the operation of future AdvSMRs. The most extensive operating experience exists for the SFR and HTGR concepts. In the case of other reactor concepts, the operating experience is either very limited (e.g., LFRs and MSRs) or does not exist to date (e.g., GFRs and SCWRs).

Some significant themes and highlights emerge from the information described in Appendix G. The operational experience for 22 SFRs (with a combined experience of approximately 400 reactor-years) is documented in numerous reports and articles with comprehensive reviews on the subject provided by Guidez et al. (2008) and Raj et al. (2010). Passive component degradation of relevance to the present study include degradation in heat exchangers, steam generators, and piping (resulting in sodium leaks), defective welds, poor material choices, fabrication flaws in materials (in both active and passive components), etc. These issues are attributable to a number of factors including manufacturing deficiencies, thermal shock, flow induced vibration, fretting, fatigue, and differences in thermal expansion coefficients at dissimilar metal joints. In addition, impurity ingress events, such as air or moisture intrusion, have resulted in unintentional reactivity insertions and resulted in shutdowns. Other issues are related to sticking of components, such as the rotating plug, as a consequence of sodium condensation.

Operating experience for several of the HTGRs is documented in multiple reports including Beck (2010), Brey (1991), Goodjohn (1991), and Copinger and Moses (2004, NUREG/CR-6839). Issues of relevance include corrosion of in-vessel and in-core components (including stress corrosion cracking of control rod drive mechanism cables and oxidation of graphite moderator blocks) due to moisture and oil intrusion events. Graphite dust production has caused blockage of primary circulator filters and fouling of heat exchanger tubes in High Temperature Test Reactor (HTTR) and High Temperature Reactor (HTR-10).

To date, only two MSRs were operated (both at Oak Ridge National Laboratory (ORNL) (Rosenthal 2009). Similarly, there is limited experience with LFRs (Weaver et al. 2001). In MSRs, the Hastelloy-N material used in the reactor vessel and piping was subject to irradiation hardening and cracking (MacPherson 1985). For LFRs, corrosion appeared to be among the dominant materials issue, with an active oxygen-control system capable of controlling the corrosion process (Loewen and Tokuhiro 2003).

3.0 Functional Requirements for PHM Systems in Advanced SMRs

Requirements for a PHM system for passive AdvSMR components will be driven by the factors discussed in Section 2.0, and include (Figure 3.1) the reactor design, the concepts of operation (including operations and maintenance practices), materials used for risk-significant components, operating environment (including temperature and fluence), degradation mechanisms in the selected materials as a result of the operational environment, the necessary interface to the plant supervisory control system, and relevant operating experience. Other drivers for these include regulatory requirements that are expected to govern all aspects of the lifecycle of a component, from design to fabrication and deployment to eventual decommissioning and disposal. It is likely that goals for reliability and integrity for each component will need to be defined (for example, as proposed under the ASME Boiler and Pressure Vessel Code, Section XI, Division 2), as the choices made in designing, deploying, and operating these components will be influenced by these goals. In turn, these choices dictate the ability to operate AdvSMRs safely and reliably over the long-term, and help ensure the viability of AdvSMRs.

Functional requirements identified using these drivers, along with a brief discussion of the basis for each requirement, are discussed next.

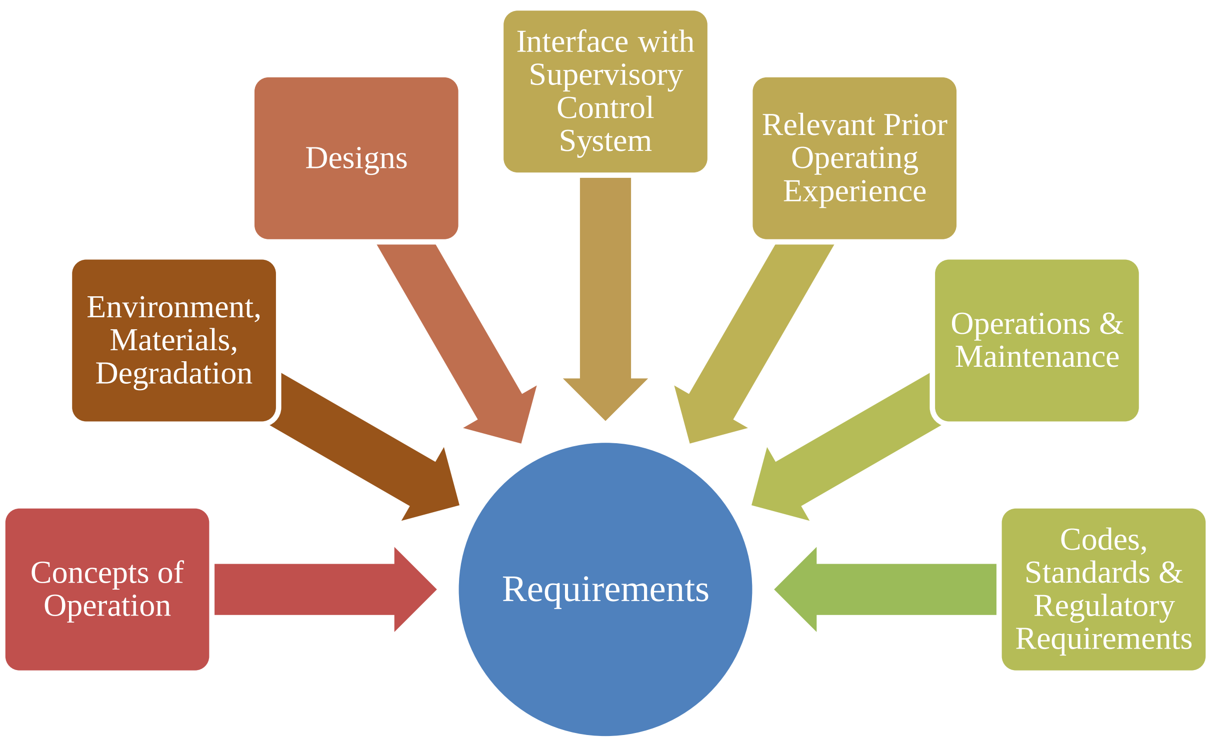


Figure 3.1. Some of the Factors that Drive Requirements of PHM Systems for Passive AdvSMR Components

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 result in 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. Anticipated conditions include high temperatures (> 550°C), corrosive coolant media, and fast neutron spectra (in some designs).
- High sensitivity, to ensure that reliable measurements from earlier stages of degradation are possible. This requirement is a result of the fact that many degradation mechanisms (such as radiation or thermal embrittlement and high-temperature creep) in AdvSMRs are distributed throughout the material volume, and macro crack formation may not occur until shortly before failure for some mechanisms. This limits the ability to perform usable RUL estimations. Measurements that are sensitive to pre-crack forms of degradation can potentially provide sufficient early warning of impending failure.
- Capability to quantify the amount of degradation from the measurements. This requirement ensures the ability to accurately estimate the present state of damage in the material and/or component from the measurement. This information, along with any available confidence bounds on the information, is the input to a PHM system for RUL estimation. The ability to accurately quantify the present state of damage may require algorithms that can integrate information from multiple sources (Section 3.2).

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. In these scenarios, greater reliance on global and local (i.e., at the component or sub-component level) measurements may be required to ensure timely information on component condition is available.

In general, measurement data may be of process parameters (such as temperature or mechanical loading) that act as stressors on the materials used in passive components, degradation indicators (such as the response of nondestructive evaluation sensors to microstructural changes) due to ongoing degradation growth, or both. All available information will need to be integrated appropriately to ensure that an accurate estimate of the level of degradation as well as the RUL may be obtained. This may necessitate models (either derived from pre-existing data sets, or physics-based models derived from first principles) that relate the level of degradation, stressor and/or condition measurement, and the rate of degradation accumulation. Further, materials used in passive components in AdvSMRs may be subject to multiple stressors that can impact the type of degradation and the rate of failure. For instance, a component subject to thermal creep may also be vulnerable to fatigue. Ensuring accuracy of prognostic information in these cases will require the fusion of information from diverse sources, such as stressor and condition measurements, and global and local measurement data from one or more sensors.

3.3 Address Coupling Between Components or Systems, and Across Modules

The potential for interaction of components and systems within a single module and across multiple modules in AdvSMRs introduces complexity that, when combined with the uncertainty introduced by load-following operation, can make it difficult to determine an optimal maintenance schedule that ensures economic viability while not compromising safety. A primary role of the PHM system in AdvSMRs is therefore to determine if a component can continue to operate until the next scheduled outage, or to help in determining an appropriate maintenance schedule. PHM for shared or interacting components will clearly need to consider operating conditions and loads in all the connected modules/units; this may include normal power transients, reactor trips, reactor runbacks, and mismatched conditions across modules. Such an arrangement results in complex load and stressor profiles on the components being monitored, and challenges stressor-informed prognostics. Additionally, the operation of connected modules may affect non-shared structures through these interconnections, although this potential effect is currently not quantifiable. These challenges point to a functional requirement for PHM systems to be able to integrate information on interconnected systems or components and to use complex stressor profiles for accurate RUL estimates. It is likely that these same challenges will make it desirable for PHM systems to synergistically work with the plant control systems (Section 3.6).

3.4 Incorporation of Lifecycle Prognostics

The lifecycle of components used in AdvSMRs generally transitions from fabrication and installation to operation, with potential degradation and failure as end-of-life. Repairs or other mitigation activities will change the time horizon for each of these phases, as do changing operational conditions such as unanticipated contamination of the primary system coolant, which can cause and accelerate component degradation (operating experience discussed in Appendix F). Degradation in materials and components also follows a lifecycle, going from precursor formation to initiation of microscopic cracks followed by coalescence and macro-crack growth to failure.

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

The requirement for integration of PHM systems with risk monitors comes from two related drivers. First, 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) (IAEA 2010). While current risk assessments are based on the use of core damage frequency (CDF) as the risk metric, other metrics related to economics may also be relevant (Coble et al. 2013). Second, as discussed in Section 3.6, 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.

It is worth noting that an assessment of risk-significance, especially if it is limited to safety-significant passive components, may not be the sole indicator of whether PHM deployment should be considered, as: (a) degradation growth may occur fastest in locations that are not considered to be high-risk, and (b) taking a plant off-line for unplanned maintenance or repairs (even on non-risk-significant components) will impact the economics of operation. Thus, it is likely that achieving any reliability and integrity goals for passive components will require careful choices in design, fabrication, operation and maintenance, with PHM systems forming the final level of defense-in-depth for selected components.

3.6 Interface with Plant Supervisory Control System

As discussed in Section 3.3, 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. A detailed specification for the interface between the two systems is presently undefined.

4.0 State of the Art in Prognostics Health Management Relevant to Passive Components in Advanced SMRs

In general, a PHM system for passive components will consist of the following elements: 1) sensors to measure variables of relevance to component health, 2) diagnostic algorithms or models to interpret measurement data in terms of present level of component health, and 3) algorithms or models to predict future component states (especially failure) based on current and past measurements. Following the prediction of RUL, mitigating actions or O&M decisions can be made and the whole process is repeated starting with an updated set of measurements. This process is illustrated in Figure 4.1.

The applications for PHM systems include many defense systems, wind turbines, oil field, and power plant applications. The current applications are generally at the component and sub-system level, and these are increasingly maturing. Many of the proposed methods are vibration-based with supplemental information and data utilized to refine and bound life and condition assessment. Both degradation and stressors are being monitored (Jarrell et al. 2004). System-level and plant-level prognostics remains, in many cases, work in progress as the ability to provide a single condition metric for many components and systems is challenging. Much of the current capability in prognostics is related to active component applications and relies on pattern recognition for anomaly detection, which is then used to trigger condition-based maintenance activities.

The following subsections summarize the state of the art of sensors and measurements relative to passive component health assessment, and algorithms and models for performing diagnostics and prognostics on passive AdvSMR components. This state-of-the-art assessment is based on a survey of available literature.

4.1 Measurements State-of-the-Art

The health of a passive component or system may be inferred from measurements of the current extent of active degradation and degradation drivers. These measurements are often referred to as condition and stressor measurements, respectively. Typical stressor measurements will include measurements of environmental or process variables in a nuclear reactor while condition measurements for passive components may refer to NDE measurements performed on materials. In some cases, environmental and process variables may change in response to degradation of a passive component. In this context, measurements of changes in environmental and process variables can be considered condition measurements. For example, simulations of an integral PWR design indicate that deviations in steam generator exit temperature from expected behavior may provide a condition indicator for heat exchanger fouling (Coble et al. 2010; Hines et al. 2011).

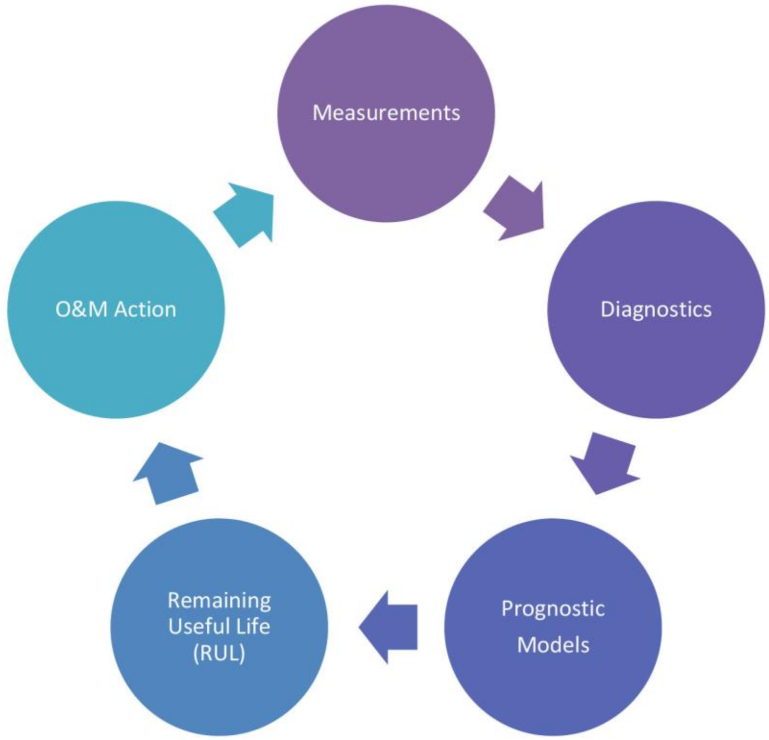


Figure 4.1. Diagram Illustrating the Process of PHM for Passive Components in AdvSMRs

Measurements can also be distinguished as being global or local, which describes the quantity or volume of a structural component that is sampled during an interrogation. A global measurement normally interrogates a significant portion of a component while local measurements interrogate portions in the immediate vicinity of a sensor. Another way to distinguish measurements is with respect to their frequency, where they may be categorized as continuous or periodic. Global measurements are often collected continuously (or at least more frequently than local measurements) during reactor operation (on-line), while local measurements are typically obtained periodically, such as during plant outages. Although local measurements are obtained less frequently, they are usually more descriptive than global measurements.

Figure 4.2 provides a notional illustration of candidate locations on an AdvSMR module for placement of sensors for performing process measurements, global condition measurements, or local NDE measurements (in this example, mostly located at weld joints between components). In general, a process measurement or global condition measurement is considered applicable to the entirety or a significant region of the component to which the sensor is mounted. Therefore, symbols for process measurements and global condition measurements in Figure 4.2 are only meant to associate measurements with a component and are not meant to accurately depict sensor placement. In practice, an assessment may be performed to prioritize sensor placement to ensure maximum coverage while minimizing the possibility of surprise failures.

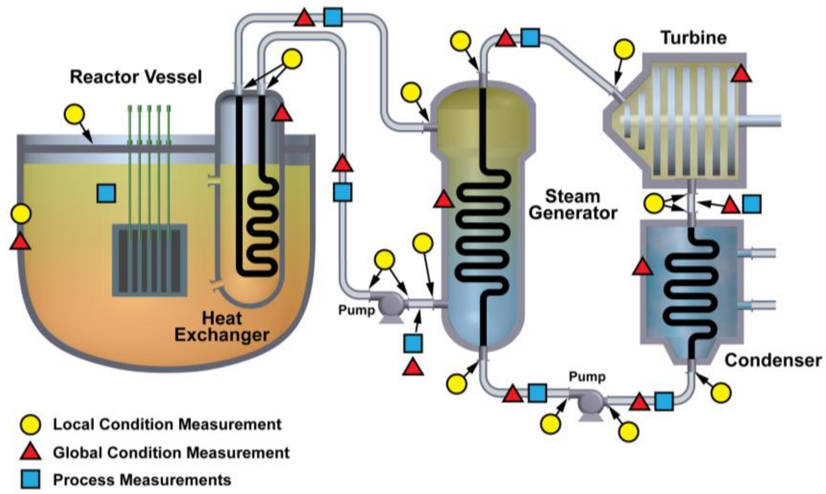


Figure 4.2. Notional Illustration of Candidate Sensor Locations in AdvSMRs for Performing Local Condition, Global Condition, and Process Measurements

One specific issue that has generated significant interest in measurements on passive components is that of reliability. The detection of flaws in materials is subject to uncertainty from measurement noise, material microstructure, surface condition and access, and human factors. Studies to evaluate the reliability of different (off-line, local) NDE measurement methods have resulted in information about the probability of detection (POD) (Berens and Hovey 1981, 1983) of a flaw of specified size, false call probability (FCP), and associated confidence bounds based on flaw type, material, and inspection technique (Singh 2000). For nuclear power applications, NDE reliability studies have resulted in performance demonstration requirements codified in the ASME Boiler & Pressure Vessel Code (Section XI, Appendix VIII) that are used to qualify equipment, procedures, and personnel prior to allowing their use in ISI. The use of automated analysis methods for flaw detection and diagnostics adds a layer of complexity to the assessment of reliability. Techniques for the qualification of such tools are being evaluated (EPRI 2009).

The following sections summarize the state-of-the-art for measurements, specifically, process/environmental measurements, global condition monitoring measurements, local NDE measurements, and sensors for harsh environments.

4.1.1 Environmental and Process Measurements

An overview of present and emerging sensors for environmental and process measurements for nuclear power plants is presented in Coble et al. (2012a). Conventional light water reactors employ sensors for measurements of temperature, pressure, flow, neutron flux, and water chemistry (e.g., pH, and conductivity) (IAEA 2011a). Electrochemical potential is an important parameter related to corrosion and described as a commonly measured electrochemical parameter at high temperatures and high pressures in the nuclear power industry (Yang and Chiang 2010).

Hashemian and Jiang (2009) report that thermocouples and platinum RTDs are employed for measurements of temperature in LWRs. Measurements of neutron flux are mostly accomplished using gas filled detectors such as fission chambers and ion chambers. Out-of-core fission chambers serve as global power indicators for PWRs, which typically include monitors to track power levels from start-up to full power. BWRs contain several fission chambers distributed throughout the core to monitor power levels. In addition to gas detectors, self-power neutron detectors may be employed for flux distribution mapping Knoll (2000). Electromechanical pressure transmitters are used for measurements of pressure and differential pressure transmitters are used for measurement of flow velocity (Hashemian et al. 1989; Hashemian et al. 1993).

Advanced and emerging sensing technologies are discussed in the context of multiple applications. The motivations for advanced sensor development mostly include improvements in accuracy, improved tolerance to harsh environments, and to measure previously immeasurable variables. An overview of several emerging technologies that are considered to have safety significance with applications in future nuclear power reactors or to upgrades at existing reactors is described in NUREG/CR-6812 (Wood et al. 2006) and NUREG/CR-6888 (Korsah et al. 2006). Hashemian et al. (1998) analyze several advanced sensing technologies to gauge their feasibility for replacing outdated or obsolete technologies in the nuclear industry or to improve plant aging management and maintenance activities in NUREG/CR-5501 (Hashemian et al. 1998). Ball et al. (2012) provide an overview of several emerging measurement technologies with potential application to HTGRs. Rempe et al. (2011) discuss potential technologies for in-pile measurements in materials test reactors including measurements of temperature and neutron flux. Emerging sensor technologies for application to harsh environments are discussed further in Subsection 4.1.4.

4.1.2 Global Condition Measurements

Vibration monitoring and neutron noise analysis techniques are both described as condition monitoring techniques applicable to detecting the degradation of core internal components undergoing flow-induced vibration in LWRs (Damiano and Kryter 1990; IAEA 2008). Damage to components such as thermal shields, core barrels, and instrumentation thimbles have been detected using these measurements. Neutron noise measurements are useful only for components located near the core, while vibration sensors may be used to monitor structural components located farther from the core.

Acoustic emission is another measurement technique that has been used for global condition monitoring of passive components in the nuclear power industry. Meyer et al. (2011; 2012) provide an overview of acoustic emission and its use for on-line monitoring of structures in the nuclear power industry. Some of the global condition measurement applications include the detection of leaks in pressure boundary components (Kupperman et al. 2004) and monitoring for loose parts in the primary system. Metal waveguides can be employed for performing acoustic emission monitoring of components at high temperatures, but with reduced sensitivity.

Crack detection and monitoring has been one of the main applications considered for acoustic emission monitoring in the nuclear power industry. However, the noise generated by reactor coolant loops and the attenuation of acoustic emission signals as they propagate through large structures limits this capability. Experiences applicable to continuous flaw monitoring in nuclear reactor structural components suggests that quantification of flaw size from acoustic emission signals in large complex structures can be difficult and that cracks must grow at a sufficient rate to be detected reliably (Bentley 1981; Runow 1985; Jax and Ruthrof 1989). A demonstration of acoustic emission for monitoring the growth of IGSCC flaws on a reactor pressure vessel nozzle-to-safe end dissimilar metal weld was performed at Limerick Unit 1 using waveguides (Hutton et al. 1993) after initial detection using other NDE methods. Some sensor degradation was observed during the two fuel cycles. Currently, AE is the only on-line monitoring technique sanctioned by the ASME Boiler and Pressure Vessel Code for performing in-service monitoring of components important to safety.

Guided ultrasonic wave techniques are also discussed as an emerging technology in the nuclear industry for numerous applications related to pipe and vessel inspections. Section V of the ASME Boiler and Pressure Vessel Code has established a working group on guided ultrasonic waves to incorporate this technology. Guided ultrasonic wave inspections can be performed with minimum removal of insulation. Guided ultrasonic waves were originally devised for pipeline corrosion monitoring in the oil and gas industries (Lowe et al. 1998; Alleyne et al. 2001) and sensitivity is often reported in terms of percent cross-sectional wall loss, with sensitivities for typical axially guided wave modes on the order of 1%–5%. Potential improvements in sensitivity may be achieved through better signal processing techniques and phased-array–type guided wave implementations (Lowe and Cawley 2006; Rose 2011). Cheong et al. (2004) discuss the application of guided ultrasonic waves to the inspection of feedwater pipes in pressurized heavy water reactors (PWHRs). The study explored the application of axial and circumferential guided ultrasonic wave modes to detection of circumferential and axial notches, respectively. Nishino (2010) presents a novel multireflecting guided wave energy trapping (MGET) method to enhance sensitivity over a limited region and apply the technique to evaluation of detectability of flaws in pipe elbows. Odakura et al. (2009) describe the development of a guided ultrasonic wave system to detect wall thinning in nuclear power plant piping components with a sensitivity of 1% for small-diameter pipes. For large-diameter pipes, a “partial” guided wave sensor is discussed in which the transducer array covers only a part of the circumference of the pipe.

Electrical probe concepts have been developed for uniform corrosion monitoring in light water reactor systems (Yang and Chiang 2010). Probes based on electrical resistance measurements, linear polarization resistance measurements, and electrochemical noise measurements are described as applicable to measuring uniform corrosion rates on surrogate samples to infer corrosion rates in surrounding components. Sensing elements consist of metal electrodes or wire loops; thus, they are robust and capable of performing measurements on-line in LWRs.

Fiber-optic technologies enable the possibility of distributed sensing of variables in nuclear reactors with high spatial resolution through the incorporation of multiple sensing points on a single fiber. Several different sensing modes can be realized using fiber-optic cables including back-scattering optical time domain reflectometers (OTDRs), fiber Bragg gratings (FBGs), and Fabry-Perot interferometers. They can be used for measurements of a number of variables including strain, temperature (de Villiers et al. 2012), pressure, acceleration, etc. (Fielder and Stinson-Bagby 2004). Distributed fiber-optic sensors are described as frequently utilized for detecting faults or anomalies in structures involved in industrial processes, where locating the position of a fault is of critical importance (Grattan and Sun 2000). The most significant challenges currently associated with deployment of fiber-optic sensing technologies in nuclear reactors are related to environmental tolerance of fiber optic cables. This will be discussed further in Subsection 4.1.4.

4.1.3 Local Condition Measurements

Standard NDE technologies exist to detect gross deformation (cracking and material loss) in materials; for example, ultrasonic, eddy current and visual techniques. Ultrasonic techniques are typically applied to the detection and sizing of flaws in components requiring a volumetric examination, such as pressure boundary components. Visual techniques are applied to examine many core internal components. Eddy current techniques are employed for the inspection of steam generator tubes. These technologies are used routinely during refueling outages for inspections. The performance of several of these techniques is summarized in Bond et al. (2008) in terms of ultimate detection limits and in terms of statistical performance metrics that provide an indication of probable detection limits. Studies (Bond 1988) indicate sub-millimeter performance for detectability of surface-breaking cracks under well-controlled laboratory conditions and a performance limit of several millimeters for surface-breaking cracks under field conditions.

To avoid unplanned outages, it may be desirable to detect degradation before it results in macroscopic degradation. Certain forms of degradation, such as creep damage, may rapidly fail upon crack initiation, leaving little time for remaining useful life predictions and meaningful O&M decisions. Sposito et al. (2010) has recently reviewed several methods for assessing creep damage in power plant steels. The review points to several works relating to the use of mostly ultrasonic and micromagnetic techniques to evaluate creep damage in Cr-Mo steels through correlation with creep strain. Some of the techniques covered include ultrasonic birefringence, ultrasonic velocity and attenuation, ultrasonic backscatter, acousto-ultrasonics, nonlinear ultrasonics, magnetic Barkhausen noise (MBN), magnetic acoustic emission, and magnetic loop measurements (coercivity, remanence, and permeability).

Raj et al. (2003) discuss the response of several techniques, including micromagnetic and ultrasonic techniques, to several basic microstructural changes such as grain growth, reorientation, and the precipitation of second phases, that occur as a result of different degradation mechanisms. Dobmann (2006) have investigated micromagnetic techniques for characterizing aging in nuclear power materials due to aging caused by thermal embrittlement, neutron radiation, and fatigue. These techniques are sensitive to the creation of conductive or magnetic regions caused by precipitation or phase transformations. The sensitivity of many of the techniques to microstructural changes as a consequence of degradation has been verified in well-controlled laboratory investigations, although the sensitivity is impacted by a number of factors such as surface-roughness, second-phase microstructures and precipitates, and the presence of other degradation mechanisms. Further work is required to characterize the performance of these techniques under applicable field conditions.

4.1.4 Measurements in Harsh Environments

In general, there is a need for environmental and process measurement technologies that are deployable in advanced reactor environments. For instance, Ball et al. (2012) report that platinum RTDs are restricted to temperatures less than 450°C for high accuracy applications and that they are not deployed for temperatures above 850°C. They also report that no commercially available technologies exist to measure neutron flux at temperatures above 550°C although some development efforts have demonstrated fission chambers that can operate at temperatures up to 800°C. However, several potential technology solutions have been identified and are at various stages of development and testing.

Various alternatives to platinum RTDs for harsh environment applications include gold-platinum (Au-Pt) thermocouples, Johnson noise thermometry (JNT), and various fiber optic and ultrasonic-based thermometry devices. High-temperature fission chambers and miniaturized fission chambers have been conceived for neutron flux measurements in HTGRs and VHTRs. Fiber optics and polymer-derived ceramic based sensors have been considered for pressure measurements (Ball et al. 2012).

Senesky et al. (2009) and Pisano and Senesky (2010) have discussed silicon carbide-based sensing for both aerospace and geothermal/oil field applications, including stable temperature and pressure measurements. There is on-going work looking at down-hole sensing (Neikirk 2011) to employ a range of electromagnetic sensors (RF – microwave, eddy current) and micro-machined devices. Fiber Bragg grating sensors for harsh environments have been discussed by Mihailov (2012). Eddy current technology is being used for on-engine applications, including blade clearance monitoring at elevated temperature (Hasse and Hasse 2013).

Non-destructive examination sensors deployed for on-line monitoring in AdvSMRs will need to withstand high temperature and irradiation. Piezoelectric sensing can be implemented in a range of forms including measurements of vibration, acoustic emission, guided ultrasonic waves, non-linear ultrasonic, ultrasonic velocity and attenuation, ultrasonic backscatter, diffuse fields ultrasonic testing, etc. Ensminger and Bond (2011) describe a range of ultrasonic measurement methods at elevated temperatures, including for on-vessel and in-sodium coolant applications. Generally, major considerations for design of high-temperature piezoelectric transducers include the choice of piezoelectric (PZT) material, techniques for bonding the material to the transducer faceplate and damping material, and techniques for coupling transducers to the test component. Most PZT materials are limited by a Curie temperature near 350°C; materials considered more suitable for high-temperature transducers include bismuth titanate, modified bismuth titanate, and lead metaniobate.

A discussion of in-sodium ultrasonic measurements is provided by Bond et al. (2012) for in-sodium applications during outages at temperatures up to 250°C. A review of ultrasonic transducers for high-temperature applications, specifically lead-bismuth applications at temperature up to 600°C, is provided by Kažys et al. (2008). The advantages of sol-gel forms are highlighted with respect to sensor bonding and coupling. An exhaustive review of piezoelectric materials for high-temperature sensing applications is provided by Zhang and Yu (2011). The authors make note that the properties of oxyborate single crystals make it a good candidate for development of sensors to tolerate high temperatures and harsh environments. In other work, Zhang et al. (2010) describes testing of a prototype accelerometer fabricated from $YCa_4O(BO_3)_3$ single crystals at temperatures up to 1000°C. Parks et al. (2010) have tested single crystal aluminum nitride (AlN) crystals at temperatures in excess of 1100°C.

Alternatives to piezoelectric sensors include electromagnetic acoustic transducers (EMATs) (Alers et al. 1988; Wilcox et al. 2005), magnetostrictive sensors (MsSs) (Kwun and Bartels 1998), and laser-based ultrasonic techniques (Scruby 1989). These sensing techniques are generally less sensitive than piezoelectric-based sensors but enable non-contact sensing of components. In the case of laser-based techniques, the standoff distance can be substantial. However, laser ultrasound techniques are very sensitive to surface conditions.

The adoption of structural health monitoring (SHM) concepts for civil structures in the chemical process, oil and gas, and nuclear power industries motivates the development of fiber-optic technologies that can withstand extremely high temperatures and exposure to radiation. The use of silica FBGs in low-temperature nuclear research reactors have been demonstrated on several occasions (Fernandez et al. 2004; de Villiers et al. 2012). An important issue for silica-based fiber-optic sensors at high temperatures is sensor packaging. Above 1,000°C in air, unpackaged standard silica single-mode fibers become very brittle due to oxidation. For temperatures higher than 1,200°C, silica-based optical fibers are no longer appropriate and single crystal sapphire fibers may be preferred. A sapphire FBG has been demonstrated to exhibit no degradation in grating strength at 1,745°C, with measurement repeatability of better than 1°C (Busch et al. 2009).

4.1.5 Measurements Status

Assuming components are accessible, technologies exist that can perform off-line examinations of AdvSMR passive components and that are sensitive to macro-degradation (i.e., cracking, material loss). For inaccessible components or regions, it may be necessary to rely on less direct global condition or environmental measurement information to detect and locate defects. Multiple concepts exist for performing process/environmental and NDE measurements on-line at high temperatures (> 550°C) and research in these technologies is ongoing. For many sensors developed for high-temperature applications, there is a trade-off in performance with respect to achievable sensitivity. The significance of the impact this will have on AdvSMR diagnostics and prognostics is unclear, especially with respect to the ability to sense signs of pre-macro degradation (e.g., creep strain, embrittlement) in high-temperature, high-radiation environments. Additional uncertainty may be associated with the performance of sensors undergoing irradiation in an AdvSMR environment, which may lead to further performance losses. Research efforts are ongoing with respect to performing irradiation testing of multiple sensor types to understand sensor survivability and performance under these conditions (Rempe et al. 2011).

4.2 Diagnostics

An overview of passive component diagnostics is provided in Coble et al. (2012b). Diagnostics in the case of passive components is the problem of estimating the amount and location of degradation from one or more measurements. The interpretation of NDE measurements belongs to a general class of problems known as inverse problems and that, as currently performed in the field, most such interpretation is not automated, and is typically performed by utilizing measurements on a standard calibration block to aid interpretation. There are a variety of approaches that may be applied to perform automated analysis of NDE measurements such as direct approaches relying on empirical data and several approaches based on solutions to the forward model (physical model). In this case, there are solution techniques which rely on iterations of the forward model along with several non-iterative approaches. In general, signal conditioning techniques are applied prior to addressing the inverse problem, to enhance signal to noise ratio, extract signal features and classify signals (ASNT 2004).

Data fusion for inverse problems in NDE (Pearson et al. 1988; Maren et al. 1989; Abidi 1992; Gros 1997; Liu et al. 2003; Ramuhalli and Liu 2004) have also been explored to improve the diagnostic result. Proposed solutions encompass a number of different algorithms, such as transform-based methods (Kumar and Ramuhalli 2005), Bayesian and other stochastic methods (Lee and Bajcsy 2004; Basseville et al. 2007; Liu et al. 2008; Khan et al. 2011), evidence-based reasoning (Liu et al. 2003), and methods based on machine learning (Ramuhalli and Liu 2004). Much of the work to date has focused on the fusion being performed at the signal level, using similar forms of measurements (for instance, image data), with little effort being expended on fusing dissimilar forms (such as fusing image data with time-series measurements). These 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 (Dion et al. 2007). 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 (Nandhakumar and Aggarwal 1997; Tian et al. 2003). These types of approaches tend to be attractive for the relatively lower data needs for training of the fusion algorithms. Fusion of local and global measurements for integrated assessment of condition has largely appeared to focus on situational awareness in large-scale sensor networks (Roumeliotis and Bekey 1997). Decentralized fusion approaches appear to play a major role in such hierarchical fusion algorithms, although the applicability of such techniques to determine component condition still needs to be determined. Evidence-based approaches (such as those proposed by Dempster and Shafer (1976)) may be appropriate for these purposes as well, especially if the information does not need to be processed in a decentralized manner.

4.3 Prognostics

Several surveys of prognostic algorithms are available (Schwabacher 2005; Schwabacher and Goebel 2007; Hines et al. 2008) and an extensive review of PHM systems is provided by Coble et al. (2012b). Prognostic algorithms can be empirical or based on physics-of-failure models. They can also be distinguished with respect to the type of data they incorporate, which may include historical failure data, stressor data, or condition data. The “No Free Lunch” Theorem implies that no one prognostic algorithm is ideal for every situation (Ho and Pepyne 2001; Koppen 2004). In fact, different algorithms may be needed for different failure mechanisms in a single component. Thus, a variety of models have been developed for application to specific situations or specific classes of systems. Table 4.1 highlights some of the key prognostic algorithms, some of their features, and references assessing their applications. Due to the significant body of literature on prognostic applications, the discussion in this section is targeted to address those topics of PHM considered most relevant to address the requirements in Subsections 3.1 through 3.6. In this case the selection of PHM algorithm can have implications with respect to all of these requirements.

The selection of appropriate prognostic algorithms depends on a number of features, some of which are highlighted in the table; for example, the phenomenological nature of models, integrated estimates of RUL uncertainty, the ability to model nonlinear degradation growth, and methods to deal with POD and periodic assessment. All prognostic algorithms require knowledge of the progression from degradation initiation to failure. This can be gleaned from historical failure data or from detailed phenomenological models (or from a combination of the two). Often, the ability to apply phenomenological models or data-based models depends on the availability of appropriate information. Phenomenological models require detailed understanding of the underlying physics of failure, while data-driven models require an extensive database of historical failure data.

In addition to a point estimate of remaining useful life, many applications require estimates of the associated uncertainty. Some prognostic models inherently produce uncertainty estimates or distributions of failure time. These models typically are probabilistic in nature and require bootstrap evaluation methods. Uncertainty estimates can be derived for other algorithms, but they are not a natural result of the prognostic method. Several fault modes present with a nonlinear degradation growth, such as crack growth. For these fault modes, prognostic algorithms must accommodate this nonlinear degradation growth. Additionally, the POD associated with a particular measurement and analysis technique will need to be incorporated in any subsequent remaining useful life analysis (Simonen et al. 2007; Kulkarni and Achenbach 2008). Several prognostic methods explicitly account for POD and periodic assessment intervals. By comparing the features of each prognostic algorithm to the requirements for a specific application, an appropriate algorithm or set of algorithms can be selected.

Often, the degradation information is reduced to a single valued parameter that can accurately track component health or condition from an initial condition to failure. In the literature, this parameter may be referred to as “condition index (CI),” “health index,” or “prognostics parameter” depending on the application. Ideally, a condition index presents a sharp threshold for failure at a single value. In reality, however, the component failure is represented by a range of condition index values due to variability in material composition and microstructure, fabrication processes, stressor history, measurements, failure definitions due to different degradation processes, etc. To be effective, the range of values for failure should be small compared to the full range of values for the condition index. In addition, an effective condition index should exhibit a monotonic relationship with component health to avoid ambiguities in component health assessment (Coble 2010).

Wang et al. (2012) distinguishes two types of condition indices: physical health indices (PHIs) and synthetic health indices (SHIs). PHIs are frequently used in PHM systems and their formation is often based on a dominant physical signal that is directly related to the physics-of-failure. Many examples of PHIs can be found in the literature regarding applications in electronics, rotating machinery, and batteries, etc. Examples include the vibration signal from a degraded bearing and the temperature of a degraded electronic circuit component. Several signal processing methods to extract features or CIs directly from measurement signals are referred to and cited by Wang et al. (2012).

Alternatively, an SHI is formed by fusing together several pieces of measurement information. Such techniques are expected to be relevant to the AdvSMR prognostics problem given the expectation that multiple measurement modes are likely needed to estimate component condition. Data fusion has been used extensively in NDE applications to enhance inspection reliability and flexibility (Zheng et al. 2007). Azarian et al. (2011) show that an improved CI can be formed from vibration and acoustic emission measurements on gearboxes by combining parameters obtained from both types of measurements through calculation of a Mahalanobis distance. Oil debris monitoring and vibration condition measurements have been combined using fuzzy logic (Dempsey and Afjeh 2002) and using physics of failure models (Roemer et al. 2005) in PHM applications for gearboxes on wind turbines.

Table 4.1. Summary of Prognostic Algorithms and Assessment of Features for Application to Passive AdvSMR Components

Algorithm	Assumptions and Comments	Pros and Cons: Phenomenological?	Pros and Cons: Integrated Uncertainty Estimates	Pros and Cons: Handles Nonlinear Degradation Growth	Pros and Cons: Handles POD/Periodic Assessment Interval	References
Weibull Analysis	Estimates lifetime based on historical failure data distributions. Ignores operating conditions and unit-to-unit variations.	No	✓			Abernethy (2004)
Proportional Hazards Models	Uses operation condition-based covariates to modify a baseline hazard function	No	✓			Dale (1985), Liao et al. (2006)
Physics-of-Failure Models	Requires well-developed models of fault-to-failure progression. Often, significant simplifying assumptions must be made to support model development and execution	Yes		✓		Finda et al. (2012), Brown et al. (2012)
Probabilistic Fracture Mechanics	Database with crack initiation/growth data available to develop probabilistic fracture mechanics models	Yes	✓	✓	✓	Harris et al. (1992), Simonen et al. (2001)
Life Consumption Models	Operation at a given condition consumes some set amount of life, which is subtracted from the expected equipment life.	Yes				Ramakrishnan and Pecht (2003)
Markov Chain Models	Future operating conditions are stochastic and do not depend on the history of operation. Transition probabilities may be dynamic, dependent on time, condition, operating history, etc. Operation at a given condition results in a set amount of degradation.	Possible	✓			Hines et al. (2008)
Shock Models	Continuous in both time and degradation, assumes shocks of random magnitude arrive at random times. Distributions are dependent on operating conditions, time, or current condition.	Possible	✓			Hines et al. (2008)
General Path Model	A parametric model (regression, neural network, etc.) is fitted to a prognostic parameter and extrapolated to the failure threshold	No		Depends on model (e.g., NN-yes, linear regression - limited)		Upadhyaya et al. (1994), Coble (2010)

Table 4.1. (cont'd)

Algorithm	Assumptions and Comments	Pros and Cons: Phenomenological?	Pros and Cons: Integrated Uncertainty Estimates	Pros and Cons: Handles Nonlinear Degradation Growth	Pros and Cons: Handles POD/Periodic Assessment Interval	References
General Path Model	A parametric model (regression, neural network, etc.) is fitted to a prognostic parameter and extrapolated to the failure threshold	No		Depends on model (e.g., NN-yes, linear regression - limited)		Upadhyaya et al. (1994), Coble (2010)
Integrated Probabilistic Models	A parametric model (semi-empirical - generally based on fracture mechanics principles) is fitted using data and extrapolated to failure threshold.	Yes	✓	✓	✓	Kulkarni and Achenbach (2008)
LEAP-Frog Model	Linear degradation extrapolation with a short window of data used for fitting to give faster response to system changes	No		No--uses linear extrapolation (could be extended?)		Greitzer and Ferryman (2001)
Particle Filter	Applied when the process model is non-linear and/or the noise terms are non-Gaussian	---	✓	✓		Ramuhalli et al. (2010), Saha and Goebel (2011), Baraldi et al. (2012), Sbarufatti et al. (2012)
Kalman Filter	Applied to linear Gaussian systems	---				Swanson (2001)
Extended Kalman Filter	Applies to nonlinear Gaussian systems.	---	✓	Handles some non-linearity- not clear if there's a limit		Ray and Tangirala (1996), Rabiei et al. (2011), Ray et al. (1995)

The concept of lifecycle prognostics has been introduced as a method to transition between different types of prognostic algorithm or failure models. In Nam et al. (2012), a Bayesian framework is proposed for transitioning between different types of prognostics over the life of a component. The proposed framework focuses on transitioning between Type I (reliability-based), Type II (stressor-based), and Type III (degradation-based) prognostics. However, a similar approach may be applicable for transitioning between models that describe different stages in degradation. (Luo et al. 2003) propose an interacting multiple model (IMM) approach for combining information from multiple models of system degradation. This method has been applied to a simulated vehicle suspension system operating under unknown load (here referred to as "modes"). The IMM algorithm tracks the degradation evolution of each mode and the probability that the system is operating in each mode. These results are combined to estimate the system RUL. This approach could be used to combine information from multiple degradation models in the face of uncertain degradation mode and operating conditions. Various classes of state prediction methods are described in broad detail in the following subsection.

4.3.1 Overview of State Prediction Methods

A summary of various prognostic approaches is included in Table 4.1. In general, the approaches are regression-based, probabilistic-based, or physics-of-failure–based. Weibull analysis and proportional hazards models estimate the reliability of a population of components based on historical failure data. These approaches can be extended to prognostics. However, historical failure data is generally not abundant for passive components in nuclear reactors and may be even more scarce for the materials, components, and failure modes of interest for advanced reactor concepts. Further, these methods impose significant conservatism as unit-to-unit variations are not accounted for.

The General Path Model and LEAP-frog models assume a curve fit to measurement data and extrapolate that curve to failure to predict RUL of individual components. Generally, the parameters of the curve fit are determined based on regression analysis or machine learning.

Probabilistic methods include Markov Chain Models, Shock Models, and probabilistic fracture mechanics models. Shock Models assume that components are subject to impulses of stress that occur randomly in time and with random amplitudes that are continuously varying. Markov Chain Models assume that degradation progresses in a discrete, stochastic manner. A transition matrix defines the probabilities for various state transitions. Probabilistic fracture mechanics models may be applied to determine the probability of crack initiation and the probability that a crack will grow to a certain size. These models have been applied to determine the failure probabilities of several passive components in light water reactors.

Physics-of-failure models are phenomenologically-based descriptions of degradation evolution in response to stressor exposure. The level of descriptiveness of physics-of-failure models can vary significantly. In theory, physics-of-failure models could describe phenomena at the meso-scale and atomistic scales. In practice, physics-of-failure models for state prediction do not yet approach that level of detail. Physics-of-failure models for some relevant degradation mechanisms will be discussed in the next subsection.

The Kalman Filter, extended Kalman Filter, and Particle Filter methods are tracking models. Unlike the methods described above, they are not models for future state estimation. Rather, they provide a framework for utilizing all relevant information for state estimation and propagation of uncertainty. Use of Bayesian inference to estimate future states based on measurements at earlier states is central to these methods. The Kalman Filter can only handle linear processes with Gaussian uncertainty distributions, while the extended Kalman Filter is also limited to Gaussian uncertainty distributions but can handle nonlinear processes as well. The Particle Filter method relies on Monte Carlo sampling and is able to handle nonlinear processes with non-Gaussian uncertainty distributions. The application of a Bayesian prognostic techniques to passive components in nuclear power plants is described by Ramuhalli et al. (2010).

4.3.1.1 Physics-of-Failure Models

Physics-of-failure models are emphasized here because of the scarcity of failure data for many passive components in nuclear reactors in general and for AdvSMRs in particular for which there is very limited experience to draw from. Physics-of-failure modeling has mostly been considered in the context of diagnostics and prognostics for several applications related to electronic components (Jie and Pecht 2008; Pecht and Jie Gu 2009), wind turbines (Hyers et al. 2006; Gray and Watson 2010), helicopter rotors (Kacprzynski et al. 2004), and aircraft panels (Sbarufatti et al. 2012). In this section, the discussion of physics-of-failure models focuses on several of the modes of degradation highlighted in Table 2.2.

Fatigue failure is an important failure mode in each of these applications and physics-of-failure modeling for fatigue crack propagation has been explored by several investigators. Generally, the growth of large fatigue cracks can be modeled by the Paris' Law. For very small crack sizes (on the order of material grain dimensions), Paris' Law is not valid and crack growth is governed by stochastic processes associated with crack initiation. Multiple investigators discuss models to account for stochastic processes of crack initiation (Ray and Tangirala 1996; Nasser et al. 2005). They discuss a materials simulation-based approach to prognostics, which they apply to solder joints of electronic circuits. A model for crack initiation and growth described as capable of accounting for microstructure variability and able to simulate crack initiation is described by Ray and Tangirala (1996). For components or structures with complex geometry, the stress intensity factor is generally used to handle multi-axial stresses (Kacprzynski et al. 2004). In Sankararaman et al. (2011) finite element methods are used to train a surrogate model which is then used to predict the stress intensity factor through Gaussian process interpolation. In Sbarufatti et al. (2012), crack propagation is modeled by the NASGRO law, which is more complex than the Paris' law in that it accounts for the load ratio and crack closure effects.

Thermal creep degradation can be modeled by equations relating the strain rate to relevant stressor parameters such as load stress and temperature. Thermal creep degradation is represented by multiple stages referred to as primary, secondary, and tertiary creep. Norton's Law is a frequently cited formula for modeling secondary creep in materials. Values for empirical constants related to creep models have been documented in numerous creep studies of austenitic stainless steels (Mathew et al. 1993; Golan et al. 1996; Nassour et al. 2001; Rieth et al. 2004; Sorkhabi and Tahami 2012). In general, the values for these constants can vary over different temperature and stress ranges. Baraldi (2012) discuss models to predict the RUL of a high-temperature gas turbine blade undergoing creep damage. The Norton Law is used to simulate creeping blade data in the creation of an ensemble of prognostics model. In this case, the measurement of creep damage is assumed to be based on strain measurements obtained by measurement of the gap clearance between the turbine blade and the turbine housing. In addition to Norton's Law, models may be available to describe degradation in the primary and tertiary creep stages. However, tertiary creep is often associated with the onset of failure and is usually short-lived. In the primary creep stage, the strain rate is initially very large and then decreases until it matches the constant value of strain rate observed in the secondary stage.

Stress corrosion cracking (SCC) is highly complex phenomena dependent on many variables. Phenomenological models have been proposed for IGSCC crack growth in LWRs (e.g., slip oxidation by Andresen and Ford 1994), while the complexity of SCC initiation limits the ability to effectively predict SCC occurrences in the field. The "Quantitative Micro-Nano (QMN)" approach seeks to obtain a more fundamental understanding of SCC through atomistic modeling (Staehle 2012) hopefully leading to more effective methods for predicting SCC occurrences. Unwin et al. (2011) have developed a physics-based component reliability model for a PWR component subject to SCC. In this case, the physical model used for SCC is divided into a nucleation stage, which is statistical, and a deterministic growth stage. It is noted that significant data exists with respect to crack growth rates in Alloys 182 and 82 for which to base models of SCC growth and that crack growth rates may be correlated with temperature and stress intensity factors. A Weibull distribution is used to quantitatively describe SCC initiation probability.

Corrosion processes in advanced reactors are relatively diverse and can encompass both uniform and local corrosion processes. A review of lead-bismuth eutectic (LBE) corrosion issues describes the factors that influence corrosion of structural steels by LBE (Zhang and Li 2008). Although many factors influence the corrosion process, the influence of flow velocity on corrosion rate and the role of oxygen concentration in inhibiting LBE corrosion are highlighted.

A common theme with all available physics-of-failure models for passive components is the need for model parameters that, in general, are empirically derived. As a result, such parameters may not be readily available for some materials, especially newer ones with limited operational experience.

A potential approach to address the lack of readily available empirical parameters is to use multi-scale modeling to simulate microstructure and property evolution, which may be useful in predicting end-of-life. McCloy et al. (2013) provides an overview of multi-scale physical modeling approaches to simulate the microstructures and property evolution in irradiated materials. Multi-scale modeling approaches encompass atomistic modeling, meso-scale modeling, and macro-scale modeling. Macro-scale modeling is applicable to many field NDE problems, which might focus on characterizing discontinuities such as cracking or corrosion. These models are typically applied to model the interaction of acoustic/elastic or electromagnetic energy with materials and include finite element methods, finite difference methods and the method of moments. In addition, semi-empirical models are also often used. These models face limitations with respect to material inhomogeneity, anisotropy, and handling the stochastic variation of microstructure within materials (Sobczyk and Kirkner 2001). Meso-scale modeling, such as phase field modeling (PFM), is applied to phenomena that occur at length scales ranging from several nanometers to several micrometers. These models generally utilize the thermodynamic and kinetic properties of materials to model the evolution of microstructure under a variety of external stimuli such as radiation. PFMs have been used to model various microstructural evolution processes, such as solidification, grain growth, and precipitation. Atomistic models can be used to calculate thermodynamic and kinetic properties that are input into PFMs. While research into these types of multi-scale models is ongoing, these face similar restrictions in practice as all other physics-of-failure models, namely, a lack of well-characterized model parameters for many materials.

4.3.2 Uncertainty Quantification in Prognostics

Quantification of the uncertainty levels in the inputs to the prognostics algorithm help better bound the uncertainty in the resulting RUL estimate. A number of studies have been conducted on uncertainty quantification (UQ) and management in prognostics algorithms (Usynin 2007; Liang et al. 2009; Sankararaman et al. 2011; Wang 2011; Wang et al. 2012). These range from closed-form equations to probabilistic approaches such as the bootstrap technique and Monte Carlo simulations. A number of other approaches to UQ exist (for instance, a survey of UQ methodologies is presented in Lin et al. (2012), although not all may be applicable to typical PHM systems.

4.3.3 Prognostics for Variable Loading Conditions

Many methods for fault detection and degradation trending assume that the SSC is operating under effectively steady-state conditions. However, SSCs in the field experience variable operating conditions due to changes in load or the environment. This assumption has only recently been relaxed to develop condition-based prognostic methods that can simultaneously account for equipment condition and variable future operating conditions. Saxena et al. (2012) use constant-load data to develop prognostic models for Li-ion batteries and apply these models to data from known, variable future load profiles. Three models are compared: polynomial regression, neural networks, and particle filters. Of the three models compared, only the particle filter was able to accurately adapt models developed with constant load data to variable load data for prognostics. Several researchers have looked at crack growth prediction under variable amplitude loads. Mohanty et al. (2011) applied a multivariate Gaussian process technique for crack growth prediction based on ultrasonic measurements. Features of the ultrasonic signal are extracted through principal component analysis and input to the Gaussian process model to predict the crack growth rate, which is then integrated to give an estimate of the crack length. The authors apply the Gaussian process model for estimating the current crack size, but it may be possible to extend this approach to prognostics with suitable adjustments. Leem et al. (2011) apply Huang's model, a semi-empirical model that describes crack growth during variable loading. Bayesian fitting with an improved Markov Chain Monte Carlo sampling is used to fit the parameters of Huang's model given the observed crack size to the current time. Here, distributions of model parameters are estimated from data for crack growth under constant amplitude loading. These distributions are then used to simulate a distribution of RULs for a sample under known variable loading. Although some efforts have been made to combine SSC condition with variable future loading for prognosis, the work reviewed to date assumes that the future sequence of operating conditions is known. In practice, this may not be true. These approaches will need to be adapted to account for uncertain (or in some cases unknown) future loading conditions. A potential (conservative) approach would assume worst-case future operating conditions, and update the remaining life estimates as conditions become known. Other approaches that utilize statistical descriptions of future loading conditions based on past history may also be applicable and will need to be evaluated.

4.3.4 Prognostics for Coupled Systems

Coupled and interconnected systems may present additional challenges to current prognostic methodologies due to the interdependencies between SSCs. Sankavaram et al. (2011) presents a general framework for prognostics of coupled systems. The approach provides a unified, data-driven framework that incorporates several types of input including failure time data, static parameter data, and time series parameter data. The framework is applied to an electronic throttle control system in Pattipati et al. (2011). In this application, the multiple-model moving-horizon estimation algorithm is used for on-line prediction of the survival function based on operating conditions. RUL estimates can then be made from analysis of the survival function.

4.3.5 PHM System Architecture and System Integration

Deployment of PHM for SSCs in nuclear power plants (NPPs) will likely require the use of a prognostics architecture (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. Lybeck et al. (2011) reviewed selected software packages for PHM system development and deployment. Thirteen products were identified through literature and internet searches and evaluated on six criteria: open, modular architecture; platform independence; graphical user interface for system development and/or results viewing; web-enabled tools; scalability; and standards compatibility. The 13 packages were classified into four types of software based on their intended use: research tools, PHM system development tools, deployable architectures, and peripheral tools. Of the eight software tools that were classified as deployable architectures, only two employ all the components of a full PHM system. Five systems did not offer prognostic estimates.

A web-based diagnostic and prognostic system for monitoring creep and low cycle fatigue in boilers is described by Kunze and Raab (2012). The fatigue monitoring system (FMS) application can be autonomous or fully integrated with a Siemen's or a compatible I&C system. The FMS is described as capable of calculating the RUL of boilers designed according to ASME standards. RUL is calculated according to European standards containing simplified rules to calculate creep and low cycle fatigue. Monitoring of several boiler components is performed on the basis of temperature and pressure measurements.

Fang et al. (2007) discuss the integration of model based prognostics for individual components with operations and maintenance decisions. In work funded by the Air Force Research Laboratory (AFRL), a "smart services" solution is presented which integrates maintenance and inventory management with system operating conditions and health information. The study also looked at using RUL information to assess different spare parts allocation schemes to maximize maintenance efficiency.

Thus, products to provide an architecture for PHM system deployment and integration with systems to help maximize effectiveness are at or nearing maturity. Thus, it may be possible to build upon existing commercial products in defining an appropriate architecture for AdvSMR PHM system deployment and integration with the plant supervisory control system and enhanced risk monitors.

4.4 Summary

The foregoing discussion provided an overview of the current status of PHM systems of relevance to AdvSMR passive components. This assessment broadly examined the state-of-the-art in PHM systems in terms of sensors and measurements, diagnostics algorithms, and prognostics methods.

Measurement technologies currently deployed in the nuclear power industry are only effective at detecting macro-scale damage (e.g., cracking, material loss) in structural materials. However, researchers are exploring measurement technologies that are sensitive to microstructural changes in materials enabling earlier detection and characterization of material damage. Several NDE techniques exist with potential application to early (pre-crack) assessment of degradation on AdvSMR passive components. Significant research is ongoing with respect to development of sensors (both process sensors and sensors for in-situ NDE measurements) that would be compatible with anticipated AdvSMR environments. Available literature indicates that improved survivability within these environments may come at the cost of reduced sensitivity, especially to earlier stages of materials degradation. The impact of this on the application of PHM for AdvSMR passive components is unclear.

A number of approaches to diagnostics (for quantifying the level of degradation, possibly using a condition-index) and prognostics (for assessing the RUL of the component with degradation) 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 this area will require adaptation address issues specific to AdvSMR passive component applications. For instance, models of degradation accumulation, especially if based on physics-of-failure data, may need to be adapted to account for the AdvSMR environment, as these models generally include empirically derived constants which depend on material type and environmental or loading conditions. In the case of PHM system architecture and integration of the prognostics results with plant O&M processes, it appears that many solutions are becoming commercially available and it may be possible to leverage these solutions in the development process of PHM systems for AdvSMR passive components.

5.0 Research Gaps and Technical Needs

An assessment of the state of the art of PHM, relevant to passive AdvSMR components, was performed to determine if the current state of technology in PHM was sufficient to address the functional requirements defined in Section 3.0. A number of technical gaps were identified as a result of this assessment. In several cases, the literature review identified potential PHM methodologies that may be applicable to the problem at hand. In these cases, there are gaps associated with tailoring the general methodologies to prognostic health management of AdvSMR passive components. This section describes the assessment of current state-of-the-art, and documents the resulting technical gaps. This assessment is preceded by a summary of the functional requirements listed in Section 3.0.

5.1 Summary of Requirements for PHM of AdvSMR Passive Components

A summary of the requirements from Section 3.0 is provided here for convenience. These are:

- Sensors and Instrumentation for Condition Assessment of Passive Components
- Fusion of Measurement Data from Diverse Sources
- Address Coupling Between Components or Systems, and Across Modules
- Incorporation of Lifecycle Prognostics
- Integration with Risk Monitors for Real-time Risk Assessment
- Interface with Plant Supervisory Control System

5.2 Research Gaps

The literature assembled and evaluated to date to identify the current state of technology is summarized in Section 4.0. An analysis of the information resulted in identification of technical gaps that are described below. The analysis and gaps are organized by relevance to the functional requirements.

5.2.1 Sensors and Instrumentation for Condition Assessment of Passive Components

Possible types of measurement data for the health of AdvSMR passive components include local NDE measurements, global condition measurements, and stressor measurements. Efforts to develop sensors that tolerate harsh environments are underway in the context of the aerospace and oil and gas industries. In addition, similar efforts have been undertaken with respect to nuclear power application in the context of sensor development for in-pile instrumentation in materials test reactors and sensor development for advanced reactors. Given the active research into harsh environment sensors at present, it is likely that sensor materials and instrumentation will be available in the future that can survive the high temperatures, neutron spectra and doses, and harsh coolant chemistry in AdvSMRs. However, from the perspective of measurements for passive component health monitoring, the sensitivity of the sensor materials being investigated for particular classes of sensors (such as ultrasonic measurement) may be lower than that necessary to ensure detection of earlier stages of degradation. This is a potential technical gap that will need to be investigated further as sensor technology for harsh environments matures.

Analysis of sensor data to understand the relationship between the condition of the component (through a condition index) and one or more measurements (of either component condition or stressors) is also considered a technical gap. Although several approaches to addressing this issue are available, these will likely need to be customized to the materials, component designs, and degradation modes anticipated in AdvSMR concepts. Analysis approaches that use physics of measurement models are generally accurate but offer no ready way to quantify uncertainty, and tend to be computationally expensive as well. In addition, the potential for reduced sensitivity of harsh-environment sensors and the resulting lower signal-to-noise levels may make it necessary to derive the relationships between CIs and measurements for these types of sensors. These gaps in data interpretation are also tied into the data fusion requirement.

There is a technical gap associated with defining the measurement data needed for providing a baseline of material or component condition prior to beginning operations. This gap revolves around the need to determine an appropriate initial condition that may be used by a PHM system in subsequent RUL estimates. The need is in determining the type of measurements and the location (on the component) of these measurements to provide adequate confidence in the initial (pre-service) condition of the component. It is unclear whether measurements obtained during a typical pre-service NDE inspection are adequate for this purpose.

A final set of gaps associated with sensors and instrumentation is the assessment of detection and characterization reliability using both conventional and unconventional measurement methods. As described earlier, a number of studies have documented the factors that affect detection probability for cracks using a number of conventional NDE methods. These efforts have led to requirements for performance demonstration for in-service inspection that are described in the ASME Boiler and Pressure Vessel Code (Appendix VIII, Section XI). However, similar studies for unconventional NDE and monitoring methods are lacking, as are reliability studies for the detection and characterization of degradation mechanisms other than cracks (such as corrosion or irradiation-related embrittlement). One limitation in this respect is the ability to define the “level” of degradation for such mechanisms (much as crack depth or length may be used as a descriptor of the “level” of cracking). Concepts such as corrosion intensity factor (National Research Council 2011) or other damage or condition indices may need to be defined for this purpose.

5.2.2 Fusion of Measurement Data from Diverse Sources

The assessment of diagnostic and prognostic algorithms indicates that data fusion may play a role in these areas. For diagnostics (i.e., determining the current condition of the component), measurements (possibly multi-modal) at the local level and global level may be integrated in a meaningful manner to derive a condition index. To achieve a high degree of reliability in diagnostics, and provide adequate defense-in-depth, the on-line monitoring measurements may need to be augmented with periodic off-line (i.e., when the plant is off-line for refueling or other maintenance) measurements of passive component condition. For prognostics, information about the current state (which may be represented by a condition index computed from one or more measurements) may need to be fused with stressor measurements (such as temperature and fluence) to estimate RUL.

Several algorithms are available that might be applicable to local-level fusion for diagnostics, but these algorithms require customization for specific applications/measurement modes. As discussed earlier, research in fusion of global and local measurements are generally focused on situational awareness in sensor networks. In most cases of relevance to passive component diagnostics, the focus is on using a distributed set of sensors on structure to measure quantities such as vibration, and use the collective information to perform modal analysis (Lynch 2007).

Specific gaps in data fusion for diagnostics include integration of different types of data (for instance, image data and time-series data), which encompasses the need to address specific algorithms and parameters. Other gaps include 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. Methods to account for differing levels of uncertainty are also available (for instance, Khan et al. 2011), but these techniques need verification and validation (V&V) prior to broad application.

An associated technical issue is the ability to determine the present state (i.e., at the time of the measurements) of the material or component. Again, while a large body of work in the area of inverse problems as applied to nondestructive evaluation is available to choose from, many of the methods proposed to date rely on empirical relationships between the measurement and condition (such as crack length and depth) using available data. Such data sets for materials of interest to AdvSMRs are still limited. Alternative approaches that use models relating the measurement to the condition are also limited, given that current models are generally computationally expensive. In all cases, UQ is always a factor, and propagating uncertainty through the diagnostic step is a challenge, particularly if using a model-based approach for diagnostics.

Data fusion approaches that integrate information from the component to diagnose the component health will need to be adapted to integrate diverse types of measurements distributed across a component. Specific gaps identified are fast algorithms for solving inverse problems for assessing component condition, quantifying the uncertainty in the resulting solution, and integrating distributed sensor information to assess component health.

Fusion for prognostics brings several challenges, not the least of which is the need for one or more models that can incorporate the diversity in information from multiple sources to produce RUL estimates. Physics-of-failure models for prognostics that utilize stressor information, in addition to condition metrics, may provide a reliable approach to RUL estimation, although data-driven models may provide equivalent results if sufficient data for training the models is available. There is a technical gap associated with the availability and applicability of accurate models for passive component prognostics that capture the degradation accumulation process under different stressor conditions, while also accounting for condition indices computed from more than one sensor measurement. An associated gap is the ability to incorporate global and local condition indices within the framework of prognostics for RUL estimation of the component. As with fusion for diagnostics, another gap is UQ and uncertainty propagation for prognostics.

5.2.3 Coupling Between Components, Systems, and Modules

An assessment using available literature of the state of the art in PHM systems indicated that there is limited work in addressing cross-system fault propagation in coupled systems. Part of the challenge appears to be limited information or models of system coupling for interconnected systems. While the available information is a function of the application domain, there is a clear gap here with respect to the use of PHM for AdvSMRs, where such models are either not available, or have limited information to date. Some specific gaps include the ability to quantify and propagate uncertainty in coupled systems. While several approaches for UQ are available, there appears to be limited research in the area of UQ in coupled systems. Modular systems are also associated with the concept of variable loading, which challenges current PHM methodologies. Although some efforts have been made to combine SSC condition with variable future loading for prognosis, the work reviewed to date assumes that the future sequence of operating conditions is known. In practice, this may not be true. These approaches will need to be adapted to account for uncertain (or in some cases unknown) future loading conditions.

5.2.4 Incorporation of Lifecycle Prognostics

The state of the art in prognostics shows that PHM systems can use one or more of several types of data, including historical failure data (to generate models of component reliability), or stressor or component condition data. These latter types of data may be used with either data-driven models of degradation accumulation or physics-of-failure models to predict RUL and time-to-component-failure. In general, even with physics-of-failure models for passive components, the parameters of models are usually derived using empirical data that may not be available for the materials of interest to AdvSMRs under loading conditions of interest. In addition, there is a distinct possibility (borne out by available information on materials) that these parameters may vary with changes in stressor values. There is thus a technical gap associated with the development of accurate physics-of-failure models for passive component prognostics that capture the degradation accumulation process under different stressor conditions. Note that this may require multiple models, each representative of a subset of stressor conditions. In addition, different models may be more appropriate (e.g., more accurate, more precise, or suitable to runtime requirements) during different stages of degradation.

The possibility of using multiple models to capture the degradation accumulation rate for RUL estimation brings with it the need for lifecycle prognostics. While there has been much work in this area, there are still limitations with respect to transitioning between models across the lifecycle of the component, according to the stressor history and anticipated stressor variability in the future. Specific gaps include how to account 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 (for instance, precursor-based to crack-growth), and combining multiple degradation models.

5.2.5 Integration with Risk Monitors for Real-time Risk Assessment

Currently deployed risk monitors provide a point-in-time estimate of risk based on probabilistic risk assessment (PRA) models and the day-by-day plant operation and configuration (e.g., changes in equipment availability, operating regime, environmental conditions). Passive components are largely unrepresented in risk monitors. Typically passive component failure is treated as an initiating event (e.g., pipe rupture leading to large break loss of coolant accidents), but it is not modeled in the fault trees that describe plant responses to initiating events. Additionally, risk monitors use population-based probability distributions in modeling plant risk. Research is currently being pursued to incorporate real-time estimates of component probability-of-failure distributions into so-called enhanced risk monitors (ERM) (Coble et al. 2013). While this work focuses on active component monitoring, information about passive component health could be incorporated. Reliability assessment of passive components has been studied as part of the Risk-Informed Safety Margin Characterization pathway in the Light Water Reactor Sustainability program (Unwin et al. 2011). This work may provide an initial platform for incorporating passive component condition information in ERMs.

5.2.6 PHM Architectures and Interface with Plant Supervisory Control System

To realize the full benefits of information provided by PHM modules, they should be integrated with control systems in a manner that best facilitates the achievement of system objectives. An example includes efforts to inform maintenance and inventory management with RUL information from specific parts. In some cases, such efforts may be at, or nearing, commercial availability for a subset of components or systems. For AdvSMRs, there are questions related to separation of responsibilities between the PHM and control system and the optimal communication interfaces for exchanging information between the PHM system and plant control system, including questions related to the necessary level and type of information that will need to be exchanged with the plant supervisory control system. Commercially available PHM architectures may be able to address a part of this gap, although there are still needs specific to likely AdvSMR operational characteristics that will need to be addressed before deployment of PHM systems that are integrated with plant control systems.

5.3 Technical Needs to Address Gaps

Several research needs are discussed below based on the gaps assessment above. In several cases, the literature review identified potential PHM methodologies to satisfy the requirements of PHM on AdvSMRs. In this case, the needs are associated with tailoring the general methodologies to AdvSMR passive component PHM applications.

5.3.1 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 which 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. Physics-of-failure models will be needed that can capture such coupled degradation modes.

5.3.2 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.

Data fusion methods also are needed to address requirements discussed in Subsections 3.2 and 3.3. Neural network and physical modeling techniques have been applied to combine NDE measurements for non-nuclear power applications. For passive components in AdvSMRs, methods will be needed to combine condition measurements (both local NDE and global condition) with stressor measurements for enhanced PHM performance. In addition, the development of models that incorporate measurement inputs for multiple components or systems will be needed to account for potential cross-coupling between components, systems, or modules.

5.3.3 Lifecycle Prognostics

While there has been some work in this area (for example, Nam et al. 2012), there are still limitations with respect to transitioning between models across the lifecycle of the component. Indeed, different models may be more appropriate (e.g., more accurate, more precise, or suitable to runtime requirements) during different stages of degradation. Specific gaps include how to account 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 (for instance, precursor-based to crack-growth), and combining multiple degradation models.

5.3.4 Uncertainty Quantification

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.

The concept of uncertainty quantification touches several of the requirements defined earlier. Transferring uncertainty estimates as PHM systems transition from one model to another during lifecycle prognostics is a key technical gap identified above. In addition, the impact of uncertainty on RUL estimates in coupled systems, as well as in systems with variable loading, is also a technical gap that will need to be resolved. Finally, the impact of prognostics uncertainty on plant supervisory control algorithms and operational risk monitors will need to be determined. As a result, methods for UQ that are applicable to PHM systems in AdvSMR environments are likely to be impactful.

5.3.5 PHM Architectures and Integration with Plant Supervisory Control Systems

Deployment of PHM for SSCs in NPPs will likely require the use of a prognostics architecture (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. Development of each of the modules in a full PHM system for deployment in an NPP is both costly and time-consuming. An existing software framework may be leveraged to develop a full PHM system with reduced development time and cost. While there are several architectures for PHM systems proposed (Lybeck et al. 2011), each of these commercially available systems has advantages and disadvantages. The applicability of any of these (or other architectures) to the problem at hand will need to be evaluated. 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, integrate prognostic results with operational risk monitors and plant supervisory control algorithms, and incorporate 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 (Coble et al. 2013).

5.3.6 Sensors for Degradation Monitoring in Harsh Environments

This technology need complements the requirement discussed in Section 5.2.1; namely, the requirement for on-line monitoring of passive components due to 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. In LWRs, on-line recalibration of sensors is only feasible for certain types of sensors (Coble et al. 2012a). In addition, there may be issues with coupling sensors to components in AdvSMR environments and the potential for reduced sensitivity if dry couplant or stand-off approaches are pursued.

5.3.7 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.

6.0 Research Plan

This section outlines a preliminary research plan to demonstrate a prototypic PHM framework for passive components in AdvSMRs. The proposed work will seek to demonstrate key capabilities of a PHM system to meet the functional requirements outlined earlier. A description of the research objectives, research assumptions, research approach, and notional schedule for research activities is provided below. At the time of writing of this document, many open questions remain with respect to potential AdvSMR concepts and designs. It is important that results of initial phases of research are AdvSMR design-neutral to the extent possible to ensure broader applicability as future prioritizations begin to narrow the scope of potential AdvSMR concepts. Thus, the research plan is developed to address key concepts that are related broadly to the application of PHM in AdvSMRs, regardless of specific reactor concepts. Nonetheless, specific decisions need to be made in order to execute research activities. These decisions are made based on multiple constraints including the analysis performed in this document, ready access to laboratory-scale facilities for materials testing and measurement, and potential synergies with other national laboratory and university partners.

6.1 Research Objective

The objective of the research described in this section is to demonstrate a prototypic PHM system to manage degradation of passive AdvSMR components. Achieving this objective will necessitate addressing several of the research gaps and technical needs described earlier. Key concepts addressed are:

- The use of multiple condition and stressor measurements to enhance the performance of diagnostics and prognostics of passive AdvSMR components and systems.
- Ability to quantitatively account for uncertainties and to propagate uncertainties in RUL predictions.
- A lifecycle prognostics framework that can enable updating of models. This includes the ability to perform accurate RUL prediction on a passive component subject to changing or time varying stressors.
- Ability to account for coupling effects between passive components in performing diagnostics and prognostics.

Greater efficiency in achieving this objective can be gained through judicious selection of materials and degradation modes that are not only relevant to proposed AdvSMR concepts, but for which significant knowledge already exists. Greater efficiency can also be achieved by leveraging existing facilities at DOE laboratories for component and system level demonstrations. These concepts will be demonstrated over three phases of research.

6.2 Assumptions

Several assumptions are made to define, focus, and help guide research efforts to demonstrate prototypic PHM for passive AdvSMR components.

This research plan assumes that modularity implies some level of interconnectedness and sharing of resources between individual modules such that operating decisions in one module can have consequences to the operation of other modules. Cross-coupling of components and systems in connected reactor modules will be assumed to be captured in well-developed models of AdvSMR operation. The initial PHM development methodology will not explicitly account for these interdependencies. However, as the research progresses, this assumption will be tested and relaxed, if necessary.

A prototypical AdvSMR design and configuration will be assumed to enable identification of AdvSMR characteristics. A pool-type liquid metal fast reactor will be assumed for the reactor modules. This reactor type offers several advantages, chief of which is the expertise available in the research team and elsewhere in the National Laboratory complex in the area of liquid metal-cooled fast reactors. Additionally, there is significant operating experience with passive components in these reactors to guide the selection of degradation modes for use in this work. However, the materials proposed for use in these types of reactors are broadly applicable to other reactor concepts, and a number of degradation modes are common. Thus, the assumption of a liquid-metal fast reactor does not significantly limit the broad applicability of the proposed research.

A generic design with multiple reactor modules connected to a common BOP, which can include both electricity generation and process heat applications, will be assumed to provide for future integration between the outcomes of this research and parallel research into enhanced risk monitors and plant supervisory control algorithms. The generic design will be referred to as a generation block (Figure 6.1). A single prototypical AdvSMR plant is assumed to contain multiple generation blocks.

Laboratory-scale experiments for degradation assessment and prognostics for a prototypical AdvSMR passive component will only simulate conditions and features necessary for proof-of-principle demonstrations of key concepts.

Sensors for monitoring in harsh AdvSMR environments will be assumed to exist. Although this is identified as a research gap for actual deployment of PHM in AdvSMRs, it is possible to develop and validate PHM algorithms for AdvSMR applications in the absence of such technology. To the extent possible, existing technology (even at an early stage of development) will be leveraged to meet any measurement needs for generating data on material degradation detection in harsh environments.

6.3 Research Approach

A depiction of a general PHM system hierarchy for AdvSMRs is provided Figure 6.2. This provides the basis for the organization of the research plan and schedule of research activities described below. The research activities to address the high priority technical needs defined in Section 5.3 are essentially divided into multiple phases with each phase associated with a level of the hierarchy. As Figure 6.2 illustrates, the PHM system will be developed to simplify any interface requirements with the supervisory control system so that information may be transmitted from the PHM system to the supervisory control system and commands may be transmitted in the other direction. The specifications of the interface between the two systems are not yet defined. Defining the interface requirements will require collaboration with other ongoing research projects within the SMR R&D program.

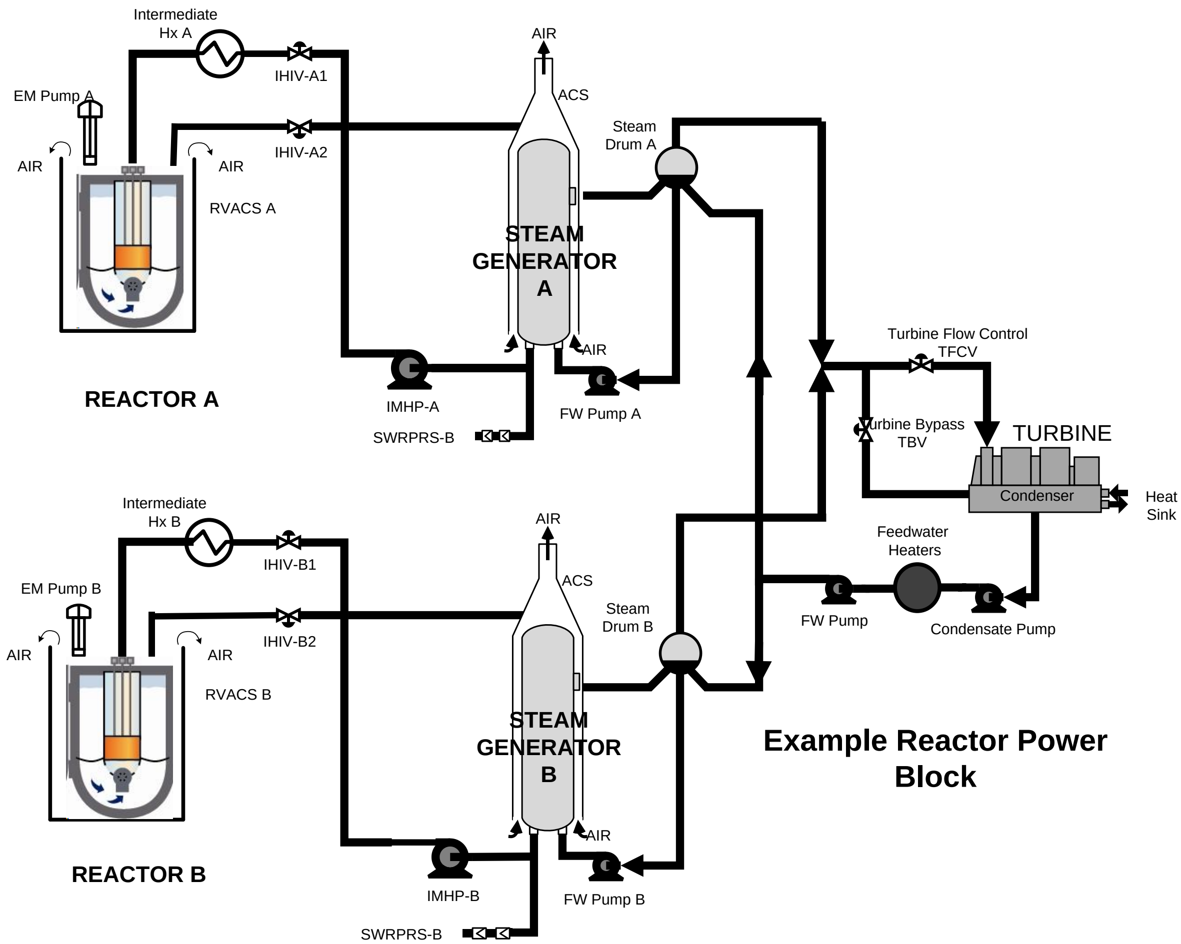


Figure 6.1. A Single Generation Block in the Proposed AdvSMR Plant Configuration. A full plant would be comprised of multiple generation blocks.

The interface between the PHM and supervisory control systems is anticipated to occur at higher levels of the PHM system hierarchy (i.e., component level and above) and have a greater influence on how PHM is performed at these levels. The uncertainty regarding the interface will have the least impact on PHM at the local level. A logical approach to research organization is to start at the bottom of the hierarchy at the local level and to work up the hierarchy in following years. Thus, the research plan described next is developed only to address tasks related to the local, component, and system levels.

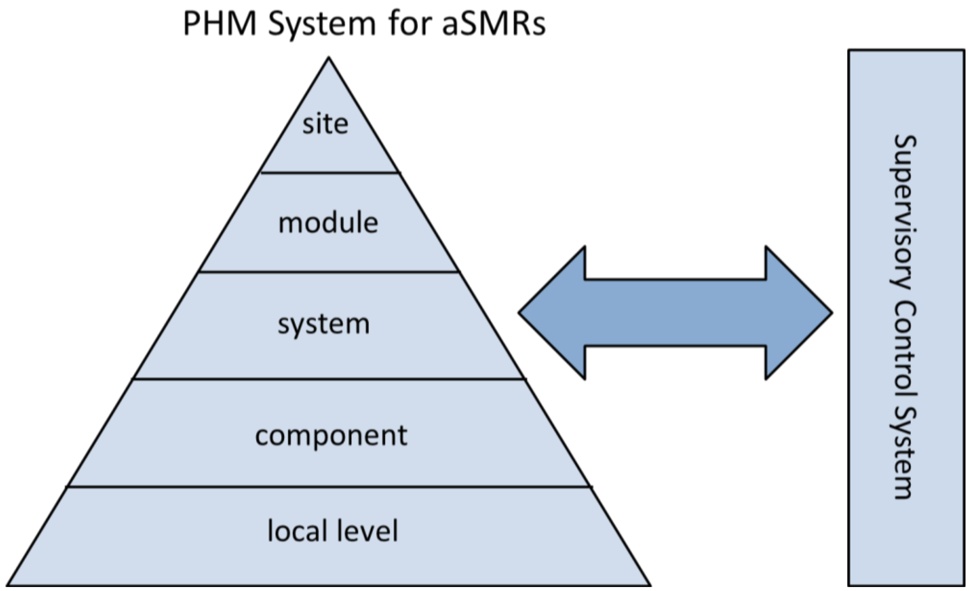


Figure 6.2. General PHM System Hierarchy for AdvSMRs

6.3.1 Phase I: Develop/Validate Local Level Prognostic Algorithms

As envisioned, the local level of the PHM system refers primarily to direct measurements of material condition performed by the application of NDE technologies during an outage or possibly on-line. This is illustrated in Figure 6.3. At this level, the PHM system can be thought of as several individual units that could be defined as a single measurement location (for instance, a portion of a weldment or other small region of a component). In addition to the condition measurements, it may be possible to combine stressor measurements with the condition measurements for local diagnosis and prognosis. Either the measurement data and/or the processed prognosis data may be transferred up to the component level for use in component health assessment.

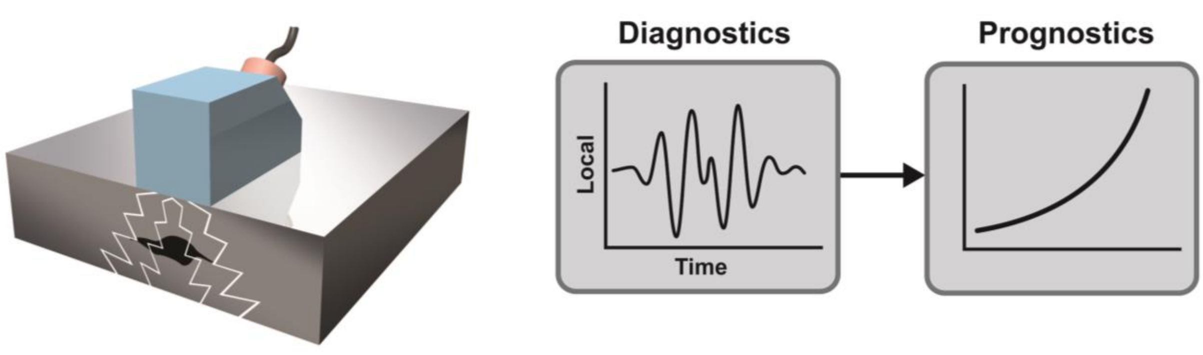


Figure 6.3. Depiction of Local PHM Based on Local NDE Measurements

Work during Phase I will focus on developing and validating prognostic algorithms using local level measurements. In this effort, validation of algorithms will be performed with measurements obtained from accelerated aging of laboratory-scale specimens. Validation of prognostic algorithms will involve demonstrations of the following concepts:

- Ability to perform accurate RUL prediction on laboratory-scale specimens subject to changing or time-varying stressors.
- Enhanced prognostics performance by fusing NDE measurement data with stressor measurement data.
- Quantitative accounting of uncertainty for prognostics performed on laboratory-scale specimens.
- A lifecycle prognostics framework that can be used to update models when performing prognostics on laboratory-scale specimens.

Creep mechanisms have been selected for performing Phase I demonstrations and likely materials candidates include austenitic stainless steels. Materials selection is mostly based on ease of inducing the selected degradation mechanism in an accelerated manner and available knowledge base (including needed parameters to model the accumulation of the selected degradation mechanism in the material) to facilitate prognostic algorithm development and validation. Continuous measurements of load, strain, and temperature will be performed during accelerated aging of laboratory specimens and the accelerated aging and NDE measurements will be collected either continuously or periodically (by pausing the test to perform measurements). This measurement protocol will simulate both the collection of in-situ online measurements and collection of NDE data during periodic in-service inspection for AdvSMRs.

Multiple NDE measurements will be performed including linear and nonlinear ultrasonic techniques, micro-magnetic techniques, and electromagnetic techniques. The goal of these NDE measurements will be to determine correlations between the responses of NDE measurements to measured true state (creep strain). Such correlations serve two purposes. First, they help provide a data base with quantitative assessments of degradation state prior to crack initiation, along with NDE measurements. Second, they help in the evaluation of several potentially applicable measurement techniques for detecting and characterizing the degradation state prior to crack formation.

In this phase, one or more prognostic algorithms from Table 4.1 will be adapted and applied to the accelerated aging data. In parallel, opportunities to leverage ongoing research in materials degradation for AdvSMRs will be explored. In particular, opportunities will be explored for obtaining any available data from instrumented degradation tests, as well as collecting NDE measurements from ongoing materials testing campaigns by instrumenting selected tests at the other national laboratories.

6.3.2 Phase II: Develop/Validate Component Level PHM

The component level of the PHM system is envisioned to consist of the measurements and algorithms used to diagnose and prognose the failure of a component. Measurements of stressor variables will be one key source of information for component level diagnostics and prognostics. Other potential sources of information include global condition measurements such as vibration measurements or acoustic emission measurements. These measurements provide an indirect assessment of component degradation which will introduce significant uncertainty into diagnostics and prognostics. The uncertainty can be reduced and the PHM performance can be enhanced by fusing component level measurements with relevant local level information. In addition to reducing uncertainty, the fusion of global and local information also potentially provides the opportunity to detect failures that might occur at non-weld locations (weldments have been the traditional focus of in-service inspections). The fusion of global condition, local NDE, and process (stressor) information to enhance PHM of a passive AdvSMR component is notionally illustrated in Figure 6.4.

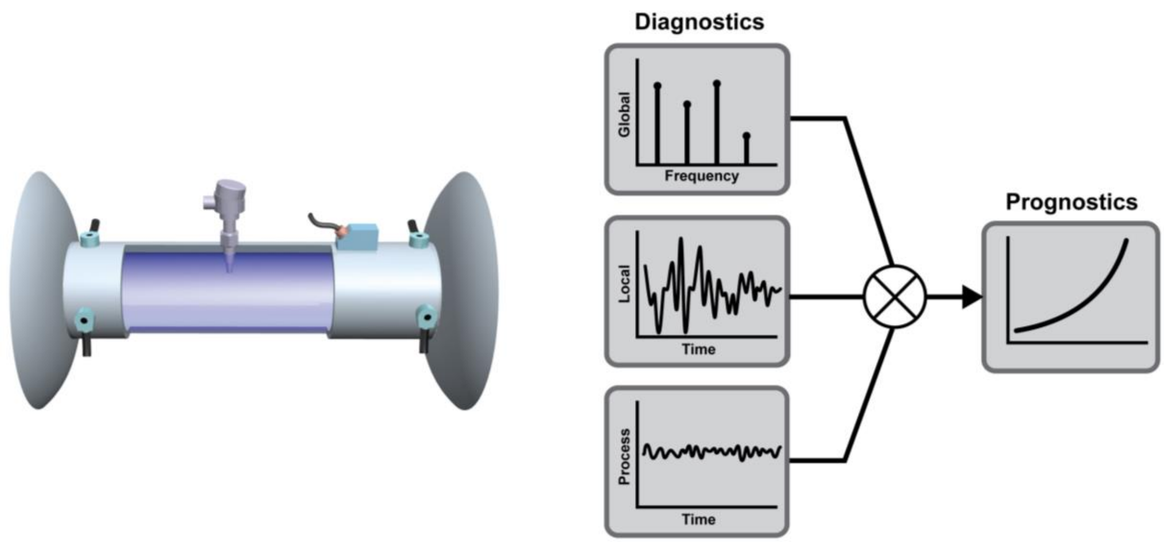


Figure 6.4. Notional Illustration of Enhanced Component Level PHM Performed by Fusing Data from Global Condition, Local NDE, and Process (stressor) Measurements

Phase II efforts will focus on developing and validating PHM at the component level. Significant activities will include developing prognostic algorithms suitable for data obtained from global condition measurements to demonstrate the following:

- Enhanced component PHM through fusion of global condition measurement data with local NDE measurement data.
- Quantitative accounting of uncertainty for component level PHM.

Two options for validating component level PHM concepts include 1) development of a dedicated test apparatus to allow testing under operational constraints and 2) leveraging existing test loops or facilities within the DOE laboratory complex. If feasible, both options should be pursued to ensure careful experimental design and verification on a dedicated test apparatus, followed by validation of concepts on available test loops.

6.3.3 Phase III: Integrate Local and Component Level Prognostics for System Level PHM

The system level consists of multiple interconnected components to perform a given function. Failure at the system level may be defined in terms of diminished functional capacity. Failure of an individual component may or may not cause the whole system to fail by itself, but its consequences could propagate through the system causing additional components to fail, eventually compromising the system functional capacity. At the system level, measurements from several components may be combined to interpret overall system health. In addition, PHM at the system level will require models to capture the interdependence and cross-coupling effects between components within the system.

Phase III research efforts will focus on integrating local and component level prognostics to perform system-level PHM. Significant activities for this Phase III will include:

- Developing a system model that can account for passive component interdependencies and cross-coupling effects.
- Fusion of data from multiple components to perform an overall assessment of system health.
- Quantitative accounting of uncertainty for system level PHM.

In this phase, existing test loops or facilities within the DOE laboratory complex may be leveraged for validation of system level PHM concepts.

6.3.4 Notional Research Schedule

An initial research plan is outlined here for the remainder of the project with a notional schedule provided in Figure 6.5. Specific tasks and choices for prototypic components and systems for Phase II and Phase III will be defined as the work progresses.

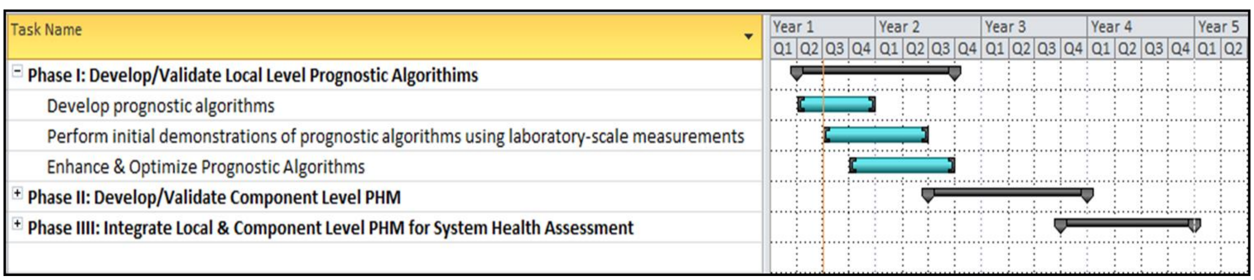


Figure 6.5. Notional Schedule for Research Activities

7.0 Summary

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 in ensuring that degradation in all passive components is well-managed. Advanced instrumentation and control technologies such as PHM 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 (O&M) costs and staffing needs. Such increased awareness can help inform O&M decisions to target maintenance activities and reduce risks associated with safety and investment protection through a greater understanding of precise plant component conditions and margins to failure.

This report documents an assessment of requirements, PHM state-of-the-art, research gaps, and technical needs relevant to the deployment of PHM systems for passive components in AdvSMRs. Drivers for PHM include the unique concepts of operation, harsher environments (when compared to conventional LWR designs) in which components operate, compact designs, and possible extended periods between inspection and maintenance opportunities. These drivers, when combined with proposed AdvSMR designs, operating experience with advanced reactors, likely concepts of operation for AdvSMRs, and potential regulatory drivers, help quantify the requirements for PHM systems to manage degradation in passive components. General requirements were identified for PHM of AdvSMR passive components in the following areas:

- Sensors and Instrumentation for Condition Assessment of Passive Components
- Fusion of Measurement Data from Diverse Sources
- Address Coupling Between Components or Systems, and Across Modules
- Incorporation of Lifecycle Prognostics
- Integration with Risk Monitors for Real-time Risk Assessment
- Interface with Plant Supervisory Control System

An overview of the PHM state-of-the-art relevant to passive AdvSMR components indicated that different types of measurements may be used to assess the health of AdvSMR passive components. These include measurements of stressors, global condition measurements, and localized NDE measurements of material degradation. This data may be applied to diagnostic algorithms (which may include data fusion approaches) to estimate the level of degradation of the components. Algorithms for state prediction were potentially applicable for estimating RUL of components. The applicability of diagnostic and prognostic techniques depends on the availability of a number of other forms of information and technologies, such as models of degradation accumulation (including physics-of-failure models) and algorithms to integrate information from multiple sources.

Based on the assessment of requirements and the state-of-the-art for PHM systems relevant to passive AdvSMR components, a technical gaps and research needs assessment was performed and documented. Gaps associated with each of the requirements were identified, and the research needs to address these gaps were defined. Key gaps exist in the availability and sensitivity of sensors tolerant to high temperatures and neutron radiation, availability of fast algorithms for diagnostics from measurement data, accurate models (including physics-of-failure models) of degradation accumulation in passive components, prognostics algorithms that are accurate over the lifecycle of the component and degradation, and prognostics in interconnected systems. Underlying all of these gaps is the need to quantify and specifically account for uncertainty in the RUL estimates.

A research plan was outlined for addressing several of the research gaps and technical needs, with the objective of demonstrating a prototypic prognostics technology to manage degradation of AdvSMR passive components. A phased approach was used, with the phases corresponding to: (1) developing and validating prognostic algorithms using localized NDE and stressor measurements, (2) developing and validating PHM at the component level, and (3) integrating local and component level prognostics to perform PHM of a system. In each phase, prototypic degradation modes (such as high-temperature creep or creep-fatigue) will need to be selected for the demonstration of the prognostics methodology. These selections will be made based on relevance of the selected degradation mode (and materials) to AdvSMRs (determined by coordinating with research on materials and degradation being performed in parallel technical pathways under the SMR R&D Program), the analysis performed in this document, ready access to laboratory-scale facilities for materials testing and measurement, and potential synergies with other national laboratory and university partners.

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Appendix A

Lead-Cooled Fast Reactor (LFR)

Appendix A

Lead-Cooled Fast Reactor (LFR)

The Lead-Cooled Fast Reactor (LFR) system features the potential for a very high reactor outlet temperature, high power density core, low system pressure, and a fast neutron spectrum. The liquid metal coolant, either lead (Pb) or lead/bismuth eutectic (LBE) can utilize natural convention for heat removal or can be pumped depending on core power requirements. The LFRs can be configured to use depleted uranium or thorium fuel matrices, and burn actinides from LWR fuel. Fuel is metal or nitride, with full actinide recycle from regional or central reprocessing plants. An illustration of an LFR system is provided in Figure A.1. Several LFR concepts may be suitable to modularization and these concepts are listed in Table A.1 with major design parameters summarized in Table A.2. Some LFR designs for small grids or developing counties, like the Gen4 and SSTAR, utilize a factory-built “battery” or “cassette” design and are optimized for power generation over long periods of time (10–30 years) without refueling. LFR development in Russia has occurred over many decades in submarines utilizing BREST fast reactor technology.

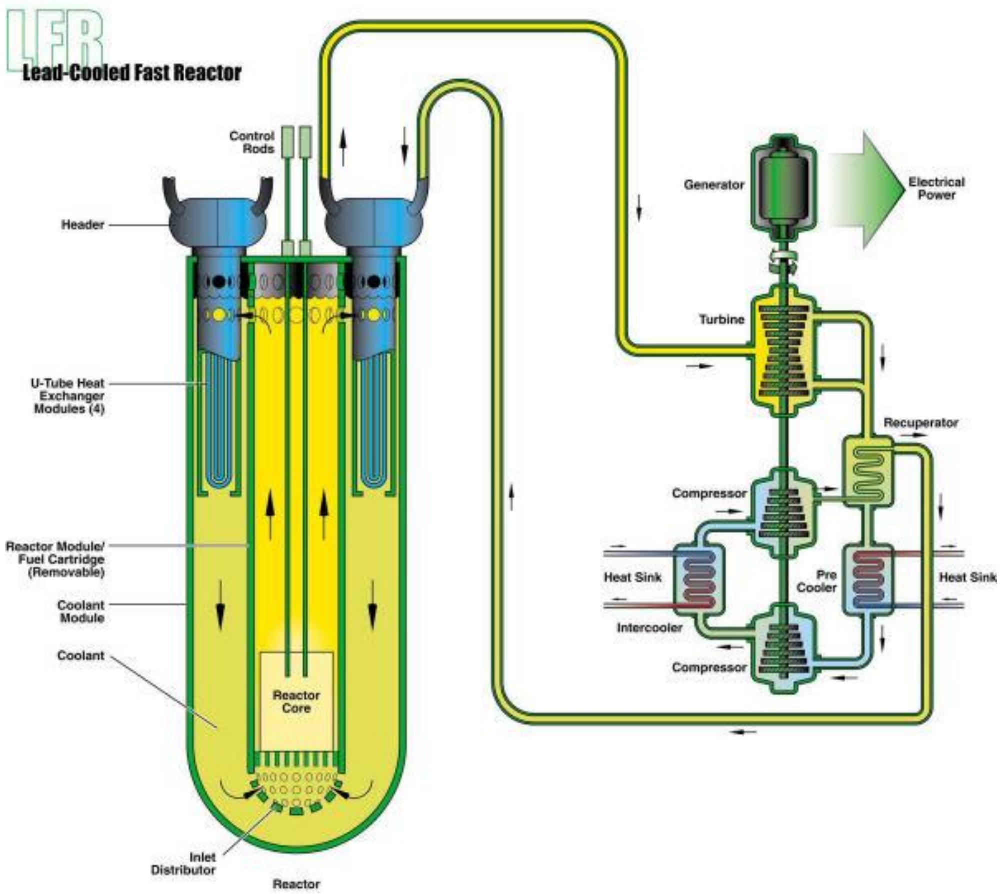

Figure A.1. An Illustration of a LFR Reactor System

Table A.1. List of Several Recent LFR Concepts for Modularization and Associated Organization/ Country

LFR Concepts	Organization/Country
USA Designs	
ENHS (Encapsulated Nuclear Heat Source)	University of California – Berkeley / USA
G4M (Gen4 Module) [formerly HPM (Hyperion Power Module)]	Gen4 Energy Inc. & LANL / USA
SSTAR (Secure, Small Transportable Autonomous Reactor) – included STAR, STAR-H2, STAR-LM	Argonne National Laboratory (ANL) / USA
SUPERSTAR (Sustainable Proliferation-resistance Enhance Refined Secure Transportable Autonomous Reactor)	
Russia Designs	
BREST-OD-300	N.A. Dollezhal Research and Development Institute of Power Engineering (NIKIET) / Russia
ANGSTREM	
SVBR-100 (Svintsovo Vismutny Bystryl Reactor)	
Other Designs	
LSPR (Long-Life Safe Simple Small Portable Proliferation-Resistant Reactor)	Tokyo Institute of Technology / Japan
PEACER (Proliferation-Resistant Environmentally-Friendly, Accident-Tolerant, Continuous -Energy, and Economical Reactor)	Nuclear Transmutation Energy Research Centre of Korea (NUTRECK) / South Korea

Table A.2. Summary of Design Parameters for Several Recent LFR Concepts

General SMR LFR Design Features	Parameters
Coolant	Lead (Pb) or Lead/Bismuth (LBE) Note: Lead / Lithium (Li) in one design
Forced or Natural Circulation	Depends on design and power density requirements
Thermal Capacity Range (MWth)	30–700
Gross Electrical Capacity Range (MWe)	6–300
Refueling Frequency (years)	Continuous; 10; 15; 20–30
Fuel Cycle	Closed

LFRs utilizing lead or lead-bismuth coolants have many positive attributes, including:

- High temperature operation – Pb melts at 327°C and boils at 1737°C, LBE melts at 125°C and boils at 1670°C. The high boiling temperature exceeds the temperatures at which steels lose their strength or melt. Thus, the primary Pb coolant is a low-pressure coolant that does not boil or flash (in the case of pressure reductions) upon failure of the primary coolant system boundary and can quickly solidify in the case of a leak. Operation at temperatures in excess of 830°C is envisioned with the development of advanced materials that could support thermochemical production of hydrogen.

- Allows for relatively high core power density, which translates to a smaller reactor core for a given amount of power. This is important given the weight of the lead coolant and in theory makes the system more cost-effective.
- Inert to air, water, and carbon dioxide eliminating the concerns of vigorous exothermic reactions associated with the use of Na coolant. This also enables the heat exchanger to be located in the primary circuit.
- High absolute thermal expansion coefficient facilitates passive circulation for decay heat removal and provides a large negative temperature coefficient for reactivity feedback.
- The Pb or LBE coolant shields gamma radiation.

Some disadvantages of LFRs include:

- The coolant can be corrosive to fuel cladding and other steel components. Corrosion is controlled by maintaining dissolved oxygen in the coolant at sufficient levels.
- Solidification of the coolant solution renders the reactor inoperable. LBE coolant has a lower melting point than PB, making de-solidification less challenging.
- Pb or LBE coolant has a low thermal capacity relative to Na. The specific heat per unit volume of LBE and Pb are similar to that of Na but the thermal conductivities are lower about a factor of four.
- Pb is the heaviest of all proposed coolants, making it expensive to pump and requiring seismically robust structures.
- Potential erosion of pump materials.

Key passive components in LFRs include:

- Steam Generators – Located in vessel on BREST-OD-300. Main type considered is the helical tube but some designs (ELSY) are considering a spiral-wound tube bundle. The installation of SGs inside the reactor vessel is major challenge of a LFR design, which includes the need for a sensitive and reliable leak detection system and a highly reliable depressurization and isolation system.
- Heat Exchangers (heating and cooling)
- Reactor Vessel, Reactor Core, Reactor Shields / Reflectors / Absorber
- Piping
- Tanks
- Filters – May be required for lead coolant to remove iron oxide formed by corrosion debris such as iron that migrates into the coolant.

Finally, Table A.3 provides a summary of typical operating parameters for LFR concepts.

Table A.3. Summary of Typical Operating Parameters for LFR Concepts

Parameter		Values	References
Temperature Range (°C)	Core Inlet	290–610	Sienicki et al. (2006)
	Core Outlet	465–*780 (* higher temperature special case for hydrogen production option STAR-H2)	Sienicki et al. (2006)
	Pb / LBE Coolant Boiling	1740 / 1670	Sienicki et al. (2006)
	Pb / LBE Melt	327 / 125	Sienicki et al. (2006)
	Fuel (Max.)	980 (Hot Spot)/814 (Nominal)	Filin (2003)
	Fuel Rod (Max.)	649 (Hot Spot)/614 (Nominal)	
	Primary Loop (Inlet/Outlet)	405 / 561	INL (2005)
	Secondary Loop (Inlet/Outlet)	392 / 541	INL (2005)
Pressure Range (MPa)	Reactor Vessel	~0.1 (1 atm)	
	CO_2 in Turbine Loop Max/Min (SSTAR)	20 / 7.4	Sienicki et al. (2006)
Flow Rate (kg/s)	Primary Loop (Lead based)	2150–16200	Sienicki et al. (2006)
	Good design practice to limit lead speed to 2 m/s to reduce both pressure loss and erosion of structural material.	2150–16200	Smith (2010)
	CO_2 in Turbine Loop (SSTAR)	245	Sienicki et al. (2006)
Power Density (MW/m^3 or kW/l)	Average	69	Sienicki et al. (2005)
	Peak	119	Sienicki et al. (2005)
Neutron Flux	Peak fast fluence	3.7×10^{23} n/cm^2	Sienicki et al. (2006)
	Neutron flux (Max.)	3.8×10^{15} n/cm^2 - s	Trallero (2011)
	Neutron flux (Average)	2.35×10^{15} n/cm^2 - s	Trallero (2011)

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Appendix B

Molten Salt Reactor (MSR)

Appendix B

Molten Salt Reactor (MSR)

The Molten Salt Reactor (MSR) features moderate to high power density, high reactor outlet temperatures, low system pressure, and in some variants, a fluid-fueled core where the molten salt coolant contains dissolved fuel that allows for refueling without reactor shutdown. This reactor type can be designed to operate with either a thermal or fast neutron flux and has the unique characteristic that, in theory, very high fuel burnup can be achieve because fuel performance in the fluid-fueled concepts is not limited to fuel cladding strength and ductility considerations. Other designs (e.g., AHTR, MARS, SmAHTR) use molten salt as the coolant and a more common solid fuel approach. The liquid-fueled MSRs can be used for production of electricity, actinide burning, and the production of hydrogen and fissile fuels.

The molten salt coolant is typically a mixture of lithium and beryllium fluoride salts with a boiling point (1400°C) significantly higher than the temperature of the fuel; however, a sodium fluoride salt reactor has recently been evaluated and shown to be feasible. The fuel dissolved in the molten salt coolant can be enriched uranium, thorium, or U-233. The molten fuel salt is circulated through a moderator core, typically unclad graphite, at relatively low pressure where fission occurs. In the core, the highly radioactive fuel salt is heated to a high temperature (700°C or more) and then flows into a primary heat exchanger where heat is transferred to a secondary circuit of clean molten salt coolant before flowing back to the core. As the fuel burns, the waste products are removed from the fuel salt and fresh fuel is added. This can be done at power and therefore plant availability is determined by maintenance schedule and not fuel cycle. This arrangement also enables the breeding of fissile U-233 using the fertile thorium in a fuel cycle. The secondary heat transfer circuit transfers the heat to a high-temperature Brayton cycle that converts the heat to electricity. The Brayton cycle (with or without a steam-bottoming cycle) may use a working gas of either nitrogen or helium. A diagram of an MSR system is provided in Figure B.1. Several MSR concepts with the potential for modularization are provided in Table B.1 with major design parameters summarized in Table B.2. Typical operating parameters for several MSRs are provided in Table B.3.

Key safety features of MSRs with liquid fuel are typically associated with the negative reactivity changes associated with elevated temperatures resulting in coolant/fuel expansion during power excursions and an actively cooled salt plug. During a reactor-overheat condition, the salt plug melts and allows the molten fuel salt mixture to drain into a holding tank configured to disperse the fuel in such a manner that stops the sustaining nuclear chain reaction, thereby shutting down the plant and allowing the mixture to safely cool. As the mixture cools in the tank via passive cooling, it will eventually solidify. Many of these reactor systems are designed to be “walk away” safe, whereby in the event of complete power loss, with no operator action, the reactor will find a safe state.

Some key passive components in MSRs include:

- Heat exchangers
- Reactor Vessel, Reactor Core, Reactor Shields / Reflectors / Absorber

- Piping
- Freeze Valve – Dissolves for coolant drainage during power loss
- Tanks – Coolant Emergency Dump Tank

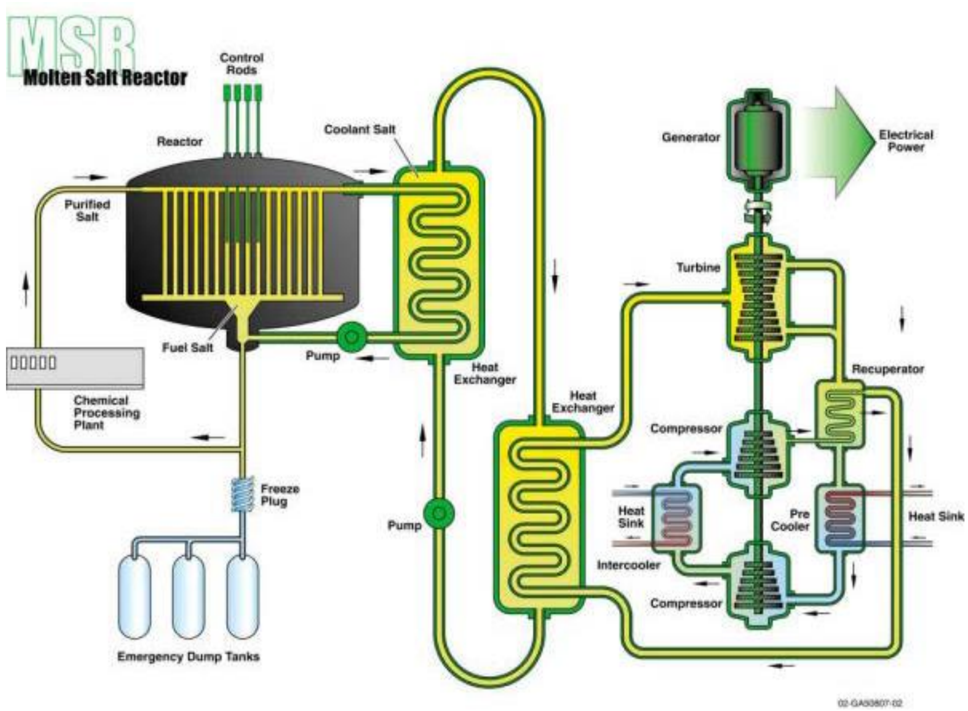

Figure B.1. Depiction of an MSR System

Table B.1. List of Several MSR Concepts and Associated Organization/Country

MSR Concepts	Organization / Country
Fuji MSR (Fuji Molten Salt Reactor)	International Thorium Energy & Molten Salt Technology Inc. Company (IThEMS) / Japan
GEMSTAR (Green Energy Multiplier*Subcritical Technology for Alternative Reactors)[(a)]	Virginia Tech & Accelerator Driven Neutron Application Corporation (ADNA) / USA
LFTR (Liquid-Fluoride Thorium Reactor)	Flibe Energy / USA
MARS (Microfuel Molten Salt Cooled Reactor of Low Power)[(b)]	Kurchatov Institute / Russia
SmAHTR (Small Modular Advanced High Temperature Reactor)[(b)]	ORNL / USA
ThorCon	Martingale, Inc. / USA
WAMSR (Waste-Annihilating Molten Salt Reactor)[(a)]	Transatomic Power / USA

(a) Fast reactor variants.
(b) Not a fluid-fueled type MSR concept. Uses clean molten salt with solid fuel.

Table B.2. Summary of Design Parameters for Several Recent MSR Concepts

General SMR MSR Design Features	Parameter	Reference
Coolant	Molten salt	European Nuclear Society (2012)
Thermal Capacity Range (MWth)	16–450	
Gross Electrical Capacity Range (MWe)	6–500+	
Refueling Frequency (years)	For fluid fueled designs – online fueling For solid fueled designs – 5, 15, and 30	
Fuel Cycle	Thorium (thermal to epithermal neutron speed) U-Pu (fast neutron spectrum)	NRC (2012)

Table B.3. Summary of Typical Operating Parameters for MSRs

Parameter	Value		Reference
Temperature Range (°C)	Core Inlet	550–650	
	Core Outlet	700–750 to 800–1000	
	Molten Salt Coolant Freezing	350	
	Molten Salt Coolant Boiling	1300	Alekseev (2010)
	Primary Loop (Inlet/Outlet)	570–650/700–1000	
	Secondary Loop (Inlet/Outlet)	454–600/633–690	
	Graphite Moderator	947 (Max)	Unknown (2004)
Pressure Range (MPa)	Molten Salt Coolant	0.1 (~ 1 atm)–0.5	
Power Density (MW/m^3 or kW/l)	MARS	0.75	
	Fuji MSR & SmAHTR	6.8–9.4	
	ThorCon	25	
Neutron Flux	Fuel Element (MARS)	0.53–2.1 × 10^{21} n/cm^2	Adamovich et al. (2007)
	Reactor Vessel (MARS)	0.33–1.0 × 10^{21} n/cm^2	Adamovich et al. (2007) Yoshioka et al. (2010)
	Graphite in Reactor (Fuji MSR)	3 × 10^{23} n/cm^2	Unknown (2004)

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Appendix C

Supercritical Water Cooled Reactor (SCWR)

Appendix C

Supercritical Water Cooled Reactor (SCWR)

The Supercritical-Water-Cooled Reactor (SCWR) concept offers moderate core power densities and simplicity in design by eliminating major components (e.g., pressurizers, primary-to-secondary heat exchangers, steam dryers, and steam generators). The simple design should translate directly into reduced overall plant construction costs. The reactor concept would operate at much higher temperatures and pressures, resulting in higher operating efficiencies (44% compared to 32% as seen in today's LWRs), but requires further development in fuels and materials. This technology is an evolution of existing LWR technology and leverages existing advanced supercritical coal-fired technology and, in theory, can be designed to have high conversion ratios but less than unity (i.e., fissile material produced divided by fissile material loaded in initial core). The energy conversion technology associated with the secondary side of the reactor plant has been fully developed and commercialized by the coal fire industry. Supercritical water technology has been used in coal power plants since the 1960s to increase plant efficiency and reduce emissions, and by the 1990s supercritical water boilers had proven themselves as a reliable and established technology. Currently 85% of the new Western coal power plants are supercritical.

As stated, the SCWR is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374°C, 22.1 MPa or 705°F, 3208 psia). At supercritical pressures, no boiling takes place in the core and the phase transition between liquid and gas is much smoother than the abrupt boiling, which occurs in a commercial boiling water reactor operating at lower pressures. An example of a SCWR system is shown in Figure C.1. These reactors can be designed to operate with either a thermal or fast-neutron spectrum.

Fast spectrum supercritical water reactors have been considered by the Japanese (Yetisir et al. 2012) and have been designed to resolve the undesirable positive void effect seen in previous fast-spectrum designs. The Korean Ministry of Science and Technology (MOST) sponsors research (Danielyan 2003) in supercritical water reactor technology and Europe's High Performance Light Water Reactor program was initiated in 2006 as part of the Gen IV International Forum (GIF) and is focused on assessing "the critical scientific issues and the technical feasibility of a High Performance Light Water Reactor operating under supercritical pressure" (Tulkki 2006).

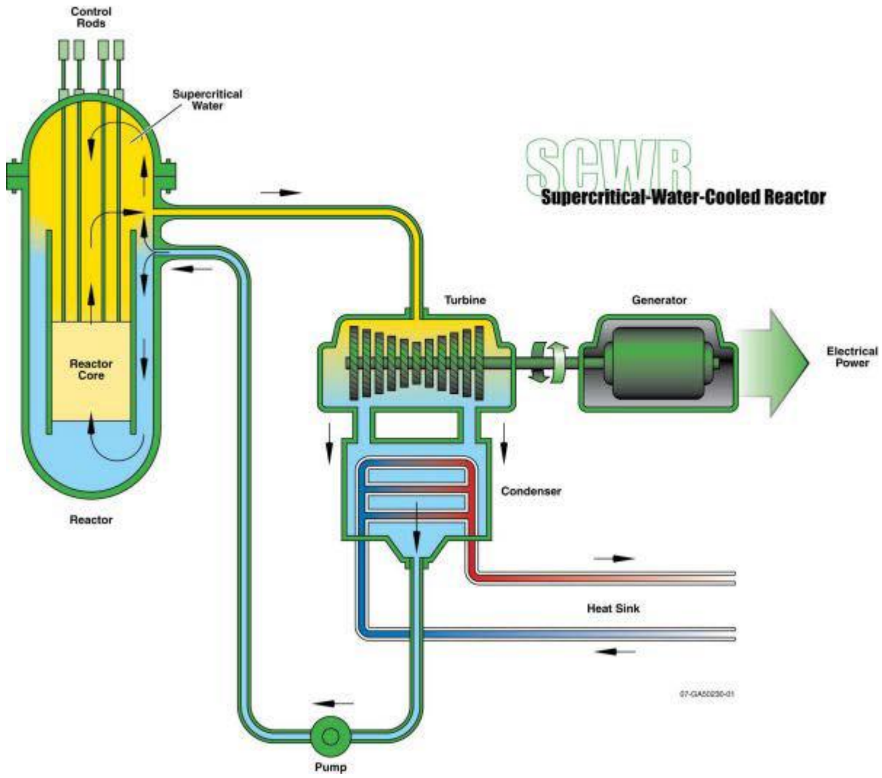

Figure C.1. General Diagram of a SCWR Reactor System

Table C.1. SCWR Concepts for Potential Modularization

Modularized SCWR Reactors	Country
300 MWe SuperSafe© Reactor (SSR)	Canada

Table C.2. Summary of Design Parameters for SCWR Concepts

General SMR SCWR Design Features	Parameters	Reference
Coolant	Water critical	
Thermal Capacity Range (MWth)	400–3800 670 (SSR)	Yetisir et al. (2012)
Gross Electrical Capacity Range (MWe)	175–1700 300 (SSR)	Yetisir et al. (2012)
Refueling Frequency (years)	2–6 yrs	
Fuel Cycle	Thermal, fast, or mixed. Once through, open or closed.	Duffey and Pioro (2005)

Table C.3. Summary of Typical Operating Parameters for SCWRs

Parameter	Value		Reference
Temperature Range (°C)	Core Inlet	350	Duffey and Pioro (2005), Yetisir et al. (2012)
	Core Outlet	625	Duffey and Pioro (2005), Yetisir et al. (2012)
	Coolant Max	625	Yetisir et al. (2012)
	Fuel	1900	
Pressure Range (MPa)	26		Duffey and Pioro (2005)
Flow Rate	1,418 Kg/s Japanese Super LWR concept		
Power Density (MW/m^3 or kW/l)	70 kW/1 (SCWR concept)		Danielyan (2003)
	67–144 MW/m^3		Tulkki (2006)
	300 MW/m3 (Japan – Super Fast Reactor)		The Energy Library (2009)

Key passive components for SCWRs include:

- Heat exchangers
- Reactor vessel, reactor core, reactor shields / reflectors / absorber
- Piping
- Tanks
- Moisture separator

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Appendix D

Sodium-Cooled Fast Reactor (SFR)

Appendix D

Sodium-Cooled Fast Reactor (SFR)

The Sodium-Cooled Fast Reactor (SFR) features very high core power densities, high reactor outlet temperatures, low system pressure, and a fast neutron spectrum. An advantage of sodium coolant is its relatively high heat capacity, which provides thermal inertia against overheating during reactor transients and accidents. While the fast neutron spectrum results in large fluences for internal core and reactor vessel components, it also enables fissile and fertile materials (e.g., plutonium, actinides, depleted uranium) to be used considerably more efficiently than thermal spectrum reactors with once-through fuel cycles.

While sodium has the advantage that it does not corrode steel components, it does react chemically with air and water so SFRs must be designed to limit the potential for such reactions. Important safety features of the SFR system include a long thermal response time, a large temperature margin to coolant boiling, a primary system that operates at essentially atmospheric pressure, and an intermediate secondary non-radioactive sodium system between the primary radioactive sodium circuit and the water or gas loop used in the secondary system. The primary coolant system can either be arranged in a pool layout (a common approach, where all primary system components are housed in a single vessel), or in a compact loop layout, favored in Japan. A diagram of a pool type system is included in Figure D.1.

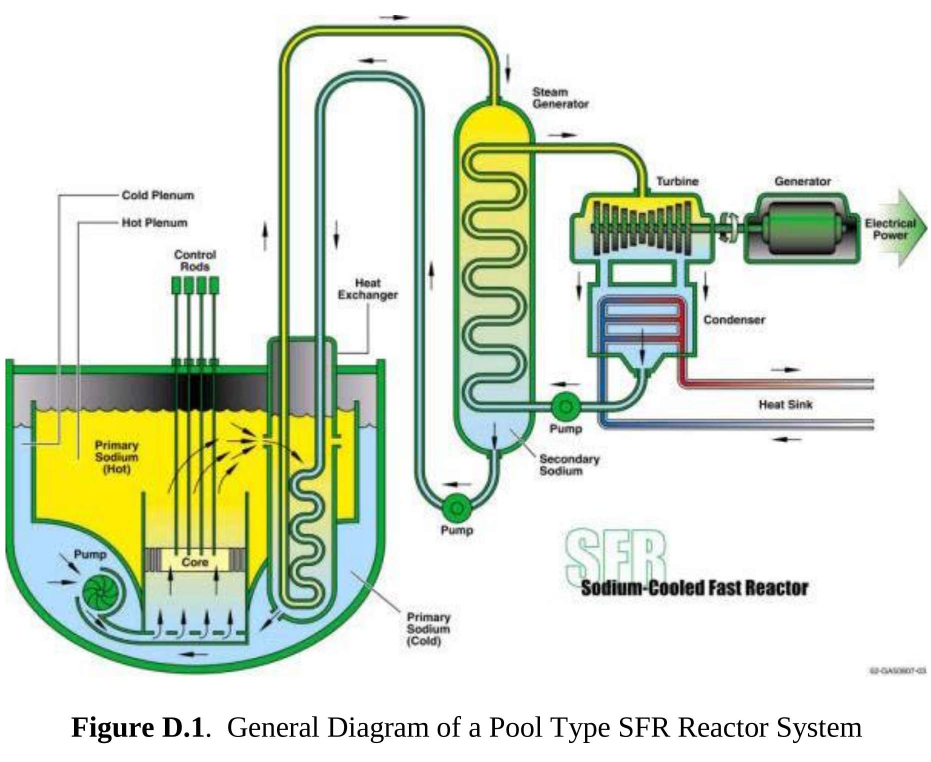

Figure D.1. General Diagram of a Pool Type SFR Reactor System

Table D.1 provides a listing of several recent SFR concepts along with the associated organization and country of origin and Table D.2 provides an overview of some design parameters. The domestic SFR designs in Table D.1 (e.g. PRISM, TWR, ARC-100) as well as the Janapese 4S design utilize a pool-type reactor vessel design containing the reactor core, primary heat exchanger, and electromagnetic (EM) pump(s). An inert cover gas system is used to keep sodium from being exposed to air and/or water and supports the reactor vessel, reactor containment vessel, heat exchangers, and steam generator. In general, all penetrations into the reactor vessel are located at the top of the vessel.

Table D.1. List of Several Recent SFR Concepts and Associated Organization/Country

SFR Concepts	Organization/Country
4S (Super Safe Small Simple)	Toshiba / Japan
PRISM (Power Reactor Innovative Small Modular)	GE Hitachi / USA
ARC-100 (Advanced Reactor Concepts - 100)	Advanced Reactor Concepts LLC / USA
RAPID (Refueling by All Pins, Integral Design)	Central Research Institute of Electric Power / Japan
TWR or TP-1 (Traveling Wave Reactor)	TerraPower / USA

Table D.2. Summary of Design Parameters for Several Recent SFR Concepts

Design Feature	Parameter
Thermal Capacity Range (MWth)	5 (RAPID)–840 (PRISM)
Gross Electrical Capacity Range (MWe)	0.5 (RAPID)–311 (PRISM)
Refueling Frequency (years)	2; 10; 20; 40–60
Fuel Cycle	Breed & burn (TWR); once through (4S, RAPID); closed (PRISM)

Although there are several SFRs, the general design and operating parameters are similar. The long refueling reactors (4S, TWR) on the order of 20–40+ years will require long-life components with the hope that routine maintenance is limited. The shorter refueling reactors (PRISM) on the order of 1.5+ years require fuel exchange operations that likely will allow some minimal maintenance to be performed. Electromagnetic (EM) pumps are generally used to pump sodium (Na) on small SFRs.

The SFR is primarily envisioned for electricity production but has also been considered for other missions requiring relatively high-temperature process heat, such as desalination, hydrogen production, and bitumen extraction from sand. The SFR design utilizes a series of sodium heat exchangers feeding steam generators and then steam turbine for electricity. Process heat can also be made available for other uses, such as production of hydrogen. Historically, some of the operational issues with SFRs have included fires as a result of heat exchanger tube leaks, sodium leaks due to structural failures in primary piping, and thermal stratification due to inadequate sodium mixing.

Key passive components in SFRs include:

- Heat exchangers
- Reactor vessel, reactor core, reactor shields / reflectors / absorber

- Piping
- Tanks

Table D.3. Summary of Typical Operating Parameters for SFRs

Parameter	Typical Values		References
Temperatures (°C)			
	Coolant Max	704 with max ramp rate of 9°C/sec	Minato and Handa (2000) Donoghue et al. (1994)
	Sodium Coolant Boiling	980 @ 0.2 MPa	TAREF (2011)
	Fuel (Max.)	810; ~ 825 (peak bounding)	Minato and Handa (2000) Arie and Grenci (2009) Toshiba (2011) Donoghue et al. (1994)
	Reactor Vessel Wall (Operating)	426	Minato and Handa (2000) Arie and Grenci (2009) Toshiba (2011) Donoghue et al. (1994)
	Reactor Vessel Wall (Max)	705	Minato and Handa (2000) Arie and Grenci (2009) Toshiba (2011) Donoghue et al. (1994)
	Primary Loop (Inlet/Outlet)	338 / 485	Donoghue et al. (1994)
	Secondary Loop (Inlet/Outlet)	282 / 443	Donoghue et al. (1994)
	Steam Generator (water)	285	Donoghue et al. (1994)
Pressures (MPa)	Primary Coolant (normal operations)	Near ambient (enough to circulate sodium) to 0.2	
	Reactor Vessel Design	0.3	Arie and Grenci (2009)
	IHX	0.88	Minato and Handa (2000)
	Water/Steam	6.9–10.5	Minato and Handa (2000) Donoghue et al. (1994)
Flow Rates (PRISM)	Primary Loop (Sodium)	174,128 (l/min)	Donoghue et al. (1994)
	Secondary Loop (Sodium)	156,148 (l/min)	Donoghue et al. (1994)
	At Steam Generator		Donoghue et al. (1994)
	Sodium	8.30×10^{6} (kg/hr)	
	Water	1.025×10^{6} (kg/hr)	
	Steam	9.30×10^{5} (kg/hr)	
Power Density	17 (4S)-210(PRISM) (MW/m^3 or kW/l)		
Neutron Fluence	Peak fast fluence limit	4.0×10^{23} n/cm^2	Hoffman et al. (2006)
	Reactor Vessel	6.8×10^{12} n/cm^2	Donoghue et al. (1994)

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Appendix E

Gas-Cooled Reactors

Appendix E

Gas-Cooled Reactors

Gas-cooled reactor (GCR) systems feature either thermal or fast-neutron-spectra. The thermal spectrum reactors are known as the high temperature gas reactors (HTGRs) and very-high-temperature reactors (VHTRs) and feature the use of TRISO-coated particle fuel dispersed in a graphite matrix and significant use of graphite moderator. The fast spectrum reactors are known as gas-cooled fast reactors (GFRs), which are associated with a closed fuel cycle. The main characteristics common to both types of GCRs include the usage of robust refractory fuel, high operating temperatures, potential direct coupling to He-Brayton energy conversion cycles, and low power density relative to SFRs. The primary coolant boundary in these systems are designed to prevent large failures, such as air ingress and unacceptable chemical reactions within the core that could cause excessive degradation of the fuel elements or other core components. VHTRs typically have no active safety features and require no operator action to ensure safety. Typical core configurations for VHTRs are based on dispersal of coated-particle fuel into graphite blocks or spherical fuel pebbles. GCRs are primarily envisioned for missions in electricity production and actinide management. Very-high-temperature designs can support hydrogen production as well. Historically, high temperature gas reactors (HTGRs) have experienced moisture ingress events into the reactor system due to leaking of helium recirculator bearings, which caused significant corrosion issues and unplanned outages (Fort St. Vrain). Newer designs propose to use magnetic bearings.

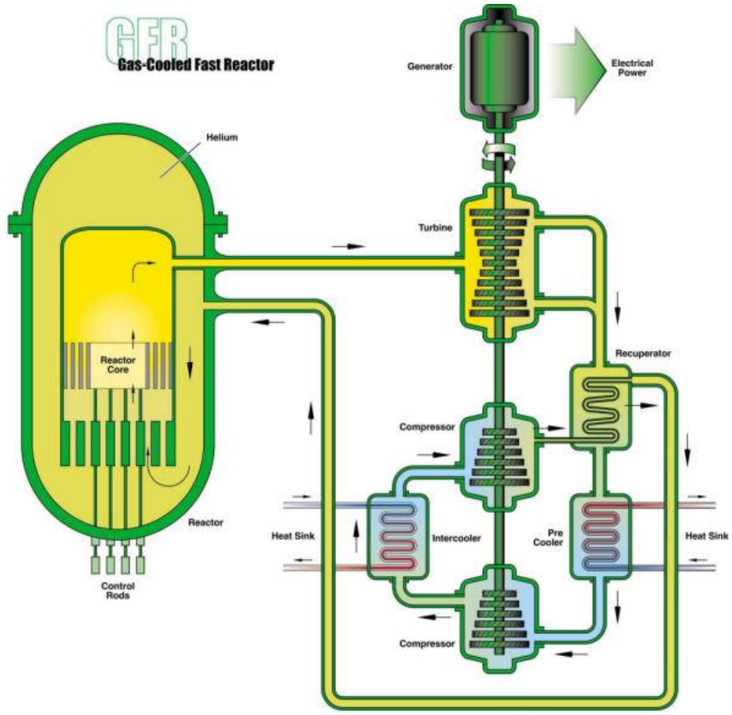

Figure E.1. General Diagram of a GFR Reactor System

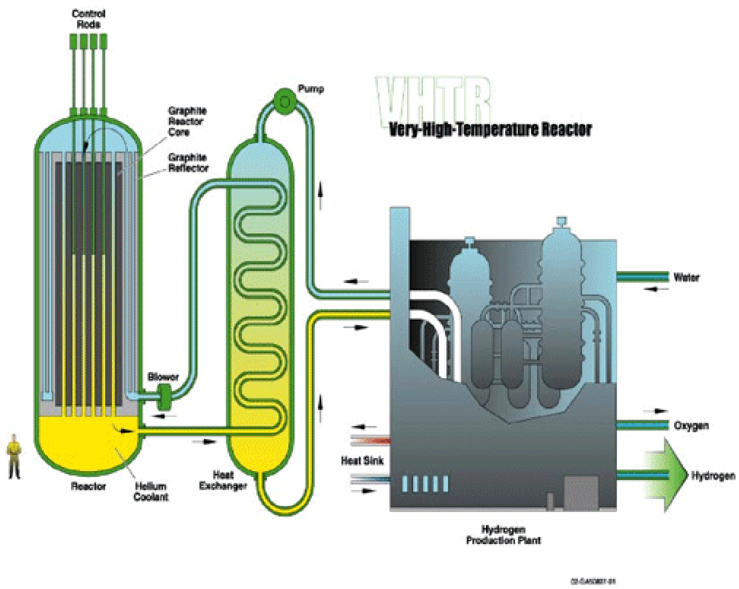

Figure E.2. General Diagram of a VHTR Reactor System

Table E.1. List of Several Recent GCR Concepts and Associated Organization/Country

GCR Concepts	Organization / Country
Fast • EM2 (Energy Multiplier Module)	General Atomics / USA
Thermal • GT-MHR (Gas-Turbine Modular Helium Reactor) • RS-MHR (Remote Site - Modular Helium Reactor)	General Atomics / USA
• SC-HTGR (Steam Cycle – High Temperature Gas Reactor) (ANTARES)	AREVA / France
• PBMR (Pebble Bed Modular Reactor)	ESKOM & Pty Limited / South Africa
• HTR-PM (High Temperature Gas Cooled Reactor – Pebble Bed Module)	Tsinghua University / China

Table E.2. Summary of Design Parameters for Several Recent GCR Concepts

General GCR Design Features	Parameters
Coolant	He (most common); other: N_2, air
Thermal Capacity Range (MWth)	~5–600
Gross Electrical Capacity Range (MWe)	2–285
Refueling Frequency (years)	1.5; 5–10; 30 (continuous for pebble bed)
Fuel Cycle	Once through, breed and burn.

Table E.3. Summary of Typical Operating Parameters for GCRs

Parameter	Value		Reference
Temperature Range (°C)	Core Inlet	250–587	
	Core Outlet	530–850	
	For Hydrogen Productions	900–1000	
	Fuel (max.)	1238 (limit 1600)	
Pressure Range (MPa)	5–~9		
He Mass Flow Rate (kg/s)	96–320		General Atomics (1996), IAEA (2011b)
Power Density (MW/m^3 or kW/l)	4–6.5		

Key passive components in GCRs include:

- Heat exchangers
- Reactor vessel, reactor core, reactor shields/reflectors
- Piping – connecting to and outside of reactor vessel

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Appendix F

Relevant Operating Experiences

Appendix F

Relevant Operating Experiences

Prior operating experience of several deployed advanced reactors is summarized in this section. The most extensive operating experience exists for the SFR and HTGR reactor concepts. In the case of other reactor concepts, the operating experience is either very limited (e.g., LFRs and MSRs) or does not exist to date (e.g., GFRs and SCWRs). Tables F.1–F.3 summarize key information for the specific reactors from which information on operating experience was gathered for this report.

Table F.1. Sodium Fast Reactors in Operation, Shutdown, and Under Construction

Reactor Acronym	Reactor Name	Country	Status	First Criticality	Final Shutdown	Thermal Power (MW)
EBR-I	Experimental Breeder Reactor I	United States	Shut Down	1951	1963	1.4
BR-5/BR-10	Bystrij Reactor (Fast Reactor)	Russia	Shut Down	1959	2002	8
DFR	Dounreay Fast Reactor	United Kingdom	Shut Down	1959	1977	60
EBR-II	Experimental Breeder Reactor II	United States	Shut Down	1963	1994	62.5
EFFBR	Enrico Fermi 1 Fast Breeder Reactor	United States	Shut Down	1963	1972	200
Rapsodie	-	France	Shut Down	1967	1983	40
BOR-60	Bystrij Opytnyj Reactor (Fast Experimental Reactor)	Russia	In Operation	1969		55
SEFOR	Southwest Experimental Fast Oxide Reactor	United States	Shut Down	1969	1972	20
BN-350	Bystrie Neytrony (Fast Neutrons)	Kazakhstan	Shut Down	1972	1999	750
Phénix	-	France	Shutdown	1973	2010	563
PFR	Prototype Fast Reactor	United Kingdom	Shut Down	1974	1994	650
JOYO	-	Japan	In Operation	1977		50/75/ 100/140
KNK-II	Kompakte Natriumgekuhlte Kerneaktoranlaze	Germany	Shut Down	1977	1991	58
FFTF	Fast Flux Test Facility	United States	Shut Down	1980	1993	400

Table F.1 (cont'd)

Reactor Acronym	Reactor Name	Country	Status	First Criticality	Final Shutdown	Thermal Power (MW)
BN-600	Bystrie Neytrony (Fast Neutrons)	Russia	In Operation	1980		1470
Superphénix	-	France	Shut Down	1985	1997	3000
FBTR	Fast Breeder Test Reactor	India	In Operation	1985		40
MONJU	-	Japan	In Operation	1994		714
BN-800	Bystrie Neytrony (Fast Neutrons)	Russia	Construction	—	—	2000
CEFR	China Experimental Fast Reactor	China	In Operation	2011		65
PFBR	Prototype Fast Breeder Reactor	India	Construction	—	—	1250

Table F.2. Summary of HTGRs that are Operating or Have Operated

Reactor Name	Country	Status	Start-up	Shutdown	Thermal Power (MW)
Dragon	United Kingdom	Shut Down	1966	1975	20
AVR	Germany	Shut Down	1976	1988	46
Peach Bottom	United States	Shut Down	1967	1974	155
Fort St. Vrain	United States	Shut Down	1979	1989	842
THTR-300	Germany	Shut Down	1985	1989	750
HTTR	Japan	In Operation	1999	---	30
HTR-10	China	In Operation	2003	---	10

Table F.3. Summary of MSRs and LFRs that have Operated

Reactor Name	Country	Status	Operating Period
Aircraft Reactor Experiment	United States	Shut Down	1954 (9 days)
Molten Salt Reactor Experiment	United States	Shut Down	1965–1969
Russian alpha class submarines and supporting reactors	Russia	---	---

Based on the operating experience of SFRs and HTGRs discussed in this section, it is clear that there is a role for PHM systems in AdvSMRs. Requirements for such systems may be informed by the operational experience presented in the following subsections. These experienced-based requirements are listed in Section 3.0.

F.1 Sodium Fast Reactors (SFRs)

Twenty-two SFRs have been constructed and operated in 9 countries for a cumulative operating experience of approximately 400 reactor-years. This operating experience is considered substantial for drawing generic inferences. The operational experience for these SFRs is documented in numerous reports and articles with comprehensive reviews on the subject provided by Guidez et al. (2008) and Raj et al. (2010). Table F.1 summarizes experience with passive components in SFRs and mostly relates to fuel cladding, steam generators, heat exchangers, and rotating plugs used for refueling. Additional information for Table F.1 comes from reports documenting experience specific to the Fast Flux Test Facility (FFTF) (Baumhardt and Bechtold 1987; Rawlins et al. 1987), the French PHENIX Fast Breeder reactor (Guidez and Jolly 1987), and experience in the Russian Federation (Saraev et al. 2012).

A number of the failures in Table F.1 relate to sodium leaks in steam generators and heat exchangers. For steam generators, tube integrity is especially important because of the potential for chemical reaction between sodium and water. All of the single-wall steam generators, except Superphenix and Fast Breeder Test Reactor (FBTR), experienced tube leaks during operations. Double-wall tubes were used in Experimental Breeder Reactor – II (EBR-II) and Dounreay Fast Reactor (DFR), where leaks could be detected from gas conditions between the tube walls. Because experience showed that sodium-water reactions could be adequately contained, all subsequent SFRs have used single-wall tubes. Some interest has recently been shown in double-wall tubes for improving steam generator reliability, although one concern with the use of double-walled tubes is that stress relaxation during operation may lead to loss of contact between inner and outer tubes resulting in loss of heat transfer capability (Kisohara et al. 2012). Some recent investigations have emphasized that weld joints, and particularly dissimilar weld joints between intermediate heat exchangers (IHXs) and steam generators, are susceptible to creep failure (Dubiez-le Goff et al. 2012; Jayakumar et al. 2012).

In addition to sodium leaks, the ingress of impurities into the cover gas and sodium has also impacted SFR operations leading to unexpected shutdowns. Impurities due to the ingress of air and oil have led to contamination of primary sodium resulting in an 18-month shutdown in the case of the Prototype Fast Reactor (PFR). Impurities from the cover gas have also had an impact on the core neutronics and thermohydraulic characteristics. In the case of FFTF, it’s noted that air contamination of the argon cover gas complicated the ability to identify fuel failures. The deposition of sodium aerosols on rotating plug components and absorber rod actuating mechanisms has also lead to issues with sticking of rotating plugs and spurious trips of the absorber rods. Fuel performance has been described as excellent with the exception of early years in the BN-350 and BN-600 reactors in Kazakhstan and Russia. During the earlier years of operation, these reactors experienced numerous fuel failures but the issues were later resolved with redesigned subassemblies. Fuel cladding failures are detected by monitoring the cover gas for fission gases and by monitoring fission product activity in the primary sodium. Tag gas analysis or a sniffer system have been employed to locate leaking fuel assemblies.

Table F.4. Summary of Generic Passive Component Experience in SFRs

Effected Components and Systems	Fault Effects	Cause	Reactors	References
Fuel cladding	Impacted plant availability and safety; impacted refueling outage length	Operational stresses	Fuel pin failures: KNK-II (5), PFR (21), PHENIX (15), FFTF (12), BN-350 (many), BN-600 (many), FBTR (0), Joyo (0), Monju (0)	Guidez et al. (2008); Guidez and Jolly (1987); Tipping (2010); Rawlins et al. (1987)
Steam generator	Leaks leading to sodium-water reactions; production loss	Manufacturing defects/material selection; fatigue crack from thermal shocks; erosion of water inlet diaphragms; formation of magnetite layers in evaporator zones; flow-induced vibration/fretting	Fermi-I (2), EBR-II (0), KNK-II (1), BOR-60 (1), PFR (40), PHENIX (5), BN-350 (12), BN-600 (12)	Guidez et al. (2008); Saraev (2012); Guidez and Jolly (1987); Tipping (2010)
Intermediate heat exchanger	Sodium leaks; production loss	Differential thermal expansion, design defects or manufacturing faults	PHENIX, Superphénix	Guidez et al. (2008); Tipping (2010)
Sodium/NaK heat exchanger	Sodium leaks	Flow blockages attributed to poor design	PFR	Guidez et al. (2008)
Primary system	Sodium leaks	Valve manufacturing defects; flange joint construction in piping and valve joints; defective welds; poor material choices; inadequate piping flexibility or inability to check flow-induced vibration; thermal striping; operator error	FBTR, Monju, FFTF, PHENIX, BN-600	Guidez et al. (2008); Baumhardt and Bechtold (1987); Tipping (2010)
Primary system	Contamination of primary sodium	Intake of air into cover gas due to defective compressor diaphragm	Superphénix	Guidez et al. (2008); Rawlins et al. (1987)
Primary system	Injection of air into cover gas led to contamination of primary sodium, led to 18-month shutdown	Oil contamination in sodium due to oil leakage from sodium pump bearing	PFR	Guidez et al. (2008)
Primary system	Disturbed core hydraulics and neutronics; unexpected control rod insertion; sodium level fluctuations	Sudden drop of impurities from reactor roof formed from poorly purified argon cover gas	BN-600	Guidez et al. (2008)
Primary system	Impact ability to identify fuel failures	Increased cover gas impurities attributed to air contamination of argon supply	FFTF	Rawlins et al. (1987)
Rotating plug	Sticking	Sodium deposits on the bearing surface	BN-600	Guidez et al. (2008)

Table F.4. (cont'd)

Effected Components and Systems	Fault Effects	Cause	Reactors	References
Rotating plug	Sticking	Accumulation of sodium and tin and sodium and bismuth in annulus between rotating plug wall and rotating plug seal support structure	EBR-II	Guidez et al. (2008)
Absorber rods	Spurious tripping	Build up of sodium deposits on electromagnet reduced holding power	PFR	Guidez et al. (2008)

The performance of austenitic stainless steels, with the exception of SS321, has been satisfactory in fast reactors. Good performance has been achieved with SS304, SS304LN, SS316, SS316L, and SS316LN. There were a number of cracks and sodium leaks associated with SS321 welds in the PHENIX secondary sodium piping and steam generators, and superheater and reheater vessel shells of the PFR. The cracks were attributed to delayed reheat cracking. Performance of C-0.3Mo steel (15Mo3) in Superphenix fuel storage drum and sodium tanks constructed for the SNR300 reactor were not satisfactory. There is interest in adopting advanced Cr-Mo steel instead of austenitic stainless steel for sodium piping to improve economics and to reduce thermal fatigue due to Cr-Mo's relatively low thermal expansion coefficient and high thermal conductivity (Tipping 2010).

F.2 High Temperature Gas Reactors (HTGRs)

HTGR technology has been demonstrated in several countries including the United Kingdom, United States, Germany, Japan, and China. A summary of HTGR operating history of relevance to passive component failures is provided in Table F.5. The information comes primarily from reports by Beck (2010), Brey (1991), Goodjohn (1991), and Copinger and Moses (2004, NUREG/CR-6839) as indicated in the final column. Significant moisture intrusion events are documented for Fort St. Vrain (FSV) and for the German AVR (Arbeitsgemeinschaft Versuchsreaktor or Working Group Test Reactor). Sources of moisture intrusion included leaks from steam generators, water-lubricated circulator bearings, and a leaking cooling jacket for the reactor vessel at FSV. The consequences of moisture intrusion events were manifest through corrosion of carbon steel components, chloride-induced stress corrosion cracking, oxidation of graphite, and unintentional reactivity insertion. At FSV, failure of control rods to insert on manual or automatic scram signal and chloride-induced stress corrosion cracking of control rod drive mechanism (CRDM) cables were consequences attributed to moisture intrusion. It is noted that Peach Bottom, AVR, and FSV did not have effective instrumentation to detect in-leakage of contaminants quickly enough to significantly mitigate their effects. At Peach Bottom, the operation of CRDMs were impacted by a high coefficient of friction while graphite dust production at High Temperature Test Reactor (HTTR) and High Temperature Reactor (HTR-10) blocked filters on the primary helium circulator and accumulated on the primary side of steam generator tubes, respectively. With respect to inspection of graphite components, it is noted by Beck (2010) that the black surfaces make visual inspections challenging and require high power lighting conditions.

Table F.5. Compilation of Component and System Issues During the Operation of HTGRs

Effected Components and Systems	Fault Effects	Cause	Reactor	References
Entire primary system	Carbon buildup in primary system	Oil intrusion from oil lubricated helium circulator bearings	Peach Bottom	Beck (2010)
Helium purification system	Chloride corrosion, cracking, leakage	Polyvinyl chloride tape applied to purification piping	Dragon	Beck (2010)
Control rod drive mechanism	Increased coefficient of friction between sliding metal surfaces	Lubrication difficulties (high coefficient of friction) in hot helium environment	Peach Bottom	Beck (2010)
Control rod drive mechanism hydraulic drive	Proof of reliability needed	Extensive testing required by NRC prior to operation	Peach Bottom	Beck (2010)
Control rod drive mechanism cables	Stress corrosion cracking of CRDM cables	Moisture intrusion	FSV	Beck (2010); Brey (1991); Copinger and Moses (2004)
Circulator mounting hardware	Stress corrosion cracking	Moisture intrusion	FSV	Beck (2010); Brey (1991); Copinger and Moses (2004)
Control rod drive mechanism	Mechanical jamming that prevented rod drop by either gravity or CRDM motor	Moisture intrusion	FSV	Beck (2010); Brey (1991); Copinger and Moses (2004)
Control rod nut and bolt	Failed nut/bolt jammed control rod and prevented insertion	Moisture intrusion	FSV	Beck (2010); Brey (1991); Copinger and Moses (2004)
Helium pressurization lines	Plugged by corrosion products	Moisture intrusion	FSV	Beck (2010); Brey (1991); Copinger and Moses (2004)
Reserve shutdown balls	Fused together in hopper and did not deploy during test	Moisture intrusion	FSV	Beck (2010); Brey (1991); Copinger and Moses (2004)
Primary system	Core outlet temperature fluctuated at operation above 70% power	Periodic swaying of fuel element stacks in helium coolant (corrected by installing Region Constraint Devices)	FSV	Beck (2010); Brey (1991)
Steam generators	Cracks developed in feed-water ring headers on steam generator modules	Inadequate heat treatment of feed-water ring header welds and/or excessive heat-up and cool-down rates	FSV	Schuetzenduebel (1971); Goodjohn (1991)
Primary system	Visual inspection proved difficult (solved with high-power lighting)	Black graphite surfaces	AVR	Beck (2010)
Primary system, helium circulators, helium circulator lube oil system	Helium circulators flooded to above the rotating shaft. Oil lube system contaminated.	Moisture intrusion through superheater tube during extended shutdown led to 27.5 tons of water in primary system	AVR	Beck (2010)
Hot gas ducts	Bolt heads and graphite dowels found in ducts	Bolts determined to have a manufacturing defect	THTR	Goodjohn (1991)

Table F.5. (cont'd)

Effected Components and Systems	Fault Effects	Cause	Reactor	References
Circulator inlet filters	Graphite dust build up on mesh filter of primary helium circulator blocked filters	Graphite dust production[1]	HTTR	Beck (2010)
Secondary helium cooling system	Helium leaks in secondary coolant system	Mechanical joints in secondary helium cooling system leakage	HTTR	Beck (2010)
Steam generators	Graphite dust collected on primary side of steam generator tubes	Graphite dust production[1]	HTR-10	Beck (2010)

F.3 LFRs and MSRs

Two molten salt reactors were operated at Oak Ridge National Laboratory (ORNL) between 1954 and 1969. The first of these was the Aircraft Reactor Experiment (ARE), intended to prototype a molten salt reactor to provide propulsion for large aircraft by an indirect cycle (Rosenthal 2009). ARE operated for 9 days in 1954, no mechanical or chemical problems were encountered, and the reactor was stable and self-regulating (Rosenthal et al. 1970). A second, larger reactor operated from 1965 to 1969, and was called the Molten Salt Reactor Experiment (MSRE) (Rosenthal 2009). While no significant operational problems were observed during operation of MSRE, there was a recognition that the Hastelloy-N material used in the reactor vessel and piping was subject to irradiation hardening and cracking, and that mitigation approaches for these issues were needed (MacPherson 1985).

The only lead-bismuth cooled reactors with significant operating experience were the ones installed in Russian Alpha-class nuclear submarines (NSs) and the prototype reactors that supported them – seven NSs and two on-shore prototypes, in all (Weaver et al. 2001). The two full-scale ground reactor test facilities prototypes were in the Institute of Physics and Power Engineering (IPPE in Obninsk) and the A.P. Aleksandrov Scientific Research Technological Institute (NITI in Sosnovy Bor) (Gromov et al. 1997). These NSs were followed by development of Russian designs for civilian fast reactors cooled by heavy liquid metals beginning in the early 1990s (e.g., the Pb-cooled fast reactor BREST-300 and lead-bismuth-cooled fast reactor SVBR concept (Smith 2010), neither of which have been built). In support of their proposed nuclear power technology (small power modular fast reactors cooled by lead-bismuth coolant), Gromov et al. (1997) briefly captured the experience of operating these nuclear submarine reactors (lead-bismuth eutectic-cooled modular type fast reactors). Specifically, the experience from the mastery of lead-bismuth-cooled reactors in Russian nuclear submarines was used for the safety concept development avoiding the need to carry out large-scale R&D prior to implementation.

Results by the Karlsruhe Lead Laboratory (KALLA) group in Germany have confirmed the Russian experience that an active oxygen-control system can control the corrosion process (Loewen and Tokuhiro 2003). Additionally, a potential method of keeping the oxygen concentration in a favorable range when using liquid lead or lead-bismuth eutectic as coolant in nuclear reactors was investigated on the basis of the experience from operating (approximately 5 years) a gas/liquid transfer device in the CORRIDA loop with an oxygen-control system (Schroer et al. 2011).

Table F.6 provides a compilation of documented issues observed during the operation of MSRs and LFRs. These experiences contributed to operational and design improvements, and provide a basis for future development of MSR and LFR designs.

Table F.6. Compilation of Component and System Issues During the Operation of LFRs and MSRs

Effected Components and Systems	Fault Effects	Cause	Reactor	References
Reactor vessel and piping	Irradiation hardening and cracking	Hastelloy-N material	MSRE	MacPherson (1985)
Primary circuit	Release of Po aerosols and the air radioactivity reduce strongly with temperature decreases and solidification of the coolant leakage.[a]	Hot lead-bismuth coolant contacts with air due to primary circuit tightness loss and coolant leakage	Russian NS	Gromov et al. (1997); Zrodnikov et al. (2005); Tucek et al. (2006)
Pumps (e.g., pump impeller and bearing materials)	Erosion of pump materials (e.g., protective oxide layers)	Lead-alloy coolant velocities	Russian NS	Tucek et al. (2006); Utili et al. (2011); Wallenius (2011)
Fuel cladding and structural materials	Corrosion/erosion during normal operation	Lack of control of oxygen content in lead or lead-alloy[b]	Russian NS	Loewen and Tokuhiro (2003); Tucek et al. (2006); Martinelli et al. (2011)
Structural materials (special test section)	Corrosion/erosion	Lead-alloy coolant flow velocity	IPPE	Loewen and Tokuhiro (2003); Weisenburger et al. (2011)

(a) This experience contributed to design improvements. Methods for individual and collective personnel protection, equipment decontamination, and radioactivity fixation on surfaces were developed for increasing safety.
(b) Pure lead was shown to be less corrosive than lead-bismuth eutectic at the same temperature.

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Appendix G

Summary of Considerations for Passive Component Monitoring in AdvSMRs

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Summary of Considerations for Passive Component Monitoring in AdvSMRs

Passive Components	Structural Materials	Degradation Modes	Desired Measurements
– Heat exchangers – Turbines/compressors – Reactor vessel – Core, shields, reflectors, absorber – Piping – Tanks	– F/M steels – ODS F/M steels – Austenitic SS – Ceramics/composites – Ni-base superalloys	– Oxidation/corrosion – Loss of fracture toughness/ embrittlement – Creep/irradiation creep – Stress corrosion cracking	– Novel coolant temperature, pressure, and flow sensors – Neutron flux sensors – Coolant level – Contamination in coolant and cover-gas[(a)] – Coolant chemistry[(b)] – Debris in coolant[(c)] – Loose parts monitoring

(a) Examples of important applications include monitoring of moisture ingress in VHTRs (Beck and Pincock 2011) and air and oil contamination of sodium coolant in SFRs (Guidez et al. 2008).

(b) Instrumentation to assess the chemical state of fluoride salts has been identified as a critical need for MSR type reactors (Unknown 2004; Greene et al. 2010). Instrumentation to monitor the oxygen content in lead coolant has been identified as a critical need for corrosion control in LFR type reactors (Smith 2010).

(c) Examples of debris-in-coolant monitoring applications include the monitoring of corrosion products in the coolant of LFRs (IAEA 2007) and monitoring of graphite dust in VHTRs (Beck and Pincock 2011).

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Appendix H

Structural Health Monitoring (SHM) – an Assessment of the State-of-the-Art Relevant to SMRs

Appendix H

Structural Health Monitoring (SHM) – an Assessment of the State-of-the-Art Relevant to SMRs

H.1 Introduction

The inspection and monitoring needs for small modular reactors (SMRs) may require moving beyond traditional inspection and monitoring regimes. Traditional regimes are mostly based on applying NDT methods of ultrasonics, electromagnetics, and radiography to perform local inspections for detection of cracks, corrosion, and other types of damage and degradation; for example, “macro-damage.” This type of implementation is described in a diverse range of codes and standards for many standard NDT methods. Accessibility limitations of SMRs drive the need to provide technologies for long-term and on-line monitoring to provide data for material state assessments.

The lexicon for material state monitoring is evolving. It now includes Structural Health Monitoring (SHM), which has been reported in various conference proceedings (e.g., International Workshop on Structural Health Monitoring, and SPIE’s NDE and SHM meetings). Terms being used to describe related fields now include on-line monitoring (commonly linked to SHM), materials damage prognosis (TMS 2004), damage prognosis (Inman et al. 2005), and various forms of “Prognosis for Engineering Systems” (e.g., Vachtsevanos et al. 2006). In addition, there are communities that have focused on prognosis and health monitoring for electronics (Pecht 2008) and aerospace applications (see *Proceedings IEEE Annual Aerospace Conferences* (~35 meeting in series), and at the Society of Machinery Failure and Prevention Technology (MFPT) meetings (part of the Vibration Society).

The applications for SHM and related “prognostics” include many defense systems, wind turbines, and “smart systems” are being developed for oil field and power plant applications. The applications are generally maturing at the component and sub-system level (e.g., pumps, valves, helicopter drive train). Many are vibration-based with supplemental information and data streams being utilized to refine and bound life/condition assessment. Both degradation and exciting stressors are being monitored (Jarrell et al. 2004). Plant level or even larger integrated system level capabilities remain in many cases a work in progress. The ability to provide a “condition metric” for current state and reliable life prediction are still in many cases challenging.

Much of the current capability is focused on active component applications (e.g., pumps, valves, motors, etc.) and using pattern recognition for anomaly detection. This information can be used to trigger condition-based maintenance activities.

H.2 Formalization Efforts for SHM

Sensor networks for SHM sensing systems generally contain three main components (Farrar et al. 2011): the sensing unit itself, communications, and computation (hardware and, as appropriate, software control and processing algorithms). The goal of any SHM system sensor network is to make the sensor reading as directly correlated with, and as sensitive to, damage as possible. At the same time, one also strives to make the sensors as independent as possible from all other sources of environmental and operational variability, and independent from each other (with respect to information) to provide maximal data for minimal sensor array outlay. To best meet these requirements, the following design parameters must be defined, as much as possible, *a priori*: (1) types of data to be acquired; (2) sensor types, number and locations; (3) bandwidth, sensitivity and dynamic range; (4) data acquisition/telemetry/storage system; (5) power requirements; (6) sampling intervals (continuous monitoring versus monitoring only after extreme events or at periodic intervals); (7) processor/memory requirements; and (8) excitation source needs (for active sensing).

Fundamentally, there are five issues that control the selection of hardware to address these sensor system design parameters: (1) the length scales on which damage is to be detected, (2) the time scale on which damage evolves, (3) effect of varying and/or adverse operational and environmental conditions on the sensing system, (4) power availability, and (5) cost.

An interesting defect taxonomy for what needs to be detected has been proposed by Neikirk (2011), resulting in the following key questions. Is the location (or region) for a defect known or is it completely unknown? How often do defects occur? How soon should they be detected? From these properties, the defect taxonomy can be generated. This results in a few defect features in a known location being easy to detect, but detecting defects distributed in a large structure is difficult. This may be obvious, but in terms of defining sensor needs, numbers and locations, understanding the effects of stressors and most probable degradation in a probabilistic framework becomes critical. This can then bound the numbers, types of sensors, and measurement methods that are practical to meet a specific need.

H.3 Sensor Technologies

The “eyes and ears” of prognostics capabilities are the sensors that are deployed. In looking at integrated systems, methods for determining exactly where and how, and how many, as well as selecting specific classes of sensors (such as those capable of detecting early damage) are still under study.

There are a range of non-nuclear technology areas where sensors are being deployed: aerospace, civil and mechanical systems (e.g., Inman et al. 2005), down hole – oil industry (Neikirk 2011), petro-chemical plants, civil structures, and there is a truly vast literature for what is now called SHM (e.g., Sohn et al. 2004). One example is condition monitoring and prognosis of utility scale wind turbines (Hyers et al. 2006).

These sensors can be “dumb” or they can include MEMS devices, distributed computing, and wireless networking. Smart sensors are already seeing application in the civil engineering field (Nagayama and Spencer Jr. 2007). There is also a growing interest in sensor and sensor networks, which have been reviewed by Lynch and Loh (2006) and more recently by Deivasigamani et al. (2013).

Looking into what comprises an individual sensor, or “node,” a range of sensor classes and element types can be considered for harsh environments. These sensors fall into families such as measuring acceleration (piezoelectric, piezoresistive, piezoceramic, capacitive, or fiber optic accelerometers), strain (resistive foil, fiber optic, or piezoelectric patch gages), and ultrasonic high-frequency waves/impedance (piezoelectric sensors or patches). A review of sensors and technologies was recently provided by Mukhopadhyay and Ihara (2011), and other chapters in the same book discuss specific technologies. This text includes mostly MEMS, optical fibers, and eddy current sensors with some discussion of piezoelectric systems.

Looking at harsh environments, there are a range of technologies that have been demonstrated for elevated temperatures. Temperature ranges for different classes of sensors are summarized by Ghoshal et al. (2012). Rempe et al. (2011) provide a technology assessment for in-pile applications that represent the harshest end of the nuclear application spectrum. In her work, the two most mature technologies were considered to be those based on optical fiber sensors and piezoelectric sensing.

Piezoelectric sensing can be implemented in a range of forms, including a passive mode, acoustic emission, and active forms that employ guided waves, diffuse fields, and other forms of reflectometry (close to conventional NDE); for example, see the references in Rempe et al (2011). Ensminger and Bond (2011) provide a chapter on the use of ultrasonic methods for process monitoring, measurement, and control (Chapter 10). This chapter includes discussion of a range of on-vessel measurement at elevated temperatures. High-temperature ultrasonic transducers, including for in-sodium coolant applications, are discussed in other parts of the text. A discussion of in-sodium work is provided by Bond et al. (2012) for in sodium applications to 250°C. A review of ultrasonic transducers for high-temperature applications, specifically lead-bismuth applications at temperature up to 600°C, is provided by Kažys et al. (2008).

Senesky et al. (2009) and Pisano and Senesky (2010) have discussed silicon carbide-based sensing for both aerospace and geothermal/oilfield applications, including stable temperature and pressure measurements. There is on-going work looking at down hole sensing Neikirk (2011) to employ a range of electromagnetic sensors (RF – microwave, eddy current) and micro-machined devices. Fiber Bragg grating sensors for harsh environments have been discussed by Mihailov (2012), and there are a number of other groups working in this field (e.g., for composite components in aircraft wings and in civil structures). Eddy current technology is being used for on-engine applications, including blade clearance monitoring at elevated temperature (Hasse and Hasse 2013). Guided waves/wave guides are also being used for use in on-engine monitoring.

In evaluating a technology, it is necessary to consider:

– Survivability – at temperature or under radiation (including accident conditions)
– Long-term sensor durability (including drift)
– Sensitivity – under the harsh environment
– Adhesion during long-term deployment
– Nature of sensing network, redundancy, and inter-compatibility to check calibration/drift
– Power requirements
– Capability to integrate into a system to enable data acquisition and transmission to monitoring location (control room)
– Ability to demonstrate that sensor not prone to EMI and can survive required temperature ranges and rates of changes.

It is also necessary to consider what it takes to see a “defect” (Neikirk 2011). In terms of systems engineering, it is necessary to consider both distributed computing and/or requirements for transmission of a condition index (small bandwidth needs) vs. a continuous or even periodic data set.

H.4 Summary

A diverse range of sensors with potential application to SMR SHM/prognostics was identified. Different classes of measurements are needed to monitor stressors (e.g., temperature, pressure, acceleration, etc.). Smart sensors with networking and wireless capabilities are seeing increasing use in civil engineering (and to some extent in aerospace). Sensors using optical fibers, piezoelectric elements, silicon carbide, and eddy current/electromagnetic sensing are all candidates for deployment. For SMRs, SHM poses several challenges related to determining sensitivity to required degradation/changes (pre-macro-degradation), reliability, accuracy, and long-term stability (i.e., the complete sensing life requirements). These challenges have to be addressed within the context of the local or distributed nature of the measurements that are required, the numbers of sensors that are practical, and the form of network in which they could be deployed. Opportunities were identified for the nuclear community to leverage SHM work being performed for other industries including for the oil/gas, aerospace, and civil engineering communities.

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