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Light Water Reactor Sustainability Program

Plant Modernization Technical Program Plan for FY-2022

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Plant Modernization Technical Program Plan for FY-2022

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ABSTRACT

This report presents the technical program plan for fiscal year (FY)-2022 for the U.S. Department of Energy (DOE) Light Water Reactor Sustainability (LWRS) Program—Plant Modernization Research Pathway. A summary of the vision and strategy is provided to explain how this program addresses key issues and barriers for modernizing instrumentation and control technologies and infrastructure in domestic nuclear power plants (NPPs). The report describes the pilot projects that have been formulated to develop and validate enabling technologies over the next several years that will result in digital alternatives to the legacy analog instrumentation and control (I&C) systems in place today. This will allow much-needed modernization of these systems to address reliability and obsolescence problems, as well as serve as a platform for substantial operational improvement. The report further describes key project resources and cooperative relationships, including the Electric Power Research Institute (EPRI), the Nuclear Energy Institute (NEI), the Institute of Nuclear Power Operations (INPO), the Institutt for energiteknikk Halden Reactor Project, the U.S. Nuclear Regulatory Commission (NRC), and industry suppliers that are instrumental to the success of the program. The report also lists the schedule for all program products, including the titles and report numbers for all published reports under this program.

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ACRONYMS

ACO	Advanced Concept of Operations
AI	artificial intelligence
AOCC	Advanced Outage Control Center
APR	advanced pattern recognition
ARMOR	Advanced Remote Monitoring for Operations Readiness
AWPs	automated work packages
BOP	balance-of-plant
BWR	boiling water reactor
CBP	computer-based procedure
CCF	common cause failure
CDA	critical digital asset
CNO	chief nuclear officer
CRADA	Cooperative Research and Development Agreement
CSAT	cybersecurity assessment team
DAS	distributed acoustic sensing
DIAMOND	Data Integration Aggregated Model and Ontology for Nuclear Deployment
DNP	Delivering the Nuclear Promise
DOE	U.S. Department of Energy
DOE-NE	DOE-Office of Nuclear Energy
EPOCH	Efficient Plant Operations Concept using Human System
EPRI	Electric Power Research Institute
EWPs	electronic work packages
FC	fiber coupler
FW-PHM	Fleet-Wide Prognostic and Health Management
FY	fiscal year
HCAI	human-centered artificial intelligence
HFE	human factors engineering
HSI	human system interface
HSSL	Human Systems Simulation Laboratory
I&C	instrumentation and control
I&RE	Industrial and Regulatory Engagement
ICAP	IO Capability Analysis Platform
IFE	Institutt for energiteknikk

II&C	Instrumentation, Information, and Control
INL	Idaho National Laboratory
INPO	Institute for Nuclear Power Operations
IO	integrated operations
ION	Integrated Operations for Nuclear
IT	information technology
LAR	License Amendment Request
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
MDAL	Monitoring, Diagnosis, and Automation Laboratory
ML	machine learning
MOOSE	Multi-physics Object Oriented Simulation Environment
MTO	Man-Technology-Organization
NDE	nondestructive examination
NEI	Nuclear Energy Institute
NITSL	Nuclear Information Technology Strategic Leadership
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
O&M	operating and maintenance
OCC	outage control center
OFDR	optical frequency domain reflectometry
OLM	online monitoring
OSSREM	Outage System Status and Requirements Monitor
PBS	polarizing beam splitter
PC	polarization controller
PdM	predictive maintenance
PM	preventive maintenance
PVGS	Palo Verde Generating Station
R&D	research and development
RUL	remaining useful life
SHM	structural health monitoring
SLR	Second License Renewal
SOER	Significant Operating Experience Report
TLS	tunable laser source
TERMS	Technology-Enabled Risk-Informed Maintenance Strategy

U.S.	United States
UWG	Utility Working Group
WRO	Work Reduction Opportunities

PLANT MODERNIZATION TECHNICAL PROGRAM PLAN FOR FY-2021

1. VISION AND STRATEGY

The Light Water Reactor Sustainability (LWRS) Program Plant Modernization Pathway conducts targeted research and development (R&D) to ensure the economic viability of nuclear power plants (NPP) in current and future energy markets through innovation, efficiency gains, and business model transformation through digital technologies [1]. This work involves two strategic goals:

1. To develop transformative digital technologies for nuclear plant modernization that renew the technology base for extended operating life beyond 60 years.
2. To enable implementation of these technologies in a manner that results in broad innovation and business improvement in the nuclear plant operating model, thereby lowering operating costs.

The R&D products will enable the modernization of plant systems and processes while building a technology-centric business model that supports improved performance at a lower cost, contributing to the long-term sustainability of the light water reactor (LWR) fleet, which is vital to the nation's energy and environmental security.

The focus of these research activities is on near-term opportunities to introduce new digital technologies into costly plant work activities, eliminating some labor-intensive activities while making the remaining work activities far more efficient. This research seeks to address inefficiencies in the operation and support of NPPs due to antiquated communication, collaboration, and analytical methods that have largely been replaced in other business sectors with modern digital capabilities.

A key tenet of the Plant Modernization Pathway is to continuously engage the nuclear power industry to ensure responsiveness to the challenges and opportunities in the present and future operating environment, to provide a correct understanding of the plant modernization technology development issues and requirements as *currently experienced in the operating NPPs,* and to develop approaches to address aging instrumentation and control (I&C) 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 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 of prior projects. This creates a stepwise approach to long-term modernization and refurbishment of I&C 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 and Control (I&C) systems are a vital part of plant safety and provisions for their refurbishment must be included in long-term planning.

Reliable I&C systems technologies are essential to ensuring safe and efficient operation of the United States (U.S.) LWR fleet. These technologies affect every aspect of NPP safety, production, and balance-of-plant (BOP) 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 I&C engineers to digital technologies. Consequently, product manufacturers refer to analog I&C as having reached the end of its useful service life. Although considered obsolete by other industries, analog I&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 I&C systems with digital I&C systems in NPPs [2]. Their findings identified the need for new I&C technology integration; 20 years later, this still has not yet been achieved.

Replacing existing analog with digital technologies is broadly perceived as involving significant technical and regulatory uncertainty. This translates into delays and substantially higher costs for these types of refurbishments. Such experiences slowed the pace of analog I&C replacement and further contribute to a lack of experience with such initiatives. In the longer run, this may delay progress on the numerous I&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 I&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 I&C may become a limiting or contributing factor that weighs against the decision to operate NPP assets for longer periods.

When they are undertaken without the needed technical bases and experience to facilitate their design and implementation, I&C replacements represent potential high-cost or high-risk activities. The I&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 the deployment of new digital I&C technologies for nuclear process control and enhanced worker performance and monitoring capabilities to ensure the continued safe, reliable, and economic operation of the NPPs in the U.S.

I&C systems can deliver new value through integrated long-term planning.

Most digital I&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, such as aging, with individual I&C components. This approach is characterized by planning horizons that are short and typically only allow for like-for-like replacement [3]. 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 I&C aging management minimizes technical and regulatory uncertainty although, ironically, it reinforces the current technology base.

To displace the piecemeal approach to digital technology deployment, a new vision for efficiency, safety, and reliability that leverages the benefits of digital technologies is needed. 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 I&C technologies is possible if they are integrated with work processes, capable of directly supporting plant staff, and used to create new efficiencies and ways of achieving safety enhancements. For example, data from digital I&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 the development of a seamless digital environment, 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 fieldwork devices, automate many manually performed surveillance tasks, and manage risk through real-time centralized oversight and awareness of fieldwork.
- **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.

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

The path to long-term operability and sustainability of plant I&C systems will likely be accomplished by measured, stepwise modernization through refurbishments. Through successive refurbishments, the resulting collection of I&C systems will reflect a hybrid mixture of analog and digital technologies. Operators and maintainers of I&C systems will, for an extended duration, require competencies with both types of technologies. This represents a lowest-risk, 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, three areas have been identified that enable capabilities needed for long-term sustainable plant operation: I&C architecture, online monitoring (OLM) and plant automation, and advanced applications and process automation. These areas provide the hardware needed to address the aging of existing I&C technologies, the information necessary to provide state awareness, and the software that will enable NPP staff to perform their jobs more efficiently. These are shown in Figure 1. In each of these areas, a series of pilot projects are planned that enable plant modernization in existing NPPs. Through the U.S. Department of Energy's (DOE) 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 I&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 NPP 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 that 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.

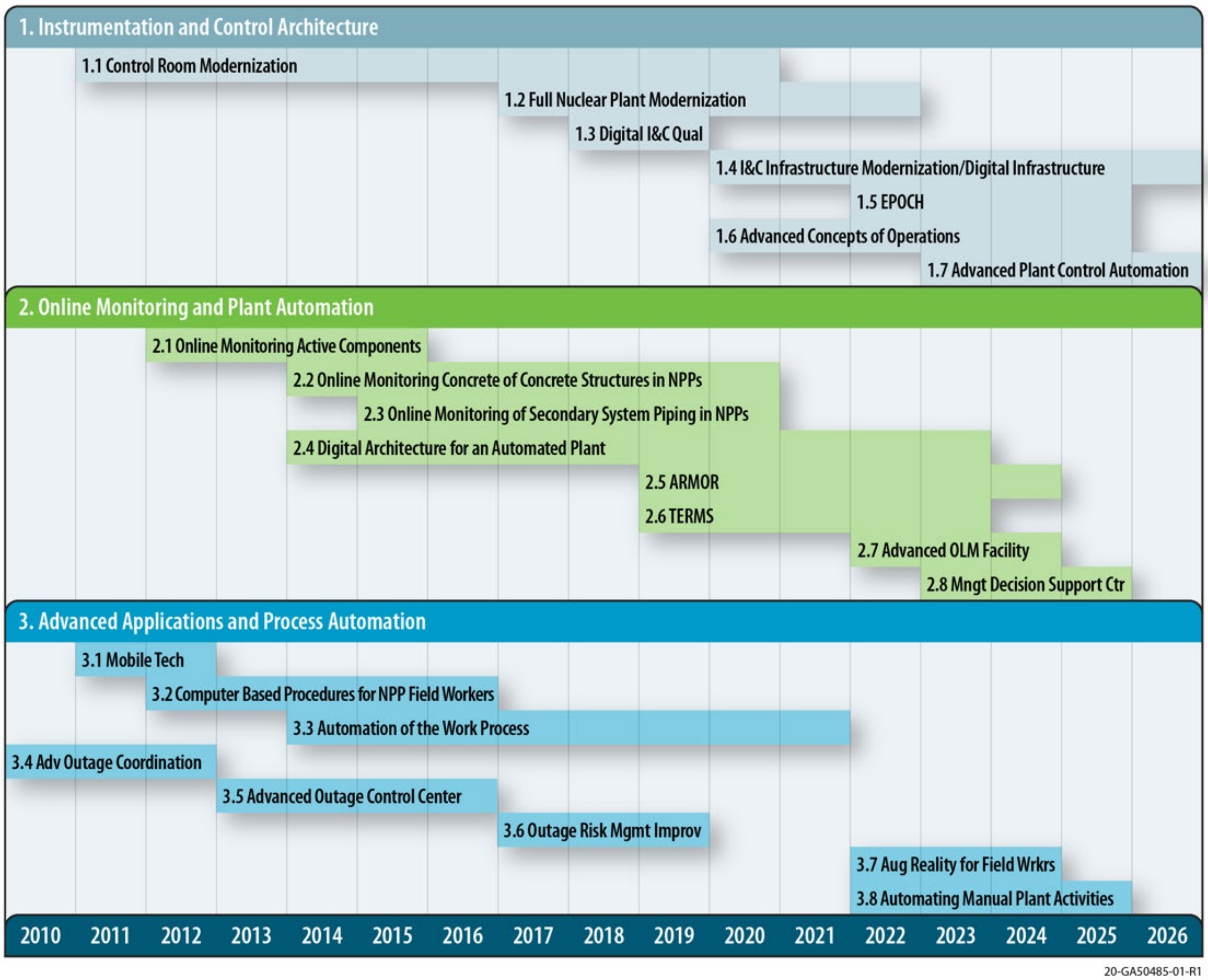

Figure 1. Pilot projects are grouped in three areas of enabling capabilities.

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

Analog I&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 I&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 in preceding decades. I&C technologies that are more highly automated and require less cost to operate and maintain are needed in the long run that are as highly reliable as those used today and will be familiar to a future workforce. They should also enable performance gains for nuclear utilities so that they are not merely a sunken cost because 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 results in substantial cost pressure on nuclear generation, particularly in non-regulated markets. The closings of several NPPs due to electricity market price are examples of such immediate impacts. For other NPPs, long-term cost implications will bear on life extension options.

Improvement in the competitive position of the NPPs 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 operating and maintenance (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-centered. Granted, for current NPPs, 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 (e.g., 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, such as through OLM of active components in lieu of periodic or condition-based testing.

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

Another opportunity is to reduce the substantial direct and indirect costs that result from human error and its consequences. This includes the immediate consequences of the error (i.e., lost production, delayed outages, etc.), as well as indirect activities such as event investigations, remedial training, apparent and root causes, an analysis of extent of condition and cause, management reviews, corrective actions, regulatory actions, operating experience reports, and so forth. When reactor trips are involved, there are 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* [4], 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 NPP field activities. This includes problems such as incorrect component identification, procedure, and 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 because 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 been demonstrated that digital technology is well-suited to help workers maintain situational awareness of plant conditions and is effective in verifying that fieldwork 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 (i.e., knowledge of plant mode and configuration, bar code readers, etc.).

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.

The Plant Modernization Pathway seeks to identify issues and priorities related to I&C technologies. It also serves as a means for utilities to participate in 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 project technical plans and in reviewing pilot project results, bringing to bear the accumulated knowledge from their own research projects and collaborations with nuclear utilities.

This program coordinates with other major industry support groups, such as INPO, the Nuclear Energy Institute (NEI), and the Nuclear Information Technology Strategic Leadership (NITSL). These organizations have active efforts in the I&C area related to operational standards of excellence, regulatory initiatives, information technology (IT) infrastructure, and cybersecurity.

Periodic meetings are held with both DOE and the U.S. Nuclear Regulatory Commission (NRC) to exchange information regarding the research plans and activities of each organization. Industry conference, workshops, and technical meetings also serve as important vehicles for information exchange and communication of the research program's 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 I&C R&D program focuses on those capabilities that are needed to position NPP 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 I&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 NPPs. Efforts were initiated and will continue to obtain perspectives and input on pathway planning and strategy from senior leadership and to learn how activities and initiatives can most benefit the fleet of LWR operators.

Through ongoing discussions during stakeholder engagement activities and interactions with individual organizations, the Plant Modernization Pathway has continued to evaluate Pathway research objectives to ensure they align closely with industry needs. These discussions confirmed many of the working assumptions of the research program. Key points highlighted by senior leadership include:

Industry Challenges

- Modernization cannot impact safety or reliability. Efficiency measures must not erode other values of nuclear safety, production, personnel safety, regulatory performance, INPO ratings, etc.
- Cost reduction is a critical issue facing the nuclear plants. Utilities must develop a modernization approach that enables nuclear to be competitive in the electric market, through business-driven innovation, with a solid business cases to justify investment.
- Knowledge retention is a serious challenge for their aging organizations and there is interest in how technology can help this. There are also concerns with attracting a young workforce into declining technologies that they did not study in their college course work.

Research Support Needs and Pathway's Perceived Role

- The Pathway research, development, and demonstration greatly helps in managing risk for new technologies. Industry looks to INL to provide basis for dependability of new technologies in a nuclear operating environment.
- The Pathway is a source of broad nuclear innovation and how these innovations can be applied wherever advantageous.
- The Pathway is especially looked to for understanding and practice in the area of human factors – for control room as well as any technology with significant human interface and human error potential.
- The Pathway/DOE is looked to for help on how to reduce physical security costs while meeting regulatory requirements.
- The Pathway is looked to for leading edge technologies such as AI/ML and how they can be prudently applied to improve performance, and how they can be justified from a regulatory standpoint.
- Utility staff get to learn in collaborating with the Pathway, important professional development for their staff.
- Technology positions the operating plants to take advantage of other product opportunities such as hydrogen.

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 currently operating commercial NPPs are already being planned and will provide a major opportunity to acquire this level of feedback on program objectives and activities.

3. PATHWAY RESEARCH AND DEVELOPMENT AREAS

3.1 Stages of Transformation

The transformation of the NPP operating model to our future vision—fully assimilating pilot project technologies into plant operations and business processes—will take more than a decade. The rate of transformation is a function of how pilot projects are defined and sequenced, such that later combinations of these technologies create new capabilities that address the requirements of more-complex NPP work activities. The transformation stages are depicted in Figure 2.

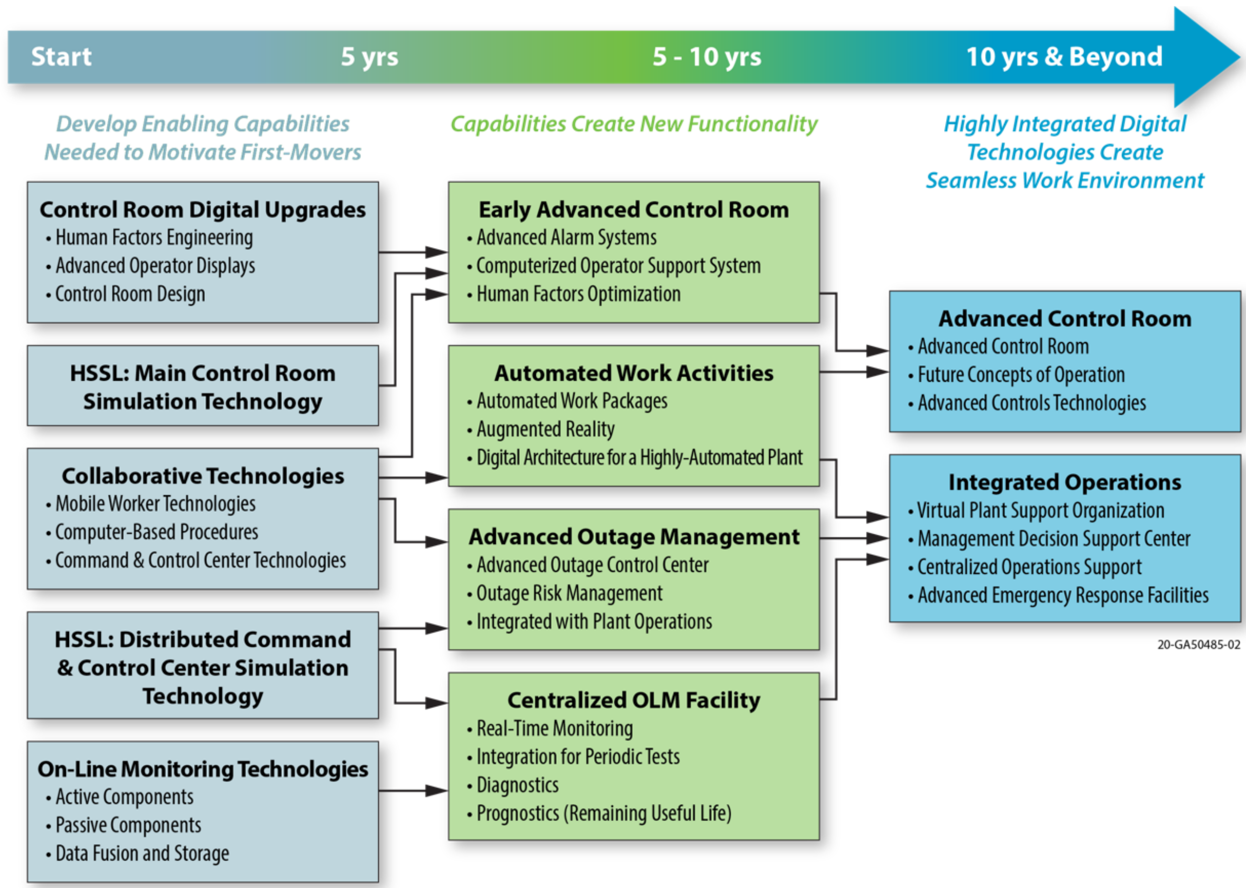

Figure 2. Stages of transformation in the Plant Modernization Pathway vision and strategy.

The first stage in this process is the development of enabling capabilities that will be needed to motivate first movers in the industry to adopt new digital technologies. Pilot projects serve to introduce new technologies to NPP work activities and validate them as meeting the special requirements of the nuclear operating environment. They must be demonstrated, not only to perform the intended functions with the required quality and productivity improvements, but also to fit seamlessly into the established cultural norms and practices that define the safety culture of the 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 OLM 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 [OCC]) simulation, as discussed in Section 3.2.

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 OLM facilities.

The third stage occurs when there is a substantial transformation of how the NPP 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 redefine and focus 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 (IOs).

3.2 Human Systems Simulation Laboratory (HSSL)

The HSSL at Idaho National Laboratory (INL) is used to conduct research in the design and evaluation of hybrid control rooms, the integration of control room systems, the development and piloting of human-centered design activities with operating crews, and the visualizations of different end state operational concepts [5]. This advanced facility supports human factors research for operating NPP control rooms, including human-in-the-loop performance and human system interfaces (HSIs), and it 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 the analog-based control room of an LWR, as shown in Figure 3.

Figure 3. HSSL reconfigurable hybrid control room simulator.

The simulator consists of 15 bench-board-style touch panels responding to touch gestures, which are 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 easily be 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 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, as shown in Figure 4. 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 4. HSSL was 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 OCC, a centralized OLM 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, the performance success criteria, and the influence of the performance characteristics of the plant or system on task performance and outcomes.
2. Usability of the HSI, 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 HSI configurations.
3. Human performance, expressed as physical and cognitive workload under different operational conditions, including:
    a. Plant status and system performance monitoring
    b. Human error, human reliability, and human-error mechanisms
    c. Task completion (e.g., accuracy, speed, tolerance, variability)
    d. Procedure following
    e. Problem diagnosis: (1) decision-making; and (2) response times.

4. Situational awareness with a given HSI and control configuration under different operational conditions.
5. Crew-communication effectiveness with given technologies under different operational conditions.
6. 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 the development and evaluation of new technologies for the main control room and other control centers. New technologies will first be staged in the HSSL for proof-of-concept prior to the demonstration at a host utility NPP. This would enable research on function allocation, task analysis, staffing, situational awareness, and workload in hybrid control rooms, such as Figure 5.

Figure 5. HSSL used for an operator workshop.

The HSSL also employs physiological measurement devices to support human factors evaluations, such as eye tracking as shown in Figure 6. These devices enable 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 I&C systems is based on demonstrated and validated scientific principles.

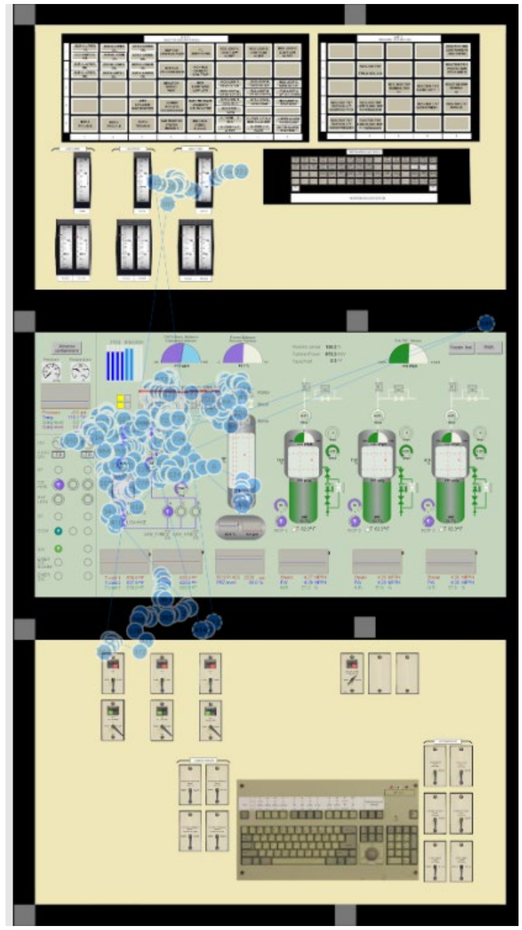

Figure 6. HSSL being used for eye tracking of operators using an advanced display.

3.3 Cybersecurity

Cybersecurity is recognized as a major concern in implementing advanced digital I&C technologies in NPPs in view of the considerable security requirements necessary to protect these facilities from potential adversaries, as well as to protect the proprietary information of these companies. UWG members have expressed the need to ensure that cybersecurity vulnerabilities are not introduced through the adoption of these advanced digital technologies. Furthermore, these utilities have internal cybersecurity policies and regulatory obligations for which compliance is required in implementing project technologies. The responsibility for cybersecurity ultimately lies within the utilities that implement the technologies from this research program. They must ensure that their own policies and regulatory commitments are adequately addressed.

DOE has significant cybersecurity expertise and resources that have been developed to address INL's security concerns, as well as those of many security-critical U.S. government facilities. DOE's experience in identifying, characterizing, and mitigating cybersecurity 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 cybersecurity issues arising from the technology developments in the pilot projects, with DOE cybersecurity experts at INL reviewing the pilot project technologies and providing a report on appropriate practices to minimize cybersecurity risk. This 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 [6].

To help nuclear utilities better understand the cybersecurity implications for the digital technologies being developed under this research program, an assessment was conducted in fiscal year (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, “Cybersecurity 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 cybersecurity program to determine what controls would be needed to support production usage. A mock cybersecurity assessment team (CSAT) was set up by the consulting firm with cybersecurity, IT, and engineering expertise represented. The principal 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 to the NEI 08-09 assessment criteria.

The results of the assessment were documented in INL/EXT-14-33609, *Cyber Security Evaluation of I&C Technologies* [7]. The major findings of the report included:

- Most I&C technologies will reside the cybersecurity 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 fieldwork 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, such as wireless valve-position status. In this case, they would be critical digital assets (CDAs) if used for automated tech specification surveillances. CDAs require full application of prescribed cybersecurity 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 CBPs with soft controls [Type 3] on a tablet); and (3) control functions from outside the plant’s protected area (fence), which only applies to a future pilot project on “Advanced Concepts of Operations,” with possible fleet-central controls on certain BOP systems or remote digital control rooms for use during severe accidents.

As a measure of assessment results confirmation, cybersecurity 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 cybersecurity evaluation for an NPP. 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 cybersecurity 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.

3.4 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* [8]. 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" [9]. 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 developmental. 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-2017 with no findings.

3.5 Digital Technology Business Case Methodology

The lack of a business case is often cited by utilities as a significant barrier to pursue wide-scale application of digital technologies to their NPP 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 resulting 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 with this offset potential, a methodology is needed to credibly capture this impact.

To address this need, the research program developed INL/EXT-14-33129, *Digital Technology Business Case Methodology* [10], by working with ScottMadden Management Consultants, a firm with years of experience in preparing performance improvement business cases for senior leadership in the NPP industry. The purpose of this 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 improved work methods. This includes direct benefits in 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 methodology workbook/spreadsheet that is customized and populated with standard NPP work activities and typical plant-staffing totals for each plant organization. It calculates the aggregate benefit of a technology across all work activities it impacts, including being able to credit the 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 identification of benefits and cost-savings. The approach enables collaboration between the Plant Modernization Pathway and utility partners in applying new technologies across multiple NPP organizations and their respective work activities wherever there is the opportunity to derive a benefit. In this way, the business case methodology takes advantage of economies of scale by maximizing the efficiency gains associated with the technologies while minimizing the fixed cost of implementation.

The business case methodology leverages the fact that, in spite of what seems to be a wide and disparate array of work activities among the operational and support organizations of an NPP, the work activities themselves are largely composed of common tasks. For example, whether the work activities are in operations, chemistry, radiation protection, or security, they have such tasks as pre-job briefs, use of procedures, correct component identification, emergent conditions requiring work package alteration, and others in common. 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-to-cost ratio. This has the added benefit of 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 the support of a large operating NPP 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 another 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 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 CBPs. This represents a net present value of over $21M through the expected 15-year life of the technology. This value is considered to be on the low end of the range of expected 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. The study is documented in INL/EXT-15-35327, *Pilot Project Technology Business Case: Mobile Work Packages* [11].

Two new studies applying the business case methodology were conducted in FY-2016 on advanced outage management and control room modernization.

INL/EXT-16-38265, *A Business Case for Advanced Outage Management* [12], documents the quantitative and qualitative performance improvement potential of advanced outage management technologies. The presented analysis is built on the business case developed for mobile work packages. The advanced outage management business case demonstrates that new communication, networking, and analytical technologies will allow nuclear utilities to conduct outages with fewer people in management roles while the remaining outage staff becomes more effective and productive. Benefits are quantified by a rough order of magnitude, thereby providing directional guidance to NPPs interested in developing similar business cases. The following improved capabilities are described in this report:

- automated status updates
- advanced bulk-work and schedule analysis
- networked meetings (remote access)
- networked emergent work teams
- coordination of dispatchable resources
- outage-configuration management
- remote job oversight
- paperless outage coordination.

The business case analysis resulted in a cost-savings present value of $27.23M, and when combined with the full benefit of mobile work packages, savings reach $48.96M. The analysis assumes a discount rate (internal rate of return) of 10% and a cost-recovery period of 15 years. These figures are not net of the application investment, which would have to be determined on a specific-utility basis and should the application investment be less than the present value of the stream of cost savings, then the investment will have a positive return.

INL/EXT-16-39098, *A Business Case for Nuclear Plant Control Room Modernization* [13], documents the cost-savings enabled by seven elements of performance improvement in the form of eliminated work, work efficiencies, and other direct cost-savings (e.g., reduced paper cost, reduced power-replacement cost due to shorter refueling outages), with a present value over 15 years of $10.46M. This figure does not count some labor savings deemed not to enable staffing reductions, but still represents opportunities to use the labor in higher-value ways. The report also documents improvements expected in key performance indicators that are over and above the estimated cost-savings.

As industry considered obsolescence management versus modernization, researchers investigated the true costs of obsolescence, detailing their approach and findings in INL/EXT-20-59371, *Business Case Analysis for Digital Safety-Related Instrumentation & Control System Modernizations* [14], which illustrates a business case methodology for utilities considering digital modernization of I&C systems. This methodology evaluates cross-functional labor and material benefits and conducts a financial analysis as part of business case development. The methodology:

- Provides a bottom-up approach to:
  - Establish labor and material costs for current systems within the defined I&C upgrade scope
  - Identify expected labor and material benefits enabled by the upgrade design concept
  - Validate the expected benefits with subject matter experts
- Demonstrates the methodology used to perform a detailed financial analysis, including:
  - Estimation of annual benefits related to organizational workload reductions for both online and outage work.
  - Estimation of annual benefits related to materials and inventory expenditures
  - Valuation of avoided lifecycle costs associated with escalation of material expenditures
  - Valuation of the modernization over the lifecycle of the station
- Illustrates the scale of benefits that can be expected from a modernization of safety-related I&C systems at a two-unit Boiling Water Reactor nuclear power station
- Provides example worksheets and templates to support a business case analysis of similar efforts by other utilities
- Provides lessons learned and opportunities for utilities that might subsequently implement a similar digital modernization effort.

The most significant finding of the business case analysis research is that material costs for sustaining obsolete I&C equipment is increasing faster than anticipated.

Based on interviews with plant staff, the Project Team investigated reports of high escalation of component prices in recent years. An analysis of material costs for one system in-scope for replacement revealed that costs to maintain the system are escalating at an annual growth rate of more than 20%. This observed rate is higher than the expected rate of 3% to 5%, which is considered typical for the industry.

Given that the obsolescence of components is the driving force behind rapidly increasing system costs, the replacement of obsolete components with a modern system would eliminate the current risks posed by this issue. A lifecycle management strategy of the newer system would further mitigate this risk from occurring in the future.

Leveraging these key business case methodologies described above and integrating them with Integrated Operations for Nuclear (ION), LWRS researcher produced INL /EXT 21-64134 *Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts* [15], which describes the ION business model, and documents an approach for implementing work reduction opportunities (WRO) that drive significant operating cost reductions at NPPs. ION Generation I refers to work reduction opportunities (technology, process, human performance, governance) that are at a sufficient technology maturity level and could be implemented within 3 – 5 years. This report documents, at a high level, the WROs under consideration, cost to implement, cost to maintain and operating cost reductions realized through implementation.

Results of this analysis show that by investing in the right technology upgrades and driving out the value of these investments through process and governance changes, nuclear plants can be competitive in most markets, achieving O&M cost reductions on the order of 30%.

4. RESEARCH AND DEVELOPMENT COLLABORATION

A systematic stakeholder engagement strategy is underway with nuclear industry owner/operators, suppliers, industry support organizations, and the NRC for collaboration and coordination in modernizing the nuclear operating fleet. This engagement ensures that Pathway research activities are focused on the most critical issues of performance improvement and cost management, that the products of research are readily deployable, and that the barriers to successful deployment are effectively resolved.

4.1 Stakeholder Engagement Strategy

The LWRS Program Plant Modernization Pathway conducts a vigorous engagement strategy with the U.S. nuclear power industry, including nuclear operating companies, major support organizations, NRC, and suppliers. This is a support function of the Pathway known as Stakeholder Engagement. The goal of this engagement strategy is to develop a shared vision and common understanding across the nuclear utilities of the need for NPP modernization, the performance and cost improvement that can be attained, and the opportunities for partnering to enact this vision.

Through efforts with multiple utility collaborators, the Pathway is developing a broad range of research findings and related technologies that support a transformation of the NPP operating model. Several early adopter utilities of modernization technologies have expressed interest in the full range of digital modernization (e.g., I&C, automation, OLM, mobile worker technology) in an integrated fashion that leads to a more economic and sustainable operating model. A continuing focus for FY-2022 will be to transfer the learnings we have to those U.S. nuclear operating companies who are ready to pursue this transformative approach to digital modernization.

General communications to U.S. nuclear operating companies and other stakeholders occurs through broad industry meetings that have substantial industry participation. The Pathway is often called upon to make technical presentations or participate in panels in the various research areas of the program. This has proven to be a very effective means of communicating the technology developments to the broader industry. In turn, contacts made in these meetings often lead to new collaborations as utilities, suppliers, and other stakeholders follow-up on the information received in these forums.

Through this and other means, nuclear industry organizations and individuals are identified and engaged in the work and value of the Pathway through the following elements of the Pathway Stakeholder Engagement Strategy:

- Utility Working Group
- Pathway Communication Materials
- Collaboration Groups
- Annual Stakeholder Engagement Meeting
- Innovation Portal for Industry Access of Research Materials

Each of these elements of the Stakeholder Engagement Strategy is discussed in the sections below.

4.1.1 Utility Working Group

Early in its history, the Plant Modernization Pathway early established a UWG composed of nuclear utilities, nuclear support groups, and nuclear suppliers. The purpose of this group is to advise the Pathway on industry needs, participate in the research activities as collaborators when there is mutual interest in the research, and communicate research results within their respective organizations to improve performance. Annual meetings of the UWG are held along with periodic conference calls to obtain input from UWG members on their technology requirements for performance improvement and to inform them of the activities and results of ongoing research projects. In recent years, these meetings have been held virtually as part of the Stakeholder Engagement Meeting (see Section 4.1.4), which has afforded the opportunity for greater participation. Since its inception, twenty nuclear utilities have participated (some have since been merged) representing over 90% of the LWR operating fleet. Many nuclear industry suppliers and the major industry groups of EPRI, NEI, and INPO have also participated. Engagement activities with the UWG include periodic meetings, conference calls, and direct communications to provide status updates on pilot project activities and to publicize opportunities to participate in development activities. Engagement through the UWG serves the following purposes:

- Provides direct input on the needs and requirements of nuclear utilities for technology.
- Provides direct input on the operating environments and safety culture aspects for which the technologies must conform.
- Provides input on the scope and priority of research projects.
- Serves as utility hosts for demonstration projects and studies to prove the effectiveness of new technologies in actual NPP settings.
- 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.

4.1.2 Pathway Communication Materials

The Pathway develops suitable communication materials for publicizing and promoting the technologies and innovations of the Pathway research projects. These materials include project flyers, white papers, standard presentations, videos, and full research reports produced as part of the project deliverables.

These materials are used in industry meetings or with individual organizations to develop interest in the research, attract potential collaboration partners, and ultimately inform industry stakeholders of the opportunities that the research affords. The communication materials also include targeted messaging at the senior executive, management, and functional levels of the nuclear utilities and the wider nuclear support industry. In this way, the significance of the Pathway research and innovation developments will be understood in the context of the business concerns and requirements, organizational objectives, and response priorities for each of these targeted groups.

The communication materials are posted to the Innovation Portal as a common repository of the Pathway publications and materials (see Section 4.1.5).

4.1.3 Collaboration Groups

Serving as collaborators for research project development and demonstrations is one of the most important ways that utilities participate in the research of the Pathway. This occurs when these utilities have their own business process and performance improvement objectives that match up with Pathway research project development plans. In this way, the utilities become “first movers” for the industry and have the opportunity to help establish the technology 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 the cost benefit of a collaborative development effort in proving the effectiveness of the technologies. Suppliers and industry support groups are also included as collaborators when development interests are mutually-beneficial.

As part of the technology transfer to the nuclear power industry in general, collaborators make the results of their experience in the projects available to other nuclear utilities (other than company proprietary information). They also participate in efforts to support the deployment of technologies and innovations, as well as conveying lessons learned from the deployments. Collaborators regularly make presentations in key industry technical meetings to describe their motivations and efforts in the pilot projects and communicate important findings to the industry.

When multiple utilities (and other collaborators) are participating in a Pathway research area, Collaboration Groups are established for these organizations to collegially share information and perspectives as a peer group. This is of great value to the Pathway to get a range of perspectives on the requirements and value of research developments to ensure that the research results are broadly applicable and useful the entire nuclear operating fleet.

Quarterly web meetings are conducted with the Collaboration Groups, consisting of detailed discussions of research activities, collaborator plans/perspectives, and open discussions on utility needs and requirements. These meetings are held jointly with the entire UWG when there is broad information to be shared such as developments beneficial to all research areas or Pathway planning for future years.

4.1.4 Plant Modernization Pathway Annual Stakeholder Engagement Meeting

The Pathway conducts an annual Stakeholder Engagement Meeting to communicate research results of the current year, to provide opportunity for research collaborators to present their work, and to obtain input from a broad range of stakeholders on this research as well as input on future industry requirements and related research. The meeting is organized into sessions that feature the development and demonstration activities of each of the Pathway's major research areas. The meetings also include presentations by the research area collaborators.

The Stakeholder Engagement Meeting is publicized to a large portion of the nuclear industry in publicizing the Pathway research program to the broadest audience possible. Potential attendees are provided detailed session descriptions and agendas, reflecting both the Pathway and collaborator presentations. Attendees can register for any and all of the sessions reflecting their individual interests. Each session will also typically feature a panel discussion involving the Pathway researchers and the collaborators, allowing attendees to ask questions and offer perspectives on the research activities in general.

These meetings have been very well attended by a representative cross-section of the nuclear industry, including advanced reactor organizations who are interested in improving the operational aspects of their reactor designs. This all confirms the success of the Pathway in engaging the stakeholders of the nuclear industry and the value that the industry places on its research program.

4.1.5 Innovation Portal for Industry Access of Research Materials

The Innovation Portal is a web-based resource catalog of advanced technologies, processes, methods, and concepts of the Plant Modernization Pathway as well as the broader LWRS Program. [1] The Innovation Portal also contains information on technologies and processes developed outside the Pathway that are useful in transforming nuclear plants. Users of the Innovation Portal have the ability to search for information by technology or nuclear plant work functions, and then extract that information for use in their own modernization plans. The Innovation Portal is directly linked to another ION development tool, the Integrated Operations Capability Analysis Platform (ICAP), enabling users to seamlessly access this technology information while developing work reduction opportunities under the ION methodology for nuclear plant transformation. [16]

The Pathway Stakeholder Engagement Strategy makes use of the Innovation Portal as an effective means of engaging the industry for disseminating Pathway research results in a self-service manner. It can be accessed through the Pathway web site as well as through general internet searches. It also provides contact information for the Pathway research areas leading to additional engagement opportunities.

Populating the Innovation Portal with Pathway research information began in FY-2021 and is continuing into FY-2022, ultimately resulting in the inclusion of all of the Pathway technologies and innovations since the beginning of the LWRS Program. From here on, all new research results will be promptly posted as the primary means of conveying this information to the industry within the context of the entire body of Pathway research for nuclear plant modernization. In addition, a study was conducted on the Innovation Portal in FY-2021 on its usability, which resulted in a number of recommendations to improve the user interface and related features. [2] These enhancements will be made during FY-2022, making this tool even more valuable in engaging the stakeholders of the Pathway research program. [17]

4.2 Electric Power Research Institute (EPRI)

EPRI is a key partner for the Plant Modernization Pathway, with collaboration made possible through a Memorandum of Understanding adopted in 2010 that links DOE's LWRS Program with EPRI's Long-Term Operations Program. Since that time, EPRI and the Pathway have collaborated on a number of technology developments, as well as jointly sponsoring meetings and other industry collaboration opportunities. The relationship with EPRI is particularly beneficial to the Pathway because of EPRI's research activities, staff expertise, and extensive relationship with utility staff in plant functions that are related to technology research activities. Periodic phone calls are held with the Pathway leadership, senior program manager, and key staff for EPRI I&C research.

The Pathway is collaborating with EPRI in their similarly named Nuclear Plant Modernization Program, which is targeted at gaps in modernization technologies and methodologies. This is a three-year initiative to enable modernization across major nuclear plant organizations with the deployment of existing and new technologies. The purpose is to enhance plant safety and reliability while reducing cost. Annual planning meetings are used to coordinate research activities in related areas. Monthly coordination conference calls are held to status the research and to share findings. There is direct collaboration on certain research activities of mutual interest.

4.3 Halden Reactor Project

The R&D programs of the Halden Reactor Project, sponsored by the Norwegian Institutt for energiteknikk (Institute for Energy Technology) (IFE), historically addressed many aspects of NPP operations; however, the main area of interest to the Plant Modernization Pathway is the Man-Technology-Organization (MTO) 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. 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 I&C modernization projects, including control room upgrades.

In past years, the Plant Modernization Pathway collaborated closely with Halden to evaluate their advanced I&C technologies to take advantage of applicable developments. In addition, human factors studies conducted on the development of the I&C technologies were performed to ensure similar considerations are incorporated into the pilot projects. Major areas of specific collaboration interest were:

- advanced control room technologies
- plant worker mobile technologies
- IO
- enhanced data collection tools and techniques
- automation technology evaluation tools and methods.

One area of particular interest moving forward is using IO concepts in transforming the operating model for NPPs. IO was developed to enable the North Sea oil industry to improve the cost-effectiveness of offshore oil platforms through the use of technology to allow onshore resources to perform many operating and support functions remotely. Halden is continuing to help the Pathway transfer these learnings to the nuclear industry through direct participation in the collaborations with nuclear utilities.

4.4 Major Industry Support Organizations

The LWR fleet is actively supported by major industry support groups; EPRI, NEI, INPO, and NITSL. The Plant Modernization Pathway engages these organizations to enable a shared vision of the future operating model based on an integrated digital environment and cooperate in complementary activities to achieve this vision across the industry. (Note: the relationship with EPRI is described in Section 4.2.)

The NEI is the policy organization of the nuclear technologies industry, based in Washington, D.C. NEI has develops policy on key legislative and regulatory issues affecting the industry. A presentation was made to NEI senior leadership on May 11, 2021, on the combined benefits of recent developments in Integrated Operations (ION) for Nuclear and Flexible Power Operations and Generation (FPOG) in addressing the economic situation for the operating nuclear fleet. The information was well-received by the NEI leaders, who expressed interest in receiving further updates on the initial projects with utilities that are implementing these technologies and concepts. A second meeting was held with NEI on May 26, 2021, to discuss a recent report commissioned by NEI on nuclear plant cost performance in the PJM electricity balancing authority area (Mid-Atlantic states). This meeting was used to validate planning assumptions in ION on target costs for electricity to be competitive in this market. These meetings exemplify how the Pathway is ensuring that the plant modernization research work is calibrated to the regulatory and market realities that the operating nuclear plants are facing.

INPO is a major nuclear industry support organization who, along with its international counterpart—the World Association of Nuclear Operators, promotes operational excellence and the highest levels of safety and reliability in the operation of commercial NPPs. It pursues this by establishing performance objectives, criteria, and guidelines for the nuclear power industry, conducting regular detailed evaluations of NPPs, and providing assistance to NPPs to improve their performance. During FY-2021, the Pathway worked with a key utility collaborator on technology development to seamlessly interface with INPO performance data (among other sources) for reduction in cost in performance improvement work activities. It is anticipated that direct interface with INPO will follow in FY-2022 as the concepts for nuclear plant performance information are further developed, leading to possible direct collaboration with them.

Discussions were initiated with NITSL in July of 2021 on the work the Pathway is doing in a comprehensive digital infrastructure and data architecture that enables integration of all operational and support work functions and processes with the minimal platform and communications elements addressing all technical, security, and regulatory requirements. This work aligns very well with the NITSL Infrastructure and Applications (I&A) Committee, which has invited the Pathway to present this work in the fall of 2021.

4.5 U.S. Nuclear Regulatory Commission

The Pathway conducts frequent communications with the U.S. NRC, addressing their stated desire to be advised of technologies and innovations that the nuclear industry might be considering in their plant modernization efforts so that they can be prepared to review them, if required. While the Pathway makes it clear that it does not speak for the industry, it endeavors to supply technical information to the NRC on the state of emerging technologies and the nuclear plant applications for which they might be useful.

A bi-weekly conference call is held with the NRC for this purpose, with each meeting focusing on particular topics of interest with invited participants from both the NRC staff and the Pathway research staff. This frequent point of coordination serves to engage the needed parties in both organizations on a topic basis, often resulting in specific ongoing discussions between responsible staff where technology development is underway.

In some instances, these discussions lead to actual NRC involvement in a Pathway research project. In FY-2021, the NRC worked with the Pathway and two utility collaborators in defining requirements for a new application that can identify, collect, and transmit nuclear plant data and information needed by the NRC to conduct a particular inspection.

Other engagements include Pathway briefings for various organizations and levels of management in the NRC, sometimes in conjunction with other LWRS Program Pathways. The Pathway has conducted technical briefings for the NRC in certain areas of research, such as the FY-2021 briefing the Pathway sponsored, assisted by Virginia Commonwealth University, and the National Institute for Standards and Technology, in presenting the research these organizations conducted for the pathway in qualification of software for common cause failure.

Each organization at times presents in each other's web meetings on particular technology topics, such as a Digital Twin workshop sponsored by the NRC and the Pathway Stakeholder Engagement Meeting, with both NRC presenters and attendees.

4.6 Suppliers

Deployment of Pathway research depends to a large degree on nuclear industry suppliers providing mature, dependable commercial products based on these developments. However, many products offered today for nuclear plant upgrades do not have all of the features that the Pathway has identified to realize the full potential of these technologies to improve nuclear operational performance and to reduce O&M costs, as well as result in a positive business case to justify the upgrade. The challenge for the Pathway is to work with the nuclear supplier community to inform them of the value and potential of these innovations to transform nuclear work functions and thus contribute to the long-term economic viability of the nuclear plants. This is also beneficial to these suppliers in that they are far more likely to have commercial success with their products when there is an immediate return-on-investment, such that it makes sense to pursue these upgrades sooner rather when later forced to by obsolescence.

In FY-2021, the Pathway engaged suppliers in the following ways:

- Working with suppliers to transfer research results on how advanced features enable labor and cost savings for a nuclear plant, thus contributing to their cost-reduction goals. This includes helping them see the synergistic benefits from related technology upgrades that enable broad work restructuring.
- Working with suppliers to help them understand how emerging technologies create opportunities for new product and service models that reduce labor costs, improve service, and streamline nuclear plant support organizations. New virtual collaboration technologies enable remote third party support that heretofore needed to be onsite to be immediately available, with the attendant overhead cost to maintain these capabilities.
- Including suppliers as collaboration partners where beneficial to the projects, and in doing so, gaining understanding from the suppliers' perspectives on what is needed to make these innovations commercially-viable.
- Including suppliers in industry engagement activities with utilities so that they can hear of technology requirements first-hand and provide information on how they are specifically addressing the stated requirements.

4.7 Department of Energy -Nuclear Energy Enabling Technologies Program

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

I&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 capable of providing higher quality data during in-pile irradiations (e.g., planned to be coordinated in other LWRS R&D pathways). It also includes technologies that will enable some of the vision elements of the I&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 LWR fleet still employs many of the same technologies and algorithms in BOP control as to 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 system 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 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 communication 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 Fukushima Daiichi reactor accidents have raised several issues regarding the ability of current I&C technologies to withstand severe environmental and accident conditions. Currently, emergency operating procedures and severe accident management guidelines in U.S. NPPs require access to reliable information from sensors and controls to manage anticipated transients. However, the severe Fukushima Daiichi accidents highlight the potential for loss of all instrumentation and ensuing difficulties in implementing emergency actions as a consequence. Further research is needed to understand the root causes of instrument failure, to determine alternative approaches to estimate plant conditions, and to determine alternatives to accident management and recovery.

5. RESEARCH AND DEVELOPMENT PRODUCTS AND SCHEDULES

DOE and partner utilities will conduct broad collaboration in R&D activities for nuclear plant modernization. The objective is to provide the technical bases for technical and process transformations that ensure and enable sustainable operating life beyond 60 years. This will have four key focus areas: (1) Control Room Modernization; (2) OLM and Plant Automation; (3) Advanced Applications and Process Automation; and (4) Informed Decision-Making.

For each of the areas of enabling capability, the current performance issues and needs are described, followed by a brief 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. A list of previously completed deliverables for all projects can be found in Appendix A.

5.1 Instrumentation and Control Architecture

The U.S. operating nuclear fleet is an important national asset providing approximately 20% of the nation's electric supply, as well as providing critical grid stability, carbon-free energy, and generation fuel-diversity. However, the economic viability of the fleet is challenged by the abundance of low-cost shale gas generation and heavily subsidized renewable generation. Electricity-capacity markets today do not compensate NPPs for distinct operational contributions they make in addition to baseload generation. As a result, there have been NPP closings due to unprofitable operations, continued economic challenges for many plants in the operating fleet, and an overarching need to address improvements to the underlying efficiencies for production.

Nuclear plants have a significant opportunity to lower their operating costs while actually improving operational performance through plant modernization. Most sectors of the industrial economy renew and modernize their infrastructure on a periodic basis, adjusting to new market conditions and applying new technologies, particularly digitally-based. The operating nuclear fleet, by contrast, is largely based on a state of technology and related operating model that is over 40 years old. It is characterized by analog technology and large operating staffs performing manual activities for most plant functions. Over the lives of these operating plants, nuclear utilities acted on a number of non-discretionary capital investments to address safety and regulatory issues. This has resulted in the deferral of much-needed reinvestment in the plants to address their aging systems and improve their operational efficiency. This reinvestment is now vital to their long-term sustainability. It is therefore critical that proven solutions be identified and become available to nuclear utilities for wide-scale plant modernization that provides near-term cost reductions while resulting in a future state that is operationally and financially sound for decades to come.

Currently, the LWR fleet has a mixture of traditional analog I&C technology and newer digital technology. Virtually all U.S. NPPs 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 LWR control rooms.

Developing and demonstrating an effective and efficient path forward for licensing and deployment of modernizing the LWR fleet through digital I&C has been elusive thus far. This has resulted in digital I&C upgrade projects at commercial NPPs costing substantially more than expected, taking longer to perform, and had a chilling effect on modernization and investments of this type in commercial NPPs.

Several challenging issues remain unresolved and require significant R&D for nuclear utilities to move forward with modernization. These key issues include defining the end state digital architecture, developing the business case for implementation, addressing licensing process burden, technical and developing implementation schedules compatible with short refueling outages.[19]

In addition to addressing the challenges associated with a modern I&C infrastructure, there have been no large-scale changes to the layout or function of LWR control rooms. Nuclear utilities have understandably been reluctant to undertake significant control room upgrades or modernization projects in the consideration of cost, regulatory risk, and impact on the large investment in procedures, training programs, and other support functions accompanying large upgrades. Also, there is a general desire to retain the high degree of operator familiarity with 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 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 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 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 (e.g., human factors design standards, 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 I&C systems are implemented to replace analog I&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 I&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 I&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, as described in Section 3.2, for development and validation studies as part of the pilot projects. In addition, the Plant Modernization 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 Plant Modernization research program is well-positioned to provide enabling science for U.S. hybrid control rooms to control enhancements.

5.1.1 Control Room Modernization

More and more digital conversions of analog I&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 HSIs. While this has minimized the cost of changes to the conduct of operations (e.g., procedures and training), it has diminished the value and potential benefits of the digital technology.

In other cases, dedicated HSIs have been incorporated into the control boards in the 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. This impacts control room human factors and can result in undesirable or unanticipated changes to the 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 mixing analog and digital HSIs 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 control room layouts in a more holistic manner to provide operators with a consistent interface for various digital systems. Such upgrades will involve significant human factors R&D to be performed to provide the needed technical bases for 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 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, as observed in Figure 7. 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 7. Advanced hybrid control room studies in the HSSL.

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

A reference HFE 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 workload, situational awareness, and changes to the conduct of operations through changes in HSI and the re-allocation of functions between operators and systems. 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 the desired outcomes are indeed obtained without introducing undesirable factors.

Work in this demonstration project started with a major focus on collaboration with Duke Energy in applying human factors to control room upgrades for the Brunswick, Harris, and Robinson Nuclear Stations. This work developed new techniques and methodologies for applying human factors to control room upgrades in the Planning and Analysis Phase, Design Phase, and Verification and Validation Phase of NUREG-0711 [22]. These methods employ the HSSL to measure human factors aspects of new I&C systems and associated HSIs through direct observation of operators performing plant evolutions on the realistic simulations of proposed control room changes. Certain portions of this project resulted 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 have published for industry use as a part of the pilot project milestone reports.

Additional human factors challenges related to control room modernization are addressed through another utility partnership with Arizona Public Services and the Palo Verde Generating Station (PVGS). The partnership with PVGS addresses the specific challenges of modernizing a control room using a phased system-by-system upgrade approach. This work identifies how to ensure consistency across all phases of the upgrades and how to leverage digital technology to enhance economic efficiency in a hybrid context. The focus of this research is to investigate how to effectively integrate advanced technology to reduce costs and enhance safety during long-term modernization projects. This research will develop new display and information technologies for control room operator to use to improve control room operator response. The transition from analog to digital systems through control room modernization efforts enables the development of new technologies and information that can be used to guide control room operator performance by integrating new data sources and providing decision support and operator aids. Digital technology also provides the opportunity to reduce costs by automating or streamlining manual processes. Alarm management and procedure use and adherence have been two of the key human and technology challenges identified in existing analog technology-based main control rooms. They have been a source of human performance challenges since the accident at Three Mile Island Unit 2. Current technologies result in a large number of control room staff required to safely operate an NPP control room.

Schedule: FY-2011 to FY-2020

Remaining Project Milestones: None

5.1.2 Efficient Plant Operations Concept Using Human System Integration

Nuclear power has a crucial role in providing safe, reliable, and economical carbon-free electricity for today and the future. For continued operation, many of the existing U.S. NPPs will begin the subsequent license renewal process for extending their operating license periods beyond their initial licensing period. As plants extend their expected operating timelines, there is a significant opportunity to modernize. These plants have a much stronger business case with these extended mission times to modernize and significantly enhance their economic viability in current and future energy markets by implementing digital technologies that support innovation, efficiency gains, and business model transformation.

Ensuring safety and reliability is crucial. Transformative digital technologies, including automation, that fundamentally change the concept of operation for the NPP operating model (e.g., control automation, new decision support capabilities, advanced displays) requires a critical focus on the human and technology integration element. Applying HFE principles and methods to plant modernization ensures safety and reliability while maximizing plant efficiency. By applying a scientific approach that accounts for the capabilities of people and technology, HFE addressed important integration challenges by minimizing workload, minimizing administrative and training burden, presenting meaningful and usable information, and ensuring compatible solutions with the work domain that the technology supports.

Efficient Plant Operations Concept using Human System Integration (EPOCH) will develop end state requirements and guidance for the integration of technology and people in the implementation of advanced control facilities that will ensure safety and reliability to support the U.S. commercial nuclear industry develop a transformative new state vision, as shown in Figure 8. These requirements and guidance will provide a cohesive strategy to complement both strengths of people and technology through targeted research that addresses the human technology integration challenges and aligns with business needs. As a result, there will be a clear end state vision and roadmap to successfully integrate technology across the plant that will leverage the complete benefits of the technology to meet the needs of the business. This work will allow utilities to implement new technologies in a way that maximizes their return on investment and ensures no new human failure modes are introduced.

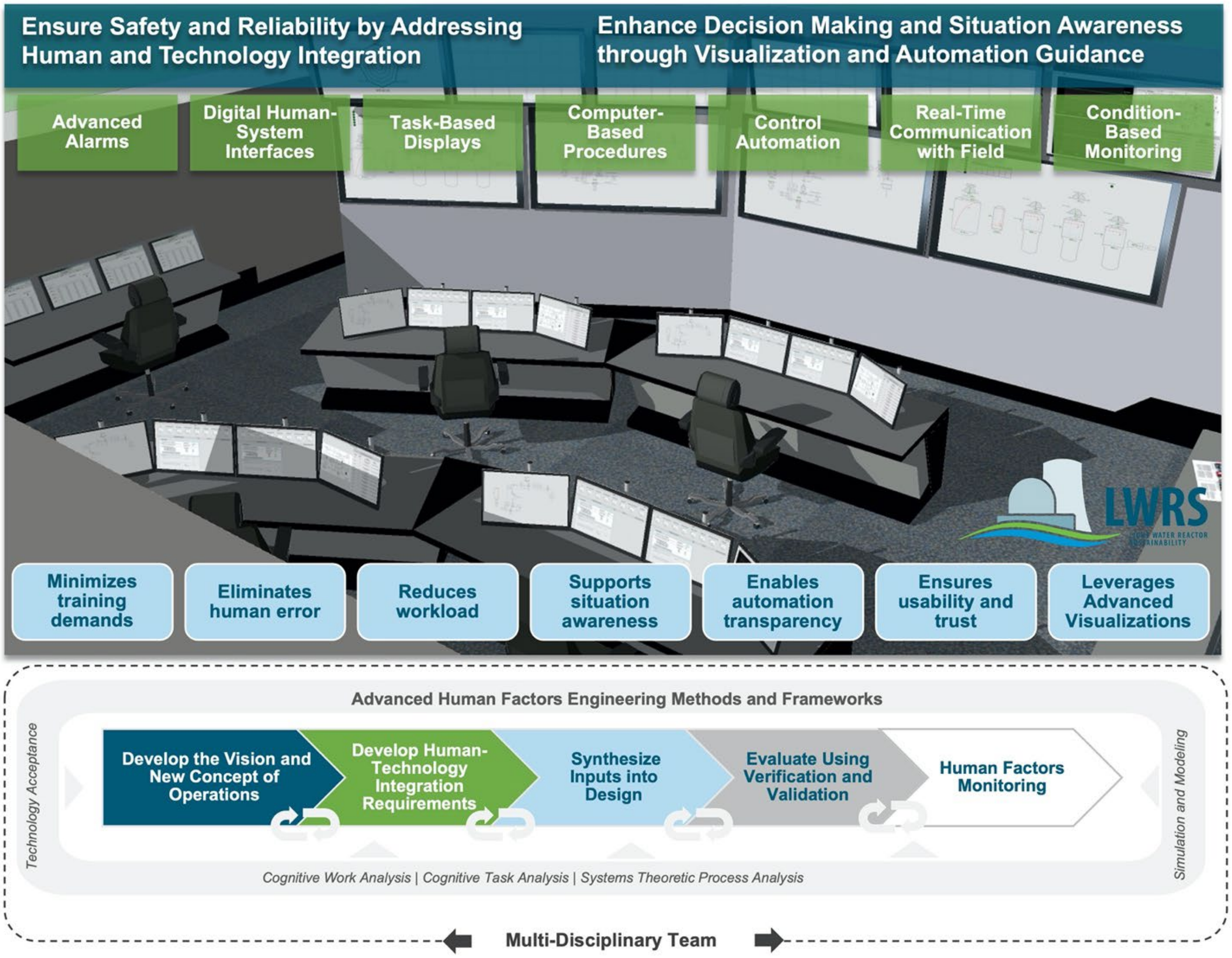

Figure 8. Advanced human factors engineering methods and framework to address human and technology integration.

EPOCH will be accomplishing its objective through: (1) engaging with multiple utilities that represent modernization approaches ranging from ranging applying advanced applications and automation capabilities to maintenance and support functions (e.g., Xcel Energy), system-by-system upgrades to a hybrid control room (e.g., PVGS), through full digital modernization (e.g., Dominion Energy); and (2) leveraging LWRS Program and industry results. It draws specifically on previous LWRS Program research in the areas of advanced alarm systems, CBPs, model-informed decision support, and advanced human system interface displays, as described in Section 5.1.6. Researchers evaluated the integration of these capabilities into an advanced control room concept. Advanced HFE techniques are integrated into this method to enhance the completeness and validity of results. Specifically, cognitive task analysis, cognitive work analysis, systems-theoretic process analysis, technology acceptance model, and simulation and modeling techniques. These techniques enrich knowledge elicitation and representation to ensure new digital technologies provide complete, transparent, and usable information to support decision-making and situation awareness.

This research is planned to continue through FY-2025. The scope of this research is to develop requirements, technical guidance, and proof-of-concept demonstrations of advanced control center concepts that leverage technologies to increase plant efficiencies to reduce costs. EPOCH will focus on the integration of technology with people to minimize training demands, reduce human error and workload, support decision-making and situation awareness, enable automation transparency, and ensure optimal usability and trust, as well as address the emerging information requirements for advanced data analytics and visualization interfaces. This work will ensure safety, as well as promote the sustainability of the LWR fleet by assisting nuclear utilities in addressing reliability and obsolescence issues of legacy analog control systems and demonstrating how strategically integrating technologies can cost-effectively transform the way in which work is done across the plant. The outcome of this work will be requirements and design guidance that utilities can use to communicate with vendors as they implement these technologies.

Schedule: FY-2021 to FY-2025

Remaining Project Milestones:

- (FY-2022): Demonstrate and evaluate the automation adoption guidance to allocate tasks between automation and people. This evaluation will be based on metrics that are developed to measure the effectiveness of autonomous operation while maintaining appropriate plant control for operators. This will include criteria to evaluate the automation's ability to reduce costs through joint optimization between people and technology.
- (FY-2023): Develop and demonstrate updated advanced automation data visualization techniques that support high levels of transparency, trust, and situation awareness for effective monitoring of automation.
- (FY-2024): With nuclear industry partners, demonstrate a full-scale assessment and adoption of advanced automation at an NPP. This full-scale demonstration will assess, at scale, the ability to evaluate the adoption of automation at an NPP and the ability for plant operators to monitor automation after implementation.
- (FY-2025): Report the findings from the full-scale demonstration of advanced automation at an NPP. This report will capture lessons learned in the use of the automation adoption guidance and application of advanced automation data visualization techniques.

5.1.3 Full Nuclear Plant Modernization

Digital upgrades are needed because analog systems, although still reliable, have reached the end of their useful service life. R&D projects are being conducted with nuclear utilities to evaluate the impact of these upgrades. Utilities operate in substantially different market settings that, in turn, affect the business case and decision-making for conducting these types of capital-investment projects. Historically, this research worked with first movers in the nuclear sector to address legacy analog technology issues of reliability obsolescence, as well as to enable improved operator and plant performance. In FY-2021, this collaborative work was still a focus of this project, and resulted in the signing of a new Cooperative Research and Development Agreement (CRADA) with Dominion Energy to collaborate on R&D that will support their Second License Renewal (SLR) project, which entails modernizing the main control rooms of Dominion's Surry and North Anna NPPs. The CRADA work with Dominion will demonstrate the feasibility and benefits of control room modernization to other commercial nuclear operators, suppliers, and the industry support community. It will provide data and results that are representative for the majority of the U.S. operators who face I&C aging and pending obsolescence concerns, and who can benefit from a longer term, complete analog replacement approach to obsolescence management that is planned and strategic (i.e., with an end state in mind, rather than piecemeal approaches necessitated by immediate replacement needs of aging systems).

This project will continue to enable additional research collaborations with other utilities through non-LWRS funding (e.g., strategic partnership program funding) obtained from the utilities. The resources that this project offers to industry fill a number of apparent gaps in capabilities and expertise needed to resolve some of the legacy I&C technology issues that may impact the long-term operation of the LWR fleet. For example, LWRS Program researchers apply state-of-the-art standards, guidance, and principles to evaluate planned digital upgrades. This research also uses the HSSL and employs a variety of data collection methods to form a technical basis for decisions to reduce risk and regulatory uncertainty. This research and its findings will be used to address the human factors and some I&C aspects of LWRS control room modernization. The objective of this research is to enable large-scale control room modernization efforts. U.S. owners/operators face unique challenges that heavily influence plans to modernize. The Plant Modernization Pathway partners with nuclear utilities in several separate large-scale, long-term control room modernization projects and will leverage these various collaboration opportunities to conduct research on a spectrum of technical and regulatory issues key to control room and plant modernization. Information will be captured, and this knowledge and technology will continue accruing to the benefit of the entire operating nuclear fleet as more and more plants undertake needed analog I&C technology transformation.

Additionally, as seen in Figure 9 this project has been synthesizing the results of other Plant Modernization Pathway research projects to provide more cohesive and structured guidance to the industry. The LWRS Program Plant Modernization pathway has performed a wide range of human factors (e.g., Analytics, Decision-support, and Advanced Procedure Tool[ADAPT], EPOCH), operations and business model (e.g., ION), and I&C (e.g., TERMS & ARMOR) research to help the nuclear industry with digital transformation. Each of these research projects is important, challenging, and impactful on their own, but their results will be even more impactful if they are synthesized into a more cohesive and structured framework. This project has been conducting research, based on a systems engineering theoretical framework, macro-ergonomic concepts, and human systems integration to synthesize and focus the results from the R&D performed across the pathway into a more integrated and organized set of solutions that are more clearly and easily communicated to others in the industry such that the pathway and the industry can achieve their common goals and objectives of extending the life and improving the performance of the existing fleet of NPPs.

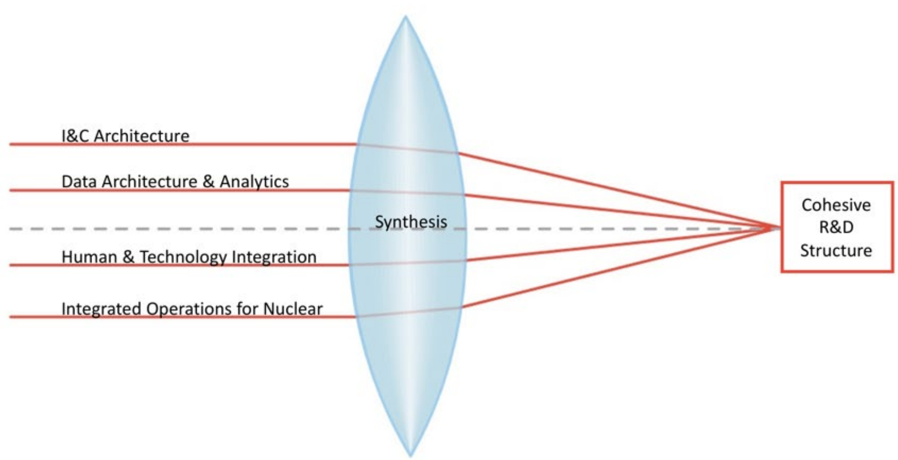

Figure 9. Full Plant Modernization Research Synthesis.

DOE and partner utilities will conduct broad collaboration in R&D activities for nuclear plant modernization that addresses critical I&C infrastructure modernization issues.

Schedule: FY-2017 to FY-2022

Remaining Project Milestones:

- (FY-2022): Provide planning tools and comprehensive guidance on organizational learning and coordination for full nuclear plant modernization.

5.1.4 Digital I&C Qualification

Research has been conducted into methods for developing the technical basis for qualifying safety-related I&C intended to be used in regulatory-approved applications. This research utilized representative near-term technologies, as well as proposed future technologies, and developed the means to demonstrate their licensing and qualification for safety-related applications (i.e., Class 1E systems) in commercial NPP systems. The qualification method selected was exhaustive (e.g., 100%) testing of a simple digital component, such as a digital transmitter.

The NRC considers testability to be one of two design attributes sufficient to eliminate consideration of software-based or software logic-based common cause failure (CCF), the other being diversity. The NRC defines acceptable "testability" as follows:

> *Testability—A system is sufficiently simple such that every possible combination of inputs and every possible sequence of device states are tested and all outputs are verified for every case (100% tested) [NUREG 0800, Chapter 7, Branch Technical Position (BTP) 7–19].*

This qualification method has never proven to be practical in view of the very large number of combinations of inputs and sequences of device states for a typical I&C device. However, many of these combinations are not unique in the sense that they represent the same state space that would not affect the critical design basis functions of the device. Therefore, the state space of interest might possibly be reduced to a manageable dimension through such analysis.

This project focused on a representative I&C device similar in design, function, and complexity to the types of devices that would likely be deployed in NPPs as digital- or software-based sensors and actuators (e.g., smart sensors). An analysis was conducted to determine the feasibility of testing this device in a manner consistent with the NRC definition.

The approach that was pursued as a test methodology is known as bounded exhaustive testing with respect to combinatorial test methods. This involves the development of the process workflow, test bed architecture, tools, resources, and computing needed to conduct an automated testing process. This information was used to fully realize the test bed and conduct the experimental study, which was to demonstrate the efficacy of digital qualification via bounded exhaustive testing with respect to CCF assessment.

A final project report released under INL/EXT-19-55606, *Preliminary Results of a Bounded Exhaustive Software Testing Study for Embedded Digital Devices in Nuclear Power Applications*, was published in September 2019. This report describes the preliminary findings of a study to support bounded exhaustive testing using combinatorial test methods in addressing NRC regulatory guidance on software CCF. The report describes the process workflow, testbed architecture, tools, resources, and computing used to conduct an automated testing process for this purpose. The report further describes how the testing of a smart sensor (e.g., pressure transmitter) was conducted. It presents the test results, which indicate that this methodology has the strong potential to support digital qualification with respect to software CCF assessment.

The major activities of this project were to:

- define acceptable test methods, needed tools (existing or new), and computing resources to conduct bounded exhaustive testing for a digital device.

- develop a specification for conducting bounded exhaustive testing to achieve regulatory qualification of a digital device.
- conduct analysis of the results from the testability demonstration for a digital device to determine whether regulatory guidance to eliminate consideration of digital CCF has been satisfied, thus validating testability as a viable digital qualification method.

Schedule: FY-2018 to FY-2019

Remaining Project Milestones: None.

5.1.5 I&C Infrastructure Modernization/Digital Infrastructure

The nuclear power industry is continuously challenged by an aging and obsolete I&C infrastructure. The industry relies heavily on 1980s technologies, which only provide a minimum level of functionality that is increasingly difficult to sustain. Industry has been reticent to employ new technologies and fully leverage associated vendor-developed capabilities and lifecycle support strategies. Contributors to this reticence include real or perceived regulatory risk and legacy processes and procedures for implementing engineering changes and sustaining I&C systems.

The implementation of modern I&C is also hindered by current industry efforts to address these challenges by piecewise, "like-for-like" replacements of the current I&C infrastructure to sustain current function. Currently available safety-related I&C technologies, as well as currently available non-safety I&C technologies commonly used in other industries, possess capabilities that can directly reduce operations workload, as well as maintenance and support costs in NPPs. A coordinated strategy for I&C infrastructure modernization as part of the transformed ION operating model described in Section 5.1.7 is needed. This will direct I&C infrastructure modernization in concert within a larger digital infrastructure toward a defined new state to obtain the maximum aggregate operational and economic benefits while maintaining and enhancing plant safety and reliability.

Challenges associated I&C infrastructure modernization within the larger digital infrastructure include:

- Identifying vendor-independent principles and attributes for I&C systems that enable I&C upgrades and provide features needed to support an Advanced Concept of Operations (ACO).
- Identifying the current state-of-the-art regarding the I&C infrastructure upgrade practices and methods in other industries.
- Leveraging experience from other industries, identifying nuclear-specific I&C infrastructure modernization obstacles, and developing solutions based on nuclear and non-nuclear industry experience to overcome these obstacles.
- Identifying methods to employ new technologies and fully leverage their vendor developed capabilities and lifecycle support strategies to lower total cost of plant ownership.
- Quantifying the value of the I&C upgrades through business case analyses.
- Minimizing the impact to plant operation while deploying the I&C upgrades including advanced methods to verify and validate the upgrades.
- Addressing regulatory risks/concerns through improved industry and regulatory engagement and use of recent industry and regulatory guidance (e.g., the alternate path for License Amendment Requests [LARs] for I&C systems [Digital I&C Interim Staff Guidance-06] and the EPRI Digital Engineering Guide).
- Defining the full scope of a larger nuclear enterprise digital infrastructure to achieve ION operating model objectives. A simplified depiction of this digital infrastructure is provided in Figure 10.

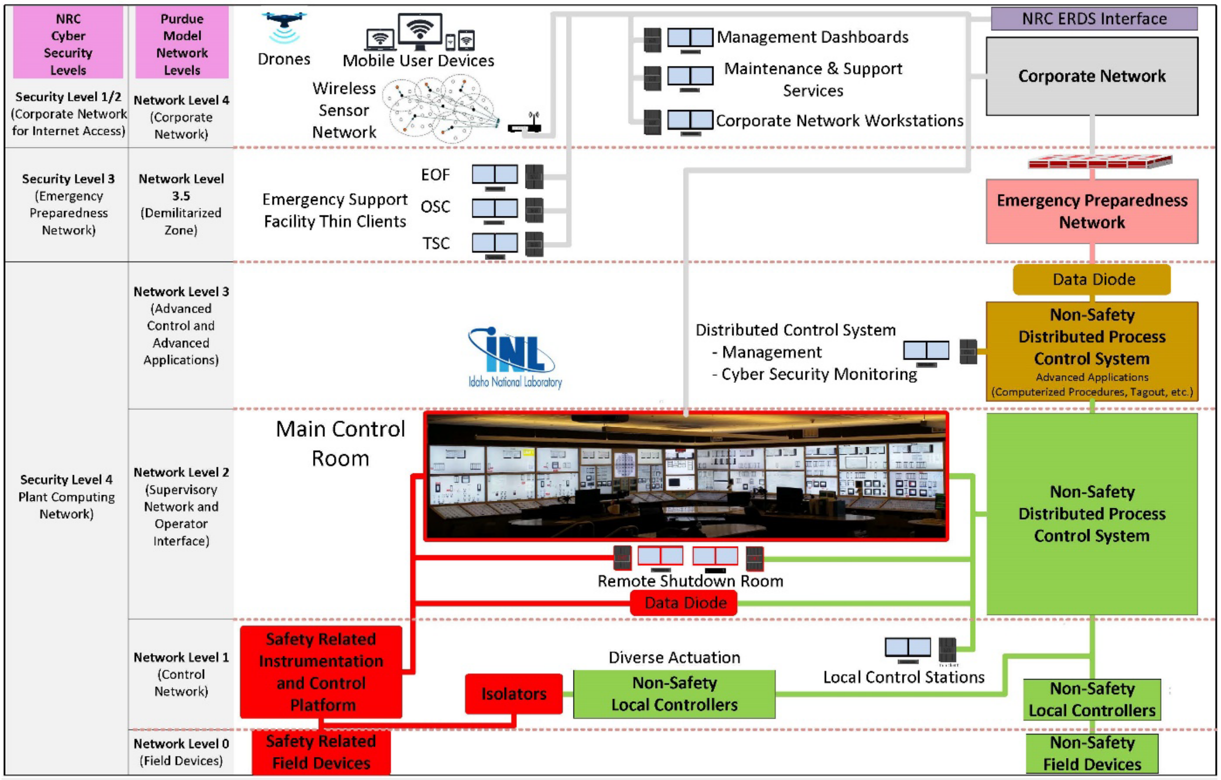

Figure 10. Block diagram of a nuclear enterprise digital infrastructure.

- Establishing how I&C modernization coupled with other digital infrastructure upgrades achieve a defined new state that achieves ION objectives while being sustainable and receptive to future technology advancements to support an 80+ year operating life for existing LWRs. This includes leveraging modern I&C systems capabilities and integrating them within a larger digital infrastructure that supports workload reduction efforts, such as OLM, data analytics, and maintenance work process optimization enabled at other levels of the digital infrastructure. Addressing hybrid digital and analog I&C infrastructure states at interim points during an I&C modernization while driving to achieve a new state defined by ION for the larger digital infrastructure.

Schedule: FY-2021 to FY-2032

Remaining Project Milestones:

- (FY-2022): Complete a technical analysis of the effectiveness of a utility's SLR I&C upgrade efforts, including an advanced main control room operations strategy.
- (FY-2023) Perform a business case study that estimates the costs and benefits for: (1) ION capabilities enabled by digital infrastructure and its supported data architecture and analytics functions; and (2) providing an update to the Limerick Safety-Related Pilot costs projections based on actual project scope.
- (FY-2023) Produce recommendations of corporate network information architecture application sets, capabilities, use cases, and benefits enabled by data transfer from nuclear plant I&C systems.
- (FY-2024) Complete the evaluation on digital infrastructure transformation efforts and lessons learned, and provide an update to the 2020 vendor-independent design requirements for a boiling water reactor (BWR) safety system upgrade report based on lessons learned.

- (FY-2025) Expand the digital infrastructure transformation evaluation to include: (1) an update to the Business Case Analysis for the BWR Safety-Related I&C Pilot to capture final as-built results; and (2) a collaboration with participating utilities to capture project lessons learned to develop a best practice strategy for an upgrade of I&C portions of a LWR digital infrastructure.
- (FY-2026 to FY-2032) Continue to evaluate SLR I&C upgrade efforts, related digital infrastructure transformation efforts, and lessons learned to be leveraged by industry.

5.1.6 Computerized Operator Support Systems

Situational awareness is critical to the safe and efficient 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 plant processes and economics, and 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. It is labor-intensive and represents an area where significant efficiencies could be achieved in the current NPP fleet by developing software tools to assist with O&M monitoring and planning.

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 current plant status and deviations from expected operations to make informed decisions relative to plant operations and maintenance. Through advanced simulation techniques, it will be possible to predict where the plant is going operationally and how long operators will have to intercede in undesirable plant trends. Advanced visualizations ensure that operators are able to understand and respond quickly to the myriad indicators available to them.

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 [23]:

- Advanced nuclear, thermal-hydraulic, and electrical models to assess actual plant performance relative to predicted plant performance and report deviations and trends to operators. It could also 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 those actions 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 emergency procedures cannot anticipate every combination of component unavailability.
- Machine learning (ML) systems that become more robust as they experience a wider variety of operational conditions. This would include systems employing advanced algorithms to monitor sensors and other inputs to perform monitoring of plant and subsystem performance.
- Advanced visualizations to help operators maintain plant situation awareness and anticipate deviations from normal operations. Monitoring and prognostics must be conveyed to plant operators in a useful and actionable manner. Effective visualization can include information to help the operator diagnose current states and extrapolate to future states. It may include aggregations of several data points in a way that allows easier at-a-glance diagnosis, or it may include information to help operators prioritize courses of action, considering economics, safety, or equipment reliability.

This pilot project conducts research to build these prognostic, monitoring, and visualization tools and connect them to current plant systems to achieve staffing efficiencies. These tools will be validated against actual plant performance at a host utility's NPP. Partnering with the host utility, this research will develop and demonstrate an advanced operations approach using a computerized operator support system that integrates safety and non-safety controls platforms, with business side IT infrastructure. This research will address staffing efficiencies using software tools to reduce the burden of monitoring, diagnosing, trending, and predicting plant conditions. While new diagnostic and prognostic tools like machine learning (ML) would greatly reduce staffing requirements for operations and maintenance, these tools first need to be validated for a nuclear context and deliver a solution to meet the Plant Modernization Pathway objectives to drive down LWR industry O&M costs.

This research is planned to continue through FY-2023 and will demonstrate computerized operator support system prototypes and concepts that may be implemented at nuclear utilities. The scope of this research will initially provide proof-of-concept demonstrations necessary to show feasible functionality and down select the best technologies. Results of research performed with utility partners will center on their efforts to modernize the entire plant, specifically with respect to I&C hardware and HFE, and regulatory considerations.

This research entails working with nuclear utilities and vendors to develop operator support tools that enhance efficiency of plant operations. The activity supports plant modernization with an emphasis on advanced monitoring and prognostics tools and technologies. Particular areas to be addressed include: the systems that would benefit from operator support systems, the technologies behind operator support systems (e.g., prognostic algorithms and visualization tools), and operator-in-the-loop validations of demonstrations to produce industry guidance for implementation of computerized operator support systems.

- This research will be integrated within EPOCH, as described in Section 5.1.2, as part of developing a clear end state vision and roadmap in integrating technology, such as the computerized operator support system across the plant, in a way that leverages the complete benefits of the technology to enhance efficiency of plant operations.

  Schedule: see Section 5.1.2.

5.1.7 Advanced Concepts of Operations

The overall objective of the ACO project is to deliver a validated means of bringing operating costs to the nuclear industry in line with the realities of the electric market through transformation of the operating model—and to accomplish this through business-driven technology innovation. This will address the two major barriers to extended plant life—long-term technical viability and economic viability.

Collaborating with Xcel Energy Nuclear Generation in their XE1 Program, the ACO project is focused on developing a business-driven approach to transforming the operating model of a commercial nuclear plant from one that is labor-centric to one that is technology-centric, as many other industry sectors have done to survive in the marketplace.

The underlying concept for this operating model transformation is known as IO. IO refers to the integration of people, disciplines, organizations, and work processes supported by information and communication technology to make smarter decisions. Over the past two decades, North Sea oil and gas companies have implemented IO to restructure their operating models to remain profitable amid declining offshore petroleum fields and depressed oil and gas prices. Using advanced digital technologies, they moved operations and support functions on shore to serve multiple platforms as one example of business model transformation.

Norway's IFE, which sponsors the Halden Reactor Project, has been a leader in developing the principles, methods, and technologies of IO enabling this transformation in applying the lessons learned to the NPP operating model. They provided a new report to the Pathway, “Lessons Learned from IO in the Petroleum Industry,” based on their deep understanding of both offshore petroleum production, NPP operations, and support. ScottMadden Management Consultants is also part of the project team to provide cost benefit analysis and innovative concepts from both nuclear and other industry sectors.

The project team is working directly with the Xcel Energy XE1 Program to analyze the nuclear generation work functions to derive more efficient means of accomplishing required outcomes through work elimination, requirement reduction, process improvement, technology application, and other forms of innovation. Through this collaboration, the Pathway is developing a framework and an accompanying tool set for the analysis and formulation of the transformed operating model, which is termed ION.

The ION framework is a business-driven approach for transforming the operating model of a commercial NPP from one that is labor-centric to one that is technology-centric, using a top-down/bottom-up process as follows:

- A market-based price point (typically bus-bar cost in $/MWH) for nuclear generation is set and then used to back out what the maximum total O&M budget of the nuclear fleet can be to support this price. This budget in turn is allocated over the nuclear organization in a top-down manner as the starting point of an iterative process (Top-Down).
- Work functions are analyzed for aggressive opportunities to reduce the workload to that which is essential and can be resourced within this budget (Bottom-Up).
- The streamlined work functions are then configured into a transformed operating model that leverages advanced technology and process innovations, resulting in a small onsite staff focused on daily operations with all maintenance and support functions centralized or outsourced in on-demand service models.

As part of this research, the Pathway has developed an ICAP to facilitate this process. In ICAP, the work functions can be related to organizational units or what is referred to as Capabilities in IO, which is a scalable, reusable ability to perform a business function that is critical to the organization’s success. The work functions can also be associated with the organizational hierarchy for the purposes of allocating the top-down budget and the development of functional responsibilities of the organizational units.

This past year, an analysis was performed to determine the necessary Work Reduction Opportunities (WROs) that a plant would have to implement to achieve a one-third reduction in O&M cost. The report also identified the necessary capital to fund the capital improvements. A research task for FY-2021 will work with industry partners to validate this analysis.

Schedule: FY-2020 to FY-2025

Remaining Project Milestones:

- (FY-2022) Complete development and validation of the IONs Generation 1 business operating model and evaluate its effectiveness to integrate the ION cost-savings methodology.
- (FY-2023) Produce a technology integration roadmap that maximizes nuclear plant performance improvement and cost reduction in plant control and monitoring, work activity automation, worker efficiency, human performance, risk management, and operational decision-making through the synergistic combination of advanced digital technologies.
- (FY-2024) Demonstrate a plan to fully deploy key enabling applications of the IONs Generation 1 business model at Xcel Energy and one other NPP. Use of the prior year technology integration roadmap will drive the deployment features and technology deployment.
- (FY-2025) Complete a business case for planning and deployment of key ION Generation 2 enabling technologies. Update the road map and business plan and demonstrate continued cost-savings through advanced technology integration to ensure long-term sustainability.

5.1.8 Advanced Plant Control Automation

Because of the pervasive analog I&C technology in NPPs today, much of plant control is conducted by operators manually manipulating a large array of discrete control devices. However, exceptions 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 changing plant conditions and automatic control system performance.

Building on work from the pilot project on automating manually performed plant activities, especially the portion concerning the conversion of standalone 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 and are time- and attention-intensive for operators, which entail some nuclear safety or production risk. Examples of such activities include:

- performing plant heat-ups and cool-downs
- automated managing 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 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 the 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. In addition, the project would develop a technical report for applying advanced plant controls in a manner consistent with human factors principles as validated in project studies.

Schedule: FY-2023 to FY-2026

Remaining Project Milestones:

- (FY-2023): 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 the design and human factors principles.
- (FY-2024): Develop and demonstrate prototype plant control automation strategies in the HSSL for representative normal operations evolutions (e.g., plant startups and shutdowns, equipment rotation alignments, test alignments).
- (FY-2025): Develop and demonstrate prototype plant control automation strategies in the HSSL for representative plant transients (e.g., loss of primary letdown flow or loss of condensate pump).
- (FY-2026): 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.

5.2 Online Monitoring and Plant Automation

As NPP systems continue to be operated during periods longer than originally anticipated, the need arises for more and better types of material and component performance monitoring. 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 regarding operation and maintenance strategies. 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 RUL estimation also enables a plant to optimize resources, ensuring low downtime and better economics of operation.

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 advanced analytics 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 conditions or behavior for targeted components. Much of the value of OLM 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, plant support staff conduct an investigative review to identify the actual failure mode and cause and then suggest the appropriate corrective actions. The review can involve many onsite operations and technical staff, consultants, and field experts in achieving a maintenance strategy. In these cases, the diagnostic process is manually intensive, consuming available warning time and potentially extending damaging operating conditions. While APR systems are effective at identifying equipment operating conditions that may shorten the RUL of the equipment, 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 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, and APR systems cannot incorporate or influence business analytics. Hence, current APR products are not suitable for long-term monitoring and management of nuclear assets and, in particular, for passive assets evaluated on an intermittent basis using nondestructive evaluation (NDE) measurement techniques.

The development and advancement in diagnostic and prognostic capabilities is required to achieve an automated ability to directly identify equipment condition from initial warning fault signatures. This will support the analysis of long-term component behavior, related risk, RUL, and economics. It will further provide verification of asset condition as evidence of design qualification and economic viability.

Advanced and digital monitoring technologies 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 a component's 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.

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

1. Develop a monitoring infrastructure at the operating and management levels of the NPP 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 on the diagnostics and prognostics technology for adaption to the NPP industry.
4. Develop the structure-specific models, component-specific models, analytical methods, and supporting-data requirements needed to enable diagnostics and prognostics analysis.
5. Obtain access to 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 or precursors.
9. Identify measurement and sensor requirements to support analytical methods.
10. Develop an end-to-end digital data architecture to enable effective use of heterogeneous data to streamline advanced analytics and information visualization.
11. Research and develop information-visualization capabilities to ensure the right information is available to the right personnel in the right format at the right time to support informed decision-making.
12. Develop scalable methods, models, and tools, thus ensuring expanded applications of diagnostic and prognostic technologies across the domestic nuclear fleet.

An effective means to accomplish portions of the above research tasks is through the conduct of pilot projects. These projects will be structured around a narrowly defined set of objectives to accomplish specific tasks requiring access to real-time plant assets and operational data. There are significant limitations to benchtop 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 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.

Research institutes, national laboratories, and U.S. utilities have been working together to develop the analytical diagnostic and prognostic framework for representative active and passive assets needed to support enhanced monitoring capabilities. It is expected that utilities will find that a central monitoring function will be the most efficient way to implement advanced monitoring for a nuclear fleet. Indeed, this has been the practice of some of the early movers for OLM using the APR technology. This concept work for centralized monitoring will be accomplished through the pilot project on the advanced OLM center (as described in Section 5.2.7). The Plant Modernization Pathway will also serve the role of integrating OLM information into the overall digital information architecture, such that it will provide needed information to other plant activities.

Within the theme of centralized monitoring, 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 benefit of remote online monitoring is an important enabler to an approach sometimes referred to as IO. Mainly IO uses this technology to overcome the need for onsite support, thereby allowing the organization to centralize certain functions and concentrate a 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 the services are provided remotely. The concept also enables standardized operations and economy of scale in maintaining a single organization instead of duplicate capabilities at each location.

One of the examples is the Halden Reactor Project, which has been quite active in this concept for Norwegian offshore oil platforms. These oil companies have developed IO to move large parts of their platform operations and support functions to centralized onshore locations. This has resulted in dramatic improvement in the efficiency and economy of operations and 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 IO.

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 can then 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 IO concept. Indeed, some steps in this direction have already been taken by utilities that have implemented a centralized OLM 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.

5.2.1 Online Monitoring of Active Components

Pilot projects were conducted involving three active components representative of those for which extended life is highly important to LWR sustainability. The components are emergency diesel generators, large power transformers, and induction motors.

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

Using EPRI's FW-PHM suite software, the pilot project developed 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 RUL database. The analytical models were those needed for the diagnostic and RUL advisors. The project also included the 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 was published that described the technical basis and analysis framework to enable OLM for these components. This technical report, along with the results and experience from the pilot projects, were used to develop guidelines for utilities to implement centralized OLM and information integration for the components and structures important to plant life extension.

This pilot project was conducted in collaboration 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 developed an experimental test bed that included two 40-horsepower induction motors instrumented with current, temperature, and vibration sensors. The experimental test bed supported the 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

Remaining Project Milestones: None.

5.2.2 Online Monitoring of Concrete Structures in NPPs

The 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 and 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 O&M decisions.

This project will be a combined effort between the Plant Modernization Pathway, the Materials Research Pathway, the University of Alabama, the University of Nebraska–Lincoln, the University of Tennessee–Knoxville, Vanderbilt University, and EPRI. It will develop a framework for the health diagnosis and prognosis of aging concrete structures in NPPs that are subject to physical, chemical, and mechanical degradation by integrating modeling, monitoring, data analytics, and uncertainty quantification techniques. Current knowledge and ongoing national and 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 for the health monitoring of NPP concrete structures, as shown in Figure 11, will include four technical elements: (1) damage modeling; (2) monitoring; (3) data analytics; and (4) uncertainty quantification [18]. The framework will enable plant operators to make risk-informed decisions on the structural integrity, RUL, 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.

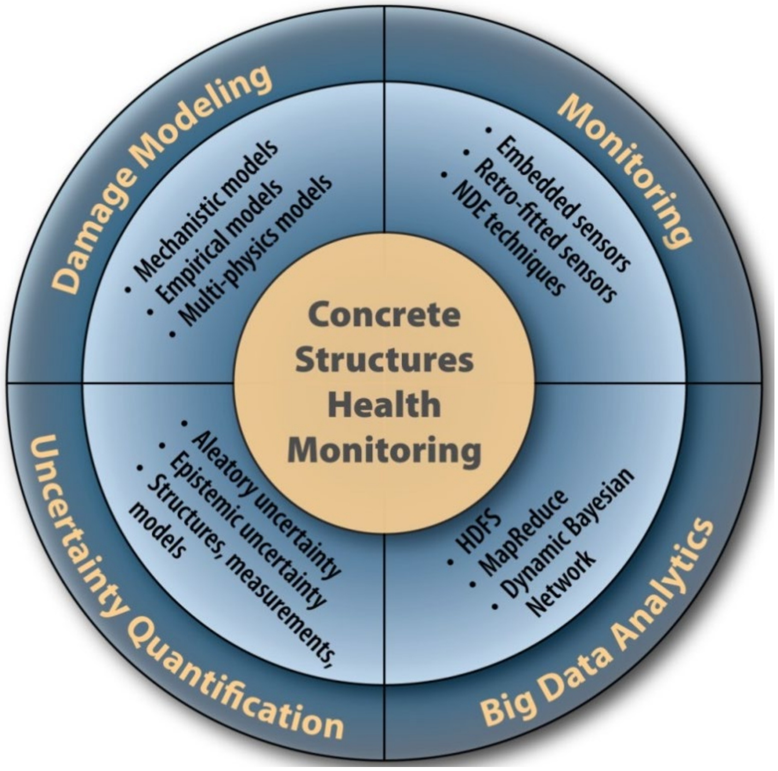

Figure 11. Framework for concrete structure health monitoring.

Damage Modeling. This task will leverage the modeling of chemical, physical, and mechanical degradation mechanisms—such as an 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 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 multiscale and micromechanics effects, and the integration of multiple models through an appropriate simulation framework. The computational models developed by Oak Ridge National Laboratory and in the Grizzly software of the Multi-physics Object Oriented Simulation Environment (MOOSE) at INL were leveraged. Gaining multiscale and micromechanics effects understanding, finite element analysis models are developed by Vanderbilt University to understand the propagation of acoustic-vibration waves through concrete specimens both with and without reinforcements. These models are also used to develop simulated data that are used to develop baseline ML models.

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), infrared imaging (thermal), velocimetry and ultrasonics (acoustic), and X-ray tomography. Within the acoustic monitoring, the vibro-acoustic technique will be evaluated as a part of the active acoustic technique, and the research would benefit from the passive acoustic technique performed at the University of Tennessee–Knoxville on large concrete specimens. 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. Efforts will be directed towards cross-verification of acoustic techniques using measurements from embedded strain and pH sensors. The application of a laser doppler vibrometer, a non-contact technique, for vibration measurement of a surface is also explored.

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 (e.g., numerical, text, 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. A Bayesian network will be used to infer the state of concrete degradation. The probabilistic relationships in the network will be updated using ML, data mining, classification and clustering, feature extraction and selection, and fault signature analyses on the heterogeneous data collected from the monitoring activities. Visualization techniques will be developed to enhance visual interpretations of data and information.

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 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.

LWRS Program's Plant Modernization and Materials Research Pathways are working with EPRI in developing a concrete NDE roadmap. The team has identified three areas needing attention going forward. These include: (1) advancement in NDE techniques; (2) SHM; and (3) approaches to understand different degradation mechanisms. Short (i.e., 1–3 years) and long-term (>3 years) research needs will be discussed and finalized in FY-2020.

Schedule: FY-2014 to FY-2020

Remaining Project Milestones: None

5.2.3 Online Monitoring of Secondary System Piping in NPPs

Based on INL/EPRI joint workshops and feedback from utilities, the OLM of structural health of secondary pipes was selected for the second pilot project on passive component sustainability. The purpose of this work is to reduce the cost of preventive maintenance (PM) of secondary structures in NPPs using state-of-the art sensor modalities, data fusion, and advanced data analytics. Specifically, this pilot project aims to develop and validate an integrated multi-sensor OLM system capable of inspecting large piping components in secondary systems and providing a pathway to move from inspection-based to condition-based maintenance. The OLM system is expected to provide a current estimate of pipe-wall thickness along with the RUL estimate. Such a system could provide the following benefits:

- improved capacity factor by reducing unplanned and planned outages
- improved safety through fewer unexpected failures and repairs
- optimized equipment O&M through early identification of faults
- improved fault diagnostics through increased availability of data relating to faults and shared knowledge of fault behavior based on case studies and expertise
- lifetime extension of existing NPPs through increased understanding of the current health of plant components and RUL estimation

- minimizing human factors effects on NDE testing.

The OLM system will have a larger area of coverage than current NDE techniques and will aim to answer the questions that current aging management programs are facing, such as the identification of inspection locations. There is no currently available technology that would pinpoint which piping component needs to be inspected. This is the major reason for redundant inspections. The conceptual representation of the OLM system output is shown in Figure 12.

Wall thickness is color-coded with green representing the safe thickness, yellow representing borderline thickness, and red representing wall thickness closest to the safety threshold, which requires immediate attention.

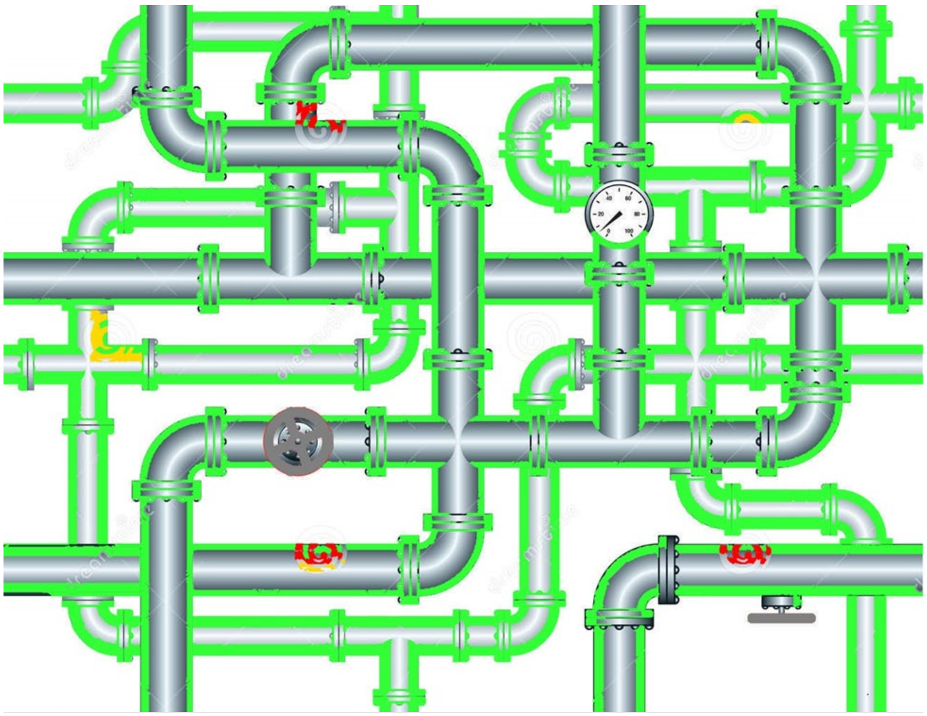

Figure 12. Conceptual representation of the OLM system's output;

In Figure 12, the wall thickness is color coded with green representing a safe thickness, yellow representing a borderline thickness, and red representing a wall thickness closest to the safety threshold that requires immediate attention.

The LWRS Program will be leading research efforts on developing artificial intelligence (AI)-enabled high-spatial-resolution fiber sensors as tools to improve the detection of corrosion-induced defects in complex piping geometries, such as elbows, tees, and bends. Also, LWRS will research the applicability of ML and big-data analytics for pipeline SHM. This knowledge and analysis will enable industry to implement OLM and forecasting for piping components to establish the methodology for industry to extend the concept to SHM of other secondary system passive plant components.

A technical report and peer reviewed publications will be published that describe the technical basis and analysis framework to enable OLM 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. INL researchers will collaborate with the University of Pittsburgh to explore AI and high-spatial-resolution fiber sensors as tools to reduce the influence of both human and hardware factors and improve pattern recognitions for corrosion-induced defect identification. Through high-spatial-resolution data gathering using distributed fiber sensors (e.g., capable of acoustic, temperature, and strain monitoring) and deep-neural-network ML, the Pathway aims to significantly improve the cost-effectiveness and measurement efficacy for multimodal sensing systems for pipeline monitoring.

Fiber-optic distributed acoustic sensing (DAS) with phase-sensitive optical time-domain reflectometry (ф, OTDR) is a powerful distributed-sensing technology used to detect acoustic and vibration signatures for a wide array of applications. The schematics of the DAS system are shown in Figure 13.

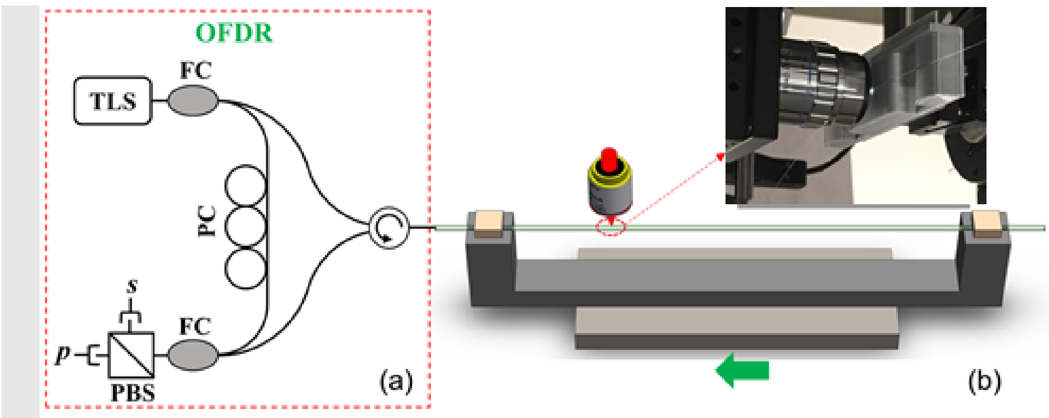

Figure 13. Schematic sketch of the DAS system based on Rayleigh Enhancement setup.

In Figure 13, (a) is the Optical frequency domain reflectometry (OFDR) system—LUNA OBR 4600 with internal components—tunable laser source (TLS); fiber coupler (FC); polarization controller (PC); and polarizing beam splitter (PBS). (b) A schematic sketch of the ultrafast laser irradiation on optical fibers.

Schedule: FY-2015 to FY-2020

Remaining Project Milestones: None

5.2.4 Digital Architecture for an Automated Plant

To automate operating NPPs to their full potential, the integration of digital technologies must extend to encompass databases from different plant processes. An NPP collects data from plant processes, work management systems, scheduling, systems engineering, operator logs, condition reporting, etc. These databases have different structures and tools and are, therefore, used independently. The integration of data from these databases is performed manually, as needed. For example, an LWRS pilot study previously attempted to integrate scheduling activities from one tool with work order steps from another for the purpose of tracking work progress in an outage. Because a scheduled activity can represent one step in a work order or a set of steps, the mapping process had to be performed manually and required tens of hours to map one work order to one schedule. The problem is much broader than this example. The tools currently used and those that may be used in the future in NPPs employ different information and data terminologies. Databases that support these tools have elements that do not represent the same data in other tools.

Data integration is the core element of creating a data warehouse for a single or multiple NPPs. See Figure 14. A data warehouse results in direct and indirect cost-savings because it automates the manual search for data, enables sharing and comparison of data from various tools of a single or multiple plants, enables digital transformation of data collected in the plant, increases time frequencies of data that are sparse in nature (such as failure signatures), facilitates the use of machine decision-making for streamlined and improved plant activities including plant compliance, reduces the need for training on various tools for plant staff, enables a holistic staff perception of plant activities, and supports as a standard visualization approach of all parts of an NPP necessary for O&M. One of the main challenges to deploy a data warehouse is associated with the integration of data sources into a data model and a developed and optimized ontology for the nuclear power industry. This model was developed by the program and is currently leveraged in piloting the feasibility of a nuclear data warehouse.

Schedule: FY-2014 to FY-2023

Remaining Project Milestones:

- (FY-2022): Complete the design and development of a pilot data portal for automated access to compliance-related data.
- (FY-2022): Demonstrate the potential for text-mining AI/ML methods to automate the review and audit process of compliance-related data and documents.
- (FY-2023): Complete and demonstrate automated data integration methods based on the developed data model for activities that require extensive manual integration work.
- (FY-2023): Complete and demonstrate a data integration method to reduce the spare parts stocking requirements in an NPP by possibly partnering with Xcel Energy. This task is aimed to reduce the inventory minimum requirements through ML.

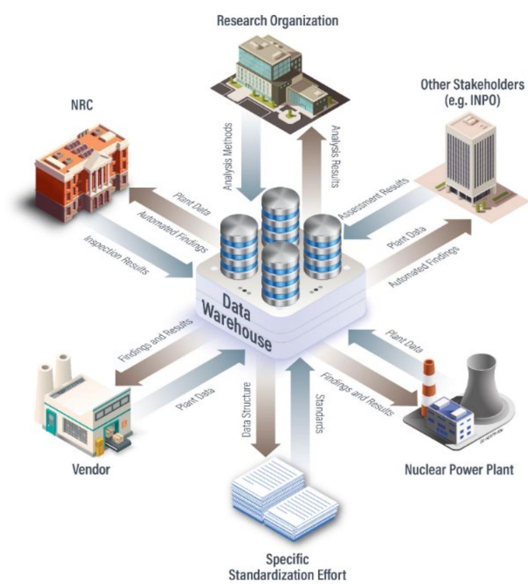

Figure 14. A data warehouse enables experience and methods to be transferred among NPPs and outside organizations, and industry-wide solutions to be established.

5.2.5 Advanced Remote Monitoring for Operations Readiness

The nuclear power industry is challenged with high operational costs, specifically for operational surveillance activities that are performed to comply with license requirements. It is currently heavily reliant on manual activities on a periodic basis, as mandated in the plant's technical specification. The main objectives of these activities are to ensure plant equipment readiness when needed and to detect process anomalies

With current technological advancements in sensors and data analytics, it is possible to replace a significant portion of operations activities with sensors and a centralized and automated analysis process. This enables appropriate organizations to address anomalies before their severity escalates. This end state requires developing methods to autonomously analyze plant process and support systems data on a holistic level. It will also require identifying plant monitoring gaps and introducing new technologies or sensors to improve the operator's decision-making process.

This project will develop an advanced operations approach that automatically ensures plant readiness and identifies plant anomalies along with the root cause as issues progress and develop a new level of condition monitoring from unsupervised intelligence to supervised methods by using condition reports as labels for process data. See Figure 16

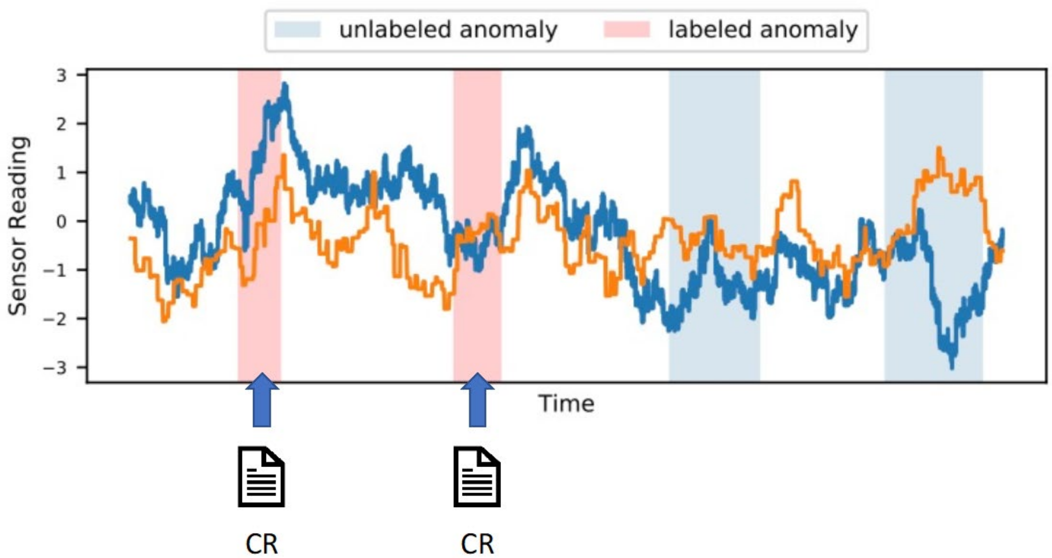

Figure 15. Condition reports in an NPP present labels for parts of the sensors' time series data and used as input for anomaly-detection methods.

This will reduce the number of plant workers gathering data, allowing the operations team to focus on ensuring optimal plant performance. This is achieved by researching and developing methods to automate data collection (i.e., transform the way surveillances are performed) to reduce the cost of manual operations processes. The project will also develop machine intelligence technologies that integrate data from various plant equipment sensors with plant process data for a holistic and continuous approach to operations monitoring, revealing anomalous conditions that cannot be inferred based on a single method of monitoring, and developing a library-based monitoring platform to enable rapid, flexible, and expandable integration of monitoring methods used by plants and vendors. See Figure 17. The project will target high-cost processes in order to ensure maximum return on investment. Existing technology capabilities, data, and expertise will be leveraged to achieve reduction in O&M costs on identified plant assets.

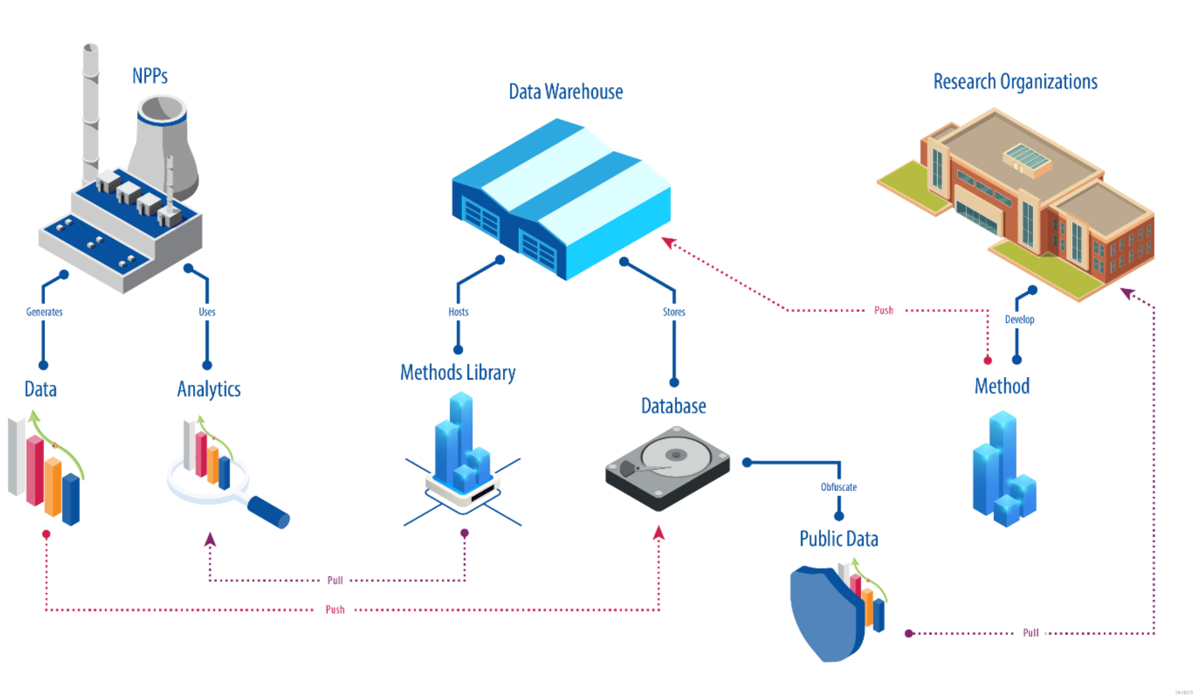

Figure 16. The methods developed using NPP data by research organizations (including INL) will be available through a data warehouse methods library for NPPs to grab and use as the need arises.

Schedule: FY-2019 to FY-2024

Remaining Project Milestones:

- (FY-2022): Complete explanation on anomalies detection methods to streamline causality determination and guide the current manual investigation process for each process anomaly in monitoring and diagnostics centers.
- (FY-2023): Scale process anomaly detection to distinguish transients from anomalies to enable the deployment of anomaly detection methods for various operations modes beyond the typical 100% power mode.
- (FY-2023): Complete a pilot library for equipment condition monitoring method-sharing with the nuclear industry as a step towards establishing a comprehensive library for all LWRS equipment condition monitoring methods with the nuclear industry.
- (FY-2024): Evaluate the regulatory basis for use of sensor-based AI in monitoring safety equipment in nuclear power applications.
- (FY-2024): Complete the structure of a library-based equipment condition monitoring platform to enable rapid, flexible, and expandable integration of plants and vendors monitoring methods.

5.2.6 Technology-Enabled Risk-Informed Maintenance Strategy

Continuing to operate NPPs in an electricity market selling wholesale electricity for $22/MWh becomes unsustainable with current O&M (as of 2019) total average operating costs for the entire fleet at $30.42/MWh. Prices for producing energy by NPPs have reduced since 2015, but remain high compared to other energy sources. In addition, the global energy market trends are driven heavily by the abundant reserves of natural gas and the declining costs of renewable energy systems. As identified, one of the major contributors to the total for operating costs today is the O&M costs, which include labor-intensive

PM programs. PM programs involves manually performed inspection, calibration, testing, and maintenance of plant assets at periodic frequency, and time-based replacement of assets, irrespective of equipment condition. This has resulted in a labor-centric business model to achieve high capacity factors. In order to be competitive, the industry must transition from this labor-centric business model to an optimal PM program. To enable this transition, as shown in Figure 18, a reliable method is needed based on available advanced technologies to support assessing the condition and risk of equipment failure. Fortunately, technologies exist such as advanced sensor, data analytics, and risk assessment methodologies for enabling the transition to a *technology-centric business model* that will significantly reduce PM activities, driving down costs since labor is a rising cost and technology is a declining cost. This transition will also enable NPPs to maintain high capacity factors (and perhaps even achieve higher ones) while still significantly reducing O&M costs.

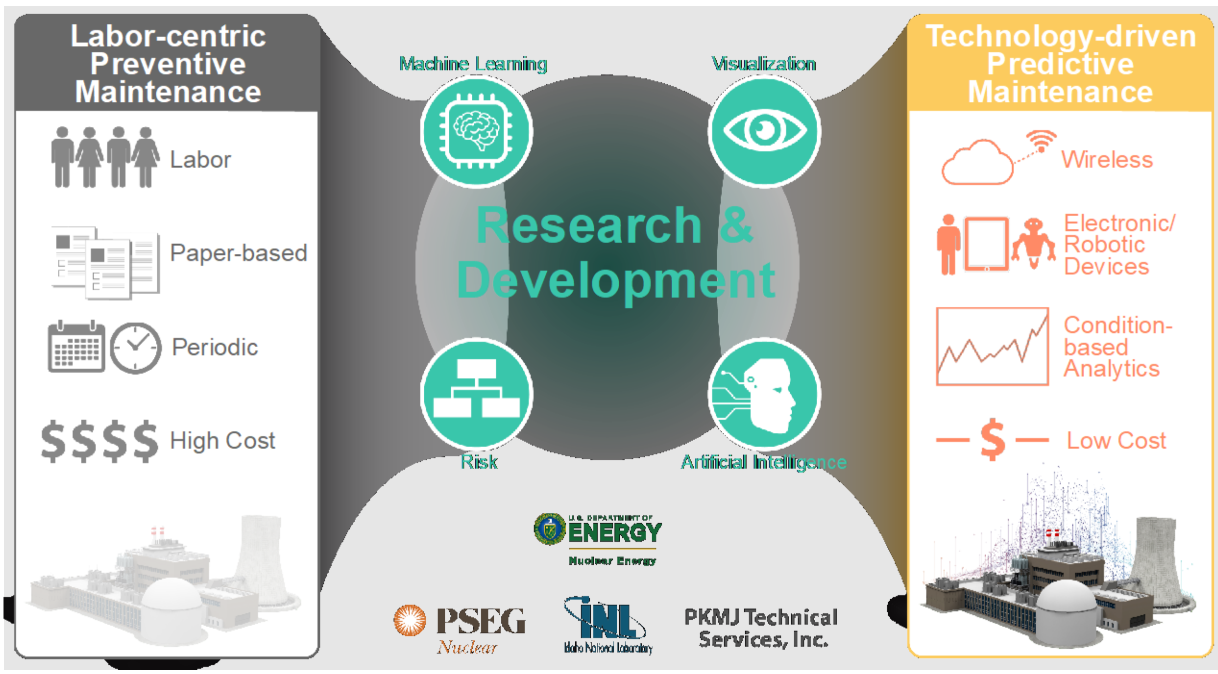

Figure 17. Transition from a PM program to a risk-informed predictive maintenance (PdM) program.

Use of a technology-centric maintenance program will lay the foundation for real-time condition assessment of plant assets; this will allow plants to implement condition-based maintenance to simultaneously enhance safety, reliability, and economics of operation. The project scope is to achieve optimization and automation of maintenance frequency at scale, and quantification of cost-savings by performing quantitative economic evaluation of implementation of the risk-informed PM strategy. Here optimization and automation of maintenance frequency at scale implies the development, demonstration, and deployment of advanced technologies and methodologies across plant systems and across the nuclear fleet. The project outcomes will provide the domestic nuclear fleet with technologies enabling them to transition from the current time-consuming and labor-intense PM strategy (Figure 19) to a more cost-effective scalable risk-informed PM strategy deployable across different plant assets. The outcomes will also provide the technical bases to reduce financial and regulatory risks of modernization and automation.

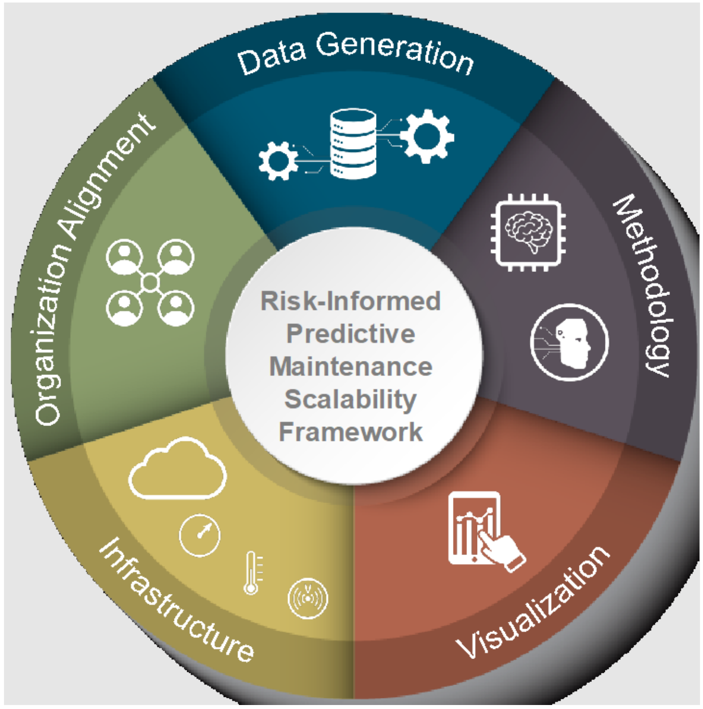

Figure 18. A framework to scale risk-informed predictive maintenance strategy.

This work package comprises R&D efforts including the development, enhancement, and utilization of a hybrid model (i.e., a representative digital twin model) of the circulating water pump motor. The developed hybrid model captures both the deterministic and stochastic operation characteristics of the circulating water pump motor and will be utilized to generate fault signatures for which minimal or no evidence is available in historical plant process data, enabling generation of comprehensive fault signatures to achieve robust predictive models.

In this work package, the coupling of a three-state Markov chain risk model and a prognostic model by using a proportional hazards model is performed to demonstrate the economics of automation by transitioning from a time-consuming, labor-intensive, cost prohibitive PM program to a risk-informed PdM strategy. In addition, research is performed to develop a user-centric visualization that provides the right level of information, in the right format, to the right person. The approach focuses heavily on ensuring that the ML models are transparent and explainable to skeptical users by implementing human-centered artificial intelligence (HCAI) concepts.

Part of the research activity proposed in this work package addresses the challenges of crediting digital equipment self-diagnostics/OLM for performing technical and non-technical (e.g., BOP) evaluations. Specification surveillance requirements in NPPs licensed to 10 CFR Part 50. While approved methods exist for extending technical specification surveillance intervals for analog equipment, there remain gaps in technology and guidance for crediting internal self-diagnostics and OLM characteristics of newer digital equipment. Addressing these gaps is likely to result in advances that reduce maintenance costs for LWRs.

Specifically, self-diagnostic/OLM capabilities of newer digital equipment being installed in non-safety and safety applications are expected to detect failures, potentially provide early warning of potential failures, and notify plant operators to take appropriate action so that safety margins are maintained. There is a need to adapt and apply OLM and diagnostics for condition assessment of digital equipment and subsequent surveillance frequency extension. This requires the development of a methodology for the analysis of both the hardware and software equipment at a component and system level to ensure that all regulations are met and that safety function performance is not degraded. The scope of this project spans methodology development for extending technical specification surveillance frequency intervals for digital equipment to account for OLM capabilities, OLM and diagnostic technology development for selected components and systems, and the development of a partnership with one or more nuclear utilities for future pilot-scale deployment of the developed technology in an operating plant.

Schedule: FY-2019 to FY-2023

Remaining Project Milestones:

- (FY-2022): Produce an advanced AI/ML methodology and metrics to achieve a fully automated risk-informed PM strategy.
- (FY-2023): Demonstrate advanced AI/ML automation technology solutions, enabling a reduction in plant operating costs through a transition to a risk-informed PM strategy.

5.2.7 Advanced Online Monitoring Facility

Rapidly developing technologies can provide early indication of in-progress component degradation. This provides a capability to move beyond mere monitoring of the condition to intelligent detection of anomalous behavior, diagnosis of the degraded equipment or processes, and prognosis of the RUL of the components to give the utility a window of opportunity to take remedial actions. These technologies are being developed under the pilot projects described in Section 5.2.

This project integrates these new monitoring capabilities into a concept of fleet asset management based on a centralized OLM facility. The underlying information structure and data warehousing process would be part of the digital plant architecture described in Section 5.2.4. The architecture would support real-time acquisition of condition monitoring data from every source, including fixed sensors embedded in components such as smart pumps. It also would collect data streamed from mobile technologies used by field workers, as described in Section 5.1.1. This would include data from hand-held condition monitoring technologies that perform thermal imaging, vibration monitoring, and acoustic sensing.

This project will develop a prototype advanced OLM facility based on state-of-the-art information technologies and collaboration facilities that will:

- provide access to industry databases on failure signatures and associated component data to assist in diagnosing component degradations
- support the concept of IO and maintenance to remotely support a number of operating plants as effectively as if it were onsite
- host a library of proven diagnostics methods, classify and evaluate them, make them accessible to NPPs to benefit from them, and present these methods for use by NPPs
- act as a hub between NPPs, vendors, and research organizations—including universities—to streamline the data exchange process.
- Test new visualization capabilities customized for OLM to create a better understanding of degrading components.

The prototype advanced OLM facility will initially be developed in INL’s Monitoring, Diagnosis, and Automation Laboratory (MDAL) and the HSSL. Next, a production facility would be developed at a host utility for actual production testing. Based on this initial experience, a technical report would be written to provide recommendations for industry-wide implementation.

Schedule: FY-2022 to FY-2024

Remaining Project Milestones:

- (FY-2022): Develop and demonstrate concepts for an advanced OLM facility in the MDAL that can collect and organize data from all types of monitoring systems and activities and provide visualization of degradation where applicable.
- (FY-2023): Develop and demonstrate concepts for real-time information integration and collaboration on degrading-component issues with remote parties in the MDAL and HSSL (e.g., control room, OCC, systems- and component-engineering staff, internal and external consultants, suppliers).
- (FY-2024): Incorporate the digital architecture created in Section 5.2.4 to provide long-term asset management and real-time information directly to operators, troubleshooting, and root cause teams, suppliers, and technical consultants involved in component support, and engineering in support of the system-health program.

5.2.8 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 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, 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 issues arising from 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 operational decisions made by plant managers. There are many examples in the industry where a plant management team made decision errors, not due to a lack of competence among management staff, but simply because they did not have an accurate picture of what 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. Of particular interest is the emerging class of data analytics, which is able to process both structured and unstructured information resources on a very large scale to produce intelligence and insights that are not practical by human efforts. This can potentially improve operational decision-making by a significant degree.

The management decision support center would be a dedicated facility where all regular and special management oversight meetings would be held. (The exception to this would be emergency response facilities, which have to be maintained in a state of readiness. The technologies of the management decision support center would be separately implemented in emergency response facilities.) It would also enable remote participation in a realistic manner comparable to being in the room. 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
- use of data analytics to develop critical insights into plant performance and threat assessment
- 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 an 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 could be applied at the fleet level where decisions involving multiple NPPs or processes between plant- and fleet-level management occur. Collaboration tools would allow information views to be pushed to other participating centers so that a shared context for discussions and decisions would be available.

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 easily understandable and do not result in information-overload. Protocols for managing the information resources during a management decision-making meeting will also 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

Remaining Project Milestones:

- (FY-2023): Develop and demonstrate concepts for a management decision support center that incorporates advanced communication, collaboration, and display technologies in the HSSL to provide enhanced situational awareness and contingency analysis.
- (FY-2024): Develop and demonstrate concepts for advanced emergency response facilities that incorporate advanced communication, collaboration, and display technologies in the HSSL 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.
- (FY-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.

5.2.9 Virtual Plant Support Organization

Due to 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 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 I&C systems in NPPs that 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 I&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 OLM 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 include:

- An onsite, demineralized water production plant that could be owned and remotely operated by the original equipment manufacturer of the equipment, with minimum onsite support for hands-on maintenance.
- Condition monitoring that 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.

- I&C system monitoring and diagnostics that could be performed by the manufacturers of the system, with a small onsite support staff to replace circuit boards once faults were isolated to a specific component.
- Radiation monitoring that could be performed remotely using data-linked monitors and video cameras to observe workers in the radiation control zones.
- Chemistry analysis that could be performed remotely using inline instruments that take either batch or continuous samples.
- System test results that could be reviewed and validated by remote engineering organizations that receive data directly from system performance tests.
- Portions of the plant support systems that 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 IO for the LWR fleet. The workforce required to conduct plant work activities could be appreciably reduced in number, resulting in a secondary proportional reduction in organizational support functions (e.g., 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 that 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 individually 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 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 enabling development of a virtual support organization. The information structure to do this will be built into the digital architecture for a highly automated plant, as discussed in Section 5.1.1. 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: See Section 5.1.7 Advance Concept of Operations.

5.3 Advanced Applications and Process Automation

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 10,000 hours worked), the sheer number of work hours accumulated by 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 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 gradually been reduced until they are, at present, relatively rare. However, other types of errors continue to cause or complicate nuclear safety challenges. In the FY-2008 to FY-2010 timeframe, a series of incidents took place at various NPPs, many of which were considered to be among the industry's best performers. These incidents were documented in INPO SOER 10-2, "Engaged, Thinking Organizations" [4], which assigned a significant portion of the causes to human error and lack of fundamental knowledge.

The focus on correcting worker behaviors typically involves an 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 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 making work tasks slow and cumbersome. To the operators, the focus seems to be more about human-error prevention tools (i.e., job aids) than the actual task or activity being conducted. Job satisfaction has eroded, and the added complexity has become an enticement to take shortcuts 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 at which the added complexity contributes to the rate of human error (due to divided attention) and that the industry has 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 on which to work. In short, technology can perform tasks at much higher reliability rates while maintaining desired worker roles of task direction, decision-making, and work quality oversight.

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) so that 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 for placing equipment in and out of service are manual. This overreliance on manual controls 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 in which 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 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.

5.3.1 Mobile Technologies for NPP 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 plant workers and to serve as the medium to direct execution and recording of the specific work activities. However, paper (as a medium) has an obvious limitations when compared to new digital options. Limitations associated with paper based work processes include 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 fieldworker requirements.

The primary difficulty in providing plant workers with technology to improve their performance has been that sometimes workers must move about the plant in environments that are relatively inhospitable for digital technology (e.g., temperature extremes, radiation, radiofrequency interference, 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 smart phones applications to 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 updates to the corporate process systems—all from where the field worker is performing the work.

These devices rely on wireless networks, digital processing devices, object-identification capabilities (e.g., bar codes, radiofrequency 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 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 OCC. The idea is to embed the field worker in 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 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 fieldworker in performing typical plant work activities, as observed in Figure 20. 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-factor evaluations to ensure the technology does not introduce negative factors that are detrimental to the job outcomes or well-being of workers.

Figure 19. Operator at Catawba Nuclear Station using hand-held technology for component identification.

The initial application of this technology will address safety tagging of components and conducting valve-lineup checklists. These two initial applications typify many other plant activities; the technology can easily be expanded into these other uses. The project will also develop a prototype of a simplified CBPs to test the suitability of the technology 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

Remaining Project Milestones: None.

5.3.2 Computer Based Procedures for NPP 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, 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. However, unlike many other safety-critical industries, the commercial nuclear industry's procedures are almost always paper-based. These procedures remain prone to certain human errors and process deviations that continue to challenge the plants. Typical problems include:

- applying the wrong procedure for the plant situation
- making unauthorized or unintentional deviations from procedure steps
- receiving unexpected results from procedure actions due to co-incident plant conditions or configuration
- introducing copy errors when transcribing plant data into the procedures
- making computational errors in processing the acquired data.

These types of problems can be largely prevented using CBPs, which inherently enforce adherence expectations and perform data manipulations in a correct manner. Furthermore, in an integrated CBP 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, as observed in Figure 21, 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)
- placekeeping
- 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.

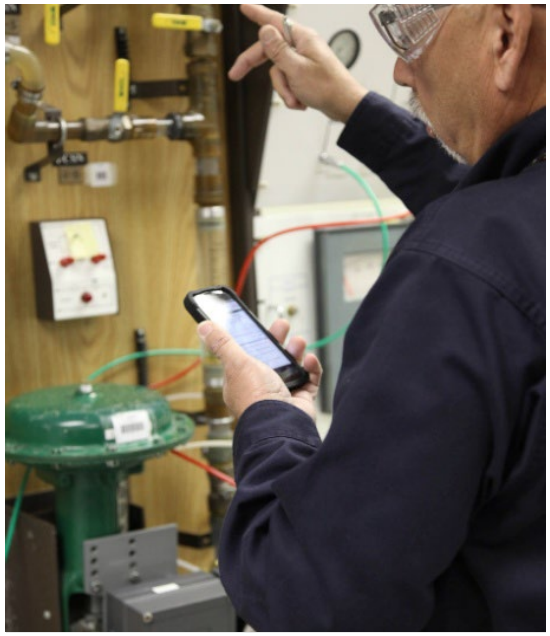

Figure 20. A field worker at Palo Verde Nuclear Generating Station uses CBPs to execute a task.

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

This pilot project will develop design guidance for CBPs for field workers in all organizations at the NPP that work outside the main control room, as observed in Figure 22. It will provide successive demonstrations of CBP capabilities as they are developed. To better illustrate the value of CBPs to NPP workers and senior management, the researchers conducted a series of field evaluation studies showing nuclear utilities using the CBP system to conduct selected tasks in the plant during a two-month period.

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 consider moving forward with this type of advanced technology.

The research objectives are to develop and publish final design guidance for CBPs 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 CBPs.

Figure 21. A control room operator and a field operator at Diablo Canyon Power Plant discuss a procedure using the CBPs system on the hand-held device.

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

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

Schedule: FY-2012 to FY-2016

Remaining Project Milestones: None.

5.3.3 Automation of the Work Process

As NPPs roll in different types of mobile work-management solutions, several high-cost tasks remain part of the work process and cannot be tackled by any mobile work-management solution. These processes need to be automated with process-complimentary technologies. A recently completed study [25] has identified multiple technologies, such as data-mining, smart-scheduling, and drones, which can save costs if augmented to the work process beyond EWPs. This project will research, develop, and demonstrate technologies that address unique nuclear industry work process challenges.

This project will research and develop technologies that would replace human actions and have the highest cost-savings of the work process by introducing new methods for sensors and data acquisition, activities execution, and process centralization, coupled with human factors research. The project will also research into means to enable a successful adoption of these technologies, such as the regularity perspective of deployment of advanced technologies. See Figure 23.

Figure 22. Drones aligning on QR Code to ensure proper orientation for gauge reading activities.

As seen in Figure 23, drones can automate several activities in a plant including operator and security rounds, and inspections of hazardous locations. The LWRS program created a technology to enable any drone to autonomously recognize and navigate their environment in a nuclear power plant.

Figure 24 depicts how automating manual logging of analog gauges (i.e., a method to recognize gauges in oblique angles and read their values) can improve the efficiency of several activities in the plant including surveillance-related activities.

Schedule: FY-2014 to FY-2021

Remaining Project Milestones: None

Figure 23. The use of digital cameras for data gathering.

5.3.4 Advanced Outage Coordination

NPP refueling outages are some of the most challenging periods in ongoing facilities operations. Usually, more than 10,000 activities need to be accomplished in a typical duration of 20 to 30 days. Enormous expenses are incurred for outage work, including employing a supplemental workforce, which sometimes totals over 1,000 contractors. Schedule delays drive these costs up proportionately. In addition, 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 plant configurations where redundant safety systems are out of service to accommodate work on 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 refueling and forced outages. They also built OCCs 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 isolation, 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 is also greatly improved. However, some significant opportunities and challenges remain for the industry, including:

- 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 the loss of residual heat removal and unintended additions of positive reactivity.
- Regulatory violations continue to occur due to subtle configuration control issues resulting 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 very basic technology: radios, telephones, and standalone computer applications. There is some growing usage of remote video for point applications and activity monitoring, but 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 for improving safety and regulatory performance.

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 the 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.

The amount of information that must be processed by the 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 fieldwork, 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.

Outage managers also deal with a continual stream of emergent issues caused by deviations in the expected progress of planned activities or new problems that arise (e.g., equipment failures, unexpected interactions between work activities, other unanticipated outage conditions). Outage managers have to quickly assess the impact of new issues on the overall outage plan and schedule, consult with knowledgeable individuals on the nature of the problems and possible solutions, 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, whiteboard 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, email, and direct telephone contact. This process is repeated tens of times per shift for the duration of an outage.

This pilot project will assess the needs of outage management and identify technologies that will greatly improve communications, coordination, and collaboration activities 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, 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, as observed in Figure 25. Human factors assessments of the use of technology will be conducted to validate that the benefits are actually obtained, and new problems are not introduced by technology usage. Results of the project will be a demonstration of the integrated technologies and a technical report for industry-wide implementation.

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

Schedule: FY-2010 to FY-2012

Remaining Project Milestones: None.

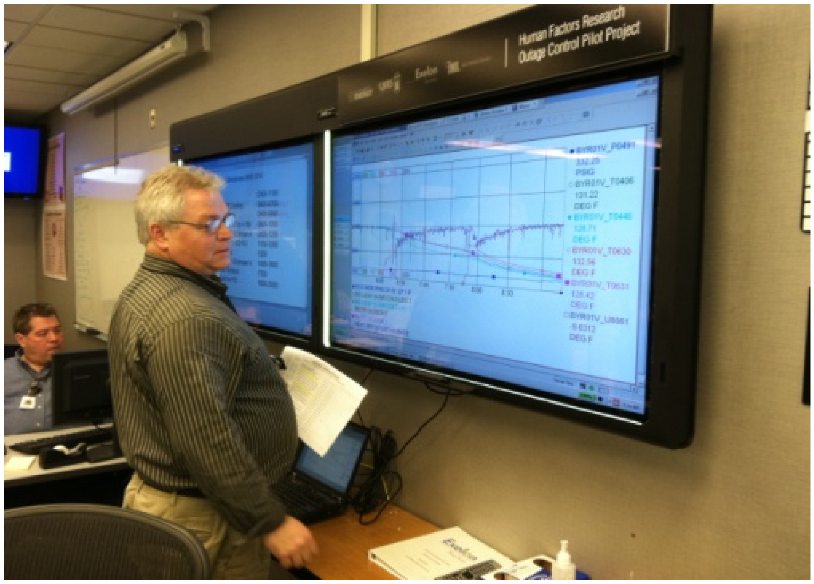

Figure 24. Remote collaboration technology in use at the spring 2011 Byron Nuclear Station refueling.

5.3.5 Advanced Outage Control Center (AOCC)

The AOCC is the central command and control point for executing NPP outages. It is staffed 24 hours a day/seven days a week 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, the radiation control organization operates a center to develop and assign radioactive work permits and authorize and brief workers who enter radiation control zones. Operations maintains centers to prepare safety tagouts, conduct risk assessments, and track plant configuration changes. Similar functional support centers are set up in 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. These technologies will:

- allow the entire OCC to share information as it develops in response to an emergent issue
- allow the OCC coordinators to meet electronically with their respective functional support centers without having to leave the OCC
- update all affected work management systems as decisions are made on how to resolve a problem
- 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 AOCC specifically designed to accommodate and maximize the value of the technologies, while preserving the features of the existing OCCs that facilitate human interaction, as observed in Figure 26. Where appropriate, these features will be extended to the functional support centers to accommodate their interface with the OCC.

Figure 25. Advanced Outage Control Center concept design.

There is significant potential to take advantage of real-time status information that will be available to field workers using 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 AOCC 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 AOCC, 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 AOCC.

This pilot project began in FY-2013, with Arizona Public Service (Palo Verde Nuclear Generating Station) serving as the host utility in Figure 27. 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 plants are in the process of implementing new OCCs incorporating advanced design features. This pilot project is now complete.

Schedule: FY-2013 to FY-2016

Remaining Project Milestones: None.

Figure 26. Advanced Outage Control Center at Palo Verde.

5.3.6 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 out-of-service equipment 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 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 of these efforts, nuclear safety challenges still occur too frequently in outages. While some of these are due to the 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 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. The project created a software application, the Outage System Status and Requirements Monitor (OSSREM) to help integrate and visualize plant status and requirements, as shown in Figure 28. This project is now complete.

Schedule: FY-2017 to FY-2019

Remaining Project Milestones: None.

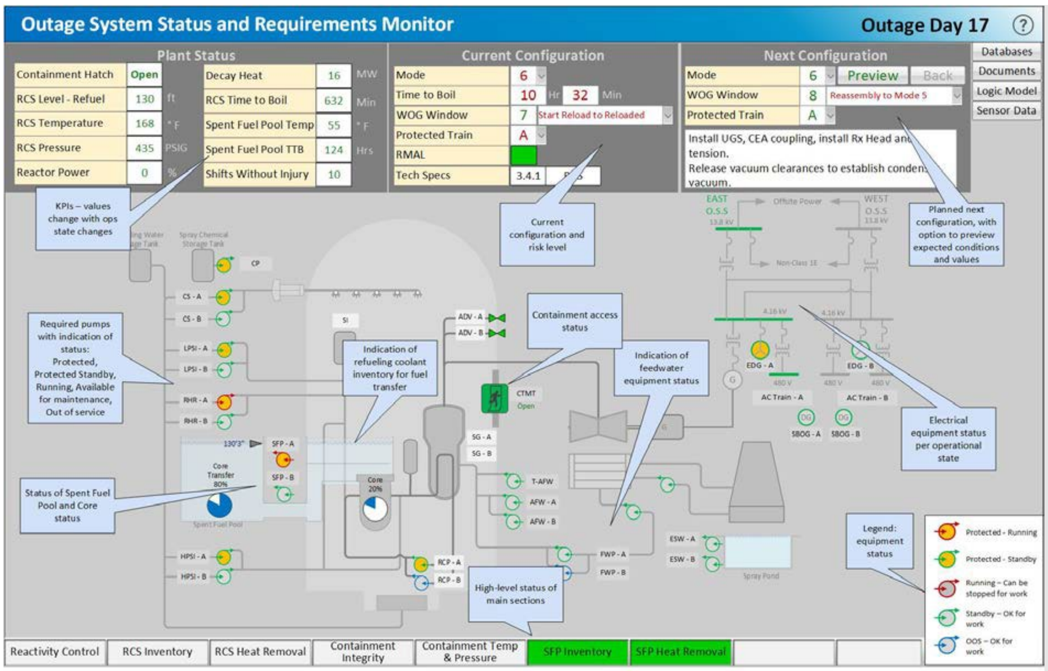

Figure 27. Outage System Status and Requirements Monitor user interface.

5.3.7 Augmented-Reality for NPP 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
- the condition (open or closed) of a valve
- proximity to reactor trip-sensitive equipment
- proximity to temporary hazard boundaries (e.g., radiography or overhead load paths)
- plant data (e.g., pressure, flow, set points) concerning nearby components
- strength of radiation fields and location of hotspots
- oxygen-deficient environments.

Therefore, plant workers must have this information provided in their work packages already or they have to rely on others to supply this information during the activity through available communication channels. This is time-consuming and often results in 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 a 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 the 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 desired information. 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 AWP 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 also 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 augmented reality technology with compatible AWPs.

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 Plant Modernization Pathway will work closely with Halden to take full advantage of augmented reality technologies as they are developed.

Schedule: FY-2022 to FY-2024

Remaining Project Milestones:

- (FY-2023): Develop and demonstrate augmented reality technologies for visualization of radiation fields for mobile plant workers.
- (FY-2024): Develop and demonstrate augmented reality technologies for visualization of real-time plant parameters (e.g., pressures, flows, valve positions, restricted boundaries) for mobile plant workers.
- (FY-2025): 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.

5.3.8 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 number of staff as a similar-sized fossil-fuel generation station. Labor is the largest component of the O&M cost for an NPP, which typically accounts for 70% of the annual operating budget.

These high staffing requirements are due to the fact that NPPs have 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 I&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, 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 include:

- Replacement of standalone analog control loops with digital technology. A typical example would be a throttle-valve control circuit, which would rely on an analog sensor and 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, eliminating time-consuming and error-prone field walk-downs of valves, breakers, and dampers to verify they are in the correct position.
- Inline 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 IO, which will support outsourcing of appropriate plant support functions.

Schedule: FY-2022 to FY-2025

Remaining Project Milestones:

- (FY-2022): For NPP operations activities, analyze the staffing, tasks, and cost models to identify the opportunities for the 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.
- (FY-2022): For NPP chemistry activities, analyze the staffing, tasks, and cost models to identify the opportunities for the 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.
- (FY-2023): For NPP maintenance activities, analyze the staffing, tasks, and cost models to identify the opportunities for the 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.
- (FY-2024): For NPP radiation protection activities, analyze the staffing, tasks, and cost models to identify the opportunities for the 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.
- (FY-2025): 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.

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Appendix A

Historical Reports

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Historical Reports

Project	Report Name	Report Number
Advanced Concept of Operations	*Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts*	INL/EXT-21-64134
Advanced Concept of Operations	*Nuclear Work Function Innovation Tool Set Development for Performance Improvement and Human Systems Integration*	INL/EXT-21-64428
Advanced Concept of Operations	Analysis and Planning Framework for Nuclear Plant Transformation	INL/EXT-20-59537
Advanced Concept of Operations	*Developing a Roadmap for Total Nuclear Plant Transformation*	INL/EXT-19-54766
Advanced Outage Control Center	*Benchmark Report on Key Outage Attributes: An Analysis of Outage Improvement Opportunities and Priorities*	INL/EXT-14-32848
Advanced Outage Control Center	*Development of an Overview Display to Allow Advanced Outage Control Center Management to Quickly Evaluate Outage Status*	INL/EXT-16-39622
Advanced Outage Control Center	*Development of Improved Graphical Displays for an Advanced Outage Control Center, Employing Human Factors Principles for Outage Schedule Management*	INL/EXT-15-36489
Advanced Outage Control Center	*Development of Methodologies for Technology Deployment for Advanced Outage Control Centers that Improve Outage Coordination, Problem Resolution and Outage Risk Management*	INL/EXT-13-29934
Advanced Outage Control Center	*Guidelines for Implementation of an Advanced Outage Control Center to Improve Outage Coordination, Problem Resolution, and Outage Risk Management*	INL/EXT-14-33182
Advanced Outage Control Center	*Status Report on the Development of Micro Scheduling-Software for the Advanced Outage Control Center Project*	INL/EXT-14-33036
Advanced Outage Coordination	*Advanced Outage and Control Center: Strategies for Nuclear Plant Outage Work Status Capabilities*	INL/EXT-12-26197
Advanced Outage Coordination	*Resolving Emergent Issues during Nuclear Plant Outages*	INL/EXT-12-26807
Advanced Remote Monitoring for Operations Readiness	*Process Anomaly Detection for Sparsely Labeled Events in Nuclear Power Plants*	INL/EXT-21-64303
Advanced Remote Monitoring for Operations Readiness	*An Applied Strategy for Using Empirical and Hybrid Models in Online Monitoring*	INL/EXT-20-59688
Advanced Remote Monitoring for Operations Readiness	*Automating Surveillance Activities in a Nuclear Power Plant*	INL/EXT-19-55620
Advanced Remote Monitoring for Operations Readiness	*Subtle Process Anomalies Detection Using Machine-Learning Methods*	INL/EXT-19-55629
Advanced Remote Monitoring for Operations Readiness	*Automation of Data Collection Methods for Online Monitoring of Nuclear Power Plants*	INL/EXT-18-51456
Advanced Remote Monitoring for	*Development of a Technology Roadmap for Online Monitoring of Nuclear Power Plants*	INL/EXT-18-52206

Project	Report Name	Report Number
Operations Readiness		
Analysis and Planning Framework for Nuclear Plant Transformation	*Analysis and Planning Framework for Nuclear Plant Transformation*	INL/EXT-20-59537
Automation of the Work Process	*Regulatory Considerations regarding the Use of Computer Vision Machine Learning in Safety-Related or Risk-Significant Applications in Nuclear Power Plants*	INL/EXT-21-64595
Automation of the Work Process	*System Integration and Pilot of Route-Operable Unmanned Navigation of Drones (ROUNDS) in a Virtual Environment*	NL/LTD-20-59682
Automation of the Work Process	*High Accuracy Self-Navigation of Drones in Indoor Environments*	INL/LTD-19-55564
Automation of the Work Process	*Automating Fire Watch in Industrial Environments through Machine-Learning-Enabled Visual Monitoring*	INL/EXT-19-55703
Automation of the Work Process	*Applications of Image Processing Technologies to Reduce Operation and Maintenance Activities in Nuclear Power Plants*	INL/LTD-18-52141
Automated Work Packages	*Automation Technologies Impact on the Work Process of Nuclear Power Plants*	INL/EXT-18-51457
Automated Work Packages	*Risk-Informed Condition-Based Maintenance Strategy: Research and Development Plan*	INL/LTD-18-51448
Automated Work Packages	*Automated Work Package: Radio Frequency Identification, Bluetooth Beacons, and Video Applications in the Nuclear Power Industry*	INL/EXT-17-43264
Automated Work Packages	*Automated Work Package: Conceptual Design and Data Architecture*	INL/EXT-16-38809
Automated Work Packages	*Automated Work Package Prototype: Initial Design, Development, and Evaluation*	INL/EXT-15-35825
Automated Work Packages	*Automated Work Packages: An Initial Set of Human Factors and Instrumentation and Control Requirements*	INL/EXT-14-33172
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Computer-Based-Procedures for Field Activities: Results from Three Evaluations at Nuclear Power Plants*	INL/EXT-14-33212
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Computer-Based-Procedures for Field Workers in Nuclear Power Plants: Development of a Model of Procedure Usage and Identification of Requirements*	INL/EXT-12-25671
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Computer-Based-Procedures for Field Workers: Results from Three Evaluation Studies*	INL/EXT-13-30183
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Computer-Based-Procedures for Field Workers—Result and Insights from Three Usability and Interface Design Evaluations*	INL/EXT-15-36615
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Computer-Based Procedures for Field Worker—Identified Benefits*	INL/EXT-14-33011
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Computer-Based Procedures for Field Workers—FY16 Research Activities*	INL/EXT-16-39984

Project	Report Name	Report Number
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Design Guidance for Computer-Based Procedures for Field Workers*	INL/EXT-16-39808
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Evaluation of Computer-Based-Procedure System Prototype*	INL/EXT-12-27155
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Evaluation of Revised Computer-Based Procedure System Prototype)*	INL/EXT-13-28226
Computer-Based Procedures for Nuclear Power Plant Field Workers	*Seamless Digital Environment – Plan for Data Analytics Use Case Study*	INL/EXT-16-39985
Control Room Modernization	*A Distributed Control System Prototyping Environment to Support Control Room Modernization*	INL/EXT-14-33957
Control Room Modernization	*A Reference Plan for Control room Modernization: Planning and Analysis Phase*	INL/EXT-13-30109
Control Room Modernization	*Alarm Design Workshop for Control Room Upgrades: Summary and Presentations*	INL/MIS-11-22907
Control Room Modernization	*Applying Human Factors Evaluation and Design Guidance to a Nuclear Power Plant Digital Control System*	INL/EXT-12-26787
Control Room Modernization	*Baseline Human Factors and Ergonomics in Support of Control Room Modernization at Nuclear Power Plants*	INL/EXT-14-33223
Control Room Modernization	*Control Room Modernization End State Design Philosophy*	INL/EXT-18-44739
Control Room Modernization	*Deployment of a Full-Scope Commercial Nuclear Power Plant Control Room Simulator at the Idaho National Laboratory*	INL/EXT-11-23421
Control Room Modernization	*Development and Evaluation of the Conceptual Design for a Liquid Radiological Waste System in an Advanced Hybrid Control Room*	INL/EXT-18-51107
Control Room Modernization	*Development of an Advanced Integrated Operations Concept for Hybrid Control Rooms*	INL/EXT-20-57862
Control Room Modernization	*Digital Full-Scope Mockup of a Conventional Nuclear Power Plant Control Room, Phase 1: Installation of a Utility Simulator at the Idaho National Laboratory*	INL/EXT-12-26367
Control Room Modernization	*Digital Full-Scope Simulation of a Conventional Nuclear Power Plant Control Room, Phase 2: Installation of a Reconfigurable Simulator to Support Nuclear Plant Sustainability*	INL/EXT-13-28432
Control Room Modernization	*Document the Implementation of the End State Concept for Turbine Control and Feedwater Systems*	INL/LTD-18-51582
Control Room Modernization	*End State Requirements for Advanced Task-Based Overviews and Advanced Alarms*	INL/LTD-19-54456
Control Room Modernization	*Evaluation of Advanced Task-Based Overview Displays and Alarms*	INL/LTD-19-55766
Control Room Modernization	*HSI Prototypes for Human Systems Simulation Laboratory*	INL/EXT-15-36839
Control Room Modernization	*Human Factors Engineering Design Phase Report for Control Room Modernization*	INL/EXT-14-33221
Control Room Modernization	*Human Factors Engineering Insights and Guidance for Implementing Innovative Technologies from the Nuclear Innovation Workshop: A Summary Report*	INL/EXT-19-55529

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Control Room Modernization	*Installation of Halden Reactor Project Digital Interface Prototypes in the Human Systems Simulation Laboratory*	INL/EXT-13-29039
Control Room Modernization	*Integration of Advanced Operator Interfaces for the Computerized Operator Support System: Example Design Study for the Palo Verde Boric Acid Concentrator*	INL/LTD-19-55430
Control Room Modernization	*LWRS Demonstration and Evaluation of an Advanced Integrated Operations Concept for Hybrid Control rooms*	INL/EXT-20-58538
Control Room Modernization	*Migration of Older to New Digital Control Systems in Nuclear Power Plant Main Control rooms*	INL/EXT-16-38576
Control Room Modernization	*Operator Performance Metrics for Control room Modernization: A Practical Guide for Early Design Evaluation*	INL/EXT-14-31511 Rev 1
Control Room Modernization	*Strategy for Migration of Traditional to Hybrid Control Boards in a Nuclear Power Plant*	INL/EXT-14-32534
Control Room Modernization	*Submit a Journal Article Documenting the Research Activities that Serve as a Technical Basis for Control Room Design*	INL/EXT-18-45755
Control Room Modernization	*The Influence of Individual Human System Interface Display Features on Visual Information Processing during Naturalistic Process Control Tasks*	INL/JOU-18-45483
Control Room Modernization	*Verification and Validation of Digitally Upgraded Control Rooms*	INL/EXT-15-36704
Cybersecurity	*Cybersecurity Considerations in Support of the Light Water Reactor Sustainability Program, Revision 2*	INL/LTD-12-27315
Cybersecurity	*Cybersecurity Evaluation of II&C Technologies*	INL/EXT-14-33609
Digital Architecture for an Automated Plant	*Industry Scaling of Condition Report Data Mining Methods for Automated Compliance*	INL/LTD-21-64306
Digital Architecture for an Automated Plant	*Technical Feasibility of a Nuclear Power Plant Data Hub at Idaho National Laboratory*	INL/LTD-21-64294
Digital Architecture for an Automated Plant	*Use Cases of DIAMOND for Data-Enabled Automation in Nuclear Power Plants*	INL/LTD-20-59683
Digital Architecture for an Automated Plant	*Method and Application of Data Integration at a Nuclear Power Plant*	INL/EXT-19-54294
Digital Architecture for an Automated Plant	*Data Integration Aggregated Model and Ontology for Nuclear Deployment (DIAMOND): Preliminary Model and Ontology*	INL/EXT-19-55610
Digital Architecture for an Automated Plant	*Seamless Digital Environment—Data Analytics Case Study*	INL/EXT-17-42918
Digital Architecture for an Automated Plant	*Digital Architecture Planning Model*	INL/EXT-16-38220
Digital Architecture for an Automated Plant	*Digital Architecture—Results from a Gap Analysis*	INL/EXT-15-36662
Digital Architecture for an Automated Plant	*Digital Architecture Requirements*	INL/EXT-15-34696
Digital Architecture for an Automated Plant	*Digital Architecture Project Plan*	INL/EXT-14-33177

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Digital Instrumentation and Control Qualification	*Strategy for Implementation of Safety-Related Digital I&C Systems*	INL/EXT-18-45683
Digital Instrumentation and Control Qualification	*Definition of the Methods, Tools, and Computing Resources for Instrumentation and Control Device Testability*	INL/EXT-18-51521
Digital Instrumentation and Control Qualification	*Specification of a Bounded Exhaustive Testing Study for a Software-based Embedded Digital Device*	INL/EXT-18-52032
Digital Technology Business Case Methodology	*A Business Case for Advanced Outage Management*	INL/EXT-16-38265
Digital Technology Business Case Methodology	*A Business Case for Nuclear Plant Control Room Modernization*	INL/EXT-16-39098
Digital Technology Business Case Methodology	*Digital Technology Business Case Methodology*	INL/EXT-14-33129
Digital Technology Business Case Methodology	*Pilot Project Technology Business Case: Mobile Work Packages*	INL/EXT-15-35327
Efficient Plant Operations Concept using Human-system-integration	*Development of an Assessment Methodology That Enables the Nuclear Industry to Evaluate Adoption of Advanced Automation*	INL/EXT-21-64320
Fleet-Based Control room Modernization	*A Human Factors Operator-in-the-Loop Evaluation of the Digital Control System Upgrades for the Braidwood and Byron Nuclear Generating Stations*	INL/LTD-18-44617
Fleet-Based Control room Modernization	*Connecting LWRS Human Factors Engineering R&D to NUREG-0711 Elements and Modification Activities in Nuclear Generating Plants*	INL/EXT-18-45149
Fleet-Based Control room Modernization	*Developing a Strategy for Full Nuclear Plant Modernization*	INL/EXT-18-51366
Fleet-Based Control room Modernization	*Human Factors Engineering Evaluations of Planned Digital Instrumentation and Control System Upgrades at the Braidwood Nuclear Generating Station*	INL/LTD-18-44295
Fleet-Based Control room Modernization	*Lessons Learned from Performing a Human Factors Engineering Validation of an Upgraded Digital Control System in a Nuclear Power Plant Control Room*	INL/LTD-18-51380
Fleet-Based Control room Modernization	*Planning and Analyses Performed to Install Halden's Advanced Control Room Concept in the Human Systems Simulation Laboratory*	INL/EXT-18-45966
Fleet-Based Control room Modernization	*The Strategic Value of Human Factors Engineering in Control Room Modernization*	INL/EXT-18-51365
Full Nuclear Plant Modernization	*Light Water Reactor Sustainability Program Guidance on Transforming Existing Light Water Reactors into Fully Modernized Nuclear Power Plants: The Role of Plant Modernization R&D*	INL/EXT-21-64369
Full Nuclear Plant Modernization	*Usability Evaluation of the Innovation Portal and Integrated Capability Analysis Platform*	INL/EXT-21-63101
Full Nuclear Plant Modernization	*Guidance on Including Social, Organizational, and Technical Influences in Nuclear Utility and Plant Modernization Plans*	INL/EXT-20-60264

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Full Nuclear Plant Modernization	*Develop and Document a State-Based Alarm System for a Nuclear Power Plant Control Room Using Machine Learning*	INL/EXT-20-60549
Full Nuclear Plant Modernization	*Developing a Human Factors Engineering Program Plan and End State Vision to Support Full Nuclear Power Plant Modernization*	INL/EXT-18-51212
Full Nuclear Plant Modernization	*Developing a Roadmap for Total Nuclear Plant Transformation*	INL/EXT-19-54766
Full Nuclear Plant Modernization	*Development of an Initial Business Case Framework for Fleet-Based Control Room Modernization*	INL/EXT-17-42604
Full Nuclear Plant Modernization	*Human Factors Engineering Aspects of Modifications in Control Room Modernization*	INL/EXT-17-42190
Full Nuclear Plant Modernization	*Human Factors Engineering Operating Experience Review of the Dominion Energy Surry and North Anna Control Room Upgrades: Results Summary Report*	INL/LTD-19-53981
Full Nuclear Plant Modernization	*Planning and Analyses Performed to Install Halden's Advanced Control Room Concept in the Human Systems Simulation Laboratory*	INL/EXT-18-45966
Full Nuclear Plant Modernization	*Preliminary Human Factors Evaluation of Control System Upgrades for the Byron and Braidwood Nuclear Power Stations*	INL/EXT-16-40705
Full Nuclear Plant Modernization	*Results from a Preliminary Dynamic Operator Workshop on Control Room Modernization Activities for Braidwood Unit 1*	INL/LTD-17-43205
Full Nuclear Plant Modernization Design	*Addressing Human and Organizational Factors in Nuclear Industry Modernization: An Operationally Focused Approach to Process and Methodology*	INL/EXT-20-57908
Full Nuclear Plant Modernization Design	*Usability Evaluation of the Innovation Portal and Integrated Capability Analysis Platform*	INL/EXT-21-63101
Halden Reactor Project	*Develop and Document a State-Based Alarm System for a Nuclear Power Plant Control Room Using Machine-Learning*	INL/EXT-19-55368
Halden Reactor Project	*Develop and Document an Advanced Human System Interface for the Generic Pressurized Water Reactor Simulator*	INL/EXT-19-55788
Halden Reactor Project	*Development of Task-Based Displays for the Fleet-Based Control Room Modernization Design Project*	INL/LTD-18-44296
Halden Reactor Project	*Software-Based Tools to Support Human System Evaluation Studies*	INL/EXT-19-55789
Halden Reactor Project	*Summarize Operator-In-The-Loop Studies Conducted in Support of the Fleet-Based Control Room Modernization Project*	INL/EXT-18-51360
Halden Reactor Project	*Support for the Human Factors Studies Conducted for the LWRS Control Room Modernization Project for PVNGS*	INL/EXT-18-51358
Halden Reactor Project	*Towards a Deeper Understanding of Automation Transparency in the Operation of Nuclear Plants*	INL/EXT-20-59469
Halden Reactor Project	*Develop and Document a State-Based Alarm System for a Nuclear Power Plant Control Room Using Machine-Learning*	INL/EXT 20-60549
Industrial and Regulatory Engagement	*Industrial and Regulatory Engagement Activities*	INL/EXT-18-51462
Instrumentation and Control Infrastructure Modernization	*Digital Infrastructure Migration Framework*	INL/EXT-21-64580
Instrumentation and Control Infrastructure Modernization	*Development of an Obsolescence Cost Model for Nuclear Power Plants*	ORNL/TM-2019/1238

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Instrumentation and Control Infrastructure Modernization	*Business Case Analysis for Digital, Safety-Related Instrumentation & Control System Modernizations*	INL/EXT-20-59707 INL/EXT-20-59371
Instrumentation and Control Infrastructure Modernization	*Vendor-Independent Design Requirements for a Boiling Water Reactor Safety System Upgrade*	INL/LTD-20-58490
Instrumentation and Control Infrastructure Modernization	*Safety-Related Instrumentation & Control Pilot Upgrade Initiation Phase Implementation Report*	INL/EXT-20-59809
Instrumentation and Control Infrastructure Modernization	*Addressing Nuclear I&C Modernization Through Application of Techniques Employed in Other Industries*	INL/EXT-19-55799
Mobile Technologies for Nuclear Power Plant Field Workers	*Advanced Instrumentation, Information and Control (II&C) Research and Development Facility Buildout and Project Execution of LWRS II&C Pilot Project 3*	INL/MIS-12-25139
Mobile Technologies for Nuclear Power Plant Field Workers	*Guidance for Deployment of Mobile Technologies for Nuclear Power Plant Field Workers*	INL/EXT-12-27094
Online Monitoring of Active Components	*Demonstration of Online Monitoring for Generator Step-Up Transformers and Emergency Diesel Generators*	INL/EXT-13-30155
Online Monitoring of Active Components	*Diagnostic and Prognostic Models for Generator Step-Up Transformers*	INL/EXT-14-33124
Online Monitoring of Active Components	*Online Monitoring of Induction Motors*	INL/EXT-15-36681
Online Monitoring of Active Components	*Online Monitoring Technical Basis and Analysis Framework for Emergency Diesel Generators—Interim Report for FY-2013*	INL/EXT-12-27754
Online Monitoring of Active Components	*Online Monitoring Technical Basis and Analysis Framework for Large Power Transformers—Interim Report for FY-2012*	INL/EXT-12-27181
Online Monitoring of Concrete Structures in Nuclear Power Plants	*A Simple Demonstration of Concrete Structural Health Monitoring Framework*	INL/EXT-15-34729
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Document the Progress of Casting of Reinforced Concrete Beam*	INL/EXT-18-51461
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Enhancement of the Structural Health Monitoring Framework by Optimizing Vibro Acoustic Modulation Technique to Localize Alkali-Silica Reaction Degradation in Medium Sized Concrete Samples*	INL/EXT-18-45212

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Online Monitoring of Concrete Structures in Nuclear Power Plants	*Interim Report on Concrete Degradation Mechanisms and Online Monitoring Techniques*	INL/EXT-14-33134
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Joint Research Plan on Structural Health Monitoring with the Electric Power Research Institute*	INL/INT-16-38821
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Monitoring, Modeling, and Diagnosis of Alkali-Silica-Reaction in Small Concrete Samples*	INL/EXT-15-36683
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Rev 1, Interrogation of Alkali-Silica Reaction Degraded Concrete Samples using Acoustic and Thermal Techniques to Support Development of a Structural Health Monitoring Framework*	INL/EXT-17-41852
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Uncertainty Quantification Methodologies Developed to Support the Concrete Structural Health Monitoring Framework*	INL/EXT-18-51460
Online Monitoring of Concrete Structures in Nuclear Power Plants	*Vibration-Based Techniques for Concrete Structural Health Monitoring*	INL/EXT-19-53248
Online Monitoring of Second Phase Structures in Nuclear Power Plants	*Describe Performance of Advanced Signal Processing and Pattern Recognition Algorithms Using Raw Data from ultrasonic Guided Waves Transducers and Provide Recommendations on Capabilities of Advanced Data Analytics*	INL/EXT-18-51429
Online Monitoring of Second Phase Structures in Nuclear Power Plants	*Flow Assisted-Corrosion in Nuclear Power Plants*	INL/EXT-15-36611
Online Monitoring of Second Phase Structures in Nuclear Power Plants	*Potential to Extend the Range of Established Online Monitoring Technologies, Such as Guided Waves in Nuclear Power Plant Systems*	INL/EXT-17-43242
Online Monitoring of Second Phase Structures in Nuclear Power Plants	*Revision 0, Framework for Structural Online Health Monitoring of Aging and Degradation of Secondary Systems due to some Aspects of Erosion*	INL/EXT-16-39903
Outage Risk Management Improvement	*Methods to Automate Assessing Outage Risk and Technical Specification Compliance for Planned Work and Current Plant Conditions*	INL/EXT-19-55308

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Outage Risk Management Improvement	*Prototype System for Detecting Interactions Between Status (Configuration) States and Concurrent Component Manipulations Directed by In-Use Procedures Including Data Integration and Industry Feedback*	INL/EXT-18-51474
Outage Risk Management Improvement	*Technologies for Detecting Interactions Between Current Plant Configuration States and Component Manipulations Directed by In Use Procedures*	INL/EXT-17-43234
Project Management	*Plant Modernization Pathway: FY-2019 External Review Summary Report*	INL/EXT-18-52030
Project Management	*Plant Modernization Technical Program Plan for FY-2021*	INL/EXT-13-28055 Rev. 10
Quality Insurance	*Light Water Reactor Sustainability Program Quality Assurance Program Document*	INL/EXT-10-19844
Risk-Informed Methodologies	*Describe the Design Basis for a Resilient Plant Based on Margin Recovery and the Application of New Technologies to Reduce the Safety Significance of Design Basis Events*	INL/EXT-18-51531
Technology-Enabled Risk-Informed Maintenance Strategy	*Scalable Technologies Achieving Risk-Informed Condition-Based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants*	INL/EXT-21-64168
Technology-Enabled Risk-Informed Maintenance Strategy	*Hybrid Modeling of a Circulating Water Pump Motor*	INL/EXT-20-59600
Technology-Enabled Risk-Informed Maintenance Strategy	*Markov Process to Evaluate the Value Proposition of a Risk-Informed Predictive Maintenance Strategy*	INL/EXT-20-59146
Technology-Enabled Risk-Informed Maintenance Strategy	*Scalability of a Risk-Informed Predictive Maintenance Strategy*	INL/LTD-20-58848
Technology-Enabled Risk-Informed Maintenance Strategy	*Technical Specification Surveillance Interval Extension of Digital Equipment in Nuclear Power Plants: Review, Research, and Recommendations*	INL/EXT-19-54251
Technology-Enabled Risk-Informed Maintenance Strategy	*Analytical Approach to Evaluate Data Completeness for Service Water Pumps to Support Sensor Installation*	INL/LTD-19-53592
Wireless Technologies	*Review of Wireless Communication Technologies and Techno-Economic Analysis*	INL/EXT-19-53966