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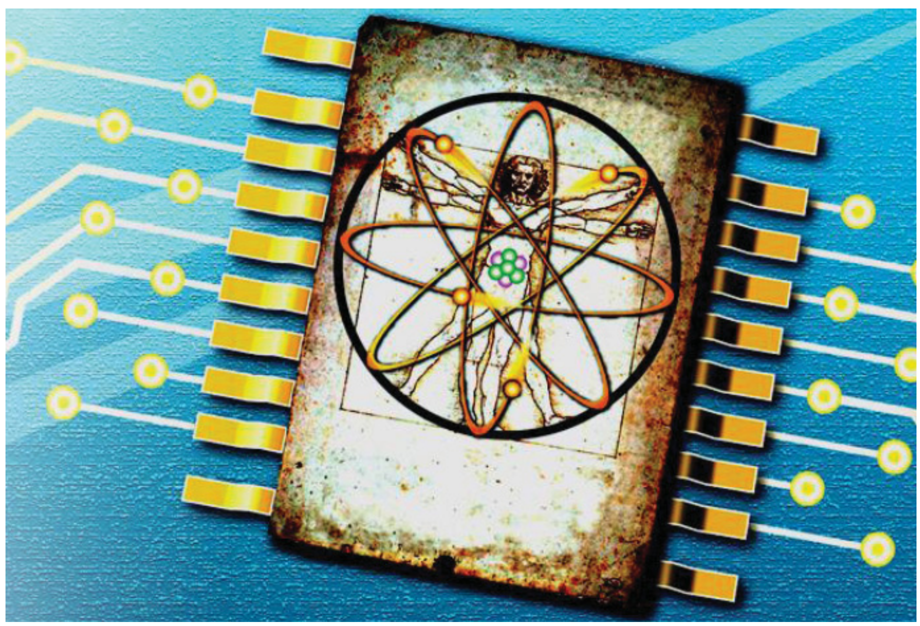
Report from the Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies

June 2010



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Report from the Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies

Held June 10–12, 2010, in Seattle, Washington

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ABSTRACT

In support of expanding the use of nuclear power, interest is growing in methods of determining the feasibility of longer term operation for the U.S. fleet of nuclear power plants, particularly operation beyond 60 years. To help establish the scientific and technical basis for such longer term operation, the DOE-NE has established a research and development (R&D) objective. This objective seeks to develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors. The Light Water Reactor Sustainability (LWRS) Program, which addresses the needs of this objective, is being developed in collaboration with industry R&D programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of nuclear power plants. The LWRS Program focus is on longer-term and higher-risk/reward research that contributes to the national policy objectives of energy and environmental security.

In moving to identify priorities and plan activities, the Light Water Reactor Sustainability Workshop on On-Line Monitoring (OLM) Technologies was held June 10–12, 2010, in Seattle, Washington. The workshop was run to enable industry stakeholders and researchers to identify the nuclear industry needs in the areas of future OLM technologies and corresponding technology gaps and research capabilities. It also sought to identify approaches for collaboration that would be able to bridge or fill the technology gaps. This report is the meeting proceedings, documenting the presentations and discussions of the workshop and is intended to serve as a basis for a plan which is under development that will enable the I&C research pathway to achieve its goals.

Benefits to the nuclear industry accruing from On Line Monitoring Technology cannot be ignored. Information gathered thus far has contributed significantly to the Department of Energy's Light Water Reactor Sustainability Program. DOE has shown great interest in supplying necessary support to help this industry to move forward as indicated by the recent workshop conducted in support of this interest. The Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies provided an opportunity for industry stakeholders and researchers to gather in order to collectively identify the nuclear industry's needs in the areas of OLM technologies including diagnostics, prognostics, and RUL. Additionally, the workshop provided the opportunity for attendees to pinpoint technology gaps and research capabilities along with the fostering of future collaboration in order to bridge the gaps identified. Attendees concluded that a research and development program is critical to future nuclear operations. Program activities would result in enhancing and modernizing the critical capabilities of instrumentation, information, and control technologies for long-term nuclear asset operation and management. Adopting a comprehensive On Line Monitoring research program intends to:

- Develop national capabilities at the university and laboratory level
- Create or renew infrastructure needed for long-term research, education, and testing
- Support development and testing of needed I&C technologies
- Improve understanding of, confidence in, and decisions to employ these new technologies in the nuclear power sector and achieve successful licensing and deployment.

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FIGURES

TABLES

ACRONYMS

AAKR	auto-associative kernel regression
AMS	Analysis and Measurement Services, Inc.
BWR	boiling water reactor
CBM	condition-based maintenance
CCM	component-centered monitoring
CM	condition monitoring
COLM	Centralized On-Line Monitoring
COTS	commercial off-the-shelf
CPU	central processing unit
CSNI	Committee on the Safety of Nuclear Installations
D/P	diagnostics and prognostics
DI&C	digital instrumentation and control
DOE	Department of Energy
EAD	elongation at break
EdF	Électricité de France
EMS	Energy Management System
EPDM	ethylene propylene diene monomer
EPRI	Electric Power Research Institute
EQ	environmental qualified
FWMIG	Fleet wide monitoring interesting group
FPGA	field programmable gate arrays
HFE	Human Factors Engineering
HOF	human organizational factors
HRP	Halden Reactor Project
HSI	human-system interface
HUMS	health and usage monitoring
I&C	instrumentation and control
IFE	Institutt for energiteknikk (Institute for Energy Technology, Norway)
INL	Idaho National Laboratory

INPO	Institute of Nuclear Power Operations
IO	integrated operations
ISG	Interim Staff Guides
ISI	in-service inspections
IT	Information Technology
IVHM	integrated vehicle health management
LIRA	line resonance analysis
LOCA	loss of coolant accident
LTO	Long Term Operation (project)
LWR	light water reactor
LWRSP	Light Water Reactor Sustainability Program
MDEP	Multinational Design Evaluation Program
MOV	Motor Operated Valve
MPE	maintenance proficiency evaluation
NCS	Norwegian Continental Shelf
NDT	non-destructive testing
NEA	Nuclear Energy Agency
NERI-C	Nuclear Energy Research Initiative Consortium
NMR	nuclear magnetic resonance
NPLED	Nuclear Power Life Extension Demonstration Project
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
O&M	operations and maintenance
OECD	Organization for Economic Cooperation and Development
OEM	original equipment manufacturer
OIT	oxidation induction time
OLF	Norwegian Oil Industry Association
ORNL	Oak Ridge National Laboratory
OSU	Ohio State University
PDA	personal digital assistant

PHM	prognostics and health management
PLiM	Plant Life Management
PNNL	Pacific Northwest National Laboratory
POF	probability of failure
PRA	probabilistic risk assessment
PSA	probabilistic safety assessment
PWR	pressurized water reactor
PWROG	Pressurized water reactor owner's group
QC	Qualified Condition
QL	Qualified Life
R&D	research and development
RTD	resistance temperature device
RUL	Remaining Useful Life
SDPM	sensor, diagnostic, prognostics, health monitoring
SER	safety evaluation report
SPRT	Sequential Probability Ratio Test
SRP	safety review plan
SSC	systems, structures, and components
SWOT	strengths, weaknesses, opportunities, and threats
TDR	time domain reflectometry
TOP	technical opinion paper
TPE	task proficiency evaluation
TTFM	transit time flow measurement
V&V	verification and validation
VHM	vehicle health management
WGHOF	Working Group on Human and Organizational Factors

Report from the Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies

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1. INTRODUCTION

1.1 Background

A safe, secure and reliable system for the generation of electricity is essential for the United States' national and economic security. The U.S. currently generates approximately 20% of its electricity through the operation of 104 nuclear power plants. This generating capacity accounts for more than 70% of carbon-emissions-free electricity generation in the nation. In global electricity generation, approximately 440 operating reactors generate power in the nuclear power plant (NPP) fleet. These plants have an average age greater than 20 years, and their original plant design life was typically either 30 or 40 years. To meet the growing global demand for electricity, particularly to support sustainable development, it is projected that about 2,300 GWe of new capacity could be built over the next 20–30 years (about 2000 plants). There are approximately 50 new plants under construction (as of February 2010, and all are outside the USA), and at least 222 new plants are being considered. As many as 45 of these could be constructed in the U.S. The costs for these plants are projected to rise significantly (up to about $7.5B for each project), and the recent economic downturn has the potential to delay or cancel many projects. The planet remains hungry for electricity, and a desire to limit carbon emissions and convert transportation to be powered by electricity in developed countries is growing. In almost all countries with nuclear power plants, authorities are looking at some form of license renewal program. To support such activities, ensuring system reliability and avoiding detrimental plant failures will be necessary.

A 20-year life extension for the current U.S. nuclear power fleet would eliminate ~12 billion tons of CO_2 emissions and provide the electricity needed to meet the power needs of ~70 million households for 20 years. More than 90% of U.S. plants are currently either considering or implementing license extensions of 20 years (to 40-60 years), and consideration is now being given to the concept of "life-beyond-60," with license extension from 60 to 80 years and potentially longer. To support such life extension, providing new methodologies and technologies to anticipate and manage equipment failures and materials degradation are critical needs. In addition to requirements for application to the legacy fleet, the potential exists for some of these technologies to be deployed within new light water reactors (at the GW+ size), in small modular reactors, and also in reactors based on advanced designs. In support of nuclear power plant license renewal over the past decade, various national and international programs have been initiated; this provides opportunities for international collaboration.

To support the expanded use of nuclear power, interest is growing in determining the feasibility of longer term operation, particularly operation extending beyond 60 years, for the U.S. fleet of nuclear power plants. To help establish the scientific and technical basis for such longer term operation, the DOE-NE has established a research and development (R&D) objective. The objective was created to develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current nuclear power reactors. The Light Water Reactor Sustainability (LWRS) Program is being developed in collaboration with industry R&D programs to provide the technical foundations for licensing and managing the long-term, safe, and economical operation of nuclear power plants already in operation. The LWRS Program focus is on longer-term and higher-risk/reward research that contributes to the science and technology needed to enable national policy objectives of energy and environmental security.

One aspect of longer term operation is to increase system state awareness, which can, in part, be achieved through the use of various forms of on-line monitoring. On-line monitoring (OLM) can be defined as (1) automated methods of monitoring instrumentation and assessing instrument calibration and (2) assess the health condition of components, equipment, and systems, including both active and passive parts of the plant, while the facility is operating. A key is to perform the required or desired monitoring without disturbing the normal operation of the instrumentation or equipment, or that testing will require destructive testing of materials or components. Within the focus area there are two emerging activities: one is focused on on-line monitoring for active components (i.e., pumps, valves, motors, cables, etc.) – and a second area where NDE and on-line monitoring is applied to the passive structure (i.e., reactor pressure vessel, core internals, concrete, and buried pipes). This report is mostly focused towards the activities that relate to active components and there are complementary activities being developed, discussed elsewhere, that address the specific issues relating to passive components. The emerging activities in on-line monitoring can be seen as a natural development from technologies that enable condition based maintenance (CBM) and its integration into more holistic approaches to plant longer term operation. These activities can leverage the capabilities that are emerging through the adoption of digital instrumentation and control technologies.

The vision of the Light Water Reactor Sustainability On-Line Monitoring Program is captured in the following statement:

> *To identify research needs to close the technical and implementation gaps for the integration of advanced on-line monitoring (OLM) technologies in to nuclear power plants.*

Management of current instrumentation and controls and functionality is limited. The U.S. nuclear power industry currently applies a conservative approach to performance testing of plant instruments. Generally, the outputs of these instruments are tested every 1-3 months and fully calibrated both at every refueling outage and whenever a component is replaced. This practice began with the operation of the first plants when there was no experience with instrumentation performance. With more than 25 years of instrumentation experience within a large fleet of nuclear power plants around the world, experience indicates that most nuclear-qualified instruments perform well, and the heretofore conservative practices can safely be relaxed. In addition, opportunities exist to provide additional data on plant current and future conditions and to bring together aspects of plant life management that cross between traditional control room and operations and maintenance functions. Such increased plant situational and condition awareness can, if integrated with concepts of operation, support high-capacity factors, reduce unscheduled outages, and enable better planning of equipment maintenance/replacement through knowledge of the equipment's remaining life. Additionally, the greater awareness provided by such instrumentation can provide early warning of problems due to degradation and aging.

In the nuclear power industry, added functionality and new technologies now enable both operations and maintenance (O&M) staff to increase the availability and diversity of data from both process parameters and maintenance-related tests/inspections. However, providing data for sub-system signatures that can be converted into equipment-condition information remains a challenge. Traditional approaches to condition assessment require equipment experts to survey a number of parameters related to plant units (e.g., pumps, valves, or motors), trend them individually, conduct visual examinations, and review supervisory instrumentation to determine equipment health.

The limitations of this current approach derive mainly from their inability to look simultaneously at all parameters that either influence or are influenced by particular component degradation. These situations are further complicated as the attention level is raised from an individual system element (i.e., a pump or motor) to a plant system (e.g., the service water system), and current technology limitations mean that interactions among various components of a major system or between sub-systems can be difficult to identify. To address this challenge, attention is being directed toward the potential for and capabilities that can be provided through the development of processing and integration of centralized on-line monitoring.

Most CBM to date is focused on individual components (i.e., pumps, valves, motors, etc.). The challenge identified is the integration of data about that component into an assessment of some plant system (e.g., a service water system) and then to the plant level. One question that can be asked is should centralized on-line monitoring try to cover all the sub-systems (e.g., pumps, valves, motors) in the plant? The answer is likely to be yes, and in covering all elements, the monitoring data needs to have a derived "condition index" for each unit being monitored, which serves to integrate data on different components, rather than requiring staff to look at all the individual raw data streams presented in a control room. There is also a need to enable O&M staff to access individual data sets if an off-normal condition develops, and this can potentially be achieved through the use of a set of nested screens in a digital instrumentation and control (I&C) system.

While the efficiency of the traditional approach to condition monitoring has improved as sensors were integrated and computer hardware and software evolved, analysis is fundamentally limited by the human analyst's available time, knowledge, and attention span. The next evolution of these techniques shall involve application of various forms of automation, including the use of filters and comparisons of the data values to limits more restrictive than supervisory controls. Whenever the data goes outside limits/bounds, an alert would then automatically be triggered, prompting an O&M staff member or analyst to analyze the situation.

New trends in on-line monitoring have the potential to improved safety and equipment reliability, to give improved performance, and to improve long-term asset management. These trends can result in operations and maintenance cost reduction, enhanced instrumentation capabilities, improved calibration monitoring, and consolidated staff activities. Enhanced system-condition knowledge provides data needed to enable both preventative-maintenance interval extension and, when integrated with plant process data, heat-rate improvement and fuel-cost reduction. All of these processes can result in the capture of knowledge, storing the enhanced data recorded in the plant historian (data recorder).

The trend towards enhanced instrumentation and controls is exemplified by online monitoring applications at nuclear utilities. Reported examples include improvements in equipment condition assessment, instrument calibration monitoring, thermal performance monitoring, knowledge capture and dissemination, shutdown and startup monitoring, alarm management, system performance, and benchmarking and data trending.

The LWRS Program advanced instrumentation, information, and control systems technology R&D pathway is being developed to establish a technical basis for new technologies needed to achieve safety and reliability of operating nuclear assets and to demonstrate these technologies. A workshop was held in order to further define the scope of these activities and the gaps in related research areas.

1.2 WORKSHOP

The Light Water Reactor Sustainability Workshop on Online Monitoring Technologies, organized by Idaho National Laboratory (INL) in conjunction with the Electric Power Research Institute (EPRI), was held in Seattle, Washington, June 10–12, 2010. The workshop included a series of keynote presentations and working group activities in which working groups discussed the challenges facing utilities in both managing current online monitoring (OLM) technologies and developing those that are or will be needed during long-term operation. The discussion also sought to identify gaps in science and technology (S&T) that must be addressed through R&D to achieve the desired end state: instrumented systems that support long-term facility operation.

In defining the scope for discussion, the objectives of OLM technology (over different time frames) can be stated as follows:

- *Long term goal.* Successful deployment of on-line monitoring technologies in aging nuclear plants to enable lifetime extension by proactively assessing the condition of key systems and components, giving estimates for remaining useful life (RUL), and identifying options for the mitigation of degradation.

- *Midterm goals.* Research, develop, validate, and implement online monitoring technologies such as self-calibrating digital sensors, automated diagnostics and prognostics, and degradation-risk management. Develop underlying crosscutting and supporting technologies such as non-destructive evaluation, monitoring, failure-mode modeling, and lifecycle prognostic modeling.
- *Short term goals.* Identify the common aims of the utilities and find the synergies existing within various existing programs, as well as the roadblocks impeding forward movement. Develop an industry-wide roadmap for achieving online monitoring success. Build an R&D plan for the industry and seek appropriate funding.

The objective of the workshop was to provide the DOE-NE with information about a potential roadmap for research and development for online monitoring aimed at extending the life of existing nuclear power plants. This roadmap attempts to describe directions toward which the community would like to move over the next 5 to 20 years and to identify S&T gaps and the challenges which impede the industry's reaching the goal of plant life extension.

The vision for online monitoring is based on three pillars, which speak to what can eventually be developed and why is it important. These pillars are:

- **Engineering** – answering questions to inform decisions regarding the feasibility of on-line monitoring to enable plant long term operations (LTO)
- **Human Factors** – supporting decision making
- **Economics** – offering realistic and affordable financial directives.

In order to fully understand the issues relating to the application of online monitoring, the following definitions were agreed upon:

- Diagnostics and Prognostics encompass the identification of anomalies or faults and the prediction of RUL of the component, equipment, system or process
- RUL is defined as the time or other usage metric (cycles, duration, etc) until the performance specification can no longer be met.

This document, the proceedings of the workshop, seeks to provide:

- An overview the current state of the technology
- Identification of gaps and challenges that must be addressed to facilitate deployment of on-line monitoring in NPP
- And provide recommendations on:
  - Research, development, and commercialization activities
  - Collaboration and partnerships
  - Funding needs
  - Regulatory and business issues that tend to impede development and implementation.

This report summarizes the community expectations and research needs with respect to advanced diagnostics and prognostics, particularly looking towards the needs and opportunities for applications to active components. As part of the report, some comments on the state of maturity of diagnostic and prognostic technologies from presentations by experts in the field have been included. The report also discusses the technology migration from CBM to OLM for advanced diagnostics and prognostics to remaining useful life estimates and integrated probability risk assessments.

Section 2 of this report summarizes the keynote presentations. Section 3 summarizes the discussions of working groups. Section 4 provides information about related efforts to develop or assess OLM technologies for nuclear plant applications being performed by others, and Section 5 provides a summary and conclusions. Appendix A includes the workshop agenda and Appendix B comprises a list of workshop participants.

1.3 References

[1] R. Shankar, *On-line Monitoring of Instrument Channel Performance*, EPRI Report #TR-104965, November 1998.

2. KEYNOTE PRESENTATIONS

Several of the keynote presentations summarize the current research and implementation of OLM technologies at the existing fleet of nuclear power plants.

A common theme in these presentations was the need to model aging in a way that describes the materials and equipment found in the critical systems of an NPP. For long-term operations, asset owners view prognostic capabilities as essential. They also perceive a need to explicitly incorporate remaining useful life prognostics and probability risk-analysis capabilities into their future business models for plant operation.

Several of the presentations describe the anticipated benefits accruing from diagnostic and prognostic methodologies, the justification for their adoption, and the barriers to their incorporation in the nuclear power industry.

In the following section, the presentation material is provided. Section 5 summarizes the workshop recommendations and path forward.

2.1 Monitoring Science & the Nuclear Power Industry

Richard (Rick) Rusaw
Electric Power Research Institute, Charlotte, North Carolina

2.1.1 The Electrical Power Research Institute's Strategic Plan

The primary objectives of EPRI's nuclear functional activities (in progress in 2010) include the direct support of system engineers as well as integration of monitoring technologies into nuclear plant management and operations. Among field applications, several significant technologies show promise. For example, a recently created Fault Signature database allows the capture of data related to off-normal conditions within nuclear plants and the data collected which anticipates faults. This research emphasizes the importance of transient analysis as part of research in the area of prognostics.

Component Centered Monitoring is also a significant monitoring tool. The development of component specific analytical methods is needed for transformers, main generators, and main turbines. Other considerations are for large motor and pump combinations, condensers, and motor operated valves (MOV's). Many of the major components require a significant degree of additional research and development. These include the main turbine, pumps and motors, the main generator and MOV's. Related work undertaken by Electricite de France (EdF) in 2011 will focus on the condensers.

Additional training for organizations such as the Nuclear Regulatory Commission (NRC) will be critical to meeting the needs in the area of online monitoring. Obviously, regulators must know the capabilities of new technologies and the advantages new monitoring techniques promise. NRC will eventually be asked to evaluate all technologies developed for their efficacy and utility in the nuclear fleet.

Several strategies have been identified to achieve cost savings. These include using the data generated by various monitoring technologies to streamline business processes and limit technical and administrative burdens. Notable ideas include providing operational efficiencies by improving capabilities for technical analysis. An increased focus will be placed on automation, which can in turn result in cost reductions. Additionally, the promotion of technology implementation, rather than isolating the scope to R&D, will promote cost savings.

2.1.1.1 LTO COLM Strategic Plan Objectives

In order to achieve the stated strategic goals of EPRI's LTO program, the nuclear power industry must develop an effective monitoring program that has a well designed data and information integration platform with advanced technologies, including anomaly detection, automated diagnostic capabilities, a repository of equipment failure signatures captured from industry events and, ultimately, prognostics capabilities designed to evaluate critical plant assets for optimized maintenance to support LTO. Each of these technical capabilities will progress through a continuum of developments that transform these elements from research and development to a full operational platform of integrated analytical tools. EPRI's goal is to develop an effective monitoring program wherein each of the analytical tools is designed to integrate well together and to provide synergistic performance with plant operations. Placing a focus on intelligence gathering from industry events to support the Asset Fault Signature Database is a priority as well. This platform must be diversified enough to analyze a wide range of system components, operational conditions, and offer many options to support a wide range of monitoring program capabilities.

To meet these goals and objectives EPRI's research will build effectively on previously developed monitoring technologies. The EPRI LTO project has completed an in-depth industry analysis of monitoring capabilities and identified the needed analytical and programmatic capabilities (gap analysis). The analysis results provide the foundation to define the project priorities, identify needed technologies, project the costs, schedule, obtain funding to execute the research, and manage all the implementation phases through successful implementation. In support of the implementation of a plant-monitoring program, EPRI is publishing a comprehensive COLM Implementation Guideline. The Guideline reflects the current technology state-of-the-art with guidance based on applications experience from the power industry's operational monitoring centers (see Figure 1).

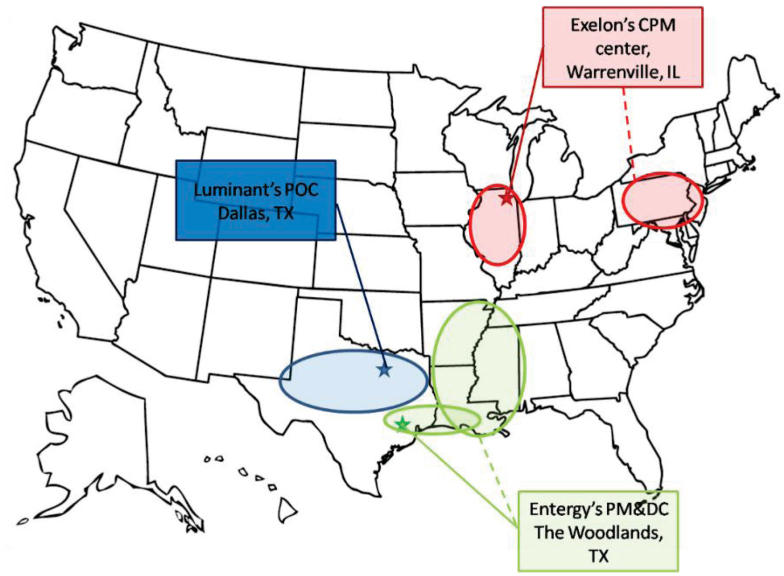

Figure 1. Locations of current EPRI-sponsored OLM projects.

The development of the required research must include broad and frequent interfacing with all of EPRI's strategic partners. The most effective monitoring program design will require partnerships with many related organizations and stakeholders. Some key partners include EPRI member utilities, their representative advisors, technical specialists, and commercial support organizations. In support of the technology R&D, partners include qualified vendors, universities, government labs, and utility research programs.

A significant focus of this strategic plan, beyond direct technology R&D, is to direct resources to foster participation by the nuclear industries active monitoring programs and encourage those programs under development. The degree of success for an industry wide implementation of monitoring programs will depend strongly on the successful demonstration of the technology by the industry's early adopters. Measurable success is needed to provide the basis for the adoption of the technology by those organizations that are currently evaluating the effectiveness of the technology to justify their significant investment in a monitoring program. This focus also supports two significant technical objectives of this plan. The first is to develop a more component centered monitoring capability that can allow application specific capabilities that may be applied at nuclear facilities in a "building block" fashion without an upfront requirement for a full scale monitoring program and the associated investment. The second objective is to develop the optimum analysis capabilities for a plant's critical assets to allow monitoring centers to adapt these tools. This will expand their existing monitoring capabilities or support new applications for critical assets. These objectives actively support the development and demonstration of the technology that is critical to the successful growth in the implementation of monitoring science in the nuclear industry

2.1.2 Barriers to Success

A number of barriers exist which threaten the progress of the strategic plan and create significant resistance. Without a continuity of success, progress toward a monitoring system fades. Therefore, an approach which unifies researchers and utilities to close knowledge gaps is crucial for continuation of progress. Several specific issues inhibit the utilization of OLM by utilities. Among these are an underdeveloped business case, a need for more evidence and proof of the viability of the technologies, the traditional and conservative nature of plant management, and the need for a comparatively large engineering staff as online monitoring is implemented. Financial barriers identified are high initial investment, high operational costs, and limited investment capital for OLM implementation.

2.1.3 Current Activities within EPRI

The LTO monitoring program will be implemented with project steps for advancing each technical element of the monitoring program from initial R&D through full program implementation by participating members. The following technical elements describe the functional requirements for creating a complete, effective and cost beneficial nuclear plant systems, structures, and components (SSCs) monitoring program. Figure 2 identifies three primary functional COLM activities that support this strategic plan. They include:

- Monitoring Analysis Methods R&D
- Functional Field Applications Development
- Monitoring Technology Applications Support Functions.

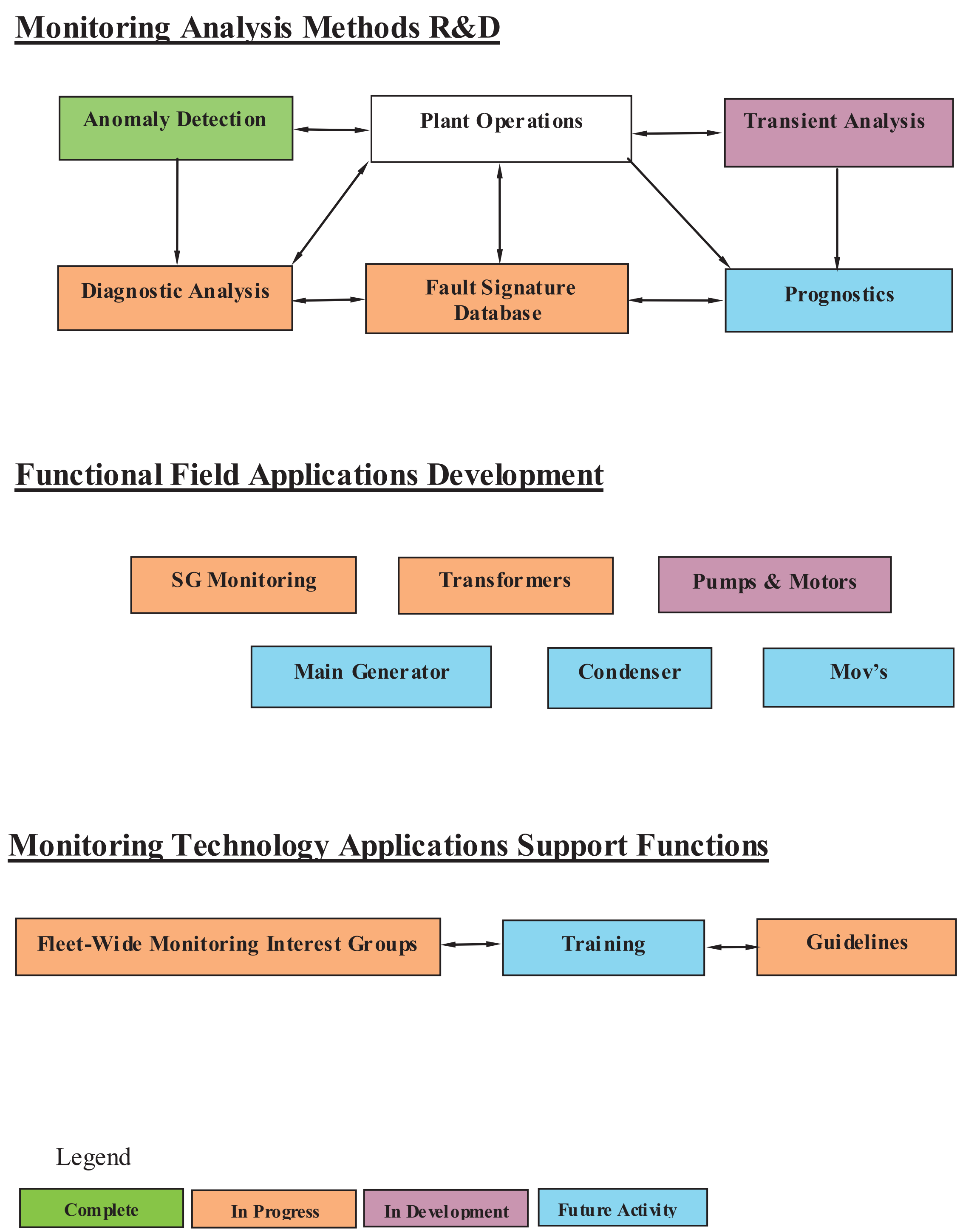

Figure 2. EPRI LTO COLM Program activities.

2.1.4 Research & Development

2.1.4.1 Anomaly Detection

Anomaly detection is a well developed, but not fully advanced technology. Several software products providing anomaly detection are available commercially and have a moderate level of technical support in the industry. Several utilities now apply these products in centralized facilities to monitor primarily fossil fueled plants. These operators are defined as early adopters of new monitoring technologies. The full implementation of monitoring technology throughout the nuclear industry will require continued and eventually diminishing support of technology implementation and application development at the field level. The technology adaption phase will require interest group organization support, advanced technical training, recruiting efforts for new users, implementation support, and performance and benefit documentation. Further development of anomaly detection technology is not required by EPRI at this time.

2.1.4.2 Diagnostics

Automated diagnostics represents one of the important current technical objectives in monitoring science. EPRI has an active R&D effort in the development of this technology. The 2010 effort is scheduled to bring the first release of a full featured, web based Diagnostic Advisor software product for use by the early adopters by mid 2011. The next phase of implementation will be to perform early field testing for nuclear plant applications and obtain performance feedback. The EPRI monitoring program is designed to provide a failure mode behavioral database (Fault Signature Database) to store the signatures of SSC degradation, onset of failure or other abnormal conditions. In full implementation, the diagnostic engine in this product will also enable an automated integration of plant operational and maintenance information.

2.1.4.3 Fault Signature Database

A critical component of the EPRI monitoring program is the Asset Fault Signature Database (AFSDB). The built in intelligence required for effective diagnostics capability is derived in part from having a well developed library of fault signatures or “evidence” that characterize the observable information that indicates for the many possible failure modes of assets monitored by the monitoring program. This database is designed to combine design based knowledge with the collection of fault signatures as they occur (experience based) in operating plants with a monitoring program. The AFSDB has an active EPRI R&D effort in progress. The 2010 LTO effort is scheduled to bring the first release of the software for use with EPRI’s Diagnostic Advisor product by mid 2011. The AFSDB is designed to be a long term “living” database managed by EPRI for access by EPRI monitoring program members.

2.1.4.4 Transient Analysis

A phase I R&D project has been approved under the TI research program to demonstrate the viability and benefit of Transient Analysis technology. Successful results of this phase I effort will provide a basis for the continuation of the R&D effort to support EPRI’s monitoring technologies. Transient behavior is expected to provide a key element for prognostic analytical capabilities. The determination of remaining useful life or time remaining until a critical failure requires the integrated processing of behavioral data, historical maintenance, and operational information. Changes in transient behavior trended over time may provide critical long term predictive capabilities. Transient analysis research may also provide short term identification of active failure modes undetected by conventional steady state analysis.

2.1.4.5 Component Centered Monitoring

Component Centered Monitoring (CCM) is a relatively new element of the EPRI Monitoring program. Based on the monitoring performance of the currently available analytical tools deployed throughout utility monitoring centers, technical gaps have been identified due to the limitations of available instrumentation in the current generation of operating nuclear power plants. Many plant critical assets may require specially developed modeling products that utilize some of the advanced instrumentation and data processing algorithms currently under development. The goal of CCM is to develop highly effective monitoring algorithms as modules that provide both sensitive anomaly detection and the quantification of current performance. It is intended that these modules will be capable of deployment independently and also as preconfigured building blocks within a comprehensive monitoring system. EPRI's current effort is a cooperative research project between EPRI and EDF developing a Steam Generator monitoring application to quantitatively assess tube support plate fouling conditions.

2.1.4.6 Prognostics

Prognostic analysis represents the primary technical capability needed to make effective determinations of RUL or time till effective failure of nuclear plant assets. It also represents one of the most challenging technologies to develop. The initial phases of research are currently in the active planning stages by some of EPRI's strategic partners. EPRI's current role is actively communicating our strategic plan for prognostics development, developing technical guidance for prognostic methods, and assessing product requirements for delivering a prognostic capability. This is to assure the resources provided and directed by others in support of our plan establish a cohesive effort in meeting our goals. As EPRI progresses beyond the current technology developments, prognostics will require direct support to bring the technology to our early adopters for real time program integration and testing.

2.1.4.7 Functional Field Applications Development

The effective application of monitoring technology to nuclear plant assets will require technical support in the development of component specific applications. Due to the limitations of available sensors and required measurements, monitoring programs have marginal capability to perform effective analysis of SSC behaviors. These limitations can be overcome by either installing additional sensors on critical assets or providing direct research and support for the development of these critical applications at the field level. Due to the high cost associated with the addition of new sensors, EPRI will assist utilities in the development and application of monitoring programs to assets like the GSU Main Transformers, Steam Generators, Large motor/pumps, Main Generators, Turbines, and Condensers. The results of these efforts will benefit all monitoring programs through the publication of the results and the availability of component specific applications to all monitoring programs. Improvements in the effectiveness of these monitoring applications will demonstrate significant improvements in plant/equipment performance and support the justification for continued growth in the application of integrated monitoring programs in the nuclear power industry.

2.1.4.8 Five to Ten Year Vision

EPRI's long term vision is based on the fundamental objective of the LTO Monitoring program to incorporate advanced monitoring technology to support the tactical and strategic long term operation and management of the nuclear fleet of power plants. Within this time frame each of the technical elements discussed above should be developed to the stage of technical completion and active implementation by a significant percentage of power plants and utilities. EPRI's role at this point will be to provide appropriate levels of technical support, user group organizational management, and long term management of the databases and software developed within the program. The functional capabilities and design of the monitoring program will allow utilities to implement a full range of monitoring options from full scale monitoring centers or the application of select targeted asset monitoring without incurring high levels of capital and resource investment.

2.1.4.9 Milestones and Deliverables

2010-Funding sources-(A-E LTO), (F-base & alternative), (G-supplemental), (H-TI)

A) Publish and deliver the Guideline for On-line Monitoring Implementation

B) Execute the final development contract to implement nuclear plant support capabilities in the Diagnostic Advisor software product. Deliverable in mid 2011

C) Execute the final development contract to implement nuclear plant support capabilities in the Asset Fault Signature Database software product. Deliverable in mid 2011

D) Develop targeted critical asset monitoring projects with member utilities operating monitoring programs. Deliverables as defined by projects

E) Start cooperative research efforts with industry partners (INL & University of Tennessee) to focus alternative research resources in support of EPRI LTO Monitoring objectives. (Diagnostics)

F) Execute cooperative research projects with EDF in support of component centered monitoring capabilities (Steam Generator Monitoring)

   1. Complete SG preliminary review of adaptability to U.S. plants

   2. Complete the code development for U.S. plant applications.

G) Start a nuclear centered Fleet-wide Monitoring Interest Group (FWMIG) to address nuclear specific monitoring issues and objectives.

H) Initiate a Phase I Transient Analysis research project.

2011

A) Complete and deliver the Diagnostic Advisor version 1 software.

   1. Start the field implementation of Diagnostic Advisor and application testing by early adopters.

B) Complete and deliver the Asset Fault Signature Database version 1 software.

   1. Develop AFSDB long term management program for EPRI.

   2. Coordinate field implementation and AFSDB testing by early adopters.

   3. Continue research to develop specific fault signatures to support the high priority monitored assets.

C) Continue field level asset monitoring development projects with member utilities.

D) Continue cooperative research with industry partners to expand research.

   1. Diagnostics R&D.

   2. Industry database research to support AFSDB signature capture.

   3. Develop design derived fault signatures to support AFSDB selected components.

E) Continue Steam Generator monitoring cooperative research with EDF.

F) Continue FWMIG activities.

G) H) Start Phase II Transient Analysis R&D (2011)

Years 2012-2017

A) Complete.

B) Execute field identified software improvements and support broad based field implementation.

C) Execute field identified software improvements and support long term database management and field implementation.

D) Complete field level component specific monitoring projects and publish project results and adoption instructions.

E) Continue cooperative efforts with industry partners to bring R&D projects to completion for integration into monitoring programs, field testing, and industry adoption.

F) Complete SG monitoring program development and commercialize for industry adoption.

G) Continue FWMIG activities including membership expansion.

H) Complete Transient Analysis development, integrate into diagnostic and prognostics capabilities, conduct field testing, deliver technical product, and support field implementation.

2.1.5 Beyond R&D – Barrier Penetration

In order to penetrate the restrictive barriers and ensure success, available resources must be directed to critical areas. A number of steps must be taken for proper recognition and understanding of the value, capabilities, and potential of monitoring science. Participation must be fostered by actively monitoring programs, and encouragement and support must be directed at programs currently under development. It is important that monitoring technology be successfully demonstrated by early adopters as well. Capturing and defining measurable successes may substantially support the business case for OLM. Technical capability gaps must be addressed. Finally, it is crucial that education be provided to utilities in order to ensure the utmost comprehension of the monitoring science advantage.

Monitoring system success is also dependent on the ability of EPRI to address the specific barriers which apply to each of the potential customers in the customer base. Our environment is divided into four areas: nuclear power plants, research organizations, commercial suppliers, and EPRI. Nuclear power plants are characteristically autonomous, financially restrained, conservative, and requiring an investment adverse-commodity product. Research organizations are still in the to-be determined status. Available commercial suppliers appear to be quite static. The search is on for growth and for the correct market with a minimum of research and development. EPRI's approach to nuclear work is to look for a restart or a green flag to improve capital investment by the utilities. The EPRI Generation program, which focuses on improving the reliability, operational and environmental performance, and efficiency of the entire power generating fleet, both nuclear and non-nuclear, has been shown to be a great program with significant participation in OLM which promises outstanding growth.

Finally, there are issues related to both information integration and limited detection. Integration requires a net reduction in workload and the requirements posed by Cyber Security create difficulty in implementing centralized monitoring. The diagnostics and prognostics capabilities will require significant plant-data integration and access. Limits to detection include the perception of the current status for monitoring capabilities, lack of deep dive into R&D on the critical assets, as well as failure to investigate or adopt the results gathered within other industries.

2.1.5.1 Project Risks

This section identifies some risks associated with the execution of the LTO Monitoring Program. Since monitoring technology does not address an active regulatory requirement and does not directly address a currently identified industry hardware issue (such as buried pipe, aging cables), the risk associated with non-performance is not currently tied to a plant's operating license. The risk of non-performance is linked directly to plant operational capacity and, thus, financial performance. A fully developed and implemented SSC monitoring program will provide significant gains in plant reliability and operational performance. Failure to implement a full-scale monitoring program will result in higher levels of hardware failure, potential loss of generating availability, increased maintenance costs for aging equipment, and elevated staffing requirements. These risks are therefore strictly financial risks.

A secondary risk is insufficient funding to support the development of monitoring technology defined by this strategic plan. The success of any new technology is dependent on the short term success of the early adopters. The continuing financial support of each development stage of an integrated set of technologies must be provided to avoid gaps in the progression of the technology development and implementation. Since the functional design of this monitoring program is intended to directly support the plant system managers, its success will be dependent on how quickly the technology can be demonstrated to meet its functional objectives.

2.1.5.2 Conclusions

The LTO COLM plan presented here represents a technically achievable set of goals and an implementation schedule that can be supported by the resources available to EPRI and its strategic partners. The success of the plan is dependent to a large extent on the support EPRI can provide its members during the implementation phases beyond the initial research and development of each technical element or activity. This capability can only be achieved through meeting the funding requirements and schedule while maintaining adequate project management, direction, and control.

2.1.6 EPRI Activities

2.1.6.1 Recent Activities

Recent activities at EPRI include the release of the 2009 Tech Report TR-1018910, "Information Integration for Equipment Reliability at Nuclear Power Plants." EPRI also recently worked with EdF research centers on enhanced integrated empirical modeling. Other research includes work focused on steam generator monitoring and machine analysis. Online monitoring of transformers is being tested at Progress Power and Exelon. Finally, work is being conducted on the transmitter calibration interval extension in conjunction with the pressurized water reactor owner's group (PWROG).

2.1.6.2 Current Activities

A number of activities are currently underway in support of the EPRI Strategic Plan. The Long-Term Operations and Generations group has carried out recent work with the diagnostics capabilities expert microsystems, which involves both a diagnostic advisor and an asset fault signature database. Another area of focus is the Prognostics Capabilities for the energy management system (EMS) to calculate the remaining useful life prediction of components. Fleet wide monitoring interesting group (FWMIG) instrumentation and control work is currently under development as well. The 2010 Technical Report TR-1021116, "Guideline for Initiating an Online Monitoring Program for Nuclear Power Plants," was released earlier this year. The most current research project is ongoing at EdF. The research covers Steam Generator Monitoring and Machine Analysis.

2.1.6.3 Where is Research Needed

Research in a number of areas is critical to the development of successful online monitor systems.

These areas include:

- Understanding the limits of detection
- Capturing, cataloging and utilization of *fault signatures*
- Automation
- Data integration
- Refinements of *anomaly detection alarms* and research into diagnostic engine and fault signatures as pre-filter for alerts
- Vibration analysis and integration into monitoring platforms

- Audio signature analysis
- CCM having effective analysis, and advanced analysis models can be used with limited data.

2.2 Failure Prevention for Nuclear Power Plants Through Proactive Management of Materials Degradation[1]

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As part of the strategy needed to meet growing energy demand, it is economically attractive to consider life extension for existing nuclear power plants. The U.S. is currently implementing license extensions of 20 years on many plants, and consideration is being given to the concept of life extension beyond 60 years. In almost all countries with nuclear power plants, authorities are looking at some form of license renewal, with various programs initiated to support this activity. Life extension is attractive when considered against the costs of building replacement generating capacity or of decommissioning legacy plants. The construction of both replacement and new capacity needed to meet the global growth in demand for electricity would challenge both the available technical and economic infrastructures. It is therefore important to see where technology can (a) help better manage existing power plants and enable license extension for the existing fleet and (b) contribute to both new advanced LWRs and new power plant designs with their demanding materials and operational requirements.

Reactor performance has, in general, been limited by materials issues. The response of the industry and regulators to issues of materials degradation in the past has generally been to develop and approve mitigation actions after the degradation has occurred. These mitigation actions involve increases and improvements to in-service inspections (ISI); changes in designs, materials and operating conditions; and repair or replacement of degraded components. This approach has maintained the safety of operating reactors, but has proved to be an inefficient and expensive way of managing materials degradation issues for the industry.

Becoming proactive through on-line monitoring for CBM and, eventually, prognostics requires advances in sensors, better understanding of what and how to measure within the plant, enhanced data interrogation, communication, and integration, new predictive models for materials damage/aging, and effective deployment and system integration. Central to all prognostics (remaining life prediction) is quantification of uncertainties in what are inherently ill-posed problems. For implementation, there is the need for integration of enhanced CBM/prognostics philosophies into new plant designs, operation, and O&M approaches [1]. The philosophical change from reactive to proactive is illustrated in Figure 3.

The adoption of new on-line monitoring, diagnostic, and eventually prognostics technologies has the potential to impact the economics of the existing NPP fleet, new plants, and future advanced designs. Attention to date has largely been focused on the active components, such as pumps, valves and other moving parts. There is also now a growing interest in monitoring the major passive components within integrated Plant Life Management (PLiM) programs and, in particular, deploying strategies and technology which minimizes surprises as, for example, water on the floor.

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[1] Abridged from the paper: L. J. Bond, S. R. Doctor, S. M. Bruemmer, S. E. Cumblidge, A. B. Hull, and S. N. Malik. 2009. "Failure Prevention for Nuclear Power Plants through Proactive Management of Materials Degradation (PMMD)." In Failure Prevention: Implementation, Success Stories and Lessons Learned: Proceedings of the 2009 Conference of the Society for Machinery Failure Prevention Technology (MFPT 2009), ed. R Wade and H Barnard, pp. 389-408. April 28–30, 2009, Dayton, Ohio. Society for Machinery Failure and Prevention Technol. (MFPT) Dayton, Ohio.

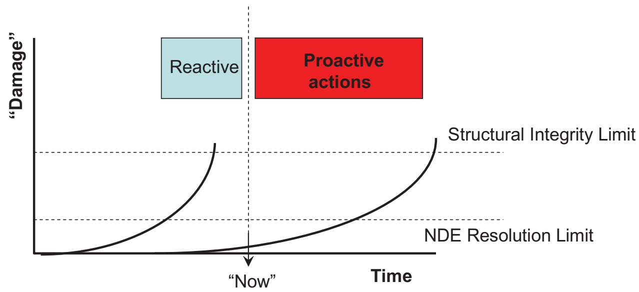

Figure 3. Diagram illustrating materials or damage development with time, and the differentiation between reactive and proactive actions. Note that the degradation process vs. time is rarely linear, as is often assumed.

2.2.1 Workforce and Economics.

For NPPs, the O&M costs are estimated for various plants and countries at between 40% and 70% of the overall generating cost. In the U.S., O&M is at the higher end of the range (~60–70%), and fuel costs are at about 15–30%. Of these O&M costs, ~80% are related to the costs of labor. In both Europe and North America, the situation is further complicated by the problem of an aging workforce and a limited supply of replacements [2]. In the rapidly growing Asian economies and developing countries, there are also challenges in meeting the skilled workforce needs [3, 4].

Significant opportunities exist for current NPPs to deploy new technologies when upgrades, including modernization of instrumentation and control systems, are implemented. The economic benefit from a predictive maintenance program can be demonstrated from a cost/benefit analysis. An example is the program for the Palo Verde Nuclear Generating Station [5]. An analysis of the 104 U.S. legacy systems has indicated that the deployment of on-line monitoring and diagnostics has the potential for saving over $1B per year when applied to all key equipment [6].

2.2.1.1 The Move to 21st Century Instrumentation and Control Systems.

The move to digital systems in petrochemical process and fossil-fuel power plants is enabling major advances in instrumentation, control and monitoring. The adoption within the nuclear power community of advanced on-line monitoring and advanced diagnostics could reduce costly periodic surveillance that requires plant shut-down. It could also provide more accurate cost-benefit analysis, "just-in-time" maintenance, pre-staging of maintenance tasks, movement towards true "operation without failures," and a jump start on advanced technologies for new plant concepts, such as those proposed under the Generation IV Program. There are significant opportunities to adopt CBM when upgrades are implemented at existing facilities. The economic benefit from a predictive maintenance program based on advanced on-line monitoring and advanced diagnostics can be demonstrated through cost/benefit analysis.

There has also been growing recognition that nuclear plant condition assessment based on nondestructive testing (NDT) at the time of fabrication, followed by intense inspections during outages, requires the adoption of conservative assumptions with regard to addressing detected indications and intervention. With aging plants, there is the risk of unanticipated findings at outages, which can cause extended down time. A recent study concluded that current inspection frequencies for some forms of degradation do not seem to match rates of degradation growth, which adds support to the conclusion that on-line monitoring is needed for both current and new reactors. To address these issues, there is a move to deploy on-line monitoring and CBM that have the potential to increase operator situational awareness, enhance safety, and provide significant cost savings.

As indicated the transition from periodic inspection to on-line monitoring for CBM and, eventually, PMMD will require advances in the monitoring system technologies for real-world deployment, understanding of material degradation, and new predictive models for damage/aging evolution.

Quantification of uncertainties in what are inherently ill-posed problems and integration of enhanced CBM/prognostics philosophies into new plant designs, operation, and O&M approaches [7] will also be necessary. A recently published report presents a methodology that incorporates predictive models and damage assessment into improvements in the American Society for Mechanical Engineers (ASME) Code Section XI [19], but additional science and technology, together with standards and regulatory guidance, will be needed as PMMD moves towards implementation.

Advances in technologies in other industries can potentially benefit NPPs, particularly when using advanced on-line monitoring and diagnostics for CBM and, in the future, prognostics. The move to digital systems is enabling major advances to occur in the instrumentation, controls, and monitoring systems, as well as the approaches employed for diagnostics. The new technologies can provide enhanced projected data for all aspects of plant status, and these are immediately available to the operator. They can supply improved measurements that enable operation nearer to component limits (power uprates) and give plant-projected performance metrics in real time to corporate operations. As diagnostic and predictive tools evolve, component health status can be continuously provided to maintenance staff. However with all these advances, there is also the potential for increased cyber vulnerability. In the digital I&C area, significant attention is being applied to defense in depth, common cause failure, and cyber security of computational infrastructures. Planning for and incorporating such technology can improve safety, improve plant economics, reduce unplanned outages, and provide better probabilistic risk assessments.

2.2.1.2 Insights from Past Experience

In the current LWR fleet, new degradation processes have appeared, on average, at a rate of one every seven years [8]. Operators need information to better manage power-plant life holistically, adjusting operating conditions to reduce the impact of stressors. Because periodic inspections, which typically occur during refueling outages, cannot be assumed adequate to help ensure fitness for service of critical safety systems and components or help ensure optimal plant life management, developing methodologies and designing systems for on-line continuous monitoring becomes critical. These are needed to provide operators with better plant situational awareness and reliable predictions of remaining service life of critical systems and components.

In the U.S., many activities have addressed the issues of aging in the current fleet of NPPs. Early insights were summarized in a 1992 report [9], and on-going NRC meetings address water reactor safety/aging issues [10].

The ASME Boiler and Pressure Vessel Code was developed for LWRs and addresses fatigue as the dominant failure mechanism. While this Code has some limitations for LWRs, it is clearly not adequate as written for Generation IV NPPs. The new materials, new degradation mechanisms, and the new operating environments mean that flaw-acceptance standards are unknown at this time, both for fabrication and service-induced flaws. The ASME Code needs evolve for Generation IV design, construction, and operation. Advanced NDE measurements might be developed to provide a means to monitor material properties so that these changes would be detected, quantified and trended during operation. Alternatively, sensors could be deployed at all key locations to monitor for the initiation and growth of degradation and to establish operational parameters and material changes that could be the precursors to degradation [7].

For the current fleet of operating LWRs, the majority of component failures are the failure of active components not operating correctly when called upon to perform a given function, such as a valve not opening or closing on demand. The failure of passive components is dominated by failures associated with service degradation. Active components are managed with a maintenance program that is based on experience and not on the known condition of the component and its need for preventive maintenance. For the passive components, their degradation is managed through periodic inspections as dictated by the ASME Code.

Over the past few years, these ISI programs have changed dramatically through the use of risk-based management. Although risk is currently managed from a safety standpoint, there are open issues that remain. These include the potential risk of having surprise failures that are related to the occurrence of new degradation mechanisms, including those that are accelerated by stressor enhancement due to altered conditions or newly introduced acceleration mechanisms (e.g., corrosion due to accidental resin intrusion). These can have a long initiation time, and because only the risk-important components (limited in number) are being periodically inspected, most of the NPP risk is associated with a small percentage of plant components. Another factor contributing to program change is the movement away from the original strategy of defense-in-depth in which ISI was to be used to detect the unexpected that had not been accounted for in design, selection of materials, fabrication processes employed, or operating conditions.

Degradation is the immediate or gradual deterioration of SSCs that could impair their ability to acceptably function. Aging is a general process in which characteristics of an SSC gradually deteriorate with time or use. When aging processes are known, they can be monitored through an appropriate aging management program (AMP) and PLiM program and potentially mitigated.

Degradation mechanisms related to aging are usually classified into two main categories: (1) those that affect the internal microstructure or chemical composition of the material and thereby change its intrinsic properties (e.g., thermal aging, creep, irradiation damage) and (2) those that impose physical damage on the component either by metal loss (e.g., corrosion, wear) or by cracking or deformation (e.g., stress-corrosion). The phenomenon of aging degradation in NPPs is complex and requires sophisticated, state-of-the-art science and technology procedures to effectively ensure continued safe and reliable operation. In addition, an effective management system is needed to correctly implement mitigation and/or monitoring actions.

The past decade has seen major developments within both the nuclear and wider engineering communities to move from the use of periodic NDT to CBM and advanced life management, also known as structural health monitoring, material damage prognostics, and PMMD. Where these approaches have been applied, they have been implemented with on-line methods developed for advanced monitoring and diagnostics. As the economic value of CBM, as well as other advanced monitoring approaches, is being demonstrated, interest grows in on-line monitoring and looking towards adopting prognostics, the prediction of the remaining safe or service life, for both active components, such as pumps, and passive components, the basic structural materials.

As a result of the changing economics of NPP life extension, national and international activities to address PLiM for long-term operation have been developed. These activities include plant modifications for power uprating. The primary drivers have been the changes in the economic/business climate, as well as a need to provide energy to support sustainable development and, in many countries, supply carbon-free electric generation. Various groups have been working to identify and address key issues in three broad areas: Technology, Regulation and Business.

The pattern of activities that are developing to meet the needs of life extension for the global NPP fleets is complex, and in many cases the relationships are interconnected and overlapping. Various international and multi-national activities overlay the national activities. To date, discussion has divided the identified technical gaps into categories: gaps in basic science; gaps in engineering; and gaps in regulation or codes and standards. The full scope of these needs is still being defined. This paper illustrates that the implementation of PMMD programs will require significant basic and applied research.

2.2.1.3 Diagnostics and Prognostics: State-of-the-Art and Potential

There has been a growing recognition that nuclear-plant condition assessment based on NDT at the time of fabrication, followed by intense inspections during outages, requires adoption of conservative assumptions with regard to addressing detected indications and intervention. In the case of aging plants the risk is unplanned shut-downs or "surprises" at an outage that can cause extended down time. Developing on-line monitoring and CBM has the potential to increase situational awareness in operators, enhance safety, and provide significant cost savings.

Diagnostics. It was recognized in the mid-1970s that NDT needed to become a quantitative, science-based technology. Research was initiated and, as a result, NDE has developed [11]. Many of the measurement capabilities for NDT/NDE were identified as set by fundamental physics [12]. Recent years have seen better understanding of the measurement processes and quantification of performance in terms of a probability of detection, rather than an ultimate detection limit number. New approaches to the management of life in mechanical systems have developed [13], and new research is ongoing into characterization of materials in aging systems, particularly looking at phenomena that occur before the defects are detected by conventional NDT develop [14].

The nuclear community is performing instrumentation upgrades to operating NPPs. It is recognized that: ". . . digital technology provides significant benefits. Modern systems provide functional upgrades and solve reliability and maintenance problems" [15]. However, to ensure the ability to license NPP technology – both in the short term and in the next generation of systems (i.e., those for deployment in association with the DOE-NP2010 Program) in the U.S., advanced on-line diagnostics and prognostics functionalities are being limited to those with proven regulatory acceptability.

Looking to the longer term, new integrated approaches to system life-cycle management are being investigated to support Generation IV system needs [6; 16; 17]. These studies are driven by economic needs and the desire to reduce radiation exposure for staff, together with needs for enhanced system assessment/life-prediction tools. These are to be used for planning, to avoid surprises during an outage, and to ensure that, at the end of an outage, there is confidence that the NPP components and systems are in a condition to operate efficiently without failure until the next planned outage.

Prognostics. Prognostics is the prediction of remaining safe or service life, based on an analysis of system or material condition, stressors, and degradation phenomena. Moving from diagnostics based on observed data to prediction of life and technologies for structural health monitoring/management based on predicted behavior requires development of new approaches, identified in schematic form in Figure 4. A review of machinery diagnostics and prognostics for CBM is provided by Jardine *et al.* [18], but the review does not consider nuclear power systems specifically.

An assessment of the state of diagnostics and prognostics technology maturity was recently provided by Howard [21]. The current status for various system elements is shown below. Technologies are being developed for non-nuclear applications, including instrumentation and system health monitoring for electronics, in what is being called "electronics prognostics" (for example, see Urmanov [19]). There are also integrated technologies being developed for advanced fighter aircraft and unmanned aerial vehicle (UAV) system health monitoring, which include both electrical/electronic and mechanical systems. Within the field of advanced diagnostics/prognostics, systems have been deployed for individual elements, but fully integrated systems are still being developed.

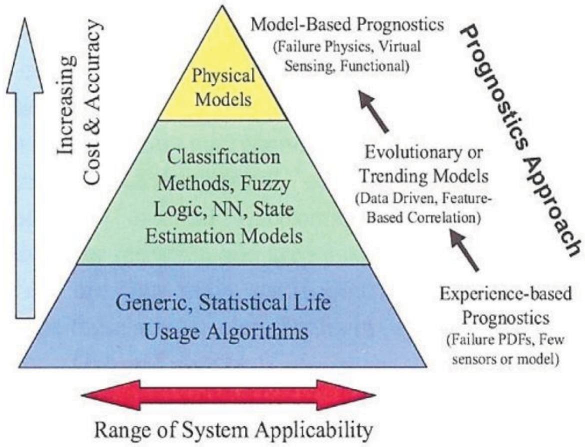

Figure 4. Range of prognostic approaches.

Table 1. State of Maturity for Diagnostics (D) and Prognostic (P) Technologies [25]

Diagnostic/Prognostic Technology for:	AP(a)	A(b)	I(c)	NO(d)
Basic Machinery (motors, pumps, generators, etc.)	D		P	
Complex Machinery (helicopter gearboxes, etc.)		D	P	
Metal Structures (passive and active)	D		P	
Composite Structures (passive and active)			D&P	
Electronic Power Supplies (low power)		D	P	
Avionics and Controls Electronics	D		P	
Medium Power Electronics (radar, etc.)		D		P
High Power Electronics (electric propulsion, etc.)				D&P

(a) AP = Technology currently available and proven effective.

(b) A = Technology currently available, but VERIFICATION AND VALIDATION not completed.

(c) I = Technology in process, but not completely ready for verification and validation.

(d) NO = No significant technology development in place.

A trend of seeking to move from periodic NDE to on-line CBM started several years ago [20]. A review of the current paradigms and practices in system health monitoring and prognostics has recently been provided by Kothamasu *et al.* [21]. Significant measurement challenges associated with characterization of aging in irradiated reactor components remain [22; 23].

Development of concepts for advanced on-line structural health monitoring for reactor designs, such as the International Reactor Innovative And Secure (IRIS), has been initiated [24]. Also, physics-based approaches to the analysis of aging for prognostics [25; 26], combined with the potential effects on probabilistic risk inspection for designs such as IRIS [27] have been reported.

There is growing interest in sensors and technology, particularly on-line monitoring for the detection of early damage in structural materials. A comprehensive review paper was provided by Raj *et al.* [28], and an assessment that relates technology to various phases in degradation development for PMMD was recently prepared by Bond *et al.* [29]. Figure 5 illustrates the relationships between the degradation regimes, the nature of degradation, and some of the methods being used to make measurements. Early detection of degradation is a key element in both system management and prognostics – estimates for the remaining life based on models for degradation development.

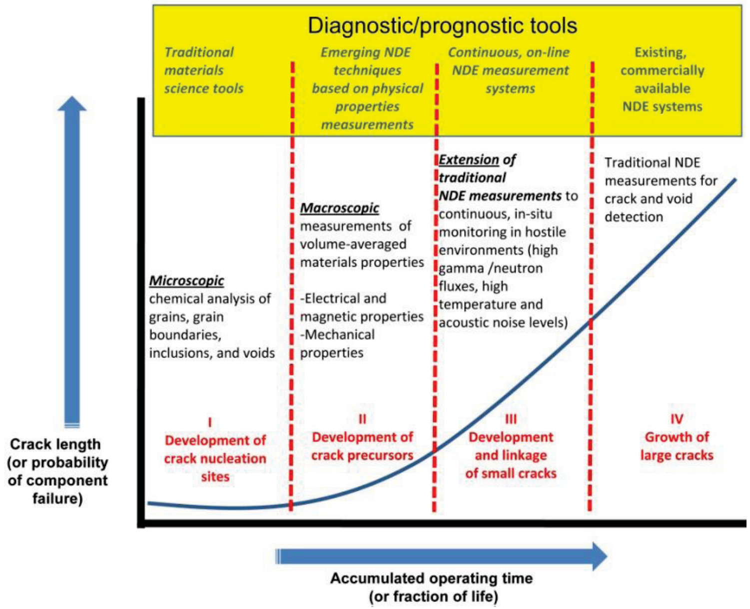

Figure 5. Strategy for development of a PMMD system.

Key to developing more advanced prognostic schemes that give maximum warning of degradation in active systems such as pumps and valves is to focus on monitoring the stressor, rather than just the subsequent effects of aging and degradation. In order for this strategy to be successful, good physics-based models relating the stressors to the rate of aging or degradation must be developed in the prognostic scheme. For the existing NPPs, particularly when life extension is being developed, there are opportunities to deploy on-line monitoring/prognostics, assuming it can be demonstrated that there is still remaining useful life in the plant.

2.2.1.4 Proactive Management of Materials Degradation

To support safe sustainability of the nation's operating commercial LWR NPPs, and in preparation for future decisions regarding new construction of plants, the NRC has initiated a new program called PMMD. The program will support the collection of data and analysis to predict aging of materials, components, and systems in operating plants, thus allowing monitoring, maintenance, and repair activities to occur in advance of adverse impacts.

PMMD trades on a long history of activities to understand materials degradation. It will develop new knowledge on materials degradation mechanisms, inspection and monitoring techniques, and related mitigation and repair. The goal of PMMD is to acquire the technical basis to answer key aging-related-degradation questions. These answers could have profound impact on the nation's energy strategies for meeting consumption needs. Among these questions are:

- Can licensees safely extend the operating life of existing power plants to 60–80 years or longer
- What are the key technical and regulatory issues that require attention to enable license extension
- What information is needed to adequately process and respond to applications for a second (subsequent) license extension
- What are the remaining open technical and regulatory issues?

To address the issue of PMMD, the NRC has initiated a program to assess ability to identify early those components that might be susceptible to future degradation so that mitigation and/or monitoring and repair actions can be proactively developed, assessed, and implemented before the degradation process could adversely impact structural integrity or safety. Two processes are envisioned for PMMD programs. These processes are (a) implementation of actions to mitigate or eliminate the susceptibility of materials to degradation; and (b) implementation of effective inspection and monitoring, with timely repair of degradation. The elements in the NRC's comprehensive PMMD Program are identified and shown in schematic form as Figure 6.

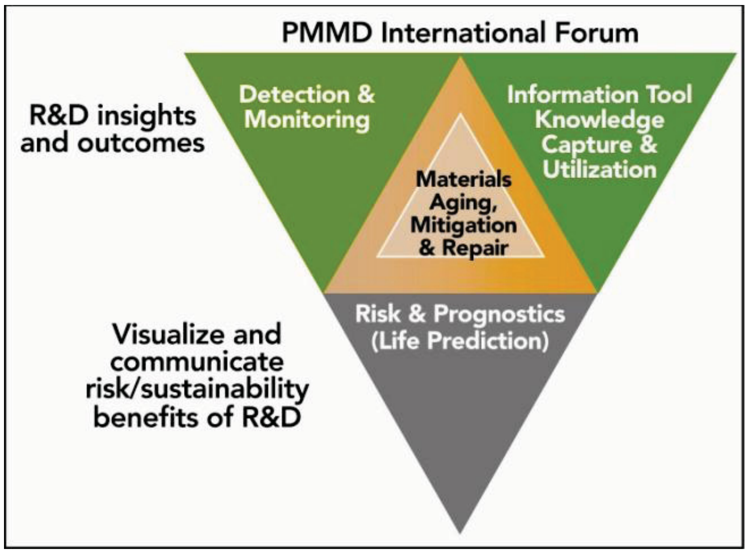

Figure 6. Elements in the NRC PMMD program.

Aging degradation mechanisms are usually classified into two main categories – those that (1) affect the internal microstructure or chemical composition of the material and thereby change its intrinsic properties (e.g., thermal aging, creep, irradiation damage), and/or (2) impose physical damage on the component by deformation, metal loss (e.g., corrosion, wear) or cracking (e.g., stress corrosion). The phenomenon of aging degradation in NPPs is complex and requires sophisticated, leading-edge science and technology procedures to effectively manage it to ensure continued safe and reliable operation. Not only is technology involved, but also an effective management system is needed to correctly implement mitigation and/or monitoring actions.

The pattern of activities developing to meet the needs of life extension for the global NPP fleet is complex, and in many cases contains interconnections and overlapping relationships. There are various international and multi-national activities that overlay national activities. This paper illustrates that the implementation of PMMD programs will require significant basic and applied research. To date, discussion has divided the identified technical gaps into three categories: (1) needs to be addressed by basic science, (2) addressed by engineering and (3) addressed from a regulatory/codes and standards point of view. The full scope of these needs is still being defined.

With appropriate design development, an opportunity exists for future systems to have integration of off-line NDE inspection information with data from intelligent, on-line self-diagnostic capabilities that will alert operators and initiate remediation strategies. Significant progress is being made, but further technological advances are needed in:

- Smart components and structures

- Self-diagnostic systems
- Embedded micro-electromechanical systems and other health-monitoring sensors
- Wireless communication
- Distributed data processing and control networks
- Prognostics implementation
- Advanced NDE technologies
- Proactive operations and maintenance program.

The result of these advances would be the realization of the optimized plant of the future.

The PMMD program examines LWR materials, and material-degradation phenomena that affect them, with the goal to effectively predict and prevent development of life-limiting problems. All parts of an NPP are subject to continuous, time-dependent materials degradation due to service conditions, which include normal operation and transient conditions; postulated accident and post-accident conditions are excluded. Some forms of degradation, such as stress corrosion cracking (SCC), often exhibit a long initiation time, followed by a rapid growth phase, prompting the need for new inspection or monitoring technologies. Examples of advanced technologies that may be needed include NDE techniques to identify SCC precursors and sensitive on-line monitoring approaches to detect cracks as they initiate and grow. In addition, certain LWR components may not have sufficient NDE programs in place to prevent failures in reactor systems operating well beyond the age range originally intended for the current NDE programs. A review of the reactor components will be needed to determine if altered inspection regimes may be required to deal with new degradation mechanisms that may emerge over time. Also, as reactors lifetimes are expanded, degradation mechanisms previously considered too long-term to be of consequence (such as concrete and wiring insulation degradation) may become more important.

2.2.1.5 Proactive Management of Materials Degradation – Principles

PMMD has the objective to identify materials and components where future degradation may occur. In some cases, the degradation may involve phenomena not yet experienced in the operating fleet, but which laboratory data and/or a mechanistic understanding indicate it may be pertinent to future reactor operations. PMMD includes the methodology and actions needed to manage both active and passive elements in the NPP systems throughout their existence to minimize the impact of degradation, maintain safety, and potentially enable extensions to system operating life [30].

Basic Principles of PMMD

In the reactive scenario, there is limited time following detection for mitigation actions to be developed before an unacceptable degree of damage occurs. This constraint may lead to the deployment of incomplete and ineffective mitigation strategies. The time constraint is considerably reduced in the proactive management scenario, with the increase in available time for mitigation development being a function of the incubation time before damage starts and the subsequent kinetics of damage accumulation.

In order to meet the objective of a proactive material degradation assessment and management program, it is necessary to understand stressors and assess various damage and damage accumulation date/severity relationships for existing and potential degradation modes, materials, environments, and operating states for each of the different LWR components. This assessment may be based on formulations for the various stressor and damage-time relationships or, more generally, on the basis of operating and laboratory experience and engineering judgment. The six principles of proactive management of materials degradation were deduced from NUREG/CR 6923 [31] and are highlighted to emphasize their importance.

1. Materials degradation has occurred in LWRs and will continue as long as LWRs are in operation. The trend within the nuclear power industry is to operate plants for longer periods of time and at increased power levels. The numbers of power plants requesting power up-rates and successfully applying for licensee renewal are examples of the trend. Material degradation (especially potential new modes of degradation) is likely to increase as NPPs are operated for longer periods of time and at increased power levels. The use of alternate materials or modified operating conditions may potentially counteract these factors, but in general, these materials and conditions changes are not fully qualified and can address only a fraction of the degradation modes. The technical reasons for these statements are outlined in detail in NUREG/CR 6923 [31].

PMMD increases the available time for mitigation, which is a function of the incubation time before significant damage starts and the subsequent kinetics of accumulating damage.

Considering license renewal, power up-rates, and the potential for "life beyond 60," addressing degradation in a reactive fashion may result in an unacceptable loss of safety margin. Current reactive management of materials degradation limits the time window following the damage observation during which mitigation actions can be developed before an unacceptable degree or level of damage is reached. This constraint may lead to the deployment of ineffective mitigation strategies.

Extended operation of an NPP requires the plant owner to address two major issues concerning degradation.

a) Developing effective aging management programs for known degradation as currently addressed in license renewal [32; 33].
b) Developing a technically based program to understand the impact of stressors that can drive "damage" or material life utilization and then detect and mitigate both stressors and degradation that has not yet happened but has the potential to occur.

PMMD programs should include degradation-mode component combinations *with applied stressors* when there is a high susceptibility to degradation, based in large part on multiple observations in operating plants regardless of the knowledge level concerning degradation.

PMMD programs should include degradation-mode component combinations where there was little or no evidence to date of degradation in the plants, but where there was sufficient evidence from laboratory investigations to indicate that degradation in the plants might be expected in the future. Reference [29] has identified specific degradation mode-component combinations where the knowledge level of the system interdependencies is low and additional proactive actions (such as research) may be warranted if PMMD by mitigation is desired.

The overall approach to developing a PMMD program involves two steps. The first is to identify the components of interest that might undergo future degradation [29]. The second step is to identify the technical gaps in plant programs that detect, characterize, and monitor stressors resulting in the degradation of susceptible LWR components. The technical gaps may require dedicated research projects to address the identified technical deficiency (e.g., develop mitigation strategies, ISI and on-line monitoring techniques, and repair procedures). Activities are being investigated in selected PMMD thrust areas:

Materials Aging, Degradation and Mitigation

This thrust will advance understanding of known degradation mechanisms and identify emerging failure processes before unsafe conditions occur. Advanced experimental techniques will be employed to determine root-cause mechanisms of aging and degradation, helping establish the basis for effective mitigation.

Detection and Monitoring

This area will develop new ISI and on-line monitoring methods using NDE techniques to enhance the safe operation of nuclear power plants. NDE helps to prevent failure in reactor components through detection of degradation before impacts occur in the structural integrity of reactor components.

Risk and Prognostics

This thrust will leverage a PMMD database that currently provides an assessment of the susceptibility of various nuclear power plant component groups to a range of aging mechanisms, in conjunction with supplemental evaluations of confidence in these assessments and knowledge required to mitigate each such mechanism. The database currently lacks improved risk implications of the assessments. This thrust area will advance the risk indices associated with each combination of component group and aging mechanisms, providing a broader basis for techniques aimed at specific degradation mechanisms. Risk and prognostic activities also will be integrated to improve the quantification of reliability and uncertainty in PMMD activities.

Information Tool, Knowledge Capture & Utilization

The PMMD Information Tool (currently derived from NUREG/CR 6923) will be expanded to include information provided in the Generic Aging Lessons Learned (GALL) Reports (NUREG-1801), and will also be augmented with a series of applications or "tools" to harvest knowledge from vast stores of information in support of PMMD subject matter experts.

PMMD International Forum

Given the global interest in life/license extension to meet electrical supply needs from existing NPPs, and in developing comprehensive PLiM for new construction, the PMMD will engage the international nuclear community on a number of fronts. A near-term activity will be the establishment of an International Forum through two workshops being planned for 2009. One workshop will be conducted in Asia, and the other, in Europe. Emerging from these workshops will be the development of a Comprehensive International PMMD Network that will address critical issues including:

- Maximizing resources and funds to engage the talent of NPP PMMD worldwide
- Increasing effectiveness and communication of research results
- Information exchanges and peer-to-peer scientist interactions on PMMD
- Identifying critical issues and tapping global talent for developing PMMD solutions
- Acquiring the data needed for the NRC and other international regulatory agencies to extend the regulatory framework needed for license extensions.

These activities and more will maximize NRC's engagement within the global PMMD community.

2.2.2 Technical Gaps that Need to be Addressed for PMMD

In understanding the nature of the challenge faced within the nuclear power community in moving towards PMMD, it is helpful to briefly provide an assessment of current practice and understanding of some on-going evolution of technologies. NDT has moved from being a "workmanship" standard to becoming part of a "fitness-for-service" assessment – combing inspection and evaluation of indication significance using engineering mechanics methods. There are already known to be significant opportunities to deploy new technologies when upgrades, including modernization of instrumentation and control systems, are implemented at existing facilities.

There is now a trend in the U.S., which is firmly rooted in current methods, to move from periodic ISI to CBM. An acute need to optimize maintenance is recognized to improve both reliability and competitiveness of NPPs within the energy sector. A recent IAEA report collects and analyses proven

CBM strategies and techniques in IAEA Member States [34] and this provides a useful benchmark regarding current practice. In addition, IAEA activity is ongoing to provide assessments for the state-of-the-art in on-line monitoring, particularly in the context of the potential form-improving performance in NPPs. The first of the two reports looks at instrument channel monitoring [35] and the second looks at process and component condition monitoring, together with diagnostics [36; 37]. As discussed earlier, there are also various research activities that are looking at the needs and potential for on-line structural health monitoring for advanced reactors (for example, see [24]).

The move from advanced monitoring, ISI, and CBM, which is seeing increasing deployment in legacy NPP, to PMMD involves a fundamental philosophical change: the move from being reactive to becoming proactive. The most advanced monitoring is being deployed, together with digital I&C systems, in new NPP outside the United States. For example, the current CBM methods and strategies are focused on active components (e.g., pumps, motors, valves) and PMMD includes and is central to the assessment of passive components (e.g., pressure vessel, piping, core internals, concrete, and cables), ensuring reliability and prediction of remaining safe and service life.

Clearly, implementation of PMMD programs will require significant basic and applied research. To date, the identified technical gaps are in the areas of basic science, engineering, and regulator, code and standards application. The full scope of these needs is still being defined [38].

2.2.3 Conclusions

Recent experience has shown the potential economic impact of adopting CBM in NPPs. A need to move beyond current approaches to CBM and into the realm of on-line diagnostics and prognostics is seen. Operators need enhanced situational awareness if unwanted outages are to be avoided. Such advances are only possible through the use of new and improved monitoring, and implementation of advanced diagnostics/prognostics. The use of digital I&C provides the opportunity to add enhanced functionality and prognostics for key system elements.

Opportunities exist to significantly impact operation and maintenance costs for the current legacy fleet, the current generation of LWRs – which are being built with digital instrumentation and controls – and most significantly next generation (Gen IV) plants that will require new ranges of operational conditions and enhanced monitoring functionality. However, before the deployment of such systems is possible, it will be necessary to demonstrate methodologies, understand stressors, sensors, and communication, and analyze and quantify uncertainty in remaining life prediction. Further, demonstrating long-term monitoring system reliability on the next generation of new LWR designs is a necessary prerequisite.

For these approaches to be successful, it will require the engagement of researchers, new reactor designers, component manufacturers, Codes and Standards personnel, material suppliers, and regulators working as a team to develop, demonstrate, and validate these new and advanced measurement and monitoring technologies for new advanced NPPs. The engagement of these many diverse experts must occur NOW in order for these advances to be realized. Otherwise, performance of new-build LWRs and then more advanced NPPs will simply be an extension of the design, operating, and performance standards of the current fleet of light-water reactors.

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2.3 The Halden Reactor Condition Monitoring Program

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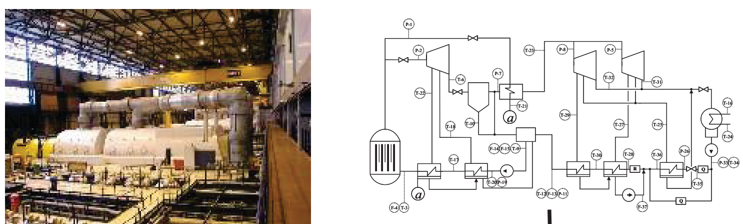
2.3.1 Physics based models for condition monitoring

The ultimate aim of OLM is to have global monitoring of the plant performance. It is expected that by modeling the whole plant and comparing actual measurements with expected values from the models, early detection of anomalies and faults will be possible. Through detailed analysis of the observed anomalies, diagnostic methods which may include physics-based monitoring can be applied to the measurements to perform fault identification.

For example, the data-reconciliation method compares a physical model of the turbine cycle to actual plant measurements. How well this model fits to the plant data is then used in fault analysis. The difference between measurement values and their fitted values is called the measurement residual. Sigma V is the uncertainty in this residual.

Each measurement point is assigned an uncertainty. How well the simulation fits to the measurements is compared to the given uncertainty. Traditionally this comparison is directly used to determine if there is a fault in the measurement. This requires that the uncertainty is a true representation of the random variance of the measured value.



Measurements: x^+, σ_{x^+} Calculations: $\hat{x}, \sigma_{\hat{x}}$

Residual: $v = \hat{x} - x^+, \underbrace{\sigma_v}_{\text{Uncertainty}}$

Figure 7. Conditioning monitoring of the plant's performance.

An example of this has been conducted with the Loviisa model. The Loviisa 2 NPP consists of two parallel turbine cycles that are connected at several locations. The model includes both turbine cycles, which are calculated simultaneously.

The model consists of 205 components, 193 measurements and 92 parameters that varied during the calculation. Calculation time is around 30 min for each data point with one year of data (366 data points) used in the analysis. The VVER-440 reactor consists of two parallel turbine cycles with connections and is modeled together in a single model. This model has been in on-line calculation mode since 2004 and consists of 184 components, 178 measurements and 63 variable parameters (see Figure 8). After a turbine trip event the Loviisa NPP unit 2 returns to full power. Following the event, a difference appeared between the physical model and actual measurements from a pressure sensor (see Figures 9 and 10).

Operating staff suggested two possible scenarios, either a fault in the instrument or a valve stuck half closed. The two scenarios were modeled and tested to see which would result in the better fit to the available data. Findings determined that the faulty measurement scenario resulted in the better fit.

Subsequently, a work order was placed to check this measurement before consideration of a valve check. It was determined that the problem had been solved. This work demonstrated that physical modeling techniques can be used to help make effective maintenance decisions.

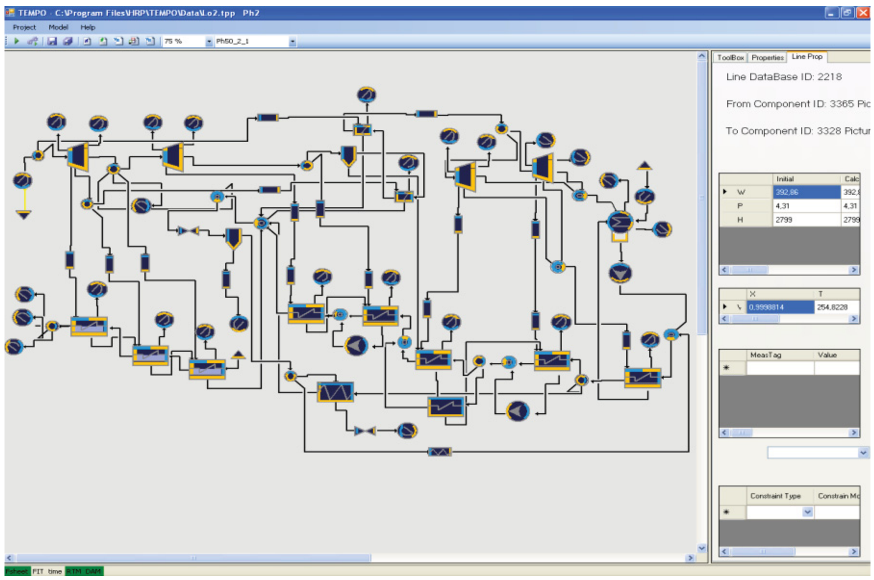


Figure 8. Screen shot of the NPP schematic.

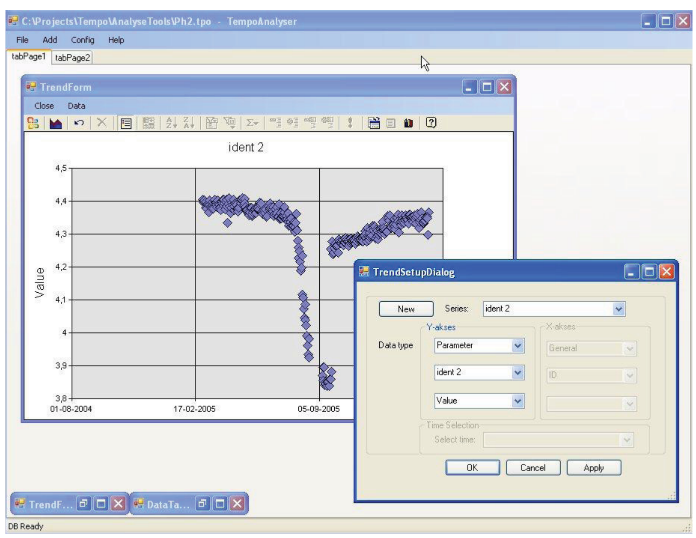


Figure 9. Tracking of a pressure measurement data.

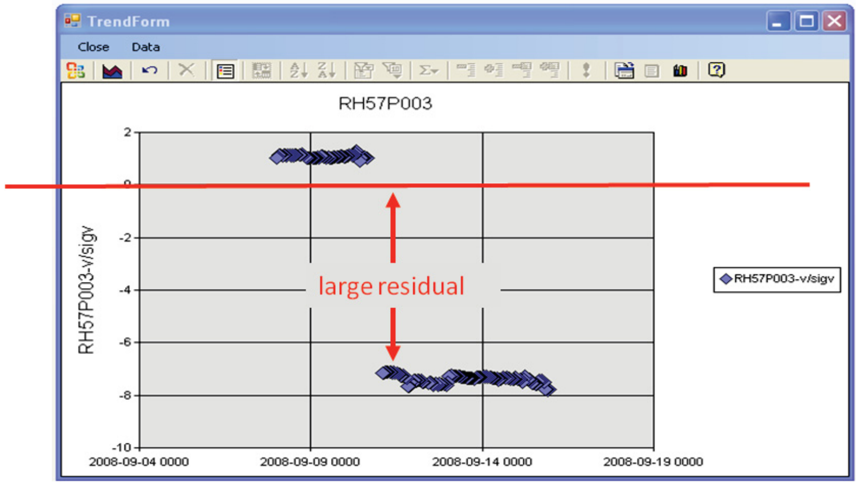


Figure 10. Correlation of the pressure sensor data with the physical model showing a large residual indicating a strong disagreement.

2.3.2 Methods for Plant-Wide Sensor Validation

Sensor Validation is a critical aspect for identifying instrumentation failures and calibration problems, which can affect the safety and economics of nuclear power plant operation. There is a significant need for on-line monitoring for sensor failure and calibration. On-line correction of degraded information is necessary as well. In order to reduce maintenance costs, calibration of the out-of-calibration instruments must occur in a timely manner. Safety may be enhanced by determining the, the availability of validated measurements.

[Editor's note: The following figures (Figure 11-Figure 15) were presented during the keynote address and provide additional clarification.]

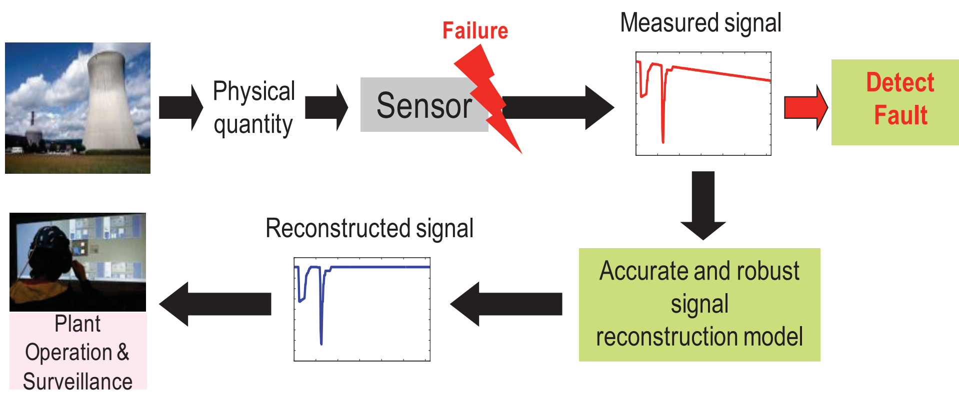


Figure 11. Sensor validation technology

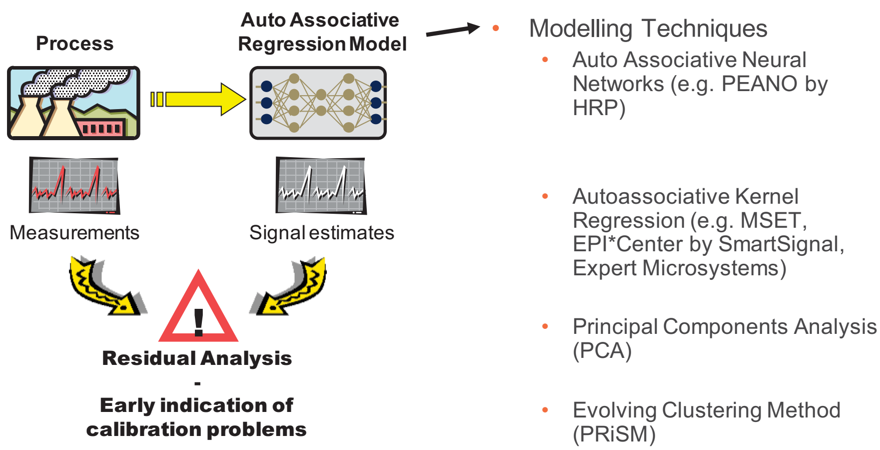


Figure 12. Sensor validation technology.

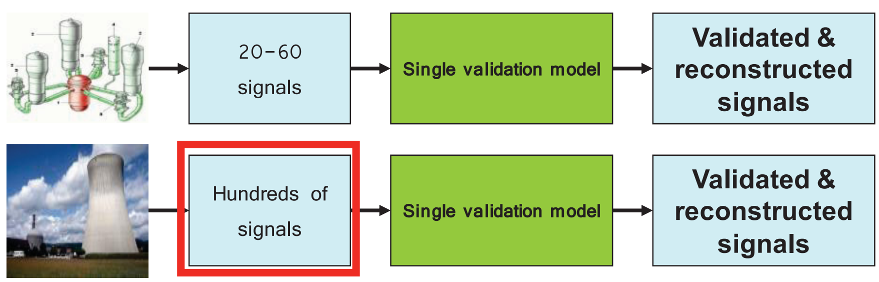


Figure 13. Large-scale sensor validation.

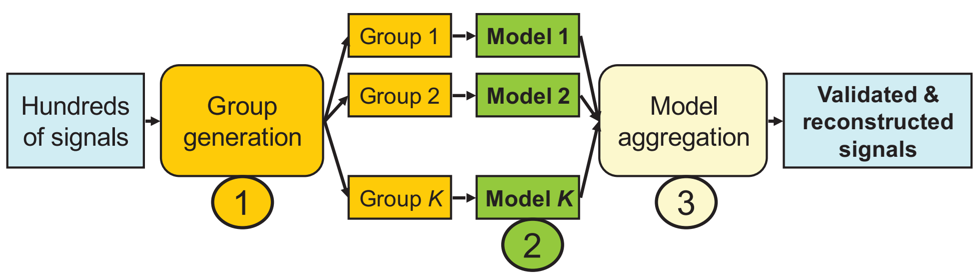


Figure 14. Multi-group ensemble approach.

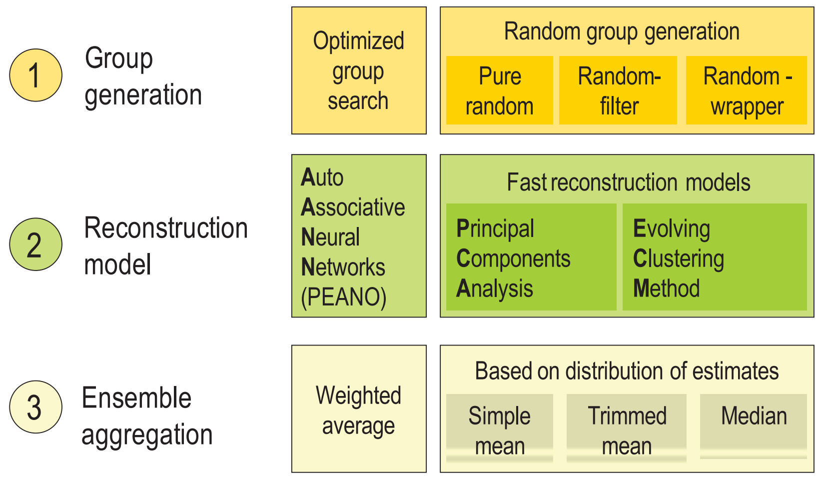


Figure 15. Multi-group ensemble approach.

2.3.3 Aging and Condition-Based models for Remaining Useful Life estimation

When deterioration and lifetime modeling are compared, results indicate that only failure times are considered. Additionally, deterioration modeling data has been shown to represent a greater amount of failure time data. The end-of- useful-life occurs when deterioration crosses a threshold. Deterioration models are required for condition-based maintenance (CBM) to be implemented.

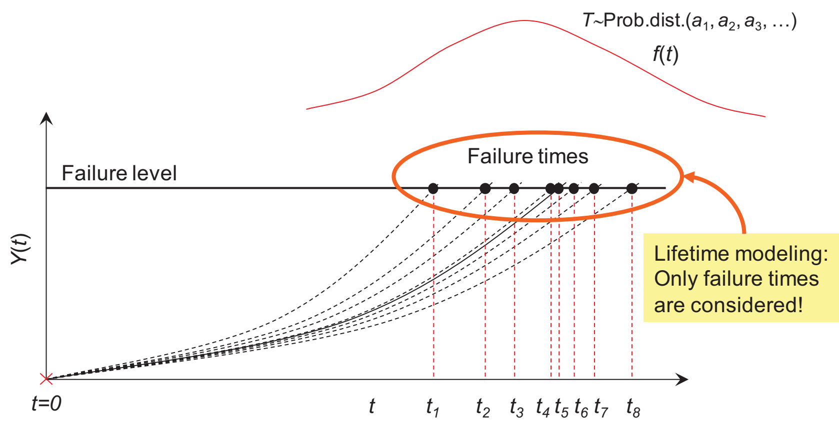


Figure 16. Defining the statistics for predicting RUL.

If the condition of the system is known, the RUL can be calculated (prognostics) using:

- General degradation path models. (Least Squares...)
- Gamma process models - Degradation is a continuous quantity.
- State space models - Degradation is discrete (good, OK, bad...)
- First principles models.

Remaining questions to be answered are

- How does the component deteriorate in average
- What is the deviation from this average path?

2.3.4 The 2012-1014 Research Program

Current research activities at the Halden Reactor Project are discussed in the following sections.

2.3.4.1 Better physical models and parameters

Many parameters used in physical models are only qualitatively determined (e.g., turbine constants, component efficiencies, etc.) and have large uncertainties associated with them. Integration of the physical models with empirical modeling could provide a way of adjusting or tuning the physical models with historical plant data to improve model fitting techniques. Additionally, it is critical to define procedures for parameter tuning with the final aim of automating model tuning.

2.3.4.2 Performance Monitoring and Optimization

Current techniques analyze a snapshot of measurements and provide methods for detecting instrument faults and some equipment faults. Time series analysis of many such snapshots can be used to reduce detection thresholds and increase the types of faults which can be detected. Methods are needed for the analysis of the data-reconciliation results to reduce the amount of expert knowledge required to utilize these techniques

2.3.4.3 Diagnostic Decision Support

Fault and anomaly detection can be performed reliably with existing techniques, either based on physical models or empirical models. The interpretation of the detected anomalies is still a manual task. New techniques are needed to support and automate the diagnostic process, e.g., the interpretation of detected anomalies including root-cause analysis and consequence analysis. These techniques will provide the ability to evaluate the use of goal-function models as well as other qualitative modeling techniques in combination with physical and empirical models to automate the interpretation of monitoring results.

2.3.4.4 Health Assessment and Prognostics

Research in the area of health assessment and prognostics aims to achieve three goals:

- Verify how enhanced instrumentation in terms of continuous measurements of degradation quantities can improve prognostics and estimates of equipment lifetime
- Investigate how empirical models can be used to improve existing technical condition indicators or define new ones
- Propose guidelines for a standard approach to assessing the technical condition of equipment (e.g., recording of operational failures, maintenance data, and inspections).

2.3.4.5 Fleet-wide Condition Monitoring

This research centers on five key areas:

- Investigation of alternative concepts for implementation of an integrated, fleet-wide condition monitoring strategy
- Creation of centralized monitoring centre with a specialized team of experts monitoring a fleet of plants with the support of computerized monitoring tools and systems
- Establishment of distributed (or virtual) monitoring organization where special expertise at different plants is coordinated to provide monitoring services to the other plants in the fleet
- Application of Integrated Operation (IO) concepts, tools, and solutions
- Adaptation of condition monitoring methods and tools to fleet-wide monitoring (including HSI designs, collaboration surfaces and solutions).

2.4 **Cable Aging Assessment**

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The interest in safety aspects of cable ageing is increasing worldwide because of the impact on several industrial fields, such as power generation, transportation and defense. Although the environmental conditions and degradation mechanisms of installed cables can be different in each application, the negative consequences of cable failures, both from a safety and performance standpoint, are so important that almost all countries in the industrialized world have some research project in progress in this area. In the nuclear field, where cables are normally qualified before installation for an expected life of 40 years, a number of issues exist for which adequately solutions have not been procured. These issues include:

- The effect of the particular adverse environment conditions (high radiation, humidity and temperature) on cables, especially during and after a Design Basis Event (DBE)
- Extending the plant life after 40 years, including the requirement to assess and qualify the cable conditions for a longer time
- Existing cable-condition monitoring techniques, which are not considered sufficiently accurate and reliable for all cable materials and types in use at their installed applications. Additionally, the bulk of theses are non-destructive techniques, not applicable *in situ*
- Accelerated ageing techniques for qualification purposes under DBE conditions, which are often not conservative and should be complemented with reliable condition-monitoring methods.

The U.S. White House National Science and Technology Council Committee on Technology issued a report in 2000 [1] in which safety issues on wire systems were addressed. The conclusions of this report are important to an understanding of the weak points of the current status and the topics which should be addressed in future research.

This keynote presentation discusses the state-of-the-art in cable ageing assessment with regard to the above-mentioned issues, limitations, and needs, with particular emphasis on the most advanced techniques for condition monitoring and residual life assessment.

2.4.1 Cable Overview

The operational environment in nuclear power plants challenges the installed electrical cables and the integrity of protective insulating jackets (a typical cable structure is shown in Figure 17). High temperatures (45 to 55°C), gamma radiation, humidity, and steam induce ageing in the cables. Long-term operation of cables in harsh environments can lead to insulation degradation and, consequently, a loss of functionality.

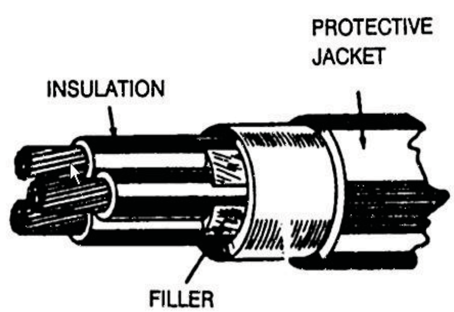


Figure 17. Structure of a typical power cable in a nuclear power plant.

Many plants that are currently in operation are approaching the end of their Qualified Life (QL). QL can be defined as the time of operation after which the equipment has been demonstrated to perform satisfactorily during and after a subsequent DBE test. A Qualified Condition (QC) can be defined as the level of degradation (given as a condition monitoring [CM] indicator value) due to aging at which the equipment has been demonstrated to perform satisfactorily during a subsequent DBE test.

The consideration of plant-life extension for another 20 years of operation brings up the question of the assessment of aging components, including cables. Recent events in operating nuclear power plants suggest that some cables may be in worse condition than had been expected. The worse-than-expected cable condition has motivated the need for a cable ageing program.

2.4.2 Cable Qualification

Environment-qualified (EQ) safety cables must be operable at the end of their qualified life, during and after a LOCA accident, in order to support the actions required to bring the plant to a safe shutdown condition. To qualify an EQ safety cable, a process of accelerated thermal and irradiation ageing followed by testing is performed on cable samples.

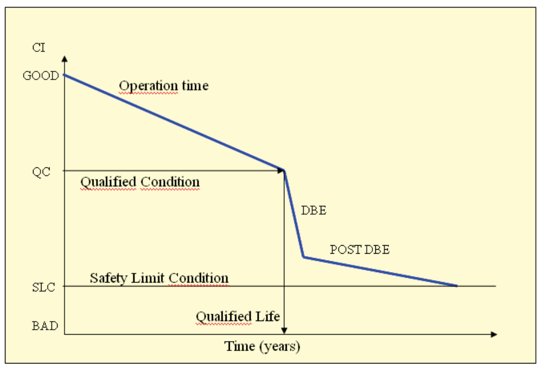


Figure 18. Qualifying the end-of-life of a cable.

The qualification processes begins by bringing a cable sample to an ageing condition equivalent to the cable's condition after a desired period of time, assuming the thermal and irradiation aging existing during normal operation. The cable sample is exposed to harsh environmental conditions, equivalent to those existing during a loss of coolant accident (LOCA). The cable is then subjected to a withstand-voltage test to verify that it is capable of performing its function. Other evaluation tests, like insulation resistance, are also performed at this time. The Arrhenius equation for accelerated aging demonstrates the relationship between time and temperature in thermal aging as shown here:

– — — (1)

where

t_s = Service time

t_a = Accelerated aging time

T_s = Service temperature (K)

T_a = Accelerated aging temperature

A number of uncertainties in qualified life may be determined from artificial accelerated aging such as:

- Uncertainty in activation energy values

- Non-Arrhenius behavior when test temperatures exceed threshold values (insulation dependent)
- Effect of simultaneous exposure to several degradation agents (e.g., radiation or temperature)
- Non-uniform conditions in the environment parameters (hot spots)
- Severity of environmental parameters during normal operation
- Number of samples used in type testing
- Test uncertainty (small volume chambers).

Advantages of the QC approach include:

- There would be no dependence on such uncertainties as activation energy, environment conditions, dose rate effects
- When the cable is exposed to milder environment conditions, it can justify operation beyond qualified life.

A Condition Monitoring technique is needed for the QC approach. Current Condition Monitoring Techniques include:

- Visual inspection (always good)
- Elongation at break (destructive)
- Indenter (local, in-situ, on-line)
- Oxidation induction time (OIT) (local, laboratory)
- Insulation resistance (in-situ, off-line)
- Time domain reflectometry (TDR)(in-situ, full-length)
- Infrared spectroscopy (local, laboratory)
- Ultrasound (in-situ, off-line, local)
- Nuclear magnetic resonance (NMR)(local, laboratory)
- Line resistance analysis (LIRA) (in-situ, on-line, full-length).

2.4.3 NKS WASCO Program

The NKS WASCO Program (2009) operates in collaboration with Ringhals AB, Forsmark AB, KTH and Wirescan AS. The program exists to assess the performance of three current condition monitoring techniques to estimate the condition of ethylene propylene diene monomer (EPDM) insulated cables (Lipalon low voltage) in thermal aging degradation (global aging). Three methods have been tested under the NKS WASCO program – elongation-at-break (EAB), indenter, and the line resonance analysis (LIRA). Three types of low voltage Lipalon cables have been aged at 140 C corresponding to natural thermal aging at 45 C between 0 and 60 years. There are ten samples for each cable type to cover the entire time interval 0-60 years. The EAB readings are averaged from 3 measurements while the indenter readings are averaged from ten measurements, and three averaged scores make up the LIRA readings.

2.4.3.1 Elongation-at-break

EAB is the strain on a sample sufficient to cause it to break. This usually is expressed as the percent of elongation achieved at the instant the sample breaks. Figure 19 shows a schematic of the equipment used to test EAB while Figure 20 shows EAB of materials as a function of exposure to excess heat.

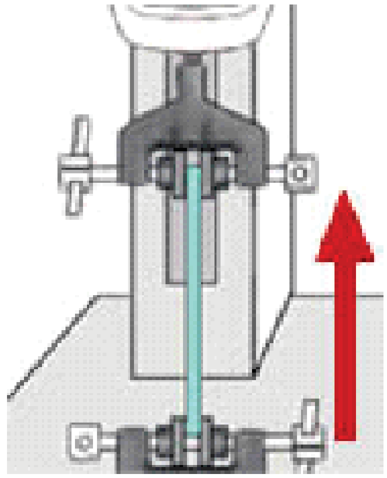


Figure 19. Cable elongation bench.

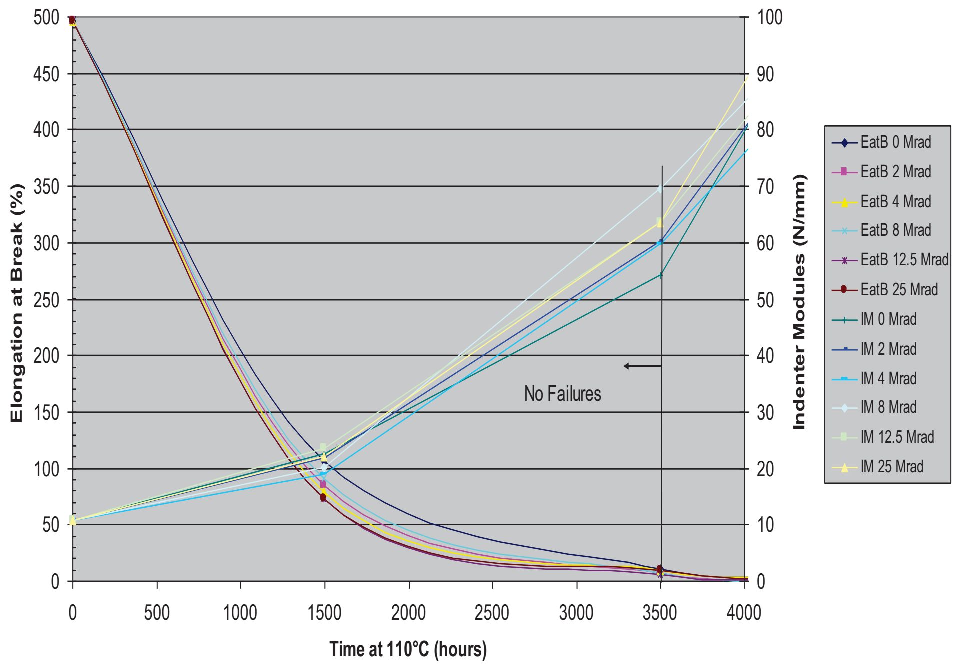


Figure 20. Cable elongation-at-break characteristics as a function of time held at elevated temperatures.

2.4.3.2 Indenter Modulus

The surface hardness of both jacketing and core insulation is monitored by micro-indentation. A sharp indenter is pressed against the surface at constant velocity, and the force is recorded as a function of penetration depth. The slope gives the indenter modulus with the unit N/mm

2.4.3.3 The Line Resonance Analysis method

LIRA was developed by the Institutt for energiteknikk (Institute for Energy Technology, IFE), Halden, Norway and a new company, Wirescan AS, was founded in 2005 to further develop and market the product. In 2005, IFE contacted EPRI concerning the use of LIRA. By mutual agreement, EPRI and IFE chose to explore the use of LIRA for nuclear cable applications. EPRI developed specimens with localized thermal damage that caused hardening of the cable materials but did not cause cracking of the insulation, and IFE brought their equipment to EPRI and tested the samples to determine if LIRA could identify and locate the thermal damages to the otherwise undamaged cables. LIRA successfully identified and located the damaged segments of the cables, both when cables were tested individually and when connected in series. Given the success of this proof of principles effort, EPRI chose to fund a larger, more formal effort to test the capabilities of LIRA to identify cuts, gouges, and thermal aging. This section highlights the results of the larger program that began in 2006 and was completed in April 2007.

Two basic types of thermal and radiation aging of cables are of concern at nuclear power plants: Bulk aging where an entire room or space within a plant has elevated temperature or radiations conditions, and local aging where a localized heat or radiation source such as a pipe is close to a cable tray or conduit. Identification of bulk area conditions are generally fairly easy in that the temperature or radiation levels in an entire room are known with a reasonable level of precision. Localized aging is somewhat more of a problem in that identifying all possible localized adverse conditions is time consuming and somewhat difficult. In addition, determining whether the localized condition has significantly affected a cable may be difficult if the cable is located inside a conduit or located in a tray that requires scaffolding or other access means to allow the condition to be assessed. Accordingly, a means of assessing the condition of a cable from its terminations by electrical means is desirable.

Until recently, the changes in the electrical characteristics of low-voltage insulations caused by thermal and radiation damage have been too subtle to be detected electrically from the terminations until the damage is so severe that cracking or powdering has taken place. Even at that point, good insulation resistance readings may occur as long as the insulation remains dry and the circuit is not physically disturbed. Accordingly, aging characterization methods have concentrated on mechanical and chemical properties. Tests such as the indenter measure modulus (a form of hardness), and many chemical tests are available for laboratory assessment. Depending on the type of insulation and jacket polymers, thermal and radiation aging causes chemical changes in the material that can be easily measured and compared to trending data from accelerated laboratory aging. These tests are useful when the surface of the cable is accessible or the insulation can be evaluated at the terminations. They cannot be used for cable contained in a conduit unless the cable is pulled out.

The advent of LIRA has provided a means to detect thermal and radiation damage to cables because it can detect small changes in electrical properties of insulation materials on the order of 1 pf. This detection capability allows localized and bulk thermal aging to be identified well before the material has aged to the point of cracking or powdering. The tests described here indicate that LIRA can identify damage below the point where a cable can no longer pass a LOCA test. The results also indicate that trending of the severity of damage is possible if LIRA tests are performed periodically.

The results indicate that LIRA may be used to assess the condition of cable circuits that traverse multiple rooms with different environmental conditions and circuits with intermediate termination points, such as splices and terminal blocks. LIRA will also be a useful troubleshooting tool if there is a concern that significant installation damage has occurred. The tests proved that LIRA can identify cuts and gouges in the insulation system and identify thermal or radiation damage. While this research used 30.5 m (100 ft) cables, other assessments performed by IFE have evaluated much longer cables and, in one case, a 128 km (~78 mile) undersea cable.

LIRA presents a significant addition to the tools available to evaluate cable condition and aging. Because the system allows the location of the adverse condition to be identified, the position of the hotspot along the length of a cable circuit can be reviewed to determine if a heat or radiation source is present or if another damage type is present in the cable. Conversely, if a heat source is identified adjacent to a conduit system, LIRA may be used to determine if significant damage has occurred adjacent to the source.

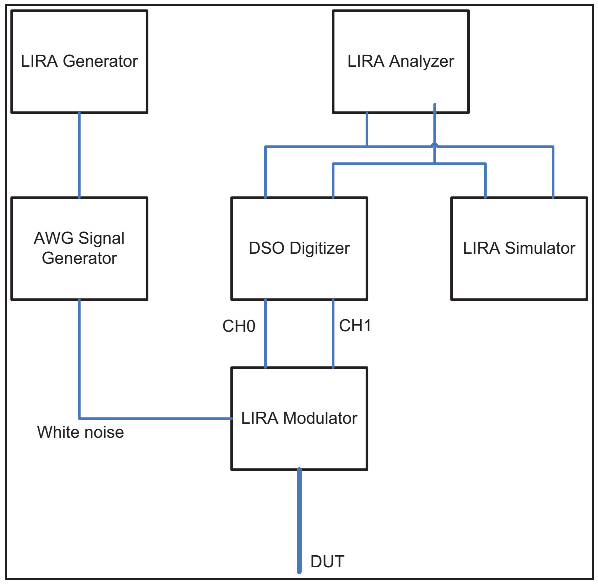


Figure 21. The LIRA approach to cable analysis

As a cable ages thermally, the dielectric capacitance increases (EPDM 2009). The capacitance characteristic is shown in Figure 22 for a cable that has experienced 140 hours of accelerated ageing at an elevated temperature of 140 degrees C.

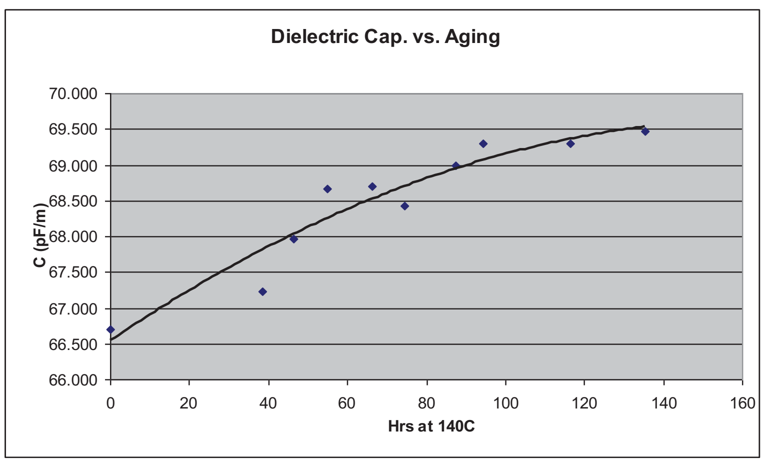


Figure 22. LIRA measurements showing change in cable capacitance over thermal ageing.

For the Global Condition Assessment, high frequency attenuation can be used as an indicator. The high frequency amplifies the effect of C and L on the attenuation (a = 0.5-1.1, depending on cable type). Attenuation is a combined effect of C, L, the cable resistance (including skin effects) and power losses (including radiation). Both the C (more) and the L (less) are sensitive to thermal and irradiation aging.

–

–

where α is the attenuation. Gamma irradiation and temperature spot effect on EPR/XLPE low voltage cables have been studied in a collaborative work between Waseda University (Tokyo), IFE and Wirescan (Norway). The effect on LIRA measurements of combined irradiation and temperature spots were studied in a report issued in November 2009. Seven cable samples (EOR and XLPE types) were artificially aged in different conditions and then analyzed with LIRA. The final report is available at Waseda University and inside the SCAP Database.

2.4.4 Conclusions

A number of conclusions can be drawn from the research done by IFE at Halden. First, a clear need has been established for the monitoring of cable conditions and the residual life of cables if plant life extension is to go forward, particularly in light of the effects of component aging. Second, the Halden cooperative effort with EPRI in testing the capabilities of LIRA show that a number of unresolved issues must be addressed by international research initiatives. The efficacy of current testing techniques is strongly suggested by a good correlation between EAB, the indenter and LIRA in global thermal-aging experiments on EPDM insulated cables showed (NKS-WASCO-2009). Finally, hot spot detection of combined gamma irradiation and temperature degradation was studied with good results using LIRA on EOR and XLPE cables (Waseda University- IFE/Wirescan).

REFERENCES

[1] National Science and Technology Council Committee on Technology, “Review of Federal Program for Wire System Safety”, U.S. White House, November 2000

3. WORKING GROUPS REPORTS

Three working groups met separately, in parallel, to discuss current limitations, potential issues that could affect long-term plant operation, and needed research in the following areas:

2. Breakout 1: OLM Implementation and Regulatory Issues – Dr. Hash Hashemian, Chair
3. Breakout 2: Diagnostics and Prognostics Technologies – Dr. Wes Hines, Chair
4. Breakout 3: Centralized OLM Strategies and Technologies – Mr. Ramesh (Rudy) Shankar, Chair

These areas were previously discussed with asset-owner representatives and were agreed upon as topics to serve as an initial point for an R&D focus for long-term collaboration and planning for implementation of OLM. Each group was assigned leaders and facilitators to motivate discussion and exploration of the issues, and each group was asked to report back to the larger workshop participant group on the following:

- **Outcome Statement.** The vision for the desired situation needed to achieve safe and efficient operation of nuclear energy systems using digital I&C systems. When considering a scenario of long-term operation (i.e., beyond a period of 60 years of operation), what is this vision as it relates to the particular technical area?
- **Capabilities.** A description of what is needed to achieve the outcomes. This includes technical advances that enable the vision, or it may address limitations or perceived shortcomings with the status quo regarding the technical area (e.g., fix, replace, reduce, etc.).
- **Critical Needs and Priorities.** Activities and outcomes that must be completed or achieved. This could include removing barriers and current limitations, demonstrating a new technology or approach, and implementing the time frames and sequencing of activities to establish priorities for research.
- **Suggested Activities and Pathways.** Potential means to achieve the outcomes or objectives. Participants were encouraged to recommend some of the potential means to achieve the outcomes or objectives that they identified. These were intended to illustrate and shape expectations for what asset owners considered successful outcomes of research and development projects.
- **Assumptions.** Suppositions or conditions that are needed in order for a proposed technical solution to achieve its desired effect. For example, one assumption that was discussed was whether current advanced LWR digital I&C licensing efforts may facilitate future introduction of digital I&C technologies into currently operating plants.
- **Technology Gaps.** Gaps in current technology capabilities that are, or could become, barriers to success in digital I&C technology integration. On the basis of discussions regarding capabilities and priorities, working groups were asked to identify these gaps, including the availability of needed technologies in the time frames desired, market factors (e.g., the ability to qualify a potential type of technology for nuclear applications), decision-making factors (e.g., the knowledge and confidence to make decisions regarding new technology introduction), and others that could be addressed through a program of collaborative R&D.

Each of the working groups addressed some aspects of these ambitious goals, and those discussions are summarized in the following section.

3.1 Implementation and Regulatory Issues

Dr. Hash Hashemian
AMS, Knoxville, TN

3.1.1 Introduction

Online monitoring technologies for equipment and process condition monitoring, diagnostics and prognostics have been under development for over 20 years. These technologies are applicable to both active and passive components, as illustrated in Figure 23and Figure 24. At the most basic level, active components are those that move, and passive components are those that do not. This is a simplification; some passive components move, and some active components never move.

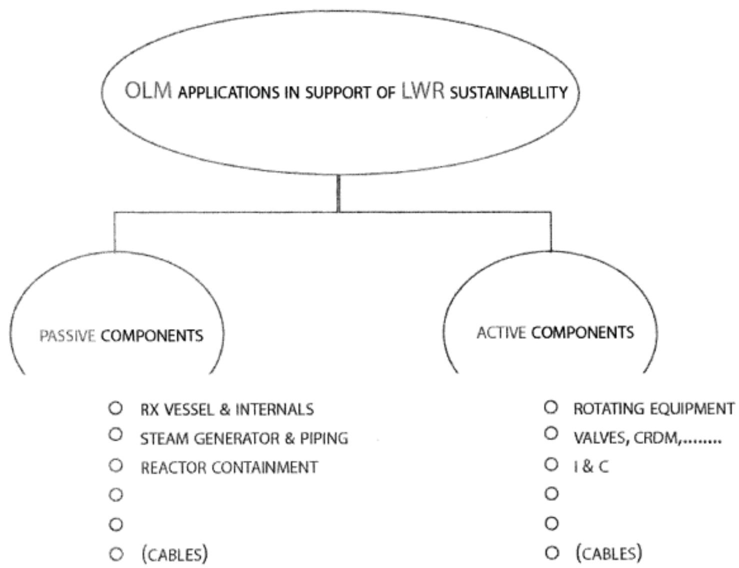


Figure 23. Division of SSCs into active and passive components for online monitoring purposes.

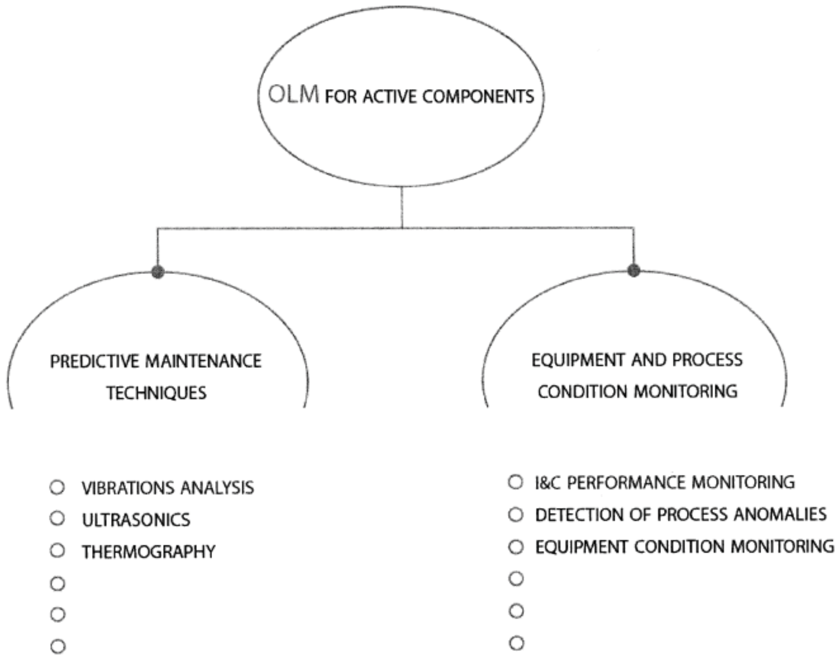


Figure 24. Technologies for Online Monitoring of Active Components.

OLM technologies for active components have come a long way, but passive component technologies are still at developmental stages. For example, there are no reliable sensors for online measurement of material properties that can be correlated to degradation. More importantly, we do not know what parameters can be measured online and correlated to material condition. There are ways to test material conditions like thickness or crack growth, but none of these methods can be applied remotely, *in-situ*, or online. Online monitoring refers to the ability to measure a parameter remotely in an active plant and correlate the results to the condition of the equipment, material, or process from which the parameter originated. During online monitoring, the plant can be at any mode of operation, including shutdown, start up, or normal operating condition.

Methods exist, e.g., vibration analysis, that lend themselves to online monitoring, and these methods have been used for over three decades. With this in mind, the focus of this report is on online monitoring techniques that go beyond vibration analysis. For example, existing data from nuclear plant temperature and pressure sensors can be used while the plant is operating, not only to measure the process temperatures and pressures, but also to verify the performance of the sensors themselves and identify certain anomalies in the process. For example, the calibration of NPP temperature and pressure sensors can be verified using the existing output of these sensors. This has been done at the Sizewell B nuclear power plant in the UK. The work at Sizewell B draws from the work of DOE, EPRI, and NRC and was conducted by AMS Corp. under a commercial contract with British Energy (BE). The U.S. nuclear industry has also used the online monitoring concept to verify the calibration of its sensors, but this implementation has been limited to temperature sensors in the primary coolant system of pressurized water reactors (PWRs). In July 2000, the U.S. Nuclear Regulatory Commission (NRC) approved the online monitoring concept for calibration verification of nuclear plant pressure transmitters, but U.S. nuclear power plants have not taken advantage of the NRC approval. As a result, no U.S. plant is formally using the online monitoring approach to extend the calibration interval of its pressure, level, and flow transmitters as is done at Sizewell B in the UK. The NRC approval is, of course, for safety-related transmitters (also called tech spec sensors). For non-safety-related sensors, regulatory approval is not needed; nevertheless, the U.S. nuclear industry does not even use the online-monitoring technology for non-safety related sensors.

The main reason for the slow implementation of OLM technologies in U.S. nuclear power plants is economics, marketing, and regulatory constraints. In particular, those who have developed OLM for nuclear power plants have not done an effective job marketing these technologies to utility executives, and a compelling cost/benefit analysis has never been done to entice the U.S. nuclear industry to take advantage of OLM technologies. BE has demonstrated that OLM can save the plant $50 million a cycle in return for a $5 million dollar investment in OLM implementation. As a result, OLM is used routinely at BE's Sizewell plant and will be expanded to cover more equipment and processes. U.S. nuclear power plants can realize as much benefit if utility executives are educated on the merits of OLM and its capabilities for plant safety, economy, aging management, and sustainability. Regulatory constraints also affect adoption: although the NRC has approved OLM, each plant must apply to NRC individually for a license amendment to use OLM for any safety-related sensors. To facilitate these requirements, the nuclear industry formed a working group in the fall of 2008 to apply for a generic license to use OLM in nuclear power plants. This effort is still underway and its final outcome is yet to be realized.

During the breakout session of the workshop, four important slides on the subject of OLM implementation and regulatory issues were presented and discussed. The contents of the slides are shown in the following four tables and explained below. Table 2 shows that many of the existing sensors in nuclear power plants are amenable to various OLM applications, especially if their signals are sampled fast (1 KH or more).

Table 2. Existing nuclear power plant sensor technologies amenable to OLM applications.

Service	OLM Static Analysis Applications			OLM Dynamic Analysis Applications			
	Calibration Monitoring	Cross-Calibration	Equipment Condition Assessment	Dynamic Response	Integrity of Reactor Internals	Core Flow Anomalies	Residual Life of Neutron Detectors
Reactor Coolant System Flow	✓			✓		✓	
Steam Generator Level	✓			✓			
Pressurizer Level	✓			✓			
Pressurizer Pressure	✓			✓			
Steam Flow	✓			✓			
Feedwater Flow	✓			✓			
Turbine Impulse Pressure	✓			✓			
Reactor Building Pressure	✓						
Reactor Coolant System Pressure	✓		✓	✓		✓	
Refueling Water Storage Tank Level	✓						
Reactor Coolant System Hot Leg Temperature	✓	✓	✓	✓		✓	
Reactor Coolant System Cold Leg Temperature	✓	✓	✓	✓		✓	
Core Exit Temperature	✓	✓	✓	✓	✓	✓	
Reactor Coolant Pump Seal Injection Flow	✓		✓	✓			
Volume Control Tank Level	✓		✓				
Chemical Volume Control System Letdown Flow			✓	✓			
Chemical Volume Control System Charging Flow			✓	✓			
Reactor Power	✓		✓		✓	✓	✓
Generator Output			✓				
Feedwater Temperature	✓		✓	✓			
Condenser Pressure	✓		✓	✓			
Reheater Outlet Temperature	✓		✓	✓			
Condenser Cooling Water Inlet Temperature	✓		✓	✓			
Reactor Vessel Level Indication System (RVLIS) Delta Pressure	✓			✓	✓	✓	
In Core Temperature				✓	✓	✓	

Table 3 summarizes the OLM implementation requirements that a user must develop in an OLM system for a nuclear power plant.

Table 3. OLM sensor requirements for selected applications.

OLM Applications	Plant Condition(s)	Sampling Period	Data Analysis Algorithm
Calibration Monitoring	Startup, Steady-State, Shutdown, Outage	10 to 60 seconds	Averaging Physical Modeling Empirical Modeling
Cross-Calibration	Startup and Shutdown	1 to 10 seconds	Averaging
Equipment Condition Assessment	Steady-State	60 seconds	Physical Modeling Empirical Modeling
Dynamic Response	Steady-State	0.001 second	Fast Fourier Transform Power Spectral Density Autoregressive Model
Reactor Internals	Steady-State	0.01 second	Fast Fourier Transform Power Spectral Density Cross Correlation
Core Flow Anomaly Detection	Steady-State	0.001 second	Cross Correlation
Neutron Detector Life Extension	Steady-State	0.001 second	Fast Fourier Transform Power Spectral Density Autoregressive Model

Table 4 shows the potential gaps in areas of OLM implementation in nuclear power plants. The gaps are broken down in terms of technical gaps or commercial gaps. Where a gap is being addressed, a checkmark is used in the table to indicate that the issue is under investigation and shall be resolved soon. When the need is still lingering, a cross is used in this table to show that the problem needs more work.

Table 4. Potential gaps in OLM implementation in nuclear power plants.

Gap	Technical	Commercial	Status
Qualification Algorithms and Software for Data Preprocessing	✓		✓
Diagnostics and Prognostics Algorithms and Software	✓		✗
Uncertainty of Modeling Techniques	✓		✗
General Licensing of OLM for Safety Related Applications	✓		✗
Validation of Modeling Techniques	✓		✓
Wireless Applications for OLM	✓		✗
Marketing		✓	✗
Implementation Experience		✓	✗
Cost/Benefit Analysis and Payback Schedule		✓	✗
Threat to Technicians		✗	✓
NRC Questions		✗	✓
Standards and Guidelines		✗	✓

Table 5shows a sample of standards, requirements, and guidelines that already exist for OLM implementation in nuclear power plants.

Table 5. Sampling of existing standards, requirements and guidelines for OLM implementation in NPP.

Test Requirement	**Test Method**	**Related Regulation/Standard**	**Related IAEA Guidelines**	**NUREG/CR**
In-situ response time testing of temperature sensors	LCSR Method	NUREG-0809 ISA Standard 67.06 IEC Standard 62385 IEC Standard 62342	IAEA TECDOC-1147 IAEA TECDOC-1402	5560
On-line measurement of response time of pressure transmitters	Noise analysis technique	Reg. Guide 1.118 ISA Standard 67.06 IEC Standard 62385 IEC Standard 62342	IAEA TECDOC-1147 IAEA TECDOC-1402	5857
On-line detection of blockages, voids and leaks in pressure sensing lines	Noise analysis technique	Reg. Guide 1.118 ISA Standard 67.06 IEC Standard 62385 IEC Standard 62342	IAEA TECDOC-1147 IAEA TECDOC-1402 IAEA Nuclear Energy Series NP-T-1.2	5501
In-situ/on-line calibration of temperature sensors	Cross calibration technique	NUREG-0800 NRC SER (July 2000) ISA Standard 67.06.01 IEC Standard 62385 IEC Standard 62342	IAEA Nuclear Energy Series NP-T-1.1	5560
On-line calibration monitoring of pressure transmitters	OLM technique	NUREG-0800 NRC SER (July 2000) ISA Standard 67.06.01	IAEA Nuclear Energy Series NP-T-1.1	6343
I&C aging management	LCSR Noise analysis Cross calibration OLM	IEC Standard 62385 IEC Standard 62342	IAEA TECDOC-1147 IAEA TECDOC-1401 IAEA Nuclear Energy Series NP-T-1.2	5501
Predictive maintenance of reactor internals	Noise analysis technique	ANSI/ASME OM-5-81	IAEA Nuclear Energy Series NP-T-1.2	5501
Neutron detector life extension	OLM, Noise analysis technique	IEC Standard 62385 IEC Standard 62342	IAEA TECDOC-1147 IAEA Nuclear Energy Series NP-T-1.2	5501
Cable testing	IR, LCR, TDR, LCSR	IEC Standard 62465 IEC Standard 62582	IAEA TECDOC-1188 IAEA TECDOC-1147 IAEA TECDOC-1402	

OLM has been used in the U.S. nuclear industry, primarily on a demonstration basis, although it has been successfully implemented in other countries, even for safety-related applications. For example, BE has implemented it for transmitter calibration-interval extension, sensor response-time testing, resistive temperature devices (RTD) cross calibration, reactor internal vibration monitoring, detection of sensing-line blockages, transit time flow measurement (TTFM) system, core-flow anomaly detection, loose parts monitoring.

Past experiences point to the potential benefits of OLM for instrumentation. For example, OLM could have caught two instrumentation problems at Calvert Cliffs. The first problem was a blockage in the sensing-line in the lube oil system of the emergency diesel generator. After a dual unit trip, the emergency diesel generator came online, then tripped due to lube oil sensing line blockage. The second problem involved a partial sensing line blockage, which created local corrosion leading to secondary side leak.

Successful collaboration is necessary for the success of OLM. The Nuclear Power Life Extension Demonstration Project (NPLED) involving technical issues for Life Beyond 60 is an example of this type of collaboration. Current NPLED collaborators include Constellation, EPRI, and the INL.

In order to ensure the critical success of OLM, sufficient marketing of OLM to utilities must be carried out. The safety and cost benefit ratio of OLM must be demonstrated to utility executives along with the demonstration of safety benefits to the NRC management. OLM is currently being demonstrated at ATR, HFIR and the OPAL reactor in Australia. DOE shall subsidize and facilitate this utility acceptance and use. Additionally, university research reactors could prove useful for gathering more evidence. In the US, OLM is currently being demonstrated in U.S. nuclear power plants located in Farley, AL, and North Anna, VA.

There are a number of recommendations for consideration to further OLM development. The first is to create a coordinated approach to use OLM at research reactors and demonstrate it to utilities and regulators. Another recommendation is the implementation of OLM at a U.S. plant at a low cost. Next, increasing the rates of demonstrations over multiple operating cycles to build a history promises to further OLM success, as does publishing EPRI report results. Additional recommendations include establishment of a Memorandum of Understanding (MOU) for OLM between EPRI, DOE, and vendors (like light water reactor sustainability MOU) and engagement from Rick Reister of DOE and John Gaertner from EPRI on the OLM development.

3.1.2 Current State

The current state of the NPP with respect to OLM implementation and regulations issues is summarized as follows:

- The existing U.S. fleet of NPP has an age range from 14 to 40 years and a median age of 22 years. A need exists to extend the operating life of the fleet by 20 or more years. At the time that the plants were built, OLM technologies were abstract research ideas. As a consequence, OLM technologies would be a retrofit for the plants.
- The body of knowledge is approaching the critical mass for implementation of online monitoring technologies for optimized maintenance and aging management of nuclear plant equipment.
- Prognostics and diagnostic tools have been developed for other industries. Computational abilities and resources are at a sufficient technical level.
- OLM has been implemented by the international nuclear power industry, but generally not in the U.S. DOE's NGNP program is driving advanced online monitoring.
- The U.S. nuclear power industry is generally not aware of the potential safety, reliability, and cost benefits of utilizing OLM.
- Specific licensing criteria for OLM do not exist within the NRC.

- Opportunity exists to move OLM knowledge from fossil fuel plants to nuclear plants.

3.1.3 Desired State

Current expectation is that OLM technologies have a widespread implementation in NPPs in twenty years. In order to achieve this, the NRC licensing process with respect to the use of OLM technologies should be accepting of OLM technologies. The NRC will be trained on the benefits and pitfalls of various OLM implementations and will develop acceptable guidance, criteria, tools, and procedures for addressing licensing applications containing OLM implementations and procedures. OLM will be integrated into probabilistic risk assessment (PRA).

In addition, the desired state of the industry is envisioned as having achieved the following:

- Widespread implementation of OLM technologies in nuclear power plants. Plants are well instrumented, and sensors operate on secure wireless system. Existing reactors have been retrofitted with OLM technology for both active/passive components.
- OLM systems reduce work load, save money, and are credible. Time-based maintenance is replaced with performance-based OLM systems. Acceptance measures exist for reliability, safety, and security of OLM. Operators support OLM on non-safety related systems. OLM shifts the equilibrium in human condition; human performance factors are enhanced as a result of increased technology.
- OLM is integrated into PRA at the system level. “Aging Management” is proven without intrusive measures (OLM, prognostics). Formal and standard methods exist to develop Verification and Validation (V&V). Redundant OLM systems are utilized.
- New generation reactors are designed with built-in ability for OLM. Integration between designers and operators is achieved. Turn-key OLM is a part of new standardized plants. Good communication and a high level of understanding exist.
- Streamlined procedures are in place to update plants and stay current with the newest OLM technologies. Systems are adaptable to improvement.

3.1.4 Assumptions

The working group established the following supportive assumptions:

- A large percentage of sensor calibration and sensor preventive maintenance is not necessary and often causes additional problems. Mistakes performed during maintenance can lead to plant trips. Technicians are doing calibrations and other maintenance procedures that are disrupting plant operations.
- The calibration period for safety related (technical specifications) equipment could be increased with effective implementation of OLM.

3.1.5 Issues and Barriers

The group noted and agreed that the comments in the following subsections represent issues and barriers that discourage NPPs in adopting OLM technologies.

3.1.5.1 Regulatory

NRC documentation NUREG-1801 discusses plant life extension issues with respect to licensing. Currently, life extension of 20-years has been considered, but extension beyond this has yet to be. The group was reminded that the NRC does not license techniques nor regulate Best Practices for safety-related system. The NRC will not and cannot mandate the use of OLM for existing or new plants. The NRC is interested in understanding how OLM can benefit safety components and systems.

- Industry's attitude towards the existing plant I&C design basis can be summarized as follows: current plants are safe enough now; OLM may not be needed.
- Questions exist on the level at which OLM is to be utilized: for non-safety related components and systems solely, for improving the availability and reliability of safety-related systems, or as an integrated part of the safety related components and systems.
- Utilities perception on the cost/benefits of working through the renewal application process with OLM as part of the safety-related systems is telling. Utilities are faced with limited staff, lack of successful examples, and no real perceived need.
- NRC will need the I&C industry and utilities to quantify the uncertainty bounds associated with OLM and to present evidence of the effectiveness of predictive maintenance technologies and condition monitoring on plant equipment and process.
- NRC has not incorporated OLM in PRA methodologies. Regulators need quality data on performance monitoring, detection of process anomalies, and prediction of equipment failures.

3.1.5.2 Technical

Technical issues that complicate the regulator and business issues related to OLM exist in the following areas:

- Obsolescence is the biggest challenge for I&C. Technology is rapidly changing
- Security and safety issues exist when using wireless technologies for I&C
- There is a lack of specialized sensors, such as high-temperature sensors, which face technical challenges in research and development, sustainability, or accuracy
- More hardened OLM products are needed for nuclear industry use. Vendors see the market as not big enough and are currently not interested in qualifying products for the nuclear environment.

3.1.5.3 Gaps and Research Needs

The group identified a number of gaps in implementation and regulatory issues that will need to be addressed to support the integration of OLM technologies in nuclear plants, including:

The topic of V&V for NPPs has not been addressed. V&V systems are needed right away (that is, within the next 5 years). This is needed to drive new OLM applications. Key needs include quantifying the uncertainty, defining appropriate applications, and establishing accepted measures of reliability and safety and security of the OLM system and software. One question regards uncertainty bounds and how they are quantified.

Prognostic capabilities must be developed and integrated into the PRA at the system level. Standardized PRA processes and methodologies are essential.

Formal methodologies for software development are needed. A Quality Assurance program for OLM software would be implemented related to these methodologies.

Aging management without intrusive inspections is a vital goal. This will require replacing time-based maintenance with performance/condition-based maintenance and developing OLM implementations that will make life easier for power plant maintenance, reducing work load and saving money for the utilities.

Expansion of the horizon for utilities to aid in the development of a 20-years vision for OLM would allow the exploration of the possibilities of extended plant life from 80 to 100 years with the aid of OLM.

Redundant OLM, coupled with a secure wireless system, avoids the costs of wiring and modifying infrastructure, making plants easy to retrofit. Already, it is easy to verify the security of a wireless system.

Reducing barriers to open communication and initiating education between regulators, reviewers, manufactures of OLM and I&C, plant users, etc., are necessary, together with developing consistent education curriculum for OLM and providing descriptions of what OLM can realistically achieve.

Sufficient references and histories of OLM experiences must be developed. By adopting the experiences of others industries and taking advantage of NRC cooperative research with others (i.e., national laboratories and EPRI), this can be achieved. Involving the NRC early into the research and development of new OLM technologies would smooth things. Utilities should be better educated on cost/benefits, advantages, and case studies.

An I&C user facility is needed to test and demonstrate OLM concepts and technologies. Demonstrated technologies for diagnostics, prognostics, and PRA are the goal. Statistics would be gathered for the industry and the NRC. V&V and formal processes could be demonstrated at such a facility, and safety, security, reliability, and human factor issues would be demonstrated. Operational experiences and demonstrations could easily be added. Based on outcomes, business cases would be developed. The facility would then provide communications and education on experiences.

OLM technology would be demonstrated and proved by first implementing technology at the 26 research reactors in the U.S. (15 on university campus), demonstrating to the commercial NPP the successful integration of the technology to solve diagnostic and prognostic problems. OLM would be qualified and proven first on non-safety-related systems before approaching the safety systems. This would require overcoming limited funding problems for implementation on non-safety systems.

The DOE could provide guidance on OLM to the NRC. The NRC needs “Objective Acceptance Criteria” to review license application/extension requests. This criteria needs to be a standardized process. Currently, the criteria are reviewer dependent. The NRC could work with the DOE to develop a set of tools and methods to apply to reviewing a license application request. Licensees should know ahead of time what the tools and methods are. Procedures would be needed on how to use the tools and methods to ensure consistency in the application and evaluations. The DOE could support the NRC and industry by providing formal training and certification on the use of the procedures and tools.

The development, security, and acceptance of secure wireless systems for I&C is a high priority. Short - and long-term implementations could result in:

- Cost savings in materials, such as cables
- Easy retrofit for existing nuclear plants
- Easy-to-replace systems
- Easy-to-verify security and prevention of attacks
- Assurance that installation and use of wireless does not negatively impact other plant systems.

3.1.6 Suggested Activities and Pathways

The activities and pathways discussed focus on the support of some of the key capabilities discussed above. In addition to these high-priority items, other suggestions were made regarding the workforce and the ability to leverage existing technology from outside of the nuclear industry:

- Experience/demonstration
- Business case/education
- Formal processes
- Human factor issues.

The first pathway suggested by the group focuses on the need to better articulate opportunities for high-value capability insertion. An activity for this topic would be to provide a formal way of assembling constraints, criteria, and opportunities for the nuclear industry's digital systems needs (current and future) as they relate to plant operation and system control. In particular, it could be valuable to prioritize/articulate the high-return technology insertions which, if fulfilled, could provide the most benefit. Highlighted in this discussion were the institution of communication techniques with plant and utility management and development of educational materials for workforce training.

The next activity discussed was leveraging experience from other industries (i.e., the creation of a dynamic database of experience in nuclear and other areas). The team's opinion was that OLM is starting to show distinct operational-cost savings throughout several industries – that is, it is becoming a much more mature science. Now is the time to take advantage of this maturity for the nuclear industry; it could be financially advantageous. As part of this effort, one pathway should be to gather information from other industries that would leverage the lessons learned, best practices, and experiences from other fields that use similar technologies, especially from conventional fossil fuel plants.

An important support pathway suggested by the team was to identify needs for research, demonstration, testing, and evaluation for each capability. In particular, learning of industry needs and how the numerous stakeholders would benefit from a project that demonstrates the benefits of OLM to the nuclear industry would be persuasive.

Finally, several points were made on the preparation for impacts of technology modernization on the workforce. Workforce development and training elements need to be present in every aspect of research, demonstration, and evaluation of new technologies. A gap between two segments of the current nuclear field workforce seems to exist: there is a generation of very knowledgeable people regarding the plants and nuclear technology, but they are less familiar with OLM technologies. On the other hand, a new generation of workforce is very familiar with advanced I&C technologies but not with the existing plant technology. This is true within the R&D community as well as industry.

From the workforce training and impacts perspective, it is also necessary to consider the change in culture surrounding the introduction of OLM technologies. Moving to OLM in plant operations and maintenance will require a change in the way people think about I&C of components and systems.

The NRC should be invited to begin cooperative research with industry and universities. Additionally, it may prove helpful to suggest that a champion/proponent be identified, preferably a licensee or licensee owners group.

Research is needed in the following areas:

- OLM technology description
- Implementation guidance
- Acceptance criteria
- Tools and methods for licensing actions
- Procedures for reviewing applications
- Training for staff and industry on licensing process.

Utilities are expecting potential licensing uncertainties in the implementation of OLM for safety-related systems. To help address these concerns, the nuclear industry and the NRC should work together with the I&C industry, national laboratories, and universities to develop standards for OLM terminology, expectations, processes, and acceptance criteria. Specific activities for the NRC to implement include providing education and involvement with pilot projects in non-safety systems to develop NRC staff expertise, establishing workshops with NRC staff to introduce concepts and define scope of regulatory issues, and finally inviting NRC to actively monitor industry/university research efforts and test cases.

3.1.6.1 Business Case/Education

The industry, especially those decision makers within the utilities, requires education on the favorable business case for OLM. Developing the educational materials requires a collaborative effort. BE, AMS, and other utility personnel must collaborate to generate quality material for presentation to the NRC and to utility executives. Good communication with the NRC and industry leadership will be critical to success. It is recommended that:

- LWRS facilitate a high-level workshop with the DOE, the nuclear power industry, and the NRC as a way to educate all involved on the potentials of OLM
- OLM researchers and vendors develop credible cost/benefit analysis, demonstrating what OLM can do
- Examples like EQ be used to show that OLM can justify its costs by preventing equipment from being replaced prematurely.

3.1.6.2 Formal Processes

Methodologies for OLM software verification, validation, and development must be defined using formal processes. International collaborations between researchers at universities and laboratories would be supported by EPRI, NEI, OECD-NEA. New capabilities, such as benchmark facilities – e.g., OSU, UoF, and Halden – are essential. The expertise that exists in other industries, but which is very limited within the nuclear field, must be recruited and could address research needs in qualifying and measurements for reliability, safety and security, test methods, formal development methods, uncertainty evaluation, failure modes, and impact on PRA.

3.1.6.3 Human Factor Issues

Of course, it will be vital that the impact of the increased information provided by OLM on the operator awareness be evaluated, and possible human errors, identified. Research needs are seen in measures of operator workload and awareness as a function of the OLM characteristics. Control room simulators and OLM implementations would be a necessary part of these evaluations.

3.1.7 References

[1] NUREG-1801, "Generic Aging Lessons Learned (GALL) Report," April 2001.

[2] NUREG/CR-6895, "Technical Review of On-Line Monitoring Techniques for Performance Assessment: State-of-the-Art," January 2006.

[3] NUREG 0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," March 2007.

[4] Solicitation RS-04-10-456, "Advanced Diagnostics and Prognostics for Safety-Related Equipment in Nuclear Power Plants (AD&P)".

[5] https://www.fbo.gov/index?s=opportunity&mode=form&id=cf6e47e5ea7d95cfa1647b932fe99bcd&tab=core&_cview=1 4 March 2010 (retrieved 26 July 2010).

3.2 Diagnostics and Prognostic Technologies

The group developed the following definition of Diagnostics and Prognostics:

Diagnostics and Prognostics encompass the classification and identification of anomalies or faults and the prediction of remaining useful life of the system, structure, or component. Remaining useful life (RUL) is defined to be the time or other usage metric (cycles, miles, etc.) until the performance specification is no longer met.

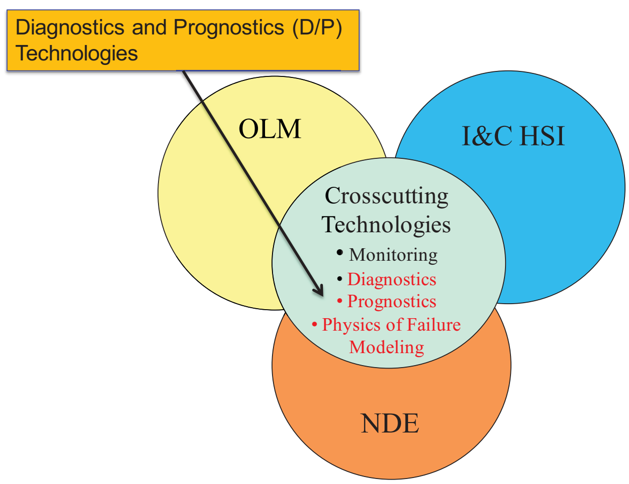
The group also developed a statement for Diagnostic and Prognostic Strategies:

Develop a standard, scalable, physical and logical infrastructure for data gathering, processing, analysis and results dissemination. This would enable centralized online maintenance solutions to maintain/improve the safety and reliability of current reactors and extend their service life in the most cost effective manner.

Presentations were given by several of the attendees starting with an invited presentation by Dr. Kai Gobel who is the director of Prognostics and Health Management for the national Aeronautics and Space Administration (NASA).

3.2.1 Introduction

Dr. Kai presented an overview of D/P technologies and a discussion of where it fits into LWRS. Included in his presentation was a summary of past reports and workshops that discussed D/P related needs. D/P technologies are crosscutting technologies across I&C LWRS R&D themes [2] (see Figure 25):



- OLM: Centralized Online Monitoring and Information Integration
- HSI: New I&C and Human System Interfaces and Capabilities
- NDE: Non Destructive Evaluation Technologies

Figure 25. I&C R&D technologies where OLM means centralized online monitoring and information integration, HSI, new I&C and human system interfaces and capabilities, and NDE, non-destructive evaluation technologies.

Condition monitoring and prognostic techniques can play an important role in increasing safety, reducing downtime, and improving the corporate bottom line. These techniques are generally components of a larger health monitoring system [3, 4]. Health monitoring systems commonly use several modules which monitor a system's performance, detect changes, identify the root cause of the change, and then predict the RUL or probability of failure (POF) (see Figure 26). The results of the monitoring and RUL estimation may be used to adjust planned operation in order to maximize RUL while minimizing the risk of failure, or to schedule maintenance to prevent in-field failure.

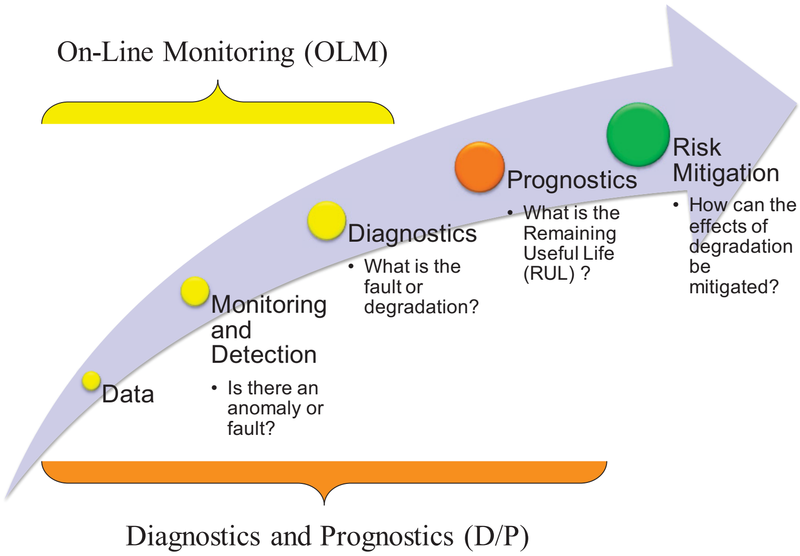


Figure 26. Pathway for OLM research and development.

Health monitoring systems commonly utilize a variety of measurements from the system of interest, including operating load information, environmental conditions, and sensed variables that may be related to system condition. A representative empirical-based monitoring, fault detection, and prognostic system is shown in Figure 27. Correlated groups of variables are used to develop a monitoring model, such as auto-associative kernel regression (AAKR), to monitor system performance. The monitoring model can be considered an error correction method, which gives the variable values expected for nominal system behavior. Monitoring system residuals are generated by subtracting the actual system behavior from the anticipated nominal behavior. These residuals are evaluated with a fault detection algorithm such as the Sequential Probability Ratio Test (SPRT) to determine if the system is operating in a nominal condition or exhibiting anomalous behavior. If a fault is detected in the system, the original data, model residuals, and detection results are used by a diagnostic (classification) system to identify the type, and in some cases, severity of the fault. The results for each previous module, together with condition monitoring, fault detection, and diagnostics, are combined to identify a prognostic parameter which can be extrapolated through a prognostic model to a predefined critical-failure threshold to make an RUL prediction.

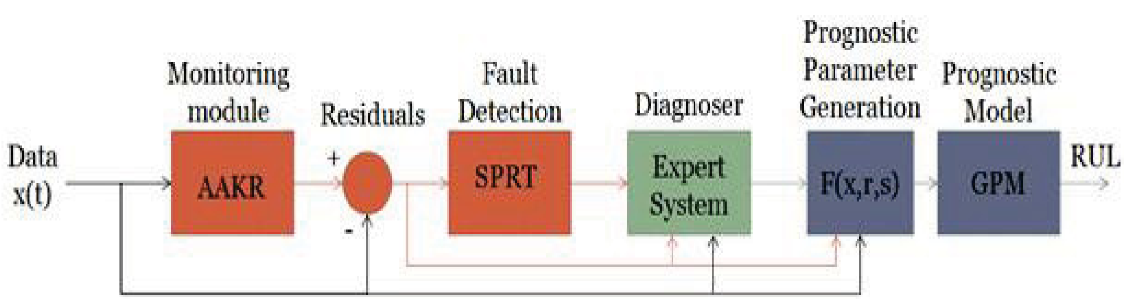


Figure 27. Traditional, multi-variable health monitoring system

Systems that perform these functions are commonly called health and usage monitoring systems (HUMS), prognostics and health management (PHM) systems, or, in transportation, vehicle health management (VHM) systems. There are two main categories of methods: empirical (data-driven) prognostics and model-based (physics of failure) prognostics, although many systems are hybrid combinations of the two. Empirical techniques are constructed from operational data and use signal processing and transformation techniques to extract information-rich features for input into a variety of models such as neural networks, nonlinear regression algorithms, and Markov Chains to name a few. Physics of failure techniques use mathematical models of the degradation mechanisms in a variety of frameworks, including Kalman filters, parameter estimation, and particle filters.

Prognostics methods can be categorized by their architecture, how they operate, the results format they produce, or through several other means. An approach that may be most instructive is to categorize them by the type of information they use. Three prognostic method types are defined this way:

Type I: Reliability Data-Based

These methods consider historical time to failure data. These data are used to model the failure distribution. The methods estimate the life of an average component under average usage conditions.

Example Method: Weibull Analysis

Type II: Stress-Based

These methods also consider environmental stresses (e.g., temperature, load, vibration, etc.) on the component. They estimate the life for an average component under the given usage conditions.

Example Method: Proportional Hazards Model

Type III: Effects-Based

These methods consider the measurable or inferred component degradation.

Example Method: General Path Model

Figure 28 provides a graphical representation of the three prognostic methods. The most common types are Type I methods, which use failure times to predict failure density functions and are the topic covered in most reliability engineering texts. If the degradation is strongly related to the operating conditions or environment, Type II prognostics can be used. Last, if a parameter or group of parameters that are related to the condition of the SSC can be measured, then Type III prognostics can be used. As one moves from Type I to Type III, the error bound variance of the RUL prediction commonly decreases making the prediction more exact.

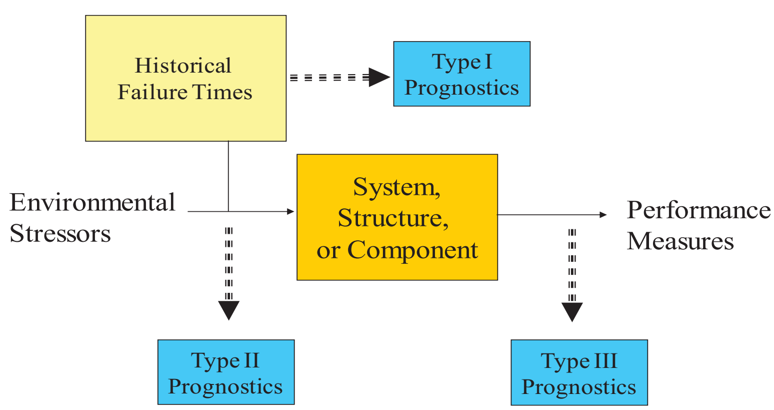


Figure 28. Prognostic method types.

3.2.2 Overview of Past DOE Workshops and Documents Related to Diagnostics and Prognostics

Several past workshops with OLM and diagnostic and prognostic (D/P) topics have been held. Additionally, several documents based on these workshops and related research have been released. This section reviews the most recent and well known workshops and documents. As will be seen these activities identified several overlapping D/P research needs.

U.S. Department of Energy, Instrumentation, Control, and Human-Machine Interface (IC&HMI) Technologies Workshop, Gaithersburg, Maryland, May 2002 [5].

The goal of this workshop was to establish the need to include instrumentation, control, and human-machine interface (IC&HMI) early in the design of Nuclear Power 2010 and Generation IV nuclear power plants. The Nuclear Energy Research Advisory Committee (NERAC) 1999 workshop report was used as a starting point and background in the current workshop discussions and as a reference point for this report that documents the workshop results and recommendations. Eight breakout groups were conducted with the D/P Breakout led by Leonard Bond and Don Jarrell, both of PNNL.

The D/P breakout identified several infrastructure needs to further the application of D/P technologies including:

- An adequate integral testing facility
- Definition of the man-machine authority split
- A well-defined protocol for documenting of process tomography
- Increased sensor accuracy under adverse environmental conditions
- D/P communication systems
- Field-hardened stressor-based sensors.

It also identified several methods-related research needs:

- Uncertainty quantification for advanced D/P methods
- Hybrid modeling
- Stressor-based first-principles D/P development
- Decoupling and recognizing the difference between control problems, process anomalies, and sensor drift
- Data fusion and data mining techniques
- Identification of minimum requirements for effective D/P.

Technology Roadmap on Instrumentation, Control, and Human-Machine Interface to Support DOE Advanced Nuclear Energy Programs, March 2007, [6]

This document was prepared by a team of researchers from national laboratories, academia, the NRC, and EPRI and was created to provide a systematic path forward for the integration of new ICHMI technologies in both near-term and future nuclear power plants and the reinvigoration of the U.S. nuclear ICHMI community and capabilities. It states that ICHMI technologies are an essential enabling element of nuclear power plant design, development, and operations. The roadmap proposed the establishment of a crosscut DOE program to address essential research on issues limiting near-term and future deployment of advanced ICHMI in current and future U.S. nuclear power plants. Topics identified included:

- Sensors and electronics for harsh environments
- Uncertainty characterization for diagnostics and prognostics applications

- Development of uncertainty analysis techniques for data-driven diagnostic models
- Development and validation of degradation models for key nuclear plant components
- Investigation of the strengths and weaknesses of advanced inverse algorithms for diagnostics
- Development of testing protocols for quantification of uncertainty in diagnostic and prognostic modules.

INPO AP-913: Equipment Reliability Process Description [7]

AP-913 is an equipment reliability process description established by the Institute of Nuclear Power Operations (INPO). The process assists INPO member utilities in maintaining high levels of safe and reliable plant operation in an efficient manner. AP-913 integrates and coordinates a broad range of equipment reliability activities to:

- Identify and evaluate critical station equipment
- Develop and implement long-term equipment health plans
- Monitor equipment performance and condition
- Make continuing adjustments/improvements to the maintenance program.

In order to develop and implement long-term equipment health plans in accordance with AP-913, plants need to address the fact that critical equipment data being collected by engineers during their inspection routes or 'walk downs' was not being captured in an effective way. A system that collects and integrates data is necessary.

"Life Beyond 60 Workshop Summary Report" NRC/DOE Workshop U.S. Nuclear Power Plant Life Extension Research and Development, Md., 2008 [8]

The Life Beyond 60 Workshop was organized by DOE and NRC to begin discussion of technologies necessary to safely operate the current U.S. nuclear fleet past 60 years. Challenges to prognostics were stated to include:

- Determining how and what to measure
- Data interrogation, communication, and integration
- Development of predictive models
- System integration and deployment
- Quantification of uncertainties.

And further details were provided in the presentations provided by panel participants.

EPRI Program on Technology Innovation: Information Integration for Equipment Reliability at Nuclear Plants: Status, Good Practices, and Technology Needs, EPRI 1018910, April 2009.

This report was funded by EPRI Project Manager John Gaertner who leads EPRI's LTO project, objective of which is to establish a sound, defensible technical basis for nuclear plant life extension decisions to 80 years and beyond. Nuclear plant owners will need to decide in the 2013-2019 timeframe whether to seek license extensions for existing facilities or replace them with new generation sources.

A survey was developed and conducted with input from all 26 U.S. nuclear power plant operators and 2 international nuclear power plant operators. Additionally, one-on-one interviews were conducted.

Using a survey of utility equipment reliability practitioners and follow-up interviews, the project described in the report identified 24 specific technology gaps in the information integration used to optimize ER process performance enhancement at nuclear plants. A significant finding was:

The performance monitoring subprocess contained the most significant gaps in information integration technologies. These gaps include the need to lower the cost of assessing on-line continuous monitoring of equipment condition; the need to extend and improve pattern recognition; the need to improve diagnostic, prognostic capabilities and equipment models; and the need to provide lower-cost solutions to instrument existing plant equipment with sensors.

Based on the results of the survey and best practices, 24 "gaps" were identified that were organized into eight functional areas. Many of these gaps can be solved without funded research, but rely heavily on software-engineered solutions, transparent communication and information sharing between competing utilities, or the investment of scarce resources by utilities. In fact, the good practices discussions in the report present cases where utilities have invested resources and closed several of these gaps. With that said, several would be appropriate for centrally funded research. These include:

- Gap #5: Risk-informed Dynamic PM Templates
- Gap #7: Availability of Condition Monitoring Sensors at Equipment Locations
- Gap #12: Estimating and Monitoring Remaining Useful Life for Critical Plant Equipment
- Gap #13: Prognostic Capabilities That Can Act Upon Initial Warning Signs
- Gap #14: Identifying Early Indications of Fast Acting Failure Modes
- Gap #16: Readily Accessible Diagnostic Guidance
- Gap #17: Industry Wide Library of Equipment Models.

Light Water Reactor Sustainability (LWRS) Research Program

The LWRS research plan identifies four pathways:

- Nuclear Materials Aging and Degradation
- Advanced LWR Nuclear Fuel Development
- Advanced Instrumentation, Control, and Information Systems Technologies.
- Risk-Informed Safety Margin Characterization.

D/P technologies fit into the Advanced Instrumentation, Control, and Information Systems Technologies pathway. The pathway is defined in this way:

Through use of scientific knowledge basis and advanced phenomenological modeling, establish advanced condition monitoring and prognostics technologies for use in understanding the aging of systems, structures and components of nuclear power plants. Develop and demonstrate information system technology enhancements for knowledge migration and regulatory compliance."

The Centralized Online Monitoring and Information Integration for Critical SSCs is in this pathway and includes R&D needed to provide information technology and models of system behavior emphasizing aging and degradation to enable real-time automatic statistical analysis, pattern recognition, and criteria to diagnose degrading conditions and predict RUL of SSCs. The LWRS document says that to perform these critical functions, one must:

- Understand the physics of failure
- Improve state awareness
- Understand fault and failure progression rates
- Understand performance properties as SSCs age
- Develop improved data-fusion methods

- Understand the effects of degradation across the systems.

Through the review of these documents, it is clear that D/P has been identified as a critical technology both to enhance reliability and improve economic viability of our aging plants. However, although D/P research topics have been identified in the past, no long term research plan has been adopted.

An example of a DOE-funded research project is the Nuclear Energy Research Initiative Consortium (NERI-C) under Grant Number: DE-FG07-07ID14895 and entitled "Advanced Instrumentation and Control Methods for Small and Medium Reactors with IRIS Demonstration". The goals of this NERI-C research project are to investigate, develop, and validate advanced methods for sensing, controlling, monitoring, and diagnosing the proposed small and medium reactors (SMR) and apply it to the International Reactor Innovative & Secure (IRIS) system. IRIS is an integral PWR developed by Westinghouse Nuclear Science & Technology Center, Pittsburgh. The University consortium project includes the following collaborators: University of Tennessee (lead institution), North Carolina State University, Pennsylvania State University, South Carolina State University, and Westinghouse (at no cost to the project). The NERI-C research focused on three topical areas with the following objectives:

Objective 1: Develop and apply simulation capabilities and sensitivity/uncertainty analysis methodologies to address sensor deployment analysis.

Objective 2: Develop and test an autonomous/hierarchical control architecture and apply to the IRIS system.

Objective 3: Develop and test an integrated monitoring, diagnostic, and prognostic system for SMRs using the IRIS design as a test platform.

This three-year project is expected to be completed this calendar year. There are other projects that are in progress or have been completed (e.g., IRIS at the CNDE, Iowa State University).

Diagnostics and prognostics have been identified as a critical technology to both enhance reliability and improve economic viability of our aging plants. Research has been identified in the past, but no long term research plan has been adopted. Europe (NULIFE), Japan (NISA) and others currently have multi-million and multi-billion dollar programs. It is critical to develop cost and safety justifications for these technologies to ensure success in plant life extension.

3.2.3 Current and Desired States of the Science and Technologies

The group completed an analysis of strengths, weaknesses, opportunities and threats. Results are listed in the following spreadsheet.

3.2.3.1 Diagnostic and Prognostic Strategies

Develop a standard, scalable, physical and logical infrastructure for data gathering, processing, analysis and results dissemination. This would enable centralized online maintenance solutions to maintain/improve the safety and reliability of current reactors and extend their service life in the most cost effective manner.

Table 6. Strengths, Weaknesses, Opportunities, and Threats chart.

Strengths	Weaknesses	Opportunities	Threats
TECHNOLOGY			
We have developed and demonstrated workable prediction and diagnostic algorithms. They are ready to be deployed in many instances.	Implementation of the state-of-the-art at the plant level	Life extension needs	Risk of incorrect prediction (e.g., failure not predicted in time)
Some ability for diagnostics and prognostics	Fault propagation for prognostics	Transition to digital technology	Piecewise implementation of solutions
technology for active system diagnostics is adequate as it exists	Technology for passive system diagnostics is not adequate (not for active systems either)	Identify model to predict condition using available sensors and non-sensors	Inability to capture degradation mechanisms over long periods
Technology that can be deployed--with some funds--on active components	Inability to process complex and diverse data	Decision making for control, CBM	Complexity of systematic modeling
Default detection capabilities	Model-based methods	Hierarchical monitoring, diagnostics, prognostics	"Retrofitting" of canaries and stress sensors and performance sensors is a challenge in existing legacy electronics
Methods are sufficiently mature		Reduce reactor internals aging surveillance	Impeded or prevented by non-coordinated digital/replacement I&C
We have too many methodologies for monitoring, diagnostics, and prognostics		System electronic interference detection/correction	We have too many methodologies for monitoring, diagnostics, and prognostics
Enough available resources		Develop integrated architectures for diagnostics, prognostics, and control: modular design methods	
Knowledge of components, behavior of systems			
DATA			
Data driven methods	Data Quality	Data mining to aid in building prognostic models	
Availability of data	Data Completeness	Develop new ways to sue and correlate data	
Lots of well documented	Data consolidation	Reduction of routine data analysis to	

Strengths	Weaknesses	Opportunities	Threats
data/information related to nuclear power plant events		provide decision support (date --> information)	
Power plants can produce a lot of date, the key is utilizing that data	Degradation measures		
Historical data	Work Processes		
	Automation of diagnostics		
	"Real age" of the electronics are not known due to lack of usage history		
	Availability of quality data		
	Current data may not be correlated with degradation and no model exists		
EXPERIENCE			
Knowledge of components, behavior of systems			
Vast experience (manual) in operating and control of plants			
Good operational history based on "traditional/human centered" monitoring			
INTEGRATION			
	Systematic integrated modeling of system and behaviors	Integrating work done by disparate groups on specific components into a system (plant) model	
	History of extending monitoring to automated diagnostics, prognostics	Use methods developed in DoD, Naas for health management	
ORGANIZED FOCUS AND DIRECTION			
	Lack of focused R&D for nuclear power plants -- both for active (e.g., pumps) and passive components		
IMPLEMENTATION			
	We have not organized the good work to actually deploy the solutions in the plants (nuclear power plants)	If we can define the problem by selecting a small number of problematic components to get good	

Strengths	Weaknesses	Opportunities	Threats
		data, we can build CBM/PNM systems for these -- start small	
		Create several successful applications in the real world of an operating plant	
IMPLEMENTATION (continued)			
		LWRS program provides a vehicle to implement monitoring and diagnostics from research to operations	
		Implementation of condition monitoring is less complicated because electronic systems are of less complex vintage	
VERIFICATION AND VALIDATION			
	We have too many methodologies, too		
	VERIFICATION AND VALIDATION pros and cons		
	In theory, VERIFICATION AND VALIDATION is possible; in practice VERIFICATION AND VALIDATION is not possible		
	VERIFICATION AND VALIDATION using collective intelligence (CE).		
Regulation			
	No licensing basis (too weak)--utilities to develop a synergized approach for monitoring and diagnostics and asset management		
	VERIFICATION AND VALIDATION pros and cons		
	In theory, VERIFICATION AND		

Strengths	Weaknesses	Opportunities	Threats
	VALIDATION is possible; in practice VERIFICATION AND VALIDATION is not possible		
SAFETY AND ECONOMICS			
		Great potential to engage longer-term operation	Not being able to detect a previously unseen fault
		Potential cost savings -- operations and monitoring	Prediction and diagnoses introduces faults
		Safety risk mitigation	Making non-conservative decisions which result in safety and cost problems
		Economy -- increased availability and decreased cost	Developers lack practical knowledge of the "business process" of diagnostics in the real world.
		Reduced inspection/maintenance	
		Nuclear power plants consider safety as well as economics	
		We can apply techniques to non-safety related SSC, then move to critical SSCs	
		For early adoption in nuclear power plants	
EDUCATION			
		Policy and public opinion--education opportunities	Not being able to detect a previously unseen fault
			Prediction and diagnoses introduces faults
			Lack of industry understanding and acceptance (no cost benefit seen)
			Power plant industry is conservative. They don't like to change their administrative procedures.

Strengths	Weaknesses	Opportunities	Threats
			Technology is good but technology needs to fit the applications
			Working in an uncoordinated, non-cooperative way
			Reluctance of industry to embrace new technology
REGULATION			
			Licensing
			Resistance to change
			Weak business cases
			Industry and regulatory acceptance

The breakout group's challenge was to provide an overview of D/P through defining the current state, desired end state, gaps, strategy/objectives, research needs and lastly capability needs. The following sections will describe each of these areas related to D/P.

3.2.3.2 Current State of D/P in the Nuclear Power Industry

Currently, condition monitoring (CM) and diagnostic technologies have been developed and demonstrated in very limited applications in the nuclear power industry. These include some continuous monitoring technologies for some high value active components such as turbines and reactor coolant pump seal systems. However, most CM technologies are limited to conventional equipment monitoring technologies such as periodic vibration analysis, motor current analysis, thermography, and acoustic emissions testing. These methods use threshold set points to detect faults and limited trending to identify degradation. The individual technologies are not usually integrated to form diagnostic decisions, and automated methods for process variable fusion are rarely employed. Utilities have vast experience in safely operating plants and have access to historical data that was usually sampled at rates of 1 minute stored using data compression techniques. These rates are useful for basic trending and modeling, but higher data rates may be necessary for specific applications. Additionally, the current data may not be correlated with the important degradation measures.

When it comes to diagnostics and prognostics in the nuclear power industry, there are few capabilities (AREVA has a 265 channel system being put into Finland 3 plant – gives data that has potential for D&P analysis) for extending the condition monitoring and fault detection technologies to include automated diagnostics and prognostics. There is also no first-principle or empirical model based prognostic methods deployed in the civilian U.S. nuclear power industry. Other fields, such as aerospace and other defense systems, have progressed and fielded some prognostic applications, but the nuclear industry has not been motivated to invest in such technologies, primarily because of their current high availability rates.

3.2.3.3 Desired End State

The desired end state would be to have optimized operations, maintenance, and asset management decisions by providing integrated detection, diagnostics, and prognostics. These technologies would protect critical components, reduce unscheduled maintenance and time for scheduled refueling outages, reduce operating and maintenance (O&M) costs, and be integrated both at the plant level and at the fleet level.

It is also desirable to for the D/P technologies to have "mixed initiative control". The group defined this as having the potential for automated component protection. An example of mixed initiative control would be an automated runback that is initiated by an imminent component failure predicted by the D/P system.

Other attributes of the D/P system would include one that is reliable and robust, flexible and adaptable, non-invasive (does not affect the system), licensable and acceptable, an integrated/unified part of I&C systems, with traceable/justifiable basis for decisions, a simple and understandable HMI, that is cyber secure, and would reduces human intervention and exposure to hazards. This is indeed a great challenge and a unified research and development is necessary to move towards this desired end state.

3.2.3.4 GAPS, CHALLENGES, AND BARRIERS

The group identified several gaps between the current state and the desired end state as well as the challenges and barriers to achieving that desired state. These were then prioritized by the breakout attendees. The top priorities were found to be:

Well defined proof of concept studies and benchmarks (including test beds)

- Specifications and regulatory guidance
- Science and technology knowledge base for diagnostics and prognostics

- Data acquisition and transmission for diagnostics and prognostics
- Knowledge capture (ES, CBR) and information tools
- Secure computational architecture to support integrated operations
- Acceptance by the user community.

Other, less vital gaps and barriers to implementing D/P methods:

- Increased requirement for monitoring
- More data and alarms to process—data overload (noise) and increased analysis
- Collaboration with others in the field (this was determined to be a strategy)
- Obsolescence (old electronics)
- Lack of a focused goal (prioritized)
- Lack of defined work processes (value chain roles, responsibilities)
- Proprietary nature of plant data
- Impact of I&C system replacement (bandwidth, dynamic range)
- Explosive number of combinations of component and failure mode types
- Dimensions scaling of PHM techniques or methods (e.g., validation for fuel sensor)
- Data not time stamped (need global time stamp for data)
- No diagnostic/prognostic technologies
- Codes and standards issues
- People must not ignore advanced diagnostic systems
- Maintaining realistic costs (integrated cost analysis).

3.2.3.5 STRATEGIC OBJECTIVES

Taking into consideration the seven prioritized gaps/challenges/barriers the group developed a set of objectives that will move the current state towards achieving the desired end state. Six objectives statements are presented below.

Objective #1: Define and conduct research to determine data, sensor, and network architecture needs.

To complete this objective, first a study would need to be conducted to identify which systems, structures and components (SSC) will be critical in 20-30 years. [need to say something about active components vs passive components – industry has already said it is the passives – active just replaces. D&P has potential to better plan replacement and maintenance – see ppt enclosed – Burns and Row] Critical equipment was defined to be those with high risk failure modes. After identifying the critical failure modes, there must be a deep science based understanding of failure modes including failure models. This will lead one to understand what data is necessary to perform D/P on the critical equipment and systems. Lastly, the sensor, communication networks (such as wireless) and centralized data processing systems must be specified.

Objective #2: Develop a repository of data/case studies/test bench experiments

Utility involvement must be acquired in a repository of critical failure data and case studies. These cases may be a result of utility reports, high fidelity simulations, or test bed experiments. It was suggested that as aged equipment is replaced, it be sent to test facilities that would perform run to failure experiments in order to collect failure data necessary to validate failure mode models and generate data for empirical prognostic models

Objective #3: Conduct research to prove solutions and develop technical requirements

Research is necessary to validate current D/P methods and develop new methods. D/P requirements must be developed that apply to various stakeholders. These should be developed with collaboration between users, suppliers, and specifiers. These requirements should include performance, false alarm rates, missed alarm rates, and be probabilistic in nature.

Objective #4: Identify dominant degradation phenomena—develop physics of failure (POF) models to fill gaps.

Plant data, experimental test beds and physics of failure models must be used to develop D/P systems which will be demonstrated and validated in the field. This will require engaging domain experts for knowledge capture and funding R&D to fill the gaps. The demonstrated systems should be integrated systems and applied to critical needs.

Objective #5: Provide secure communication architectures to support integrated operations

Current nuclear power plant analogue systems will need to be replaced with digital I&C and incorporate cyber security. To do this, regulatory guidance is necessary for digital I&C for D/P. It is suggested that domain/subject matter experts from other fields (aerospace, defense, telecommunications, etc.) be engaged to identify technologies and implementation processes.

Objective #6: Communicate benefits to end-user and promote their involvement/ownership/engagement

The current plant culture does not appreciate the expected benefits that may be attained from D/P systems. With plant availability currently averaging over 90%, utilities do not see the need for investing in D/P technologies. The future needs and benefits need to be communicated to the end user through successful implementation (plant staff) and business plans (management). This will include promoting end user involvement/ownership at the outset through engagement and integrating D/P systems into work practices.

3.2.4 Research and Funding Recommendations

The last task for the group was to identify short term research needs (for FY 2011) and longer term research to be completed by 2020. This research has been identified to help bridge the gaps so that the D/P objectives can be met. The identified research is expected to not only benefit the current aging reactor fleet, but to also provide a solid D/P foundation for next generation reactors and fuel cycle facilities identified in the NEET program.

3.2.4.1 Research Needs for 2011

Critical equipment identification (risk significance)

Looking out 20 years, the critical plant systems structures and components must be identified. This research task is crosscutting in nature in that the same information is necessary for the successful completion of the LWRS Risk-Informed Safety Margin Characterization pathway. High risk components are those with a high probability of failure and a high cost of failure. Cost can be interpreted as a financial cost or even more importantly a safety or environmental cost.

Quantification of prognostics uncertainty

This task has been identified by many of the earlier workshops and reports. Prognostic uncertainty must be characterized – more than just characterized – need to understand the fundamental mathematical issues that relate to spare data, ill-posed problem, constraining (bounding) a solution to insure proper actions follow the prognostics predictions. As an example, if the uncertainty associated with the prediction is larger than expected, an un-conservative decision could result in the unexpected failure of a SSC. The uncertainty/accuracy will be closely tied to the D/P method, development data, application specifications, and many other factors. A knowledge of the sources of uncertainty, how they interact, and are constrained in forming a prognostic solution is critical to technology acceptance, usage, and benefits afforded.

Integrated, life-cycle DP algorithm development

Prognostic algorithms use different data and methods during different stages of the lifecycle. During the first stage of a SSC lifecycle, usage and degradation information is not known and only historical failure data from a similar population can be used to predict SSC Remaining Useful Life (RUL). As the SSC is operated, environmental information such as loads can be used to form a better RUL estimate. Finally, as the system shows signs of degradation, this information can be used to improve the prognostics estimate. Algorithms and application methods must be developed to step between these three stages using the maximum information available to produce optimal RUL estimates along with their uncertainty predictions.

Diagnostic and prognostic information integrated into dynamic PRA

Accurate prognostic information will be primarily used to optimize operation and maintenance decisions. One avenue for making these decisions is through the use of real time risk monitors, sometimes called dynamic probabilistic Risk Assessment (PRA). The objective of the proposed research is to develop methods to utilize prognostic information in the context of Dynamic PRAs. Specifically, the objective is to use prognostic technologies to calculate probability of failure distributions for critical SSC. These dynamic failure probability predictions can be used to replace the traditionally static failure probabilities incorporated into risk monitors [9].

3.2.4.2 Research Needs (to be completed prior to 2020)

The following are additional research needs that were identified as being important in meeting the D/P objectives. Each of these also has cross cutting impact to other programs identified in NEET.

- Develop standardized specification language for PHM
- Develop textbook that addresses digital I&C, diagnostic and prognostic for NPP
- Provide demonstrated results in integrated systems applied to critical needs
- Determine how to scale-up and how many sensors can be put on a system to still be feasible – optimal location for sensors
- Automate diagnostics methods
- Develop optimal sensor placement strategies.

3.2.4.3 Capabilities Needed

This section presents several critical needs that are necessary for effective D/P system implementation and usage.

Design communications network architecture

Currently plants do not have the ability to retrieve sensed information from the fielded critical components. It is well known that installing cabling to each sensor on each component is probably cost inhibited. Cyber secure networks architectures, such as wireless sensor networks must be developed and proven. Research topics include power scavenging, on-sensor signal processing, etc.

Host for PHM database containing D/P info

Since diagnostic and prognostic models are constructed through the knowledge of SSC faults, fault propagation paths, and failure thresholds; the algorithms can be greatly improved through the integration of knowledge captured from actual SSC degradation and failure. A PHM data warehouse that contains D/P data including ground truth (actual degradation and failure) data, test bed data, and high fidelity simulation data would make D/P algorithm development more efficient and would improve D/P performance.

Regulatory guidance for digital I&C and for D/P

There is currently no regulatory guidance for the implementation of D/P. One potential use of D/P information is to optimize specific maintenance intervals. If D/P results resulted in extended maintenance or surveillance intervals, it could reduce maintenance costs; even more importantly, if D/P resulted in reduced maintenance intervals, it could potentially improve plant safety.

Engage cyber security SME in other areas of application, educate them on NPP needs, and transfer technology to nuclear.

The propagation of digital I&C throughout the plant, especially with wireless, brings with it new avenues for potential cyber attacks. Other application areas have similar vulnerabilities and have developed technology and implementation practices to successfully deal with them. The nuclear power community needs to learn from the experience of others and utilize validated techniques to improve D/P communication system reliability.

3.2.4.4 RECOMMENDATIONS

The breakout session group made the following recommendations:

- Develop and fund a multi-year research program to develop, validate, integrate, and deploy D/P methods for LWRS
- Communicate and collaborate with SMEs from other industries/applications to transfer technology to nuclear
- Work to educate other stakeholders: NRC, plant staff, DOE managers, etc., on the benefits and limitations of D/P technologies
- Engage the nuclear industry to understand their needs and constraints.

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3.3 Centralized OLM

Dr. Ramesh Shankar
TVA

3.3.1 Introduction

The goal of this break-out session was to look at the potential opportunities and research needs related to centralized OLM. As real-time OLM, data archiving and mining/analysis, and communications technologies continue to improve, the business case for integrating and centralizing the monitoring function grows.

At the beginning of this breakout session, the participants were asked to define a strategy and vision. These are the definitions which served as the basis of later discussion:

> ***Strategy:*** *Develop a standard, scalable, physical and logical infrastructure for data gathering, processing, analysis and results dissemination. This would enable centralized online maintenance solutions to maintain/improve the safety and reliability of current reactors and extend their service life in the most cost effective manner.*
>
> ***Vision:*** *The implementation of the OLM strategy as a phased approach through demonstration of incremental improvements.*

This section of this report, therefore, is designed to elaborate on the vision and strategy as set forth. Accordingly, the purpose or possible benefits of centralizing OLM have been enumerated as enabling a central resource to manage power industry assets, early detection (prevention and mitigation) of plant problems, and a reduction of operating and maintenance costs. Three specific areas where centralized online monitoring may be effective and yield cost savings are (1) thermal performance monitoring solutions (by enabling the monitoring of plant operational efficiencies, emissions, fuel performance, and costs); (2) vibration analysis (when applied to condition-based monitoring of rotating machinery); and (3) equipment condition assessment technologies based on empirical modeling, (enabling fleet-wide diagnostics and prognostics).

Some of the key and emerging drivers that make centralized online monitoring feasible and useful are new technologies. A wide variety of these exist now in a number of related areas. Improvements are expected in several areas – including operations, maintenance planning and strategy, and thermal performance. All of these would be expected, under normal business conditions, to drive both the development and adoption of centralized OLM. At its heart, the promise of the new technology is improved asset management tools.

A number of questions need to be asked about OLM and creating a centralized function. Three of these are:

1. Do we have the right set of sensors to be able to do reliable CBM
2. Do we have the right set of technologies (are they available from aerospace, medical, petrochemical, defense applications, non-nuclear power, etc.)
3. Has a meta approach emerged to pre-process all the data presently collected and have modeling capabilities improved sufficiently to support centralized OLM needs?

Additionally, several requirement areas for implementing centralized online monitoring were noted, including: defined objectives. Knowing the requirements for data acquisition and applications for the use of the data are key, a system architecture must be envisioned and defined. Consistent naming conventions would need to be adopted across the spectrum of researchers and users for coordination between the many different entities involved in the CBM project. Similarly, staffing questions must be answered: what will the structure of the staff look like, and what expertise would be required. Problems of remote access, both technical and security-related will need to be answered. Ideally, the goal is to provide early warning of events, diagnostics, and prognostics.

Time did not allow extensive discussion of most of these areas in this break-out session.

3.3.2 Current State

Over the last decade significant progress has been made by non-nuclear industries in centralizing monitoring functions. Several cases where such integration had been successfully implemented were repeatedly cited during the plenary and break-out sessions. Entergy and Luminant, for example, had accomplished this for their fossil fuel plants with important operational benefits being realized (prediction and prevention, more rapid understanding of trends, earlier and more systematic responses, etc.) Centralization may also lead to significant staff reductions and cost savings. The following brief timeline sketches the context for this breakout area:

- 1990's - EPRI obtains NRC approval for:
  - On-line monitoring for calibration extension of safety related instruments
  - Instrument drift analysis for instrument calibration extension
- 2002 to 2005 - EPRI demonstrates on-line monitoring at several nuclear utilities
- 2003 - **Entergy** becomes the first utility to implement fleet wide monitoring for fossil
- 2005 - EPRI demonstrates use of wireless sensors for equipment health assessment at **Luminant**
- 2005- EPRI launches fleet wide monitoring interest group.

To date, fleet-wide monitoring is widely implemented, and cost benefits have been realized. Most of the cost benefits have been for better operational oversight. Diagnostics and prognostics have not been implemented. As illustrated by the timeline above, while OLM applications have progressed, large gaps persist between research results and practical needs.

The workshop participants attending this break-out session performed a strengths, weaknesses, opportunities, and threats (SWOT) analysis of centralized online monitoring. Table 7 represents the thinking of the participants gleaned from the SWOT analysis.

Table 7. SWOT analysis of centralized OLM at present.

Strengths	**Weaknesses**	**Opportunities**	**Threats**
TECHNICAL			
Computing capability continuing to improve steadily	No global agreement on the definition of OLM and of a standardized nomenclature	Demonstration of success cases	Obsolescence of digital electronics technology (and re-qualification)
Data analysis acquisition technologies that are well developed—there is an understanding of what needs to be done	Immaturity of diagnostic technologies	Expanding volume of research results from a number of sources	Incompatibility of software--software interfaces not standard
Wide-spread recognition that technology can be used to improve plant performance	Lack of deep R&D and standardization of OLM findings	Rapidly maturing methods, tools, and philosophies	Configuration control, configuration management, particularly dealing with worldwide vendors
Demonstrated technical capacity – operational programs exist for non-nuclear power generating fleets	Lagging and immature integration of OLM with emerging guidance and systems for alert/alarm management	Opportunity to apply centralized OLM from the very beginning in new builds, including small, modular reactors	Lack of allowance for human factors issues
Documented cost benefits – potential to reduce labor costs post implementation	Lack of vendor participation in technology design and implementation	Increased safety margins for equipment	
Ever increasing acceptance of technology in the nuclear area	Less than ideal management and standardization of large databases	Improved feasibility of building in long-term expandability of the backbone (optimism that good planning now can enable rather than prevent adoption as OLM matures)	
Early adopters in the nuclear area: (e.g., BE and EdF)	Lack of common understanding of allowed data flows \between electronic systems/devices	Improved equipment reliability/power production capability	

Strengths	Weaknesses	Opportunities	Threats
Widely recognized need to transfer knowledge from aging workforce	Lack of software quality assurance rules for analysis software and for procurement of equipment to permit interconnectivity		
Many countries seriously considering adopting nuclear power (e.g., UAE, Vietnam and Chile)			
EXPECTATION MANAGEMENT (INTERNAL TO NUCLEAR)			
	Lack of understanding by some nuclear industry executives (need for better education/training)	Nuclear power acceptance on the rise (e.g. nuclear is now being supported by many former opponents as "green" and earth friendly)	Lack of a coordinated vision
	Hype – expectations too high (e.g., talking about prognostics when diagnostics need to be fully developed and implemented)	Plant updating/modernization that is happening and will increase	Lack of progress/growth and pilots/initiatives
	Over-ambitious or “all or nothing” thinking: the only approach is to eat the whole elephant at once as opposed to a more phased implementation strategy	OLM technology that can be an enabler to re-establish nuclear as "first in class" for the nation (help understand and monitor/manage the inherent risks)	
		DOE seemingly willing to support/co-fund strategic R&D and encourage collaboration needed for pilot implementation	

Strengths	Weaknesses	Opportunities	Threats
		User groups to collaborate between R&D and plant demonstration that can/would improve success potential	
EXPECTATION MANAGEMENT (BEYOND NUCLEAR)			
	Lack of public understanding/acceptance	OLM technology applicable and starting to show improved fleet/plant efficiency in a wide range of industries (not an isolated need)	Renewable energy, distributed systems
		Other industries of equal/greater risk already pioneering the way. (US Navy, military, conventional power producers, aerospace).	Any nuclear power accident (unrelated to OLM)
ECONOMICS			
	Cost/benefits not universally accepted		Cost of capital
	Limited field demonstrations and proof of economic viability—most examples are in the non-nuclear arenas		
	Constant competition for limited resources (Globally, dollars following to new plants may shrink availability of funds to upgrade/modernize existing plants. Locally, always a long list of investment needs.)		

Strengths	Weaknesses	Opportunities	Threats
	Increased costs – a healthy labor and equipment investment would be required before ROI is achieved		
	Savings due to consolidating over an entire fleet not immediately available to smaller utilities		
REGULATION			
	Lack of regulatory guidance and acceptance		NRC definitions of defense in depth and diversity
			Lack of standards
			Changing approaches/regulatory stance regarding cyber security

3.3.3 Desired State

As noted in the breakout-session introduction, the following strategy and vision statements were crafted:

> *Strategy: Develop a standard, scalable, physical and logical infrastructure for data gathering, processing, analysis and results dissemination. This would enable centralized online maintenance solutions to maintain/improve the safety and reliability of current reactors and extend their service life in the most cost effective manner.*
>
> *Vision: The implementation of the OLM strategy as a phased approach through demonstration of incremental improvements.*

The concepts of standardization and incremental improvement are key to strategy and vision. The desired state, therefore, is not just one end state, but a series of progressively more challenging, yet rewarding (in terms of effectiveness and efficiency), interim end states as shown in Table 8 below. The participants were emphatic that this was an evolutionary process. Getting to wrapped up in defining the perfect long-term end state may actually preclude near-term efforts that must be performed before any long-term benefits/goals/capabilities could be achieved.

Table 8. Projected interim end states for centralized OLM monitoring.

Time Frame (When)	5 years (2015)	Between 5 and 10 Years (2016-2020)	between 11 and 20 years (2021-2030)
Scope of Implementation (Who)	U.S. based utilities with large nuclear assets (5 or more operating units)	All large U.S. utilities and all smaller nuclear utilities under a consortium or outside support	Entire nuclear U.S. utilities; and select international fleet Integration of SMR advanced next generation PWRs and BWRs Engagement of the USNRC to monitor "any-where, any-time" performance of nuclear plants in the U.S. , Europe and Russia
Active vs Passive	Passive	Active and Passive	Methodology to accomplish 95% to 100%monitoring with sensor technologies, Sophisticated FPGA and on-board sensor calculations to embed algorithms
Diagnostics and Prognostic	Very little diagnostics--mostly detection of anomalies	Preliminary diagnostics functions installed and validated for reactor integrity, reactor coolant pump monitoring, etc.	Complete Diagnostics and Prognostics Capabilities
Equipment	Critical components health monitoring, providing assurance that all safety systems are operating satisfactorily	Critical components health monitoring and diagnostics capability and other targeted equipment health monitoring and limited diagnostics	Health Monitoring, Diagnostics and Prognostics, CBM for Maintenance Strategy Safety Systems Monitoring On-Line Peer Review
Other	Reliable metrics be developed to document improvement in performance	Metrics developed to show improvements across the nuclear fleet (INPO)	Nuclear Plant O&M costs several multiples below operational costs

3.3.4 Research Needs

For research to progress, four capabilities needs were identified. The first is component prioritization, the identification of those components that are most important to the centralized OLM effort. Second, the need to identify those technologies available to apply is recognized. Standardization, whether in consistent taxonomies or in identifying needs and approaches, is vital. Finally, existing, available technologies must be integrated.

3.3.5 Funding Recommendations

There were fourteen research needs identified. Priority was determined by each participant giving one vote to each of five needs. All fourteen needs are listed below with the top five listed in order. These top vote getters were:

1. Critical assessment of OLM technologies
2. Data fusion and data mining
3. Optimal sensor placement strategies and measurement frequency to ascertain key failure modes for critical components
4. Formation of a destructive test lab/run to failure
5. Creation of a failure signature library from lab and other sources.

Other research needs included:

- Identification of minimum requirements for effective D/P
- Uncertainty quantification of D/P methods
- Hybrid modeling (empirical & model-based)
- Stressor based first-principle D/P development
- Decoupling and recognizing differences between control problems, process anomalies and sensor drift
- Lessons-learned on OLM experience
- Human factors field experience in implementation of OLM
- Theory to practice on representative components to demonstrate LWR sustainability.

3.3.6 Research and Funding Recommendations

The recommendation of the breakout group was for continued funding and research into the areas of data fusion and data mining, optimal sensor placement strategies and measurement frequency to ascertain key failure modes for critical components, and critical assessment of OLM technologies. Additionally, the formation of a destructive test lab with run to failure capabilities and the concurrent creation of a failure signature library from lab and other sources are regarded as vital.

Table 9. Research direction for Centralized OLM.

Scenario	Active/Passive	Diagnostics /Prognostic	Operational	Equipment Health	Other	Vision
5 years	Mainly Passive	Very little Diagnostics. More detection of anomalies	High Operational Use and Benefits	Critical Components Health Monitoring	Assurance that all safety systems are operating satisfactorily	U.S. based utilities with large nuclear assets (5 or more operating units) Reliable metrics be developed to document improvement in performance
5<N<10 years	Active and Passive	Preliminary Diagnostics functions installed and validated: for example for reactor integrity; reactor coolant pump monitoring, etc.	High Operational Use; Targeted Equipment Health Monitoring Limited Diagnostics	Critical Components Health Monitoring and Diagnostics Capability	Safety Systems Monitoring On-Line Peer Review	All large U.S. utilities included Smaller nuclear utilities under a consortium or outside support Metrics developed to show improvements across the nuclear fleet (INPO)
10<N<20 Years	Methodology to accomplish 95% to 100%monitoring with sensor technologies, Sophisticated FPGA and on-board sensor calculations to embed algorithms Integration of SMR advanced next generation PWRs and BWRs	Complete Diagnostics and Prognostics Capabilities	Broad usage for operational appl., equip. health monitoring and instant peer review capability	Health Monitoring, Diagnostics and Prognostics, CBM for Maintenance Strategy	Nuclear Plant O&M costs several multiples below operational costs	Entire Nuclear U.S. utilities; and Select International Fleet Engagement of the U.S. NRC to Monitor “any-where; any-time” performance of any nuclear plant in the U.S. and Europe and Russia

4. WHAT ARE OTHERS DOING?

4.1 U.S. Nuclear Regulatory Commission (USNRC)

Mike Waterman
U.S. Nuclear Regulatory Commission

Mr. Waterman from NRC presented an overview of the NRC's connection with the OLM research being carried out. The U.S. NRC is an important stakeholder, with the NRC Office of Nuclear Regulatory Research responsible for I&C research. The NRC releases safety evaluation reports (SERs), many of which are noted below. The NRC additionally provides Standard Technical Specifications for the five reactor types and requires plants to operate within these specifications. Each plant in the NPP operates under specific technical specifications (TSs), and the NRC actively encourages licensees to upgrade TSs as generic changes (called Travelers) are issued.

The goal of sensor, diagnostic, prognostics, health monitoring (SDPM) is to identify, monitor, and mitigate errors and impending failures in order to maintain equipment operability. Advances in microelectronics, smart-sensor technology, and artificial intelligence are making it possible to advance the SDPM state of the art. SDPM assists plant operators with

- Detecting anomalies in dynamic systems
- Identifying faulty components responsible for anomalies
- Optimizing responses to upset conditions.

4.1.1 Past Activities

The 1995 report, NUREG/CR-6343, "On-Line Testing of Calibration of Process Instrumentation Channels in Nuclear Power Plants," focused on the on-line testing and calibration of process instrumentation channels in NPPs. The research report was prepared by the Analysis and Measurement Services Corporation (AMS). The report concluded that it is possible to non-intrusively monitor calibration drift in field sensors and associated signal electronics and to determine the performance of instrument channels.

Collaborative work in 1998 with EPRI led to EPRI TR-104965, "On-Line Monitoring of Instrument Channel Performance." The report describes non-intrusive methods for monitoring the performance of instrument channels and extending calibration intervals. A regulatory review revealed that 5% of instrumentation surveillances found instrumentation to be out of calibration. The calibration extension method described in the report requires an algorithm to estimate process parameters. The topical report describes two algorithms.

4.1.2 Regulatory Position

In 2000 the NRC SER for EPRI TR-104965 concluded that the generic concept is acceptable. It listed 14 requirements to be addressed by plant-specific license amendment requests for relaxing TS-required calibration frequencies. Also, the NRC did not review or endorse either of the two algorithms in EPRI TR-104965, but allowed licensees to choose either algorithm.

The nuclear power industry should adopt sets of objective acceptance criteria for implementing OLM technologies. The current specified criteria tend to be subjective in nature. This reliance on subjective acceptance criteria has introduced licensing uncertainty because specific objective acceptance criteria are required to assure that a new technology or procedure is acceptable for use in a nuclear power plant safety system application. The NRC Standard Review Plan (SRP) for instrumentation and control systems is not supported by underlying review procedures. Currently, NRC staff use existing subjective criteria from the SRP to qualitatively conclude acceptability of a proposed design or process. The industry and the DOE need to encourage the development of objective acceptance criteria.

Nuclear personnel require training in OLM capabilities and limitations, which could be supplied by DOE.

The NRC acknowledges that intrusive calibration processes can be problematic to instrumentation operability. However, the NRC does not specify particular products or operating procedures. That is, it licenses nuclear power plants, not nuclear components or nuclear procedures. The industry and DOE should develop specific uncertainty limits for safety-related instrumentation and control systems. These uncertainty limits must be objectively verifiable.

4.1.3 Recent Activities

The following reports provide a listing of recent activities engaged by the NRC:

- NRC Vol 1 – State of the Art – ML060610394
- Vol 2 – Theoretical Issues – ML081430058
- Vol 3 – Limiting Case Studies – ML082530158.

NUREG/CR-6895 Summary and Overview:

- On-Line Monitoring for Calibration Extension: an Overview and Introduction (ML091400211)
- Contractor (University of Tennessee) prepared summary and overview for NRC staff as an aid to verify conformance of OLM systems with regulations.

Collaborative work also include:

- Research project NUREG/CR-6895:
  state of the art: ML060610394, theoretical issues: ML081430058, limiting case studies: ML082530158
- Research through a cooperative agreement with ORNL and the University of Tennessee. Published under NUREG/CR-6895.

4.1.4 Pending Activities

Advanced Diagnostics and Prognostics research activities:

- NRC is exploring the current state of the art to gain insight in areas that may be expected to become feasible within the next several years
- NRC needs to determine whether changes to NRC regulations or guidance are needed
- NRC published a Sources sought announcement on FedBizOps.gov, RS-04-10-456. This announcement closed March 20, 2010.

4.2 The EPRI Power Generation Asset D&P Software Development

Randy Bickford
Expert Microsystems, Inc.

4.2.1 Guideline for Initiating OLM Programs

EPRI has compiled a guideline to support utilities desiring to build new capability in online monitoring for equipment-condition assessment [1]. The guideline addresses a range of issues, covering people, processes, and tools.

4.2.1.1 Findings

Plant staff can see centralized online monitoring as a threat to the security of employment. For this reason, utilities should plan and execute a mitigation strategy that focuses on the relationship between OLM and the staff. Successful OLM programs observed in practice had policies to overcome the big brother mentality by focusing on providing a service, allowing field staff to make final decisions, and not reporting different viewpoints, regardless of outcome.

Online monitoring projects succeed because the technology creates a central conversation that brings new thoughts and approaches to improving asset performance. Once the plant staff and the online monitoring personnel become a team, decision-making moves towards a centralized risk management approach. The integration of operations, maintenance expertise, and engineering skills facilitate this shift in decision-making.

4.2.2 Power Generation Asset Diagnostic and Prognostic Software Development

4.2.2.1 Suite of Four Enterprise Software Products

EPRI has produced a suite of four software products which provide an industry-shared diagnostic and prognostic platform for nuclear and fossil power plant assets. These are shown in schematic form in Figure 29.

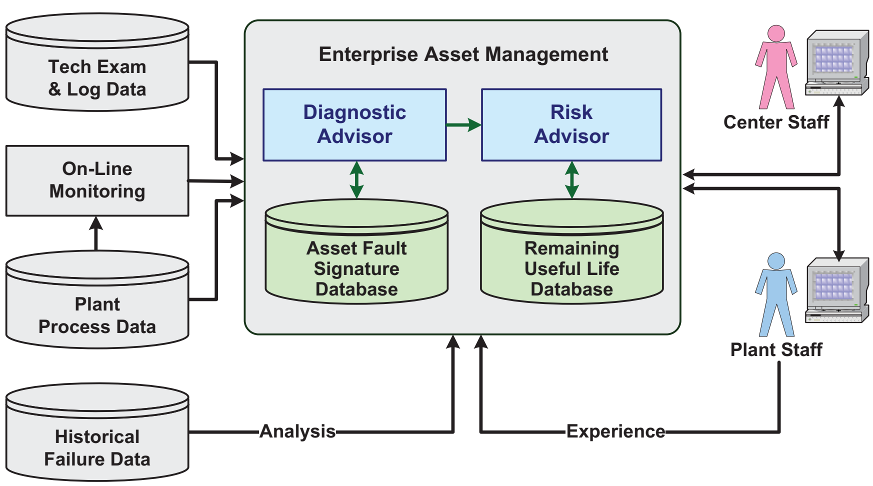


Figure 29. Overview of the EPRI suite of enterprise-software products.

Development funding and guidance for these software projects was provided by five U.S. and three European utilities. Each of the four products is described in greater detail below.

4.2.2.2 Diagnostic Advisor

The purpose of the Diagnostic Advisor is to better determine the health of plant assets based on:

- On-line monitoring of plant process data
- Thermal performance model results
- Predictive maintenance information, operator rounds and technology-examination results.

The Diagnostic Advisor assists the plant operators to remedy asset health problems sooner and at lower cost. It ameliorates risk by providing interactive troubleshooting advice and enabling optimal maintenance.

The knowledge base is constantly updated using automated population of the AFS Database with new diagnostic results. The goal is to create a comprehensive industry database of symptoms for detecting degradation or incipient failure of power plant equipment. The database is augmented by capturing (i) design-derived knowledge of fault signatures, (ii) experience-derived fault signatures for each new problem that is detected and diagnosed, and (iii) related cause, effect, and remedy information. The database engine provides highly efficient access to fault signatures by the Diagnostic Advisor and other monitoring software.

EPRI's aim is to enable industry-wide sharing of asset fault signatures and provide reference asset taxonomy for indexing data.

4.2.2.3 Risk Advisor

The Risk Advisor implements multiple life-estimation algorithms. It acquires estimation parameters from the RUL database. The computed RUL estimates and associates confidence estimates are based on the plant-asset operating history and condition information, historical life information for similar assets, and user selectable life estimation methods. The database manages asset operating history and condition information either through on-line or manual input. The tool captures service life basis data into the RUL Database.

The RUL Database is a knowledge base of life-estimation parameter data for power plant assets. It contains the parameters needed for reliability-based, stress-based, and effects-based estimation methods. The aim of the database is to support all types of life-estimation algorithms. The database should be broad enough to support new algorithms implemented in the Risk Advisor and other prognostic software. The database is designed to acquire new information during use by capturing new RUL signatures and model types, to construct metrics for the accuracy and utility of RUL signatures, and to provide service-life-basis data for monitored assets.Figure 30 shows the interaction of the various inputs in the Risk Advisor approach.

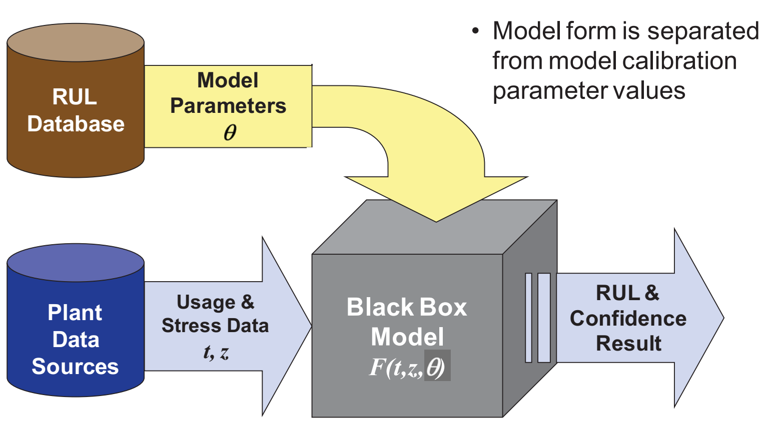


Figure 30. Risk Advisor approach for RUL estimation.

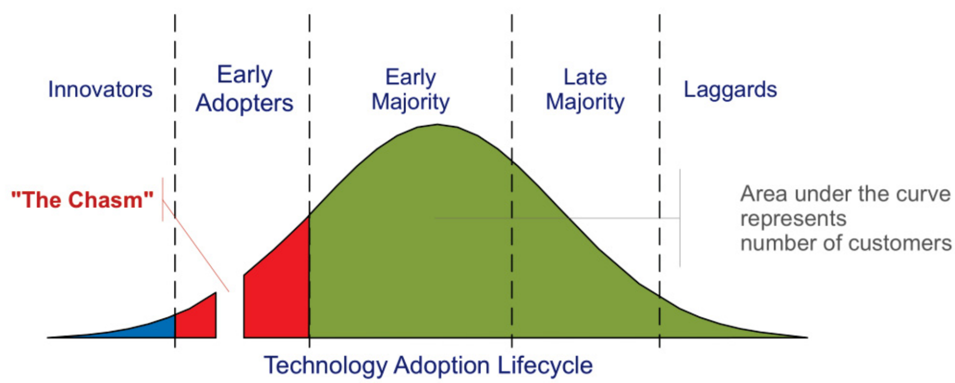
The two tools share common objectives. These include:

- An industry database of asset fault signatures facilitating utility use of DOE research results
- An industry database of remaining useful life models to facilitate utility use of DOE research results
- An industry reference asset taxonomy to enable sharing of diagnostic and prognostic knowledge
- Enterprise software designed specifically for system and plant engineers in power utility environments.

4.2.3 The Need: Content Development

This software suite is dependent on the quality of information contained in the described databases. A key need for continued improvement is the development and distribution of fault signatures for a wide variety of power plant assets. These can be captured as a result of monitoring faults in the plants of early adopters. Increased information permits the simulation of nuclear-asset fault features, increasing the understanding of failure mechanisms. The development and distribution of remaining useful life models for a wide variety of power plant assets is the envisioned end state, with models for each phase of the service life cycle. Only by acquiring this information can the eventual goals related to prognostics be realized.

No single organization or utility can likely complete the necessary content development on their own. This development can only succeed as a cooperative effort among many utilities.



Source: http://en.wikipedia.org/wiki/File:Technology-Adoption-Lifecycle.png
Author: Craig Chelius; 10 February 2009

Figure 31. Bridging the technology adoption chasm through the technology adoption process.

4.3 NASA Prognostic Roadmap

Kai Goeble
National Aeronautics and Space Administration

To ensure mission success, NASA has at its disposal a suite of tools and methods that relate to safety of operations. These include the use of reliable components that are designed to ensure that mean time between failures satisfies mission requirements. Next, hardware redundancy is employed to provide backup capability of critical components. Finally, and to complement the other two methods, active systems health management must be ongoing. Here, autonomous online component-performance monitoring is performed. This includes not only the detection of abnormal conditions, but also the determination of fault root causes, the assessment of the degree of damage, and the estimation of remaining component life.

There are some particular challenges that dictate which approaches may be chosen. For example, if a data-driven technique requires access to large quantities of data of faults and failures observed in the field, this becomes a problem where the fleet size is small (perhaps it is just one of a kind). In such situations, it is necessary to look towards the feasibility of model-based approaches. Other constraints come from the lack of availability of sensors. More often than not, the number of sensors available is very small. Each sensor adds a few grams of weight and has to buy its way onto a platform. But sensors are still considered the "weak link". That is, they are often times less reliable than the systems they are deployed to monitor. Advanced sensor validation and qualification is required to overcome this issue. More challenges come from the unique environments to which NASA's systems are exposed. These include extreme thermal cycles (can a ± temp range and rate of change be indicated?), possibly highly corrosive conditions, high accelerations and shocks (jerks), other forms of stress due to causes such as lightning and radiation.

Other challenges encountered come not from the hardware but from the software that implements systems health and controls. These system needs result in increasing software complexity which is posing enormous challenges for current V&V methods. Exhaustive testing of all possible data ranges and conditions generates copious traces, the analysis of which will soon become intractable. Novel ways to provide automated V&V are needed. In addition, new methods to perform V&V on adaptive systems are required and flight certification methods needed to accommodate the unique requirements of health management systems. For systems that will venture into deep space, these will encounter new and unknown faults that a health management system must be prepared to tackle. Given that communication times for systems deployed in space may make interaction prohibitively long, autonomous learning must be considered to deal with new faults.

Determining the health of a subsystem is only a means to an end. What we are really trying to accomplish is to ensure a safe completion of a mission (whether it is in the aeronautics domain or in space). To that end, one needs to consider how to turn the health information into actionable decisions. This is not a trivial process because the answer depends on a number of possibly conflicting objectives. These can include the impact on safety, the confidence of the health assessment, the availability of resources to mitigate the problem, the cost to the operator, and the ability to reschedule portions of the mission. Solving this dynamic multi-objective problem will ultimately provide a real benefit for prognostics and health management.

NASA has invested heavily in prognostic technologies, partially evidenced by the development of their "Integrated Vehicle Health Management Technical Plan: *Automated detection, diagnosis, prognosis to enable mitigation of adverse events during flight*," December, 2008 [1]. The document was developed to define the rationale, scope and detailed content of a comprehensive Aviation Safety, Integrated Vehicle Health Management research project. It contains references to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The stated goal of the Integrated Vehicle Health Management (IVHM) project is to develop validated tools, technologies, and techniques for automated detection, diagnosis and prognosis that enable mitigation of adverse events during flight. These goals align with their Aviation Safety Program goals which include the following: Develop technologies, tools, and methods to i) improve aircraft safety for current and future aircraft, ii) overcome safety technology barriers that would otherwise constrain the realization of the Next Generation Air Transportation System, and iii) support space exploration activities, such as enabling self-reliant and intelligent systems necessary for long-duration travel requirements of future space vehicles.

Figure 32 shows the NASA program's technical approach. This figure shows that the research agenda incorporates foundational methods, sub-system specific applications, themes which relate to IVHM tasks, and system level integration. NASA has an integrated five year research program with milestones dedicated to each of the four levels.

A similar research program could be developed for the nuclear industry. These IVHM/ASP NASA goals are surprisingly well aligned with the Nuclear Engineering Enabling Technologies crosscutting D/P goals of the nuclear power industry which include i) improving the safety, reliability, profitability of the ageing nuclear fleet, ii) the next generation of reactors, and iii) advanced fuel cycle facilities. This workshop and session was primarily focused on the Light Water Reactor Sustainability (LWRS) program for the ageing fleet.

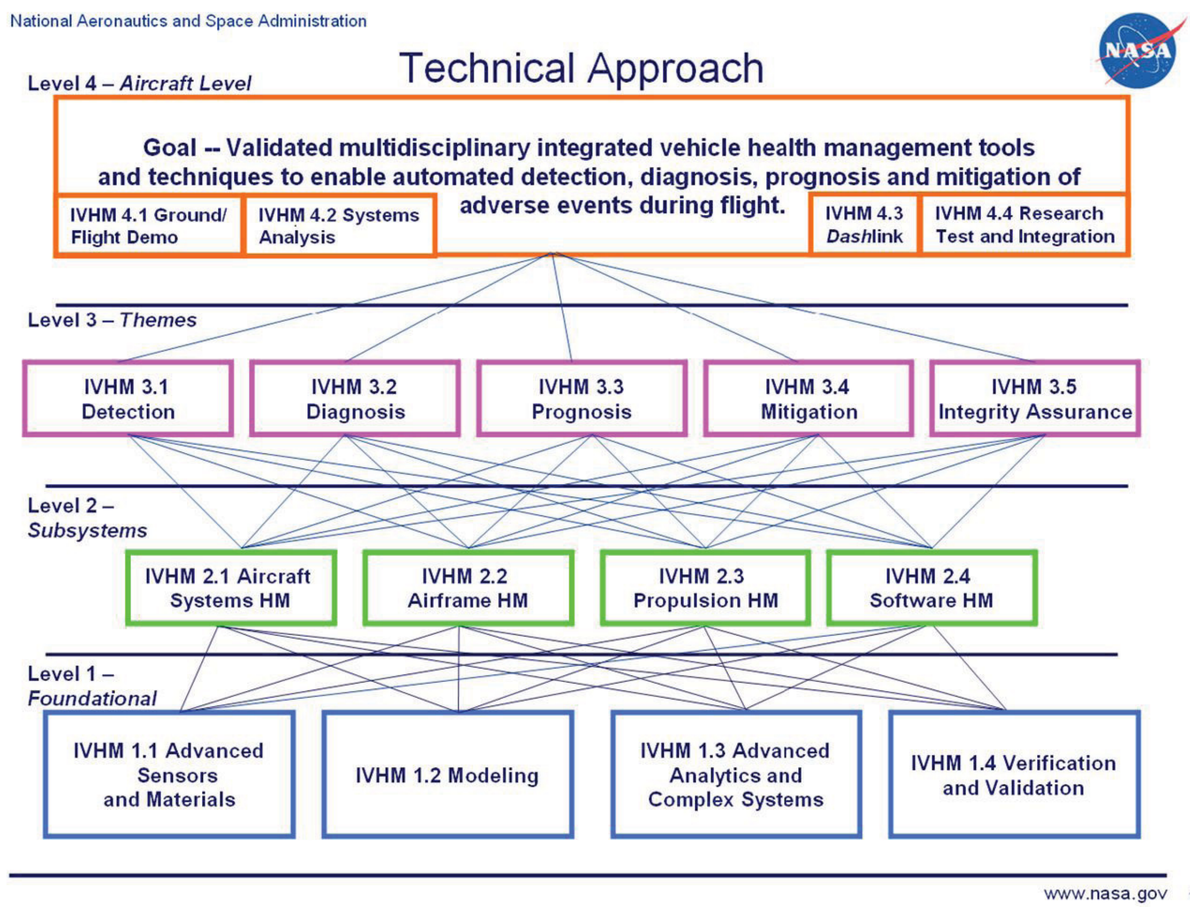


Figure 32. NASA Integrated Vehicle Health Management Technical Plan Technical Approach

4.4 British Energy Experiences

Dave Lillis
British Energy

4.4.1 Overview

Dave Lillis from BE presented the background of the nuclear installation inspectorate permission, a program initiated at Sizewell which has resulted in significant extensions of the duration between calibration in nuclear power plants. Information presented discusses the agreed to paper principle and phased implementation. Mr. Lillis elaborated on the history of the project along with the successes, barriers and methodology associated with the calibration period. The financial costs associated with the daily use and the projected savings of the OLM use were provided as well.

4.4.1.1 Calibration Period Extension History

The following timeline recapitulates significant milestones in the history of the movement toward calibration extension.

- EPRI OLM Since early - 1980s
- NRC SER issued September - 2000
- EPRI OLM User Group Established - 2000
- Sizewell 'B' Joined OLM User Group - 2001
- Sizewell 'B' Paper of Principle to Nuclear Safety Committee - 2002
- Nuclear Installations Inspectorate Permission - March 2005
  - Agreed to Paper of Principle
  - Agreed to a Phased Implementation
- Implementation Commenced - April 2005
- Implementation Completed October - 2009
  - Reactor Protection Pressure & Δ Pressure Sensors
- Post Fault Monitoring & Other Sensor Types – Ongoing.

4.4.1.2 Recent Successes

Among recent successes in work at BE is an increase in the calibration period designed to reduce unnecessary calibrations. Currently, plant personnel expend about 5000 man hours per 18 months in sensor calibrations. Data gathered have shown that there is increased reliability when sensor calibration is reduced. Analysis of the data indicates technician-driven errors accounted for a significant reduction in reliability, with between 2 to 3% of sensors incurring maintenance-induced defects during unnecessary calibrations. A significant reduction in workload, up to 75%, improves work health without having to send workers into the containment area, reducing radiological dose. This reduction supports the 20 day outage effort as well. Historically, every-18-months calibration frequency led to a 25-day outage for instrumentation calibration.

Another successful endeavor involves extending the drive-extended calibration period for safety-related (tech spec) sensors from once every two years to once every eight years. The utility provides on-line monitoring system to monitor all sensors. The proposed plan is to calibrate one set. The process began with an examination of existing safety cases, prompting an alternative calibration strategy. Under this monitoring and calibration system, the final decision as to whether to wait for the next cycle or to go in immediately and perform a calibration is left to engineering judgment.

In the process of moving to an unattended calibration monitoring system, the program encountered issues with British regulators. Lack of sufficient evidence of successful unattended operation presented a significant barrier. This created a circular argument as the utility could not operate with an unattended operation to generate the data required to prove the safety of the new regime to the regulators. Hence, the move forward has become a procedural, rather than a technical problem.

Implementation of OLM has begun for pressure and differential-pressure sensors in the plant. The challenges faced have been difficulties with management sign-on and initial funding. Cost/benefit questions abound as to potential saving as well as quantifying the improvements gained from technology implementation. Management has shown little desire to be the first utility to invest in these changes.

4.4.2 Calibration Extension Methodology

Several significant results occur as the result of an increase in the calibration period such as:

- Reduction in unnecessary calibrations: currently expend about 5000 man hours per 18 months
- Increase in reliability with fewer operator induced errors: About 2-3% of sensors incur maintenance induced defects
- Reduction in workload: Up to 75%
- Reduction in radiological dose: 5 man.mSv (500 man.mrem) per cycle
- Support of a 20 day outage: 18 month calibration frequency = 25 day outage for transmitters alone.

The basis of the methodology was the implementation of EPRI Topical Report (TR-104965-R1 & NRC Safety Evaluation Report). This called for an extension of the calibration period for safety-related (Tech Spec) sensors from once every two years to once every eight years. Key elements included the provision of an On Line Monitoring system to monitor all sensors and calibrate one safety train per cycle rather than four, as well as others identified from OLM.

The implementation strategy consisted of two components: examination of existing safety cases and provision of alternative calibration strategies. The examination of existing safety cases involved gathering historical data, performing drift analysis on the data, examining reliability impacts, and making a case for extending the calibration period. The alternative calibration strategy provided a secondary means for initiation of calibration when necessary. This strategy consisted of gathering sensor data on-line and performing data analysis. During each plant shutdown cycle, a single train of sensors are calibrated along with any sensors indicating a predicted degradation.

Initial implementation required some forethought when transitioning from the old calibration strategy to the new. The concern was driven by regulatory issues based on insufficient evidence of unattended operation. Figure 33 illustrates the revised implementation strategy for initiating the calibration extension.

Train	RFO6	RFO7	RFO8	RFO9	RFO10	RFO11	RFO12	RFO13
1	Calibrate	OLM	OLM	OLM	Calibrate	OLM	OLM	OLM
2	Calibrate	Calibrate	OLM	OLM	OLM	Calibrate	OLM	OLM
3	Calibrate	Calibrate	Calibrate	OLM	OLM	OLM	Calibrate	OLM
4	Calibrate	Calibrate	Calibrate	Calibrate	OLM	OLM	OLM	Calibrate

Time Now

Figure 33. Revised implementation strategy.

4.4.3 Hurdles and Barriers

Impediments to the change in calibration frequencies began with difficulties in getting management to "sign on, and with problems finding initial funding. Management was naturally interested in costs and had to be persuaded that OLM is a long term insurance investment. It does not "stack-up" against short term issues. A better question would be what is it going to save? Management, particularly managers of nuclear facilities, are conservative and had no desire to be first in adopting a new technology, particularly one that substitutes complex algorithms and statistical models for historically demonstrated and accepted methods. As with all new technologies, these changes required additional skills in the workforce and imposed additional costs.

What was needed was some early wins. Once proponents were able to provide evidence that OLM works, saves money, and is not a science project or an insurance scam, the results were positive. Management came to accept the advantages and, in particular, the cost benefits. But as might be expected, management acceptance was reflected in reluctance in the workforce. Workers are likely to see automation, computerization, and reduction in any calibration frequency as a staff reduction program.

Additionally, the proponents of the new system faced regulator concerns. Some of these were technical. Regulators worried that OLM is only carried out at a single operating point. This suggests a potential impact on reliability and channel uncertainty calculations. A single point of operations can represent a potential common mode of failure or provide an unrevealed time dependent fault.

Regulators also worried that key skills might be lost due to the reduction in work. They feared an increasing reliance on expert vendors. Beyond this, the replacement of human observers with online monitors raised concerns about computer software integrity and security, cyber security (arising either from an accidental or an intended attack). V&V was not proven, nor was the availability and reliability of commercial off-the-shelf software.

Underlying concerns about included worries that OLM is typically not applied to safety equipment or the processes on which diagnosis of the condition and operability of safety equipment depends. It could be inferred that claims of reliability for the results provided by the monitoring systems may be determined by the very systems whose reliability remains to be demonstrated. False confidence in the results could be detrimental if the software "gets it wrong."

IT issues are often cited, but BE's experience was that each problem has a solution. For example, RTD Dynamic Cross Calibration is a solution, but the OLM application runs on PC under Microsoft Windows. The question could be raised, what happens if the application has an implementation error? The solution is to build diverse models in Excel. It is a legitimate concern that the operating system could compromise the application. This is solved by running the same application on a Macintosh operating system and comparing results, thus further demonstrating reliability. Of course, it is important to subject the software application to statistical testing in order to demonstrate software integrity and to prove software intact prior to each use. Finally, it is vital to prove the data/signal thread prior to each use, by subjecting the software to standard test cases.

4.4.4 OLM Finances

Figure 34 and Figure 35 illustrate the financial costs and benefits of OLM during a scheduled plant outage (refueling).

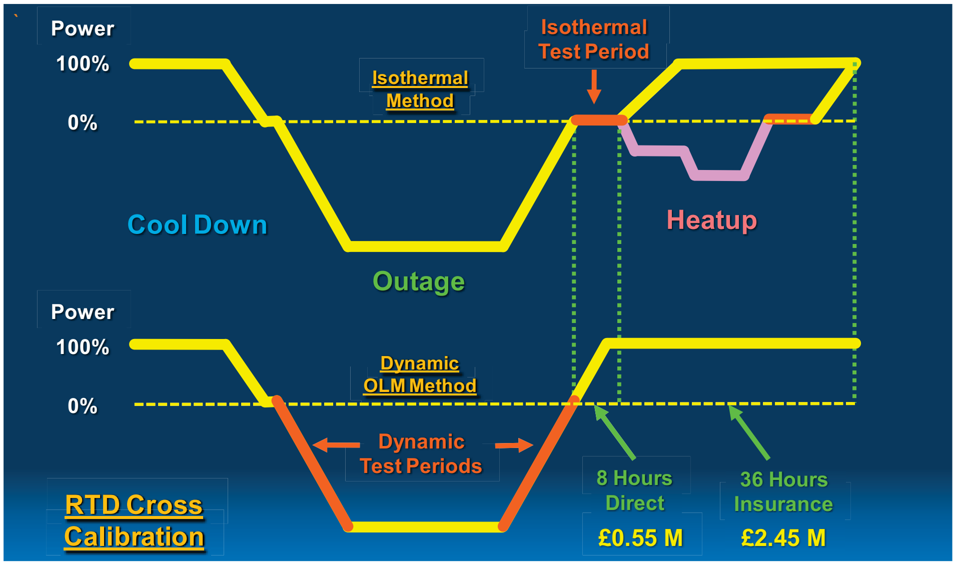


Figure 34. Comparison of RTD calibration events scheduled during a plant shutdown.

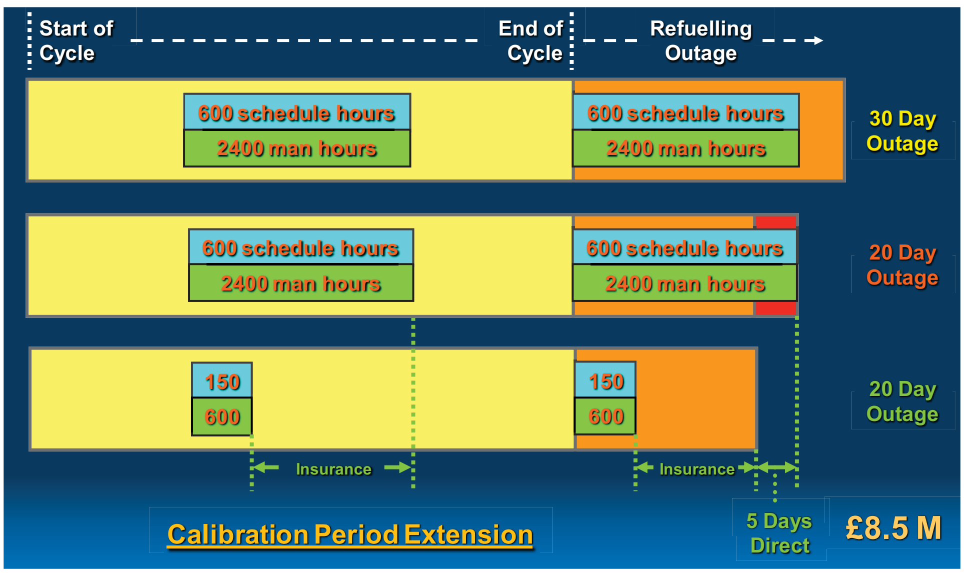


Figure 35. Labor and work hour schedule comparison of the RTD calibration period extension.

The paybacks associated with the use of OLM include the identification of plant instrument anomalies. The advantages included:

- RCS Flow adjustment by operations was able to be eliminated
- Pressurizer-level transmitter temperature bias was identified
- Feed and steam flow spatial bias were identified and corrected.

Additional information about instrument health could be obtained by looking at data statistics and quality, for example:

- RCS flow anomalies
- Onset of instrument line blockage.

The bottom line was OLM is cost effective. The calibration period extension can save more than 8.5 million pounds (i.e., upwards of 13 million dollars) per fuel cycle. Additionally, dynamic RTD cross calibration has saved £10 M ($15 million) since 2003. The costs are shown in greater detail in Table 10.

Table 10. Financial costs associated with British Energy's implementation of OLM.

Data		
Generation Costs		£42 ($70) MW/Hr
Daily Cost (Normal)		£1.26 M ($2.1 M)
Daily Cost (Outage)		£1.65 M ($2.75 M)
Saving from OLM already Implemented		
Dynamic Cross Calibration		
Direct Saving (8 Hours)		£0.55 M ($0.9 M)
Insurance (36 Hours)		£2.45 M ($4.1 M)
Calibration Period Extension		
Direct Savings (5 outage days)		£8.25 M ($13.8 M)
Future Potential OLM Gains	**MW**	**Saving / Yr**
Feed Water Flow Uncertainty	24	£8.4 M ($14 M)
Secondary Calorimetric	4	£1.4 M ($2.3 M)
Feed Temperature	3.5	£1.2 M ($2.0 M)
Cooling Water Optimization	3	£1.1 M ($1.8 M)
Optimize Steam Drainage	2	£0.7 M ($1.2 M)
Potential Savings per Annum		£12.8 M ($21.3 M)

4.4.5 Conclusions

All that Sizewell has accomplished has already been approved for U.S. NPP implementation by the NRC. The technology was developed in the U.S., but only Sizewell has implemented and received the benefits. No U.S. utility has followed suit. The DOE should not fund development activities that have already been completed, but rather assist in overcoming the hurdle of having one U.S. utility be the first to implement the technology and demonstrate it successfully.

No matter what, Sizewell could not reduce the outage period to less than 25 days as this can be seen as a "calibration" elimination. The US industry could be helped by understanding the inability or inappropriateness of cascading the reductions of regulations or calculating the savings. The industry is trying to develop very complex techniques, while simple OLM techniques have never been used. Education on the success of Sizewell is critical. Additionally, it is suggested that the first U.S. OLM implementations remain on non-NRC regulated subsystems.

Interim staff guides (ISG):

- NRC licensing is "plan" oriented. Describe your process and assurance plan
- A need exists to shift from process orientation to result orientation. Move beyond a plan and look at performance
- Life extension should continue to not be tied to licensing. Life extension is the same as licensing for the utility
- Proof is needed for online monitoring. Sell the benefit to utilities
- For passive components, what happens when the pressure vessel runs out of coupons? (taps for testing the metal)
- Problems exist in the electrical system review side of the NRC, a.k.a., licensing uncertainty.

5. SUMMARY AND CONCLUSIONS

5.1 Summary

5.1.1 Path Forward and Direction Setting

Several common themes ran through the three breakout groups. A key theme is education and industry communication. The nuclear industry must be informed on the various changes and benefits that are found in OLM. The information deemed critical to get before management and staff are:

- The cost benefits of OLM. This requires preparation to analyze the various possible uses of OLM, gather the information, and provide examples, such as run-to-failure tasks and verification of data
- The applications where OLM makes sense.

The information is critical for the advancement of the nuclear power plant industry. It was suggested that the advancement and applications of OLM, along with the results of these DOE workshops, be presented at such forums as the ANS Meetings, perhaps as a keynote presentation. Another education and communication recommendation is to hold this type of DOE/NRC/EPRI Workshop on an 18-month cycle.

Other important areas of research in the technical aspects include the following:

- Collecting and documenting Historical Data. Key questions to be addressed include
  - determination if the monitored data is the right data to collect
  - development of techniques to fill in missing measurement gaps.
- Building a failure data library with collaboration from other industries. Key technologies to focus on include:
  - Large motors
  - Petrol/chemical industries
  - DOE communication with the Navy for sharing signature information
  - Acoustics.
- Developing an industry-supported Test-to-Fail facility where equipment failures can be investigated and OLM technologies can be tested and proven. Key deliverables from such a facility include a baseline for OLM (which takes into account variances in plant configurations) and quantifying the appropriate parameters for the physical models of the NPP's.
- Developing the Physics of Failure modeling, including:
  - Signature physics
  - Optimal sensor placement
  - Optimal sensor type with its frequency response, bandwidth, dynamic range, and robustness in harsh environments.
- Developing a Do No Harm approach to OLM implementation, including:
  - Cyber security
  - An understanding of how increased monitoring and communications can affect system operations.
- Identifying where we think our problems are going to be in 30 years, defining critical equipment, both short term and long term, and requesting regulatory guidance
- Structuring a phased approach for incremental buy in by utilities.

5.1.2 Workgroups recommendations and path forward:

The three breakout session groups developed highly consistent lists of priority research and action needs. These needs were focused on:

(1) Modeling the physics of failures

(2) Establishing a test-to-fail facility

(3) Collection of information for the creation of a failure data library

(4) Developing a structured, phased approach to implementing OLM and gaining incremental buy in from the NPPs

(5) Establishing decision-making support for management, including cost-benefit analysis, historical data, and regulatory guidance. In general, there was an emphasis on a need for improvement in the presentation and visualization of information that can be used to improve communication and data sharing (within the plant and throughout the industry) as a suggested research pathway in conjunction of what is mentioned in 5.1.1.

All groups supported the idea that an automated knowledge database system that can help manage information exchange among plants would be desirable. Such a system would include operator tacit knowledge and experience that could be potentially automated for designers and operations.

5.2 Conclusions

The benefits to the nuclear industry from OLM technology cannot be ignored. Information gathered thus far has contributed significantly to the Department of Energy's Light Water Reactor Sustainability Program. DOE has shown great interest in doing what is needed to help this industry to move forward, as indicated by the recent workshop conducted in support of this interest. The Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies provided an opportunity for industry stakeholders and researchers to gather in order to collectively identify the nuclear industry's needs in the areas of OLM technologies, including diagnostics, prognostics, and RUL. Additionally, the workshop provided the opportunity for attendees to pinpoint technology gaps and research capabilities along with fostering future collaboration in order to bridge the gaps identified. Attendees concluded that a research and development program is critical to future nuclear operations. Program activities would result in enhancing and modernizing the critical capabilities of instrumentation, information, and control technologies for long-term nuclear asset operation and management. Adopting a comprehensive On Line Monitoring research program intends to:

(1) Develop national capabilities at the university and laboratory level

(2) Create or renew infrastructure needed for long-term research, education, and testing

(3) Support development and testing of needed I&C technologies

(4) Improve understanding of, confidence in, and decisions to employ these new technologies in the nuclear power sector and achieve successful licensing and deployment.

Appendix A

Workshop Schedule of Events

Thursday June 10, 2010

1:00 pm	Welcome and Introductions	Bruce Hallbert INL
1:20 pm	Logistics and Agenda Review	Facilitator
1:30 pm	Background, Meeting Purpose, Goals and Objectives	Tom Baldwin, Ph.D. INL
2:00 pm	EPRI Research Plan, Gap Report and Strategic Outlook	Rick Rusaw EPRI
2:45 pm	NASA Online Monitoring Experience	Kai Goeble, Ph.D. NASA
3:30 pm	Break	
3:45 pm	Cable Aging Condition Monitoring	Paolo Fantoni OECD Halden Reactor Project
4:30 pm	Overview from IAEA Workshop	Leonard Bond. Ph.D. Pacific Northwest National Laboratory
5:15 pm	Outline remainder of workshop schedule and identify teams for Friday	Facilitator
5:30 pm	Adjourn	

Friday, June 11, 2010

7:00 am	Working Breakfast	Breakout Chairs
7:30 am	OLM Implementation and Regulatory Issues	Hash Hashemian, Ph.D.
7:50 am	Centralized OLM Strategies and Technologies	Ramesh Shankar, Ph.D.
8:10 am	Diagnostics and Prognostics Technologies	Wes Hines, Ph.D.
8:30 am	Breakout Sessions in Parallel	Facilitator

- Breakout 1: OLM Implementation and Regulatory Issues — Hash Hashemian, Ph.D.
- Breakout 2: Centralized OLM Strategies and Technologies — Ramesh Shankar, Ph.D.
- Breakout 3: Diagnostics and Prognostics Technologies — Wes Hines, Ph.D.

10:00 am	Break	

10:15 am	Continue Breakout Sessions.	Facilitator
12:00 pm	Working Lunch – Prognostics & Health Management: Challenges and Ways Forward	Piero Baraldi, Ph.D. Dept. of Energy, Politecnico di Milano
1:00 pm	Continue Breakout Sessions.	Facilitator
3:00 pm	Break.	
3:15 pm	Presentation Development.	Breakout Teams
5:00 pm	Adjourn	

Saturday, June 12, 2010

7:30 am	Networking Breakfast	Workshop Participants
7:50 am	Introduction to Breakout Presentations	Facilitators
8:00 am	Presentation, Q&A Group 1.	Group Selected Spokesperson
8:40 am	Presentation, Q&A Group 2.	Group Selected Spokesperson
9:20 am	Break	
9:35 am	Presentation, Q&A Group 3	Group Selected Spokesperson
10:15 am	Path Forward	Technical Chair & Facilitators
11:45 am	Wrap-up and Thank-you	Workshop Leader
12:00 pm	Adjourn	

Appendix B

Workshop Attendees

Name	Organization
Tunc Aldemir	Ohio State University
Sergey Anikanov	Westinghouse
Tom Baldwin	Idaho National Laboratory
Piero Baraldi	Politecnico di Milano
Randy Bickford	Expert Microsystems, Inc.
Gautam Biswas	Vanderbilt University
Tom Blue	Ohio State University
Leonard Bond	Pacific Northwest National Laboratory
Neil Brooks	FirstEnergy Nuclear Operating Company
Jamie Coble	University of Tennessee
Abhijit Dasgupta	University of Maryland
Michael Fallin	Constellation Energy Nuclear Group, LLC
Paolo F. Fantoni	OECD Halden Reactor Project
Kai Goebel	NASA
Alireza Haghighat	University of Florida
Bruce Hallbert	Idaho National Laboratory
Dr. H. M. Hashemian	Analysis and Measurement Services Corporation
Gyunyoung Heo	Kyung Hee University
Wes Hines	University of Tennessee
Paul J. Hunton	Westinghouse Electric Company
Mark Jekel	Northrop Grumman
Jung Taek Kim	Korea Atomic Energy Research Institute
Dave Lillis	British Energy
Frank Lipinski	Entergy Services, Inc.
Charlie McCarthy	Northrop Grumman Corp.
Ryan Meyer	Pacific Northwest National Laboratory
Davide Roverso	Institutt for energiteknikk
Rick Rusaw	Electric Power Research Institute
Rudy Shankar	Tennessee Valley Authority

Brent Shumaker	Analysis and Measurements Services Corporation
Dr. Carol Smidts	Ohio State University
Samy Tawfik	Idaho National Laboratory
Charles Tolle	Idaho National Laboratory
Belle Upadhyaya	University of Tennessee
Mike Waterman	US Nuclear Regulatory Commission
Graeme West	University of Strathclyde