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Revision 5

Light Water Reactor Sustainability Program

Advanced Instrumentation, Information, and Control Systems Technologies Technical Program Plan for FY 2016

October 2015

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Office of Nuclear Energy

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Advanced Instrumentation, Information, and Control Systems Technologies Technical Program Plan for FY 2016

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ABSTRACT, SUMMARY, FOREWORD, AND ACKNOWLEDGEMENTS

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ACRONYMS

ANS	American Nuclear Society
AOCC	Advanced Outage Control Center
APR	advanced pattern recognition
ASR	alkali-silica reaction
AWPs/EWPs	automated/electronic work packages
BOP	
CAVE	Computer-Assisted Virtual Environment
CBP	
CDA	critical digital asset
CNO	Chief Nuclear Officer
CSAT	Cyber Security Assessment Team
DOE	Department of Energy
EMC	electromagnetic compatibility
EPRI	Electric Power Research Institute
FAC	
FOAK	First-Of-A-Kind
FW-PHM	Fleet-wide Prognostic and Health Management
FY	fiscal year
HSSL	Human Systems Simulation Laboratory
I&A	Infrastructure and Application
II&C	instrumentation, information, and control
INL	Idaho National Laboratory
INPO	Institute for Nuclear Power Operations
IT	Information Technology
KAERI	Korean Atomic Energy Research Institute
KPI	key performance indicators
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
NEI	Nuclear Energy Institute
NITSL	Nuclear Information Technology Strategic Leadership
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
O&M	

OCC	outage control center
R&D	research and development
RUL	remaining useful life
SCCF	software common cause failure
SHM	structural health monitoring
SOER	Significant Operating Experience Report
SPE	Solid Particle Erosion
UWG	utility working group

Advanced Instrumentation, Information, and Control Systems Technologies Technical Program Plan for FY 2016

1. VISION AND STRATEGY

The Advanced Instrumentation, Information, and Control (II&C) Systems Technologies Pathway conducts targeted research and development (R&D) to address aging and reliability concerns with the legacy instrumentation and control and related information systems of the U.S. operating light water reactor (LWR) fleet. This work involves two major goals: (1) to ensure that legacy analog II&C systems are not life-limiting issues for the LWR fleet, and (2) to implement digital II&C technology in a manner that enables broad innovation and business improvement in the nuclear power plant (NPP) operating model. Resolving long-term operational concerns with the II&C systems contributes to the long-term sustainability of the LWR fleet, which is vital to the nation's energy and environmental security.

A key tenet of the Advanced II&C Systems Technologies Pathway is to continuously engage the nuclear power industry to ensure a correct understanding of the II&C issues and requirements *as currently experienced in the operating nuclear power plants*, and to develop approaches to address aging instrumentation and control systems and demonstrate these systems in individual pilot projects with operating NPPs. This provides validation of the developed technologies as fully meeting utility requirements. The results can be used by other owner-operators to address similar aging issues and to achieve new efficiencies. This approach is unique to this pathway and is essential because future planned R&D efforts are built on the concepts and successes from prior projects. This creates a stepwise approach to long-term modernization and refurbishment of instrumentation and control technologies across the LWR fleet. The engagement strategy with nuclear utilities serves to identify priorities for modernization and safety enhancement, timeframes for action, a means of coordinating resources and research partnerships, and a forum to communicate the results of research efforts to the broader nuclear industry and vendor community.

Instrumentation, Information, and Control Systems are a vital part of plant safety and provisions for their refurbishment must be included in long-term planning

Reliable instrumentation, II&C systems technologies are essential to ensuring safe and efficient operation of the U.S. LWR fleet. These technologies affect every aspect of NPP and balance-of-plant operations. They are varied and dispersed, encompassing systems from the main control room to primary systems and throughout the balance of the plant. They interact with every active component in the plant and serve as a kind of central nervous system.

Current instrumentation and human-machine interfaces in the nuclear power sector employ analog technologies. In other power generation sectors, analog technologies have largely been replaced with digital technologies. This is in part due to the manufacturing and product support base transitioning to these newer technologies. It also accompanies the transition of education curricula for II&C engineers to digital technologies. Consequently, product manufacturers refer to analog II&C as having reached the end of its useful service life. Although considered obsolete by other industries, analog II&C continues to function reliably, though spare and replacement parts are becoming increasingly scarce as is the workforce that is familiar with and able to maintain it. In 1997, the National Research Council conducted a study concerning the challenges involved in modernizing existing analog-based instrumentation and controls with digital instrumentation and control systems in NPPs. Their findings identified the need for new II&C technology integration.

Replacing existing analog with digital technologies has not been undertaken to a large extent within the nuclear power industry worldwide. Those efforts that have been carried out are broadly perceived as involving significant technical and regulatory uncertainty. This translates into delays and substantially higher costs for these types of refurbishments. Such experiences have slowed the pace of analog II&C replacement and further contribute to a lack of experience with such initiatives. In the longer run, this may delay progress on the numerous II&C refurbishment activities needed to establish plants that are cost competitive in future energy markets when plants enter long-term operation. Such delays could lead to an additional dilemma: delays in reinvestment needed to replace existing II&C systems could create a "bow wave" of needed future reinvestments. Because the return period on such reinvestments becomes shorter the longer they are delayed, they become less viable. This adds to the risk that II&C may become a limiting or contributing factor that weighs against the decision to operate nuclear power assets for longer periods.

II&C replacement represents potential high-cost or high-risk activities if they are undertaken without the needed technical bases and experience to facilitate their design and implementation. The II&C R&D program addresses critical gaps in technology development and deployment to reduce risk and cost. The objective of these efforts is to develop, demonstrate, and support deployment of new digital II&C technologies for nuclear process control, enhance worker performance, and provide enhanced monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation's NPPs.

II&C Systems can deliver new value through integrated long-term planning.

Most digital II&C implementation projects today result in islands of automation distributed throughout the plant. They are physically and functionally isolated from one another in much the same way as were their analog predecessors. Digital technologies are largely implemented as point solutions to performance concerns with individual II&C components, such as aging. This approach is characterized by planning horizons that are short and typically only allow for "like-for-like" replacements. It is reactive to incipient failures of analog devices and uses replacement digital devices to perform the same functions as analog devices. Consequently, many features of the replacement digital devices are not used. This results in a fragmented approach to refurbishment that is driven by immediate needs. This approach to II&C aging management minimizes technical and regulatory uncertainty though, ironically, it reinforces the current technology base.

To displace the piecemeal approach to digital technology deployment, a new vision for efficiency, safety, and reliability is needed that leverages the benefits of digital technologies. This includes considering goals for NPP staff numbers and types of specialized resources; targeting operation and management costs and the plant capacity factor to ensure commercial viability of proposed long-term operations; improving methods for achieving plant safety margins and reductions in unnecessary conservatisms; and leveraging expertise from across the nuclear enterprise.

New value from II&C technologies is possible if they are integrated with work processes, directly support plant staff, and are used to create new efficiencies and ways of achieving safety enhancements. For example, data from digital II&C in plant systems can be provided directly to work process applications and then, in turn, to plant workers carrying out their work using mobile technologies. This saves time, creates significant work efficiencies, and reduces errors. A goal of these efforts is to motivate development of a seamless digital environment (Figure 1) for plant operations and support by integrating information from plant systems with plant processes for plant workers through an array of interconnected technologies, which include:

- **Plant systems**. Beyond centralized monitoring and awareness of plant conditions, deliver plant information to digitally based systems that support plant work and directly to workers performing these work activities.

- **Plant processes**. Integrate plant information into digital field work devices, automate many manually performed surveillance tasks, and manage risk through real-time centralized oversight and awareness of field work.
- **Plant workers**. Provide plant workers with immediate, accurate plant information that allows them to conduct work at plant locations using assistive devices that minimize radiation exposure, enhance procedural compliance and accurate work execution, and enable collaborative oversight and support even in remote locations.

Figure 1. Seamless information architecture.

To create capabilities needed for long-term operation, an approach to R&D is being taken that enables the stepwise deployment of new II&C technologies.

The path to long-term operability and sustainability of plant II&C systems will likely be accomplished by measured, stepwise modernization through refurbishments. Through successive refurbishments, the resulting collection of II&C systems will reflect a hybrid mixture of analog and digital technologies. Operators and maintainers of II&C systems will, for an extended duration, require competencies with both types of technologies. This represents a least-risk and most realistic approach to refurbishment that allows plant personnel to become familiar with newer digital systems as they gradually replace analog devices.

Within this R&D framework, six areas have been identified that enable capabilities needed for long-term sustainable plant operation. Through a consensus development process involving industry staff representing 70% of the existing LWR fleet, these areas were identified to address the aging of existing II&C technologies, to create capabilities needed to enable power plant staff to perform their jobs more efficiently with digital technologies, and to create the underlying digital II&C architecture that is needed by plants during periods of long-term operation. These are shown in Figure 2. In each of these areas, a series of pilot projects are planned that enable the development and deployment of new II&C technologies in existing nuclear plants. Through the Light Water Reactor Sustainability (LWRS) program, individual utilities and plants are able to participate in these projects or otherwise leverage the results of projects conducted at demonstration plants.

The pilot projects conducted through this program serve as stepping-stones to achieve longer-term outcomes of sustainable II&C technologies. They are designed to emphasize success in some crucial aspect of plant technology refurbishment and sustainable modernization. They provide the opportunity to develop and demonstrate methods to technology development and deployment that can be broadly standardized and leveraged by the commercial nuclear power fleet. Each of the R&D activities in this program achieves a part of the longer-term goals for safe and cost-effective sustainability. They are limited in scope so they can be undertaken and implemented in a manner that minimizes technical and regulatory risk. In keeping with best industry practices, prudent change management dictates that new technologies are introduced slowly so that they can be validated within the nuclear safety culture model.

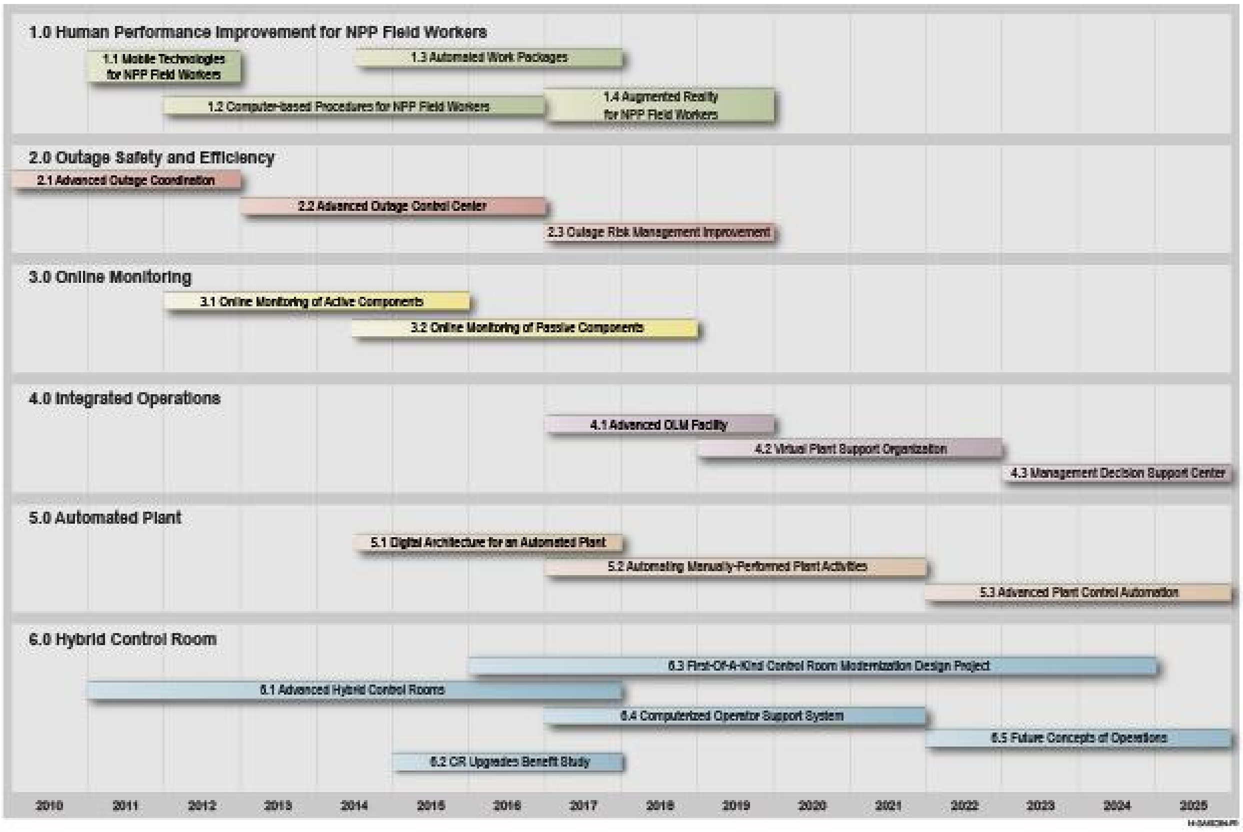

Figure 2. Pilot projects grouped in six areas of enabling capabilities.

Cost and Performance improvements are being targeted through II&C R&D to enhance the existing fleet's long-term viability.

Analog II&C has been the predominant means used for process control in the nuclear power industry for decades. Its use dates back to an era when human labor was more affordable, and maintaining an II&C technology base through a larger workforce conducting frequent rounds for surveillances, inspections, and tests was accepted in the nuclear power generation business model. Today's power generation business climate is much different than the preceding decades and II&C technologies are needed in the long run that are more highly automated and require less cost to operate and maintain, are as highly reliable as those used today, and will be familiar to a future work force. They should also enable performance gains for nuclear utilities so that they are not merely a sunken cost, as this would weigh heavily on the balance sheet at a time of particularly high-cost competitiveness in electricity markets. The growing presence of gas generation is resulting in substantial cost pressure on nuclear generation, particularly in non-regulated markets. The closing of Kewaunee Nuclear Station is such an example of an immediate impact. For other nuclear plants, long-term cost implications will bear on life extension options.

Improvement in the competitive position of the nuclear plants can come from either higher capacity factors or lowered costs. There remains some upside in capacity factors, but the industry has been quite successful in maximizing this opportunity. Now the larger opportunity is in cost reduction. For a typical plant, around 70% of non-fuel O&M costs are labor. Therefore, work efficiency and work elimination are the most promising means of appreciable reductions. In non-nuclear power generation sectors, this has taken the form of a shift in the business model from one that is labor-centric to one that is technology-centric. Granted, for current nuclear plants, many labor requirements are embedded in and reflect elements of plant design. However, there is an ever-expanding opportunity to reduce labor dependence with the development and application of advanced technologies.

Digital technology has long been an enabler of business models in power generation that seek to lower production costs. Significant efficiencies can be gained in process improvement through applications of this technology. For example, for a typical plant support activity, no more than 35% of the labor effort is applied directly to the task (wrench time); the bulk of the labor effort is associated with various pre-and post-job activities, or resolving issues that arise during the course of work execution. Real-time process-related information access as well as collaboration with remotely situated support staff can greatly improve the efficiency of in-plant activities. In some cases, activities can be eliminated altogether, such as through online monitoring of active components in lieu of periodic or condition-based testing.

Results of II&C R&D will support continued safe operation.

Another opportunity for reducing cost and enhancing safety is by reducing human error and its consequences. There are substantial direct and indirect costs that result from human error. This includes the immediate consequences of the error (lost production, delayed outages, etc.), as well as the indirect activities such as event investigations, remedial training, apparent and root causes, analysis of extent of condition/cause, management reviews, corrective actions, regulatory actions, operating experience reports, and so forth. When reactor trips are involved, there are even further costs in reactor trip reports, plant safety committee reviews, and recovery and restart activities. An appreciable percentage of plant staff time is consumed in these types of activities when they occur.

In 2010, the Institute for Nuclear Power Operations (INPO) issued *Significant Operating Experience Report (SOER) 10-02 Engaged, Thinking Organization* [1], which described a number of safety lapses that had recently occurred in the industry and highlighted a number of human performance concerns associated with these events.

The SOER recommended reinforcing desired operator behaviors as the means of resolving these human performance issues. While this is certainly appropriate, technology remains underutilized in the nuclear industry as a means to improve human performance, as well as to correct performance deficiencies. Other power generation and process control industries have demonstrated that technologies, such as operator advisory systems, can significantly enhance operator performance without supplanting their licensed role as ultimate decision-makers.

Similar human performance problems occur in nuclear plant field activities. This includes problems such as incorrect component identification, procedure use, and procedure adherence. The current approach to address this problem frequently employs human performance improvement techniques that add additional time and labor to the task. Current human performance improvement techniques may asymptote in their potential to reduce human error and its consequences since there is a practical limit to how far human performance issues can be dealt with through additional human performance.

This research program investigates a variety of ways that technology may enhance human performance. It has already demonstrated that digital technology is well-suited to help workers maintain situational awareness of plant conditions, and is effective in verifying that field work activities are appropriately conducted on the correct components. Technology can also alleviate the need for independent verifications in some situations due to the highly reliable confirmations that can be obtained with advanced digital capabilities (knowledge of plant mode and configuration, bar code readers, etc.).

These efforts are coordinated with relevant stakeholders to ensure their relevance and adoption to maximize benefits and deliver value from federal R&D and private investments.

This R&D initiative engages relevant stakeholders to plan and execute the appropriate R&D activities needed to create a sustainable and efficient plant technology base for operating organizations. It is a public-private partnership with each party making in-kind contributions through R&D, engineering, infrastructure, investments, and finances to address common issues and needs.

A Utility Working Group (UWG), currently comprised of 13 nuclear operating companies, provides a forum for utility input regarding issues and priorities related to II&C technologies. It also serves as a means for utilities to participate in the pilot projects when there is a match between their own performance improvement needs and the objectives of the research program.

The Electric Power Research Institute (EPRI) participates in the research program in a jointly coordinated and collaborative research role. EPRI technical experts directly participate in the formulation of the project technical plans and in the review of the pilot project results, bringing to bear the accumulated knowledge from their own research projects and collaborations with nuclear utilities.

The LWR fleet coordinates with other major industry support groups such as the Institute of INPO, the Nuclear Energy Institute (NEI), and the Nuclear Information Technology Strategic Leadership (NITSL). These organizations have active efforts in the II&C area related to operational standards of excellence, regulatory initiatives, IT infrastructure, and cyber security.

Periodic meetings are held with both Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) to exchange information regarding research plans and activities of each of the respective organizations. Industry conference, workshops, and technical meetings also serve as important vehicles for information exchange and communication of the research program developments to the industry at large. Likewise, direct discussions with major nuclear industry suppliers ensure that there will be a viable technology transfer path from research results to solid commercial product offerings.

Altogether, these partnerships and collaborations ensure that the II&C R&D program focuses on those capabilities that are needed to position nuclear power assets to remain a safe and viable source of long-term electricity. By coordinating with relevant stakeholders who play vital roles in the nuclear power industry, the investments in R&D are targeting issues and priorities incrementally. This improves the chances that individual utilities can apply the results of individual pilot projects—technologies and methods for their successful introduction—to address challenges of aging II&C technologies at their own sites.

2. INDUSTRY LEADERSHIP PERSPECTIVES

It is important to understand the perspectives of nuclear industry leaders in regard to the needs and requirements for technology in addressing long-term sustainability issues facing the nuclear plants. Efforts were initiated and will continue to obtain senior leadership perspectives and input on pathway planning and strategy, as well as to learn how activities and initiatives can most benefit the fleet of LWR operators. The following summarizes some of these initial efforts.

An interview was conducted with the Chief Nuclear Officer (CNO) of one of the participating utilities in the II&C UWG. The discussions confirmed many of the working assumptions of the research program. Key points made were:

- There is a high probability of pursuing life extension beyond 60 years, and the plants are being maintained in a manner to minimize the effects of aging to the degree practical.
- Digital upgrades for II&C systems are necessary, but must be done in a deliberate manner. They are not pursued for the sake of modernizing II&C, but are undertaken when replacement is needed.

- Some analog systems will be retained if there is no reason to change them out, so staff must be trained to maintain it on an ongoing basis.
- The control and information systems must be contained within the plant "protected area" due to cyber security concerns. This may limit wireless applications for certain functions for some time.
- Many digital-based process improvements are potentially advantageous, including electronic work packages, robotics, and remote dose monitoring. The challenge is to get the maximum efficiency out of these applications.
- New condition-monitoring technologies will be important, especially in the areas of metallurgy, concrete, and cabling.
- The business case for these projects must be based on "quality, safety, and dollars." While cost savings are always desired, quality and safety benefits are also recognized in the decisions to undertake these types of projects.

This CNO noted that his company valued the relationship with the LWRS program in pursuing joint development projects under this research program. He stated that his company was a good partner in this arrangement because "we are big and we like our people to learn." He elaborated on this to say that they have the need and resources to participate effectively in this type of arrangement. He noted that the mission of his organization is not research, but he sees the value of a relationship with an organization that is research-based.

Another CNO recently addressed an industry technology conference and commented on the need for greater operational efficiencies. He noted that cost is measured in dollars per megawatt-hour ($/MWH) of which the "denominator" is hard to change (apart from uprates and outage length reduction). Therefore, improvement must come from the "numerator" or cost side and that technology can play a key role. He further indicated that costs are going up due to a variety of factors, so it is even more important to pursue applications in the areas of electronic work orders, paperless processes, "hardhat cameras" to stream video to engineers for improved understanding, etc. He stressed that we can use these technologies to create new efficiencies in our work activities, which would improve cost performance.

Meetings were held with the INPO senior management. The emphasis of these meetings were on several of the individual pilot projects from the II&C R&D pathway, namely those associated with the hybrid control room, advanced outage control center, computer-based procedures for field workers, and online monitoring of active and passive components. After individual briefings on these projects, a number of points were made:

- The approach to development and implementation of digital technologies in existing analog control rooms emphasizes systematic interactions with licensed operations personnel as a key stakeholder in the process that is based upon best practices and regulatory guidance. This was viewed as a strong point of the II&C research pathway and an area where an opportunity to jointly pursue this further as a beneficial industry practice.
- Advanced outage control technologies are being deployed today, and the LWRS program's partnership with several industry organizations that are recognized for their performance in this area could create an opportunity for an industry community of practice. Informal methods of best practice dissemination facilitated and supported by INPO may be appropriate.
- Hand-held electronic field procedures may be a key to overcoming some of the challenges in human performance that are regularly observed in operating events and industry experience. In addition, this technology may be able to address some of the recent concerns identified regarding the cumulative impact of industry corrective action programs.

- Online monitoring may alleviate some of the burden of time-consuming work that can be better accomplished through remote monitoring. It may provide some advantages over manual surveillances but has to be balanced with the need to have plant workers in the field maintaining their proficiencies.

A discussion with the CNO of a large southern nuclear utility at the 2014 American Nuclear Society (ANS) Utility Working Conference confirmed an interest in new technologies to improve nuclear plant work efficiency. He mentioned that the “cumulative effect” of more process requirements does not mean that we are safer and that these measures are becoming less effective due to the burden imposed on workers. In hearing more detail about the ongoing pilot projects, he expressed interest in the work of the LWRS Program and the potential for benefit within his company.

The additional emphasis that has been placed on obtaining industry leadership perspectives is made possible, in part, by the maturation and deployment of LWRS technologies at operating plants. As technologies and partnerships with the industry continue and broaden, efforts will continue to obtain input from senior industry leadership. These will be used to verify that pathway research priorities address long-term industry needs. Future meetings with the CNOs of the operating commercial nuclear plants are already being planned and will provide a major opportunity to acquire this level of feedback on the program objectives and activities.

3. PATHWAY RESEARCH AND DEVELOPMENT AREAS

3.1 Stages of Transformation

The transformation of the nuclear plant operating model to that which is described as the future vision will take more than a decade to fully assimilate the pilot project technologies into the plant operations and business processes. The rate of transformation is a function of how the pilot projects are defined and sequenced, such that later combinations of these technologies create new capabilities that address the requirements of more complex nuclear plant work activities. The stages of transformation are depicted in Figure 3 below.

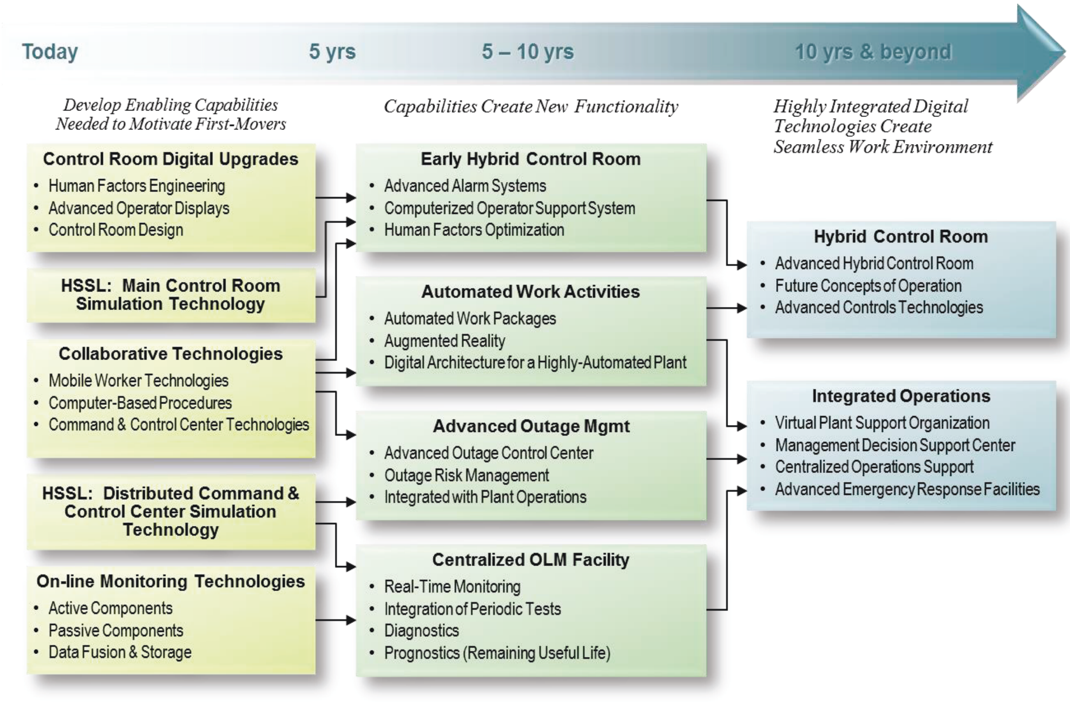

Figure 3. Stages of transformation in the II&C Pathway Vision and Strategy.

The first stage involves the development of enabling capabilities that are needed to motivate the first movers in the industry to adopt new digital technologies. The pilot projects serve to introduce new technologies to the nuclear plant work activities and validate them as meeting the special requirements of the nuclear operating environment. They must be demonstrated to not only perform the intended functions with the required quality and productivity improvements, but they must also fit seamlessly into the established cultural norms and practices that define the safety culture of nuclear power industry. This stage is characterized as new digital technologies improving the quality and productivity of work functions as they are now defined.

The outcomes of the first stage are Control Room Digital Upgrades, Collaborative Technologies, and Online Monitoring Technologies. The Human Systems Simulation Laboratory (HSSL) is a key development focus of this stage to enable studies and validations of main control room simulation as well as distributed command and control center (e.g., outage control center) simulation. (Refer to Section 3.3, "Human Systems Simulation Laboratory").

The second stage occurs when the enabling capabilities are combined and integrated to create new functionality. This is something of an aggregation stage; however, it includes the introduction of even more enabling capabilities as further advancements are made. The pilot project technologies have been formulated in anticipation of this integration stage such that they will work in cooperation with each other to support large organizational functions. This stage is characterized as the reformulation of major organizational functions based on an array of integrated technologies.

The outcomes of the second stage are the Early Hybrid Control Room, Automated Work Activities, Advanced Outage Management, and Centralized Online Monitoring Facilities.

The third stage occurs when there is substantial transformation of how the nuclear plant is operated and supported based on all major plant functions being embedded in a seamless digital environment. Again, this transformation is enabled by both newly developed technologies and the continued creation of new capabilities based on previously developed technologies. This stage is characterized as a transformation of the nuclear plant organization and plant operating model based on advanced digital technologies that redefines and focuses the roles of plant workers and support organizations on value-added tasks rather than organizational and informational interfaces.

The outcomes of the third stage are the Hybrid Control Room and Integrated Operations.

3.2 Product and Schedule Summary

3.2.1 Mobile Technologies for Nuclear Power Plant Field Workers

The full project description can be found in Section 5.1.1. This project was completed at the end of fiscal year (FY) 2012.

Schedule: FY 2011 to FY 2012

Milestones:

- (2012) Publish a technical report for implementing integrated mobile technologies for NPP field workers that provide real-time connections to plant information and processes, thereby reducing human error, improving human performance and productivity, enabling distance collaboration, and maximizing the "collective situational awareness." (Complete: Published report INL/MIS-12-25139, *Advanced Instrumentation, Information and Control (II&C) Research and Development Facility Buildout and Project Execution of LWRS II&C Pilot Project 3*).
- (2012) Publish a technical report on guidance for the implementation of mobile technologies for NPP field workers. (Complete: Published report INL/EXT-12-27094, *Guidance for Deployment of Mobile Technologies for Nuclear Power Plant Field Workers*).

3.2.2 Computer-Based Procedures for Nuclear Power Plant Field Workers

The full project description can be found in Section 5.1.2.

Schedule: FY 2012 to FY 2015

Milestones:

- (2012) Develop the requirements for computer-based procedures for NPP field workers. (Complete: Published report INL/EXT-12-25671, *Computer-Based Procedures for Field Workers in Nuclear Power Plants: Development of a Model of Procedure Usage and Identification of Requirements*).
- (2012) Complete evaluation of a computer-based procedures prototype for NPP field workers. (Complete: Published report INL/EXT-12-27155, *Evaluation of Computer-Based Procedure System Prototype*).
- (2013) Complete evaluation of a final computer-based procedures prototype for field workers. (Complete: Published report INL/EXT-13-28226, *Evaluation of Revised Computer-Based Procedure System Prototype*).
- (2013) Publish a report summarizing the pilot project results in the use of the field worker computer-based procedure system prototype at host utility NPPs. (Complete: Published report INL/EXT-13-30183, *Computer-Based Procedures for Field Workers: Results from Three Evaluation Studies*).
- (2014) Publish a report on the results of a computer-based procedures validation study conducted at a nuclear power plant. (Complete: Published report INL/EXT-14-33212, *Computer-Based Procedures for Field Activities: Results from Three Evaluations at Nuclear Power Plants*).
- (2014) Complete a report documenting the benefits of field-based computer based procedures technologies. (Complete: Published report INL/EXT-14-33011, *Computer-Based Procedures for Field Worker – Identified Benefits*).
- (2015) Complete a report of the field evaluation of the added functionality and new design concepts of the prototype computer-based procedure system. (Complete: Published report INL/EXT-15-36615, *Computer-Based Procedures for Field Workers—Result and Insights from Three Usability and Interface Design Evaluations*).
- (2016) Complete a report describing the final results from FY 2015 field study, simulator demonstration, performance test, and the result from the FY 2016 field study.
- (2016) Develop final CBP Design Guidance documentation.

3.2.3 Automated Work Packages

The full project description can be found in Section 5.1.3.

Schedule: FY 2014 to FY 2017

Milestones:

- (2014) Develop a requirements document for an automated work package prototype for NPP work processes. (Complete: Published report INL/EXT-14-33172, *Automated Work Packages: An Initial Set of Human Factors and Instrumentation and Control Requirements*).

- (2015) Develop a report on an automated work package prototype, which supports paperless work flow and improved human performance, and communication platform for information exchange. (Complete: Published report INL/EXT-15-35825, *Automated Work Package Prototype: Initial Design, Development, and Evaluation*).
- (2016) Develop a report summarizing digital features required to integrate work order, procedures, mobile communication, and smart devices to achieve higher worker efficiency.
- (2017) Enhance the automated work package prototype by integrating an interoperable communication platform and demonstrating these new capabilities for NPP surveillances.
- (2017) Publish a report on automated work package implementation requirements for both NPP field worker usage and self-documenting surveillances.

3.2.4 Augmented Reality for Nuclear Power Plant Field Workers

The full project description can be found in Section 5.1.4.

Schedule: FY 2017 to FY 2019

Milestones:

- (2017) Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers.
- (2018) Develop and demonstrate augmented reality technologies for visualization of real-time plant parameters (e.g., pressures, flows, valve positions, and restricted boundaries) for mobile plant workers.
- (2019) Publish a technical report on augmented reality technologies developed for NPP field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities.

3.2.5 Advanced Outage Coordination

The full project description can be found in Section 5.2.1. This project was completed at the end of FY 2012.

Schedule: FY 2010 to FY 2012

Milestone:

- (2012) Publish a technical report for implementing digital technologies that facilitate communications, coordination, and collaboration in obtaining accurate outage activity status, managing the flow of information through the OCC, and enabling the resolution of emergent problems in an efficient and effective manner, resulting in improved work efficiencies, production success, and nuclear safety margins. (Complete: Published report INL/EXT-12-26197, *Advanced Outage and Control Center: Strategies for Nuclear Plant Outage Work Status Capabilities*).
- (2012) Publish a technical report on the use of digital technology for resolving emergent issues in NPP outages. (Complete: Published report INL/EXT-12-26807, *Resolving Emergent Issues During Nuclear Plant Outages*).

3.2.6 Advanced Outage Control Center

The full project description can be found in Section 5.2.2.

Schedule: FY 2013 to FY 2016

Milestones:

- (2013) Develop technologies for an advanced OCC that improves outage coordination, problem resolution, and outage risk management. Complete: Published report INL/EXT-13-29934, *Development of Methodologies for Technology Deployment for Advanced Outage Control Centers that Improve Outage Coordination, Problem Resolution and Outage Risk Management*).
- (2014) Develop human factors studies and publish a technical report for an advanced OCC that is specifically designed to maximize the usefulness of communication and collaboration technologies for outage coordination, problem resolution, and outage risk management. (Complete: Published report INL/EXT-14-33182, *Guidelines for Implementation of an Advanced Outage Control Center to Improve Outage Coordination, Problem Resolution, and Outage Risk Management*).
- (2014) Complete report describing advanced outage functions, including the results of the real-time support task involving coordination and automated work status updating. (Complete: Published report INL/EXT-14-33036, *Status Report on the Development of Micro-Scheduling Software for the Advanced Outage Control Center Project*).
- (2014) Complete benchmark report documenting priorities and opportunities for outage improvement that can be addressed through pilot project technologies. (Complete: Published report INL/EXT-14-32848, *Benchmark Report on Key Outage Attributes: An Analysis of Outage Improvement Opportunities and Priorities*).
- (2015) Complete a report describing the development of improved graphical displays for an Advanced Outage Control Center, employing human factors principles for effective real-time collaboration and collective situational awareness. (Complete: Published report INL/EXT-15-36489, *Development of Improved Graphical Displays for an Advanced Outage Control Center, Employing Human Factors Principles for Outage Schedule Management).*
- (2016) Complete a report describing the development of an overview display to allow Advanced Outage Control Center (AOCC) management to quickly evaluate outage status.

3.2.7 Outage Risk Management Improvement

The full project description can be found in Section 5.2.3.

Schedule: FY 2017 to FY 2019

Milestones:

- (2017) Develop and demonstrate (in the HSSL) technologies for detecting interactions between plant status (configuration) states and concurrent component manipulations directed by in-use procedures, in consideration of regulatory requirements, technical specifications, and risk management requirements (defense-in-depth).
- (2018) Develop and demonstrate (in the HSSL) technologies to detect undesired system configurations based on concurrent work activities (e.g., inadvertent drain paths and interaction of clearance boundaries).
- (2019) Develop a real-time outage risk management strategy and publish a technical report to improve nuclear safety during outages by detecting configuration control problems caused by work activity interactions with changing system alignments.

3.2.8 Online Monitoring of Active Components

The full project description can be found in Section 5.3.1.

Schedule: FY 2012 to FY 2015

Milestones:

- (2012) Publish an interim technical report on the online monitoring technical basis and analysis framework for large power transformers. (Complete: Published report INL/EXT-12-27181, *Online Monitoring Technical Basis and Analysis Framework for Large Power Transformers; Interim Report for FY 2012*).
- (2013) Publish an interim technical report on the online monitoring technical basis and analysis framework for emergency diesel generators. (Complete: Published report INL/EXT-12-27754, *Online Monitoring Technical Basis and Analysis Framework for Emergency Diesel Generators—Interim Report for FY 2013*).
- (2013) Publish a technical report on for the demonstration of online monitoring technology for large power transformers and emergency diesel generators. (Complete: Published report INL/EXT-13-30155, *Demonstration of Online Monitoring for Generator Step-up Transformers and Emergency Diesel Generators*).
- (2014) Complete a report describing the diagnostic and prognostic models for generator step-up transformers. (Complete: Published report INL/EXT-14-33124, *Diagnostic and Prognostic Models for Generator Step-Up Transformers*).
- (2015) Complete a technical report describing the diagnostic and prognostic models for induction motors. (Complete: Published report INL/EXT-15-36681, *Online Monitoring of Induction Motors*).

3.2.9 Online Monitoring of Passive Components and Structures

The full project description can be found in Section 5.3.2.

Schedule: FY 2014 to FY 2018

Milestones:

- (2014) Complete interim report on the results of the concrete degradation mechanisms and online monitoring techniques survey. (Complete: Published report INL/EXT-14-33134, *Interim Report on Concrete Degradation Mechanisms and Online Monitoring Techniques*).
- (2015) Investigate and advance individual techniques for damage modeling, health monitoring, data analytics, and uncertainty quantification with respect to alkali-silica reaction (ASR) damage in NPP concrete structures. (Complete: Published reports: (1) INL/EXT-15-34729, *A Simple Demonstration of Concrete Structural Health Monitoring Framework*; (2) INL/EXT-15-36683, *Monitoring, Modeling, and Diagnosis of Alkali-Silica Reaction in Small Concrete Samples*).
- (2015) Complete interim report on the results of the flow-accelerated corrosion mechanisms and online monitoring techniques survey. (Complete: Published report INL/EXT-15-36611, *Flow-Assisted Corrosion in Nuclear Power Plants*).
- (2016) Develop modeling, detection, and big data analytics techniques considering multiple damage mechanisms in NPP structures, and demonstrate these techniques for small laboratory-scale structural components.
- (2016) Complete a report documenting the development of a model of degradation for flashing erosion in NPP piping.

- (2017) Develop an integrated framework for multi-physics simulation, full-field imaging, data analytics, and uncertainty quantification; demonstrate for large laboratory structures; and develop a validation strategy.
- (2017) Development of structural health monitoring framework for piping in secondary systems.
- (2018) Develop and validate a health risk management framework for concrete structures in NPP, demonstrate for illustrative concrete structures in the NPP environment, and develop an implementation strategy for NPPs.
- (2018) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a second large passive plant component, involving nondestructive examination-related online monitoring technology development, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

3.2.10 Advanced Online Monitoring Facility

The full project description can be found in Section 5.4.1.

Schedule: FY 2017 to FY 2019

Milestones:

- (2017) Develop and demonstrate (in the HSSL) concepts for an advanced online monitoring facility that can collect and organize data from all types of monitoring systems and activities and can provide visualization of degradation where applicable.
- (2018) Develop and demonstrate (in the HSSL) concepts for real-time information integration and collaboration on degrading component issues with remote parties (e.g., control room, outage control center, systems and component engineering staff, internal and external consultants, and suppliers).
- (2019) Develop a digital architecture and publish a technical report for an advanced online monitoring facility, providing long-term asset management and providing real-time information directly to control room operators, troubleshooting and root cause teams, suppliers and technical consultants involved in component support, and engineering in support of the system health program.

3.2.11 Virtual Plant Support Organization

The full project description can be found in Section 5.4.2.

Schedule: FY 2019 to FY 2022

Milestones:

- (2019) For chemistry activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for a highly automated plant. Demonstrate representative remote activities with a host NPP.
- (2020) For maintenance activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for a highly automated plant. Demonstrate representative remote activities with a host NPP.

- (2021) For radiation protection activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for a highly automated plant. Demonstrate representative remote activities with a host NPP.
- (2022) Publish human and organizational factors studies and a technical report for a virtual plant support organization technology platform consisting of data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment for a geographically dispersed NPP support organization.

3.2.12 Management Decision Support Center

The full project description can be found in Section 5.4.3.

Schedule: FY 2023 to FY 2025

Milestones:

- (2023) Develop and demonstrate (in the HSSL) concepts for a management decision support center that incorporates advanced communication and collaboration, and displays technologies to provide enhanced situational awareness and contingency analysis.
- (2024) Develop and demonstrate (in the HSSL) concepts for advanced emergency response facilities that incorporate advanced communication and collaboration, and displays technologies to provide enhanced situational awareness and real-time coordination with the control room, other emergency response facilities, field teams, the NRC, and other emergency response agencies.
- (2025) Publish human and organizational factors studies and a technical report for a management decision support center consisting of advanced digital display and decision-support technologies, thereby enhancing nuclear safety margin, asset protection, regulatory performance, and production success.

3.2.13 Digital Architecture for a Highly Automated Plant

The full project description can be found in Section 5.5.1.

Schedule: FY 2014 to FY 2017

Milestones:

- (2014) Publish a project plan for the development of a digital architecture for the integration and automation of nuclear plant work activities. (Complete: Published report INL/EXT-14-33177, *Digital Architecture Project Plan*).
- (2015) Complete a Digital Architecture Requirements Report documenting the information technology requirements for advanced digital technology applied as envisioned to be applied to NPP work activities. (Complete: Published report INL/EXT-15-34696, *Digital Architecture Requirements*).
- (2015) Complete a Digital Architecture Gap Analysis Report documenting the gap between current typical II&C and information technology (IT) capabilities in NPPs versus those documented in the Digital Architecture Requirements Report. (Complete: Published report INL/EXT-15-36662, *Digital Architecture – Results From a Gap Analysis*).
- (2016) Complete a Digital Architecture Planning Model.
- (2017) Complete a Digital Architecture Implementation Guideline, documenting a graded approach in applying the conceptual model to selected digital technologies and in determining the incremental IT requirements based on a current state gap analysis.

3.2.14 Automating Manually Performed Plant Activities

The full project description can be found in Section 5.5.2.

Schedule: FY 2017 to FY 2021

Milestones:

- (2017) For NPP operations activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2018) For NPP chemistry activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2019) For NPP maintenance activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2020) For NPP radiation protection activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- 2021) Develop and publish a transformed NPP operating model and organizational design derived from a top-down analysis of NPP operational and support activities, quantifying the efficiencies that can be realized through highly automated plant activities using advanced digital technologies.

3.2.15 Advanced Plant Control Automation

The full project description can be found in Section 5.5.3.

Schedule: FY 2022 to FY 2025

Milestones:

- (2022) Develop concepts for advanced control automation for control room operators based on human technology function allocation developed in the pilot project for automating manually performed plant activities. Publish a technical report on candidate applications for automation reflecting design and human factors principles.
- (2023) Develop and demonstrate (in the HSSL) prototype plant control automation strategies for representative normal operations evolutions (e.g., plant start-ups and shut-downs, equipment rotation alignments, and test alignments).
- (2024) Develop and demonstrate (in the HSSL) prototype plant control automation strategies for representative plant transients (e.g., loss of primary letdown flow or loss of condensate pump).
- (2025) Develop the strategy and priorities and publish a technical report for automating operator control actions for important plant state changes, transients, and power maneuvers, resulting in nuclear safety and human performance improvements founded on engineering and human factors principles.

3.2.16 Advanced Hybrid Control Rooms

The full project description can be found in Section 5.6.1.

Schedule: FY 2011 to FY 2017

Milestones:

- (2011) Complete a workshop on design of replacement annunciator systems for control rooms. (Complete: Published report INL/MIS-11-22907, *Alarm Design Workshop for Control Room Upgrades: Summary and Presentations*).
- (2011) Complete at least one commercial NPP full-scope, full-scale simulator in the II&C laboratory. (Complete: Published report INL/EXT-11-23421, *Deployment of a Full-Scope Commercial Nuclear Power Plant Control Room Simulator at the Idaho National Laboratory*).
- (2012) Develop a digital, full-scale mockup in the HSSL of a conventional NPP control room. (Complete: Published report INL/EXT-12-26367, *Digital Full-Scope Mockup of a Conventional Nuclear Power Plant Control Room, Phase 1: Installation of a Utility Simulator at the Idaho National Laboratory*).
- (2012) Develop digital displays in support of control room modernization. (Complete: Published report INL/EXT-12-26787, *Applying Human Factors Evaluation and Design Guidance to a Nuclear Power Plant Digital Control System*).
- (2013) Complete the assembly of the HSSL and demonstrate its capability to model a hybrid (analog and digital) NPP control room. (Complete: Published report INL/EXT-13-28432, *Digital Full-Scope Simulation of a Conventional Nuclear Power Plant Control Room, Phase 2: Installation of a Reconfigurable Simulator to Support Nuclear Plant Sustainability*).
- (2013) Publish a reference human factors engineering plan for an optimized, human-factored control board layout for integrating digital operator interface screens with analog controls and indicators. (Complete: Published report INL/EXT-13-30109, *A Reference Plan for Control Room Modernization: Planning and Analysis Phase*).
- (2013) Complete LWRS II&C Halden Project report documenting conclusion of installation exercise of digital interface prototypes in Human Simulation Systems Laboratory (HSSL). (Complete: Published report INL/EXT-13-29039, *Installation of Halden Reactor Project Digital Interface Prototypes in the Human Systems Simulation Laboratory*).
- (2014) Complete report on operator performance metrics for use in control room modernization projects. (Complete: Published report INL/EXT-14-31511, *Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation*).
- (2014) Develop a strategy for migration of II&C functions from traditional control boards to compact operator control consoles. (Complete: Published report INL/EXT-14-32534, *Strategy for Migration of Traditional to Hybrid Control Boards in a Nuclear Power Plant*).
- (2014) Complete a report on human factors engineering design phase for control room modernization. (Complete: Published report INL/EXT-14-33221, *Human Factors Engineering Design Phase Report for Control Room Modernization*).
- (2014) Complete a report documenting a methodology for conducting baseline human factors and ergonomics review using a host NPP control room. (Complete: Published report INL/EXT-14-33223, *Baseline Human Factors and Ergonomics in Support of Control Room Modernization at Nuclear Power Plants*).

- (2015) Develop a Distributed Control System Prototype. Using a participating utility's simulator plant model installed at the Human System Simulation Laboratory (HSSL), develop a functional prototype for the turbine control system upgrade. Document the design, development, and functionality of the prototype replacement system. (Complete: Published report INL/EXT-14-33957, *A Distributed Control System Prototyping Environment to Support Control Room Modernization*).
- (2015) Complete a report on Operator Performance Metrics for Verification and Validation, documenting the process on how simulator studies should be performed including the various operator performance metrics in support of control room upgrades (Complete: Published report INL/EXT-14-31511, Revision 1, *Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation*).
- (2015) Develop prognostic software for control indicators. Provide demonstration and software for prognostic system and display interface for installation at the HSSL: (Complete: Published report INL/EXT-15-36839, *HSI Prototypes for Human Systems Simulation Laboratory*).
- (2015) Develop Operator Performance Metrics for Verification and Validation. Document the process how simulator studies should be performed including the various operator performance metrics that can be collected in support of control room upgrades. (Complete: Published report INL/EXT-15-36704, Verification and Validation of Digitally Upgraded Control Rooms).
- (2016) Develop lessons learned from performing integrated system validation on a digitally upgraded system in the main control room that conforms to regulatory requirements for human factors engineering.
- (2017) Develop a migration strategy for upgrading control systems such as the plant process computer from older to new digital technology in the control room.

3.2.17 Control Room Upgrades Benefit Study

The full project description can be found in Section 5.6.2.

Schedule: FY 2015 to FY 2017

Milestones:

- (2015) Complete a report describing requirements of control room computer based procedures. (Complete: Published report INL/EXT-15-35284, *Requirements for Control Room Computer-Based Procedures for use in Hybrid Control Rooms*).
- (2015) Develop a prototype of an advanced hybrid control room in the HSSL that includes advanced operator interface technologies such as alarm management systems, computerized procedures, soft controls, large displays, and operator support systems. (Complete: Published report INL/EXT-15-3538, *Benefits of Advanced Control Room Technologies: Phase One Upgrades to the Human Systems Simulation Laboratory and Performance Measures*).
- (2015) Test HSSL System in Preparation for Conducting Benefits Study with Operations – Test HSSL systems in representative configurations to verify that systems are able to function reliably in operational sequences and scenarios, test data logging and collection systems, and verify the stability of different combinations of digital systems with human interactions in preparation for data collection with actual operating crews. (Complete: Published report INL/EXT-15-36432, *A Pilot Study Investigating the Effects of Advanced Nuclear Power Plant Control Room Technologies: Methods and Qualitative Results*).
- (2016) Complete a report describing the experimental design, scenarios, and performance measures used in the baseline study of operating crews.

- (2017) Publish a report documenting the Control Room Upgrades Benefit Study that presents the data, findings, and conclusions on performance improvements that can be obtained through the technologies of an advanced hybrid control room.

3.2.18 First-Of-A-Kind Control Room Modernization Design Project

The full project description can be found in Section 5.6.3.

Schedule: FY 2016 to FY 2024

Milestones:

- (2016) Develop a baseline room configuration document of the existing host nuclear station control room that includes board layouts, room arrangement, operator station, and control system operator interfaces.
- (2016) Develop a control room end-state concept for a modernized control room for an operating NPP.
- (2017) Implement the host nuclear station training simulator in the HSSL reflecting the baseline control room configuration.
- (2017) Publish interim human factors engineering guidance for the host nuclear station for the implementation of II&C digital upgrades affecting the control room.
- (2017) Develop the framework of the business case for the control room concept based on work efficiency gains and improved operator performance.
- (2018) Complete the preliminary design for the control room end-state concept.
- (2018) Complete human factors engineering review of the preliminary design of the control room end-state concept.
- (2018) Complete a phased implementation strategy for the preliminary design of the control room end-state concept.
- (2018) Develop the final business case for the control room end-state concept.
- (2018) Conduct an industry peer review of the preliminary design and the business case for the control room end-state concept.
- (2019) Publish a summary report on the preliminary design and the human factors engineering review of the control room end-state concept, providing lessons learned on plant system interface and the phased implementation strategy.
- (2019) Complete the detailed design for the Phase 1 modification for the control room end-state concept.
- (2019) Complete human factors engineering review of the detailed design of the Phase 1 modification for the control room end-state concept.
- (2020) Complete the implementation package for the Phase 1 modification for the control room end-state concept.
- (2021) Publish a summary report on the detailed design and human factors engineering review of the Phase 1 modification for the control room end-state concept, providing lessons learned on plant system interface and the phased implementation strategy.
- (2021) Complete the detailed design for the Phase 2 modification for the control room end-state concept.

- (2021) Complete human factors engineering review of the detailed design of the Phase 2 modification for the control room end-state concept.
- (2021) Complete the implementation package for the Phase 2 modification for the control room end-state concept.
- (2022) Complete the detailed design for the Phase 3 modification for the control room end-state concept.
- (2022) Complete human factors engineering review of the detailed design of the Phase 3 modifications for the control room end-state concept.
- (2023) Complete the implementation package for the Phase 3 modification for the control room end-state concept.
- (2024) Publish a summary report on the implementation phase of the First-Of-A-Kind (FOAK) Control Room Modernization Design Project providing lessons learned and initial operational benefits.

3.2.19 Computerized Operator Support Systems

The full project description can be found in Section 5.6.4.

Schedule: FY 2017 to FY 2021

Milestones:

- (2017) Develop concepts for using NPP full-scope simulators as operator advisory systems in hybrid control rooms and complete a technical report on prototype demonstrations in the HSSL.
- (2018) Develop concepts for a real-time plant operational diagnostic and trend advisory system with the ability to detect system and component degradation and complete a technical report on prototype demonstrations in the HSSL.
- (2019) Develop an operator advisory system fully integrated into a control room simulator (HSSL) that provides plant steady-state performance monitoring, diagnostics and trending of performance degradation, operator alerts for intervention, and recommended actions for problem mitigation, with application of control room design and human factors principles.
- (2020) Develop an operator advisory system that provides plant transient performance monitoring with operator alerts for challenges to nuclear safety goals.
- (2021) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, based on an operator advisory system that provides real-time situational awareness, prediction of the future plant state based on current conditions and trends, and recommended operator interventions to achieve nuclear safety goals.

3.2.20 Future Concepts of Operations

The full project description can be found in Section 5.6.5.

Schedule: FY 2022 to FY 2025

Milestones:

- (2022) Complete a technical report on operator attention demands and limitations on operator activities based on the current conduct of operations protocols. This report will identify opportunities to maximize operator efficiency and effectiveness with advanced digital technologies.

- (2023) Develop and demonstrate (in the HSSL) prototype mobile technologies for operator situational awareness and limited plant control capabilities for NPP support systems (e.g., plant auxiliary systems operations and remote panel operations).
- (2024) Develop and demonstrate (in the HSSL) new concepts for remote operator assistance in high-activity periods (e.g., refueling outages) and accident/security events, allowing offsite operators to remotely perform low safety-significant operational activities, freeing the control room operators to concentrate on safety functions.
- (2025) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new technologies that provide mobile information and control capabilities and the ability to interact with other control centers (e.g., emergency response facilities for severe accident management guidelines implementation).

3.3 Human Systems Simulation Laboratory

The HSSL at Idaho National Laboratory (INL) is used to conduct research in the design and evaluation of hybrid control rooms, integration of control room systems, development and piloting of human-centered design activities with operating crews, and visualizations of different end-state operational concepts. This advanced facility supports human factors research for operating nuclear plant control rooms, including human-in-the-loop performance and human-system interfaces, and can incorporate mixtures of analog and digital hybrid displays and controls. It is applicable to the development and evaluation of control systems and displays of NPP control rooms, and other command and control systems.

The HSSL consists of a full-scope, full-scale reconfigurable control room simulator that provides a high-fidelity representation of a LWR analog-based control room (Figure 4).

Figure 4. Human Systems Simulation Laboratory - Reconfigurable Hybrid Control Room Simulator.

The simulator consists of 15 bench board-style touch panels that respond to touch gestures similar to the control devices in an actual control room. The simulator is able to run actual LWR plant simulation software used for operator training and other purposes. It is reconfigurable in the sense that the simulator can be easily switched to the software and control board images of different LWR plants, thus making it a universal test bed for the LWR fleet.

For this research program, the HSSL will be mostly used to study human performance in a near-realistic operational context for hybrid control room designs. New digital systems and operator interfaces will be developed in software and depicted in the context of the current state control room, enabling comparative studies of the effects of proposed upgrade systems on operator performance

(Figure 5). Prior to full-scale deployment of technologies (such as control room upgrades), it is essential to test and evaluate the performance of the system and the human operators' use of the system in a realistic setting. In control room research simulators, upgraded systems can be integrated into a realistic representation of the actual system and validated against defined performance criteria.

Figure 5. HSSL used to evaluate digital upgrades in a hybrid control room

The facility is equally suitable for human performance measurement in other NPP control centers such as an outage control center, a centralized online monitoring center, and emergency response facilities. An assessment of human performance in a naturalistic setting includes studies in a range of the following focus areas:

1. Human-system performance relationships between the reliability of the operator, the time available to perform an action, performance success criteria, and the influence of the performance characteristics of the plant or system on task performance and outcome(s).
2. Usability of the human systems interface, which includes the effectiveness, efficiency, safety, and reliability with which an operator can perform specific tasks in a specific operational context (e.g., normal or emergency). This includes the effect on human performance with different technologies and different human-system interface configurations.
3. Human performance expressed as physical and cognitive workload under different operational conditions, including the following:
    a. Monitoring of plant status and system performance
    b. Human error, human reliability, and human error mechanisms
    c. Task completion (e.g., accuracy, speed, tolerance, and variability).
    d. Procedure following
    e. Problem diagnosis: (1) decision making and (2) response times.
4. Situational awareness with a given human-system interface and control configuration under different operational conditions.
5. Situational awareness with a given human-system interface and control configuration under different operational conditions.
6. Crew communication effectiveness with given technologies under different operational conditions.
7. Human performance with different staffing configurations and a given control room configuration.

The HSSL provides the simulation, visualization, and evaluation capabilities needed for pilot projects involving development and evaluation of new technologies for the main control room and other control centers. As such, the new technologies will first be staged in the HSSL for proof-of-concept prior to demonstration at host utility NPPs. This will enable research on function allocation, task analysis, staffing, situational awareness, and workload in multiple-unit control rooms (Figure 6).

Over time, the HSSL will be upgraded with additional capabilities as needed to support the pilot projects such as eye tracking (Figure 7), which enables researchers to determine where an operator's attention is focused. It is envisioned that the HSSL will be used to validate new operational concepts, human centered design methods, and many first-of-a-kind technologies for the LWR fleet, thereby ensuring that NPP modernization of II&C systems is based on demonstrated and validated scientific principles.

Figure 6. HSSL used for an operator work shop.

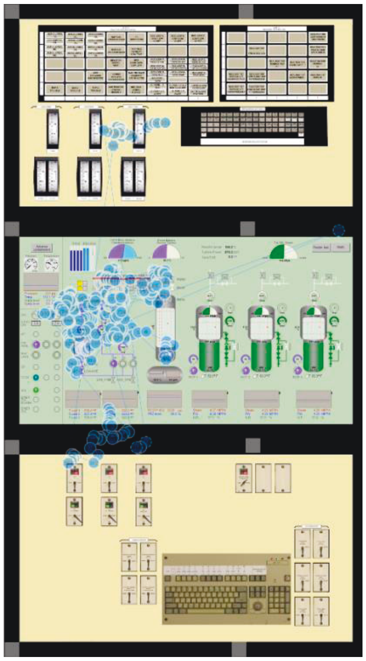

Figure 7. HSSL being used for eye tracking of operators using an advanced display.

3.4 Cyber Security

Cyber security is recognized as major concern in implementing advanced digital II&C technologies in NPPs in view of the considerable security requirements necessary to protect these facilities from potential adversaries, as well as protect company-proprietary information. The members of the UWG have indeed expressed the need to ensure that cyber security vulnerabilities are not introduced through the adoption of these advanced digital technologies. Furthermore, these utilities have internal cyber security policies and regulatory obligations that must be upheld in implementing the project technologies.

DOE has significant cyber security expertise and resources that have been developed to address the security concerns of the laboratory, as well as those of many security-critical U.S. government facilities. DOE’s experience in identifying, characterizing, and mitigating cyber security threats is highly applicable to the type of concerns that potentially would be created in technology areas of the pilot projects.

To this end, a project task was created to address cyber security issues arising from the technology developments in the pilot projects, with DOE cyber security experts at INL reviewing the pilot project technologies and provide a report on appropriate practices to minimize cyber security risk. The report is entitled *Cyber Security Considerations in Support of the Light Water Reactor Sustainability Program*, Revision 2 (INL/LTD-12-27315), with the latest revision having been published in July 2013.

Responsibility for cyber security ultimately lies with the utilities that implement the technologies from this research program. They must ensure that their own policies and regulatory commitments are adequately addressed.

To help nuclear utilities better understand the cyber security implications for the digital technologies being developed under this research program, an assessment was conducted in FY 2014 of the pilot project technologies against the requirements of 10 CFR 73.54, “Protection of Digital Computer and Communication Systems and Networks,” and the associated regulatory guidance of NEI 08-09, “Cyber Security Plan for Nuclear Power Reactors.”

A nuclear industry consulting firm that routinely conducts these types of assessments for utilities was contracted to perform this assessment. It consisted of a table-top exercise to evaluate developed technologies against the requirements of a typical nuclear utility cyber security program to determine what controls would be needed to support production usage. A mock Cyber Security Assessment Team (CSAT) was set up by the consulting firm with cyber security, information technology, and engineering expertise represented. The principle investigators of each of the pilot projects presented relevant computer and communication aspects of their respective pilot project technologies to the CSAT, which systematically analyzed them according the NEI 08-09 assessment criteria.

The results of the assessment were documented in project report M3LW-15IN0603013, *Cyber Security Evaluation of II&C Technologies.* The major findings of the report were:

- Most II&C technologies will reside the cyber security business layer and will probably be treated as workplace tools, like Measurement and Test Equipment. This is particularly true of the mobile work technologies (including field work CBPs and automated work packages [AWPs]). This is also true of the AOCC technologies.
- OLM technologies will also reside in the business layer, except for the special case where they might be used for real-time configuration status (re: current EPRI project on valve status). In this case, they would be critical digital assets (CDAs) if used for automated Tech Spec Surveillances. CDAs require full application of prescribed cyber security controls, or acceptable alternates, if they are applicable to the particular component.
- The hybrid control room technologies will mostly be CDAs in that they provide real-time information to plant operators during transients and accidents.

- Three currently-prohibited situations were identified: (1) wireless connection to safety-related and important-to-safety equipment, (2) wireless control in the main control room (e.g., use of computer-based procedures with soft controls (Type 3) on a tablet, and (3) control functions from outside the plant protected area (fence), this relating only to a future pilot project on Advanced Concepts of Operations with possible fleet-central control certain BOP systems or remote digital control rooms for use during severe accidents.

As a measure of confirmation of the results of this assessment, cyber security experts from two large nuclear utilities reviewed the report and stated that the assessment conclusions appeared to be accurate based on their experience and that their respective utilities would likely draw similar conclusions regarding the pilot project technologies.

It is recognized that these technologies represent a "proof-of-concept" state; therefore, these technologies are not as prescriptive in terms of underlying technologies as might normally be required in an actual cyber security evaluation for a nuclear plant. For example, a technology might refer to the use of wireless transmission of information to mobile field workers, without specifying the type of wireless protocol. Therefore, in future utility evaluations of actual implementations of the pilot project technologies, assessment outcomes might be different according to implementation options.

The research pathway will continue to apply the cyber security resources, expertise, and experience of DOE as well as the nuclear industry to provide a sound information basis for utilities in prudent technology implementation practices and mitigation measures.

3.5 Quality Assurance

Quality assurance requirements for this research program are defined in INL/EXT-10-19844, *Light Water Reactor Sustainability Program Quality Assurance Program Document*. This Quality Assurance Program is based on the requirements in American Society of Mechanical Engineers NQA-1-2008, 1a-2009, "Quality Assurance Requirements for Nuclear Facility Applications." It covers all of the R&D activities of the program, including any quality assurance requirements applicable to the technologies and related concepts developed and implemented under the pilot projects.

A specific quality assurance plan is developed for the work package associated with each pilot project, employing an assessment matrix that examines each task in the project to classify it according to the type of research it represents: basic, applied, or development. These research types correspond to a graded approach to the quality assurance requirements, in which the quality assurance requirements appropriate to each type are applied.

An audit of the Quality Assurance requirements was conducted in FY 2015 with no findings.

3.6 Digital Technology Business Case Methodology

The lack of a business case is often cited by utilities as a significant barrier in pursuing wide-scale application of digital technologies to their nuclear plant work activities. While the performance advantages of these new capabilities are widely acknowledged, it has proven to be difficult for utilities to derive business cases that result in actual cost offsets that can be credited in budget allocations for site organizations, and thereby truly reduce O&M costs. This is because the technologies are typically applied in a manner that simply enhances existing work methods rather than eliminates work or makes it significantly more efficient, such that it changes overall staffing and material cost requirements. For technologies that have this offset potential, a methodology is needed to capture this impact in a credible manner.

To address this need, the research program developed INL/EXT-14-33129, *Digital Technology Business Case Methodology* working with ScottMadden Management Consultants, a firm that has years of experience in preparing performance improvement business cases for senior leadership in the nuclear power industry. The purpose of the Business Case Methodology is to provide a structure for building the business case for adopting pilot project technologies in a manner that captures the total organizational benefits that can be derived from the improved work methods. This includes direct benefits in the targeted work processes, efficiencies gained in related work processes, and avoided costs through improvement in work quality and reduction in human error.

The Business Case Methodology consists of a Business Case Methodology Workbook (spreadsheet) that is customized and populated with standard nuclear plant work activities and typical plant staffing totals for each plant organization. It calculates the aggregate benefit of a technology across all of the work activities that it impacts, including being able to credit reduction in recovery costs for rework and performance errors, based on the historical rate of their occurrence in the targeted activities.

Specifically, the Business Case Methodology also serves as a user guide, presenting a structured approach to developing a sound business case, as well as identifying where in the process to employ the Business Case Methodology Workbook for benefits/cost savings identification. The approach enables collaboration between the II&C Pathway and utility partners in applying new technologies across multiple NPP organizations and their respective work activities, wherever there is opportunity to derive benefit. In this manner, the Business Case Methodology drives an “economy of scale” that maximizes the value of the technologies relative to the implementation cost.

The Business Case Methodology leverages the fact that, in spite of what seems to be a wide and disparate array of work activities among a NPP’s operational and support organizations, the work activities themselves are largely composed of common tasks. For example, whether the work activities are in operations, chemistry, radiation protection, or even security, they have in common such tasks as pre-job briefs, use of procedures, correct component identification, emergent conditions requiring work package alteration, etc. It is at this task level that the technologies are applied; therefore, the benefits of the technologies can be realized across as many plant activities as can be identified to employ these tasks. In this manner, a much more comprehensive business case can be derived that greatly increases the benefit/cost ratio. This has the added benefit of driving consistency across the NPP organizations, which is a fundamental principle of successful NPP operational and safety management.

In FY 2015, a Business Case Study was conducted with a large operating nuclear plant to determine the cost and performance benefits that could be obtained with wide-scale implementation of mobile worker technologies. ScottMadden Management Consultants were again contracted to conduct the study using the Business Case Methodology Workbook. In addition to determining the benefits of the technology, the study was used to confirm the adequacy and accuracy of the features of the Business Case Methodology Workbook. The study resulted in the identification of approximately $6.5M in annual savings for the plant with full implementation of mobile work packages, including computer-based procedures. This represents a net present value of over $21M through the expected 15-year life of the technology. This value is considered to on the low end of the range of expected of benefits due to conservative assumptions that were made in the analysis. In addition to the cost savings, considerable benefits were identified in reduced human error, with positive impacts on a number of important plant key performance indicators (KPIs). The study is documented in report INL/EXT-15-35327, *Pilot Project Technology Business Case: Mobile Work Packages.*

Two new business case studies will be conducted, applying the Business Case Methodology. The targeted pilot projects are the Advanced Outage Control Center and the Hybrid Control Room. Plant work activities associated with each of these pilot project technology areas will be identified and investigated for performance improvement and cost-savings opportunities. The quantitative and qualitative improvements will be documented in a project report for use by nuclear utilities in developing their own proprietary business cases for digital technology implementations. The business cases will be limited to the benefit side of the expected performance improvements and will not address the utility costs to implement and maintain the technology application.

A utility partner for each of the exercises will be obtained to provide the detailed work requirements, as well as direct access to the work performers and the supporting documentation. Work activities will be observed and analyzed to identify and quantify opportunities for the pilot project technologies to enable labor savings and quality improvements through work efficiencies and reductions in human error. These savings and improvements will be projected over an appropriate payback period to derive the total benefit and then recorded in the Business Case Methodology Workbook. A report will be developed to summarize the business case for each of the targeted pilot project technology areas.

4. RESEARCH AND DEVELOPMENT COOPERATION

A systematic engagement activity is underway with NPP owner/operators, suppliers, industry support organizations, and the NRC. Together, these engagement activities are intended to ensure that R&D activities focus on issues of challenge and uncertainty for NPP owners and regulators alike, the products of research can be commercialized, and roadblocks to deployment are systematically addressed.

4.1 Utility Working Group

The Advanced II&C Systems Technologies Pathway sponsors a UWG that serves several important functions:

1. Provides direct input on the needs and requirements of nuclear utilities for technology.
2. Provides direct input on the operating environments and safety culture aspects for which the technologies must conform.
3. Provides input on the scope and priority of pilot projects.
4. Serves as utility hosts for pilot project activities and studies to prove the effectiveness of new technologies in actual NPP settings.
5. Provides a means of developing industry consensus on the requirements for technologies so that they are widely suitable across the range of individual utility work practices. This also enables a robust supplier market for these technologies due to common requirements.

At the present, the UWG consists of 13 leading U.S. nuclear utilities. Additional membership for the UWG is constantly pursued with the intent to involve every U.S. nuclear operating fleet in the program. The UWG has one general purpose meeting each year, held in late summer at INL, to review the technologies that have been developed in all of the pilot projects and to provide input on priorities for the coming fiscal year. In addition, there are regular conference calls for the UWG to receive status updates on the pilot project activities and to learn of opportunities to participate in the development activities. There are other special purpose meetings and conference calls that focus on particular sets of the technologies and they are attended by the utility members that have near-term interests in those technologies.

Serving as host utilities for pilot project development and study activities is perhaps the most important way that utilities participate in the work of the pathway. This occurs when utilities have their own business process and performance improvement objectives that match up with pilot project development plans. Thus, the utilities become “first movers” for the industry and have the opportunity to help set the requirements for the industry. The utilities serving as hosts benefit from both the process and technology expertise that the pathway brings to the projects as well as cost benefit of a cooperative development effort in proving the effectiveness of the technologies.

In turn, to benefit the nuclear power industry in general, the pilot project hosts will make the results of the R&D available and accessible to other commercial nuclear utilities and participate in efforts to support deployment of systems, technologies, and lessons learned by other NPP owners. Host utilities regularly make presentations in key industry technical meetings to describe their motivations and efforts in the pilot projects and to communicate important findings to the industry.

4.2 Electric Power Research Institute

The EPRI is a member of the UWG and serves in a direct role in collaborative research with the II&C Pathway. EPRI has conducted numerous R&D activities over the past several decades in support of NPP digital implementation and related issues and has made relevant reports and guidelines available to this research pathway. EPRI technical experts directly participate in the formulation of the project technical plans and in the review of the pilot project results, bringing to bear the accumulated knowledge from their own research projects and collaborations with nuclear utilities. EPRI will assist in the transfer of technology to the nuclear utilities by publishing formal guidelines documents for each of the major areas of development (see Section 5.7).

Regular meetings and conference calls are conducted with EPRI to coordinate R&D plans, share insights on technology requirements for nuclear utilities, and coordinate plans for publicizing and disseminating the information produced through the projects. In addition, each organization participates in industry meetings of the other, thereby maximizing the understanding of the utilities of the developments of the coordinated research. This has proven to be an effective means of ensuring the capabilities and benefits of the new technologies are known to the entire commercial nuclear power industry.

4.3 Halden Reactor Project

The R&D programs of the Halden Reactor Project extend to many aspects of NPP operations; however, the main area of interest to the II&C Pathway is the man-machine-technology research program that conducts research in the areas of computerized surveillance systems, human factors, and man-machine interaction in support of control room modernization. Halden has been on the cutting edge of new NPP technologies for several decades and their research is directly applicable to the capabilities being pursued under the pilot projects. In particular, Halden has assisted a number of European NPPs in implementing II&C modernization projects, including control room upgrades.

The II&C Pathway will work closely with Halden to evaluate their advanced II&C technologies to take advantage of the applicable developments. In addition to the technologies, the validation and human factors studies conducted during development of the technologies will be carefully evaluated to ensure similar considerations are incorporated into the pilot projects. Specific Halden developments of interest to the pilot projects are as follows:

- Advanced control room layout
- Computer-based procedures
- Advanced, state-based alarm systems
- Integrated operations
- Plant worker mobile technologies.

In addition, DOE will enter into a bilateral agreement in areas of research where collaborative efforts with Halden will accelerate development of the technologies associated with the pilot projects.

4.4 Major Industry Support Organizations

The LWR fleet is actively supported by major industry support groups; namely EPRI, the NEI, the INPO, and the NITSL. These organizations have active efforts in the II&C area, including technical developments, regulatory issues, and standards of excellence in conducting related activities. It is important that these organizations be informed of the purpose and scope of this research program and activities be coordinated to the degree possible. In the case of EPRI, even though they are a partner in development activities, there are opportunities to collaborate with other major programs they sponsor such as the Instrumentation and Control Program and the Nuclear Maintenance Application Center.

It is a task of this research program to engage these organizations to enable a shared vision of the future operating model based on an integrated digital environment and to cooperate in complementary activities to achieve this vision across the industry with the maximum efficiency and effectiveness.

The collaborations with EPRI have been previously presented in Section 4.2. Regarding NEI, a new level of collaboration was established in FY 2015 with a representative of the II&C Pathway participating in the NEI Digital II&C Working Group, which has been tasked by the CNOs of the nuclear utilities to work with the NRC to find resolutions to certain long-standing barriers to implementing digital technologies. The Working Group is now actively engaged with the NRC and the work will continue in FY 2016. The technologies, facilities, and expertise of the II&C Pathway will likely be of use in working through these regulatory barriers.

Engagement with INPO was enhanced in FY 2015 by way of meetings with INPO senior leadership on how the new technologies can improve performance and reduce burden on NPP workers and managers. Similar to EPRI, both organizations have participated in the other’s industry meetings to increase awareness of these development activities and to share insights and requirements. Of particular note, areas for specific collaboration have been identified in the areas of nuclear work process improvement and control room operator performance enhancement. INPO has been a participant in several development activities with utility project hosts, thus helping to ensure that the technologies are in concert with the broad principles of nuclear operational excellence.

There is considerable ongoing collaboration with NITSL in the area of mobile worker technologies and digital architecture. The II&C Pathway is partnered with the NITSL Infrastructure and Application (I&A) Committee to define the requirements for mobile worker technologies for NPPs. In addition, the I&A Committee is also a development partner in the Digital Architecture Pilot Project (see Section 5.5.1), hosting a working meeting for the past 2 years on this topic at its annual workshop. NITSL and the II&C Pathway conduct regular conference calls on these topics, which provide needed utility input on these development topics and provides access to utility experts in the implementation aspects of these technologies.

4.5 Nuclear Regulatory Commission

Periodic informational meetings are held between DOE Headquarters personnel and members of NRC management to communicate about aims and activities of individual LWRS Program pathways. Briefings and informal meetings will continue to be provided to inform staff from the NRC’s Office of Nuclear Regulatory Research about technical scope and objectives of the LWRS Program.

Also, as described in Section 4.4, there is ongoing engagement with the NRC through participation in the NEI Digital II&C Working Group on certain regulatory topics that have become some degree of impediment to digital implementation in NPPs. These include digital implementation without prior NRC approval under 10 CFR 50.59, new rulemaking (10 CFR 50.55 a(h)) incorporating new revisions of standards into regulations, methods of addressing software common cause failure (SCCF), and treatment of NPP components with embedded digital devices. The II&C Pathway will assist in the resolution of these issues both in direct communications with the NRC and through the efforts led by NEI.

4.6 Suppliers

Ultimately, it will be the role of the nuclear industry II&C suppliers to provide commercial products based on technologies developed under this research program. In the absence of an industry-wide II&C modernization strategy, products currently offered by these suppliers reflect the more limited approach of fragmented, like-for-like digital implementations as driven by the market. As a collective vision for an improved operating model based on an integrated digital environment takes hold within the LWR fleet, leading suppliers will seize the market opportunity to provide products that enact this vision.

An engagement strategy for nuclear industry II&C suppliers will be conducted with the following tasks:

- Communicate to suppliers the objectives of the research program and the specific technologies and operational concepts that are being developed and validated through the pilot projects.
- Obtain input from suppliers on how they are developing their products with respect to this market.
- Set up a mechanism for ongoing communications.
- Facilitate a long-term commercialization strategy for the program’s developed technologies.

4.7 Department of Energy - Nuclear Energy Enabling Technologies Program

The DOE Office of Nuclear Energy sponsors a crosscutting technology R&D program addressing common II&C needs in all Office of Nuclear Energy-sponsored programs. This program, the Advanced Sensors and Instrumentation crosscut, is conducting research that is intended to address gaps and needed capabilities for II&C technologies in all Office of Nuclear Energy-sponsored R&D programs.

II&C-related technologies are or will be needed to meet some of the long-term sustainability goals that are beyond the scope of LWRS Program research activities today. This includes improved technologies to support fuels and materials research that are capable of providing higher quality data during in-pile irradiations (planned to be coordinated in other LWRS R&D pathways). It also includes technologies that will enable some of the vision elements of the II&C research pathway. Examples of these include digital technologies that can reduce the highly labor-intensive aspects of plant maintenance (such as inspections, tests, and surveillances of sensors and controllers). In addition, digital technology introduction still presents a challenge for most plants because of the considerable regulatory uncertainties—both real and perceived—to obtain approvals, creating significantly higher costs and schedule uncertainty.

The current fleet of LWRs still employs many of the same technologies and algorithms in balance of plant control as when the systems were originally commissioned. Because of the amount of system noise and measurement uncertainty, set point regulation imposes a high burden on plant margins and creates a control structure that is inflexible. Consequently, control system behavior is deterministic and cannot easily or rapidly account for small system disturbances or significant external transients without quickly reaching protection system set points. This results in more “unavoidable” shutdowns and runbacks than would be necessary if installed control systems could be made more resilient and better able to cope with anticipated transients. Advances in control systems technologies would enable a range of operational improvements that would support higher rates of plant availability and reduced thermal cycling on major plant components caused by rapid plant shutdowns.

Two significant issues confront the massive communications architectures that are required to transmit signal and control data from and between the more than 100,000 individual plant components. The first relates to the material aging of copper cables for medium and low-voltage cables, especially the performance of insulating material. Although research is underway to understand and propose mitigations to counter the effects of material aging and degradation, a diversification of communications approaches may reduce the amount of amelioration that is eventually necessary once a solution is found. In addition, many plant components are not physically “wired” to the control system and exist outside the awareness of the control system and the operational staff. This introduces significant challenges in maintaining a desired plant configuration and requires substantial manual efforts to periodically assess and verify configuration status. In both cases, wireless communications technologies may one day be substituted for many physical cabling. In concert, power-harvesting technologies would help realize the goal to have all components physically coupled to plant control systems without imposing additional requirements for power cabling.

Finally, the reactor accidents at Fukushima Daiichi have raised a number of issues regarding the ability of current II&C technologies to withstand the environmental and accident conditions of severe accidents. Currently, emergency operating procedures and severe accident management guidelines in U.S. NPPs require access to reliable information from sensors and controls in order to manage anticipated transients. However, the severe accidents at Fukushima Dai-ichi highlight the potential for loss of all instrumentation and the ensuing difficulties in implementing emergency actions as a consequence. Further research is needed to understand the root causes of instrument failures, alternative approaches to estimate plant conditions, and to determine alternatives to accident management and recovery.

5. RESEARCH AND DEVELOPMENT PRODUCTS AND SCHEDULES

For each of the areas of enabling capability, the current performance issues and needs are described, followed by a description of how technology developments can improve performance. Each of the pilot projects is then described in terms of activities and deliverables, including a concise summary of each project.

5.1 Human Performance Improvement for Nuclear Power Plant Field Workers

Despite over a decade of strong emphasis on human performance improvement, the LWR fleet continues to be impacted by human error, resulting in plant transients, nuclear safety challenges, and equipment damage. While consequential error rates are relatively low (typically measured in the range of 10^{-4} consequential errors on a base of 10 K hours worked), the sheer number of work hours accumulated by the plant staff over time means that errors impacting plant safety and reliability still occur too frequently.

The traditional approach to improving plant worker human performance has been to focus on correcting worker behaviors. This has indeed produced substantial improvement since the time this emphasis began in the mid-1990s. Up to that time, there were frequent plant trips and transients due to human error (such as working on the wrong component or even the wrong operating unit). These types of errors have been gradually reduced until they presently are relatively rare. However, other types of errors continue to cause or complicate nuclear safety challenges. In the 2008 to 2010 timeframe, there were a series of incidents at various NPPs, many of which were considered to be among the industry's best performers. These incidents were documented in the INPO SOER 10-2, "The Thinking, Engaged Organization," which assigned a significant portion of the causes to human error and lack of operator fundamental knowledge.

The focus on correct worker behaviors typically involves analysis of the inappropriate worker actions and implementation of corrective actions in the form of additional training, procedure upgrades, job and memory aids (i.e., acronyms and neck strap cards), additional peer checking, management job observations, and so forth. While some improvement is usually obtained from these corrective actions, there has been a cumulative negative effect in adding complexity to work activities that make work tasks slow and cumbersome. To the operators, the focus seems to be more about the human error prevention tools (job aides) than the actual task or activity being conducted. Job satisfaction has been eroded and the added complexity has become an enticement to take short-cuts with these additional requirements, further perpetuating the cycle of human error. Much frustration on the part of workers and their managers has resulted from the ever-increasing job expectations added to work activities with, in actuality, diminishing returns in terms of error-free performance. Some industry observers believe that a saturation point has been reached, where the added complexity is contributing to the rate of human error (due to divided attention) and that we have reached the practical limits of human reliability at the present error rates.

To further improve human performance for NPP field workers, a fundamental shift in approach is needed. Digital technology can transform tedious error-prone manual tasks in NPP field activities into technology-based structured functions with error-prevention features. This has the potential to eliminate human variability in performing routine actions such as identifying the correct components to be worked on. In short, the technology can perform tasks at much higher reliability rates, while maintaining the desired worker roles of task direction, decision-making, and work quality oversight.

5.1.1 Mobile Technologies for Nuclear Power Plant Field Workers

Virtually all plant work activities are conducted under the control of rigorous work processes that convey the required job quality and technical requirements. Up until now, these work processes have generally relied on printed paper to present information to the plant workers and to serve as the medium to direct execution and recording of the specific tasks of the work activities. However, paper (as a medium) has the obvious limitations of not being interactive with real-time information sources; it is inflexible in its usage, leaves room for interpretation, and is incapable of enforcing its printed requirements. Technologies that have replaced the use of paper processes in the office environment have not been as easily adapted to field worker requirements.

The primary difficulty in providing plant workers with technology to improve their performance has been the fact that sometimes the workers must move about the plant in relatively inhospitable environments for digital technology (e.g., temperature extremes, radiation, radio frequency interference, and confined spaces). Also, there has been no practical way to connect these devices for real-time interactions to assist mobile workers.

Outside the nuclear industry, the use of mobile technologies to improve human performance is far more pervasive. A rapid transformation is in progress in the use of mobile technologies to revolutionize how humans conduct their routine personal and work-related activities. These technologies range from the applications in the latest smart phones to the hand-held business technologies used to receive and track mobile objects such as overnight packages, rental cars, and warehouse inventories. What these technologies have in common is that they correctly identify the intended work object, apply the correct process, guide the worker through the correct process steps, validate information, and post real-time work status to the corporate process systems—all from the job location.

These devices rely on wireless networks, digital processing devices, object identification capabilities (e.g., bar codes and radio frequency identification), voice command capability, and information processing software. In other words, many different technologies can be bundled in a single mobile device to address all aspects of a particular work activity. These technologies also have been "hardened," such that they are rugged and can perform reliably in challenging environments, including those found in an NPP.

However, it is not enough to simply provide field workers with mobile technologies. These technologies must be integrated into the plant work processes and must be able to access real-time plant information. Further, they must provide the ability for real-time interaction and collaboration with workers in other locations, in particular those who are coordinating overall plant operations, such as the NPP control room or outage control center. The idea is to embed the field worker in the plant processes and plant systems with wearable technologies, such that the worker is an integral and connected part of the seamless digital environment supporting plant operations and related activities.

These integrated technologies must first be validated using human performance evaluations to ensure they are not introducing negative factors into the work setting. It is essential that they be packaged and used in a manner that is intuitive, promotes situational awareness, and does not distract the worker from key job requirements or safety hazards in the area.

This research project will develop the basic mobile technology capabilities needed by an NPP field worker in performing typical plant work activities (Figure 8). It will include general work process instructions, component identification capability, wireless communications to transmit and receive real-time information, audio, picture, and video streaming, and use of heads-up, hands-free displays for workers involved in hands-on work. It also will include human factors evaluations to ensure the technology does not introduce negative factors that are detrimental to the job outcomes or well-being of the workers.

Figure 8. Operator at Catawba Nuclear Station using hand-held technology for component identification.

The initial applications of this technology will address safety tagging of components and conducting valve line-up checklists. These two initial applications typify many other plant activities such that the technology can easily be expanded into these other uses. The project also will develop a prototype of a simplified computer-based procedure to test the suitability of the technologies to handle interactive and shared content.

This pilot project is now complete with Duke Energy (Catawba Nuclear Station) having served as the host utility.

Schedule: FY 2011 to FY 2012

Milestones:

- (2012) Publish a technical report for implementing integrated mobile technologies for NPP field workers that provide real-time connections to plant information and processes, thereby reducing human error, improving human performance and productivity, enabling distance collaboration, and maximizing the “collective situational awareness.” (Complete: Published report INL/MIS-12-25139, *Advanced Instrumentation, Information and Control (II&C) Research and Development Facility Buildout and Project Execution of LWRS II&C Pilot Project 3*).
- (2012) Publish a technical report on guidance for the implementation of mobile technologies for NPP field workers. (Complete: Published report INL/EXT-12-27094, *Guidance for Deployment of Mobile Technologies for Nuclear Power Plant Field Workers*).

5.1.2 Computer-Based Procedures for Nuclear Power Plant Field Workers

The commercial nuclear industry conducts virtually all plant activities using standard or special procedures. This includes operational activities, abnormal or emergency actions, maintenance, testing, security measures, plant chemistry control, and radiation protection. The quality of the procedures, refined by operating experience over decades, has been an important contributing factor to the overall success of plant operational excellence and nuclear safety. Strict adherence to written procedures is a key tenet of operational standards.

Unlike many other safety-critical industries, procedures in the commercial nuclear industry are almost always paper-based. As such, these procedures remain prone to certain human errors and process deviations that continue to challenge the plants. Typical problems are as follows:

- Applying the wrong procedure for the plant situation
- Making unauthorized or unintentional deviations from procedure steps
- Receiving unexpected results from procedure actions due to coincident plant conditions/configuration
- Introducing copy errors when transcribing plant data into the procedures
- Making computational errors in processing acquired data.

These types of problems can be largely prevented using computer-based procedures (Figure 9), which inherently enforce adherence expectations and perform data manipulations in a correct manner. Furthermore, in an integrated computer-based procedure environment using wireless technology, it is possible to track the timing of real-time actions of procedure steps to detect unintended interactions among procedures or with the desired plant configuration. The following important benefits are possible with such a system:

- Integration with real-time plant data and system status
- Time monitoring for time-critical actions
- Detection of undesirable interactions
- State-based and mode sensitive context
- Sequencing of steps and other procedures (workflows)
- Place-keeping
- Seamless transitions to other procedures
- Computational aids and validation of results
- Embedded job aids: reference material, training material, and operating experience reports
- Automatic information insertion and verification of plant response
- Remote concurrences and authorizations
- Soft controls—platform for the future “highly automated” plant
- Real-time task status
- Real-time risk assessment.

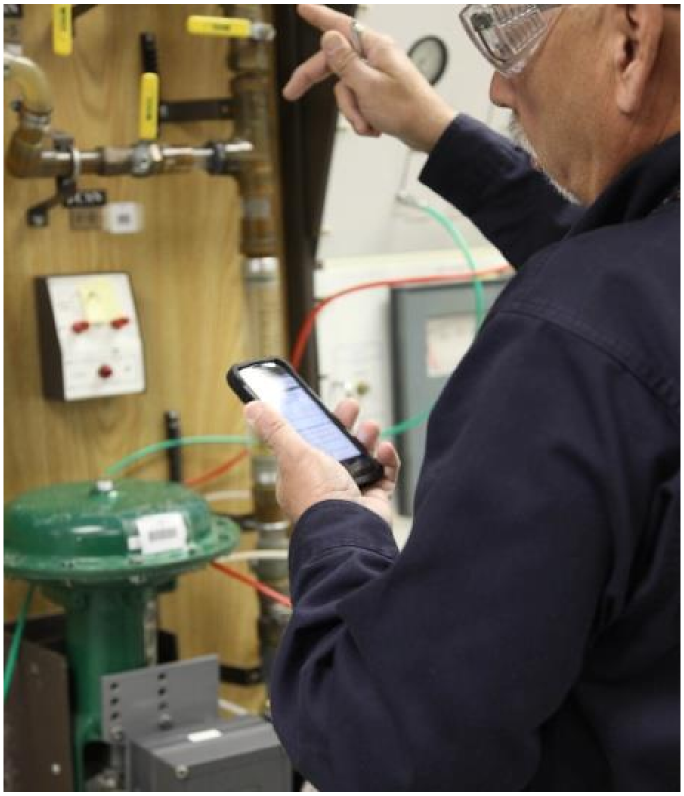

Figure 9. A field worker at Palo Verde Nuclear Generating Station uses the CBP to execute a task.

DOE has considerable expertise in computer-based procedures, having produced papers and reference material for the NRC on this topic. Further, the DOE agreement with the Halden Reactor Project provides access to considerable research and products for computer-based procedures, including direct experience in implementing such systems.

This pilot project will develop design guidance for computer-based procedures for field workers (i.e., all organizations at the NPP that work outside the main control room [Figure 10]). It will provide successive demonstrations of computer-based procedure capabilities as they are developed. To better illustrate the value of computer-based procedure to the NPP workers and senior management, the researchers conducts a series of field evaluation studies nuclear utilities used the computer-based procedure system to conduct selected tasks in the plant during a couple of months.

Figure 10. A control room operator and a field operator at Diablo Canyon Power Plant discuss a procedure using the CBP system on the hand-held device.

Putting the system in the hands of the field worker in the actual plant during normal operations makes the research more approachable and relatable to the industry. These are factors of great importance for the industry to even consider moving forward with this type of advanced technology.

The research objectives are to develop and publish the final design guidance for computer-based procedures for field workers. The guidance will be presented both as a report and as an interactive tool. The researchers will also address the design and development of an authoring and editing tool for computer-based procedures.

To date, the following utilities have hosted one or multiple studies:

- Arizona Public Service (Palo Verde Nuclear Generating Station)
- Duke Energy (Catawba Nuclear Station)
- Pacific Gas and Electric (Diablo Canyon Power Plant).

Utilities (or research organizations) ramping up to host field evaluation studies include:

- INL (the Advance Test Reactor)
- NextEra Energy (Point Beach Nuclear Plant).

Schedule: FY 2012 to FY 2016

Milestones:

- (2012) Develop the requirements for computer-based procedures for NPP field workers. (Complete: Published report INL/EXT-12-25671, *Computer-Based Procedures for Field Workers in Nuclear Power Plants: Development of a Model of Procedure Usage and Identification of Requirements*).
- (2012) Complete evaluation of a computer-based procedures prototype for NPP field workers. (Complete: Published report INL/EXT-12-27155, *Evaluation of Computer-Based Procedure System Prototype*).

- (2013) Complete evaluation of a final computer-based procedures prototype for field workers. (Complete: Published report INL/EXT-13-28226, *Evaluation of Revised Computer-Based Procedure System Prototype*).
- (2013) Publish a report summarizing the pilot project results in the use of the field worker computer-based procedure system prototype at host utility NPPs. (Complete: Published report INL/EXT-13-30183, *Computer-Based Procedures for Field Workers: Results from Three Evaluation Studies*).
- (2014) Publish a report on the results of a computer-based procedures validation study conducted at a NPP. (Complete: Published report INL/EXT-14-33212, *Computer-Based Procedures for Field Activities: Results from Three Evaluations at Nuclear Power Plants*).
- (2014) Complete a report documenting the benefits of field-based computer based procedures technologies. Complete: Published report INL/EXT-14-33011, *Computer-Based Procedures for Field Worker – Identified Benefits*).
- (2015) Complete a report of the field evaluation of the added functionality and new design concepts of the prototype computer-based procedure system. Complete: Published report INL/EXT-15-36615, *Computer-Based Procedures for Field Workers—Result and Insights from Three Usability and Interface Design Evaluations*).
- (2016) Complete a report describing the final results from FY 2015 field study, simulator demonstration, performance test, and the results from the FY 2016 field study.
- (2016) Develop final CBP Design Guidance documentation.

5.1.3 Automated Work Packages

Work packages for NPP field activities are typically bulky and cumbersome. They are expensive and wasteful of paper to print, and the volume of paper can be overwhelming to transport to the job site and manage while there. Further, for activities in a radiation control zone, taking the needed and contingency paperwork to the job site often increases the amount of contaminated waste generated.

Moreover, the paper-based work processes rely on human performance to correctly obtain plant information, enter it into the work packages and procedures, successfully complete the steps of the process in the right sequence, and ultimately validate that the correct results have been obtained. Because of the complexity of these activities and the sheer bulk of the paperwork, errors frequently occur that cause incorrect final results, rework, time delays, excessive safety system unavailability, and latent nuclear safety issues, if errors go undiscovered.

Based on mobile technologies for NPP plant workers developed under the first pilot project of this enabling area, it will be possible to automate large portions of plant activities in a manner that improves human performance, makes workers more productive, and enhances nuclear safety by reducing active and latent component failures. Specific capabilities would include the following:

- Organize and control the sequence of all tasks performed under the work package
- Retrieve documentation directly from the utility’s document management system, eliminating reference material from the work package that often proves to be unneeded.
- Obtain plant data inputs directly from the plant systems and components, eliminating reading and transcribing errors. This data could be obtained wirelessly from the plant computer and locally by connecting directly to smart devices such as digital transmitters.

- Insert results directly into plant work processes and plant systems. This would include system health applications, data historians, plant computer, and the work package and procedure archival system.
- Obtain real-time concurrences and verifications from remote locations.
- Directly download updates and deviation approvals if revisions are needed to complete the work package.
- Directly access supplemental information such as training videos, operating experience, similar historical work packages, and corrective action reports.
- Provide real-time task status to work execution centers, eliminating the need to call field workers to obtain updates.
- Validate results based on real-time plant data, historical results, and engineering acceptance criteria.

This project will develop a prototype work package that can be executed on the mobile technologies for field workers. The work package will be tested in a host utility NPP, exercising all the capabilities of the mobile technologies and interconnectivity among those technologies. Human factors evaluations will be conducted during these tests to determine the gains in productivity and human performance, as well as identifying and mitigating any negative human factors that are introduced.

A parallel activity of this project will develop and demonstrate a prototype for the automatic creation of a work package to document that surveillance requirements have been met through the acquisition of plant performance data through wireless instrumentation and monitoring technology. This would automate the production of surveillance or test work packages when requirements can be verified to have been met through normal or test alignments for plant systems. This capability has the potential to reduce labor requirements for a significant number of plant test activities. Even when some operator or technician involvement is needed to conduct the test or surveillance, the production of the documenting work package can be highly automated.

To enable this plant data acquisition, an interoperable communication platform will be developed, which will be expandable to multiple communication technologies. This capability will be tested in a host utility NPP or in a laboratory set-up that will mimic a representative nuclear environment. Communication resilience evaluations will be conducted during these tests to determine the gains in productivity, as well as identify and mitigate any communication or security related negative concerns that are introduced.

The final activity in the project will be to merge the wireless instrumentation and monitoring technology with the automated work package prototype. The purpose is to develop and demonstrate this enhanced prototype system for NPP surveillance and maintenance tasks. The final product will be a technical report on automated work package implementation requirements for both NPP field worker usage and self-documenting surveillances.

Schedule: FY 2014 to FY 2017

Milestones:

- (2014) Develop a requirements document for an automated work package prototype for NPP work processes. (Complete: Published report INL/EXT-14-33172, *Automated Work Packages: An Initial Set of Human Factors and Instrumentation and Control Requirements*).
- (2015) Develop a report on an automated work package prototype, which supports paperless work flow and improved human performance, and communication platform for information exchange. (Complete: Published report INL/EXT-15-35825, *Automated Work Package Prototype: Initial Design, Development, and Evaluation*).

- (2016) Develop a report summarizing digital features required to integrate work order, procedures, mobile communication, and smart devices to achieve higher worker efficiency.
- (2017) Enhance the automated work package prototype by integrating an interoperable communications platform and demonstrating these new capabilities for NPP surveillances.
- (2017) Publish a report on automated work package implementation requirements for both NPP field worker usage and self-documenting surveillances.

5.1.4 Augmented Reality for Nuclear Power Plant Field Workers

NPP field workers are often in a plant environment where information critical to successful completion of their activities and even their well-being is not visually available, including the following:

- Temperature of surrounding components
- Whether a valve is open or closed
- Proximity to reactor trip-sensitive equipment
- Proximity to temporary hazard boundaries (e.g., radiography or overhead load paths).
- Plant data (pressure, flow, and set points) concerning nearby components
- Strength of radiation fields and location of hotspots
- Oxygen-deficient environments.

Therefore, plant workers must have this information already provided in their work packages or they have to rely on others to supply this information during the activity through the available communication channels. This is time-consuming and often results in an inadequate understanding of the actual field conditions.

Technologies are emerging that will connect the field worker to this information in a dynamic and context-based way. These technologies will allow the worker to “see” otherwise invisible information that will enable them to make informed decisions about their activities and their personal proximity to hazards. For instance, this might include smart safety glasses that can superimpose a transparent color-shaded representation of a radiation field directly into the worker’s field of view. Similarly, plant data could be superimposed directly onto the components in the field of view, allowing the worker to “read” the data by merely looking at the components.

This capability would be made possible through use of wireless communications to supply information from the plant computer and other sources, in combination with technologies that can determine the worker’s location, orientation, and field of view. Further, the information provided would be context-based because the worker’s purpose for being in that location would be known to the information system. In this way, only data relevant to that purpose would be automatically pushed to the worker. However, the worker could request any other information desired. In addition, it would be possible to remotely monitor personal physiological data, when necessary, such as workers in high-temperature work environments or during confined space entries with the potential for hazardous gases.

These capabilities would create a whole new dimension in the concept of an "intelligent plant worker." They could be combined with the concept of automated work packages to produce extraordinary efficiencies in conducting plant activities and keeping the worker safe. There would be secondary benefits to knowing the location and surrounding environment of each worker. For example, this would greatly simplify accounting for personnel in emergency situations such as containment evacuations and security events. It could enable remote monitoring of radiation dose and allow for optimized dispatch of field workers supporting concurrent work activities such as quality control inspectors. It could enable the concept of "picture procedures" in which images of the actions required by a procedure step are superimposed on the equipment being manipulated via the worker's heads-up display.

This project will develop the needed technologies to create augmented realities for NPP field workers and will test these technologies in the HSSL and, ultimately, in a host utility NPP. Studies during testing will include both technical and human factors evaluations. The final product will be a technical report on how to implement these technologies in conjunction with the previously developed mobile technologies for NPP field workers. It also will provide guidance for integrating the augmented reality technology with compatible automated work packages.

The Halden Reactor Project is already developing these types of technologies, including those that can determine the location and orientation of a field worker. The pathway will work closely with Halden to take full advantage of the augmented reality technologies as they are developed.

Schedule: FY 2017 to FY 2019

Milestones:

- (2017) Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers.
- (2018) Develop and demonstrate augmented reality technologies for visualization of real-time plant parameters (e.g., pressures, flows, valve positions, and restricted boundaries) for mobile plant workers.
- (2019) Publish a technical report on augmented reality technologies developed for NPP field workers, enabling them to visualize abstract data and invisible phenomena, resulting in significantly improved situational awareness, access to context-based plant information, and generally improved effectiveness and efficiency in conducting field work activities.

5.2 Outage Safety and Efficiency

Nuclear plant refueling outages are some of the most challenging periods of time in the ongoing operations of the facilities. There are usually more than 10,000 activities to be accomplished in a typical duration of 20 to 30 days. Enormous expenses are incurred for outage work, including supplemental workforce, which sometimes totals over 1,000 contractors. Schedule delays drive these costs up proportionately. In addition, the utilities incur additional costs for replacement power for the time NPPs are out of service. Nuclear safety is a particular challenge during outages due to the degraded configurations an NPP is sometimes in to accommodate work on the plant systems. In fact, a large percentage of the annual incremental core damage frequency of the plant's probabilistic risk assessment is incurred during outages. There is also a special regulatory risk because the plants are challenged to meet shutdown technical specifications and "maintenance-rule" risk mitigation measures. Finally, an outage is especially challenging from the standpoint of industrial safety in that the risk of plant workers getting hurt is highly elevated due to the types of activities that are conducted.

Managing nuclear outages in a safe and efficient manner is a very difficult task. In fact, the early history of refueling outages was one of significant cost and schedule overruns, as well as troubling nuclear safety challenges. This led utilities to develop formal outage organizations dedicated to planning and executing their refueling and forced outages. They also built outage control centers that co-locate the activity managers for all of the major site organizations so that they can closely coordinate their activities. In addition, they maintain a number of other work execution centers that control critical elements of the work, such as safety tagging for system and component isolations, nuclear risk management coordinators, and similar functions needed to address other constraints on how the outage is conducted.

As a result of these practices, today's outage performance is greatly improved from what it once was. Outage cost and durations are considerably lower than in the past. Nuclear safety also is greatly improved. However, there remain some significant opportunities and challenges for the industry and are as follows:

- Further reducing the duration of refueling outages remains the largest opportunity to improve plant capacity factors and increase the economic value of the facilities.
- In spite of impressive gains in shutdown safety, there are still too many serious safety challenges (such as loss of residual heat removal and unintended additions of positive reactivity).
- Regulatory violations continue to occur due to subtle configuration control issues that result from unintended interactions among concurrent work activities.

In spite of the impressive organizations and facilities that have been implemented to improve outage performance, outage management generally relies on the very basic technology of radios, telephones, and stand-alone computer applications. There is some growing usage of remote video for point applications and activity monitoring. Utilities have not made widespread usage of mobile technologies for controlling field work, collaboration technologies for coordinating issues across the broad organization, or advanced configuration management technologies to improve safety and regulatory performance.

There is no question that improved technology for outage management would provide a step change in a utility's ability to conduct outages in a safe and efficient manner. This research program is well positioned with its HSSL, human and organizational factors expertise, and knowledge of NPP outage practices to demonstrate and provide guidance for application of advanced digital technologies to achieve substantial economic value and nuclear safety enhancement through outage performance improvement.

5.2.1 Advanced Outage Coordination

The amount of information that must be processed by the outage control center (OCC) is staggering. OCC managers must obtain the status of thousands of ongoing work activities, project the expected progress of the activities, and then adjust near-term activities for gains or losses in the overall schedule. Accurate work status is difficult to obtain due to communication barriers with field work, particularly in hard-to-access areas of the plant. Also, work status sometimes reflects an overly optimistic outlook by those performing the work. The term "real-time truth" is sometimes used by outage managers to refer to this need for the true status of the work-in-progress.

The outage managers also deal with a continual stream of emergent issues caused by deviations in the expected progress of the planned activities or new problems that arise (e.g., equipment failures, unexpected interactions between work activities, and other unanticipated outage conditions). The outage managers have to quickly assess the impact of the new issues on the overall outage plan and schedule, consult with knowledgeable individuals on the nature of the problems and possible solution options, determine the solution that results in the least impact on the overall outage objectives, and communicate changes to plans and schedules to the affected activity managers.

These typical outage management activities rely on telephone calls, impromptu meetings, "white board" solution sessions, manual transcribing of agreed-upon changes into a number of work process systems (e.g., work orders, schedules, risk management, radiation work permits, safety tagging, and warehouse parts), and communication throughout the organization using outage status meetings, e-mail, and direct telephone contact. This process is repeated tens of times per shift for the duration of the outage.

This pilot project will assess the needs of outage management and identify technologies that will greatly improve communications, coordination, and collaboration activities that are needed to minimize the impact of challenges to the outage plan and schedule. It will focus on capabilities that facilitate natural human interaction, while ensuring a high degree of situational awareness and shared understanding. Further, the technologies will be integrated in a way that minimizes the effort to keep all work management systems synchronized with changing plans.

The project will also develop dynamic interfaces for information coming from mobile field workers, the plant control and information systems, and the fluid information developed in the OCC (and other control centers) as the greater organization develops solutions to emergent outage problems (Figure 11). Human factors assessments of the use of the technology will be conducted to validate that the benefits are actually obtained and new problems are not introduced by technology usage. The results of the project will be a demonstration of the integrated technologies and a technical report for industry-wide implementation.

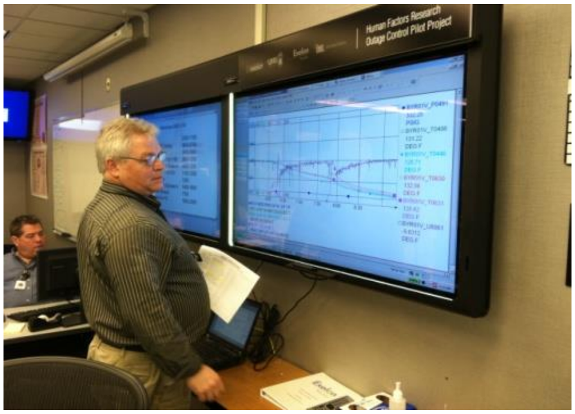

Figure 11. Remote collaboration technology in use at the spring 2011 Byron Nuclear Station refueling.

This pilot project currently is now complete with Exelon Nuclear (Byron Nuclear Station) having served as the host utility.

Schedule: FY 2010 to FY 2012

Milestone:

- (2012) Publish a technical report for implementing digital technologies that facilitate communications, coordination, and collaboration in obtaining accurate outage activity status, managing the flow of information through the OCC, and enabling the resolution of emergent problems in an efficient and effective manner, resulting in improved work efficiencies, production success, and nuclear safety margins. (Complete: Published report INL/EXT-12-26197, *Advanced Outage and Control Center: Strategies for Nuclear Plant Outage Work Status Capabilities*).
- (2012) Publish a technical report on the use of digital technology for resolving emergent issues in NPP outages. (Complete: Published report INL/EXT-12-26807, *Resolving Emergent Issues during Nuclear Plant Outages*).

5.2.2 Advanced Outage Control Center

The OCC is the central command and control point for executing NPP outages. It is staffed 24/7 during outages and accommodates 10 to 15 managers and coordinators from the site and fleet organizations supporting the outage. These positions are typically grouped according to organization and informally interact with one another to coordinate their specific work activities and problem resolutions. Various types of meetings are held on a regular schedule each shift to communicate outage status, share information on upcoming activities and emergent issues, and verify with each organization that they are prepared to support the upcoming activities.

Many of the organizations represented in the OCC also maintain a functional support center at their own site locations to provide the specific services they conduct. For example, radiation protection operates a center to develop and assign radiation work permits and authorize and brief workers who enter radiation control zones. The Operations organization maintains centers to prepare safety tagouts, conduct risk assessments, and track plant configuration changes. There are similar functional support centers set up in the other organizations such as chemistry and engineering. One of the key tasks of the OCC coordinators is to ensure these functional centers are aware of changing needs as determined in the OCC and are responding accordingly. The coordinators typically have to leave their positions in the OCC several times a shift to attend coordination meetings back in their functional support centers and are not available for coordination with other OCC positions during those times.

In considering coordination activities, there is a significant need for advanced technologies to facilitate the information flow into, across, and out of the OCC. These include technologies to conduct interactive meetings with participants in other locations. They will allow the entire OCC to share information as it develops in response to an emergent issue. They will allow the OCC coordinators to meet electronically with their respective functional support centers without having to leave the OCC. They will update all affected work management systems as decisions are made on how to resolve a problem. Finally, they will provide the overall outage managers with the true status on the progress of work and the implementation status of outage plan changes from the OCC managers and coordinators.

These technologies will be integrated into an advanced OCC specifically designed to accommodate and maximize the value of the technologies, while preserving the features of the existing OCCs that facilitate human interaction (Figure 12). Where appropriate, these features will be extended to the functional support centers to accommodate their interface with the OCC.

Figure 12. Advanced Outage Control Center concept design.

There is significant potential to take advantage of real-time status information that will be available by field workers using automated/electronic work packages (AWPs/EWPs). Technologies are being developed to collect status information effectively, display this information, and assist outage decision making. This work will coordinate with research from other LWRS pilot projects.

This pilot project will integrate these technologies into a prototype advanced OCC using HSSL. It will be set up to facilitate the display and processing of information and collaboration within the OCC or with parties remote to the OCC. This prototype facility will be used to simulate outage coordination functions so the technology and associated human factors can be evaluated. It will test interaction with all required sources of information needed by the OCC, including mobile technology operated by NPP field workers, plant control and information systems, other control and functional support centers, and information sources external to the plant. As a final product, a technical report will be developed for industry-wide implementation of the advanced OCC.

This pilot project began in FY 2013, with Arizona Public Service (Palo Verde Nuclear Generating Station) serving as the host utility (Figure 13). Currently, AOCC concepts have been implemented at plants in the Southern Nuclear fleet, Tennessee Valley Authority Fleet, Byron Nuclear Station, and South Texas Project. Several Duke Energy fleet plants are the process of implementing new OCCs incorporating advanced design features.

Figure 13. Advanced Outage Control Center at Palo Verde.

Schedule: FY 2013 to FY 2016

Milestones:

- (2013) Develop technologies for an advanced OCC that improves outage coordination, problem resolution, and outage risk management. Complete: Published report INL/EXT-13-29934, *Development of Methodologies for Technology Deployment for Advanced Outage Control Centers that Improve Outage Coordination, Problem Resolution and Outage Risk Management*).
- (2014) Develop human factors studies and publish a technical report for an advanced OCC that is specifically designed to maximize the usefulness of communication and collaboration technologies for outage coordination, problem resolution, and outage risk management. (Complete: Published report INL/EXT-14-33182, *Guidelines for Implementation of an Advanced Outage Control Center to Improve Outage Coordination, Problem Resolution, and Outage Risk Management*).
- (2014) Complete report describing advanced outage functions, including the results of the real-time support task involving coordination and automated work status updating. (Complete: Published report INL/EXT-14-33036, *Status Report on the Development of Micro-Scheduling Software for the Advanced Outage Control Center Project*).

- (2014) Complete benchmark report documenting priorities and opportunities for outage improvement that can be addressed through pilot project technologies. (Complete: Published report INL/EXT-14-32848, *Benchmark Report on Key Outage Attributes: An Analysis of Outage Improvement Opportunities and Priorities*).
- (2015) Complete a report describing the development of improved graphical displays for an Advanced Outage Control Center, employing human factors principles for effective real-time collaboration and collective situational awareness. (Complete: Published report INL/EXT-15-36489, *Development of Improved Graphical Displays for an Advanced Outage Control Center, Employing Human Factors Principles for Outage Schedule Management*).
- (2016) Complete a report describing the development of an overview display to allow AOCC advanced outage control center management to quickly evaluate outage status.

5.2.3 Outage Risk Management Improvement

Significant efforts are expended to manage the nuclear risk of an outage. The utilities conduct pre-outage risk assessments, based on a very detailed review of the outage schedule, to identify where combinations of outage work and equipment out-of-service would result in degraded conditions with respect to nuclear safety or regulatory compliance. Probabilistic risk assessment studies are conducted to quantify the incremental core damage frequency as a result of the outage activities and system unavailability. These studies are usually presented to site and fleet management, the site plant operational review committee, and the NPP's independent Nuclear Safety Review Board for concurrence that the outage is planned safely and that reasonable measures have been taken to reduce the added risk of conducting the outage.

During the outage, the plant configuration is monitored continuously to ensure that it conforms to the approved safety plan. Deviations must be assessed and approved by management committees and, in some cases, the plant operational review committee. In virtually all outage meetings and job briefings, the current nuclear safety status of the plant is communicated, including information on the specific equipment that is being relied on to meet the requirements of the nuclear safety plan. In addition, Operations and the Outage organizations implement several layers of physical and administrative barriers to prevent unintended interaction with the systems and equipment credited for nuclear safety.

In spite of all these efforts, nuclear safety challenges still occur too frequently in outages. While some of these are due to failure of equipment credited for safety, the majority occur because of human error. These typically involve some form of interaction between work activities and plant configuration changes. Some of them are very subtle and are extremely challenging to detect in advance. Nevertheless, they are not acceptable and represent clear opportunities to improve nuclear safety during outages.

This pilot project will investigate methods to improve real-time plant risk management and configuration control during outages as a function of work activities and plant system alignments. It will develop a means for combining actual plant status information with intended component manipulations embedded in procedures and work packages that are underway. This information will, in turn, be compared to design information (e.g., piping and instrumentation diagrams and one-line diagrams) to identify the set of possible interactions. Finally, the information will consider the technical specifications (and other licensing basis requirements), probabilistic risk assessment information (e.g., accident precursors), and ongoing risk mitigation plans to report possible interactions of concern. The project will demonstrate the techniques and underlying technologies to perform this type of outage safety analysis. The project deliverables will include the new technologies and guidance for integrating them into outage preparation and execution activities.

Schedule: FY 2017 to FY 2019

Milestones:

- (2017) Develop and demonstrate (in the HSSL) technologies for detecting interactions between plant status (configuration) states and concurrent component manipulations directed by in-use procedures, in consideration of regulatory requirements, technical specifications, and risk management requirements (defense-in-depth).
- (2018) Develop and demonstrate (in the HSSL) technologies to detect undesired system configurations based on concurrent work activities (e.g., inadvertent drain paths and interaction of clearance boundaries).
- (2019) Develop a real-time outage risk management strategy and publish a technical report to improve nuclear safety during outages by detecting configuration control problems caused by work activity interactions with changing system alignments.

5.3 Centralized Online Monitoring and Information Integration

As NPP systems begin to be operated during periods longer than originally anticipated, the need arises for more and better types of monitoring of material and component performance. This includes the need to move from periodic, manual assessments and surveillances of physical components and structures to centralized online condition monitoring. This is an important transformational step in the management of NPPs. It enables real-time assessment and monitoring of physical systems and better management of active components based on their performance. It also provides the ability to gather substantially more data through automated means and to analyze and trend performance using new methods to make more informed decisions concerning component health. Of particular importance will be the capability to determine the "remaining useful life (RUL)" of a component to justify its continued operation over an extended plant life.

The current technology base for monitoring in the U.S. nuclear industry consists of signal processing techniques and advanced pattern recognition (APR) programs that are technically mature and commercially supported. The application of this technology is in the early stages of implementation by leading nuclear utilities. The implementation rate has been slow due to the required funding and infrastructure development for integrating monitoring programs within the operating and business environment.

APR provides highly sensitive anomaly detection of current condition or behavior for targeted components. Much of the value of online monitoring comes from early warning of imminent component failures. Commercial APR products rely on the continuous input of well-correlated plant data to provide this early warning. (These products typically have been applied only to active plant components). After the initial warning, the plant support staff conducts an investigative review to identify the actual failure mode and cause, and then suggests appropriate corrective actions. The review can involve many onsite operations and technical staff, consultants, and field experts in predictive maintenance. In these cases, the diagnostic process can be manually intensive and can consume available warning time and extend damaging operating conditions. While APR systems are effective at identifying equipment operating in conditions that may shorten the equipment's RUL, they are limited to identifying operating data values that are "not normal" in comparison to a historical baseline. Commercially available APR products cannot perform the next essential step of diagnosing the underlying cause for the abnormal data values. This diagnosis step *relies entirely* on a staff of highly trained specialists to troubleshoot and diagnose the underlying problem and to recommend a corrective action response. Furthermore, the RUL of the monitored asset cannot be determined by APR technology. In addition, there are long-term failure modes that are not detectable with APR technology.

Hence, current APR products are not capable of providing directly useful information to life-cycle management and long-term asset management. Commercially available APR technologies in their current form are unable to detect long-term failure modes, thereby making them unsuitable for long-term monitoring and management of nuclear assets and, in particular, for passive assets evaluated on an intermittent basis using nondestructive evaluation measurement techniques.

The development of diagnostics and prognostics capabilities will provide an automated capacity to directly identify the equipment condition from the "signature" of the initial warning. This will support analysis of long-term component behavior, related risk, and RUL. It will further provide verification of asset condition as evidence of design qualification and economic viability.

This new monitoring technology will enable early detection of degradation conditions that can be addressed before they significantly contribute to life-limiting damage. The early detection of degradation is one of the more significant factors in extending component lifetime. A more timely response to the causes of degradation also can significantly improve nuclear safety and prevent collateral damage to other nearby components and structures. Finally, these new capabilities will reduce the cost of manual diagnostic work.

EPRI is active in various research and demonstration projects for maturing prognostic and health management technology to help assure the long-term, reliable operation of the nation's fleet of NPPs. EPRI's current research includes developing a Fleet-wide Prognostic and Health Management (FW-PHM) Suite software solution designed for compatibility with existing NPP troubleshooting and asset management processes while leveraging tools already used for online monitoring (Figure 14). No commercial products are available that perform the full functionality intended for the FW-PHM Suite. The Suite's four primary functional modules are built on a common reference database of diagnostic and RUL models for power generation assets.

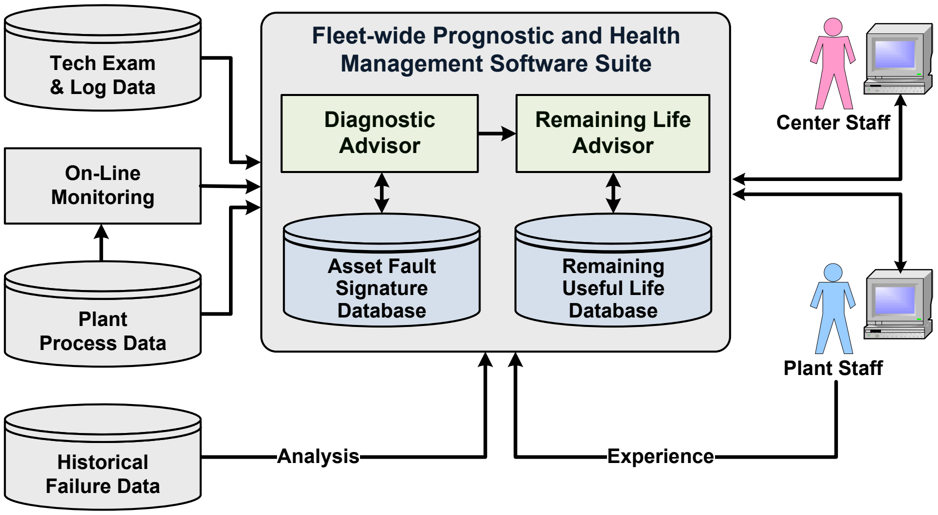

Figure 14. Fleet-wide prognostics and health management in an online monitoring environment (diagram courtesy of EPRI).

The FW-PHM Suite includes specific knowledge capture capabilities that learn diagnostic and prognostic information from in-service experience in industry-deployed applications and structure this information for pooling and analysis by EPRI, government, and industry experts. This information can be used by experts in combination with EPRI's extensive library of reference documents to create and maintain an industry-wide database of verified diagnostic and RUL models for NPP assets.

The FW-PHM Suite software is, at present, a research grade product available to EPRI members that have sponsored its development. The Suite's databases are populated with limited knowledge derived from various preliminary pilot applications involving a small set of nuclear and fossil plant equipment and from technology demonstration projects. EPRI has identified the long-term need for ongoing research to develop the diagnostic and remaining life prediction models for power generation assets that will populate this industry-shared database of models, because no one utility or vendor alone could compose such a comprehensive model reference collection. In fact, collaboration among the industry, EPRI, the national laboratories, and universities is needed to accomplish the R&D effort to identify a model or a set of models as required for a particular component to create verified diagnostic and prognostic models to support PHM processes and to provide accurate, substantiated input to life-cycle management and long-term asset management capabilities. In particular, diagnostic and prognostic models for passive nuclear assets require significant future research, which should include formulating the resulting diagnostic and prognostic models and their basis information for inclusion in the FW-PHM Suite's knowledge database.

Therefore, a gap exists between the current state of technology development and the effective application of diagnostics and prognostics to nuclear plant assets. To address this gap, the following research tasks have been defined.

1. Complete development of a monitoring infrastructure at the operating and management levels of the nuclear power industry.

2. Develop an organizational structure that defines the contributing research organizations, their roles, resource availability, and utility hosts. This includes EPRI, national laboratories, universities, utilities, and technology developers.

3. Continue R&D of the diagnostics and prognostics technology for adaption to the nuclear power industry.

4. Develop the structure-specific models, component-specific models, analytical methods, and the supporting data requirements needed to enable diagnostics and prognostics analysis.

5. Obtain access to the real physical assets in service in an NPP and determine the critical measurements needed to support the analysis.

6. Develop additional monitoring methods (such as transient analysis) to support RUL analysis.

7. Identify environmental conditions detrimental to aging mechanisms, including fatigue monitoring and assessment.

8. Identify component-specific failure and aging mechanisms/precursors.

9. Identify measurement and sensor requirements to support analytical methods.

An effective means to accomplish portions of the above research tasks is through conduct of pilot projects. These projects will be structured around a narrowly defined set of objectives to accomplish specific tasks that require access to real-time plant assets and operational data. There are significant limitations to bench-top modeling and scaled-down component behavior analysis in the progression of technologies from proof-of-concept to real-world component applications. The utilization of real physical components and operational data is required to develop the technologies beyond the laboratory. The process of applications engineering and research is not within the capabilities of the utilities or the engineering staff at NPPs. Host utilities are required to support the needed research to provide access to major components in actual service.

EPRI will provide the lead role in providing online monitoring capabilities through their continued development and support of the FW-PHM Suite software, in addition to their other online monitoring research activities. The II&C research program will support EPRI by conducting the pilot projects to develop the diagnostic and prognostic analytical framework for representative active and passive component/structures whose extended life supports LWR sustainability.

In regard to the “centralized” aspect of the project concept, it is expected that utilities will find that a central monitoring function within their nuclear fleet will be the most efficient way to implement this technology. Indeed, this has been the practice of some of the early movers for online monitoring using the APR technology. This concept work for centralized monitoring will be accomplished through the pilot project on the advanced online monitoring center (as described in Section 4.4.1). The II&C research program will also serve the role of integrating the online monitoring information into the overall digital information architecture such that it will provide needed information to other plant activities.

5.3.1 Online Monitoring of Active Components

A pilot project will be conducted involving three active components representative of those for which extended life is highly important to LWR sustainability. The components are emergency diesel generators and large power transformers and induction motors.

The objective will be to develop the diagnostic and prognostic analysis framework for these components, including the ability to predict RUL. These capabilities will enable industry to implement online monitoring for these components and will establish the methodology for industry to extend the concept to other active plant components where aging and degradation mechanisms must be managed for extended life.

Using the EPRI FW-PHM Suite software, the pilot project will develop the databases and analytical models needed to process sensor signals to identify specific component degradation and fault conditions. The databases include the asset fault signature database and the RUL database. The analytical models will be those needed for the diagnostic and RUL advisors. The project also will include identification of additional sensor development and monitoring capabilities needed to enhance the monitoring capabilities for these components.

For each of these component types, a technical report will be published that describes the technical basis and analysis framework to enable online monitoring for these components. These technical reports, along with the results and experience from the pilot projects, will be used to develop guidelines for utilities to implement centralized online monitoring and information integration for the components/structures important to plant life extension.

This pilot project currently is underway with two host utilities: Exelon Nuclear (Braidwood Nuclear Station) for emergency diesel generator monitoring and Progress Energy (Harris Nuclear Station) for large power transformer monitoring. For the induction motor project, Idaho State University will develop an experimental test bed that will include two 40-HP induction motors instrumented with current, temperature, and vibration sensors. The experimental test bed will support development of diagnostic models for loss of bearing lubrication, contamination of bearing lubrication, misalignment, and loss of cooling degradation.

Schedule: FY 2012 to FY 2015

Milestones:

- (2012) Publish an interim technical report on the online monitoring technical basis and analysis framework for large power transformers. (Complete: Published report INL/EXT-12-27181, *Online Monitoring Technical Basis and Analysis Framework for Large Power Transformers; Interim Report for FY 2012*).
- (2013) Publish an interim technical report on the online monitoring technical basis and analysis framework for emergency diesel generators. (Complete: Published report INL/EXT-12-27754, *Online Monitoring Technical Basis and Analysis Framework for Emergency Diesel Generators—Interim Report for FY 2013*).
- (2013) Publish a technical report on for the demonstration of online monitoring technology for large power transformers and emergency diesel generators. (Complete: Published report INL/EXT-13-30155, *Demonstration of Online Monitoring for Generator Step-up Transformers and Emergency Diesel Generators*).
- (2014) Complete a report describing the diagnostic and prognostic models for generator step-up transformers. (Complete: Published report INL/EXT-14-33124, *Diagnostic and Prognostic Models for Generator Step-Up Transformers*).
- (2015) Complete a technical report describing the diagnostic and prognostic models for induction motors. (Complete: Published report INL/EXT-15-36681, *Online Monitoring of Induction Motors*).

5.3.2 Online Monitoring of Passive Components and Structures

The initial pilot project focuses on concrete structures. Concrete structures are present in all NPPs and are grouped into four categories: (1) primary containment, (2) containment internal structures, (3) secondary containment/reactor buildings, and (4) other structures such as used fuel pools, dry storage casks, and cooling towers. The age-related deterioration of concrete needs to be measured, monitored, and analyzed to support long-term operation and maintenance decisions.

This project will be a collaborative effort between the II&C research, Material Aging and Degradation pathways, and Vanderbilt University. It will develop a framework for health diagnosis and prognosis of aging concrete structures in NPPs subject to physical, chemical, and mechanical degradation, by integrating modeling, monitoring, data analytics, and uncertainty quantification techniques. Current knowledge and ongoing national/international research efforts in individual directions will be leveraged and synthesized to advance the state of the art in full-field, multi-physics assessment of concrete structures.

The framework (shown in Figure 15) for the health monitoring of NPP concrete structures will include four technical elements: (1) damage modeling, (2) monitoring, (3) data analytics, and (4) uncertainty quantification. The framework will enable plant operators to make risk-informed decisions on the structural integrity, remaining useful life, and performance of concrete structures. The framework will be generalizable to a variety of aging passive components in NPPs. The four tasks corresponding to the four technical elements are outlined below.

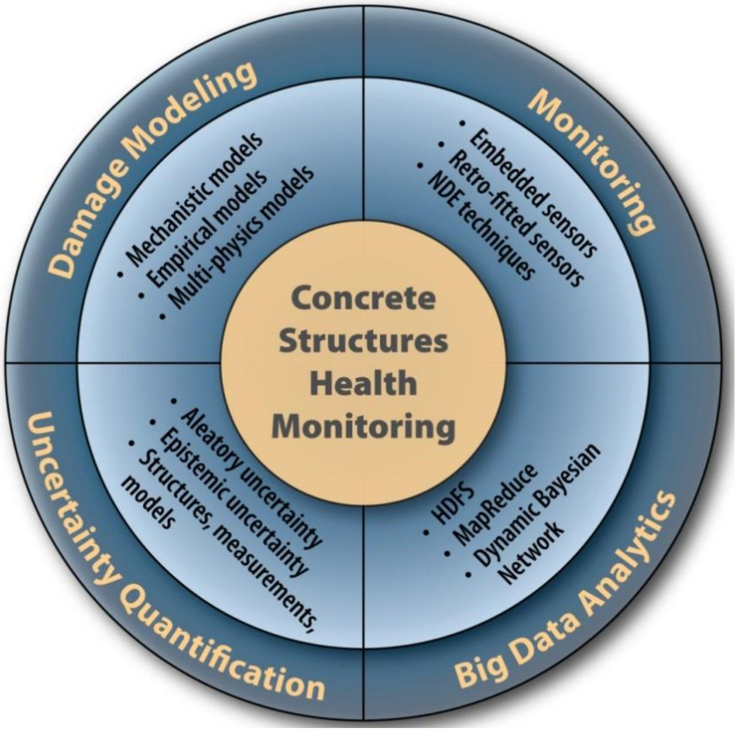

Figure 15. PHM framework for concrete structure health monitoring.

Damage Modeling. This task will leverage the modeling of chemical, physical and mechanical degradation mechanisms (such as alkali-silica reaction, chloride penetration, sulfate attack, carbonation, freeze-thaw cycles, shrinkage, and radiation damage) to assist monitoring and risk management decisions. Alkali-silica reaction (ASR) is currently receiving prominent attention and will be used for initial development; other damage mechanisms will be included in subsequent years. The interactions of multiple mechanisms will receive significant consideration. The task requires modeling and computational advances and combined-physics experiments (including multi-scale and micromechanics effects), and the integration of multiple models through an appropriate simulation framework.

Monitoring. This task will explore the effective combination of promising structural health monitoring (SHM) techniques for full-field multi-physics monitoring of concrete structures. Optical, thermal, acoustic, and radiation-based techniques will be investigated for full-field imaging. Examples of these techniques include digital image correlation (optical), infra-red imaging (thermal), velocimetry and ultrasonics (acoustic), and X-ray tomography. Particular considerations include interaction effects in SHM measurements under operational environments, and the linkage of chemical degradation to the observed mechanical degradation, which requires synergy between damage modeling and monitoring.

Data Analytics. The information gathered from multiple health monitoring techniques results in high volume, rate, and variety (heterogeneity) of data. This task will incorporate big data techniques for storage, access and analysis of heterogeneous data (numerical, text, and image) and effective inference of concrete degradation. The data analytics framework will also integrate information from model prediction, laboratory experiments, plant experience and inspections, and expert opinion. Data mining, classification and clustering, feature extraction and selection, and fault signature analyses with heterogeneous data will be orchestrated through a Bayesian network for effective inference.

Uncertainty Quantification. This task will quantify the uncertainty in health diagnosis and prognosis in a manner that facilitates risk-management decisions. Sources of natural variability, data uncertainty and model uncertainty arising in both modeling and monitoring activities will be considered and their effects quantified. In addition to measurement and processing errors, data uncertainty due to sparse and imprecise data for some quantities, and due to large data on other quantities (i.e., data quality, relevance, and scrubbing), will be considered. Model uncertainty in multi-physics degradation modeling due to model form, model parameters, and solution approximations will be included. The various uncertainty sources do not combine in a simple manner; therefore, a systematic Bayesian network approach will be developed for comprehensive uncertainty quantification that facilitates risk-informed operations, maintenance, inspection, and other risk-management activities.

A second pilot project will be conducted involving passive components and structures representative of those for which extended life is highly important to LWR sustainability. The passive components or structures will target large and economically important plant assets for which the science of managing long-term material degradation is yet unsolved. Candidates may include the structural health monitoring of primary system components, secondary systems, and other components found throughout the plant such as cables. In this effort, the II&C research program and EPRI will work with the LWRS Program's Materials Aging and Degradation Pathway to select suitable components or structures based on importance to utility decision-making in pursuing additional life extension (beyond 60 years) and the prospects for research success within the timeframe of this project. The Materials Aging and Degradation Pathway will be responsible for developing the scientific basis for modeling the degradation mechanisms and determining the types of information needed to monitor the degradation. It is possible that new types of sensors will have to be fabricated for this purpose. The II&C research program will devise the material interrogation techniques on conjunction with the Materials Aging and Degradation Pathway, signal processing capabilities to convey the sensed parameters to the monitoring system, data analytics, and trending used for analyzing and visualizing the results of materials interrogation, and uncertainty quantification of the results. The LWRS Program also will develop the technologies needed to enable utilities to retrieve, store, process, and integrate the large volumes of information collected through the online monitoring systems installed on these passive plant components.

The online monitoring of structural health of secondary pipes is the primary candidate for the second pilot project on passive components sustainability. The erosion and corrosion processes affect carbon steel piping carrying both hot liquid water and wet steam. They are important degradation mechanisms in NPP piping systems. Flow-assisted corrosion, for example, came into focus on December 9, 1986, after an elbow rupture at Unit 2 of the Surry plant. The accident had devastating consequences, which included fatalities. Currently, each plant has a dedicated FAC management program that is implemented with a close collaboration with EPRI. However, while the FAC programs demonstrated their effectiveness, they did not completely remove the hazards associated with FAC. The programs are based on two major components: EPRI's FAC predictive modeling software, CHECWORKS^{TM}, and periodic inspections performed during outages. The results of the inspections are entered into CHECWORKS, which produces an updated forecast of wear rate for the next fuel cycle. The offline inspections are very labor intensive and include removal of pipe's insulation. Also, the results of ultrasonic inspections are subject to interpretation and statistical processing, which not always produce consistent results.

Whereas the FAC models have ±50% prediction accuracy, the existing erosion models are more uncertain. In general, there are no universally accepted models for most common erosion mechanisms, particularly under plant operating conditions. There are four predominant erosion mechanisms in NPPs: Cavitation Erosion, Flashing Erosion, Liquid Impingement Erosion, and Solid Particle Erosion (SPE). Liquid impingement erosion is second only to the FAC in its effects on piping degradation. Flashing Erosion, while less common, has currently no available models. The development of such models for these two types of erosion mechanisms would greatly improve the understanding, and add a valuable tool to the existing pipe degradation management programs and would enhance capabilities for the long-term material management of existing NPPs. Based on this effort, the Advanced Instrumentation, Information, and Control Systems Technologies Pathway of the LWRS Program and EPRI will work with the LWRS Program's Materials Aging and Degradation Pathway, to implement first principles and data-driven models for Flashing and Liquid Impingement erosion, which can be used for diagnostics and prognostics of remaining useful life of piping components as a part of structural health monitoring of secondary system piping.

A technical report and peer-reviewed publications will be published that describes the technical basis and analysis framework to enable online monitoring for selected secondary system components. These technical reports, along with the results and experience from the pilot projects, will provide guidance for utilities to implement centralized monitoring and information integration for the passive components and structures important to plant life extension.

Schedule: FY 2014 to FY 2018

Milestones:

- (2014) Complete interim report on the results of the concrete degradation mechanisms and online monitoring techniques survey. (Complete: Published report INL/EXT-14-33134, *Interim Report on Concrete Degradation Mechanisms and Online Monitoring Techniques*).
- (2015) Investigate and advance individual techniques for damage modeling, health monitoring, data analytics and uncertainty quantification with respect to ASR damage in NPP concrete structures. (Complete: Published reports: (1) INL/EXT-15-34729, *A Simple Demonstration of Concrete Structural Health Monitoring Framework*; (2) INL/EXT-15-36683, *Monitoring, Modeling, and Diagnosis of Alkali-Silica Reaction in Small Concrete Samples*).
- (2015) Complete interim report on the results of the flow-accelerated corrosion mechanisms and online monitoring techniques survey. (Complete: Published report INL/EXT-15-36611, *Flow-Assisted Corrosion in Nuclear Power Plants*).
- (2016) Develop modeling, detection, and big data analytics techniques considering multiple damage mechanisms in NPP structures, and demonstrate for small laboratory-scale structural components.
- (2016) Complete a report documenting the development of a model of degradation for flashing erosion in NPP piping.
- (2017) Develop an integrated framework for multi-physics simulation, full-field imaging, data analytics, and uncertainty quantification; demonstrate for large laboratory structures; and develop a validation strategy.
- (2017) Development of structural health monitoring framework for piping in secondary systems.
- (2018) Develop and validate a health risk management framework for concrete structures in NPP, demonstrate for illustrative concrete structures in the NPP environment, and develop an implementation strategy for NPPs.
- (2018) Publish a technical report on measures, sensors, algorithms, and methods for monitoring active aging and degradation phenomena for a second large passive plant component, involving nondestructive examination-related online monitoring technology development, including the diagnostic and prognostic analysis framework to support utility implementation of online monitoring for the component type.

5.4 Integrated Operations

Many industries have taken advantage of new digital technologies to consolidate operational and support functions for multiple production facilities to improve efficiency and quality. This concept is sometimes referred to as integrated operations. Mainly, it uses technology to overcome the need for onsite support, thereby allowing the organization to centralize certain functions and concentrate the company's expertise in fewer workers. These workers, in turn, develop higher levels of expertise because they are exposed to a larger variety of challenges and issues than if they supported just a single facility. It allows them to outsource functions, where beneficial, while maintaining immediate access to the services even if provided remotely. The concept also enables standardized operations and economy of scale in maintaining a single organization instead of duplicate capabilities at each location.

The Halden Reactor Project has been quite active in this concept for the Norwegian off-shore oil platforms. The oil companies have developed integrated operations to move large parts of their platform operations and support functions to centralized on-shore locations. This has resulted in dramatic improvement in the efficiency of operations and the quality of life for participating workers. While there remains a need for sufficient staff on the platforms to conduct the hands-on work, virtually any activity that can be controlled or monitored through a digital system is a candidate for integrated operations.

Likewise, for years, airlines have maintained centralized flight monitoring centers, recognizing the impracticality of providing this as an onboard service. Data links are used to stream in-flight performance data to the centers, where they are monitored by systems experts. The experts then can confer directly with the pilots on any immediate operational concerns. Otherwise, minor issues can be documented and addressed at the next convenient opportunity.

NPPs have a similar opportunity to improve support functions by developing an integrated operations concept. Indeed, some steps in this direction have already been taken by utilities that have implemented a centralized online monitoring center for plant components equipped with remote monitoring capability. However, there are many more opportunities to consolidate support services across the fleets using digital technologies that enable work to be performed just as effectively as if it were onsite. Furthermore, the concept can extend beyond the utility organization to create seamless interfaces with suppliers, consultants, and original equipment manufacturers. In this way, an operating company could build a virtual organization of trusted partners rather than providing all services in-house.

5.4.1 Advanced Online Monitoring Facility

Sustainability for the U.S. LWR fleet is dependent on the preservation of plant assets far beyond the original life of 40 years. With most utilities pursing life extension to 60 years (with the possibility of 80 years), long-term plant asset management will have to be a prominent focus of the utility's technical staff.

Technologies are being rapidly developed that can provide early indication of component degradation in progress. Moving beyond empirical models of the degradation factors, physics-based models are now being developed that can mimic the effects on the overall component in response to degradation in one of the subcomponents. This provides capability to move beyond mere monitoring of the condition to diagnosis of the degradation mechanism and prognosis of the remaining useful life of the component and give the utility a window of opportunity to take remedial actions. These types of technologies are being developed under pilot projects described in Section 4.3.

This project integrates these new monitoring capabilities into a concept of fleet asset management based on a centralized online monitoring facility. The underlying information structure would be part of the digital plant architecture as described in Section 4.5.1.

The architecture would support the real-time acquisition of condition monitoring data from every type of source. This would include fixed sensors embedded in components such as in "smart pumps." It also would collect data streamed from mobile technologies used by field workers (see Section 4.1.1). This would include data from hand-held condition monitoring technologies such as thermal imaging, vibration monitors, and acoustic probes.

The architecture would organize the information in a manner that could be used for a variety of purposes. In addition to being available for the centralized asset management facility, the information would be available to other plant support functions such as the plant engineering system health program, troubleshooting and root cause teams, original equipment manufacturers and technical consultants involved in component support, and the data historian and plant records archive.

This project will develop a prototype advanced online monitoring facility based on the state-of-the-art information technologies and collaboration facilities, and will provide the following:

- Employ new visualization capabilities to create a better understanding of the condition of degrading components
- Have video conferencing capability for direct collaboration with plant staff in a variety of settings (e.g., the control room, the outage control center, or engineering support groups)
- Have access to industry databases on failure signatures and associated component data to assist in diagnosing component degradations
- Support the concept of integrated operations to remotely support a number of operating plants as effectively as if it were onsite.

The prototype advanced online monitoring facility initially will be developed in the HSSL, where technology developments and human factors studies can be conducted in a test environment. Following that, a production facility would be developed at a host utility location for actual production testing. Based on this initial experience, a technical report will be written to provide recommendations for industry-wide implementation.

Schedule: FY 2017 to FY 2019

Milestones:

- (2017) Develop and demonstrate (in the HSSL) concepts for an advanced online monitoring facility that can collect and organize data from all types of monitoring systems and activities and can provide visualization of degradation where applicable.
- (2018) Develop and demonstrate (in the HSSL) concepts for real-time information integration and collaboration on degrading component issues with remote parties (e.g., control room, outage control center, systems and component engineering staff, internal and external consultants, and suppliers).
- (2019) Develop a digital architecture and publish a technical report for an advanced online monitoring facility, providing long-term asset management and providing real-time information directly to control room operators, troubleshooting and root cause teams, suppliers and technical consultants involved in component support, and engineering in support of the system health program.

5.4.2 Virtual Plant Support Organization

Because of the complexity of plant systems and the large number of components in NPPs, utilities maintain a large staff of highly trained operators, engineers, technicians, and other types of specialists to ensure safe and successful operations. Considerable ongoing investment in the form of training and development is made in this workforce to enable them to maintain the unique and aging technologies in the plants.

At present, the nuclear industry has arguably the most experienced workforce in its history. This is undoubtedly a significant factor in the operational success the industry has enjoyed over the last decade. However, this is an unsustainable path because, like the aging II&C systems that plants must be replaced, the aging workforce is on the brink of a substantial retirement wave in which a significant portion of the workforce will have to be replaced in a relatively short amount of time.

Going forward, there are concerns whether the commercial nuclear industry will be able to attract the needed engineers and technicians given the looming shortage of technically trained workers in this country. In addition, the model of having career-long employees who develop deep expertise will likely be less successful in the future with a new generation of workers who will be more prone to change jobs.

A better model would include the ability to build a virtual plant organization that is seamlessly connected through advanced II&C technologies. A virtual support organization is a combination of an NPP's own organization plus external organizations that have been delegated direct support roles in operating and maintaining the plant. The term "virtual" implies that the organization is interconnected through a digital architecture for data exchange, communications, and collaboration as opposed to having to be located onsite. This allows the NPP to tap into far greater resources and expertise than can be practically maintained at the NPP facility.

In general, this is an extension of the concept introduced with the advanced centralized online monitoring facility. It will allow specialty organizations, both within the utility and with outside companies, to assume full responsibilities of portions of the ongoing operations and support of the plants. Some examples of these types of operational and support roles would be as follows:

- An onsite, demineralized water production plant could be owned and remotely operated by the original equipment manufacturer of the equipment, with minimum onsite support for hands-on maintenance.
- Condition monitoring could be performed by remote experts in vibration analysis, oil sample analysis, and loose parts monitoring analysis rather than having to maintain this specialized expertise within the general plant engineering staff.
- II&C system monitoring and diagnostics could be performed by the manufacturers of the system, with a small onsite support staff to replace circuit boards once faults were isolated to the specific component.
- Radiation monitoring could be performed remotely using data-linked monitors and video cameras to observe workers in the radiation control zones.
- Chemistry analysis could be performed remotely using inline instruments that take either batch or continuous samples.
- System test results could be reviewed and validated by remote engineering organizations that directly receive data from system performance tests.
- Portions of the plant support systems could be monitored, or even operated remotely, by a centralized staff. This would exclude safety-related systems and those systems that are major transient initiators such as the main feedwater system. There could be a significant reduction in burden on the control room for having many of the auxiliary systems under centralized operations. Examples would include auxiliary steam systems, hydrogen purification skids, oil purification skids, chemistry systems, and radwaste systems.

A virtual support organization would be a significant step toward the concept of integrated operations for the LWR fleet. The workforce required to conduct the plant work activities could be appreciably reduced in number, resulting in a secondary proportional reduction in organizational support functions (number of supervisors, human resources specialists, trainers, etc.). This concept would move the NPP operating model away from a labor-centric model to a technology-centric model. This could greatly enhance LWR fleet cost competitiveness because technology is generally a declining cost factor while labor is always an increasing cost factor. By purchasing only the services a plant needs, rather than maintaining a full-time staff for all technical functions, considerable cost savings could be obtained.

The following are examples of specific benefits of a virtual organization:

- Specialty organizations could attract and maintain experts much more effectively than could individual operating companies. The experience base of a specialty organization would be much deeper in that they would see phenomena and problems across the entire industry and not just a few plants.
- The monitoring capabilities of a third party (or even a fleet-centralized service) would be more uniform over time because it would not depend on the work schedules of one or two experts onsite.
- The NPP would be relieved of continual hiring, transferring, and training of replacement workers for these positions as inevitable attrition occurred.
- In the case of having some plant auxiliary systems monitored or operated remotely by support organizations, there would be a net safety benefit in allowing the control room and onsite operations staff to concentrate more on the safety-significant portions of the plant.

This project will develop the underlying technologies that will enable development of a virtual support organization. The information structure to do this will be built into the digital architecture for a highly automated plant (see Section 4.5.1). Human and organizational factors will be incorporated into a technical report for integrating external organizations directly into the line functions of the plant organization, as enabled by data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment. These technologies will first be created and studied in the HSSL reconfigurable simulator, where it will be possible to evaluate the dynamics of a remote organization conducting a key plant support function. An open standard for data sharing technology will be developed for this architecture to promote a fair and competitive market for external services.

The project will identify which plant functions are priorities for outsourcing using the virtual plant support organization concept. The project will work with a host utility NPP to implement some trial instances of remote support. Evaluations of these initial examples will be the basis for a technical report on how to implement the virtual plant support organization on an expanded scale.

Schedule: FY 2019 to FY 2022

Milestones:

- (2019) For chemistry activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for a highly automated plant. Demonstrate representative remote activities with a host NPP.
- (2020) For maintenance activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for a highly automated plant. Demonstrate representative remote activities with a host NPP.
- (2021) For radiation protection activities, conduct a study and publish a technical report on opportunities to provide remote services from centralized or third-party service providers, based on advanced real-time communication and collaboration technologies built on the digital architecture for a highly automated plant. Demonstrate representative remote activities with a host NPP.
- (2022) Publish human and organizational factors studies and a technical report for a virtual plant support organization technology platform consisting of data sharing, communications (voice and video), and collaboration technologies that will compose a seamless work environment for a geographically dispersed NPP support organization.

5.4.3 Management Decision Support Center

Operational decision-making is a foundational element of safe nuclear operations. Processes for decision-making are formal and rigorous in all levels of the nuclear utility management structure. Nuclear managers are required to be technically competent and actively engaged in the issues facing their nuclear facilities, such that they can effectively participate and be held accountable in the ongoing operational decisions.

Plant functional managers typically serve in both standing and special-purpose decision review boards that are formally invoked for significant plant issues. One such example required by a nuclear utility's Quality Assurance Program is the onsite Plant Operational Review Committee, or a similarly titled group. The Plant Operational Review Committee is required by the facility license to have a broad range of technical expertise and competence in plant issues and is required to review a number of different types of plant issues and provide a recommendation to the plant manager on the advisability of proposed plant actions. There are similar groups that are appointed for other special purposes (such as to provide oversight of operational decision-making and risk management).

On a more informal basis, the plant management typically meets early every weekday morning to review current operational concerns and to ensure that all work plans are well-coordinated and meet risk management expectations. This is yet another forum for operational decision-making on the adequacy of the daily work plan and the response to emergent problems. A similar daily management meeting is held during outages to address the issues arising from the ongoing work.

Another category of management decision-making pertains to the emergency response organization. These are the decisions on how to classify, mitigate, and provide protective actions for nuclear emergency events. These deliberations occur in the dedicated emergency response facilities, namely the Technical Support Center, the Operations Support Center, and the Emergency Operations Facility; the latter of which is offsite and sometimes serves the entire fleet.

What these decision-making processes and forums have in common is the critical need for accurate, timely information on which to base the operational decisions made by the plant managers. There are many examples in the industry where a plant management team made decision errors, not due to lack of competence among the managers, but simply because the managers did not have an accurate picture of what actually was happening at the time and what was at stake.

To improve understanding in these settings, technology will be introduced that provides a better visual picture of the situation (such as real-time video taken at the location of the problem). In other cases, where pictures of the problem are not practical (e.g., core power imbalances due to dropped rods), simulations and symbolic presentations of the issues will be developed.

The concept of a management decision support center would address these needs by employing advanced digital technologies to improve the quality of operational decision-making. It would be a dedicated facility where all regular and special management oversight meetings would be held. (The exception to this would be the emergency response facilities, which have to be maintained in a state of readiness. The technologies of the management decision support center also would be separately implemented in the emergency response facilities.) The following are examples of the types of technologies that would be implemented:

- Multiple large-screen displays that can handle many different data sources at a time
- Video streaming capability directly onto any of the large displays, including video conferencing
- Access to all data and displays of the plant computer and Safety Parameter Display System
- Real-time images of the main control room control boards, with real-time data refreshing
- Ability to run the plant simulator for the scenario of concern

- Real-time plant risk assessments and defense-in-depth measures
- Severe accident management guidelines and extensive damage mitigation guidelines
- Access to all plant process applications (e.g., technical specification logs, operator logs, schedules, work orders, and test results)
- Access to all plant documentation through the electronic document management system
- Access to NPP field worker mobile technologies for streaming of activity-related information
- Access to outside data sources such as weather, media, regulatory information, and external databases
- Decision support and resource allocation software
- General presentation capabilities.

This concept also could be applied at the fleet level where decisions involve multiple NPPs or involve decision processes between the plant and fleet-level management. Collaboration tools would allow information views to be pushed to other participating centers so that there would be a shared context for discussions and decisions.

Obviously, this project will build on many of the capabilities that are developed in other pilot projects, but will focus them on the unique aspects of nuclear management decision-making. The project will team with a host utility to identify the needed capabilities in such a facility. The digital architecture pilot project will address the information requirements of this facility. The facility will be prototyped in the HSSL to demonstrate and evaluate the various capabilities. Human factors studies will be a key part of the evaluation to ensure the information presentations are well-designed for comprehension and do not result in an information-overload situation. Protocols for managing the information resources during a management decision-making meeting also will be developed. Following the laboratory demonstration, a management decision support center will be implemented at the host utility NPP for trial usage. Field studies will assess any needed corrections to the concept or implementation. A technical report will be developed for industry-wide implementation.

Schedule: FY 2023 to FY 2025

Milestones:

- (2023) Develop and demonstrate (in the HSSL) concepts for a management decision support center that incorporates advanced communication, collaboration, and display technologies to provide enhanced situational awareness and contingency analysis.
- (2024) Develop and demonstrate (in the HSSL) concepts for advanced emergency response facilities that incorporate advanced communication, collaboration, and display technologies to provide enhanced situational awareness and real-time coordination with the control room, other emergency response facilities, field teams, the NRC, and other emergency response agencies.
- (2025) Publish human and organizational factors studies and a technical report for a management decision support center consisting of advanced digital display and decision-support technologies, thereby enhancing nuclear safety margin, asset protection, regulatory performance, and production success.

5.5 Automated Plant

NPPs are perhaps the only remaining safety-critical operations that rely to a large degree on human skill to conduct routine and emergency activities. Adoption of digital technologies has transformed other high-risk industries (e.g., aviation, medical procedures, and high-precision manufacturing) to where tedious control functions are performed by automation while the operator remains in an oversight, directory role.

This situation is largely due to technology limitations during the 1970s and early 1980s when the currently operating NPPs were designed. While main processes pertaining to reactor operations are automated (e.g., core power level with automatic rod control), the vast majority of plant controls for configuration changes or placing equipment in and out of service are manual. This over-reliance on manual control on such a large scale challenges operators and results in human error rates that are unacceptable.

The concept of a highly automated plant is one where the most frequent and high-risk control activities are performed automatically under the direction of an operator. Because of higher reliability in well-designed automatic control systems, improvements will be realized in nuclear safety, operator efficiency, and production. The chief impediment to the widespread implementation of this concept is the cost of retrofitting new sensors, actuators, and automatic control technology to the existing manual controls. The goal of this research will be to demonstrate that the resulting improvement in safety and operating efficiencies will offset the cost of making these upgrades.

5.5.1 Digital Architecture for an Automated Plant

To automate operating NPPs to their full potential, integration of digital technologies must extend beyond plant control and information systems to that of the domain of plant work processes and plant worker activities. This will require a plant digital architecture that is more encompassing than is currently available to the industry.

Even in today's more advanced plants, the digital architecture typically extends only to the major protection and integrated controls systems. Data architectures to support plant work processes are intentionally separate due to cyber security concerns. No comprehensive data schema is available that relates all plant functions in the context of their real-world relationships, thereby defining the needed data interfaces to conduct plant functions and support activities in an integrated manner. This architecture would define the following:

- Systems that need to be integrated for robust plant protection and control
- Types of data busses and interfaces
- Cyber security requirements
- Failure and recovery requirements
- Necessary segmentation of the overall architecture to ensure independence of function and defense-in-depth
- Data relationships that are required to support plant functions, plant systems, plant processes, or plant worker activity
- External interfaces to enable remote operations and support activities, either at a fleet or industry level.

This pilot project will define an advanced information and control architecture that will accommodate the entire range of system, process, and plant worker activity to enable the highest degree of integration, thereby creating maximum efficiency and productivity. This pilot project will consider a range of open standards that are suitable for the various data and communication requirements of the seamless digital environment. It will map these standards into an overall architecture to support the II&C developments of this research program.

The objective of this project will be to develop an industry consensus document on how to scope and implement the underlying information technology infrastructure that is needed to support a range of real-time digital technologies to improve NPP work efficiency, reduce human error, increase production reliability, and enhance nuclear safety. A consensus approach is needed because:

- There is currently a wide disparity in nuclear utility perspectives and positions on what is prudent and regulatory-compliant for introducing certain digital technologies into the plant environment. For example, there is a variety of implementation policies throughout the industry concerning electromagnetic compatibility (EMC), cyber security, wireless communication coverage, mobile devices for workers, mobile technology in the control room, and so forth.
- There is a need to effectively share among the nuclear operating companies the early experience with these technologies and other forms of lessons learned. There is also the opportunity to take advantage of international experience with these technologies.
- There is a need to provide the industry with a sense of what other companies are implementing, so that each respective company can factor this into their own development plans and position themselves to take advantage of new work methods as they are validated by the initial implementing companies. In the nuclear power industry, once a better work practice has been proven, there is a general expectation that the rest of the industry will adopt it. However, the long-lead time of information technology infrastructure could prove to be a delaying factor.

A secondary objective of this effort will be to provide a general understanding of the incremental investment over the current infrastructure that would be required to support the targeted digital technologies. This will be required for business cases to support the adoption of these new technologies.

To achieve these objectives, a meeting was held in July of 2014 with NITSL and EPRI to discuss mutual objectives in the area of digital architecture. The result of this meeting was an agreement to work together in the pursuit of the project milestone deliverables.

Work continued in FY 2015 to define an initial set of requirements for the digital architecture in terms of II&C and IT capabilities needed to support NPP work activities employing the new digital technologies identified and developed in other research efforts with in the LWRS II&C pathway. The requirements are stated in terms of user functions rather than IT requirements. For example, a requirement would be for a worker with mobile technology to download a certain number of documents, as opposed to the files sizes and transmission rates of the downloads themselves, which will be determined in the FY 2016 project task. These requirements were documented in the report INL/EXT-15-34696, *Digital Architecture Requirements*.

Also in FY 2015, a gap analysis was conducted to determine where typical NPPs are today in terms of deploying the required digital architecture. This was accomplished using surveys and onsite assessments with partnering nuclear utilities to determine to what extent they could support the future digital technology environment with their existing II&C and IT structure, and where gaps exist with respect to the full deployment of technology over time. This information was compiled and summarized, along with general observations and recommendations and documented in report INL/EXT-15-36662, *Digital Architecture – Results from a Gap Analysis*. It will be used in the next phase of this pilot project to prioritize where focus is needed in defining and providing guidance for enhancing the digital architecture of nuclear plants.

Schedule: FY 2014 to FY 2017

Milestones:

- (2014) Publish a project plan for the development of a digital architecture for the integration and automation of nuclear plant work activities. (Complete – Published report INL/EXT-14-33177, *Digital Architecture Project Plan*).
- (FY 2015) Complete a Digital Architecture Requirements Report documenting the information technology requirements for advanced digital technology applied as envisioned to be applied to NPP work activities. (Complete: Published report INL/EXT-15-34696, *Digital Architecture Requirements*).
- (FY 2015) Complete a Digital Architecture Gap Analysis Report documenting the gap between current typical II&C and IT capabilities in NPPs versus those documented in the Digital Architecture Requirements Report. (Complete: Published report INL/EXT-15-36662, *Digital Architecture – Results from a Gap Analysis*).
- (FY 2016) Complete a Digital Architecture Planning Model.
- (FY 2017) Complete a Digital Architecture Implementation Guideline, documenting a graded approach in applying the conceptual model to selected digital technologies and in determining the incremental IT requirements based on a current state gap analysis.

5.5.2 Automating Manually Performed Plant Activities

NPPs have a higher ratio of staffing to unit of power output than any other form of electrical generation. For example, an NPP will typically have ten times the amount of staffing as a similar-sized fossil generation station. Labor is the largest component of an NPP's operating and maintenance cost, typically accounting for 70% of the annual operating budget.

These high staffing requirements are due to the fact that NPPs have such a large number of systems and that most operations are manually performed. Work processes tend to be fairly complex due to nuclear quality and documentation requirements. Because of nuclear safety concerns, there are time-consuming human performance protocols for virtually all work activities. For example, most plant manipulations have to be verified by a second person and sometimes even a third person in high-risk situations.

As current II&C systems in the plants today approach end-of-life and are faced with reliability and component aging issues, an opportunity presents itself to upgrade the systems in a manner that can reduce dependence on manual activity. Whereas this once would have been thought to be cost-prohibitive, new advances in technology now make this economically feasible. Some of these advances are as follows:

- Low-cost, highly reliable sensors and actuators (with low maintenance requirements).
- Wireless technology, avoiding the need for long runs of expensive instrument cable
- Easy-to-maintain control technologies such as field programmable gate arrays, programmable logic controllers, and other digital control devices
- Power harvesting from ambient energy (e.g., light, heat, and vibration).

To make this automation cost effective, plant activities must be transformed so that the cost of automation is offset by reductions in plant staff required to conduct these activities. Otherwise, the technology upgrade costs would simply be added to the cost of the present plant structure of staffing and manual processes and no real efficiencies would be gained. Therefore, research is required to determine how to conduct these activities in a fundamentally different way, relying on automation rather than manual efforts to accomplish the end objectives.

Examples of these kinds of opportunities are as follows:

- Replacement of stand-alone analog control loops with digital technology. A typical example would be a throttle valve control circuit, which would rely on an analog sensor/transmitter hard-wired to the control room, a controller with a set point or manual control, and an output circuit with a current loop connected to a pneumatic control loop connected to the valve's air operator. The objective would be to replace these analog technologies with digital equivalents, eliminating the frequent maintenance work required for these legacy technologies, while gaining improved accuracy and reliability of the digital technology.
- Elimination of manual gauges and displays that have to be locally read on a frequent basis by replacing them with wireless equivalents.
- Addition of low-cost, wireless component position indicators, thereby eliminating time-consuming and error-prone field walk-downs of valves, breakers, and dampers to verify they are in the correct position.
- In-line chemistry instruments, eliminating the effort to obtain field samples that have to be transported to an analysis laboratory for processing.
- Replacing local control panels with automated soft controls that can be operated from more convenient locations.
- Conversion of protective relays to integrated digital relay systems that would eliminate tedious manual testing of these individual devices and greatly reduce the effort to modify settings.

This project will analyze the NPP current staffing and cost model in a top-down manner to identify opportunities to significantly lower operating costs through selective automation of frequently performed manual activities. It will examine the technologies from a maturity perspective and a human factors perspective. It will make broad recommendations on gradually transforming the operating model of NPPs from one that is labor centric to one that is technology centric. In making this transformation, the underlying technologies that are deployed will enable a concept of integrated operations, which will support outsourcing of appropriate plant support functions.

Schedule: FY 2017 to FY 2021

Milestones:

- (2017) For NPP operations activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2018) For NPP chemistry activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2019) For NPP maintenance activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.

- (2020) For NPP radiation protection activities, analyze the staffing, tasks, and cost models to identify the opportunities for application of digital technologies to improve nuclear safety, efficiency, and human performance based on optimum human-technology function allocation. Demonstrate representative activities as transformed by technology with results published in a technical report.
- (2021) Develop and publish a transformed NPP operating model and organizational design derived from a top-down analysis of NPP operational and support activities, quantifying the efficiencies that can be realized through highly automated plant activities using advanced digital technologies.

5.5.3 Advanced Plant Control Automation

Because of the pervasive analog II&C technology in NPPs today, much of plant control is conducted by operators manually manipulating a large array of discrete control devices. The exceptions to this include the process control system for the reactor coolant system, heat transfer (steam generators for pressurized water reactors), and turbine-generator controls for power production. Also, the emergency core cooling system is typically auto-started on certain emergency signals, but has to be manually adjusted as the accident mitigation sequence progresses. Other plant systems are largely reliant on manual operator actions for normal and emergency operations.

In converting manual operator actions to plant control automation, nuclear safety and plant production can be enhanced by reducing the opportunity for human error. Further, this results in improved situational awareness for the operator, maintaining more of an oversight role of the changing plant conditions and the performance of the automatic control systems.

Building on work from the pilot project on automating manually performed plant activities, especially the portion concerning conversion of stand-alone control loops to digital technologies, it is possible to implement a distributed control system in a way that automates large sequences of commands to relieve the operators of tedious plant manipulations. This concept also involves converting some manually-operated components to automatic functions.

Priorities for advanced plant control automation concepts would be those activities that are frequently performed, time and attention-intensive for the operators, and entail some nuclear safety or production risk. Examples of such activities are as follows:

- Plant heat ups and cool downs
- Automated management of plant transients
- Swapping operating trains where there are redundant systems
- Aligning systems to their test configuration
- Placing systems into service
- Conducting in-service maintenance activities such as backwashes of strainers.

Human factors evaluations would be a key element of this project because there are significant concerns on how this level of automation will affect operator skills and knowledge. Operator performance studies would be run in the HSSL to address the following issues:

- Would an over-reliance on the automation technology be created so operators would not maintain the skills necessary for performing the actions manually if the technology failed?
- Would operators have a sufficient understanding of what the automated systems were doing throughout any automated plant evolution?

- Would operators lose focus in monitoring the plant during long sequences of automated control?
- Would operators immediately recognize a control system failure even when there was no significant plant excursion?

Working with a host utility NPP, this project would use HSSL to develop a prototype of plant control automation to conduct human factors studies to answer these questions. The project would develop a prioritized list of plant control functions to be included in an advanced plant control implementation for a first-mover NPP. Also, the project would develop a technical report for applying advanced plant controls in a manner consistent with the human factors principles as validated in the project studies.

Schedule: FY 2022 to FY 2025

Milestones:

- (2022) Develop concepts for advanced control automation for control room operators based on human technology function allocation developed in the pilot project for automating manually performed plant activities. Publish a technical report on candidate applications for automation reflecting design and human factors principles.
- (2023) Develop and demonstrate (in the HSSL) prototype plant control automation strategies for representative normal operations evolutions (e.g., plant start-ups and shut-downs, equipment rotation alignments, and test alignments).
- (2024) Develop and demonstrate (in the HSSL) prototype plant control automation strategies for representative plant transients (e.g., loss of primary letdown flow or loss of condensate pump).
- (2025) Develop the strategy and priorities and publish a technical report for automating operator control actions for important plant state changes, transients, and power maneuvers, resulting in nuclear safety and human performance improvements founded on engineering and human factors principles.

5.6 Hybrid Control Room

Hybrid control rooms are ones that have a mixture of traditional analog II&C technology and newer digital technology. Virtually all U.S. nuclear plants have undertaken some amount of digital upgrades over the lifetime of the stations. In some cases, digital systems were the only practical replacement option for legacy analog components. In other cases, digital systems were the preferred technology in that they could provide more precise control and greater reliability. The cumulative effect for the LWR fleet has been an ever-increasing presence of digital systems in the LWR control rooms.

In spite of a significant number of digital systems now having been implemented, there have been no large-scale changes to the layout or function of the LWR control rooms. Nuclear utilities have understandably been reluctant to undertake significant control room upgrades or modernization projects in consideration of cost, regulatory risk, and impact on the large investment in procedures, training programs, and other support functions that may accompany large upgrades. Also, there is a general desire to retain the high degree of operator familiarity with the current control room arrangements, and thereby avoid potential human performance issues associated with control board configuration changes.

Nuclear utilities constantly strive to improve operator performance, and in particular address performance weaknesses that are identified as contributors to plant safety challenges. This usually takes the form of enhancements to operator performance protocols and expected behaviors. The difficulty with this approach lies in trying to correct human performance deficiencies with additional expectations, which can never entirely eliminate the effects of human variability. There is no question that technology is underutilized in the control rooms as a means of enhancing operator performance. Many other safety-critical industries, notably aviation, have made effective use of advanced digital technologies to improve operations and safety, without supplanting the role of the operator (or pilot) as the ultimate authority and decision maker.

Introducing digital systems into the control rooms creates opportunities for improvements in control room functions that are not possible with analog technology. These can be undertaken in measured ways such that the proven features of the control room configuration and functions are preserved, while addressing gaps in human performance that have been difficult to eliminate. By applying human-centered design principles in these enhancements, recognized human error traps can be eliminated and the introduction of new human error traps can be avoided.

Digital technology introduction provides an opportunity to enhance human performance in the control room. The process of designing and implementing digital control room technologies to replace analog systems serves as an opportunity to implement human-centered design activities throughout the various stages of design, acquisition, and implementation. These design activities and their technical bases – human factors design standards and cognitive science research – were not available at the time of the original design of main control rooms. Considerable progress has been made in these fields since the completion of the industry's response to the Three Mile Island-2 Action Plan, which requires a human factors approach to control room changes. Replacement digital technologies having more powerful and flexible graphical and informatics capabilities, together with a substantially improved understanding of how to leverage these capabilities to support effective human performance, afford the opportunity to realize a more human-centered main control room. This does not require a full-scope approach to control room modernization, such as refurbishing or replacing an entire main control room as a single engineering project. Rather, it can be accomplished through gradual and step-wise related projects that are carried out when digital II&C systems are implemented to replace analog II&C systems to address near-term reliability and operational needs. These types of enhancements can be performed anytime in the life cycle of the main control room and can add to the business case for implementing digital II&C.

Pilot projects have been defined to develop the needed technologies and methodologies to achieve performance improvement through incremental control room enhancements as nuclear plant II&C systems are replaced with digital upgrades. These pilot projects are targeted at realistic opportunities to improve control room performance with the types of digital technologies most commonly being implemented, notably distributed control systems and plant computer upgrades.

This work employs HSSL as a test bed providing a realistic hybrid control room simulation (refer to Section 3.3) for development and validation studies as part of the pilot projects. In addition, the II&C research program has an agreement in place for access to control room upgrade technologies developed by the Halden Reactor Project, which has played a key role in several of the European control room upgrades. The II&C research program is well-positioned to provide the enabling science for control room enhancements for U.S. hybrid control rooms.

5.6.1 Advanced Hybrid Control Rooms

More and more digital conversions of analog II&C systems will be undertaken by U.S. nuclear utilities as concerns over reliability and component aging continue to accrue. These new systems typically come with advanced operator interfaces that are quite different than the analog control devices of the legacy systems. This raises the questions of how to incorporate the new technology into the existing control room and what the impact on operator performance and regulatory requirements will be. One strategy has been to preserve the same operator interfaces of the old analog controls with the same or similar board-mounted discrete control and indication devices, in lieu of modern human systems interfaces. While this has minimized the cost of changes to operator procedures and training, it has diminished the value and potential benefits of the digital technology.

In other cases, dedicated human systems interfaces have been incorporated into the control boards in the general area where the former analog controls were located. However, this has sometimes introduced different types of operator interfaces, such as integrated flat-panel displays, large-screen overview displays, touch panels, track balls, a standard computer mouse, and multiple keyboards. Obviously, this impacts control room human factors and can result in undesirable or unanticipated changes to operator and team performance if not properly implemented. Further, nuclear utilities plan to implement these modifications over an extended period of time, which will result in a progression of interim hybrid control room states that mix analog and digital human systems interfaces in different proportions. Each of these interim states must be evaluated from a human factors perspective to ensure that operator performance is not diminished.

Therefore, the prospect of multiple, disparate digital interfaces in a hybrid control room will drive the need to readdress the control room layout in a more holistic manner in order to provide the operators with a consistent, uniform interface for the various digital systems. Such upgrades to will involve first-of-a-kind technical developments and regulatory submittals.

It is imperative that control room upgrades reflect the correct application of human factors principles. Expertise in human factors has been substantially lost in the nuclear utility staffs since the days of completing the Three Mile Island-2 Action Plan in the late 1980s. Furthermore, the understanding of human factors has substantially improved since that time and regulatory requirements and guidance have continued to evolve. DOE maintains considerable expertise in human factors research and application and has the capabilities of the HSSL to develop and validate design methods and technologies for control room modernization, including requirements for safety-related systems (Figure 16). DOE collaborates with leading international efforts (such as those conducted by the Halden Reactor Project) to leverage the expertise in modernizing control rooms that has been developed in other countries and, in particular, those that have been undertaken in Europe.

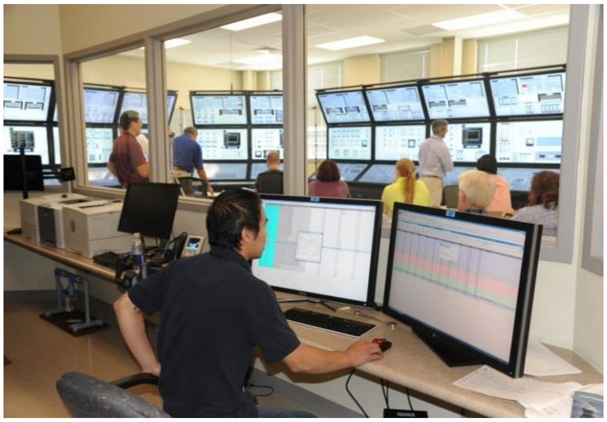

Figure 16. Advanced Hybrid Control Room Studies in the HSSL.

This pilot project will develop principles that can be used in guidelines for design and layout of a modernized analog control room and for standardized operator interfaces, according to the human factors' engineering principles. It will develop standardized operator interface displays and control board layout guidelines based on human factors engineering principles and regulatory guidance.

This project will also develop a prototype of an advanced alarm system would be capable of suppressing non-essential alarms (e.g., redundant or low-priority) and improve the usability of alarms (manageable numbers, salience, acoustic design, display and organization, etc.) so the operator is not distracted with superfluous information during the time-critical phase of an event. Rather, the goal of an advanced alarm system would be to alert the operating crew to valid plant conditions (i.e., for the mode and condition of the plant) with valid and understandable information that serves as a conduit for effective decision-making and action. An advanced alarm system should be state-based and operating mode-sensitive, meaning that alarms that are not meaningful in the present operating state are suppressed.

A reference human factors engineering plan will be developed for control room modernization for use by industry based on the practical knowledge gained in this pilot project. It will involve workshops conducted in the HSSL with utility licensed operators to address human factors issues such as functional requirements analysis, function allocation, task analysis, and operator sequence analysis. These activities will lead to the ability to conduct integrated system validation, which looks at the total effect of hardware, software, and human factors changes to ensure that desired outcomes are indeed obtained without introducing undesirable factors.

Work in this pilot project is being conducted in three major focus areas as follows:

1. Collaboration with Duke Energy in applying human factors to control room upgrades for the Brunswick, Harris, and Robinson Nuclear Stations. This work involves developing new techniques and methodologies for applying human factors to control room upgrades in Planning and Analysis Phase, the Design Phase, and the Verification and Validation Phase. These methods employ the HSSL to measure human factors aspects of new II&C systems and associated human-system interfaces through direct observation of operators performing plant evolutions on realistic simulations of the proposed control room changes. Certain portions of this project will result in proprietary documentation for Duke Energy, which will be accomplished through cost-recovery contractual arrangements as associated work with the pilot project. However, the general information gained from these efforts will be published for industry use as part of the pilot project milestone reports. It is anticipated that similar collaboration of this nature will be conducted with other nuclear utilities where there are additional aspects of control room human factors to be developed or where it is advantageous to assist the industry with control room modernization.
2. Over a multi-year project, develop methodologies for creating and validating an end-point vision for advanced hybrid control rooms for operating NPPs. Working with a partner utility, studies will be conducted to baseline an existing NPP control room with respect to human factors engineering considerations. Then, a series of workshops will be held with the operations and engineering staff of the partner utility to envision, test, and validate various proposed control room upgrades. The plant simulator for the host nuclear plant will be installed in the HSSL to enable studies of the utility operators in the simulation of actual responses to various normal, abnormal, and emergency scenarios both with and without the proposed upgrades. A control room three-dimensional modeling program will be used to model the host plant control room to validate the proposed upgrades from the standpoint of the human factors and ergonomics. And the INL Computer-Assisted Virtual Environment (CAVE) will be used by the study team to validate the layout of the upgraded control room using virtual reality. These new methodologies are needed to provide utilities with a validated and regulatory-compliant approach to pursuing improvements in operator performance through enhanced control room capabilities as they upgrade legacy II&C systems over time.

Schedule: FY 2011 to FY 2017

Milestones:

- (2011) Complete a workshop on design of replacement annunciator systems for control rooms. (Complete: Published report INL/MIS-11-22907, *Alarm Design Workshop for Control Room Upgrades: Summary and Presentations*).
- (2011) Complete at least one commercial NPP full-scope, full-scale simulator in the II&C laboratory. (Complete: Published report INL/EXT-11-23421, *Deployment of a Full-Scope Commercial Nuclear Power Plant Control Room Simulator at the Idaho National Laboratory*).
- (2012) Develop a digital, full-scale mockup in the HSSL of a conventional NPP control room. (Complete: Published report INL/EXT-12-26367, *Digital Full-Scope Mockup of a Conventional Nuclear Power Plant Control Room, Phase 1: Installation of a Utility Simulator at the Idaho National Laboratory*).

- (2012) Develop digital displays in support of control room modernization. (Complete: Published report INL/EXT-12-26787, *Applying Human Factors Evaluation and Design Guidance to a Nuclear Power Plant Digital Control System*).
- (2013) Complete the assembly of the HSSL and demonstrate its capability to model a hybrid (analog and digital) NPP control room. (Complete: Published report INL/EXT-13-28432, *Digital Full-Scope Simulation of a Conventional Nuclear Power Plant Control Room, Phase 2: Installation of a Reconfigurable Simulator to Support Nuclear Plant Sustainability*).
- (2013) Publish a reference human factors engineering plan for an optimized, human-factored control board layout for integrating digital operator interface screens with analog controls and indicators. (Complete: Published report INL/EXT-13-30109, *A Reference Plan for Control Room Modernization: Planning and Analysis Phase*).
- (2013) Complete LWRS II&C Halden Project report documenting conclusion of installation exercise of digital interface prototypes in Human Simulation Systems Laboratory (HSSL). (Complete: Published report INL/EXT-13-29039, *Installation of Halden Reactor Project Digital Interface Prototypes in the Human Systems Simulation Laboratory*).
- (2014) Complete report on operator performance metrics for use in control room modernization projects. (Complete: Published report INL/EXT-14-31511, *Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation*).
- (2014) Develop a strategy for migration of II&C functions from traditional control boards to compact operator control consoles. (Complete: Published report INL/EXT-14-32534, *Strategy for Migration of Traditional to Hybrid Control Boards in a Nuclear Power Plant*).
- (2014) Complete a report on human factors engineering design phase for control room modernization. (Complete: Published report INL/EXT-14-33221, *Human Factors Engineering Design Phase Report for Control Room Modernization*).
- (2014) Complete a report documenting a methodology for conducting baseline human factors and ergonomics review using a host NPP control room. (Complete: Published report INL/EXT-14-33223, *Baseline Human Factors and Ergonomics in Support of Control Room Modernization at Nuclear Power Plants*).
- (2015) Develop a Distributed Control System Prototype. Using a participating utility's simulator plant model installed at the HSSL, develop a functional prototype for the turbine control system upgrade. Document the design, development, and functionality of the prototype replacement system. (Complete: Published report INL/EXT-14-33957, *A Distributed Control System Prototyping Environment to Support Control Room Modernization*).
- (2015) Complete a report on Operator Performance Metrics for Verification and Validation, documenting the process on how simulator studies should be performed including the various operator performance metrics in support of control room upgrades (Complete: Published report INL/EXT-14-31511, Revision 1, *Operator Performance Metrics for Control Room Modernization: A Practical Guide for Early Design Evaluation*).
- (2015) Develop prognostic software for control indicators. Provide demonstration and software for prognostic system and display interface for installation at the HSSL. (Complete: Published report INL/EXT-15-36839, *HSI Prototypes for Human Systems Simulation Laboratory*).
- (2015) Develop Operator Performance Metrics for Verification and Validation. Document the process for how simulator studies should be performed including the various operator performance metrics that can be collected in support of control room upgrades. (Complete: Published report INL/EXT-15-36704, *Verification and Validation of Digitally Upgraded Control Rooms*).

- (2016) Develop lessons learned from performing integrated system validation on a digitally upgraded system in the main control room that conforms to regulatory requirements for human factors engineering.
- (2017) Develop a migration strategy for upgrading control systems, such as the plant process computer from older to new digital technology in the control room.

5.6.2 Control Room Upgrades Benefit Study

Today, aging and obsolescence are the main drivers of control room system replacement and refurbishment projects. System replacements provide opportunities to incorporate new technologies that include new functions to create new efficiencies. Complex, labor-intensive, and sometimes error-prone operational evolutions can be programmed into digital systems, reducing demands on control room staff and creating more reliable "human-machine" systems. These technologies can also enhance plant monitoring and situational awareness. This has the potential for significant improvement in operator performance, safety margins, and work efficiencies.

A business case to implement these types of technologies for nuclear utilities is needed, one that is broadly inclusive of the types of costs and benefits associated with newer technologies for operating a more modernized plant. To this end, the II&C Pathway will conduct a series of studies to investigate the benefits of these technologies and will work with utilities and vendors to identify the costs associated with the types of modernization efforts planned or anticipated by participating utilities.

The II&C Pathway will investigate technologies and methods to most efficiently and safely refurbish predominantly analog-based main control rooms with digital technologies and will partner with commercial utilities to conduct this research. The II&C Pathway will make available near-term state-of-the-art digital technologies ready for adoption and use in existing analog control rooms through obsolescence management and other technology replacement projects. The technologies are being fitted into the DOE's HSSL, located at INL. The HSSL can host plant simulator models from the U.S. fleet of LWRs, allowing the possibility of retrofitting an existing plant control room model in the HSSL with more modern digital control room technologies, for purposes of test and evaluation and to support these cost-benefit studies. This provides a low cost, no risk option for participating utilities and their Operations, Training, Engineering, and other organizations, to obtain first-hand experience in seeing what these new technologies may offer their plant without the expense and commitment of purchasing and implementing the technologies. In turn, partner utilities provide engineering and operations assistance to the LWRS program to plan and design the test and evaluations (i.e., with utility input) providing volunteers from their pool of licensed reactor operators to collect data at the partner utility training simulator and in the HSSL, for review of plans and reports associated with the project on a periodic basis, and a model of the plant simulator for use in the HSSL.

Expected benefits of an upgraded control room include:

Plant Operations

- Improved plant monitoring and compliance with operational requirements
- Better management of plant upsets
- Seamless interfaces for operational support (reduced operator distractions).

Avoided Operational Events

- Reduced efforts to manage real-time unit threats or plant transients/upsets
- Reduced CAP workload (all phases of investigation, recovery, and prevention efforts)
- Reduced INPO evaluation impact (cost of AFIs)
- Reduced regulatory impact (SDP-level events, safety-culture assessments).

Cost Savings in Support Organizations

- Direct costs related to operational events (overtime, chemical additions, auxiliary equipment operation, etc.)
- Reduced effort for work process interfaces (planning, scheduling, risk management)
- Avoided work inefficiencies (scheduled work interruptions, lost productivity)
- Reduced administrative support for operations (printing procedures, archiving procedures, archiving logs, etc.).

Improved Job Satisfaction

- Better technology for operators on conforming to expectations and observing human error prevention techniques
- Reduced administrative burdens.

Candidate scenarios will be developed specifically to test the benefits of the near-term digital control room technologies being considered. The scenarios used will be tailored specifically to the technologies used, and the proposed benefits of those technologies. In general, a broad range of scenarios will be considered, including:

- Normal, routine activities
- Unanticipated activities
- Anticipated transients
- Anticipated design basis accidents
- Beyond design basis accidents (contingent on expected upgrades to the HSSL).

A baseline study will be conducted at the utility partner simulator to document operator performance standards and expectations for the selected scenarios. Following this baseline study, a similar workshop will be conducted in the HSSL to evaluate the Phase I Technology Configuration. The host plant's simulation model will be installed in the HSSL, and candidate near-term digital technologies will be integrated into the HSSL. Static tests of the technologies will be conducted to evaluate the performance of the systems and to verify their readiness in FY 2015, for hosting a dynamic test with crews planned in FY 2016.

The research will evaluate the Phase I Technology Configuration in the HSSL during dynamic test and evaluation conditions. Data will be collected on the performance of the candidate digital control systems and the experience of operators in using the new systems to perform their tasks on the set of scenarios developed. In addition to customary operator performance standards used for studying crew performance, additional metrics for measuring the benefits of the technologies will be employed. The emphasis in this phase of research is on observing how crew members use near-term digital technologies, how they adapt to their introduction in a prototype control room representative of their own plant, and how the new technologies facilitate individual and crew performance, that is, what benefits a plant can expect in terms of operator performance and reliability.

During FY 2016, a subsequent technology configuration will be defined that represents a further progression to a modernized control room, with capabilities that go beyond what is typical of current new builds, and that is of interest to current utility owner-operators and industry stakeholders for test and evaluation. This configuration of near-term digital technologies will be implemented in the HSSL. Subject matter experts from the partner utility will validate the configuration in the HSSL to ensure that the next phase of the study is adequately supported by the simulator.

The research will evaluate the Phase II Technology Configuration in the HSSL. The research will evaluate the Phase II Technology Configuration in the HSSL during dynamic test and evaluation conditions. Data will be collected on the performance of the candidate digital control systems and the experience of operators in using the new systems to perform their tasks on the set of scenarios developed. In addition to customary operator performance standards used for studying crew performance, additional metrics for measuring the benefits of the technologies will be employed.

The emphasis in this phase of research is on observing how crew members use more advanced near-term digital technologies, how they adapt to their introduction in a prototype control room representative of their own plant, and how the new technologies facilitate individual and crew performance – that is, what benefits a plant can expect in terms of operator performance and reliability, and whether more advanced digital technologies provide greater improvements than some near-term digital technologies alone. In addition, some of the technologies from the Phase I configuration may be included in the Phase II test and evaluation to permit more direct comparisons of the different technology configurations to be made experimentally, and their effects on crew performance to be studied.

A final report will be written in FY 2017covering the analysis and results of the studies. The report will be peer reviewed by industry experts and study stakeholders, and then will be published. One or more workshops will be held for utility staff and industry stakeholders to see the technologies demonstrated, understand the findings of the studies, and develop actions to promote appropriate control room upgrades.

Schedule: FY 2015 to FY 2017

Milestones:

- (2015) Complete a report describing requirements of control room computer based procedures. (Complete: Published report INL/EXT-15-35284, *Requirements for Control Room Computer-Based Procedures for use in Hybrid Control Rooms*).
- (2015) Develop a prototype of an advanced hybrid control room in the HSSL based that includes advanced operator interface technologies such as alarm management systems, computerized procedures, soft controls, large displays, and operator support systems. (Complete: Published report INL/EXT-15-3538, *Benefits of Advanced Control Room Technologies: Phase One Upgrades to the Human Systems Simulation Laboratory and Performance Measures*).
- (2015) Test HSSL System in Preparation for Conducting Benefits Study with Operations – Test HSSL systems in representative configurations to verify that systems are able to function reliably in operational sequences and scenarios, test data logging and collection systems, and verify the stability of different combinations of digital systems with human interactions in preparation for data collection with actual operating crews. (Complete: Published report INL/EXT-15-36432, *A Pilot Study Investigating the Effects of Advanced Nuclear Power Plant Control Room Technologies: Methods and Qualitative Results*).
- (2016) Complete a report describing the experimental design, scenarios, and performance measures used in the baseline study of operating crews.
- (2017) Publish a report documenting the Control Room Upgrades Benefit Study that presents the data, findings, and conclusions on performance improvements that can be obtained through the technologies of an advanced hybrid control room.

5.6.3 First-Of-A-Kind Control Room Modernization Design Project

To mitigate the substantial technical, financial, and regulatory risks in a FOAK control room modernization project, the II&C Pathway will seek to partner with a nuclear utility in a FOAK Control Room Modernization Design Project. The purpose is to assist a first-mover nuclear operator in addressing legacy analog technology issues of reliability, obsolescence, as well as to enable improved operator and plant performance. This will also demonstrate the feasibility and benefits of control room modernization to the commercial nuclear operators, suppliers, and industry support community. This project will be a major step in resolving legacy II&C issues that potentially impact long-term sustainability of the LWR fleet.

The II&C project commitment will be a significant cost contribution over several years, with similar utility and NSSS supplier cost-share. In addition, the II&C Pathway will make commit facilities such as the HSSL and expert staff to participate in this project. The II&C Pathway, with participating collaborators, will work with the utility to develop one or more end-state control room concepts. International and domestic experience would be leveraged in developing the concepts though current associations (Halden, EPRI, Korean Atomic Energy Research Institute [KAERI], and domestic new builds). DOE facilities at INL will be used to develop and validate the design concepts, including the reconfigurable control room simulator (HSSL), the virtual reality laboratory, and three-dimensional design and ergonomics software.

The optimum end-state concept will be selected for conceptual design in order to determine a cost estimate and work scope for implementing the modernized control room. An architect-engineer will be contracted to perform the conceptual design, determining what modifications will need to be made to the existing II&C and control room. This design will be scoped to take advantage of the capabilities of the digital upgrades for II&C systems (current and future) to enhance the business case for the modernization effort. Implementation planning will also be conducted to determine the various transition states for the control room, as well as human factors considerations for these intermediate states. Finally, a business case will be developed that captures the cost and operator performance improvements resulting from the modernized control room.

Schedule: FY 2016 to FY 2024

Milestones:

- (2016) Develop a baseline room configuration document of the existing host nuclear station control room that includes board layouts, room arrangement, operator station, and control system operator interfaces.
- (2016) Develop a control room end-state concept for a modernized control room for an operating NPP.
- (2017) Implement the host nuclear station training simulator in the HSSL reflecting the baseline control room configuration.
- (2017) Publish interim human factors engineering guidance for the host nuclear station for the implementation of II&C digital upgrades affecting the control room.
- (2017) Develop the framework of the business case for the control room concept based on work efficiency gains and improved operator performance.
- (2018) Complete the preliminary design for the control room end-state concept.
- (2018) Complete a human factors’ engineering review of the preliminary design of the control room end-state concept.
- (2018) Complete a phased implementation strategy for the preliminary design of the control room end-state concept.
- (2018) Develop the final business case for the control room end-state concept.
- (2018) Conduct an industry peer review of the preliminary design and the business case for the control room end-state concept.

- (2019) Publish a summary report on the preliminary design and the human factors engineering review of the control room end-state concept, providing lessons learned on plant system interface and the phased implementation strategy.
- (2019) Complete the detailed design for the Phase 1 modification for the control room end-state concept.
- (2019) Complete human factors engineering review of the detailed design of the Phase 1 modification for the control room end-state concept.
- (2020) Complete the implementation package for the Phase 1 modification for the control room end-state concept.
- (2021) Publish a summary report on the detailed design and human factors engineering review of the Phase 1 modification for the control room end-state concept, providing lessons learned on plant system interface and the phased implementation strategy.
- (2021) Complete the detailed design for the Phase 2 modification for the control room end-state concept.
- (2021) Complete human factors engineering review of the detailed design of the Phase 2 modification for the control room end-state concept.
- (2021) Complete the implementation package for the Phase 2 modification for the control room end-state concept.
- (2022) Complete the detailed design for the Phase 3 modification for the control room end-state concept.
- (2022) Complete human factors engineering review of the detailed design of the Phase 3 modifications for the control room end-state concept.
- (2023) Complete the implementation package for the Phase 3 modification for the control room end-state concept.
- (2024) Publish a summary report on the implementation phase of the FOAK Control Room Modernization Design Project providing lessons learned and initial operational benefits.

5.6.4 Computerized Operator Support Systems

Situational awareness is critical to the safe operation of NPPs. It requires an accurate understanding of the current plant state and operating configuration, the intricacies of the plant process and control systems, the physics of the plant processes (nuclear, thermal, fluid, and electrical), and the current operating margins with respect to safety and regulatory limits. Today, this enormous amount of information has to be mentally integrated by the operators to arrive at an accurate understanding of how the plant is operating and where it is headed. This is a daunting task for even the most experienced operators and could become a significant concern in the future as a wave of new operators replaces the aging nuclear workforce.

As more and more plant information becomes available in a digital form, it will be possible to provide operators with advanced information systems that aid in assessing the current plant status, safety margins, and deviations from expected operations. Through advanced simulation techniques, it will be possible to predict where the plant is going operationally and how long the operators have to intercede in undesirable plant trends.

A computerized operator support system is a collection of capabilities to assist operators in monitoring overall plant performance and making timely, informed decisions on appropriate control actions for a projected plant condition. It could contain the following features:

- Advanced nuclear, thermal-hydraulic, and electrical models to assess actual plant performance relative to the predicted plant performance and report deviations and trends to the operators. It could use directly measured parameters and derived parameters to analyze plant performance. It could distinguish between real plant performance deviations and those due to failed instruments.
- A faster-than-real-time simulator that could predict the effect of operator actions prior to them being taken. This would detect interactions that might not be apparent to the operator due to unusual plant configurations and other operating restrictions. It could project the timing of the gradual effect of actions on reactor power such as boration and dilution. Depending on the fidelity of the simulator, it could be very helpful in off-normal conditions where the emergency procedures cannot anticipate every combination of component unavailability.
- Learning systems that become more robust as they experience a wider variety of operational conditions. This would include systems that employ advanced algorithms to monitor many sensors and other inputs to perform monitoring of plant and subsystem performance.
- Continual reinforcement of training within the control room by providing direct reference to training material when it would not be a distraction to operational duties. This form of embedded training has been used elsewhere in other industries (notably aviation) with beneficial effect.

This pilot project conducts research to build these aggregate plant models and connect them to current and new advanced sensors to obtain precise measurements of the current operating parameters. These models will be validated against actual plant performance at a host utility's NPP. They will be refined until they produced an accurate picture of the plant operating state and degree of deviation from expected performance.

It should be noted that this project will require a substantial cost-share on the part of the host utility. DOE's responsibility in the project will be to provide the computerized operations support system platform suitable for testing and demonstration. However, the largest portion of the work will be in modeling the host utility NPP to a degree of detail that will provide useful information to the operators. This would be the responsibility of the host utility.

Schedule: FY 2017 to FY 2021

Milestones:

- (2017) Develop concepts for using NPP full-scope simulators as operator advisory systems in hybrid control rooms and complete a technical report on prototype demonstrations in the HSSL.
- (2018) Develop concepts for a real-time plant operational diagnostic and trend advisory system with the ability to detect system and component degradation and complete a technical report on prototype demonstrations in the HSSL.
- (2019) Develop an operator advisory system fully integrated into a control room simulator (HSSL) that provides plant steady-state performance monitoring, diagnostics and trending of performance degradation, operator alerts for intervention, and recommended actions for problem mitigation, with application of control room design and human factors principles.
- (2020) Develop an operator advisory system that provides plant transient performance monitoring with operator alerts for challenges to nuclear safety goals.
- (2021) Develop an end-state vision and implementation strategy for an advanced computerized operator support system, based on an operator advisory system that provides real-time situational

awareness, prediction of the future plant state based on current conditions and trends, and recommended operator interventions to achieve nuclear safety goals.

5.6.5 Future Concepts of Operations

The control room staffing and protocols for the current LWR fleet are based on operational concepts that go back to the beginning of the industry. Staffing is generally sized to handle plant emergencies. Operational concepts employ protocols that maximize command and control, rigorous formality, and operator attention-to-detail. They mandate minimum staffing present in the control room due to the need for physical proximity to the information displays and controls. These protocols are absolutely essential today because the operator is the point of integration for information about the current operating state of the plant.

While this operating model has been very successful in safe and productive operation of the LWR fleet, it drives a number of inefficiencies in staffing because operators who are monitoring the plant systems generally cannot be involved in other activities. Therefore, additional operators are required for work management functions, system tag-out developments, plant rounds and field operations, and monitoring special processes such as reactor refueling or dry cask storage loading.

In the future, it will be possible to gain significant efficiencies by employing new concepts of operation made possible by the combined technologies for control room upgrades and enhanced operator performance. Specifically, there could be a reduction in the number of operators who are required to be either onsite or in the control room on a continual basis. In addition, the operating protocols could be substantially more flexible in allowing operators to conduct auxiliary tasks while maintaining adequate situational awareness of the operating units while being immediately available to take necessary control actions.

These future concepts of operations may alleviate the need for as large a physical presence to effectively control the plant; the new levels of automation may relieve the operators of performing tedious diagnosis and control functions, enhancing their roles to one of oversight of plant protection and control systems and intervening only as needed.

We have strong precedents for this concept in aviation today. For example, with current flight control technology, pilots do not have to actually be in the cockpit to fly an airplane. Unmanned aerial vehicles have systems that can perform real-time flight control functions by responding to broader directions and objectives given by a remote pilot. A similar concept is employed in virtually all modern aircraft cockpits, where the flight controls, throttles, avionics, and navigation systems are coupled under a flight management system that automatically directs the flight according to the flight plan and pre-determined instructions of the pilot, freeing the pilot to stay in an oversight mode of ensuring all systems are operating correctly and the flight is proceeding as planned.

The idea of using technology to reduce control room staffing or to permit plant control from outside the control room using advanced display and communication technologies will be highly controversial, notwithstanding the potential efficiency gains. This concept will run against the grain of deeply held beliefs on the conduct of nuclear operations. However, there is already a provision for some of the control room staff to be out of the control room provided they can return within a set time (e.g., the shift technical advisor). Therefore, with no additional risk imposed, this concept can first be validated by giving these technologies to control room crew members that can already be out of the control room to determine their effectiveness in increasing situational awareness while away. The concept can slowly evolve from there as experience and human factors studies determine whether there are efficiency gains without undue concerns over loss of effectiveness of the control room crew.

These technologies and capabilities would include the following:

- Portable interface devices (e.g., tablets and heads-up displays) that will provide continual plant status and control capability anywhere in the plant.
- New control capabilities that automate large operational sequences such as power maneuvers and putting systems into service. Further, they could diagnose and manage (without manual operator actions) the early portions of transients and accidents for the time required for operators to return to the control room. These capabilities can transform required operator actions from long sequences of individual control actions to broad, high-level objective commands (e.g., “place alternate letdown in service”).
- Computerized operations support systems that detect deviations and trends very early and provide much more response time to operators to react to and intervene in the situation.
- Ability of qualified operators to assist with certain tasks from where they are (i.e., at home, in remote parts of the plant facility, or at a sister nuclear unit).
- For operators in the control room, technology would enable them to participate in activities that today would require them to be present in other parts of the facility (e.g., pre-job briefings). This capability would rely on real-time video, collaboration tools, and virtual meeting software to allow participation in these activities from their normal operating station.

The Halden Reactor Project is already experimenting with high-fidelity control room displays on portable devices (such as digital tablets) to study potential improvement in situational awareness for operators temporarily away from the control room. This effort, and other similar research studies, will provide insight into how these technologies can safely be used by control room crews.

This project will assess the capabilities beneficial to an updated control room and develop concepts for operating the nuclear unit in a more flexible and efficient manner. This will include a minimum presence of staffing in the control room, assessment of the control room workload based on advanced technologies, and flexibility for crew members to conduct activities outside the control room while remaining “in-the-loop” through the technologies. A human factors study of crew dynamics would be conducted and would focus on collective situational awareness.

Other future concepts of operation would be explored, with the objective to enhance how the control room interacts with special-purpose control centers such as the outage control center, work execution center, technical support center, operational support center, and the emergency operations facility.

Schedule: FY 2022 to FY 2025

Milestones:

- (2022) Complete a technical report on operator attention demands and limitations on operator activities based on the current conduct of operations protocols. This report will identify opportunities to maximize operator efficiency and effectiveness with advanced digital technologies.
- (2023) Develop and demonstrate (in the HSSL) prototype mobile technologies for operator situational awareness and limited plant control capabilities for NPP support systems (e.g., plant auxiliary systems operations and remote panel operations).
- (2024) Develop and demonstrate (in the HSSL) new concepts for remote operator assistance in high activity periods (e.g., refueling outages) and accident/security events, allowing offsite operators to remotely perform low safety-significant operational activities, freeing the control room operators to concentrate on safety functions.
- (2025) Develop validated future concepts of operations for improvements in control room protocols, staffing, operator proximity, and control room management, enabled by new

technologies that provide mobile information and control capabilities and the ability to interact with other control centers (e.g., emergency response facilities for severe accident management guidelines implementation).

5.7 Publications of Guidelines

To ensure appropriate transfer of technology to the nuclear power industry, guidelines documents will be published for each of the areas of enabling capabilities, incorporating the specific technologies and technical reports produced under each of the pilot projects for the respective areas. EPRI has agreed to assume responsibility for development and publication of these guidelines, using their standard methods and utility interfaces to develop the documents and validate them with industry. The LWRS Advanced II&C Pathway will support this effort by providing the relevant information and participating in the development activities.

The following milestones have been established to produce the guidelines for each area of the enabling capability:

Human Performance Improvement for NPP Field Workers

- (2018) Publish interim guidelines to implement technologies for human performance improvement for NPP field workers.
- (2020) Publish final guidelines to implement technologies for human performance improvement for NPP field workers.

Outage Safety and Efficiency

- (2017) Publish interim guidelines to implement technologies for improved outage safety and efficiency.
- (2020) Publish final guidelines to implement technologies for improved outage safety and efficiency.

Centralized Online Monitoring and Information Integration

- (2017) Publish interim guidelines to implement technologies for centralized online monitoring and information integration.
- (2019) Publish final guidelines to implement technologies for centralized online monitoring and information integration.

Integrated Operations

- (2020) Publish revised interim guidelines to implement technologies for integrated operations.
- (2022) Publish final guidelines to implement technologies for integrated operations.

Automated Plant

- (2021) Publish interim guidelines to implement technologies for an automated plant.
- (2025) Publish final guidelines to implement technologies for an automated plant.

Hybrid Control Room

- (2018) Publish interim guidelines to implement technologies for a hybrid control room.
- (2021) Publish revised interim guidelines to implement technologies for a hybrid control room.
- (2025) Publish final guidelines to implement technologies for a hybrid control room.

6. REFERENCES

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