LWRS Newsletter
Light Water Reactor Sustainability
Issue 21 • July 2016

Introduction

Kathryn A. McCarthy
Director, LWRS Program Technical Integration Office

Welcome to the 21st issue of the Light Water Reactor Sustainability (LWRS) Program newsletter, which features the following articles highlighting recent program accomplishments:

Modeling of the Reactor Core Isolation Cooling Response to Beyond Design Basis Operation: One observation from the Fukushima Daiichi accident was that the reactor core isolation cooling terry turbine-pump in Unit 2 operated in unregulated mode after loss of direct current power and provided core cooling for days longer than expected. If this mode of operation can be successfully exploited by plant operators, additional operational flexibility and improved safety could be achieved. A first step in exploring this option is development of a simulation model to explore operation of the terry turbine-pump under a full range of potential scenarios. This involves developing a dynamic and mechanistic system-level model of the terry turbine-pump system that is capable of predicting system performance for reactor core isolation cooling and turbine-driven auxiliary feedwater applications under beyond-design-basis conditions.

Nuclear Electronic Work Packages – Enterprise Requirements Initiative: This initiative is a step toward the vision of implementing an electronic work package framework. Electronic work packages will enable immediate paper-related cost savings in work management and provide a path to future labor efficiency gains through enhanced integration and process improvement in support of the Nuclear Promise (Nuclear Energy Institute 2016).

A Business Case for Advanced Outage Management: This article describes recently developed standard methodology for measuring the financial impact of new technologies. This methodology is expected to become a key aspect of how individual utilities quantify the value of proposed new technologies. The methodology is applied to advanced outage management technologies to show how automating outage management functions can save time and money.

In addition, the newsletter features a recent award given to an LWRS Program researcher by Idaho State University's College of Science and Engineering.

Table of Contents

U.S. DEPARTMENT OF ENERGY

Modeling of the Reactor Core Isolation Cooling Response to Beyond Design Basis Operation



Douglas M. Osborn, Randall O. Gauntt, and Michael L. Corradini
Reactor Safety Technologies Pathway

Prior to the accidents at Fukushima Daiichi, performance modeling of key critical components (e.g., the reactor core isolation cooling [RCIC] steam-driven turbine pump and safety relief valves [SRVs]) is based mostly on design basis conditions. Their performance under severe accident conditions is poorly known and largely based on conservative assumptions used in probabilistic risk assessment (PRA) applications. For example, common PRA practice holds that battery power (i.e., direct current) is required for RCIC operation to control the boiling water reactor (BWR) vessel's water level and that loss of direct current power results in RCIC flooding of the steam lines. Flooding of the steam lines is assumed to lead to a subsequent failure of the RCIC system due to two-phase water ingestion into the turbine-side of the pump. This assumption for accident analysis implies that RCIC operation should terminate upon battery depletion, which can range from between 4 and 12 hours. In contrast, real-world observations from Fukushima Unit 2 show that the RCIC function was affected, but not terminated, by uncontrolled steam line flooding. In fact, it provided coolant injection for 3 days.

Similar issues and uncertainties exist for pressurized water reactors (PWRs) and use of the turbine-driven auxiliary feedwater system to feed steam generators (i.e., the same steam-driven turbine pump is used for RCIC and auxiliary feedwater systems).

Use of conservative assumptions regarding equipment functioning as found in PRA applications may limit the anticipated mitigation options considered for emergency operations and severe accident management procedures. Improvements to reactor safety can be realized for severe accident management if real-world performance of critical components (such as the RCIC steam-driven turbine pump) can be more accurately characterized. Improved understanding of this critical component can be realized through a combination of advanced modeling methods (such as those under development in the LWRS Program and as embodied in the U.S. Department of Energy [DOE]/industry-sponsored modeling and simulation projects [e.g., Consortium Advanced Simulation of Light Water Reactors]) and through scaled testing.

This research work focuses on developing a dynamic and mechanistic system-level model of the Terry turbine-pump system that is capable of predicting system performance for RCIC and turbine-driven auxiliary feedwater applications under beyond-design-basis conditions. These applications include two-phase water ingestion into the Terry turbine at various potential reactor operating pressures and characterization of its ability to maintain adequate water injection with sufficient pump head under degraded operating conditions. This model will also demonstrate the self-regulating mode of operations as was observed in the Fukushima Daiichi Unit 2 accident, where RCIC ran uncontrolled and successfully maintained reactor water inventory for nearly 3 days.

Once developed, this first principles' model can be refined through detailed computational fluid dynamics (CFD) models and can be incorporated into a systems-level code for simulation purposes (Figure 1).

Several analytical tools are being applied to investigate RCIC behavior for severe accidents. The tools include reactor system modeling codes, such as MELCOR and RELAP, and CFD codes, such as FLUENT. The primary goal is a mechanistic, system-level model that permits fast execution of long transient simulations (i.e., several hours to days for severe accidents). This will enable simulation capabilities for Fukushima forensic analyses, development of technically defensible severe accident management guidelines/FLEX strategies, and design analysis of potential upcoming RCIC experiments. The intent of using several codes, both system-level and CFD, is to inform and enhance system-level modeling efforts using focused CFD analyses of key components, particularly where lumped-parameter methods and simple hand calculations have limited capability. An example is CFD analysis of the steam nozzles that drive the RCIC turbine. These detailed models can provide better modeling of nozzle performance.

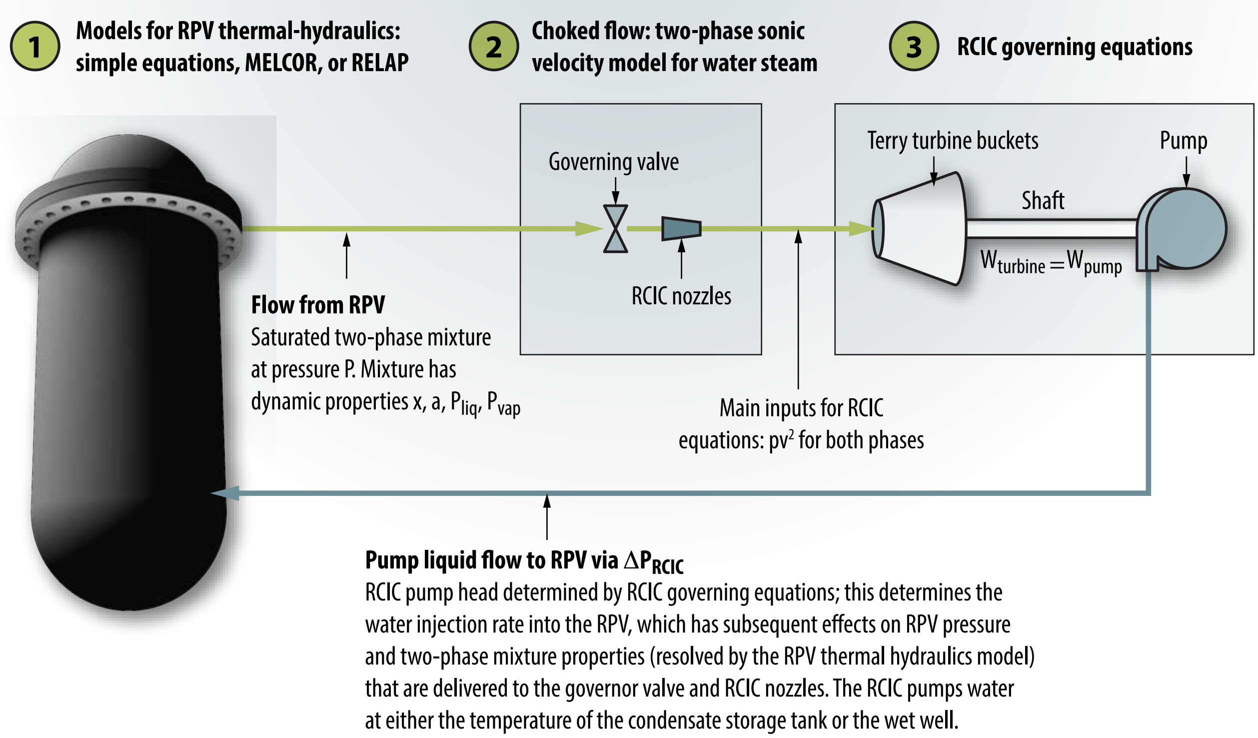
System-level computer codes that are being used to incorporate this model are as follows:

- MELCOR: MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor nuclear power plants. MELCOR is being developed at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission as a second-generation plant risk assessment tool and the successor to the source term code package. A broad spectrum of severe accident phenomena in both BWRs and PWRs is treated in MELCOR in a unified framework. Current applications of MELCOR include the U.S. Nuclear Regulatory Commission-sponsored state-of-the-art reactor consequence analyses and the DOE-sponsored Fukushima Daiichi accident analyses.
- RELAP5-3D: RELAP5-3D is a system-level, two-phase, thermal-hydraulic code used in transient analyses of nuclear power plant systems. It is a general systems code for use in design basis accident analyses and a range of other thermal-hydraulic analyses. RELAP5-3D has been developed by Idaho National Laboratory (for DOE's Office of Nuclear Energy) to simulate BWR and PWR thermal-hydraulic responses during nominal and off-nominal operation.
- RELAP-7: RELAP-7 is the nuclear reactor system safety analysis code currently under development at the Idaho National Laboratory for the Risk Informed Safety Margin Characterization Pathway as part of the LWRS Program. It is an evolution in the RELAP-series reactor systems safety analysis applications. The RELAP-7 code development is taking advantage of progress made in the past three decades to achieve simultaneous advancement of physical models, numerical methods, coupling of software, multi-parallel computation, and software design.

A first principles model of the Terry turbine-pump system was developed for a RCIC BWR design and was tested by incorporating it into the MELCOR systems level code. To demonstrate its usefulness, an accident scenario that is

Continued on next page

Figure 1. Simplified representation of physical coupling of the test model.



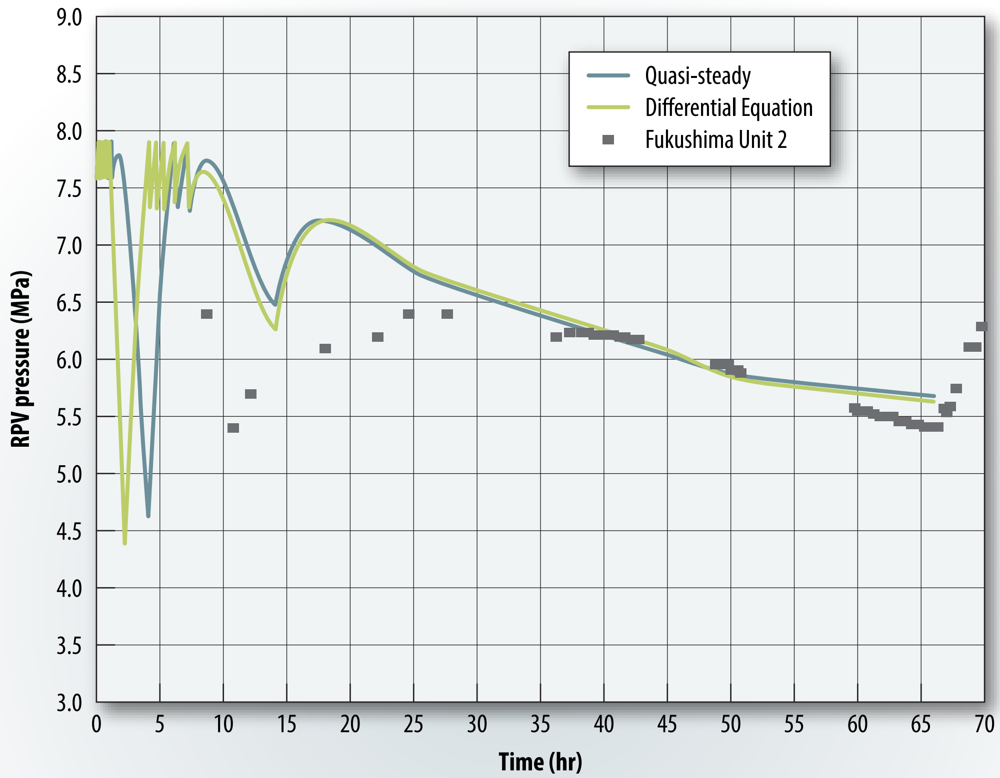


Figure 2. RPV pressure for the first principles model (differential equation), the RCIC-MELCOR test model (quasi-steady), and Fukushima Unit 2 data.

Continued from previous page

comparable to Fukushima Unit 2 was chosen. No 'tuning' or rigorous benchmarking against data was attempted here. There are still too many unknown and uncertain model parameters (e.g., bucket angles and velocity coefficients) for such an effort to be meaningful. Moreover, available plant data are sparse. Instead, test calculations are deliberately performed for a non-Fukushima model to demonstrate that the models have not just been forced to agree with the Fukushima data. For example, the model demonstration uses an arbitrary power level of 2,000 MW and boiler properties from the Peach Bottom state-of-the-art reactor consequence analyses, including relatively high SRV set points.

The test calculation is an extended station blackout, where reactor scram occurs at t = 0. The only credited safety systems are RCIC and the automatic SRV operation. After t = 1 hour, the RCIC is allowed to run uninhibited by any controllers (i.e., no operator throttling or automated trips); its behavior is resolved entirely from the Terry turbine-pump model that has been incorporated into the MELCOR thermal-hydraulic calculations. The calculations assume that the governor valve is opened fully at 1 hour and all water injection by the RCIC pump flows to the reactor pressure vessel (RPV); this means no water is diverted back to the condensate storage tank. The RCIC pump initially takes suction from the condensate storage tank, which has a water temperature of about 290 K, and switches over to the wet well, which is assumed to occur at 14 hours in the test calculations. At this time, the wet well pool water is assumed to have a temperature of 387 K. Thus, the switchover manifests itself as a sudden and large increase in water temperature that is injected into the RPV by RCIC.

Figure 2 shows calculated RPV pressures compared to plant data for Fukushima Unit 2. In Figure 2, the red line represents the first principles model (differential equation model), which includes the complete differential equation with inertial terms for the Terry turbine-pump system; the blue line represents the simplified first principles model (quasi-steady) incorporated into MELCOR, ignoring the inertial terms in the original differential equation model. The models are predicting key features of the RPV pressure trend that are in reasonable, qualitative agreement with plant data, despite the simple nature of the RCIC-MELCOR model and the deliberate modeling of a non-Fukushima reactor. The first drop in RPV pressure in the models near 2 hours is the result of the RPV filling rapidly due to full RCIC operation, which is more than capable of handling the decay heat and refilling the vessel, especially with the governor valve fully opened and no recirculation of injection water. RPV overfill is typically prevented either by operator throttling (e.g., recirculation of water back to the condensate storage tank or wet well via the test and recirculation lines), or by automatic high-level detection that trips the RCIC, neither of which are included in the Fukushima test calculations. During the first hour of the Unit 2 accident, the RCIC was started and stopped at least two times, possibly due to water high-level and manual restarts. The operators may have throttled injection before they lost all direct current power due to the tsunami. The operators had restarted RCIC just before the tsunami arrived, and it appears to have run until at least 66 hours after scram. The calculations corroborate the notion that the system may have operated in a self-regulating fashion for most of this time period.

The calculations predict complete RPV flooding to the main steam line elevation near 3 hours. After the RPV water level reaches this elevation, significant saturated water is ingested by the turbine and void fraction at the nozzles decrease, which results in an immediate reduction in RCIC speed and a sharp increase in RPV pressure back to the SRV set point. This trend is mainly the result of decreasing sonic velocity at the nozzles due to increased liquid content in the two-phase mixture. In general, the critical velocity for saturated water and steam (i.e., a two-phase, one-component system) decreases with increasing liquid fraction as the mixture expands through a nozzle. Thus, the momentum flux that drives the turbine decreases considerably.

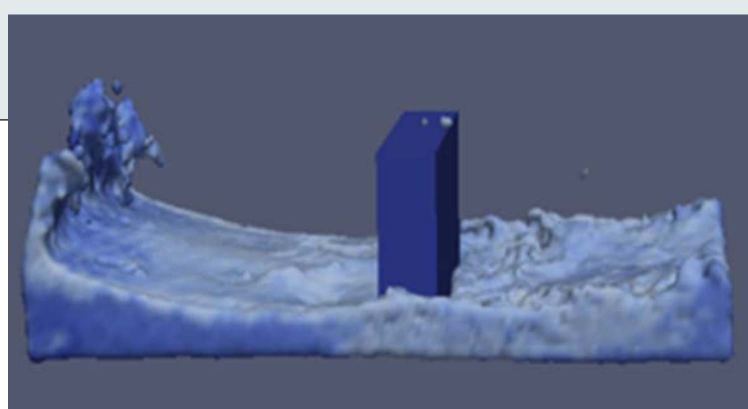
This same Terry turbine-pump model can be incorporated into a RELAP system model. This was done for RELAP5-3D. In our current efforts, the Sandia Terry turbine-pump model is being incorporated into RELAP-7. During this fiscal year, the focus of the effort is to complete the RCIC model to analyze behavior under normal working conditions. More complex off-design conditions will be pursued subsequently. In the Sandia model, the turbine nozzle inlet velocity is provided according to a first principles model, which was obtained from a series of CFD simulations. The RELAP-7 model will use an under-expanded jet model to obtain the velocity and thermodynamic conditions for the turbine stator inlet, which is simple and generic.

Outstanding Student Award – Idaho State University College of Science and Engineering

Emerald D. Ryan
Risk Informed Safety Margin Characterization Pathway

Emerald D. Ryan, an Idaho State University (ISU) student, received the College of Science and Engineering Outstanding Student Award. As noted by the President of ISU, Dr. Arthur Vailas, "This is a prestigious student award presented by Idaho State University." Emerald received this award, in part, for her work supporting the LWRS Program in the area of smoothed particle hydrodynamics for simulation of flooding scenarios. Over the previous 2 years, she has contributed to several technical LWRS Program-related deliverables within the Risk-Informed Safety Margin Characterization Pathway, including progress on industry applications (i.e., external events) and modeling and simulation on river-based flooding scenarios.

Emerald graduated from ISU in the fall of 2015 with a dual major in mechanical engineering and nuclear engineering. She has accepted a position as a graduate research assistant with ISU and will continue her work supporting the LWRS Program under the research led by Professor Chad Pope. Her research focus will be on application and validation of smoothed particle hydrodynamics-based methods for advanced computational risk analysis.



The Nuclear Electronic Work Packages – Enterprise Requirements Initiative

Johanna H. Oxstrand and Aaron D. Bly
Advanced Instrumentation, Information, and Control Systems Technologies Pathway

Today's society is very reliant and more efficient thanks to computer-based tools. Gone are the days when purchasing new equipment meant paging through a paper catalog, transcribing product numbers, and calculating totals. Today, a consumer can find a product online with a simple search engine and then purchase it with a few "clicks." Paper catalogs still have their place, but it is hard to imagine life without online shopping sites.

All tasks conducted in a nuclear power plant are guided by instructions or work orders that help ensure safe and reliable operation. Paper-based work packages contain items such as work instructions, various forms, drawings, and material requirements. These work packages are like paper catalogs. A field worker may carry a large stack of documents needed to complete a task in the field. The paper-based work package process currently used by most utilities has a demonstrated history of ensuring safety; however, improving the process could yield significant savings in increased efficiency, use of paper, and improved safety through human performance gains. Paper work packages are static (i.e., the content does not change after the document is printed), difficult to search, and rely heavily on the field worker's situational awareness and ability to consistently meet the high expectation of human performance excellence.

The commercial nuclear industry is working to reduce operation and maintenance costs as they continue operating in competitive energy markets. Computer-based or electronic work package (eWP) systems are one means of reducing administrative burdens and costs by reducing the use of paper and making the process more efficient. An eWP system would enable more effective and efficient completion of work in the nuclear power industry.

Thomas, Lawrie, and Niedermuller (2015) recently developed a business case for dynamic electronic work orders for the nuclear industry. They concluded that, in the future, approximately $3.5M (about $3.3M of harvestable labor savings and $0.2M of non-labor savings) could be saved annually by using an eWP system, which would allow an investment of over $20M in present terms. However, it is important to point out that potential cost savings will depend on the solution and its specific implementation. The main cost-saving opportunities identified in the business case are from reduced human errors and more streamlined work processes. This business case focused on a system for field workers and maintenance technicians.

Instead of navigating through a maze of cross references, computer-based tools enable intelligent work path navigation that accounts for past decisions and observation, thereby enabling more efficient and safe task completion. In other words, a streamlined work process and dynamic support to guide the worker through task execution will help them focus on the task at hand rather than on the process.

LWRS Program research has been producing functional requirements and design concepts for automated work packages and computer-based procedures for workers in the field since 2012. This research has demonstrated that work orders (and hence the eWP system) have to be more dynamic than presenting a paper copy on a screen in order to provide significant efficiency and human performance improvements. As a result, vendors who offer solutions for eWPs and work orders are beginning to incorporate design concepts that have been developed and demonstrated through this research.

The Nuclear Electronic Work Packages - Enterprise Requirements (NEWPER) initiative is a step toward a vision of implementing an eWP framework that includes many types of eWPs. This will enable immediate paper-related cost savings in work management and provide a path to future labor efficiency gains through enhanced integration and process improvement in support of the Nuclear Promise (Nuclear Energy Institute 2016).

The NEWPER initiative is organized by the Nuclear Information Technology Strategic Leadership (NITSL) group, which is an organization that brings together leaders from the nuclear utility industry and regulatory agencies to address issues involved with information technology used in nuclear power utilities. NITSL strives to maintain awareness of industry information, technology-related initiatives, and events and communicates those events to its membership. NITSL and LWRS Program researchers have been coordinating activities, including joint organization of NEWPER-related meetings and report development.

The main goal of the NEWPER initiative is to develop a set of utility generic functional requirements for eWP systems. This set of requirements will support each utility in their process of identifying plant-specific functional and non-functional requirements. The overall goals of the initiative are as follows:

- Define core components of an eWP system
- Define functional requirements for these core components, covering the full spectrum of eWPs from basic pdfs to dynamic smart documents
- Share operational experience that is related to ongoing eWP implementation activities in industry (e.g., benefits gained and identified issues)
- Communicate utilities needs and wants to vendors
- Standardize terminology related to eWP and smart documents.

In addition, the NEWPER initiative provides an opportunity for establishing new or reinforcing existing relationships between utilities and eWP vendors.

Currently, the NEWPER initiative has 116 members and the group continues to expand. Figure 3 illustrates the distribution of members. The largest group of members consists of 14 commercial nuclear utilities that represent 70% of the U.S. commercial nuclear industry. The second largest member group includes 10 of the most prominent vendors of eWP solutions, along with two management consultant companies. The "other organizations" group consists of organizations such as the Electric Power Research Institute (EPRI), the Institute of Nuclear Power Operations, and EDF Energy. Three national research laboratories are also included in this group: Idaho National Laboratory, Los Alamos National Laboratory, and Savannah River National Laboratory. In addition to NITSL, the Nuclear Information and Records Management Association and the Procedure Professionals Association are also represented in the member pool.

Activities in NEWPER are mainly conducted via telephone conferences and face-to-face workshops. The NEWPER planning committee (see Figure 4) plans and organizes activities. Arizona Public Service hosted the first NEWPER workshop from December 8 to 10, 2015, in Avondale, Arizona. The 68 participants represented 63% of the U.S. commercial nuclear industry, 12 vendors, and other organizations such as the Institute of Nuclear Power Operations, EPRI, the Advanced Test Reactor at Idaho National Laboratory, and Los Alamos National Laboratory.

The workshop successfully established a dialogue between all parties (i.e., utilities and vendors), where valuable operational experience was shared and ideas and concerns were discussed. The main workshop objectives were to define a vision statement for eWP system implementation, define a common taxonomy for eWPs and the documents included in these eWPs, and identify generic minimum requirements for eWP systems.

The following vision statement was developed during the workshop: "Implement an open eWP framework, which covers the entire eWP spectrum, enabling immediate

Continued on next page

Figure 3. NEWPER member distribution.

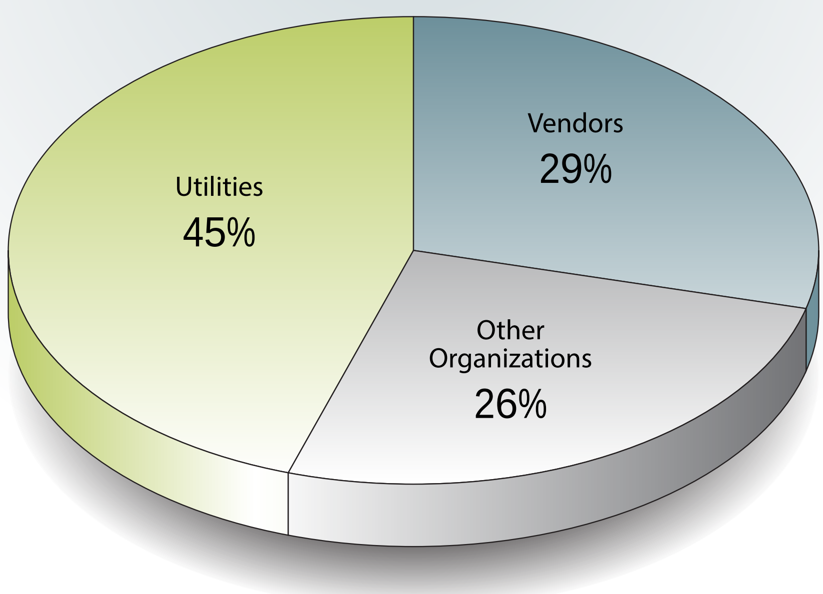


Figure 4. The NEWPER Planning Committee: Pete Muller (Exelon), Carlos Williams (Arizona Public Service), Nick Camilli (EPRI), Aaron D. Bly (Idaho National Laboratory), Bruce Gordon (Arizona Public Service), Eric Jurotich (Southern Company), and Johanna H. Oxstrand (Idaho National Laboratory). Also, the LWRS Program Advanced Instrumentation, Information, and Control (II&C) Systems Technologies Pathway Lead, Bruce P. Hallbert.

Continued from previous page

paper-related cost savings in work management and providing a path to future labor efficiency gains through enhanced integration and process improvement in support of the nuclear promise."

The participants agreed to use a slightly revised version of EPRI's taxonomy for smart documents that is described in EPRI (2015). Figure 5 represents the revised version of the taxonomy. The part of the eWP that is most affected as the level of incorporated technical solutions increases will be the documents. Hence, the taxonomy only refers to documents and not to the work package as a whole.

One of the main differences between the NEWPER taxonomy and EPRI's taxonomy is the exclusion of wireless network needs. It was concluded that other solutions (such as docking stations and Wi-Fi hot spots) could be sufficient for gaining benefits from different types of smart documents. The taxonomy consists of four levels: (1) basic, (2) moderate, (3) advanced, and (4) adaptive. Table 1 summarizes each of the levels.

The identified minimum requirements include an authoring tool, compatibility with legacy plant systems, a human-factored user interface, and the system has to be operational in both online and offline modes. These minimum requirements served as starting point for the next NEWPER activity, where utility generic functional requirements for eWP systems (more specifically for basic and moderate levels of smart documents) were identified.

A second workshop was hosted by EPRI in Charlotte from March 22 to 23, 2016. The purpose of the workshop was for utility representatives to define a set of utility generic functional requirements for an eWP system and capture any non-functional requirements identified in the process.

Two of the participants, Exelon and Los Alamos National Laboratory, have already implemented eWP systems at their sites. These two participants have implemented solutions from different vendors. The operational experience and lessons learned from both Exelon and Los Alamos National Laboratory were very valuable to the exercise of identifying functional requirements.

The outcome of the March workshop was a set of high-level functional requirements for a generic eWP system. A set of more detailed requirements related to each of the high-level requirements was also identified. The 72

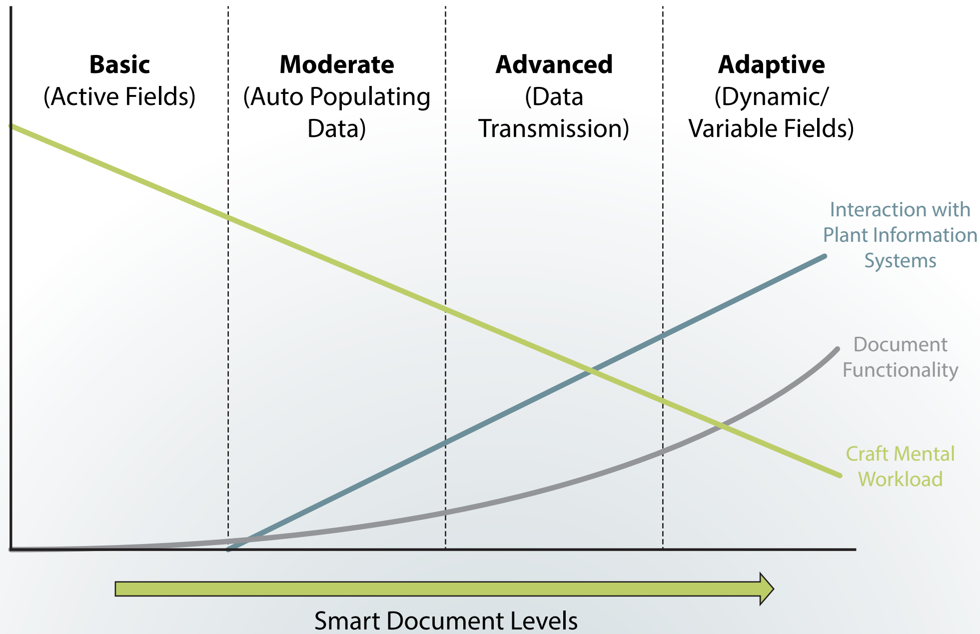


Figure 5. The NEWPER taxonomy for smart documents, which is based on a taxonomy developed by EPRI (2015).

identified high-level requirements were grouped into role-based categories. Table 2 shows most of the categories and examples of high-level requirements:

The immediate upcoming activity for NEWPER will be to communicate the functional requirements that were defined during the March 2016 workshop to all members, including vendors. In addition, the task of identifying requirements for advanced and adaptive smart documents and eWP systems has already been initiated. The LWRS Program's researchers have expert knowledge related to this type of more dynamic documents; therefore, they will be able to provide great support and insights to industry members.

Continued on next page

Table 1. Summary of smart document levels.

Level	Summary
Basic (Active Fields)	The document has fields for recording input such as text, dates, numbers, and equipment status.
Moderate (Automatic Population of Data)	The document incorporates additional functionalities such as form field data "type" validation (e.g., date, text, number, and signature) of data entered and/or self-populated basic document information (usually from existing host application meta data) on the form when the user first opens it.
Advanced (Data Transmission)	The document provides the capability to transmit data entered into other data systems.
Adaptive (Dynamic/Variable Fields)	The document uses variable (i.e., dynamic) field options based on previously completed data entries or links to other electronic documents or media.

Planner	
	Ability to validate that documents are in the most current revision
	Ability to add hold points, critical steps, and other status markers
	Ability to route work package for approvals
Supervisor	
	Ability to create and complete work packages for unplanned tasks
	Ability to assign craft or crew to a work package
	Ability to monitor work and track status during execution
Craft	
	Ability to execute task in the field
	Ability to use the mobile device to conduct a walkdown of the work package prior to work execution to determine workability and acceptability
	Ability to use multiple types of input (e.g., text input, camera, barcodes, and voice-to-text)
	Ability to capture annotations
Operations	
	Ability to create pre-authorization of work order tasks
	Ability to conduct sign-offs prior to task execution
Supporting Functions	
	Ability for recorded inputs/data to be routed to other organizations and users for review
	Ability to coordinate with additional disciplines and teams during work execution via alerts or notifications
	Ability to present task status on an outage control center dashboard for outage management
Records	
	Ability to generate a quality assurance record
	Ability to identify which document types are not retained as quality assurance records
	Ability to capture data points recorded in the work package
Information Technology	
	The eWP application must work in offline mode
	Ability to support multiple form factors (e.g., devices and operation systems)
	Ability for eWP system to interface with legacy systems
	Ability for eWP system to adjust status in work management systems and/or work control systems

Table 2. Examples of high-level requirements for basic and moderate smart documents and eWP systems.

Continued from previous page

The next face-to-face meeting will be a part of the NITSL annual meeting in Charlotte, North Carolina, from July 18 to 21, 2016.

References

EPRI, 2015, "Improving the Execution and Productivity of Maintenance with Electronic Work Packages," EPRI 3002005363, Electric Power Research Institute.

Nuclear Energy Institute, 2016, "Delivering the Nuclear Promise: Advancing Safety, Reliability, and Economic Performance," Nuclear Energy Institute.

Thomas, K., S. Lawrie, and J. Niedermuller, 2015, *Advanced Instrumentation, Information, and Control System Technologies - Pilot Project Technology Business Case*: *Mobile Work Packages*, INL/EXT-15-35327, Idaho National Laboratory, Idaho Falls.

A Business Case for Advanced Outage Management




Bruce P. Hallbert and Kenneth D. Thomas
Advanced Instrumentation, Information,
and Control Systems Technologies Pathway

Sean A. Lawrie and Josef M. Niedermuller
ScottMadden, Inc.

Introduction

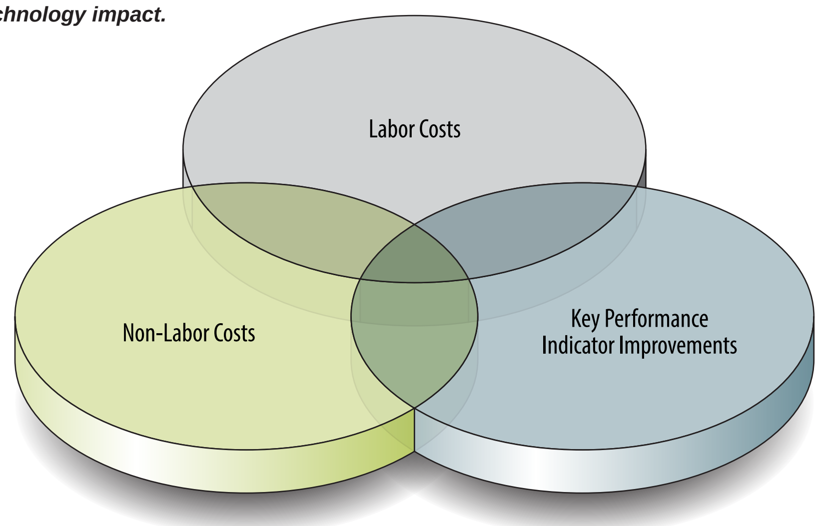
The Advanced Instrumentation, Information, and Control (II&C) Systems Technologies Pathway is conducting a series of pilot projects that enable development and deployment of new II&C technologies in operating nuclear power plants. The performance advantages of these new pilot project technologies are widely acknowledged; however, utilities require business cases for justifying investments in these new technologies. Lack of a business case is often cited by utilities as a barrier to pursuing wide-scale application of digital technologies to nuclear power plant work activities. The decision to move forward with funding usually hinges on demonstrating actual cost reductions that can be credited to budgets and, thereby, truly reduce operations and maintenance (O&M) or capital costs.

Technology enhancements, while improving work methods and creating efficiencies, may fail to eliminate workload that changes overall staffing and material cost requirements needed to conduct necessary work activities. Demonstrating cost reductions or impacts on non-cost performance objectives is critical in order for the business case to justify investments in new technologies by nuclear operators. For these reasons, the LWRS Program has worked with business management consultants in the energy sector to create a standard methodology for measuring the impact of new technologies. This methodology is expected to become a key aspect of how individual utilities evaluate the value of proposed new technologies from the perspective of a business case – that is, the business cost perspectives of long-term asset management.

A business case methodology (BCM) has been developed with the assistance of ScottMadden, Inc. (a management consulting company). The business case has been designed with the goal of valuing the costs and benefits associated

Continued on next page

Figure 6. Key areas of technology impact.



Continued from previous page

with adopting (e.g., procuring and implementing) pilot project technologies to reflect the total organizational benefits that can be derived from the improved work methods (Thomas et al. 2014). This includes considering factors such as the direct benefit to targeted work processes, efficiencies gained in related work processes, and avoided costs through the improvement of work quality and reduction of human error.

This BCM develops a business case for a particular technology or suite of technologies by accounting for how they impact plant staff work activities in one or more of the three following areas: (1) labor costs, (2) non-labor costs, and (3) key performance indicators (Figure 6). A key aspect of those impacts is identifying where the savings are "harvestable," meaning where they result in an actual reduction in the headcount needed to perform work with new technologies and work processes and/or associated other costs (e.g., consumable materials expended to support work).

Impacts to nuclear power plants in these three areas are quantified and built into a comprehensive business case for the adoption of a technology.

The BCM identifies questions to ask, guides the utility through areas of work performance that need to be assessed, and identifies where in the process to employ the BCM workbook (BCMW) for benefits/cost savings identification. This approach enables collaboration between LWRS Program researchers and utility partners who are considering approaches for implementing new digital technologies in individual or across multiple nuclear power plant organizations. The BCM is designed to be suitable for assessing the "economy of scale" that maximizes the value of the technologies relative to implementation cost.

Business Case for Advanced Outage Management

The business case for advanced outage management (AOM) includes technologies being developed in the Advanced Outage Control Center pilot project and predecessor technology projects. This business case was developed during March 2016 and is documented in Thomas et al. (2016). The business case was built in aggregation with a previous business case for mobile work packages, which is documented in Thomas et al. (2015). The AOM business case assumes that outage workers are equiped with mobile work packages.

Considerable effort is expended during outages when monitoring field activities, gathering information, analyzing plans and schedules, and redirecting workforce in order to achieve outage objectives. Modernizing the tools available to managers and field teams can eliminate much of the manual communications and analysis similar to the way that technologies allow us to perform tasks like calling a cab or depositing a check as part of our everyday lives.

Therefore, a set of technologies were identified that, when combined in beneficial ways, can substantially automate these outage management functions, relieving the outage managers and coordinators of these time-consuming tasks. These technologies include the following:

- High-bandwidth wireless networks
- Mobile devices
- Component identification technology
- Mobile wireless video cameras
- Touch-enabled interactive displays
- Computer-based procedures and automated work packages
- Intelligent plant configuration
- Advanced data analytics
- Micro-scheduling
- Meeting collaboration tools
- Team collaboration tools.

An analysis was conducted to determine how these technologies might impact outage operations at a nuclear power plant. An "Opportunity Worksheet" was created to guide users through a process that identifies capabilities' improvements. These improved capabilities were then examined further to quantify the benefits of using the BCMW. The project team identified the following AOM capabilities that are founded on the set of technologies described above:

- Automated status updates – The progress and completion status of field work activities is automatically updated in the Outage Control Center by mobile work package technology without distracting the field workers. This can release dependent downstream work activities with no delay. The net effect is more effective schedule management with less effort.
- Advanced bulk work and schedule analysis – Emerging analytical software will enable a new level of data analysis that will more thoroughly detect schedule problems and resource conflicts (i.e., similar to how humans are able to do this). This software will be able to do this exhaustively for the entire outage activity schedule, uncovering the problems that are typically missed by human analysis and that may later contribute to outage schedule delays.
- Networked meetings (remote access) – Network meetings supported by high-bandwidth wireless networks that display customizable dashboards with real-time status will improve communications and reduce the need for personnel to be physically present in the Outage Control Center. This technology, along with others, can enable an evolving paradigm shift in how a large and fluid

organization stays synchronized in time-critical work with safety implications.

- Networked emergent work teams – This is enabled by a new set of real-time collaboration tools that allow dispersed parties to effectively pool their knowledge and coordinate their activities as work activities transpire.
- Coordination of dispatchable resources – Micro-scheduling, which is a new technology that enables just-in-time scheduling of dispatchable resources, will result in reduced wait times for crews, efficiency gains due to timely dispatch of resources that result in lower required staffing levels, and overtime required to handle variable work load.
- Outage configuration management – New technologies are emerging that can integrate diverse sources of plant configuration information (e.g., plant instrumentation and controls systems), work packages and procedures that are in use, and real-time plant component status that is supplied by new wireless networks to provide status on components that originally did not have such capability.
- Remote job oversight – Technology can play a role in reducing the supervisor's burden without loss of effectiveness through use of remote job oversight capabilities. These include the use of video to observe the job site through any office or portable device.
- Paperless outage coordination – There is an enormous amount of paper usage during an outage to supply printed material for the array of outage meetings. The partner nuclear power plants estimate that they use more than 5,000 pages of paper per day just for an outage control center's functions, not counting what is used in other satellite control centers.
- Bulk work optimization – Because outage bulk work activities use their schedule margin (by not completing by their early finish date), a bow wave of work is created that imposes burdens on the downstream groups that have to absorb the bow wave in a fixed amount of time. The new technologies described above in the advanced bulk work and schedule analysis list item are applicable to this situation.

Business Case Validation with a Partner Nuclear Power Plant

To validate the benefit of these postulated capabilities, a partner nuclear power plant was enlisted to provide feedback on how they would impact outage management as it is conducted today. To prepare for these discussions, an opportunity worksheet was developed and incorporated into the BCMW. A calculation of the benefits was then derived for each of the AOM capabilities listed above.

Once the opportunity worksheet and the BCMW were completed, the results were validated through a series of interviews with plant personnel at a partner nuclear power plant. A list of personnel interviewed is provided in Table 3. In all cases, nuclear power plant personnel confirmed that the results, in their experience, were directionally correct and reasonably accurate if not conservative.

Business Case Results

The study demonstrates the scale of savings that can be achieved when digital technologies are applied to work processes to benefit the nuclear power plant. Costly manual handoffs of information are reduced, communications are in real-time, analysis is supported in real-time by analytical tools, and the risk of a costly outage extension is reduced through better management of the bulk work and improved situational awareness of work

Continued on next page

Table 3. Partner nuclear power plant personnel interviewed during BCM validation.

Work Management Manager	Maintenance Manager – Valves and Civil
Outage Manager	Maintenance Manager – Electrical/Instrumentation and Controls
Shift Outage Manager	Fleet Reactor Services Manager
Shift Outage Manager and Design Engineering Director	Steam Generator Services Manager
Shift Outage Manager and Engineering Director	Plant Modification Supervisor
Work Management Manager	Turbine Services Manager
Operations Supervisor	Reactor Engineering Supervisor
Operations Shift Manager (2)	Radiation Protection Manager
Chemistry Supervisor (2)	Radiation Protection Supervisor
Performance Improvement Manager	

Continued from previous page

activities. In addition, the partner nuclear power plant confirmed that, on average, one day of an outage length overrun could be prevented through application of these capabilities; this does not include labor savings. This has substantial benefits in reducing replacement power costs for a full day, as well as releasing a significant portion of the outage contractors a day early. The combined business case indicates that a typical two-unit plant can save in excess of $7.7M annually in O&M costs. A summary of the annual savings is presented in Figure 7.

All labor savings identified and attributed to AOM were considered harvestable. Harvestability is defined as the fraction of cost savings that can be taken as budget reduction. When examining online labor, labor savings are only considered harvestable if they result in a reduction in work force. However, because AOM applies to outage work, it is assumed that all work force reductions would be accomplished through reduction of contracted labor, augmented staff, and overtime. As such, 100% of labor savings attributable to AOM is harvestable, even though no reduction to the standard organization is envisioned. Moreover, an ancillary benefit of allowing staff to move out from the control centers and into the field is that their expertise and the power of observation can influence work performance in a positive way.

Figure 8 provides a breakdown of labor savings by site organization.

Non-labor savings were largely estimated in the following three categories:

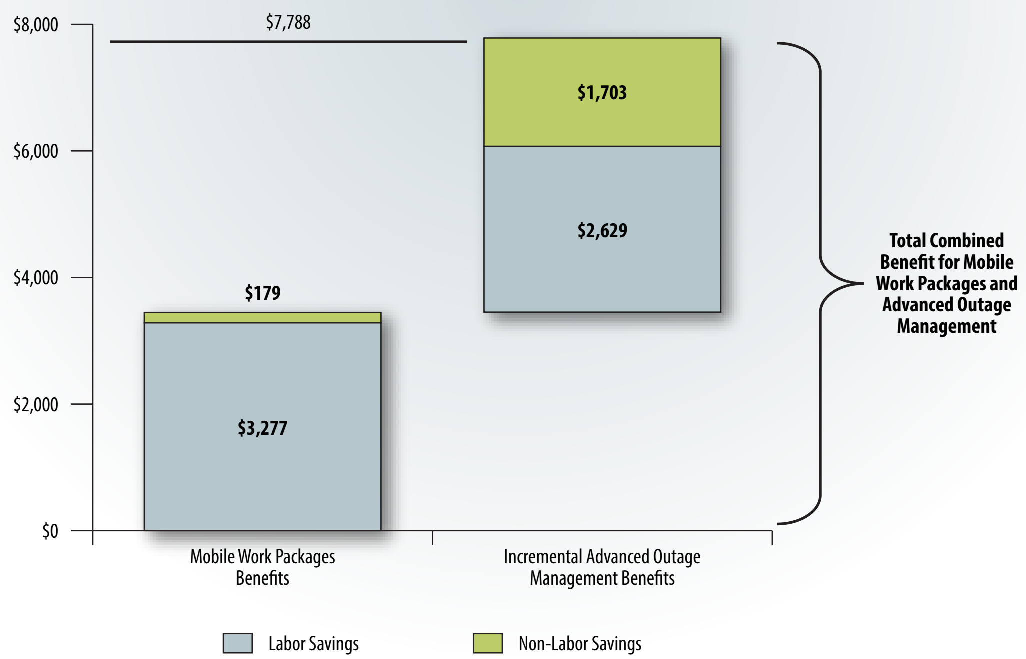
1. Elimination of paper in work processes
2. Avoidance of contractor costs due to outage extension
3. Avoidance of purchasing replacement power due to outage extension.

Paper savings were largely estimated due to the elimination of printed work packages, drawings, schedule updates, and meeting presentation materials and the corresponding reduction of consumable office products that include, but are not limited to, paper, printer and plotter consumable supplies, and printer and plotter maintenance. An all-in rate of 10 cents per standard sheet of paper was used as the cost of consumable produce paper deliverables.

Reduction in contractor labor costs is driven by better bulk work management and reduced risk of schedule extension. It is estimated that 30% of contractors will be released on the date originally planned due to improved bulk work schedule adherence.

In addition, schedule adherence and timely restart of the nuclear power plant also allows the operator to avoid costly purchases of replacement power. Replacement power was roughly estimated at $400,000 per day.

Figure 7. Business case annual O&M benefits ($000s).



Finally, the following key performance indicators were positively impacted:

- Production cost ($/megawatt-hour) – direct reduction of O&M expenses related to field work activities and more generation days due to shorter outages
- Unit capability factor – shorter refueling outages due to improved work coordination
- Radiation exposure – improved coordination efficiencies and less wait time for work activities performed in radiation areas.

Conclusion

There is a substantial business case for nuclear utilities to implement AOM technologies in conjunction with mobile work package technologies. The annualized savings and the present value of these savings should be more than sufficient to justify the costs of implementation. The AOM BCMW delineates the savings attributed to each individual capability that is described in the opportunity worksheet, thereby describing the proportional benefit that can be expected for partial implementation of the AOM technologies. Further, many intangible benefits (such as worker satisfaction and reduced manager burden) are not fully accounted for in the analysis. Finally, there are beneficial impacts on the nuclear power plant's key performance indicators.

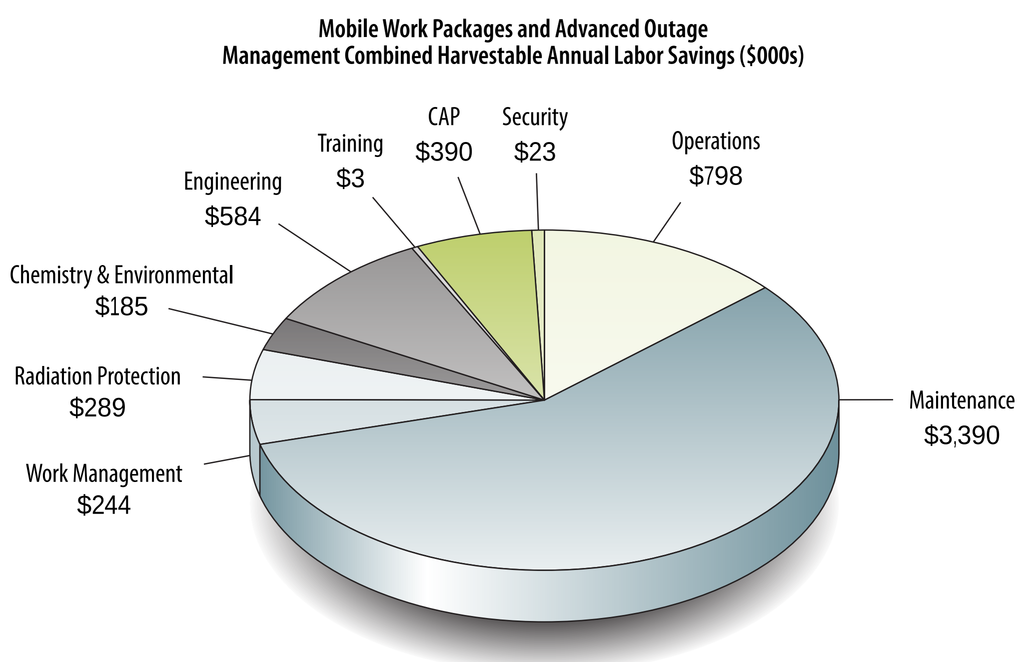
This business case substantiates a fundamental assertion in formulation of the pilot projects for the LWRS Program's Advanced II&C Systems Technologies Pathway (i.e., the benefits of the technologies for the individual pilot project are accretive when aggregated to address complementary functions in nuclear power plant operations and maintenance). The BCM was specifically designed to be able to capture the leveraged effect of multiple business cases working together. In this particular study, the AOM business case is significantly improved when built on top of the mobile work package business case.

Through publication of the findings in this business case study and the availability of the BCMW, the nuclear industry is provided with a sample business case for pilot project technologies that can be used as a template for pursuing similar implementations at other nuclear power plants.

References

1. Thomas, K., S. Lawrie, C. Vlahapolis, and A. Hart, 2014, *Digital TechnologyBusiness Case Methodology Guide*, INL/EXT-14-33129, Idaho National Laboratory.
2. Thomas, K., S. Lawrie, and J. Niedermuller, 2016, *A Business Case for Advanced Outage Management*, INL/EXT-16-38265, Idaho National Laboratory.
3. Thomas, K., S. Lawrie, C. Vlahapolis, and J. Niedermuller, 2015, *Pilot Project Technology Business Case: Mobile Work Packages*, INL/EXT-15-35327, Idaho National Laboratory.

Figure 8. Business case annual labor savings by site organization.



Recent LWRS Program Reports

Technical Integration Office

- ***Light Water Reactor Sustainability Accomplishments Report 2015***
- ***Light Water Reactor Sustainability Program Integrated Program Plan***
- ***DOE-NE Light Water Reactor Sustainability Program and EPRI Long Term Operations Program – Joint Research and Development Plan***

Materials Aging and Degradation

- ***Finite Element Analysis Based Thermal-Mechanical Stress Analysis of PWR Pressure Vessel with/without Pre-existing Crack to Study the Effect of Cyclic Hardening Material Properties Under Grid Load Following Mode: An Interim Report***
- ***Thermodynamic and Kinetic Model Development of Thermal Segregation of Phosphorus in Iron, Fe-Cr, and Fe-Ni Systems – Towards the Development of a Comprehensive Solute Segregation Model***
- ***Modeling Late Blooming Phase Evolution during Post-irradiation Annealing in Select Reactor Pressure Vessels: Milestone 2 Report***
- ***Mechanical Properties of Model Cast Austenitic Stainless Steels after Thermal Aging for 1500 Hours***
- ***Linear Array Ultrasonic Test Results from Alkali-Silica Reaction Specimens***
- ***Progress in Characterizing Naturally Aged Nuclear Power Plant Cables***
- ***Evaluation of Localized Cable Test Methods for Nuclear Power Plant Cable Aging Management Programs***
- ***Effect of Thermo-Mechanical Processing and Aging on the Stress Corrosion Cracking Resistance of Alloy 690***

Risk-Informed Safety Margin Characterization

- ***RAVEN Beta 1.0 Release***
- ***RAVEN User Manual***
- ***Grizzly Usage and Theory Manual***
- ***Development Plan for the External Hazards Experimental Group***
- ***RISMC Toolkit and Methodology Research and Development Plan for External Hazards Analysis***
- ***RELAP-7 Pressurizer Component Development Updates***
- ***R&D Plan for RISMC Industry Application #1: ECCS/LOCA Cladding Acceptance Criteria***

Advanced Instrumentation, Information, and Control System Technologies

- ***Digital Architecture Planning Model***
- ***A Business Case for Advanced Outage Management***
- ***A Demonstration of Concrete Structural Health Monitoring Framework for Degradation due to Alkali-Silica Reaction***
- ***Migration of Older to New Digital Control Systems in Nuclear Power Plant Main Control Rooms***
- ***Automated Work Package: Conceptual Design and Data Architecture***

(Click on the report title to download the document.)

Editor: LauraLee Gourley
Designer: David Combs

To submit information or suggestions, contact Cathy J. Barnard at **Cathy.Barnard@inl.gov**.

10-GA50624-21