LWRS LIGHT WATER REACTOR SUSTAINABILITY

Overview and Accomplishments – 2021

Sustaining National Nuclear Assets

U.S. DEPARTMENT OF ENERGY

Overview and Accomplishments – 2021

Sustaining National Nuclear Assets

LIGHT WATER REACTOR SUSTAINABILITY

From the LWRS Program Technical Integration Office Director

Bruce Hallbert, Director, LWRS Program Technical Integration Office.

The United States (U.S.) Department of Energy's (DOE's) Office of Nuclear Energy (NE) recently issued its Strategic Vision. The Strategic Vision identified five goals

1. Enable continued operation of existing U.S. nuclear reactors.
2. Enable deployment of advanced nuclear reactors.
3. Develop advanced nuclear fuel cycles.
4. Maintain U.S. leadership in nuclear energy.
5. Enable a high-performing organization.

The Light Water Reactor Sustainability (LWRS) Program is the primary programmatic activity that addresses NE's first goal.

The LWRS Program conducts research to develop technologies and other solutions to improve economics and reliability, sustain safety, and extend the operation of the nation's fleet of nuclear power plants. The program and accomplishments summarized in this report are achieved through close coordination with industry, vendors, suppliers, regulatory agencies, universities and other research and development (R&D) organizations.

The LWRS Program has two objectives to maintain the long-term operations of the existing fleet:

1. to provide industry with science and technology-based solutions to implement technology that can exceed the performance of the current business model.
2. to manage the aging of structures, systems, and components (SSCs) so nuclear power plant lifetimes can be extended and the plants can continue to operate safely, efficiently, and economically.

The LWRS Program carries out its mission to accomplish the following objectives:

- Enhance the economic competitiveness of operating light water reactors in current and future energy markets
- Ensure the performance of SSCs.

The LWRS Program, in close collaboration and cooperation with industry, provides technical foundations for the continued operation of the nation's nuclear power plants using the unique capabilities of the national laboratory system.

This report provides an overview of the LWRS Program and recent select accomplishments that directly support the continued operation of existing U.S. nuclear reactors.

Federal Program Management

William Walsh
Federal Program Manager
Office of Nuclear Energy
U.S. Department of Energy
william.walsh@nuclear.energy.gov

Savannah Fitzwater
Safeguards and Security Federal Lead
Office of Nuclear Energy
U.S. Department of Energy
savannah.fitzwater@nuclear.energy.gov

Sue Lesica
Materials Research Federal Lead
Office of Nuclear Energy
U.S. Department of Energy
sue.lesica@nuclear.energy.gov

Jason Marcinkoski
Flexible Plant Operation and Generation Federal Lead
Office of Nuclear Energy
U.S. Department of Energy
jason.marcinkoski@nuclear.energy.gov

Technical Integration Office

Bruce P. Hallbert
Director
Idaho National Laboratory
bruce.hallbert@inl.gov

Cathy J. Barnard
Operations Manager
Idaho National Laboratory
cathy.barnard@inl.gov

Research and Development Pathway Leads

Craig A. Primer
Plant Modernization
Idaho National Laboratory
craig.primer@inl.gov

Richard D. Boardman
Flexible Plant Operation and Generation
Idaho National Laboratory
richard.boardman@inl.gov

Svetlana (Lana) Lawrence
Risk-Informed Systems Analysis
Idaho National Laboratory
svetlana.lawrence@inl.gov

Thomas (Tom) Rosseel
Materials Research
Oak Ridge National Laboratory
rosseeltm@ornl.gov

Douglas M. Osborn
Physical Security
Sandia National Laboratories
dosborn@sandia.gov

Contents

Light Water Reactor Sustainability Program

1. Overview

This report provides an overview of the United States (U.S.) Department of Energy's (DOE's) Light Water Reactor Sustainability (LWRS) Program and summarizes recent accomplishments that support the continued operation of the domestic fleet of operating nuclear power reactors. The importance of sustaining the existing nuclear fleet of reactors is broadly acknowledged and supported for energy and national security, environmental attributes, and its value to the nation and communities surrounding nuclear power plants, as well as in achieving the nation's clean energy economy:

- Nuclear energy is highly reliable and highly available, serving a vital role in securing our nation's energy supply. Nuclear energy has reliably generated 20% of our nation's electricity since the early 90s and currently provides more than half of our clean power, which is more than all other sources of emissions-free power combined.
- Nuclear power is a vital part of a long-term strategy to ensure a reliable supply of electricity while reducing carbon emissions.
- The commercial nuclear power industry contributes importantly to the U.S. economy. The Brattle Group estimates that the commercial nuclear industry produces 475,000 jobs and contributes $60 billion annually to U.S. Gross Domestic Product.
- States recognize the value of the continued operation of plants to their communities and their economies. In 2021, the Illinois General Assembly passed sweeping clean energy legislation, preventing the closure of its nuclear plants. Said Dave Rhoades, Exelon Generation's Chief Nuclear Officer, "These plants are not only important for the clean energy they produce, but they are massive economic engines for their local communities, contributing more than $1.6 billion to Illinois' GDP each year."
- The continued operation of these plants provides price stability in electricity markets and environmental security. Premature closures of commercial nuclear plants lead to higher electricity prices and an increase in carbon emissions.
- As our country shifts to a clean energy economy, nuclear power plants can be used to produce products beyond electricity that are used as intermediate inputs by other industries and segments of the economy. In 2021, Congress passed a $1.2 trillion infrastructure package. A dominant focus of the bill is on clean energy, as the U.S. seeks to scale-up clean technologies, decarbonize the electrical grid, and meet our ambitious climate targets. Major support for nuclear in the bill includes:
  - A demonstration program for Regional Clean Hydrogen Hubs, at least one of which is required to demonstrate the production of clean hydrogen from nuclear energy.
- Nuclear power is also a key to achieving the Secretary of Energy's announced Earthshot: Hydrogen Initiative: "By achieving Hydrogen Shot's 80% cost-reduction goal, we can unlock a five-fold increase in demand by increasing clean hydrogen production from pathways such as renewables, nuclear, and thermal conversion. This would create more clean energy jobs, reduce greenhouse gas emissions, and position America to compete in the clean energy market on a global scale."

The LWRS Program, in close collaboration and cooperation with industry, provides the technical foundation for the continued operation of the nation's nuclear power plants. This involves engaging national laboratory facilities, staff, and expertise to conduct research needed to inform decisions, demonstrate technical solutions, and provide methods needed for the long-term management and operation of nuclear power systems. In addition, government and industry cost-sharing promotes advances in needed capabilities and the transition of technological solutions from the laboratory to the program's industry stakeholders.

Through the variety of R&D activities carried out together with and used by industry, the LWRS Program reduces key uncertainties and risks that many owners-operators face regarding the long-term performance of vital materials, plant modernization, efficiency improvement, and other issues needed to make the investments required to extend nuclear power plant operation up to and beyond 60 years.

1.1 Research to Enable Sustainability

Sustainability, in the context of this program, is the ability to maintain safe and economic operation of the existing fleet of nuclear power plants for as long as possible and practical. It has two facets with respect to long-term operations: (1) to provide industry with science-based solutions to implement technology that can exceed the performance of the current business model; and (2) to manage the aging of plant SSCs so that nuclear power plant licenses can be extended, and the plants can continue to operate safely, efficiently, and economically. The goals of the R&D activities conducted by this program are to ensure operating nuclear power plants are economically competitive within their energy markets and proactively address aging and obsolescence of plant SSCs, and technologies.

The LWRS Program carries out its mission through a set of five R&D pathways that are summarized below:

Plant Modernization: R&D to address nuclear power plant economic viability in current and future energy markets. The goal of these activities is the broad modernization of the existing LWR fleet by transforming the nuclear power plant operating model through the application of digital technologies.

Flexible Plant Operation and Generation: R&D to evaluate economic opportunities, technical methods, and licensing needs for LWRs to directly supply energy to industrial processes. The goals of these efforts are to support the development and deployment of technologies for diversification of products and revenue from plant operations.

Risk-Informed Systems Analysis: R&D to optimize safety margins and minimize uncertainties to achieve high levels of safety and economic efficiency. The goal of these activities is to develop and deploy risk-informed technologies for use by industry to enable more cost-effective plant operations.

Materials Research: R&D to develop the scientific basis for understanding long-term environmental degradation behavior in key materials and develop technologies for their mitigation in nuclear power plants. The goals of these activities are to provide the technical basis for the continued safe operation of the existing fleet.

Physical Security: R&D to develop and enhance methods, tools, and technologies for physical security. The goals of these activities are to deploy advanced technologies and approaches to optimize physical security at nuclear power plants.

The technical program plans for each of these pathways are produced and updated annually and will be made available through the LWRS Program's website (see https://lwrs.inl.gov). Progress is being achieved in each of these areas, and several outcomes from these efforts are summarized in the performance indicators in Table 1-1.

Table 1-1. Performance Indicators to Enable the Continued Operation of Existing U.S. Nuclear Reactors.

Performance Indicators
1. By 2023, demonstrate a scalable hydrogen generation pilot plant.
2. By 2023, demonstrate a technical basis for the deployment of advanced technologies to enhance physical securities at operating plants.
3. By 2023, demonstrate and support development of advanced risk analysis and simulation tools to enable plants to improve operations, reduce operating costs, and enhance existing safety features at operating plants.
4. By 2024, demonstrate the use of Integrated Operation Methods to achieve plant operating cost reductions by $5/MWh.
5. By 2026, complete engineering and licensing activities needed to demonstrate successful deployment of a digital reactor safety system in an operating plant.

1.2 Program Research and Development Interfaces

Planning, execution, and implementation of the LWRS Program are done in coordination with the nuclear industry, Nuclear Regulatory Commission (NRC), universities, and related DOE R&D programs to assure relevance, efficiency, and effective management of the work. Coordination, with both industry and the NRC, is needed to ensure a uniform approach, shared objectives, and efficient integration of collaborative work for the LWRS Program.

1.2.1 Industry

The LWRS Program works with industry on nuclear energy-supply technology R&D needs of common interest. The interactions with industry are broad and include cooperation, coordination, and direct cost-sharing activities. The guiding concepts for working with industry are leveraging limited resources through cost-shared R&D, direct work on issues related to the long-term operation of nuclear power plants, and the need to focus government-sponsored R&D on the higher-risk and/or longer-term projects.

The Electric Power Research Institute (EPRI) has established programs that are complementary to the activities of the DOE LWRS Program. EPRI and industry's interests include applications of scientific understanding and tools to achieve safe and economical long-term operation of the current LWR fleet. The interface between DOE-NE and EPRI is defined in a memorandum of understanding.

1.2.2 Nuclear Regulatory Commission

The NRC employs a memorandum of understanding with DOE that specifically allows for collaboration on research supporting the long-term operation of nuclear power plants. Fundamental data and technical information obtained through joint research activities are of interest and useful to each agency. Accordingly, to conserve resources and avoid duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost-sharing may be done in a mutually beneficial fashion.

1.2.3 International

DOE coordinates LWRS Program activities with several international organizations with similar interests and R&D programs. The LWRS Program continues to develop relationships with international partners, including the following international organizations, to maintain awareness of emerging issues and their scientific solutions:

- **Organization for Economic Co-operation and Development:**
  - **Halden Project:** The Halden Project is a jointly financed R&D program under the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD).
  - **Working Groups of the NEA:** The OECD forms committees and working groups within NEA to assist member countries in maintaining and further developing the scientific and technical knowledge base required to address current issues related to nuclear reactors and fuel-cycle facilities.
- **International Atomic Energy Agency (IAEA) Plant Life Management:** IAEA is the world's center of cooperation in the nuclear field and works with its member states and multiple partners worldwide to promote safe, secure, and peaceful nuclear technologies.
- **Bilateral Activities:** There are several U.S. bilateral activities underway (e.g., U.S.-Argentina, U.S.-Japan, U.S.-India, U.S.-Canada) that include activities specific to the LWRS Program. These bilateral activities provide an opportunity to leverage work ongoing in other countries.

1.2.4 Universities

Universities participate in the LWRS Program in at least two ways: (1) through awards made by DOE from the Nuclear Energy University Program (NEUP); and (2) via direct contracts with the national laboratories that lead the directed R&D activities of the LWRS Program. NEUP funds nuclear energy research and infrastructure upgrades at U.S. colleges and universities and provides scholarships and fellowships to students (see https://neup.inl.gov).

2. Sustaining the Existing Fleet

The LWRS Program focuses its research activities on two objectives needed to sustain the existing operating fleet in current and future energy markets, as observed in Figure 1. Efforts to enhance the economic competitiveness of the existing fleet are being accomplished through research that aims to reduce the operating costs of nuclear power plants and diversify the sources of revenue available to generate income. Ensuring the performance of structures, systems, and components is being achieved through understanding and mitigating the effects of environmental conditions on materials and addressing the obsolescence of aging plant technologies. The programmatic activities and selected recent accomplishments toward these objectives are described in Sections 2.1 and 2.2.

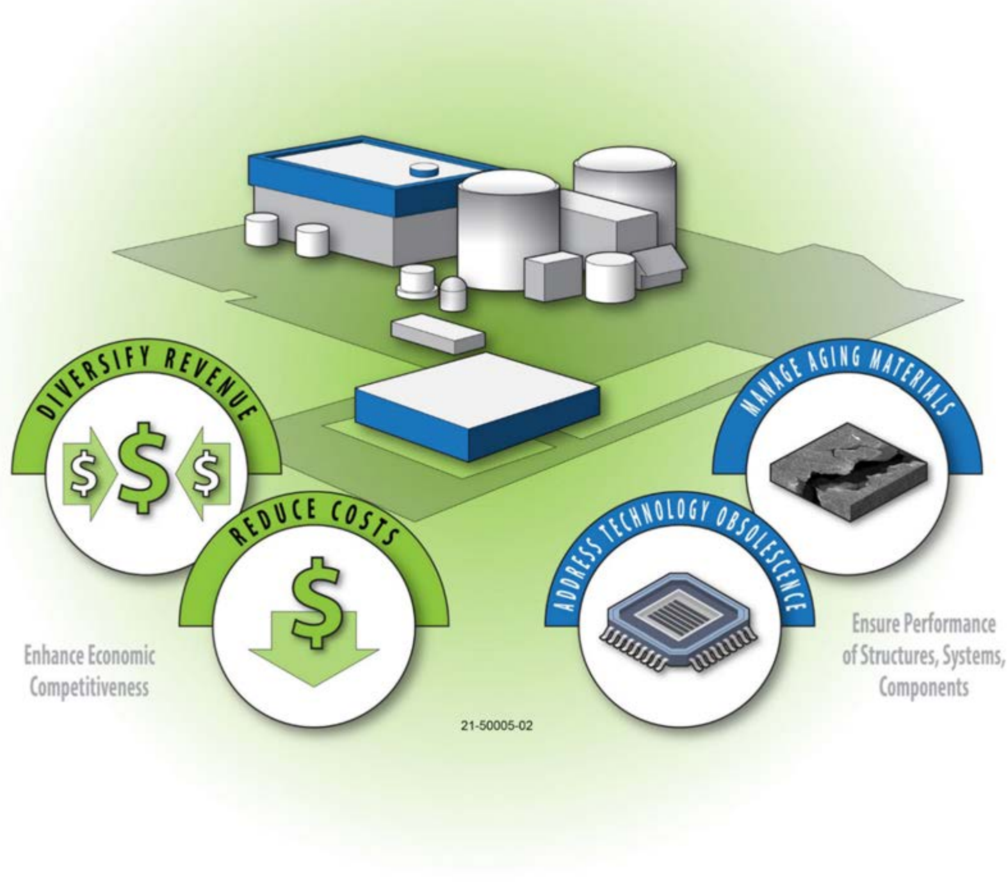


Figure 1. Paths to sustaining the existing fleet of LWRs through collaborative R&D.

2.1 Enhancing the Economic Competitiveness of the Existing Fleet

2.1.1 Research to Enable Diversification of Revenue and Expand to Markets Beyond Electricity

The objective of this research is to enable nuclear power plants to diversify their revenue by producing products beyond electricity for the life of the plants. Research in this area emphasizes the evaluation of potential energy storage options and products beyond electricity, developing the technical systems approach to accomplish integration of these systems with an operating LWR, and developing and demonstrating methods in analyzing the safety of these transformed operations.

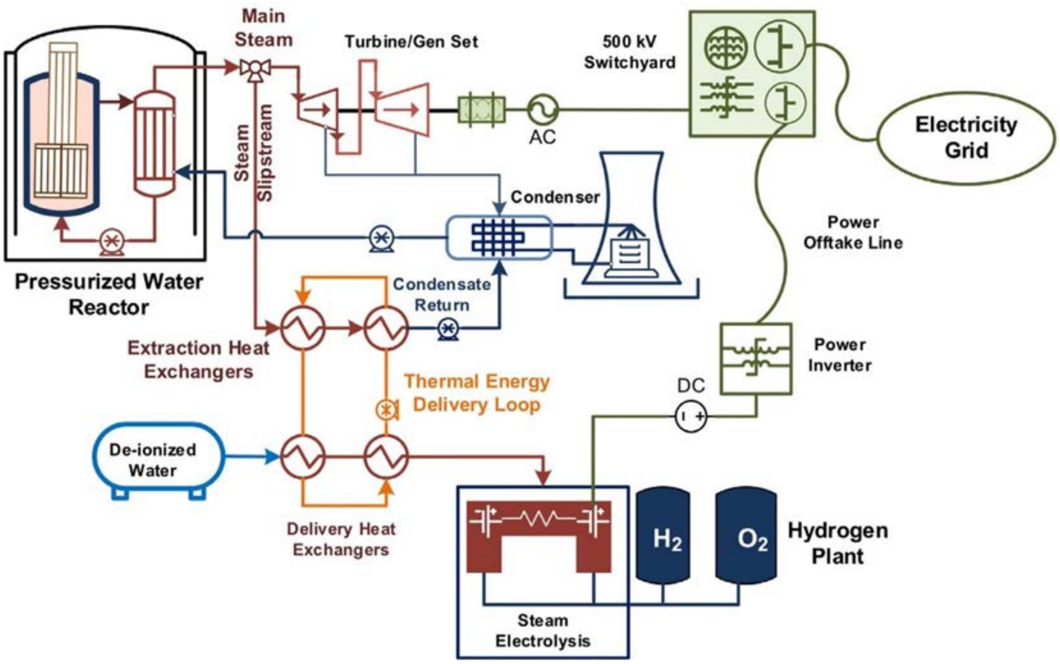


Figure 2. Illustration of flexible plant operations and generation of hydrogen by high-temperature steam electrolysis.

Electricity markets are undergoing radical changes as society is increasingly looking to reduce net CO_2 emissions to the atmosphere. In just the past year, more utilities have signed on to the goal of increasing the production of clean energy within the next decade. Some have committed to eliminating CO_2 emissions by 2045–2050. This presents both challenges and opportunities for nuclear power plants.

Utilities across the country are looking to add wind and solar energy to their energy portfolio to achieve their clean energy goals. This leads to regional instances of variable net over-generation throughout the year, resulting in spot electricity prices far below the marginal cost of production for most nuclear power plants. Unable to clear the day-ahead or hourly markets, nuclear power plants are being asked to throttle operations or pay others to curtail generation. This challenge is compounded by the addition of natural gas peaking plants that are being built to support load and supply balancing. The build-out of natural gas plants is partially driven by recent advances in CO_2 capture and sequestration technology, which reduces emissions from these plants.

The LWRS Program conducts R&D to use the full capacity of operating nuclear power plants by directing thermal power and/or electricity to a nearby storage unit or to a close industrial customer either full-time or variably as electricity is dispatched to the grid. This model of operation is referred to as flexible plant operation and generation (FPOG), the goal of which is to maintain full power during periods of variable demand by the electric grid due to capacity or price-related variation. This supports the use of energy from nuclear power plants even during periods of reduced electric grid demand by enabling them to variably supply their energy to other industrial processes, decarbonizing them in the process.

The conceptual design of a hybrid flexibly operated plant producing other products, such as hydrogen and grid electricity, is shown in Figure 2 . This new operating paradigm requires the development, analysis, and testing of new thermal and electrical power dispatch hardware and power electronics. The associated operations will require new operating concepts that consider combining digital controls tied to the thermal energy delivery systems with the traditional analog controls that are still used to operate most nuclear power plants today.

2.1.1.1 Deployment of Scalable Hydrogen Generation at Operating Nuclear Power Plants

The LWRS Program and other DOE program offices are conducting and sponsoring research to support the demonstration and deployment of scalable hydrogen generation coupled to operating nuclear power plants. In 2021, a fourth demonstration project was awarded to a consortium comprised of PNW Hydrogen LLC (a wholly owned subsidiary of Pinnacle West Capital Corporation), Xcel Energy, and Energy Harbor, with support from Idaho National Laboratory (INL), EPRI, the National Renewable Energy Laboratory, and the National Energy Technology Laboratory. This project will demonstrate advanced Integrated Energy Systems technologies that provide nuclear plants with large-scale responsive load. The consortium's goal is to minimize or obviate the need for nuclear power curtailment as variable renewable generation continues to expand, challenging the viability of the U.S. domestic nuclear fleet.

The consortium is taking a phased approach to advance Integrated Energy Systems hydrogen generation from carbon free nuclear power. Phase I (Energy Harbor – Davis-Besse Plant) will integrate low temperature electrolysis. Phase II (Xcel Energy – Prairie Island Station) will integrate high-temperature steam electrolysis. The consortium's goal is to safely demonstrate low-temperature electrolysis and high-temperature steam electrolysis at nuclear plants and to facilitate the future scale-up and generation of large-scale carbon free hydrogen. This proposal describes the consortium's Phase III effort.

The principal objective of Phase III is to demonstrate specific end uses of hydrogen produced from carbon-free nuclear power. The project will demonstrate the optimization and economic value of hydrogen production as a vector for electric power storage, and as a feedstock for the synthesis of liquid hydrocarbons. Hydrogen generated during periods of low grid demand can be stored and later co-fired in large combined-cycle gas turbines during periods of high demand, effecting large-scale and longer-term storage capacity as compared to batteries. The existing fleet of combined-cycle gas turbines, however, has limited capability to combust hydrogen. This proposal advances hydrogen combustion limits and de-risks the safe use of hydrogen in these existing plants and large frame turbines.

The four hydrogen demonstration projects will collectively accomplish the following goals:

1. Demonstrate hydrogen production using direct thermal and electrical power offtake from a nuclear power plant
2. Develop monitoring and controls procedures for scale-up to large commercial-scale hydrogen plants

3. Evaluate the feasibility of dynamic operations of an electrolyzer coupled with nuclear plant operations and transmission system needs
4. Produce hydrogen for captive use by nuclear power plants and first movers of clean hydrogen.

The following summarizes the four projects:

Exelon. In 2021, following a strategic review of their nuclear plants, power markets, and public regulatory conditions, Exelon announced the selection of the Nine Mile Point Nuclear Plant in upstate New York as the location of their hydrogen production demonstration. Exelon completed preparations to install and test a larger 1.25 MWe polymer electrolyte membrane commercial prototype unit that will be supplied in 2022. The project expects to complete the installation of this unit to begin hydrogen production in 2022.

Energy Harbor. The Energy Harbor project is proceeding with an engineering design to modify their existing power transmissions switch yard to dispatch power to a 2 MW polymer electrolyte membrane electrolysis unit. The upgrade to the switch yard will allow future expansion of hydrogen production ranging up to 60 MW electrical capacity. The upgrade to the switch yard is planned for the Spring 2023 outage at the Davis-Besse Power Generation Plant. In 2022, the electrolysis unit will be procured and installed in preparation for completing the electrical connection to commence testing in 2023.

Xcel Energy. Xcel Energy has completed a preliminary engineering study to install a high-temperature (steam) electrolysis unit at one of its nuclear plants in Minnesota. At the end of 2021, a Request for Proposals was publicly released seeking proposals for a commercially provided high-temperature electrolysis test stand of at least 150 kWe-DC Power. Xcel Energy will provide a clean steam source, with a pressure of approximately 3 bar, generated within the nuclear power generation station. The project plans to procure a unit by the end of 2022. Testing is planned to commence in 2023.

Arizona Public Services/PHW (Pinnacle West Hydrogen, LLC). The award made to PWH was announced mid-year 2021 and is being finalized under DOE's Office of Energy Efficiency and Renewable Energy. This project will engage two universities (e.g., Arizona State University and University of California–Irvine), three national labs (Idaho National Laboratory, National Energy Technology Laboratory, and National Renewable Energy Laboratory, EPRI, and OxEon Energy. Coordination of the project plan and funding directed to the project participants is being worked out in anticipation of starting the project in 2022.

2.1.1.2 Technical and Economic Studies to Support the Development and Deployment of Hybrid Energy Systems at Commercial Nuclear Power Plants

Beginning in 2019 and 2020, market analyses identified those industrial markets that are growing, and therefore provide an opportunity for new manufacturing plant construction. The first technical and economic assessments evaluated the potential to produce and sell hydrogen in local markets. Interest in producing hydrogen using zero-carbon energy produced by nuclear plants continued to grow in 2021. This was manifest by the first U.S. DOE's Energy Earthshot initiative announced by the Secretary of Energy being the production of zero-emissions hydrogen at the price of one dollar per kilogram by 2030 (1:1:1). The assessments provided by the joint LWRS Program and Energy Efficiency and Renewable Energy-Hydrogen and Fuel Cell Technology Office research programs were taken into consideration when this goal was set.

In 2021, LWRS Program research affirmed that hydrogen production is a viable path for nuclear power plants to generate net positive revenue. The most recent efforts have refined cost estimates for electrolysis of steam that can be safely produced by extracting heat from the nuclear power plant power cycle. Both the capital and operating costs of the hydrogen plant have been re-evaluated and strongly suggest that it will be possible to produce hydrogen for less than the current DOE-Energy Efficiency and Renewable Energy goal of $2 per kilogram of hydrogen (i.e., <$2/kg-$H_2$) when the supply chain for electrolyzers reaches its projected maturity.

The decision to consider alternative markets requires an understanding of changes to electrical grid markets as utilities strive to reach the goal of 100% emissions-free electricity generation. Capital investment decisions are measured in terms of the financial returns on these investments using discounted cash flows that depend on the sale of products. In some cases, utilities need the tools to determine how they can recover operating costs of nuclear power plants. Additionally, new requirements for utility-scale energy storage are being established to deal with the intermittency associated with wind and solar energy. This led the LWRS Program to develop computational tools capable of projecting the net present value of FPOG operations. These tools characterize the uncertain dynamics of the grid and estimate grid prices for the future to help determine the dynamic requirements and operating schedules of energy dispatch from the nuclear power plant while simultaneously optimizing the scale of the FPOG unit operations. The Risk Analysis Virtual ENvironment (RAVEN) code plug-in tool named Holistic Energy Resource Optimization Network (HERON) was developed to complete technical and economic assessments based on region-specific capacity expansion projection and the projected grid market prices.

RESEARCH ACCOMPLISHMENT

Establishing the Case for Non-Electricity Markets and Energy Storage for Operating Light Water Reactors

In collaboration with the NE Integrated Energy Systems Program, LWRS Program researchers completed the development of a family of tools that optimize the design, scale, and operating schedule of flexible plant operations. Two new RAVEN plug-ins were developed to evaluate alternative plant operation scenarios: (1) TEAL (Tool for Economic Analysis) and (2) HERON. Synthetic time histories are created using capacity expansion models that are being developed and continuously improved by other institutions such as EPRI and the National Renewable Energy Laboratory.

HERON is a software plug-in for the uncertainty framework RAVEN. HERON provides a set of tools specifically for using RAVEN to perform stochastic technical and economic assessments for systems of components connected through mutual resource production and consumption in the presence of economic drivers. More specifically, it was designed to perform uncertainty-centric analysis of generation units (or components) with multiple potential resource markets (energy, hydrogen, water, etc.).

HERON involves a two-layer optimization approach, as shown in Figure 3. In the outer layer, macro variables such as component capacity, market sizes, and tuning variables are analyzed. In the inner layer, the macro variables are taken as constant, while generations of synthetic multi-year scenarios are produced to assess the economic viability of the selected component mix. Each inner-layer analysis results in a statistical representation of economic metrics such as the net present value, given optimized component dispatch for the generated scenarios. The outer layer is then informed by the economic metric distribution to determine how, and if possible, to further improve the financial performance of the system. The manner of dispatch optimization depends on the nature of the system under analysis.

HERON is available via the RAVEN plug-in system (github.com/idaholab/raven).

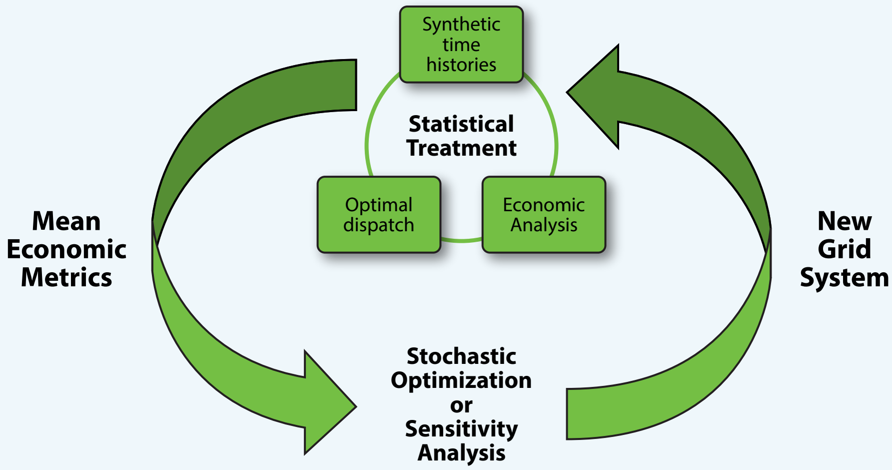


Figure 3. HERON computation workflow for systems optimization satisfying designated economic metrics such as net present value.

2.1.1.3 Technical and Economic Analysis of Commercial Nuclear Power Plants Energy Storage and Arbitrage

Based on input from nuclear utility stakeholders, the need to better understand the role of energy storage became a priority of the research conducted in 2021. This is driven largely from technical and regulatory requirements to deal with the increase of non-dispatchable variable power generation sources. Energy storage can be used strategically by the plant's operator to engage in energy arbitrage, the process of generating a profit by exploiting price differences in the same commodity. By purchasing electricity from the grid when the price is low and selling it when the price is high, the plant is able to capture the difference in the two prices as profit. The leading technological options for facilitating energy arbitrage are Li-ion batteries, reversible hydrogen electrolysis or gas turbine combustion, and reversible heat pumps with thermal energy. Battery storage is straight forward and can be tied to the grid at practically any location and scale. However, hydrogen production and thermal energy storage require close coupling to the nuclear plant and therefore fall within LWRS Program R&D. An assessment of these options requires close approximation of the capital expenses, process responsiveness, and thermodynamic round-trip efficiencies.

Also, in 2021, an evaluation on the costs of compressing and liquifying hydrogen was completed. The costs of producing liquified nitrogen that can be used as a refrigerant and the potential to support CO_2 capture at fossil-fired plants were also evaluated.

RESEARCH ACCOMPLISHMENT

Establishing the Case for Non-Electricity Markets and Energy Storage for Operating Light Water Reactors

Leading options of energy storage and arbitrage were evaluated in 2021, including Li-ion batteries, hydrogen and thermal energy reservoir, and the production of liquid nitrogen via air separation and liquefaction, liquefaction of hydrogen, compressed hydrogen.

The analysis is based on storage systems with discharge capacities of 500 MW for which various durations of storage and costs of charging (electricity cost) are examined. A relative ranking of energy storage options was done using a levelized cost of storage (LCOS) metric. The LCOS metric calculates a rough

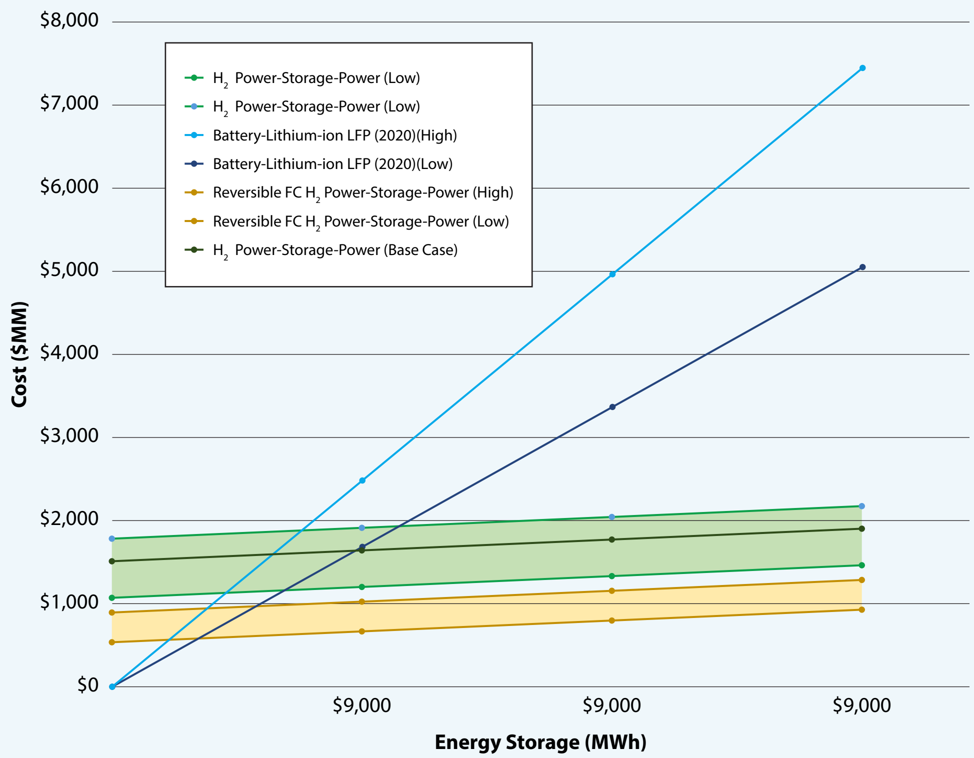


Figure 4. Energy storage and arbitrage cost comparison for lithium-ion batteries versus H_2 using high-temperature electrolysis for hydrogen production and polymer electrolyte membrane Fuel Cells to convert H_2 back into power.

breakeven cost for the system, considering the capital and operating costs, as well as the revenue from arbitrage.

The outcomes of this activity indicate energy arbitrage will likely be more profitable in regulated markets that provide a premium for energy storage to cover power generation when variable, non-dispatchable generation sources are inactive. Hydrogen production and storage at a nuclear plant for energy arbitrage outperforms Li-ion batteries for grid-scale periods of more than a few hours of storage as shown in Figure 4. Although some thermal energy storage and recovery systems were shown have a slightly lower LCOS than hydrogen system power arbitrage, hydrogen provides the overall greatest flexibility throughout the year because it can be sold into a wider end-user market.

2.1.1.4 Thermal-Electrical Energy Dispatch to Enable Hybrid Nuclear Plant Operations

Close coupling of a nuclear power plant to an industrial user necessitates engineering design changes to the nuclear power plant to deliver thermal energy and/or electricity to the industrial user in a new manner. Every nuclear plant is unique beginning at the reactor core and continuing through the thermal-hydraulic, power generation, and cooling systems. Each electricity transmission switch yard line up with the grid is also unique. Consequently, plant design modifications will be required to tap any substantial amount of electricity or steam for FPOG applications.

In addition, new concepts of operations need to be developed. This will likely entail new nuclear plant control procedures, new (digital) instrumentation, and controls to divert thermal energy and electricity to hybrid users. At a minimum, increased operator cognizance will be required because the NRC currently requires that the licensed operators maintain direct control of all nuclear plant operations that could impact core heating. Hence, the implementation of new human-machine control interfaces, addressing corresponding human factors issues, may be needed to demonstrate how to maintain the safety of the plant efficiently and reliably during normal and postulated off-normal FPOG conditions.

Research by the LWRS Program to develop hybrid energy delivery systems includes the expansion of full-scope nuclear power plant simulators that incorporate new thermal energy delivery systems as well as modifications that are necessary to dispatch power between the grid and the second user.

RESEARCH ACCOMPLISHMENT

Thermal-Electrical Energy Dispatch to Enable Hybrid Nuclear Plant Operations

A test of operational concepts for dispatching a portion of the steam from a nuclear power plant for an industrial user was completed at the Human Systems Simulation Laboratory located at the Idaho National Laboratory. A prototype human-system interface was developed and displayed in tandem with the virtual control panels to support operators executing procedurally driven evolutions and transient responses (see Figure 5). The operators performed

15 scenarios covering normal evolutions to transition the plant from full turbine operation to joint turbine and thermal power dispatch operations, in addition to transient response scenarios induced with simulated faults. The impact of the thermal power dispatch system on operator and plant responses was evaluated with a particular emphasis on the amount of workload and attention required to operate in tandem with the thermal power dispatch and existing plant systems.

An interdisciplinary team of operations experts, nuclear engineers, and human factors experts observed the operators performing the scenarios to evaluate the operations. Several different measures were collected including expert observer performance-based metrics, plant parameter logs, operator attention via eye-tracking, debriefs, and self-report questionnaires. The outcomes of this activity revealed it may be beneficial to support thermal energy dispatch with supplemental automation to augment the anticipated operator tasking required to control and monitor an additional system in addition to existing operations.

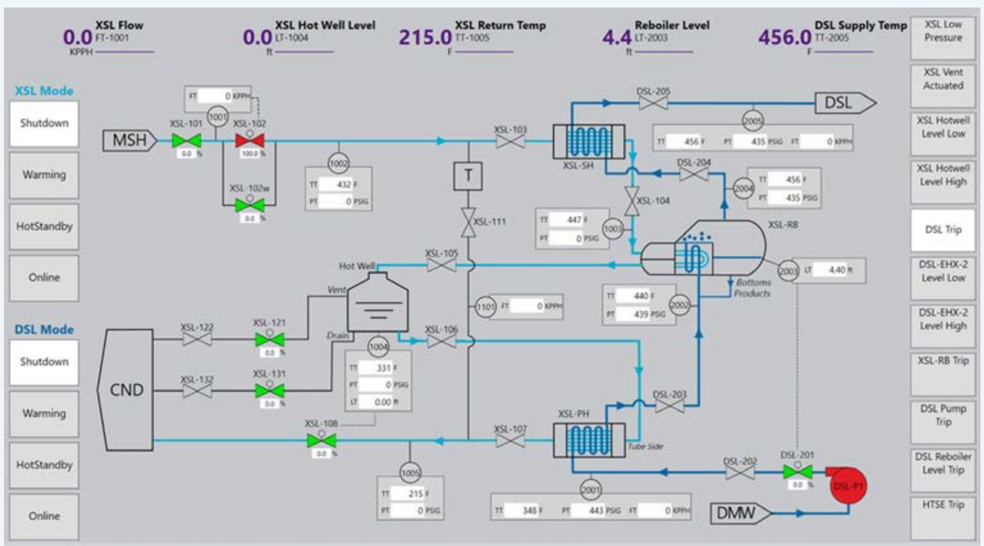


Figure 5. Thermal energy dispatch indication display.

2.1.2 Research to Reduce Operating Costs and Improve Efficiencies to Enhance Economic Competitiveness

Many commercial nuclear power plants face increasing economic pressures. These pressures arise from the historically low cost of natural gas and the correspondingly low operating costs of natural gas combined-cycle power plants, combined with an increase in renewable energy capacity (specifically solar and wind) on the power grid. Although the nuclear power industry has achieved record plant availability and electricity production, the electricity prices in many domestic markets coupled with reduced electrical demand have forced some plants out of business. For nuclear power plants to remain economically viable and competitive, they will need to address the long-term cost of operation by adopting methods to reduce operating costs while maintaining high performance. The LWRS Program's R&D activities provide the industry with modernization solutions. Results from programmatic efforts will enable nuclear power plants to enhance their efficiency and performance while reducing costs.

LWRS Program research enables widespread cost-reduction and operational improvements by addressing critical gaps in technology development and deployment. These solutions reduce the risks and costs of substantial modernization efforts at operating nuclear power plants. These efforts aim to develop, demonstrate, and support the deployment of new digital instrumentation and control (I&C) technologies for process control, enhance worker performance, and provide enhanced monitoring capabilities.

This research has two strategic goals:

1. to develop digital technologies and improve work processes that renew the technology base for extended operations beyond 60 years
2. to transform the nuclear power plant operating model through digital technologies to enable a new approach to operations that ensures long-term technical and economic sustainability.

2.1.2.1 Advanced Concept of Operations for Improved Cost and Performance

The nuclear industry must adopt digital technologies and processes widely deployed in other industrial sectors for the nuclear fleet to become economically competitive. These technologies include digital control and monitoring, advanced analytics, including artificial intelligence, machine learning, and modern business processes. Nuclear power enjoys the highest reliability of any energy source in the nation. Still, this achievement has come at the expense of increased costs—primarily driven by the ubiquitous use of legacy analog systems throughout the plants. Utilizing advanced digital systems combined with the transformative business process will allow world-class reliability and safety at a much lower cost of operations.

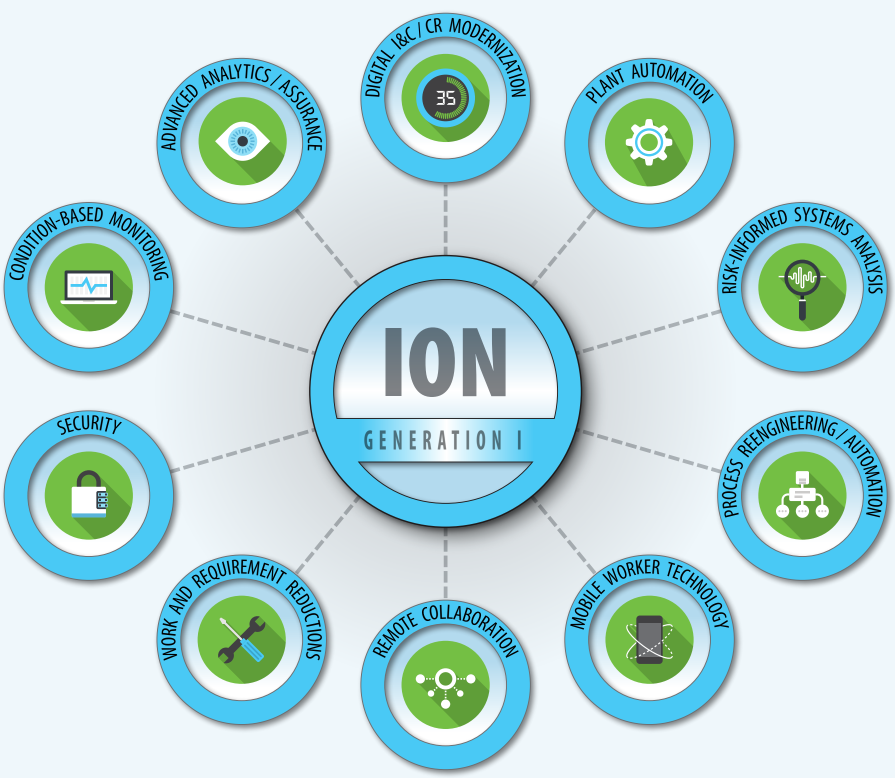
Research is being conducted with nuclear power plant owner-operators to develop and deploy an economically competitive advanced concept of operations approach. This approach employs restructuring plant processes and existing technologies to reduce operating costs using advanced technologies. Adopting an advanced concept of operations provides opportunities to restructure the nuclear power plant operating model to result in new and more efficient working methods. The model for this, Integrated Operations for Nuclear (ION), uses plant-specific market analysis to identify goals for operation and management costs and a plant capacity factor needed for long-term commercial viability. The technical and economic assessment results provide the crucial information necessary for developing a site-specific transformation strategy. The transformation strategy identifies needed technology and process modifications to achieve the targeted sustainability goals. The transformation strategy also provides improved methods for achieving plant safety margins through reductions in unnecessary conservatisms and leveraging expertise from across the nuclear enterprise.

RESEARCH ACCOMPLISHMENT

Reducing Operating Costs Using the ION Framework

An LWRS Program research collaboration is delivering a validated approach to the commercial nuclear power industry to reduce operating costs. The goal of this research is to deliver demonstrated methods that can be used by operating nuclear plants to bring costs in line with long-term market expectations for price competitiveness. This involves transforming the approach to conducting work from one that is labor-centric, the current operating model, to one that is more technology-centric. This transformation can be achieved by adopting advanced technologies implemented in a comprehensive plant business ecosystem that integrates people, technology, processes, and governance. The technology for guiding business transformation, termed ION, was developed together with Xcel

Figure 6. ION Generation 1 Work Domains.



Energy Nuclear Generation to enhance the economic performance of plants and enable sustained long-term economic operation of the nuclear industry.

Strategically applying advanced technology across the nuclear enterprise allows utilities to select the most effective pathway to transformation while avoiding technology dead ends. The ION process analyzes work functions that offer the greatest potential for cost-reductions across the plant and categorizes them into Work Domain groupings, as shown in Figure 6. These Work Domains are analyzed to identify advanced digital technologies that enable cost reductions and achieve the necessary and sustainable operating costs and required performance. Utilities can apply the results of this analysis to select the best available technologies in an integrated and coordinated manner.

LWRS Program researchers worked directly with Xcel Energy, Norway's Institute for Energy Technology, and Scott Madden Associates to validate the ION method. The team analyzed current nuclear generation work functions to derive more efficient means of accomplishing the required functions. This analysis evaluated work elimination, requirements reduction, process improvement, technology application, and other forms of innovation to determine the impact on costs. The results of the analysis projected long-term operating and maintenance (O&M) cost reductions of over 30%, if broadly applied, potentially yielding long-term cost-savings on the order of hundreds of millions of dollars annually, depending on the scale of deployment and scope of improvements that are finally implemented.

ION leverages advanced monitoring and data processing to achieve these cost-savings to replace labor-intensive plant support tasks. A good example of a

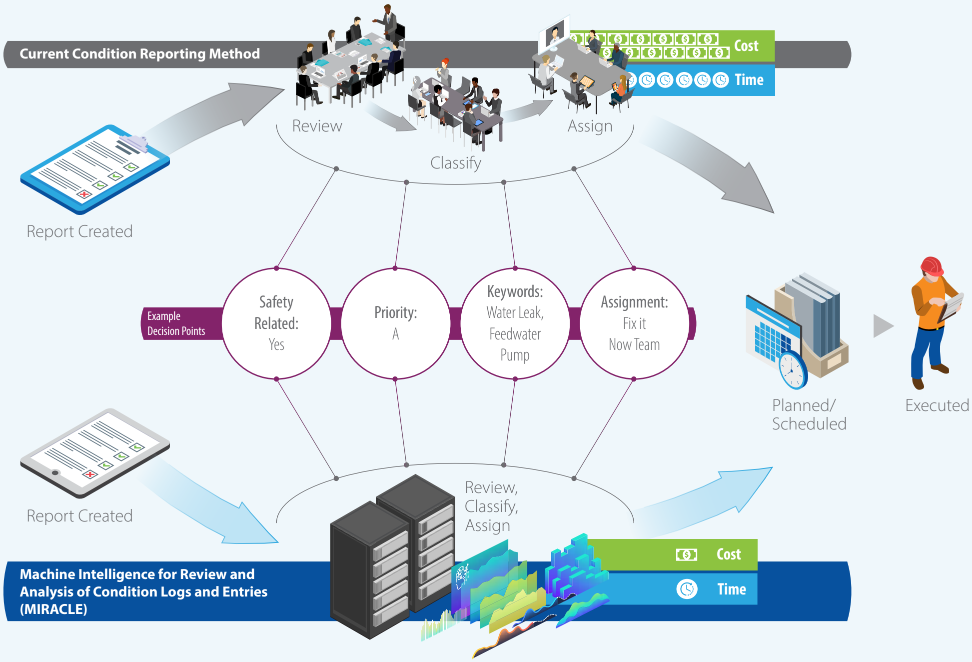


Figure 7. MIRACLE is a tool created by the LWRS Program to replace or assist the currently expensive, time-consuming condition report screening process.

technology that can reduce O&M costs while improving plant staff efficiency is the Machine Intelligence for Review and Analysis of Condition Logs and Entries (MIRACLE) tool applied to the plant's Corrective Action Program (CAP), which is the primary method for capturing and trending problems across a plant, fleet of plants, or even the industry. Because automating various aspects of the CAP can increase program efficiency, reduce human errors, and improve plant safety, the LWRS Program has launched efforts to apply artificial intelligence/machine learning to automate aspects of the CAP process, particularly the screening of condition reports. This effort supports the industry's broader implementation of artificial intelligence/machine learning and expands their potential and uses, as observed in Figure 7. Three tasks accomplished in 2021 in this area include:

- Evaluating whether integrating data from multiple plants would result in more capable artificial intelligence/machine learning models than if done by individual utilities.
- Developing mechanisms to create industry-scalable models for text-mining methods.
- Standardizing the trending process in nuclear power plants by creating data-driven topics for trending and maximize benefits to plants and regulators.

Utilizing advanced technologies, such as MIRACLE, combined with the transformative business process of ION is one-way that LWRS Program research is being used to enhance business processes (like CAP) using advanced technologies to reduce costs and improve work.

2.1.2.2 Technologies and Approaches to Monitor Plant Components and Materials

DOE-NE and the LWRS Program fund awards and research projects to enable broad adoption and implementation of advanced technologies for nuclear plant operation. These awards provide utilities, industrial partners, and national laboratories funding to develop and demonstrate innovative technologies that enable significant cost-reduction. Specifically, within this scope of research, DOE has awarded two projects.

In 2019, an award was made to the PKMJ Technical Services LLC, Public Services Enterprise Group, Nuclear Team, and Idaho National Laboratory, to develop and demonstrate a fully integrated, risk-informed, condition-based maintenance capability and a digital platform to optimize automated work management. The results of the research, which was completed in 2021, identified savings of $4.37M over the next six years for the plant system that served as the testbed for this research, the circulating water system. Additional cost-savings are possible via implementing risk-informed predictive maintenance architecture (software copyrighted to Battelle Energy Alliance, LLC, operator of Idaho National Laboratory).

Sustaining the long-term economical operation of the domestic LWR fleet is a key focus area of the LWRS Program. One of the significant costs for a nuclear power plant is ensuring plant equipment is maintained in good working order. Over the years, the nuclear fleet has relied on periodic, manually performed labor-intensive, time-consuming preventative maintenance programs to maintain the systems of a plant.

To address these costs, the LWRS Program is performing research, development, and demonstration of technologies that transition the preventative maintenance program to a technology-enabled risk-informed predictive maintenance strategy. These research results demonstrate the automation that is required for a long-term economically sustainable maintenance program for the domestic fleet of reactors. This predictive maintenance strategy integrates advancements and innovations in sensing, communication, data processing, machine learning, artificial intelligence, and visualization to develop scalable technologies across plants assets and the fleet. The implementation and scalability of these technologies provide broad impact and benefits across the nuclear industry. The predictive maintenance strategy provides a proven approach for seamless deployment of technologies on a common platform, with standardized requirements, minimizing technical and regulatory concerns.

A second award was made to Utilities Service Alliance, a consortium of operating nuclear utilities, to research, develop, and deploy automation and advanced remote monitoring technologies into the U.S. nuclear fleet to reduce O&M costs while improving safety and reliability. In 2021, Utilities Service Alliance and INL established the foundation for deploying advanced remote monitoring technologies: anomaly detection methods, fire watch, transformer health monitoring, operator rounds, and thermal performance. The LWRS Program research team successfully integrated Talen Energy's Columbia Generating Station and Talen Energy's Susquehanna Steam Electric Station into Luminant's Power Optimization Center. This research effort demonstrated the use of a monitoring and diagnosis center across multiple nuclear utilities for the first time. This centralized operations model introduces immediate cost-savings to participating utilities as it enables them to leverage current Power Optimization Center capabilities. This integration also enables the award team to share research, development, and deployment benefits in leveraging the Power Optimization Center as the technology-sharing platform.

RESEARCH ACCOMPLISHMENT

Scalable Technologies Achieving Risk-informed Condition-based Predictive Maintenance Enhancing the Economic Performance of Operating Nuclear Power Plants

A key plant monitoring research accomplishment in 2021 came through a Private-Public partnership, demonstrating the application of advanced machine learning techniques to a new risk-informed predictive maintenance strategy at nuclear power plants. These research results enable a deployable risk-informed predictive maintenance strategy and involve the integration of three technologies:

(1) advanced data analytics to continuously monitor and analyze data for the identified plant system.

(2) a federated-transfer learning predictive modeling approach coupled with risk models to assess the economics of automation.

(3) a user-centric visualization tool that helps plant personnel understand results and make informed decisions.

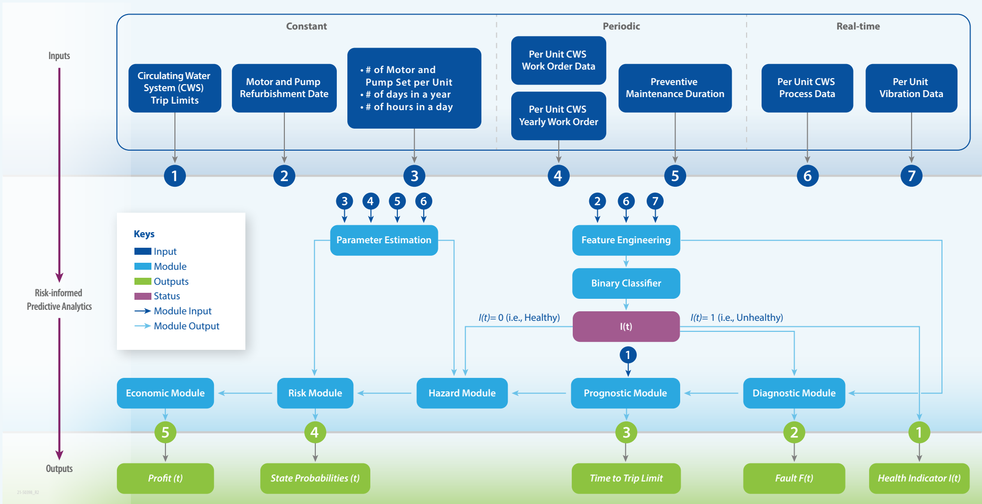


Figure 8. Risk-informed condition-based maintenance architecture.

The resulting capabilities developed in partnership with Public Services Enterprise Group, Nuclear LLC, and PKMJ Technical Services LLC contribute to long-term safe and economical operation, automation, efficiency, and enhanced reliability of plant systems in nuclear power plants.

The notable accomplishments achieved as part of this research include:

1. Development of a risk-informed condition-based maintenance analytics architecture, as can be seen in Figure 8. The modularity of the architecture provides advanced data analytics and continuous monitoring of the plant cooling water system. The architecture allows heterogeneous data and integration of different modules—such as fault signature analysis, diagnostic and prognostic models, risk, and economic models via interfaces. The software developed through this project related to the architecture in Figure 8 was copyrighted. The architecture informed the development of PKMJ's Microsoft Azure™ cloud-based centralized Nuclear Digital Platform to achieve automated work management and preventative maintenance optimization.

2. Development and integration of component-level predictive models into a robust system level model enabled by federated-transfer learning, as observed in Figure 9. Federated learning is a decentralized approach to machine learning that collects data from plant components to develop robust models combined for representation in the machine learning algorithm or model. Transfer learning is an approach that allows the application of a developed "model" to different but related systems within the same plant site or the same system (i.e., cooling water systems) at different plant sites. This advancement is a first-of-a-kind application of federated-transfer learning in the nuclear industry. The software developed to achieve federated-transfer learning is pending copyright.

Other accomplishments of this research include the development of detailed, physics-informed models of plant components that capture the dynamics of system operation to enable early fault detection, development of prognostics (predictive) modeling capability, and a user-interface that supports visualization of system operation and results to enable monitoring and decision-making by plant personnel.

Adoption of these technologies are demonstrating substantial cost-savings by dramatic reduction or elimination of unnecessary time-consuming and labor-intensive maintenance activities. Transferring these scalable technologies to other systems and plants enables industry implementation of a cloud-based digital platform for automated monitoring and improved maintenance of plant components. It also demonstrates an approach for the nuclear industry to adopt risk-informed predictive maintenance strategies to achieve the economic benefits of automation for long-term sustainability.

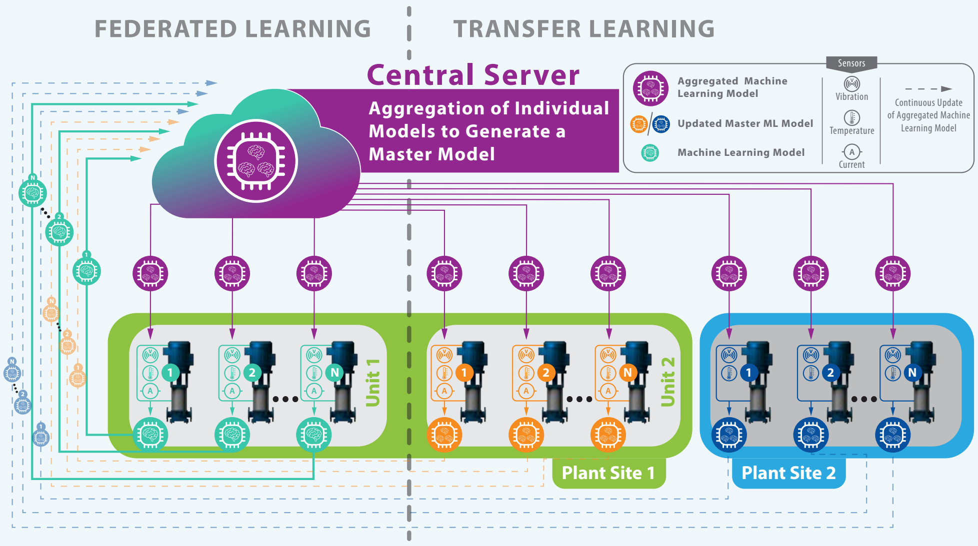


Figure 9. A schematic representation of federated-transfer learning approach.

RESEARCH ACCOMPLISHMENT

Machine Learning Technologies to Enable More Efficient Plant Work

Through a DOE award to the Utilities Service Alliance, research is successfully demonstrating the potential for using machine learning to automate aspects of plant monitoring and fire watch, as well as processing data used in industry corrective action programs. This research is demonstrating how advanced technology can augment existing programs and activities such as completing rounds and other manual activities conducted daily to reduce operating costs and improve the efficiency of many operations-related and other routine activities in the plant.

Monitoring activities are regularly performed to ensure the expected performance of plant equipment and systems used in the daily operation of nuclear power plants. Detecting anomalies, abnormal or unexpected behavior in plant systems, provides the first warning to operators that something unexpected is about to occur, alerting plant staff of the need to identify and correct the cause. An approach to anomaly detection is being developed and demonstrated by using nuclear power plant data to automate this detection process using machine learning methods. Preprocessing plant data enables automating robust anomaly detection with minimal false positives. This step, preprocessing the plant data, is usually the most expensive part of data-driven automation. It is especially challenging in a nuclear power plant because there are thousands of sensors in a plant with a wide spectrum of data or sensor 'issues' that could exist, as seen in Figure 10. To achieve the benefits of automation, preprocessing itself must be scalable and automated.

In 2021, LWRS Program researchers automated scalable data evaluation and preprocessing methods. In collaboration with Xcel Energy, the methods were deployed in Luminant's Power Optimization Center. Researchers screened out the anomalies due to sensor failures and data quality issues. It is also necessary to detect and correct for process lag, different measurement scales of the data, and high-dimensional data. Once data is prepared, common sensor anomalies are detected and mitigated, including outlier data, failed-constant data, increased noise, and drift. The developed methods were coded into a Python-based application, integrated into Luminant's Power Optimization Center and available for broader industry use.

Similar methods used in anomaly detection can be applied to text-based data like that found in utility CAP data and databases. Anomaly detection typically uses unsupervised machine learning methods, which do not require labeling of the data that is fed into the machine learning model. Recently Florida Power &

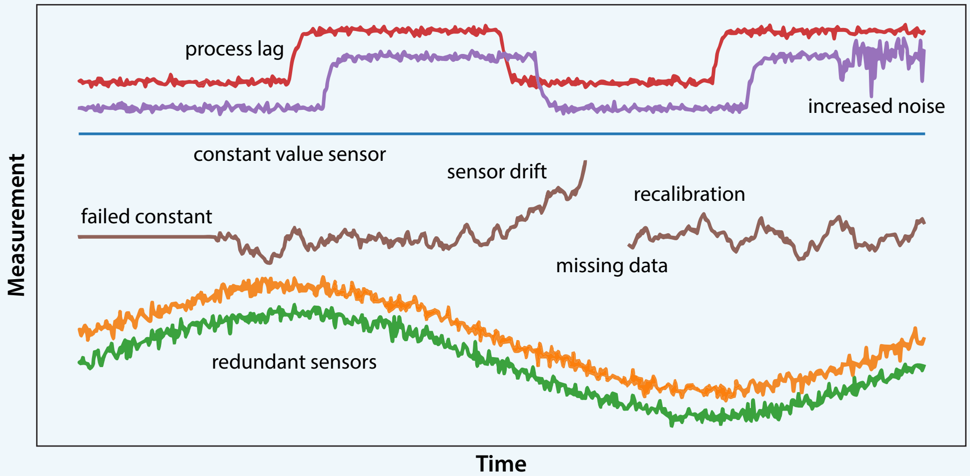


Figure 10. Plot of example data representing many of the issues encountered in nuclear plant data.

Light Company, owned by NextEra Energy, developed an artificial intelligence and machine learning-based classifier together with LWRS Program researchers to categorize a condition report into classes that can label the data as normal or anomalous. Adding these labels improved the overall accuracy in the detection of the machine learning algorithm and generally outperform unsupervised machine learning methods. The resulting algorithm and test results offer promising results to improve the quality of CAP analyses using automated machine learning tools. This conclusion was validated using two methods, and the results were published in INL/EXT-21-64303, Process Anomaly Detection for Sparsely Labeled Events in Nuclear Power Plants.

Another accomplishment in 2021 was the automation of fire watch, an activity that can cost a nuclear power plant an excess of $1M per month to perform manually. The research advanced a camera-based automated fire watch detection method to achieve more than 99.3% accuracy with a missed positive (i.e., missed fire) ratio of 0.6% of all fire cases (i.e., the system missed a fire once every 166 fires). This is a considerable improvement over the currently evaluated fire models and was accomplished by combining nine of the commonly used models for computer vision into an ensemble of those models, as shown in Figure 11. Researchers evaluated the model's performance by creating an explainability approach (i.e., you can explain what happens in your model from input to output) using a heat map of the regions to identify key drivers for the decision on the fire classification. Due to the very common occurrence of smoke when there is fire, visual explainability demonstrated that the computer vision models learned to expect smoke with fire. As shown in the green regions of Figure 11, detection models classified images of smoke as fire too, which

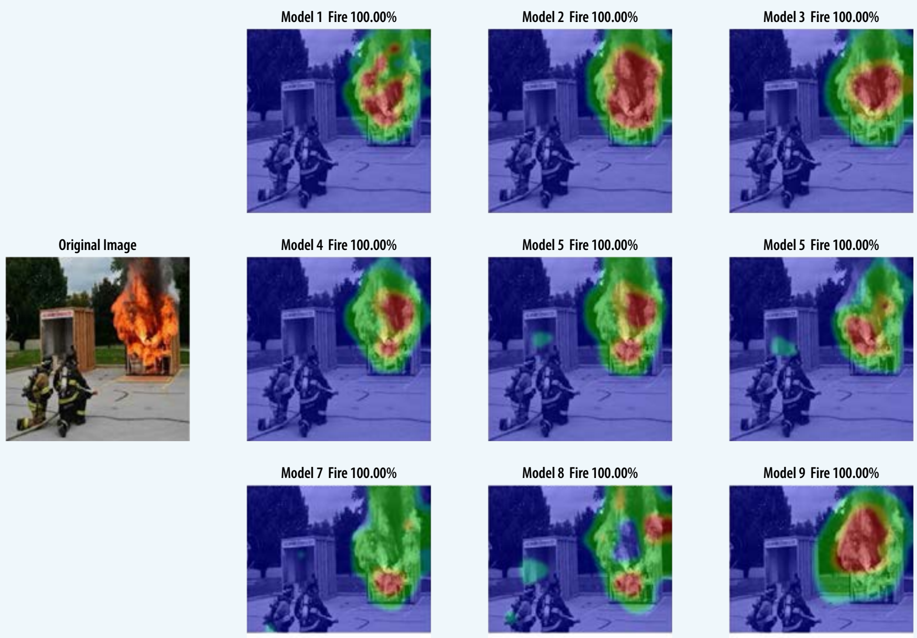


Figure 11. The application of nine different computer vision models to detect fire and the visual explainability of each.

is not always the case (i.e., smoke can occur without visible fire). This finding emphasized the need to detect and isolate smoke from the fire. As part of the Utilities Service Alliance award, this technology is deployed on dedicated fire carts. These carts fuse this new automated fire detection with other sensors (e.g., infrared, acoustics, etc.) to achieve even higher performance accuracy to ensure no expected missed fires, key criteria for the successful deployment of this technology.

2.1.2.3 Research to Optimize Nuclear Fuel Utilization

Nuclear fuel costs represent approximately 20% of the total generating cost, a substantial expense for a nuclear utility. As such, optimization of fuel reload is one of the top-priorities of industry. This project aims to optimize reactor core thermal limits through the development and implementation of state-of-the-art computational techniques. The optimization of core thermal limits allows a smaller fuel batch size to produce the same amount of electricity. This reduces new fuel costs and may save a significant amount of money on the back end of the fuel-cycle by reducing the volume of spent fuel that needs to be processed. The reduction of new fuel volume is expected in the range of 5–10% or $2.5–5M in cost-savings per reactor for each refueling outage.

The current practice of the fuel reload analyses is to complete a comprehensive evaluation for many fuel cycles (i.e., 10–15 years ahead). Then, only a simplified evaluation is performed at each fuel reload to check if the safety limits are still within the regulatory-acceptable boundaries given the plant performance in the previous cycles. This approach was developed and designed for base load operation of the nuclear power plants (i.e., a steady power output at capacity of 90% and above). However, today nuclear power plants are operating at flexible power outputs instead of baseload. This is driven by electricity market conditions and grid demands where power output required from a plant is dependent on availability of renewable sources of energy, local grid conditions, weather-related power demand fluctuations, etc. Flexible power operation significantly alters fuel performance compared to the originally designed and planned base load operation. This necessitates a more detailed core evaluation at every refueling cycle since the power production profile of a core is very different from cycle to cycle. A proper fuel assessment at each refueling allows appropriate fuel configuration for the next cycle to ensure optimized core performance given specific power output profile in the previous cycles.

RESEARCH ACCOMPLISHMENT

Optimizing Core Reload

The LWRS Program is developing a platform utilizing state-of-the-art computational and modeling techniques that integrates all the required tasks to plan and optimize core reload into a single automated process. This includes an analysis of core design, safety margins, fuel performance, and fuel optimization.

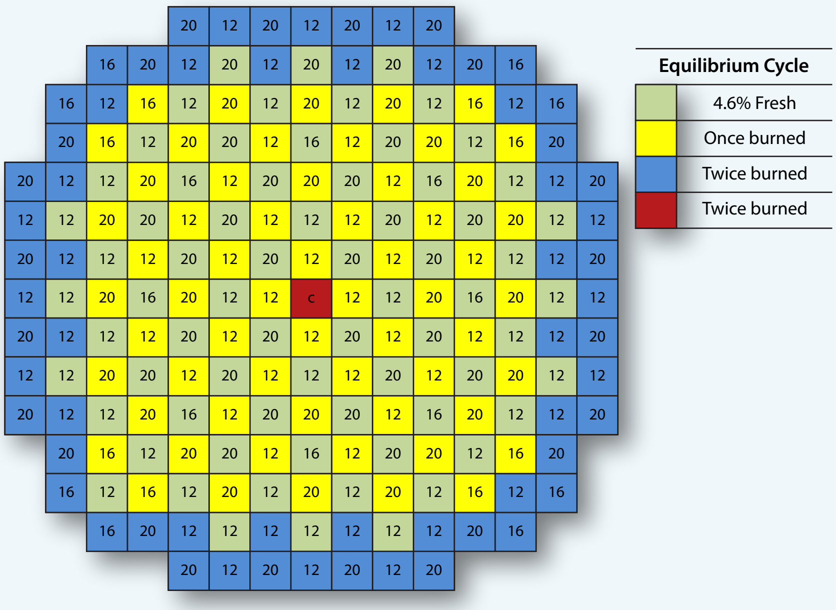


Figure 12. Sample Equilibrium Cycle Reactor Core Load.

Core load and fuel analyses today necessitate multiple analyses that are typically performed independently (e.g., neutronics analyses, thermo-hydraulic analyses) using different software tools and mostly deterministic methodologies. The purpose of the analyses is to assure safety of the fuel design based on deterministic safety limits and they rarely, if at all, address fuel optimization (i.e., options to reduce the amount of fuel for a given core reload).

In 2021, the project progressed from the planning and methodology development phase to the early demonstration phase with initial demonstration conducted for a generic PWR see "Demonstration of the Plant Fuel Reload Process Optimization for an Operating PWR" report for details.

The integrated platform allows a quicker and simpler fuel assessments, which enables all required analyses to be performed at each refueling cycle or on-demand to support plant modifications or Significance Determination Process evaluations. The product of the R&D is an integrated platform that combines multiple tasks required for a fuel reload analysis. This integration removes manual data transfer between tasks, thus eliminating human errors and significantly reducing time required to perform the analyses.

This platform also allows the transition from a deterministic approach to transient and accident analyses completed following the requirements in NUREG-0800 Chapter 15 to a probabilistic (risk-informed) approach outlined in NUREG-0800 Chapter 19. The risk-informed approach to safety evaluations is expected to enable further optimization of core thermal limits and, subsequently, an additional reduction in the size of a fuel batch.

This R&D work is very timely considering that the industry is preparing to transition to accident tolerant fuels. The developed framework will be capable to perform evaluations of accident tolerant fuels both during the licensing phase and plant normal operations. Since licensing efforts represent substantial investments, it would be advantageous for the licensees to include a modern-day fuel assessment platform into upcoming license amendment requests associated with accident tolerant fuel.

RESEARCH ACCOMPLISHMENT

Terry Turbine Expanded Operating Band Research

Historically, the steam-driven Terry turbine pump is credited to operate, then to fail about 6-8 hours after the onset of a station blackout event a dominant risk significant event in plant probabilistic risk assessment. As was observed during the Fukushima Dai-ichi Unit 2 accident, the Reactor Core Isolation Cooling system remained operable for a few days following the accident. Tests completed as part of the project confirmed that the Terry turbine remains operational for several days after a postulated event. As such, steam-driven pumps, like the one observed in Figure 13, may be credited, with high confidence, for the entire probabilistic risk assessment mission time of 24 hours and possibly beyond.

Figure 13. Crystal River-3 Terry Turbine (GS-2) used for testing.

2.1.2.4 Terry Turbine Expanded Operating Band Research to Credit Longer System Performance during Accident Conditions

In 2021, LWRS Program completed a multi-year project with industry and universities. The project, called "Enhanced Operation Strategies for System Components," was conducted to understand the true operating limits of Terry turbine systems. The details and results of the experimental work are presented in the *"Comprehensive Technical Report on Terry Turbopump Expanded Operating Band Testing at Texas A&M University"* report.

The research of Terry turbine operating limits provides a significant value to the industry via the ability to credit the extended operating time to the entire probabilistic risk assessment mission time of 24 hours and beyond.

This extended credit may potentially have a measurable effect on the probabilistic risk assessment model results in terms of increased safety margins (i.e., decreased core damage frequency and large early release frequency for station black out scenarios). The increased safety margins could provide economic benefits through increased flexibility in risk-informed applications (i.e., risk-informed technical specifications) where the success of the application depends on available safety margins. The increased reliability of the steam-driven system may offer regulatory requirement relaxation for other components which is an additional cost benefit.

2.1.2.5 Advanced Technologies for Physical Security

Research by the LWRS Program also aims to enhance the cost effectiveness of plant operations through efforts in Physical Security. Physical security of nuclear power plant sites is an important aspect of maintaining a safe, secure, and reliable nuclear energy fleet. Physical security programs at U.S. nuclear sites (government and commercial) grew to meet changes in their design basis threat over time and especially after

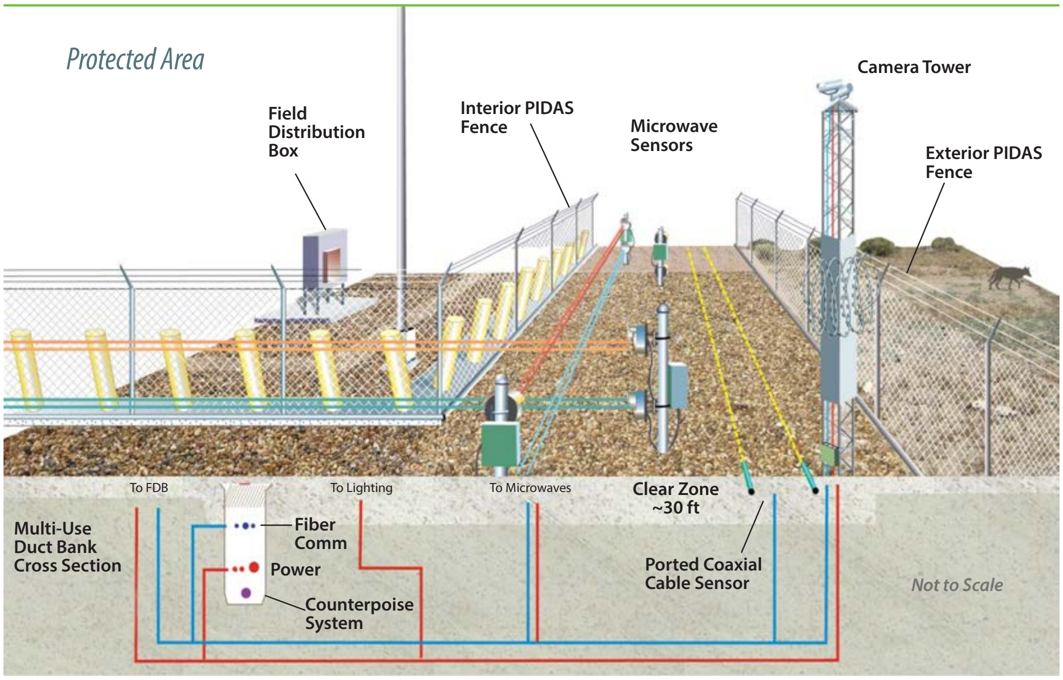


Figure 14. Example of current perimeter intrusion detection and assessment system technologies at a nuclear power plant site for adversary detection and assessment entering the protected area.

the events of September 11, 2001. The need for U.S. nuclear power plant sites to maintain a large onsite physical security force ranks high in comparison to other plant operational costs. Figure 14 provides an example of the current security technologies used for a nuclear power plant site within the perimeter intrusion detection and assessment system, which can cost $20,000 to $100,000 per foot for installation at such a high-security facility. The goal of near-term research efforts is to enable the fleet to operate more closely to the security staffing requirements established in 10 CFR 73.55.

As domestic nuclear power plants modernize their infrastructure and control systems, an opportunity exists to apply advanced tools, methods, technology, and automation to optimize physical security postures and risk-inform their security regime. These include higher-fidelity models that reduce conservatisms in security models, leverage technology and automation as a force multiplier, and use advances in risk-informed methods to optimize security postures.

The objectives of Physical Security research are to develop and deploy technologies to enable the commercial LWR fleet to adopt advanced security technologies. These R&D efforts will assist the LWR fleet in addressing the challenges in optimizing their physical security within a near-term (e.g., 2–5-year) timeframe.

RESEARCH ACCOMPLISHMENT

Development of a Technical Basis for a Remote Operated Weapons System

Current research focuses on incorporating the use of a remote operated weapon system (ROWS) into the physical security posture at commercial nuclear power plants; an example of ROWS can be seen in Figure 15. The application of advanced security technologies into LWR physical security postures potentially provides significant force multipliers for the industry and may enable an optimized physical security posture without negatively impacting required physical security capability.

Figure 15. Example of Precision Remotes T-360 GEN-2 ROWS.

The near-term research supports an assessment of current ROWS technologies which are applied in other security regimes, and an evaluation of ROWS technical and economic feasibility as a significant component of the physical security posture of a commercial nuclear power plant. These evaluations include detailing the safety basis for use of ROWS, its feasibility to be accepted by the NRC into a site's physical security posture, and exploring the economic benefit for a ROWS installation at a collaborating nuclear utility. These near-term efforts will create the ROWS technical basis information to inform industry and regulatory standards.

As a result of this research, efforts are underway with several operating nuclear power plants to adapt the technical bases for a ROWS developed through this research area to a plant-specific application that will be used to support a decision on the final design and use for deployment. This ROWS solution is considered a Government-off-the-shelf solution. Alignment of the U.S. Government sponsor to the purpose of the proposed commercialization was conducted early in the transfer process and included a clearly stated benefit.

2.1.2.6 Risk Informing Physical Security

The objective of this research is to use risk-informed methods and tools that enable nuclear utilities to optimize and appropriately balance their physical security posture and demonstrate the updated physical security posture is as effective as before the change. This research advances risk-informed technologies for physical security by integrating dynamic risk methods, physics-based modeling and simulation, operator actions, and onsite emergency response equipment, which should extend the adversarial timeline for response force success. This research will explore the expansion of existing risk-informed methods for nuclear security. The risk tools developed will enable commercial nuclear utilities to incorporate increased realism in their force-on-force models, take credit for operator actions and emergency equipment, and move towards greater use of quantitative measures of performance in security posture. This research forms the technical basis for risk-informed physical security at nuclear power plants. Additionally, risk-informed approaches will add deeper insight into performance-based assessments.

RESEARCH ACCOMPLISHMENT

Improving the Technical Basis for Physical Protection of Unattended Openings

This research provides the technical basis for reducing conservatisms for two and three-dimensional unattended openings, which potentially lead to over protection of attack paths resulting in inefficiencies in a site's security posture. Applying a risk-informed approach to unattended openings can reduce some of these conservatisms. The design of the experiment, performance test results, and statistical analyses created through this research are intended to develop a structured approach that can simultaneously support consistency in security-related decision-making and address the unique security-related concerns for each nuclear power plant site. Ultimately, insights from unattended opening testing provides a framing to leverage the advantages of risk-informed approaches in helping to improve physical security while modernizing nuclear power plant sites against a 21st century threat environment.

Testing was conducted at Sandia National Laboratories and the results will be used to provide the technical basis to re-evaluate and redefine the minimum opening size that a person can effectively pass through and navigate. The tests are on both simple two-dimensional (up to 36-in. in depth) and more complex three-dimensional (longer lengths and changes in direction) configurations. Figure 16 shows an example of the three-dimensional testing using modular circular pipe sections with predetermined internal dimensions. The primary impact of this effort defines credible scenarios where an adversary could successfully pass through a potentially complex opening, as well as define the scenarios in which defined adversary capabilities would not be expected to successfully traverse a complex opening. At its inception, this research intended to investigate openings that could be found to intersect security boundary layers, but through careful experimental design, the testing seeks to further understand the delay characteristics of engineered openings, as well as the potential breach points.

Nuclear utilities and NRC have an established minimum passable opening, and while these dimensions have been the accepted standard for decades, there

Figure 16. Example of a three-dimensional pipe test configuration.

is little information to their origin, correlation to the adversary size that could exploit the minimum openings, or how much delay is generated by openings of different sizes. This research not only determined the smallest area in which an adversary can pass, but also correlates passable apertures with statistical person size data for various populations, and how fast they can successfully navigate different configurations. The size of the person attempting to breach the opening will be a primary influence on opening size, and there are critical dimensions of the human body that cannot be easily manipulated, such as hip-width, chest depth, and head diameter. Conversely, other adversary factors are less fixed, such as choice of clothing, body armor, or equipment and weapons being carried that could be dragged behind during the passthrough to successfully traverse the opening. The time and rate that it takes to successfully navigate a longer opening, such as a pipe, will depend on variables such as person size, pipe diameter, internal surface friction, and the ability to navigate corners. Personality variables like claustrophobia, mental fortitude, determination, etc., were not considered as it is assumed a determined adversary will mentally prepare and allow themselves to be placed in uncomfortable and stressed positions to achieve their goal.

Performance-based testing included both male and female test participants ranging in size as determined by interrogating human factors databases with large sample size populations. All testing was broken into two distinct activities: (1) two-dimensional testing; and (2) three-dimensional testing. For the two-dimensional tests, participants navigated through rectangular and square openings that can be varied incrementally in both horizontal and vertical major dimensions, and a circular aperture to simulate a round hole. The depth of the two-dimensional fixture is approximately 3.5-in., which approximates a thin wall section. Additionally, each participant attempted to traverse a series of pipe sections of varying diameters, which are each 36-in. long. The three-dimensional testing utilized modular circular pipe sections with predetermined internal dimensions; see Figure 16. These tests are configured to provide a long 24-ft. straight section, an "L" with a single 90° elbow, or a jog section with two 90° elbows.

RESEARCH ACCOMPLISHMENT

Enhancing Methods for use in Risk-Informed Physical Security

This research explores the expansion of existing risk-informed methods for nuclear security. This includes a review of different risk-informed approaches for application to physical security, such as System Theoretic Process Analysis (STPA), Risk-Informed Management of Enterprise Systems (RIMES), Multi-Objective Decision Analysis (MODA), dynamic Probabilistic Risk Assessment, and other potential dynamic risk approaches. As shown in Figure 17, a two-tiered approach of risk-informed decision-making may inform decisions on how to best manage and prioritize approaches to physical security. Using just a preliminary assessment of the Tier 1 approach can justify to a site's decision-

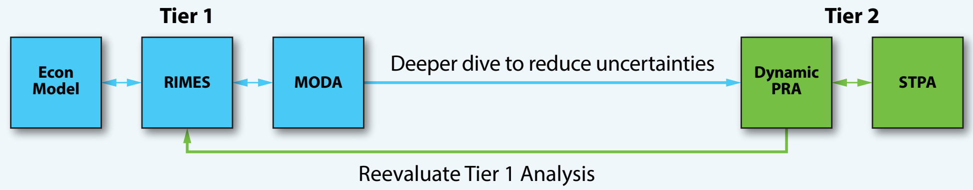


Figure 17. Two-tiered near-term threat approach to physical security risk.

makers whether current performance-based assessments are sufficient for their given regulatory requirements and budget constraints. Consideration of advanced metrics to consider measures of system effectiveness for physical security posture with performance-based inputs are also evaluated.

Additionally, dynamic Probabilistic Risk Assessment research is being performed to develop a dynamic modeling and simulation framework to enable balanced physical security optimization at commercial nuclear power plant sites. The framework is based on the dynamic modeling tool EMRALD and is demonstrated for applications that can result in physical security optimization. Two main applications under consideration are:

1. Integrating onsite emergency response portable equipment performance within force-on-force models to better inform a nuclear power plant site's physical security posture.
2. Location and optimization of blast and bullet resistant enclosures.

For this research, the generic framework for modeling onsite emergency response portable equipment was established, followed by a case study modeling an adversarial attack aimed at causing a radiological release by sabotaging the nuclear plant's power supply and its ultimate heat sink capabilities at a hypothetical pressurized water reactor site.

Two distinct post-sabotage emergency response deployment strategies, series and parallel, were modeled with distinct timelines. The results of the adversarial attack modeled in a commercial force-on-force tool, AVERT, are integrated with the emergency response deployment model in the dynamic software, EMRALD. Monte Carlo simulation was used to model the distribution of the timeline in deployment strategies. Thermal-hydraulic analysis of reactor system performance was performed in the RELAP5 software and integrated with the EMRALD simulations to provide more realistic timelines in the models (adversary vs. response force vs. reactor system response).

The results demonstrate that even in the extreme case of a successful adversarial attack, the deployment of onsite emergency response equipment can result in a significantly high likelihood of preventing an offsite release from radiological sabotage. The modeling and simulation framework of integrating onsite emergency response equipment with force-on-force models can enable the nuclear utilities to credit onsite emergency response equipment within the security posture of a plant, resulting in more efficient, balanced, and optimized physical security.

Lastly, a related research activity developed risk-informed timeline software that focuses on reducing conservatisms in adversary timelines. Current adversary timelines potentially lead to overprotection of a potential attack path resulting in inefficiencies and imbalance in areas of the security posture of a nuclear power plant. Applying a risk-informed software tool to these adversary timelines reduces some of these conservatisms.

Collectively, these efforts are developing new capabilities in dynamic risk assessment that can be used to better represent and analyze physical security issues and develop effective security programs to secure nuclear facilities. The use of risk-informed physical security methods is expected to yield similar advantages to a nuclear power plant site as what has evolved through risk-informed nuclear safety; however, unlike safety, the evolution of the dynamic nature of threat must be considered. For example, threat evolution, quantification of deterrence, and threat-shifting are active areas of research outside of the LWRS Program, which will be reviewed and leveraged, as appropriate, within LWRS Program developed risk-informed methods.

2.1.2.7 Advanced Sensor and Barrier Systems for Physical Security

The objective of this research is to develop advanced sensor and barrier (delay) systems for physical security, which have the potential to significantly improve industry response time to a design-basis threat adversary early in the attack phase. Successful efforts in this area would increase the likelihood of defending against an attack and enhance the economics of doing so. As domestic nuclear power plants modernize their infrastructure and control systems, opportunities exist to leverage advances in sensor and barrier technologies to provide an improved technical basis necessary to modernize and optimize physical security capabilities.

RESEARCH ACCOMPLISHMENT

Development of a Multi-Year R&D Roadmap for Advanced Physical Security Sensors and Delay Technologies

A multi-year research roadmap for advanced physical security sensor and delay technologies was developed to guide and prioritize current and future R&D tasks. The physical security sensor and barrier technology roadmap includes efforts to employ new methods, tools, and technologies to achieve optimized physical security. Projects included in this roadmap vary from those that are nascent to the well-developed, and LWRS sponsorship will affect the development timeline. This roadmap highlights R&D efforts related to physical security sensor and barrier technologies, including available commercial-off-the-shelf sensors, using low-cost materials, and robust, remotely deployable attachment methods. The goal of these efforts is to improve LWR physical security systems via the implementation of highly reliable detection systems that reduce nuisance alarms.

This research leverages technology to develop such advanced sensing capabilities as those shown in Figure 18. It provides a notional improvement beyond the perimeter security systems by advancing the use of U.S. Government developed security technologies at U.S. nuclear power sites to assist in overall cost reductions, reduced nuisance alarm rates, and increases in adversary detection. These advanced sensor technologies will also enhance a site's early response by improved interdiction, adversary neutralization, and raise the overall physical security system effectiveness.

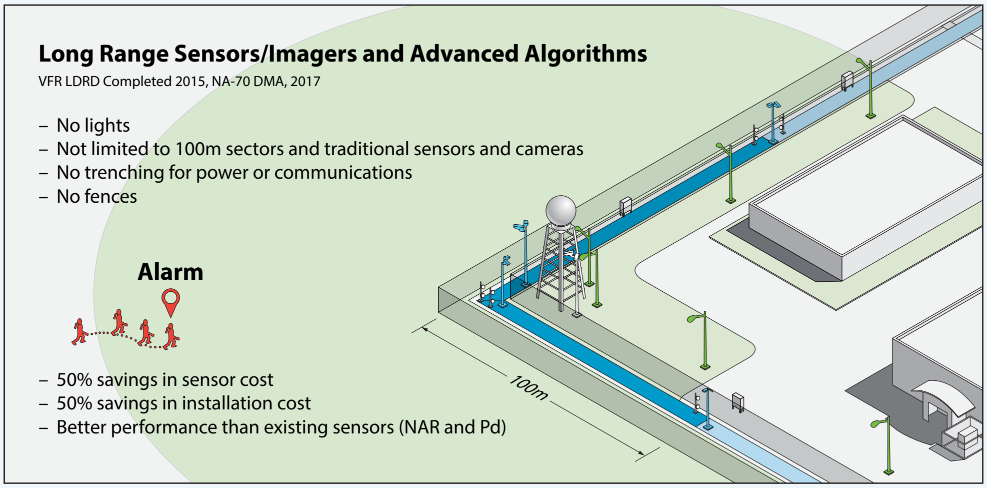


Figure 18. Example of U.S. Government technologies that could be leveraged at a nuclear power plant site for early adversary detection and assessment.

2.2 Delivering the Scientific Basis for Continued Safe Operation

2.2.1 Understanding and Managing the Aging and Performance of Key Materials for Long-Term Operation

Nuclear reactors present a variety of challenging environments to materials that comprise structures, systems, and components. Many components in an operating reactor must tolerate high-temperature water, stress, and vibration, as well as an intense neutron field. Degradation of materials in this environment can affect component performance and, without accurate predictive knowledge of component lifetime or if degradation is left unmitigated, can lead to unexpected and costly repairs or failure of these components while in-service. More than 25 different metal alloys can be found within the primary and secondary systems, along with additional materials in concrete, the containment vessel, I&C equipment, cabling, and other support structures. This diversity of material types, challenging environmental conditions, stress states, and other factors make material degradation in a nuclear power plant a complex phenomenon. In simplified form, illustrates that many variables

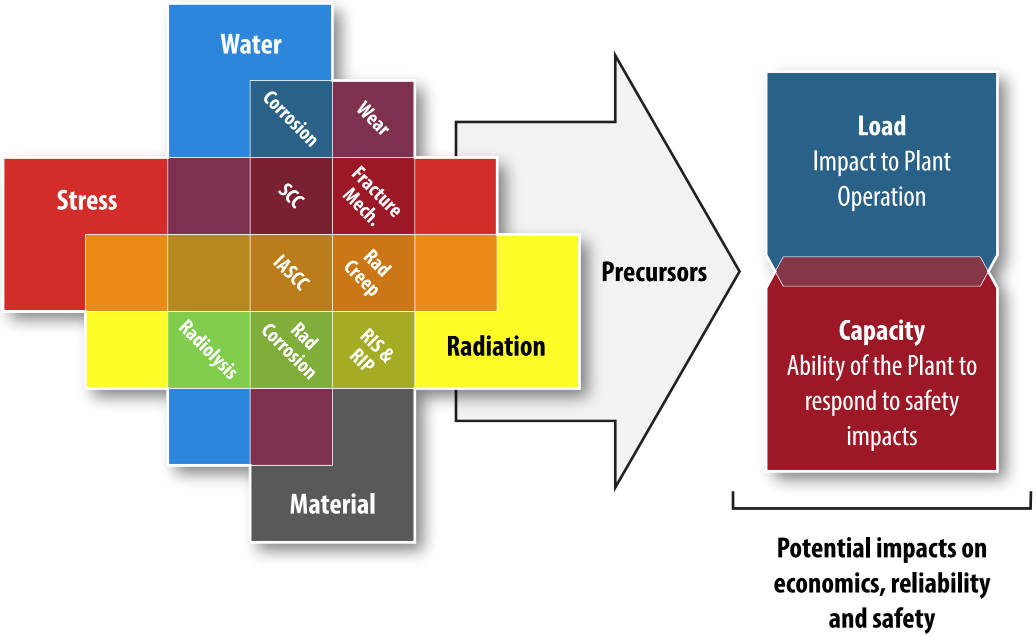


Figure 19. Complexity of interactions between materials, environments, and stresses in a nuclear power plant.

have complex and synergistic interactions that affect materials performance in ways that can impact plant operation or reduce the safety performance of a nuclear power plant. Furthermore, unexpected failures or, conversely, the unnecessary repair of components due to overly conservative estimates of degradation can lead to higher operational costs.

The continued operation of the existing nuclear power fleet beyond 60 years will place continued demands on materials and components in their in-service environments. Understanding the performance of these materials during these longer periods of operation entails characterization of the materials as they age under the demands of in-service conditions and relating that knowledge to the performance characteristics of the different SSCs. The research conducted through the activities described here is intended to provide data, models, methods, and techniques to inform industry on long-term materials performance. Research activities focus on the following materials and novel mitigation strategies to address aging, degradation: (1) reactor metals, (2) concrete, (3) cables and (4) weld repair and advanced replacement materials.

Over the last decade, great gains have been made in techniques and methodologies that can be applied to the current nuclear materials problems. Modern materials science tools such as advanced characterization and computational tools must be employed. Furthermore, because of the complex nature of these degradation modes and the synergistic effects between them, combined approaches must be taken. Materials research must include a mix of experimental testing performed in simulated reactor environments under accelerated conditions, the examination of harvested components that experienced actual service conditions over long periods of time, and the modeling or simulation of degradation effects.

The strategic goals of the Materials Research are to develop the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants and to provide data and methods to assess the performance of SSCs essential to safe and economically sustainable nuclear power plant operations. Moreover, Materials Research tasks support industry by providing expertise, unique facilities, and fundamental knowledge in the form of data, analysis, characterization techniques or predictive models, improved codes, and reduced uncertainties. Additionally, enhanced engagement with the nuclear industry to address specific needs and issues through direct interactions has accelerated over the past two years.

2.2.1.1 Ensuring the Long-Term Performance of Reactor Metals

Numerous types of metal alloys can be found throughout the primary and secondary systems of reactors. Some of the components made of those materials (in particular, the reactor internals) are exposed to high temperatures, water, and neutron flux. This challenging operating environment creates degradation mechanisms in the materials that are unique to reactor service. Research programs in this area will provide a technical foundation to establish the ability of those metals to support nuclear reactor operations to 60 years and beyond. The high-priority metals research efforts are described below.

Mechanisms of irradiation assisted stress corrosion cracking in stainless steels: This task is developing an understanding of role of composition, material history, and environmental influence on irradiation assisted stress corrosion cracking and developing modeling capabilities based on a strong mechanistic understanding.

IASCC has been widely recognized as a major degradation mode for reactor core structural materials and is of most concern for reactors with a life extension to 60 or 80 years. IASCC occurs under the combination of applied stress and a corrosive environment in irradiated materials. Neutron irradiation induces a build-up of damage that leads to a change of microstructure (e.g., dislocation loops, precipitates, voids) and microchemistry (e.g., segregation), which can potentially enhance stress corrosion cracking susceptibility.

RESEARCH ACCOMPLISHMENT

Estimating the Effects of Irradiation Assisted Stress Corrosion Cracking in Reactor Metals

Dose and stress threshold concept: Since the first observation of IASCC in 304 stainless steel fuel cladding in the early 1960s in light reactors, many studies have been conducted to investigate the correlation of IASCC susceptibility with irradiation damage. In pressurized water reactor (PWR) primary water, the practical IASCC threshold of austenitic stainless steel is approximately three dpa, below which no significant degradation of the resistance to SCC is observed. Above this number, IASCC susceptibility was observed to increase with dose up to 73 dpa. However, it is still unknown whether susceptibility continues to increase with dose to very high dose levels corresponding to a service lifetime of 60 to 80 years.

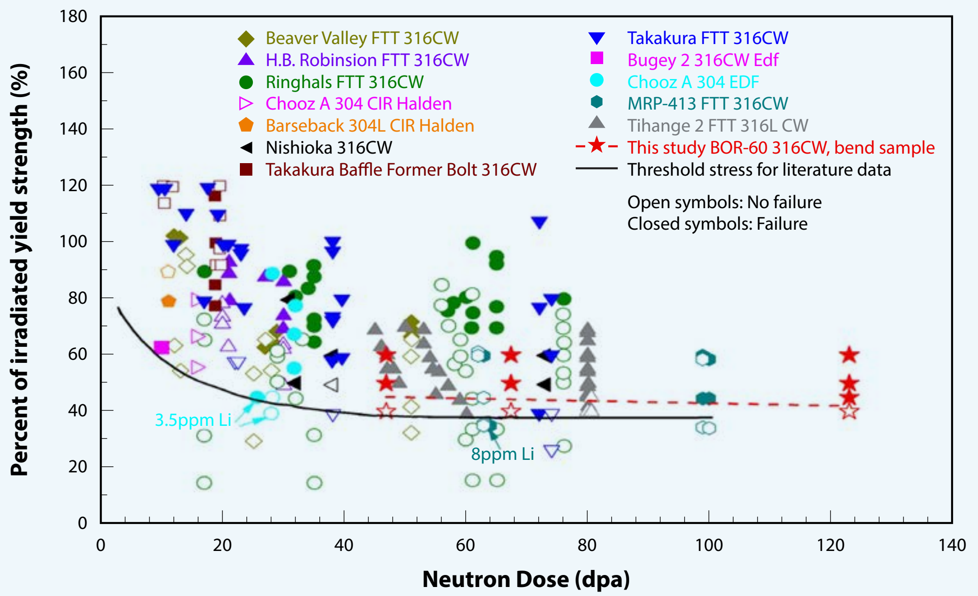


Figure 20. Stress as a percent of irradiated yield strength vs. neutron dose for IASCC crack initiation in austenitic stainless steels in a PWR primary water environment for the cold-worked 316 stainless steel samples tested in four-point bend mode.

IASCC of structural materials consists of two steps—crack initiation and crack growth. The crack growth rate of neutron-irradiated stainless steels is in the range of 10-7-10-5 mm/s, which means the lifetime of a core internal component is mainly determined by the crack initiation time. Like the dose threshold of IASCC susceptibility, a stress threshold below which no IASCC crack initiation occurs has also been proposed. With the increase of data obtained at higher dose, lower stress, and longer exposure times in PWR relevant environments, the semi-empirical threshold has dropped from 62% of the irradiated yield strength to 50% and further to 40%. It is not clear whether this value will continue to drop with additional higher dpa data or much longer exposure times, as shown in Figure 20.

Localized strain as a mandatory condition for crack initiation: Based on previous LWRS Program research, it was established that the intersection of discontinuous dislocation channels with grain boundaries are sites at which extremely high tensile stresses are generated. These sites are likely the cause of failure at applied stresses well below the bulk yield stress. However, while a necessary condition for stress corrosion cracking, stress alone is insufficient. The LWRS Program research described below, has identified what is a precursor condition for the initiation of grain boundary cracks.

Four-point bend samples of cold-worked 316 stainless steel were stressed in simulated PWR primary water. Figure 21 shows the evolution of an IASCC crack with increasing stress in a cold-worked 316 stainless steel sample irradiated to 125.4 dpa. No cracks were visible at 40% of the yield stress and at 45% of the irradiated yield strength (σy), a grain boundary is just visible by virtue of a slight degree of oxidation that appears dark in the secondary election image. At 0.5σy, oxidation along the grain boundary is more prevalent and non-uniform, but there is no evidence of a crack. At 0.6σy, the boundary has now cracked both above and below the triple junction. The backscattered electron image also shows evidence of a localized deformation band (e.g., dislocation channel or twin) intersecting the grain boundary at the crack initiation site. Similar experiments on cold-worked (CW) 316 stainless steel samples irradiated to 46.7 and 67.4 dpa revealed that cracking started at 0.6σy and 0.5σy, respectively, though the stress increments were larger. These bend test results agree well with the database as shown in Figure 20. The agreement in the magnitude of the stress threshold for cracking between ring tests and the four-point bend tests indicates that failure in the former test types is controlled by crack initiation processes.

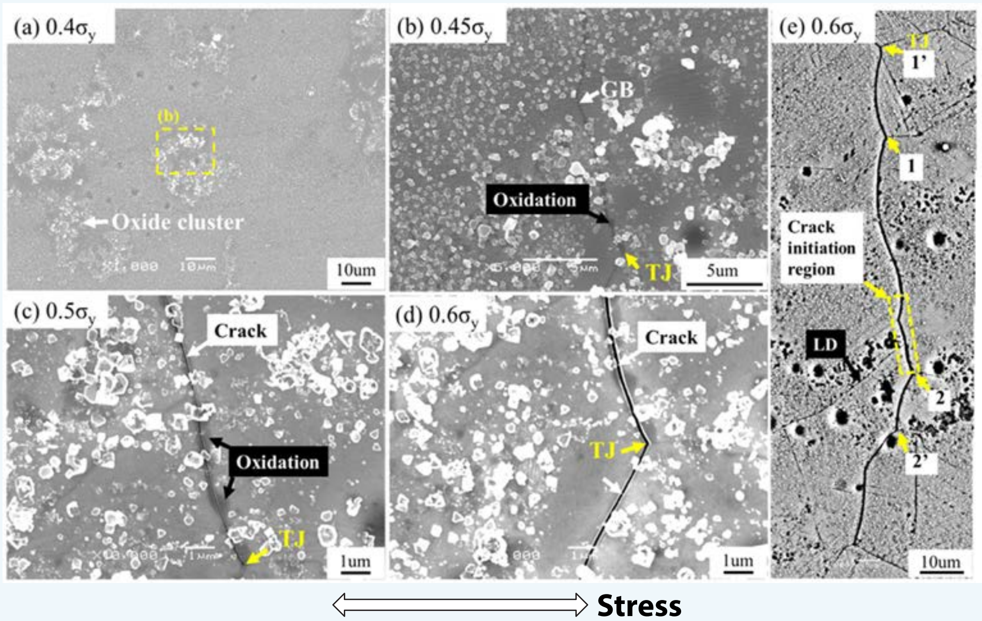


Figure 21. Stages of crack initiation and propagation in a CW 316 stainless steel sample irradiated to 125.4 dpa. (a) oxide cluster formation, (b) GB oxidation after straining to 0.45σy, (c) crack initiation at triple junction (TJ) and localized deformation (LD) sites after straining to 0.5σy, (d) crack propagation in the direction relatively normal to the applied stress after staining to 0.6σy, and (e) SEM-back scatter electron image of a long crack.

New precursor to IASCC?: As shown in Figure 21, the value of the four-point bend technique developed within the LWRS Program is that this technique is able to capture the evolution of a crack with stress and in doing so, identify features of the microstructure that correlate with cracking, as well as precursor conditions to cracking such as grain boundary oxidation. Figure 22 provides a look at localized deformation in the form of dislocation channels or deformation twins and triple junctions. This process is sensitive to mechanical stress level, as depicted in Figure 21, and damage dose. Being a precursor to the crack initiation, grain

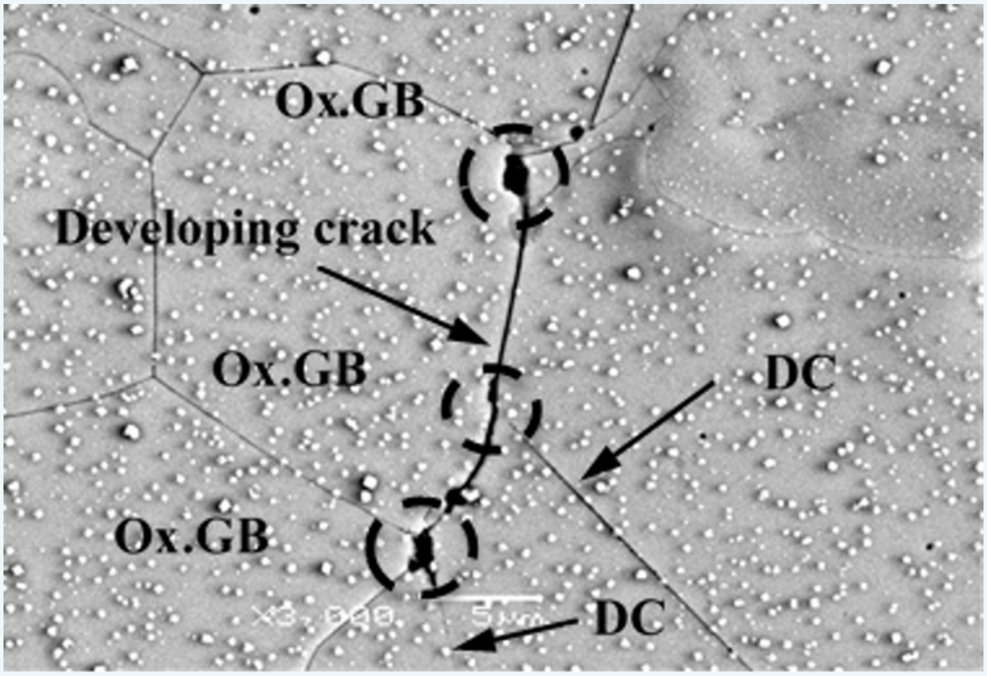


Figure 22. Complexity of processes during IASCC crack initiation: Ox.GB – oxidized grain boundaries, DC – dislocation channels. Dashed ovals show localized corrosion damage (pits) which correlate with DC. SA304L, 5.4 dpa. SEM-back scatter electron image.

boundary oxidation may be easy to detect using modern techniques like scanning electrochemical microscopy.

This critically important research has revealed a new, very comprehensive picture of the IASCC crack initiation and evolution that is being used to develop a better understanding of the mechanism by which IASCC cracks initiate. And with the enhanced understanding, it will open the path to predictive model development and, ultimately, the developing advanced sensor(s) for detecting critical material conditions while in-service.

2.2.1.2 Assessing the Possible Replacement of LiOH with KOH in Nuclear Power Plant Primary Water to Reduce Costs

The U.S. nuclear industry is considering replacing lithium hydroxide (LiOH) with Potassium Hydroxide (KOH) for pH (a measure of the acidity or basicity of an aqueous solution) and corrosion control in PWR primary water due to rising costs and fluctuating availability of LiOH. Among the many aspects of reactor operation that need to be assessed before switching to KOH, it is necessary to evaluate the stress corrosion cracking response of Ni-base alloys in a KOH environment to ensure that stress corrosion cracking susceptibility is not increased by KOH water chemistry. In collaboration with an ongoing EPRI -led KOH qualification program, this research is performing stress corrosion cracking evaluations on selected materials in both LiOH and KOH-containing PWR primary water chemistries.

RESEARCH ACCOMPLISHMENT

Support for Switching from LiOH to KOH in Nuclear Power Plant Primary Water

Research has focused on evaluating stress corrosion cracking growth behavior of two high-strength Nickel (Ni)-based alloys—alloy X-750 and alloy 718 using in situ measurement of crack length in PWR primary water chemistry. The Potassium Hydroxide (KOH) and Lithium Hydroxide (LiOH) concentrations were selected to achieve the same pH with the chemistries changed on-the-fly, allowing uninterrupted, direct comparison of stress corrosion cracking growth rates of KOH vs. LiOH. In addition, stress corrosion cracking initiation behavior of alloy X-750 was assessed in KOH and LiOH water chemistries. Thus far, no obvious difference has been observed in stress corrosion cracking initiation and growth behavior between the KOH and corresponding reference LiOH water chemistries as shown in Figure 23.

While some scatter exists, the stress corrosion cracking initiation times of the specimens tested in these two water chemistries generally fall within the same range. Standard and censored Weibull analyses on the two data sets also revealed a large overlap in the 95% confidence intervals for any given cumulative failure probability. The preliminary results suggest that the stress corrosion cracking initiation time of Alloy X-750 in the KOH beginning-of-cycle water chemistry might be slightly longer than in the LiOH beginning-of-cycle water chemistry. Additionally, post-test characterization found no obvious difference in the initiation morphology between these two sets of specimens. These results indicate that replacing LiOH with KOH would not adversely impact the stress corrosion cracking initiation susceptibility of Alloy X-750 in PWR primary water.

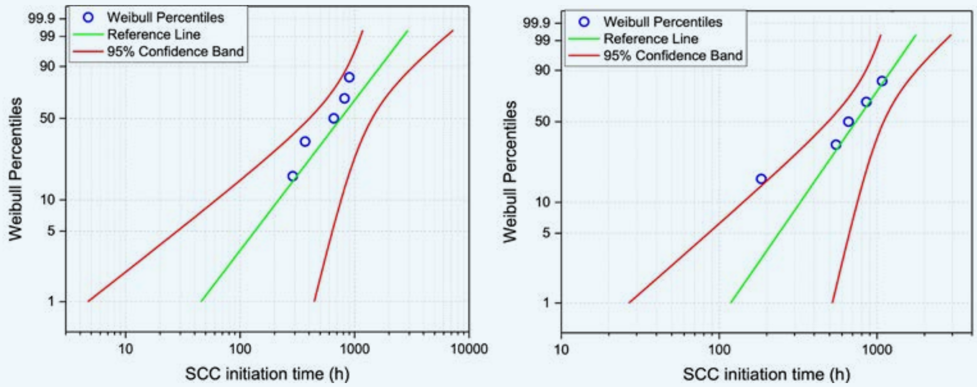


Figure 23. Censored Weibull analysis (cumulative failure vs. hours) with a 95% confidence interval based on the stress corrosion cracking initiation times acquired on alloy X-750 at yield stress in 360°C PWR primary water containing (left) LiOH and (right) KOH.

2.2.1.3 Modeling Aging and Degradation of Concrete in in-Service Environments

As concrete ages, changes in its properties will occur because of continuing microstructural changes (e.g., slow hydration, crystallization of amorphous constituents, and reactions between cement paste and aggregates) as well as environmental influences. These changes must not be so detrimental that the concrete is unable to meet its functional and performance requirements. Concrete can suffer undesirable changes with time because of improper specifications, a violation of specifications, adverse performance of its cement paste matrix, or adverse environmental influence on aggregate constituents. The long-term performance of concrete in nuclear power plants varies with environmental and operational conditions (temperature, humidity, in-service mechanical loading, and irradiation).

In nuclear power plants, the primary function of the concrete biological shield is to contain neutron and gamma radiation emitted by the reactor. The secondary function is to provide support for the reactor system depending on its design. Depending on the operating conditions and the design of the reactor, the surface of the concrete biological shield near the reactor cavity may be exposed to high levels of neutron- and gamma-ray doses. To address aging nuclear power plants and future license renewals, it is critical to understand and assess the effects of irradiation on the structural performance of the concrete biological shield over extended periods of operation.

RESEARCH ACCOMPLISHMENT

Development of the Microstructure-Oriented Scientific Analysis of Irradiated Concrete (MOSAIC) to assess concrete performance

LWRS Program research is developing rigorous methodologies for the predictive assessment of the effects of irradiation on concrete. This combines advanced characterization techniques capable of imaging any harvested concrete specimen with high-resolution (10 to 15 microns), a comprehensive database of concrete and its constituents, and the Fast-Fourier Transform-based software, MOSAIC, which was developed by the LWRS Program.

The capabilities of MOSAIC-2D have been extensively tested and validated with irradiated concrete data obtained in accelerated test reactor conditions. This research significantly benefited from a collaboration with the Japan Concrete Aging Program (JCAMP) through the DOE / Civil Nuclear Energy Working Group collaborative framework between the DOE and the Japan Ministry of Economy, Trade, and Industry. Pristine and irradiated aggregates and concrete specimens and data were shared with the LWRS Program by JCAMP. The simulation results using MOSAIC, as shown in Figure 24, were found to predict and obtain accurate estimates of irradiated properties, such as radiation-induced volumetric expansion and the loss of elastic (mechanical) properties. Based on these validated results, a tool suite has been developed to assess the tolerance of any LWR concrete to the long-term effects of irradiation using unirradiated concrete specimens obtained from the plant. With the ongoing development of MOSAIC-3D, it is expected that additional properties, such as changes in mechanical strength, will also be effectively predicted.

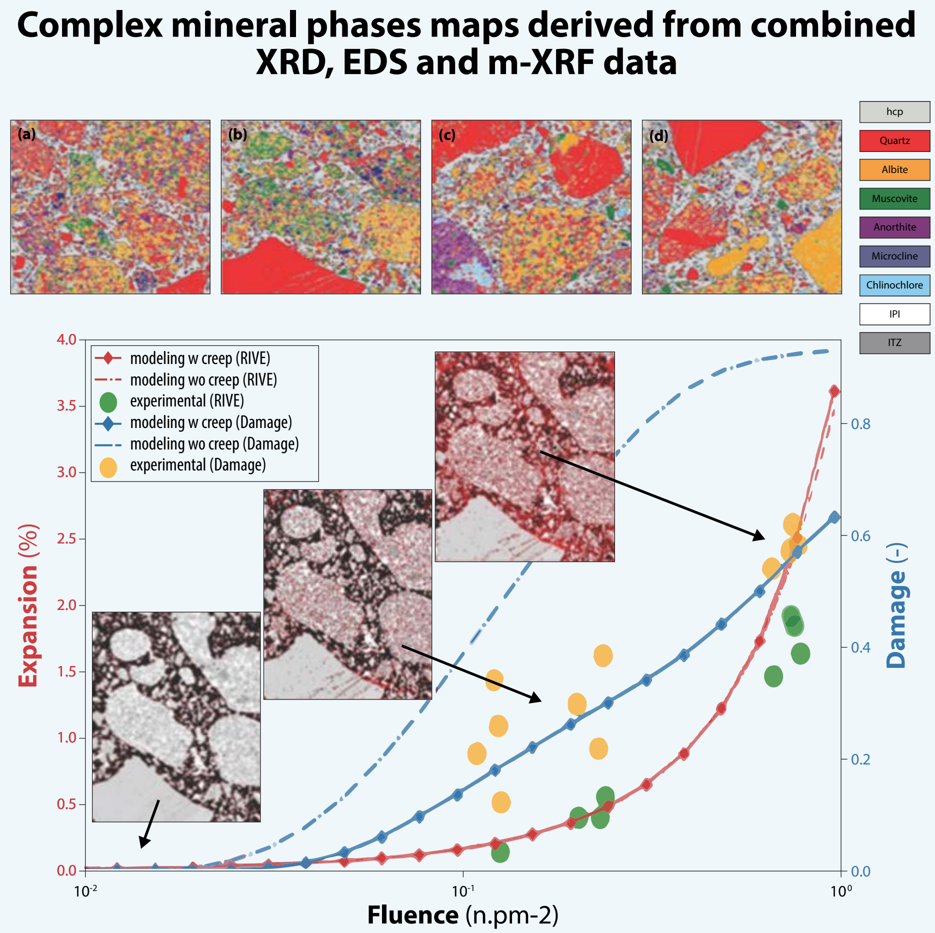


Figure 24. Validation of 2D MOSAIC tool using JCAMP data.

2.2.1.4 Assessing the Performance of Cables to Support Long-Term Operation

The technical approach to evaluating cable lifetime is shown in Figure 25. This approach utilizes harvested and representative cables that are historically similar cable formulations used in reactors that were stored appropriately and not used in reactor service. Testing involves the isolation of the effects of various environmental stressors, as well as the synergistic effects that create changes in mechanical, physical, and electrical properties due to chemical changes in the insulation. These changes are also being evaluated via nondestructive (NDE) techniques to develop methods suitable for in-field condition monitoring. The goal of the accelerated aging testing and NDE is to determine the remaining useful life of the cables.

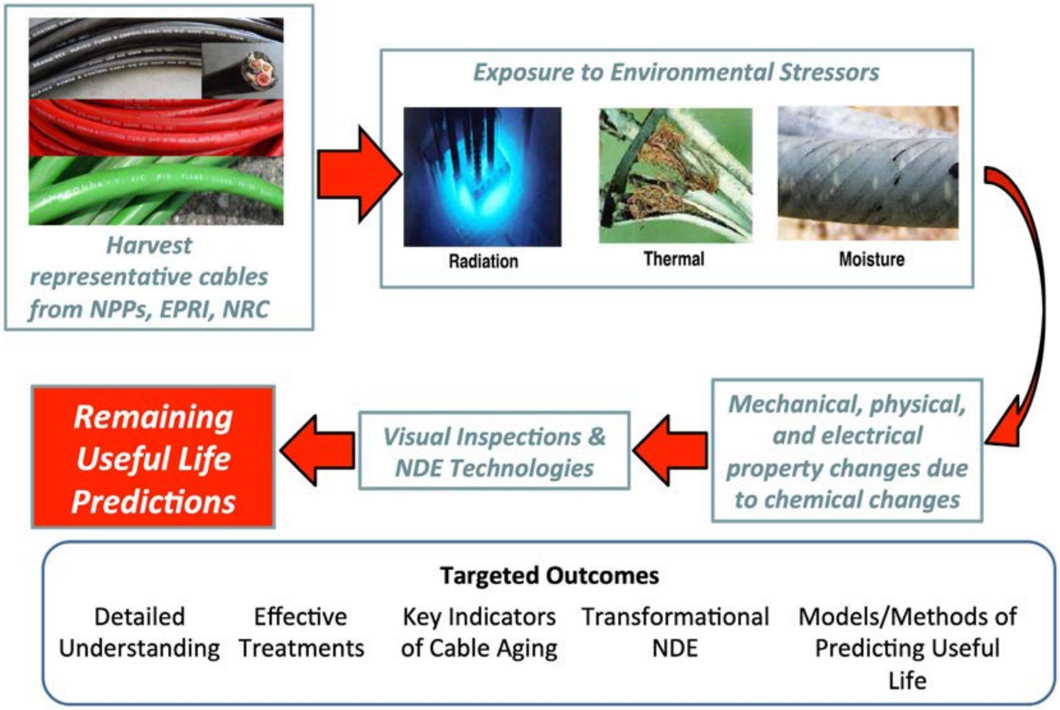


Figure 25. Diagram of the technical approach to cable aging studies to understand the different degradation modes affecting cable lifetime and to evaluate deployable NDE methods for determining remaining useful life.

The most important criterion for nuclear power plant cable performance is its ability to withstand a design basis accident. With nearly 1,000 km of power, control, instrumentation, and other cable types typically found in a nuclear power plant, inspecting all the cables would be a significant undertaking. Degradation of the cable jacket, electrical insulation, and other cable components is a key issue that is likely to affect the ability of the currently installed cables to operate safely and reliably for another 20 to 40 years beyond the initial operating life. The development of NDE techniques and models that could assist in determining the remaining useful life of cables or their current degradation state would be of significant interest. The ability to nondestructively determine material and electrical properties of cable jackets and insulation without disturbing the cables or connections is essential.

A primary objective of cable research is the development and validation of new NDE technologies for monitoring the condition of cable insulation. This research involves the development of a physics-based model for NDE signal response of compromised or degraded cables. This includes techniques for both global (long-length) cable NDE techniques, such as frequency-domain reflectometry (FDR), and local techniques, such as interdigital capacitance spectroscopy.

RESEARCH ACCOMPLISHMENT

New technologies to monitor Cable material and component performance

In 2021, research focused on evaluating the feasibility of using FDR to determine electrical cable submergence using Pacific Northwest National Laboratory's Accelerated and Real-Time Environmental Nodal Assessment (ARENA) cable/motor test bed shown in Figure 26. Nuclear power plants have experienced various electrical cable failures related to water exposure. The current industry response involves actions to de-water cable vaults, manholes, and other cable locations. These efforts require considerable expenditure of resources, which makes it desirable for the industry to have information on cable condition and history regarding their submergence and water exposure. To address this issue, two low-voltage NDE tests, time-domain reflectometry (TDR) and FDR, are gaining usage because testing can be applied at a cable end. Testing from the cable end is important because local inspection along the cable length is very difficult because of cables being routed within trays, conduits, underground, and through walls.

Both TDR and FDR techniques have been shown to locate cable insulation damage caused by thermal, radiation, and mechanical damage. However, FDR measurements are more sensitive than TDR to temperature changes, low-bend radius bends, and cable contact with various materials, including conductive materials such as steel and water. As shown in Figure 26, the test results demonstrated that FDR detected the presence of water in unshielded cables and that the FDR data obtained with and without the motor were equivalent. The ability to test cables and motors in place without disconnection will not

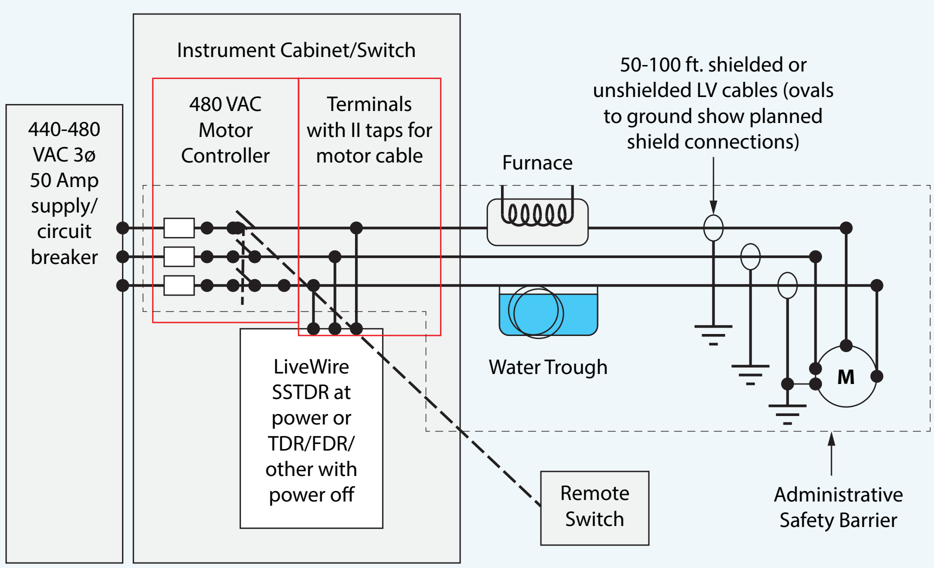


Figure 26. Schematic of the ARENA cable/motor test bed at Pacific Northwest National Laboratory.

only reduce labor and downtime costs associated with the testing, but more significantly will reduce costs associated with workmanship-based defects.

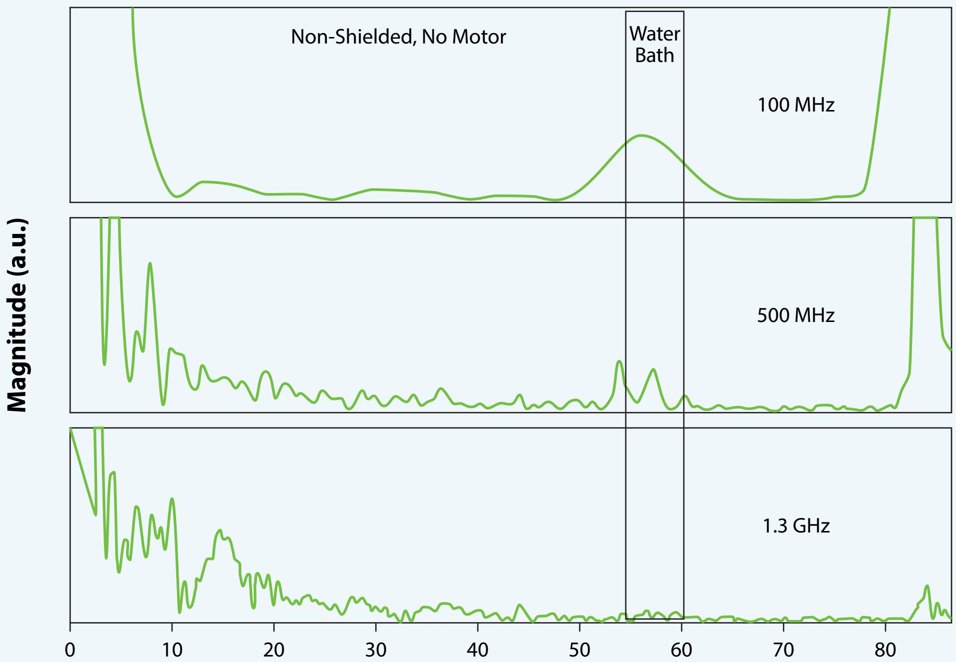


Figure 27. FDR measurements were made on shielded and unshielded cables with the 55 to 60 ft section submerged and dry, with and without motor connections, and over frequencies from 0.1 to 1.3 GHz, confirming the feasibility to extend FDR NDE to indicate submergence and submergence location.

2.2.2 Addressing Aging and Obsolescence of Plant Technologies

2.2.2.1 Research to Enable Analog Safety System Replacement with Digital Technology

Analog instrument and control (I&C) systems used by the nuclear industry continue to function reliably (Figure 28). However, spare and replacement parts are becoming increasingly scarce, as is the workforce familiar with maintaining these analog I&C systems. Even though the costs of obsolescence management are high, the nuclear industry has delayed modernizing the analog I&C systems. The delay in modernizing is primarily due to the perception that replacing existing analog with digital technologies involves significant technical and regulatory uncertainty. This perception formed largely when early modernization projects encountered delays and substantially higher costs than initially predicted. These early setbacks have slowed the pace of analog I&C system replacement and contributed to an overall lack of experience with plant modernization initiatives.

Figure 28. Much of the current instrumentation and controls in a nuclear power plant control room is analog technology.

This collection of analog I&C systems are more costly to maintain than modern digital systems, requires a specialized workforce, and is not supported by the modern I&C supply chains. By choosing to maintain aging analog systems rather than modernize, utilities are tying their business model to a highly labor-centric plant operation method, an approach with rising future costs rather than the declining costs of modern technology. Ultimately these I&C refurbishments delays have put the nuclear industry at a distinct disadvantage to remain competitive in future energy markets. Additionally, these delays in reinvestment create a "bow wave" for needed future reinvestments. Because the return period on reinvestments becomes shorter, the longer they are delayed, the less financially viable they become, adding to the risk that I&C may become a limiting or contributing factor against the decision to operate nuclear power assets for longer periods.

LWRS Program researchers working with the nuclear industry have developed a comprehensive digital infrastructure architecture to address the challenges associated with I&C system obsolescence and help utilities develop their specific modernization strategies. This digital infrastructure incorporates the ION Framework principles presented in Section 2.1.2.1 and provides a sustainable architecture that extends plant life, enables a cost-competitive business mode, and includes business case analysis research to justify investments in digital technology modernization. Digital technology and related human and technology integration research projects target realistic opportunities to address I&C system obsolescence, improve human performance while reducing O&M costs, making existing nuclear plants cost-competitive to operate. Their research employs unique DOE facilities and testbeds such as the one shown in Figure 29. These provide a realistic setting for developing and validating new digital technologies to retrofit existing nuclear power plants.

Figure 29. Human Systems Simulation Laboratory: a reconfigurable hybrid control room simulator.

RESEARCH ACCOMPLISHMENT

Private-Public Partnership with Exelon To Demonstrate the Approach for Digital Safety System Upgrades in the U.S. Nuclear Industry

LWRS continues critical research in the area of digital modernization and obsolescence management. In 2021 DOE announced an award to Exelon for $50 M to support the modernization of analog safety systems at its Limerick Generating Station. The DOE funding awarded to Exelon Generation enables continued collaboration between LWRS researchers and Exelon Generation, providing an at scale demonstration of a full safety system digital upgrade – the first of its kind attempted in over 10 years in the U.S. These research results provide necessary modernization guidance to the U.S. nuclear fleet and evidence that the appropriate value from investments in modernization over the life of the existing fleet of domestic reactors is achievable. The success of this project enables the broad transfer of knowledge and methodologies to the U.S. nuclear operators, vendors, and suppliers who all face similar challenges to perform safety system upgrades.

In 2021, LWRS researchers developed a Human Factors Engineering Program Plan and performed an Operating Experience Review Workshop with initial funding provided by Exelon as part of the public/private partnership enabled by the DOE funding award. These activities initiated human factors engineering work for this effort that will continue throughout the Exelon safety system digital upgrade pilot project

In 2021, LWRS researchers also developed a detailed Digital Infrastructure (DI) framework, providing both the Exelon I&C upgrade pilot and other nuclear utilities the enterprise-wide physical and logical foundation necessary to consolidate separate islands of analog and legacy digital I&C systems with information systems into a single, comprehensive architecture that transforms labor-centric work activities performed by personnel to supervised, technology-centric nuclear activities. This framework provides a roadmap for modernization while ensuring continued plant safety, reliability, and economic performance. The detailed results are available in report INL/EXT-21-64580, "Digital Infrastructure Migration Framework Report."

The Exelon safety system upgrade pilot is being pursued in a manner consistent with the DI framework. By replacing analog safety-related I&C systems with digital technologies and consolidating non-safety I&C applications on a distributed control system, Exelon is establishing a foundation that enables implementation of the larger DI framework. These I&C system upgrades, built on modern automation and digital technologies, ensure the nuclear industry remain economically competitive with other power generation sources. By transmitting plant data from these I&C systems to the larger DI data architecture, the data can be analyzed using artificial intelligence and machine learning to enable automated diagnostic and prognostic capabilities. These reduce surveillances and enable condition-based maintenance to lower O&M costs. Ultimately, the LWRS DI infrastructure along with related Data Architecture and Analytics research provides the nuclear industry with a demonstrated modernization strategy to overcome key barriers to maintaining its technical and economic viability.

The 2022 research collaboration targets improving the effectiveness of a utility's subsequent license renewal I&C upgrade effort and associated main control room operations strategy by applying the larger DI framework strategy produced in 2021. These results and lessons learned from the multi-year Exelon project at Limerick will be made available to the nuclear industry through LWRS public reports to enable similar safety system upgrades as a foundation for a more comprehensive digital infrastructure as described above.

More information on the safety-related I&C upgrade related research is provided at: https://lwrs.inl.gov/SitePages/IC_Modernization_Safety-Related_IC_Pilot_Project.aspx

2.2.2.2 Human Technology Integration

For nuclear generating stations to reduce costs and remain economically competitive, measures to improve efficiency need to leverage advanced digital technologies. This requires integrating new technologies into nuclear power plants' concept of operations. These transformative digital technologies—including automation, new decision support capabilities, and advanced displays—fundamentally change nuclear power plants' operating model through reallocating tasks from people to technology. By applying human factors engineering and systems engineering principles to plant modernization activities researchers are developing technology adoption methods that eliminate human error, improve personnel situation awareness, and provides automation transparency, all aimed at ensuring safety and reliability are maintained while maximizing plant efficiency.

RESEARCH ACCOMPLISHMENT

RESEARCH ACCOMPLISHMENT 18

Establishing a Roadmap for Safe and Reliable Digital Transformation

LWRS Program researchers are developing and demonstrating human and technology integration methods in collaboration with Dominion Energy and Arizona Public Services. Researchers and industry are evaluating methods to determine the optimum approach for implementing these advanced automation and digital technologies (e.g., Figure 30 shows a conceptual design of an advanced main control room developed in collaboration with Dominion Energy).

In 2021, researchers and industry developed a methodology to enable an advanced concept of operation (Figure 31) that leverages advanced digital technology.

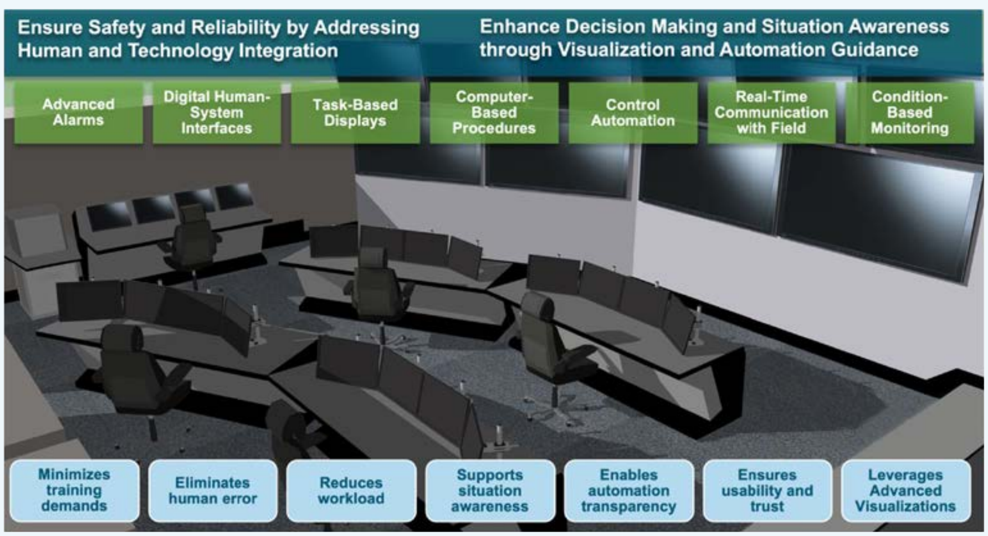


Figure 30. Conceptual design of an advanced main control room developed in collaboration with Dominion Energy.

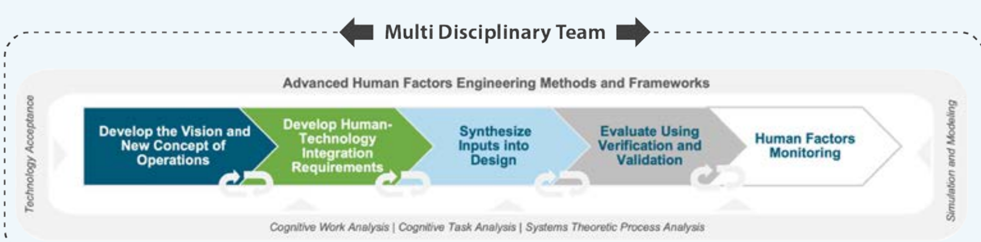


Figure 31. Human and technology integration methodology.

Notable elements of the 2021 research include:

- Ensuring safety and minimizing the risk associated with licensing and regulatory considerations by closely following and extending known standards and guidelines from the NRC, EPRI, the Institute of Electrical and Electronics Engineers (IEEE), International Atomic Energy Agency, and other standards relevant to human factors and systems engineering.
- Applying state-of-the-art human factors engineering principles and technical guidance from previous LWRS Program research, such as advanced alarm systems, computer-based procedures, model informed decision support, and advanced displays, to provide guidance on evaluating other advanced digital technologies.
- Expanding guidance on safety and power generation through integration of advanced human factors and systems engineering techniques such as cognitive task analysis, systems-theoretic process analysis, and simulation and modeling techniques.

This multi-disciplinary research working closely with industry and other LWRS Program sponsored research like ION and Digital Infrastructure, is expected to be complete by 2025. The results of this work will provide industry a detailed process to maximize the benefits of advanced digital technology adoption while ensuring continued safe and reliable plant operation.

2.2.2.3 Risk Assessment Method Development to Support Deployment of Digital I&C

The LWRS Program is developing integrated risk assessment methodologies for digital I&C systems to both manage the aging of analog instrumentation and controls and to support the transition of nuclear power plants to digital technologies. The goal is to assure the long-term safety and reliability of vital engineered systems, eliminate or reduce the need in diverse actuation systems, reduce uncertainty in licensing costs and time, and support integration of digital systems in the plant and more efficient upgrades of technology for the entire lifecycle of nuclear power plants.

As discussed in , the qualification of digital technologies remains a challenge, especially the issue of software common cause failures. Existing analyses of common cause failures in I&C systems mainly focus on hardware failures. With the application and upgrading of new digital I&C systems, software common cause failures due to design flaws might become a potential threat to plant safety, considering that most redundancy designs use similar digital platforms or software in their operating and application systems. With complex multi-layer redundancy designs to meet the single failure criterion, these I&C safety systems are of particular importance in U.S. NRC licensing requirements.

The work in this project directly coordinates with the NRC's guidance for digital I&C licensing process DI&C-ISG-06 , which addresses digital I&C design and provides information for license amendment requests. The use of "risk" in DI&C-ISG-06 is solely focused on project or quality assurance risk and states that "reliability" should be considered but does not provide directions on how that should be done. This R&D demonstrates how digital I&C systems can be represented in reliability and risk models.

RESEARCH ACCOMPLISHMENT

Development of an Integrated Risk Assessment Approach for Safety-Related Digital Instrumentation and Controls

Upgrading existing safety-related analog I&C systems to state-of-the-art digital I&C systems provides a means to improve performance and reduce operating costs for existing LWRs. As discussed in , substantial benefits are expected from modernizing safety-related I&C systems via labor and material cost-savings. Implementation of this technology requires a rigorous safety analysis, which is the scope of this project.

An Integrated Risk Assessment for Digital I&C technology identifies potential key digital-induced failures, implements reliability analyses of related digital safety I&C systems, and evaluates the unanalyzed postulated sequences introduced by these failures, particularly software common cause failures. Systematic methods and risk-informed tools are incorporated to address both hardware and software common cause failures, which provides guidance to eliminate the causal factors of potential single point failures in the design of digital safety systems.

The Risk Assessment for Digital I&C technology is instructive for nuclear vendors and utilities on how to effectively lower the costs associated with digital compliance and the speed that industry advances by:

1. Defining an integrated risk-informed analysis process for digital I&C upgrade, including hazard analysis, reliability analysis, and consequence analysis.
2. Applying systematic and risk-informed tools to address common cause failures and quantify responding failure probabilities for digital I&C technologies, particularly software common cause failures.

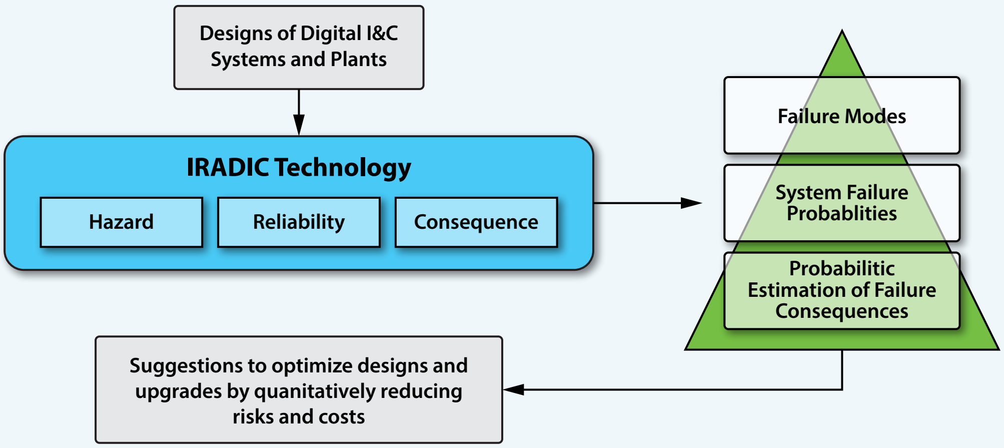


Figure 32. Placement of Risk Assessment for Digital I&C technology within Digital I&C Risk Assessment.

3. Evaluating the impact of digital failures at the individual level, system level, and plant level.
4. Providing insights and suggestions on designs to manage the risks, thus, to support the development, licensing, and deployment of advanced digital I&C technologies at nuclear power plants.

The value proposition of the IRADIC technology is illustrated in Figure 32.

This methodology, when fully developed, will provide a risk-informed approach and technical basis for the safety assessment of digital I&C systems to support license amendment requests to be submitted by the industry for the modernization of safety-related I&C systems at LWRs. The method also provides a technical basis for implementing cybersecurity, reliability, and consequence analysis on unanalyzed sequences and optimizing the use of defense-in-depth analysis in a cost-effective way. Technical details of Risk Assessment for Digital I&C technology can be found in "Quantitative Risk Analysis of High Safety-significant Safety-related Digital Instrumentation and Control Systems in Nuclear Power Plants using Risk Assessment for Digital I&C Technology."

References

1. Huff, Kathryn. "Saving Existing Nuclear Fleet Brings Net-Zero Future Closer." Energy.gov, 6 Dec. 2021, https://www.energy.gov/articles/saving-existing-nuclear-fleet-brings-net-zero-future-closer.
2. Berkman MP, Murphy DM. 2015. The Nuclear Industry's Contribution to the US Economy. Boston: Brattle Group.
3. Illinois Clean Energy Legislation Spurs Exelon Generation to Fill 650 Jobs, Invest $300 Million in Capital Projects, Sept. 29, 2021. See https://www.exeloncorp.com/newsroom/illinois-clean-energy-legislation-spurs-exelon-generation-to-fill-650-jobs-invest-$300-million-in-capital-projects.
4. Hallbert, Bruce P, and Kenneth D Thomas. "Sustaining the Value of the US Nuclear Power Fleet." The Bridge Nuclear Energy Revisited, Fall 2020, vol. 50, no. 30, 15 Sept. 2020, https://doi.org/https://www.nae.edu/239120/Fall-Issue-of-The-Bridge-on-Nuclear-Energy-Revisited.
5. Bipartisan Infrastructure Package Includes Major Investments in Nuclear Energy, Nuclear Energy Institute, Nov. 9, 2021. See https://www.nei.org/news/2021/infrastructure-package-major-investments-nuclear.
6. Secretary Granholm Launches Hydrogen Energy Earthshot to Accelerate Breakthroughs Toward a Net-Zero Economy, Department of Energy, June 7, 2021. See https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net.
7. "Memorandum of Understanding between United States Department of Energy (DOE) and The Electric Power Research Institute (EPRI) on Light Water Reactor Research Programs," dated December 15, 2015, and signed by John E. Kelly, Deputy Assistant Secretary for Nuclear Reactor Technologies, Office of Nuclear Energy, DOE, and Neil Wilmshurst, Vice President Nuclear, EPRI.

8. "Memorandum of Understanding between U.S. Nuclear Regulatory Commission and U.S. Department of Energy on Cooperative Nuclear Safety Research," dated May 01, 2014, and signed by Brian W. Sheron, Director, Office of Nuclear Regulatory Research, NRC, and John E. Kelly, Deputy Assistant Secretary for Nuclear Reactor Technologies, DOE-NE.
9. "RAVEN GitHub Repository." Risk Analysis Virtual Environment (RAVEN), https://github.com/idaholab/raven#readme.
10. Paul W. Talbot, et al, Evaluation of Hybrid Flexible Plant Operation and Generation Applications in Regulated and Deregulated Markets Using HERON, December 2020, INL/EXT-20-60968.
11. https://github.com/idaholab/teal.
12. Knighton et al, 2021. Energy Arbitrage: Comparison of Options for use with LWR Nuclear Power Plants, INL/EXT-21-62939, Revision 2, September 2021.
13. USNRC 10CFR50.54(i) Conditions of Licenses specifies "except as provided in 55.13 of this chapter, the licensee may not permit the manipulation of the controls of any facility by anyone who is not a licensed operator or senior operator as provided in part 55 of the chapter".
14. https://www.ans.org/news/article-183/us-nuclear-capacity-factors-resiliency-and- new-realities/.
15. Explainability and Auditability in ML: Definitions, Techniques, and Tools, https://neptune.ai/blog/explainability-auditability-ml-definitions-techniques-tools.
16. Nuclear Energy Institute (NEI), "Nuclear Costs in Context," 2020.
17. Y.-J. Choi, M. Abdo, D. Mandelli, A. Epiney, J. Valeri, C. Gosdin, C. Frepoli and A. Alfonsi, "Demonstration of the Plant Fuel Reload Process Optimization for an Operating PWR," Light Water Reactor Sustainability Program, INL/EXT-21-01580, September 2021.
18. U.S. Nuclear Regulatory Commission, NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition".
19. K. Kirkland, A. Delgado, Y. Hassan, T. Nguyen and A. Patil, "Comprehensive Technical Report on Terry Turbopump Expanded Operating Band Testing at Texas A&M University," Light Water Reactor Sustainability Program, SAND2021-7815, June 2021.
20. Precision Remotes LLC: https://www.precisionremotes.com/nuclear-power-plant-solutions/ (site accessed December 29, 2021).
21. A. Jennsen, private communication, 2011.
22. H. Zhang, H. Bao, T. Shorthill and E. Quinn, "Integrated Risk Assessment of Digital I&C Safety Systems For Nuclear Power Plants," 2021.
23. U.S. Nuclear Regulatory Commission, DI&C-ISG-06, "Digital Instrumentation and Controls Licensing Process," Interim Staff Guidance, Revision 2, 2018.
24. P. Hunton, R. England, S. Lawrie, M. Kerrigan, J. Niedermuller and W. Jessup, "Business Case Analysis for Digital Safety-Related Instrumentation & Control System Modernizations," Light Water Reactor Sustainability Program, INL/EXT-20-59371, 2020.
25. H. Bao, T. Shorthill, E. Chen and H. Zhang, "Quantitative Risk Analysis of High Safety-significant Safety-related Digital Instrumentation and Control Systems in Nuclear Power Plants using IRADIC Technology," Light Water Reactor Sustainability Program, INL/EXT-21-64039, 2021.

22-50799