LWRS LIGHT WATER REACTOR SUSTAINABILITY

Overview and Accomplishments – 2022

Light Water Reactor Sustainability Program

U.S. DEPARTMENT OF ENERGY

Overview and Accomplishments – 2022

Light Water Reactor Sustainability Program

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From the LWRS Program Technical Integration Office Director

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The United States (U.S.) Department of Energy's (DOE's) Office of Nuclear Energy (NE) is guided by a Strategic Vision [1], which is "A thriving U.S. nuclear energy sector delivering clean energy and economic opportunities." The Strategic Vision identifies the following 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 LWRS 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.

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.

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Contents

Figures

Tables

Acronyms

AI	artificial intelligence
BAHAMAS	Bayesian and HRA-Aided Method for the Reliability Analysis of Software
BOC	beginning-of-cycle
CAP	corrective action program
CCF	common-cause failures
CFR	Code of Federal Regulations
CNWG	Civil Nuclear Working Group
DMA	deliberate motion analytics
DNP	Delivering the Nuclear Promise
DOE	Department of Energy
EDS	energy-dispersive spectroscopy
EOC	end-of-cycle
EPRI	Electric Power Research Institute
FPOG	flexible plant operation and generation
FT	Fisher-Tropsch
GB	grain boundary
HERON	Holistic Energy Resource Optimization Network
HRA	human reliability analysis
HSSL	Human Systems Simulation Laboratory
HUNTER	Human Unimodel for Nuclear Technology to Enhance Reliability
I&C	instrumentation and control
IAEA	International Atomic Energy Agency
IASCC	irradiation-assisted stress corrosion cracking
IES	Integrated Energy Systems
INL	Idaho National Laboratory
ION	Integrated Operations for Nuclear
JCAMP	Japan Concrete Aging Management Program
KOH	potassium hydroxide
LAR	License Amendment Request

LCOS	levelized cost of storage
LiOH	lithium hydroxide
LWR	light water reactor
LWRS	Light Water Reactor Sustainability
M&D	monitoring and diagnostic
MFSP	minimum fuel selling price
MIRACLE	Machine Intelligence for Review and Analysis of Condition Logs and Entries
ML	machine learning
NE	nuclear energy
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Co-operation and Development
ORCAS	Orthogonal-defect Classification for Assessing Software
ORNL	Oak Ridge National Laboratory
PI	probability of interdiction
PIDAS	perimeter intrusion detection and assessment system
PN	probability of neutralization
PRA	probabilistic risk assessment
PSEG	Public Service Enterprise Group
PWR	Pressurized-Water Reactor
PWROG	Pressurized-Water Owners Group
R&D	research and development
RESHA	Redundancy-guided Systems-theoretic Hazard Analysis
ROWS	remote operated weapon systems
SCC	stress corrosion cracking
SSC	structures, systems, and components
TVA	Tennessee Valley Authority

Overview and Accomplishments Report 2022

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 approximately half of our clean power. [1]
- Nuclear power is a vital part of a long-term strategy to ensure a reliable supply of electricity while reducing carbon emissions. Nuclear power is recognized for its contribution to the nation's clean energy goals as written in the Inflation Reduction Act of 2022. This new law provides up to $15 per megawatt-hour for existing nuclear power plants, lasting until 2032. This supports the competitive operation of the existing fleet and sustains the highly skilled work force at these plants, further extending the benefits of nuclear power operation in and around their surrounding areas. [2]
- The commercial nuclear power industry plays a significant role in the U.S. economy. The Brattle Group [3] estimates that the commercial nuclear industry produces 475,000 jobs and contributes $60 billion annually to U.S. Gross Domestic Product.
- 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 known as the Infrastructure Investment and Jobs Act. 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. [4]
    - The Civil Nuclear Credit Program provides a new national strategic investment in the operating fleet of nuclear power reactors. [5] The Civil Nuclear Credit Program provides credits to support the continued operation of plants that are expected to close due to economic reasons, that would lead to a rise in air pollutants and carbon emissions. In November 2022, Diablo Canyon Units 1 and 2 were conditionally selected to receive the first round of funding from the Civil Nuclear Credit Program. [6] This will enable these plants to continue operation and avoid their scheduled closures of 2024 and 2025, respectively, and enable California to maintain the 16 TWh of clean energy annually

produced by these plants. [7] In March 2023, DOE released application guidance for the second award cycle of the Civil Nuclear Credit Program. While the first award cycle limited eligibility to owners or operators of nuclear power reactors that had announced intentions to retire within the four-year award period, the second award cycle is open to owners or operators of nuclear reactors that are at risk of closure by the end of the four-year award period, including such reactors that ceased operations after November 15, 2021.

- Nuclear power is 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." [8]
- Nuclear power is also a key to achieving the DOE's announced Industrial Heat Earthshot. This Earthshot aims to develop cost-competitive industrial heat decarbonization technologies with lower greenhouse gas emissions. This supports the nation's objectives to achieve industrial decarbonization and lower carbon emissions in industry. [9]
- 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. [10]

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 LWRS Program's industry stakeholders.

Through a program of directed research and development activities, the LWRS Program complements policy and enacted law to address the long-term safe and competitive operation of the existing fleet of operating nuclear power reactors. These activities, summarized below, target the long-term capabilities and performance of our nation's nuclear plants to ensure that they operate using the best available technologies, are and remain cost-sustainable, support national missions to reduce carbon emissions in industrial sectors beyond electricity, and attract and retain a highly skilled work force.

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 the 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 performance and 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.

Table 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 of $5/MWh.
5. By 2025, 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. [11]

1.2.2 Nuclear Regulatory Commission

The NRC employs a memorandum of understanding [12] 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 Human Technology Organization (HTO) Project:** The Halden HTO 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):** 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 shown 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 are being achieved by understanding and mitigating the effects of environmental conditions on materials and addressing the obsolescence of aging plant technologies. The LWRS Program programmatic activities and selected recent accomplishments toward these objectives are described in Sections 2.1 and 2.2.

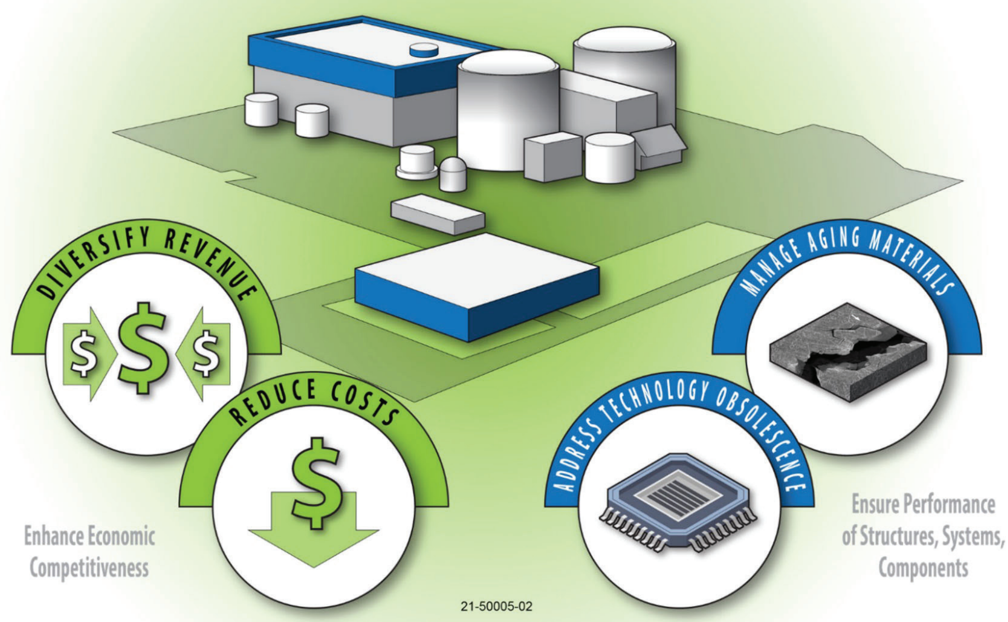


Figure 1. Paths to sustaining the existing fleet of LWRs through collaborative R&D.

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 products that contribute to national clean energy goals and sources of revenue. Electricity markets are undergoing radical changes as society is striving to reduce net CO_2 emissions to the atmosphere. An increasing number of utilities are signing on to the goal of increasing the production of clean energy. Some have committed to eliminating CO_2 emissions by 2040 to 2050. This is mainly being done by adding wind and solar energy capacity to their energy portfolio, spurred by investment and production tax credits for renewable energy. [13] 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.

The LWRS Program conducts R&D with nuclear power plants that are considering participating in alternative markets by directing their energy to a close-coupled industrial user such as a hydrogen plant. This model of operation is referred to as flexible plant operation and generation (FPOG), the goal of which is to maintain full power operations during periods of variable demand by the electric grid due to capacity or price-related variation. Technical and economic assessments are completed to support nuclear plant owners and project investors who are evaluating alternative markets in their region. In some situations, the best option may be energy storage to produce electricity for the grid when demand peaks and the selling price of electricity is high.

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. These changes to the nuclear plant and the proximity of the industrial users requires additional safety analysis to ensure the plants will comply with their operating license.

2.1.1.1 Safety Analysis and Regulatory Research Guidance

The coupling of a nuclear power plant with a hydrogen plant requires a new operating paradigm involving changes to plant design, new actions by plant operators, and could necessitate new safety assessments. It may require modifications to the electricity transmission switch yard and thermal hydraulics systems. Therefore, it is important to address the licensing and regulatory framework to implement the necessary changes.

Design changes are routinely performed at operating U.S. nuclear power reactors, in part through a process where the licensee confirms that a proposed design change is permitted under the Code of Federal Regulations (CFR), Title 10 Part 50.59 (10 CFR 50.59). A probabilistic risk assessment (PRA) is used to risk-inform the NRC's decision regarding a plant design change proposition. Within this assessment, the quantitative risk insights on necessary modification to the plant electrical and thermal-hydraulic systems required to integrate hydrogen production at a nuclear power plant will be important decision-making inputs under the 10 CFR 50.59 process because they will characterize the potential consequences of undesired events and failures to nuclear safety. Additionally, if a proposed change to the facility is determined not to be within the limits specified in 10 CFR 50.59, a formal license amendment request (LAR) and specific NRC approval will be required under 10 CFR 50.59.

The LWRS Program is addressing the potential safety hazards related to hydrogen production beginning with an assessment of potential accident-initiating events associated with modification to electrical and thermal systems and the operation of a hydrogen plant connected to a nuclear plant. In 2021, an initial hazard and safety assessment for a conceptual hydrogen plant located near a nuclear plant was completed by researchers at Sandia National Laboratories. [14] This study was then used as input to complete a preliminary PRA, which included the design changes and operational effects of the new electricity connections and thermal energy extraction systems as well as the hazards associated with accidental hydrogen releases, fires, and explosions at the electrolysis plant used to produce industrial hydrogen. In this study, this assumed a hydrogen facility with a capacity of 1,000 MW and was located within one kilometer of a pressurized water reactor (PWR) nuclear power plant. [15] This work was foundational in establishing a set of bounding generic hazard conditions associated with coupling high-temperature electrolysis hydrogen technology with an existing nuclear power plant.

RESEARCH ACCOMPLISHMENT

Creation of a Hydrogen Regulatory Research Group

In 2022, a Hydrogen Regulatory Research Review Group (H3RG) was established with two primary goals; (1) to further characterize generic technical and safety risks that could reasonably be employed under a 10 CFR 50.59 evaluation (without entering the LAR process) and (2) to conduct foundational research which nuclear power operators could use if the LAR process is required.

In support of these goals, the H3RG includes a broad collaboration with participants from DOE national laboratory researchers, contracted architecture/engineering participants, and nuclear utility licensing and design experts. A nuclear-integrated hydrogen conceptual design was developed by an architectural/engineering company, which provided a practical generic design to further develop electric power utility at-scale adoption strategies for nuclear-integrated hydrogen. The structure of the H3RG is shown in.

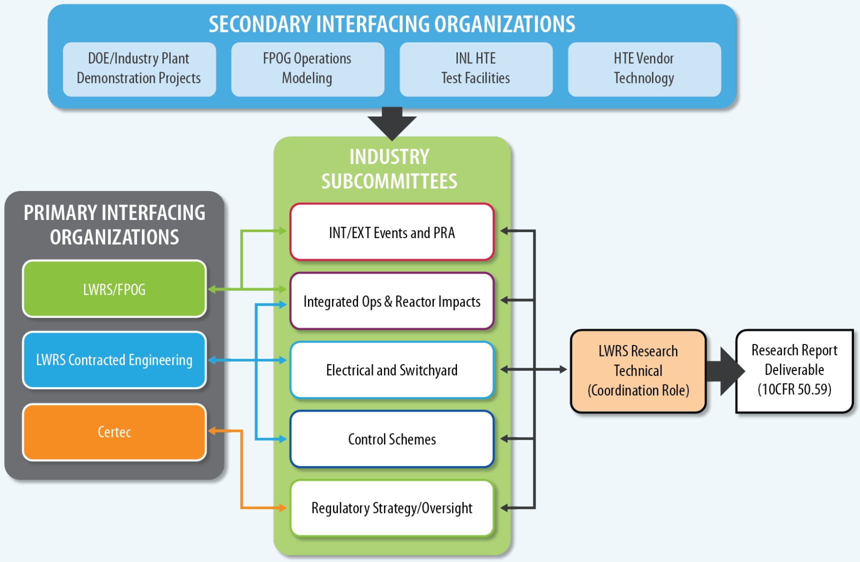


Figure 2. Structure of the Hydrogen Regulatory Research Review Group (H3RG) established in 2022.

H3RG technical and regulatory research findings, associated with the pairing of a 1,200 MWe generic pressurized-water reactor design with a 100 MW high-temperature electrolysis plant, [16] appear favorable with respect to the potential use of the 10 CFR 50.59 evaluation process through a detailed review of the eight 10 CFR 50.59 standard evaluation questions that ensure the safety review bounds all potential safety concerns. This evaluation also serves as generic design input for use by industry stakeholders considering the proposed coupling of an actual nuclear power plant to a future hydrogen production facility.

RESEARCH ACCOMPLISHMENT

Updated Safety Assessment for Hydrogen Products in a Nuclear Power Plant Setting

An important recommendation of H3RG was to update the initial preliminary PRA completed in 2020 using the conceptual design reported in a related 2022 accomplishment [16]. The updated PRA [17] was completed in November 2022 for both a generic boiling-water reactor and a generic PWR. The latest updated design data available were used in this revision. The updated PRAs now include an assessment of two options for thermal energy transfer, the connection of electrical power from the nuclear power plant high and medium voltage switch gear, and two sizes of hydrogen electrolysis facilities.

In summary, the results of the updated, more realistic PRA for the conceptual design indicated that the 10 CFR 50.59 licensing evaluation approach showed a minimal increase in initiating event frequencies that can produce a radiological release that could exceeding the maximum dose allowed at the site boundaries. The PRA results for core damage frequency and large early release frequency support the use of NRC Regulatory Guide 1.174 as further risk information that supports a change without a full LAR. The updated PRA study also informs a utility of a pathway to follow when moving to the site-specific case, which is valuable to nuclear power plant owners and operators. A sensitivity study for the generic case provides suggestions for best engineering practices that can be implemented to ensure plant safety.

As a result of this research two notable supporting R&D projects, that will further refine the results of these laboratory accomplishments, were initiated in 2022.

- An award was made to the University of Tennessee at Knoxville under the 2022 NEUP, Integrated Research Projects. [18] The project will address the challenges and regulatory concerns related to operations and maintenance, human factors, and risk assessment to enable light water reactors to support on- and off-grid applications.
- Idaho National Laboratory and Sandia National Laboratories will collaborate to update the PRA and safety analyses with the following goals:
  - Hydrogen safety will be quantified for lower temperature and pressure electrolysis modules to include the layout of the modules into a completed production facility,

- Common nuclear power plant site layout safety considerations will be evaluated for potential placement of the newly specified hydrogen production facilities both within and outside of nuclear power plant protected areas,
- Investigation into external events hazards for both the nuclear power plant thermal energy delivery system and the electrolysis facility,
- Translation of the reference plant PRA into a more standardized industry-used PRA program for ease of use by utilities.

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

Utilities across the country continue to add wind and solar energy to their energy portfolio to achieve clean energy goals. The resulting regional instances of variable net over-generation throughout the year drive spot electricity prices below the marginal cost of production for some nuclear power plants. Unable to clear the day-ahead or hourly markets, nuclear power plants are being asked to curtail power generation or pay other generators to curtail generation to avoid down powering the nuclear plants. Some nuclear power plants are already routinely forced to curtail up to 30% of their full electrical generation capacity in response to drops in electricity demand or increased power generation by solar and wind. In 2021, the LWRS Program research affirmed that hydrogen production is a viable path for nuclear power plants to generate net positive revenue. [19] Technical and economic assessments have shown that in many situations, a nuclear power plant can optimize its revenue by shifting between the electricity market and a non-electricity market customer to produce a second product (e.g., hydrogen). This will require a new operating concept and new thermal and electrical power connections between the nuclear power plant and the industrial process plant. The LWRS Program has carried out further analyses in 2022 to deliver new conceptual designs and concepts answering those needs. It is anticipated that demonstrations on a scale of 100 to 500 MWe will be carried out with nuclear power plants in 5 to 10 years. Early demonstrations may benefit from recent legislation related to hydrogen production from the Infrastructure Investment and Jobs Act (also referred to as the Bipartisan Infrastructure Law) and the Inflation Reduction Act.

RESEARCH ACCOMPLISHMENT

A Preconceptual Design of Thermal and Electrical Power Delivery Systems to Upgrade Existing Nuclear Power Plants

Prior to 2022, thermal-hydraulic designs were completed by professionally licensed engineers employed by Idaho National Laboratory using process models, such as HYSYS™ and RELAP-5. In 2022, the LWRS Program engaged an architecture/engineering firm to begin transitioning the initial designs to detailed plant designs that can be leveraged by an Engineering and Plant Construction Company for a commercial project. With a consistent focus on hydrogen production as directed by the LWRS Program, a preconceptual design was developed for the thermal and electrical offtake for a 100 MWe hydrogen plant (completed September 2022), Figure 3 and a 500 MWe hydrogen plant. These designs are in final review and will be released in 2023.

Figure 3 illustrates the layout of the thermal and electrical power offtake that was used to complete the preconceptual design. This design enables power to be distributed to an industrial user before it is sent to the electricity grid.

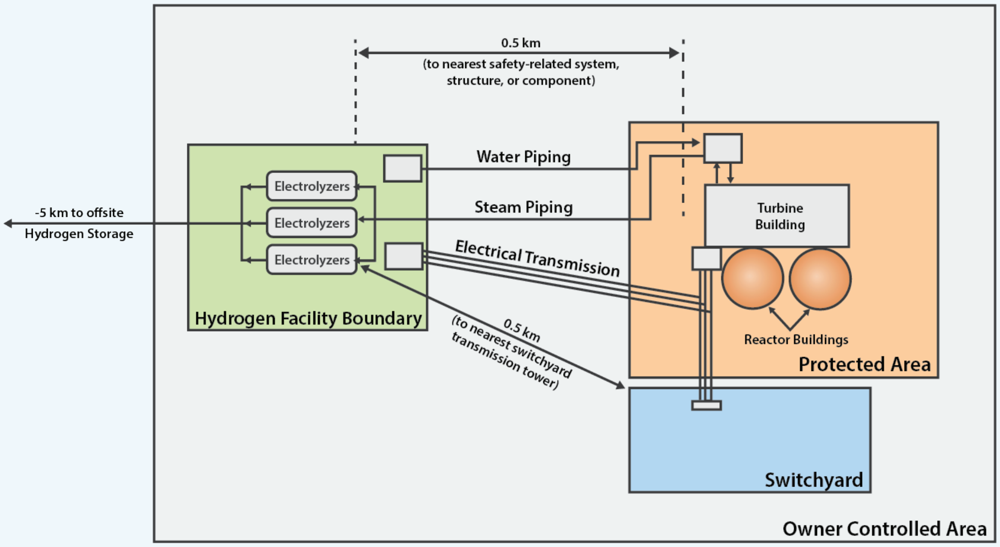


Figure 3. Architecture/Engineering conceptual site layout for a 100 MWe hydrogen facility design.

The preconceptual design was used to estimate the capital costs of the thermal-hydraulic and electricity connections to the hydrogen plant. The design will lead in turn to a construction plan and schedule to upgrade existing nuclear power plants with minimal impact on plant outages. The preconceptual design is now being used to analyze the potential risks introduced by the modifications to the nuclear power plant. It is also being incorporated into operator training simulators to develop and prove the feasibility and safety of dispatching thermal energy to the industrial user.

In 2023, a preliminary engineering design, technical analysis, and cost of thermal energy extraction and temporary storage systems supporting up to 50% of the total thermal energy produced by a nominal 1,000 MWe pressurized-water reactor will be completed for thermal energy power arbitrage and industrial users. This addresses an interest to consider how some nuclear power plants may transition to solely providing electricity and thermal energy needs for industry process customers due to their unique advantages in efficiently producing abundant high-quality steam and large amounts of electricity.

RESEARCH ACCOMPLISHMENT

Testing of New Control Concepts to Safely Manage Future Flexible Plant Operation and Generation

The NRC requires that nuclear power plant licensed operators maintain control of all operations that could affect nuclear safety. [20] Flexible plant operations and generation require new operating concepts and operator training that ensure the operators can respond to anticipated and unanticipated events associated with flexible plant operations. These new operating concepts will include new instrumentation and automated controls and require rigorous testing.

Development, testing, and implementation of new human-machine interfaces and control systems began in 2020. Under the LWRS Program umbrella, GSE Systems, Inc. modified a generic pressurized-water reactor simulator to model the thermal and electrical connections to a high-temperature steam electrolysis plant. A dynamic model for the electrolysis plant was added to the plant simulator to provide a realistic simulation of the thermal energy delivery system and to provide feedback to the plant operators regarding the status of the hydrogen plant. In 2021, an interdisciplinary team of operations experts, nuclear engineers, and human factors experts conducted the first test of nuclear power plant operators' ability to support flexible plant operations and generation of hydrogen (see Figure 4). The results of this test show that it may be necessary to support thermal energy dispatch with supplemental automation to mitigate increased operator tasking required to control and monitor an additional system beyond existing operations.

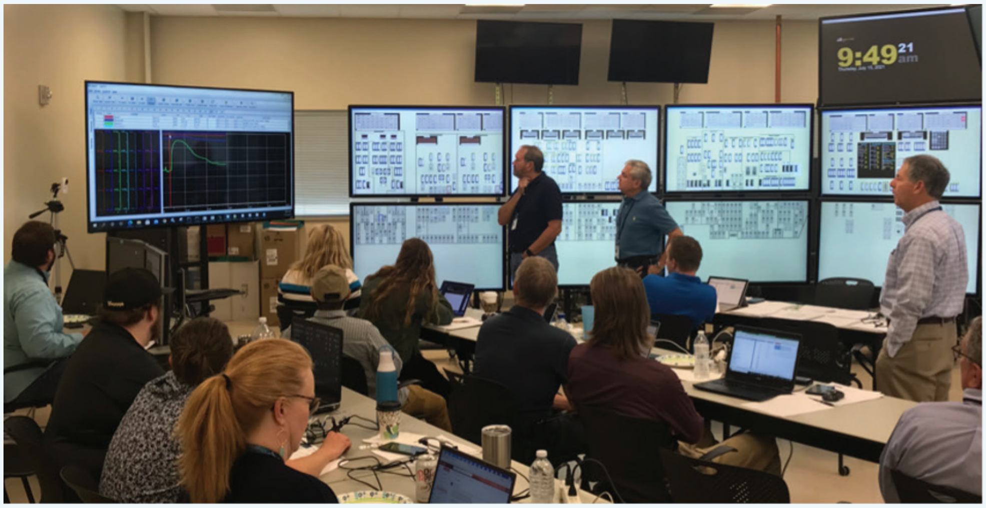


Figure 4. Idaho National Laboratory, GSE Systems Boiling-Water Reactor/Hydrogen Plant Simulator installed at the Human Systems Simulation Laboratory.

A boiling-water reactor plant simulator has also been modified by GSE Systems for thermal power dispatch. These simulators were installed on the simulator at the Human Systems Simulation Laboratory at the Idaho National Laboratory and tested to prove they can continue to support the development of human-machine interfaces, new operating concepts, and controls systems. The simulator shown in Figure 5 will be used in 2023 to develop and test operator control strategies for energy dispatch to a hydrogen plant.

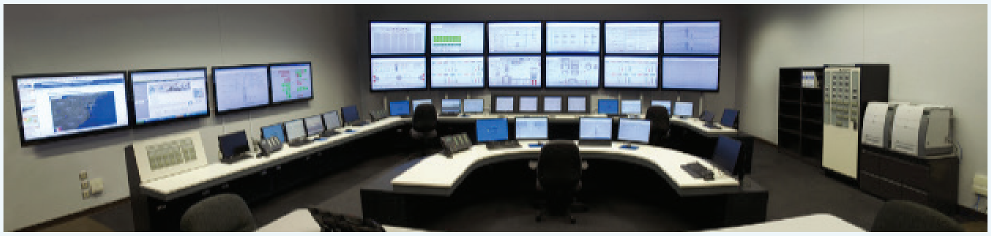


Figure 5. Photo of AP1000 nuclear power plant control room simulator used to train reactor operators.

RELAP5-3D and HYSYS™ were used to validate the modifications that were made to the GSE Systems PWR simulator modifications for thermal energy delivery to a hydrogen plant. Additional modeling and simulation are being conducted in 2023 to validate the proposed modifications to the electric power dispatch design and improve its fidelity. A reduced-order nuclear power plant simulator was developed and interfaced with a Digital Real-Time Grid Simulator at Idaho National Laboratory for hardware-in-the-loop testing. The results indicate that the simulator can model the steady-state and transient response of a PWR plant with acceptable accuracy.

Future efforts include plans to modify nuclear power plant operator room simulators to dispatch thermal and electrical power to a close-coupled hydrogen plant. This effort will help LWRS Program researchers develop and implement controls methods and human-machine interfaces enabling the safe and efficient operation of nuclear plants that switch between the electricity grid and hydrogen supply markets.

The efforts of LWRS Program human factors and human-machine interface development researchers are essential to implementing flexible plant operations. Proof of operability at the Human Systems Simulation Laboratory, with human-in-the-loop and hardware-in-the-loop, is helping nuclear power plant owners and electrolysis technology companies understand how real-world systems can be cooperatively operated.

2.1.1.3 Technical and Economic Assessments of Flexible Plant Operation and Generation Alternatives

Even with clear federal goals and significant financial assistance to change the operational paradigm of nuclear reactors to create non-electric products such as hydrogen, notable barriers remain for the widespread adoption of these opportunities within the U.S. nuclear fleet, including:

- Electric utility and public utility long-standing traditional bias for electric-only plant operating philosophies versus product diversification to flexible operations producing non-electric products,

- Proving the economic viability and technical feasibility of flexible energy product integration with nuclear power,
- Alternate product stream, such as heat and hydrogen, market assurance to support decision-making for large capital modification investments.

Understanding with better certainty the future of electricity markets, including the growth of wind and solar energy, the volatility of natural gas prices, and the certainty of climate change actions and regulations. To address these issues, the FPOG Pathway is conducting technical and economic assessments of alternatives that may be competitive with current market positions. With the expansion of renewables on the grid across the U.S., there is a need to balance the grid using baseload nuclear power. Dispatchable loads such as the generation of non-electric products like hydrogen can help balance the grid while maintaining resiliency. The U.S. manufacturing industry accounts for around 30% of total U.S. energy demand. A large share of this energy is intermediate steam and process heat that is currently produced by burning oil or natural gas on site. An alternative solution would be to deliver heat and steam, in addition to electricity, from nuclear power plants directly to these industries. The case for this solution continues to be evaluated under FPOG studies. Agreements between owners of nuclear power plants and industry energy users are being explored with the aim to decarbonize industrial energy use.

Hydrogen production and energy storage continue to receive strong interest by all stakeholders given the increasing market demand for clean hydrogen (hydrogen produced without the emission of CO_2). In 2022, LWRS Program continued to improve the fidelity and reliability of energy delivery systems and electrolysis plants that produce hydrogen. In addition, economic models that project the selling price of electricity have been validated and used to compare hydrogen production with the leading energy storage options, such as utility-scale lithium-ion batteries, to help guide utilities' decisions on how to balance the grid, given the fact that the share of variable renewable energy generation on the grid will continue to increase. The increasing confidence in nuclear power plants producing hydrogen at a price that is competitive with the conventional hydrogen production process of steam methane reforming is gaining the attention and backing of nuclear utilities (as energy providers), electrolysis development companies (as U.S. manufacturing companies, and beneficiaries of an expanding hydrogen market), and hydrogen user industries and industrial energy users striving to reduce their carbon footprint.

RESEARCH ACCOMPLISHMENT

Modeling to Confirm that Nuclear Power Plants Can Produce Hydrogen Economically

In 2022, an Aspen- HYSYS™ (Aspen Technology Inc.) process model of a high-temperature electrolysis plant using nuclear heat and electricity developed by LWRS Program was refined and generalized with sensitivity studies to be widely applicable for all interested stakeholders. For this analysis, this specific process model was used to support a top-down capital and operating cost evaluation and dynamic operations analysis of high-temperature electrolysis. This analysis used near-term assumptions (judged to be achievable in the next

5 years) and feasible sensitivity studies as shown in the "tornado chart" (Figure 6) to confirm previous evaluations that projected nuclear power plants will be able to produce clean, pure hydrogen at a levelized cost for less than $2 per kilogram by 2026 when high volume manufacturing is established for modular electrolysis units. As shown in the figure, the price of electricity for electrolysis (energy price) is the dominant factor in the determination of the levelized cost of hydrogen. This underscores the importance of reducing the cost of producing power at nuclear power plants since it will be the dominant cost in producing hydrogen, as well. Reducing the cost of power production to around $20/MWh, combined with electrolysis technology advances are important steps to achieving the Hydrogen Earthshot goal of producing clean hydrogen for $1 per kilogram by 2031.

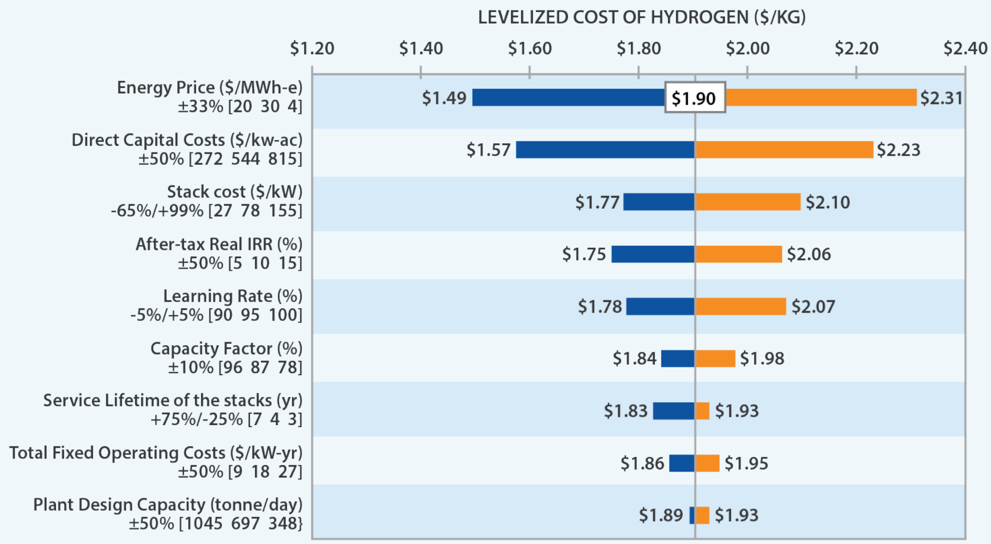


Figure 6. Sensitivity of Levelized Cost of Hydrogen to Price of Electricity, Technology Maturity, Performance Parameters, and Plant Scale.

The left side of Figure 6 shows the parameter that was varied and gives a low, mid, and high value for each parameter. The mid-value is considered the baseline. Also given is the percentage deviation up and down from the baseline value. The bars show the impact of the variation of the parameter from low to mid to high on the levelized cost of hydrogen. The levelized cost of hydrogen is the total cost to produce the hydrogen considering all capital and operating costs over the lifetime of the project.

Capital investment decisions are measured in terms of the financial returns and risk of these investments. In collaboration with the DOE Nuclear Energy's Integrated Energy Systems (IES) Program, LWRS Program developed a computation and optimization tool referred to as Heuristic Energy Resource Optimization Network (HERON) to complete rigorous technical and economic assessments based on region-specific capacity expansion projections. An improved version of this tool, HERON 2.0, was validated and made available for public use. [21] It is now being used to support industry-led technical and economic assessments of nuclear-based hydrogen production, hydrogen storage and power generation, thermal energy storage for industrial supply or power generation, and electricity storage and discharge using utility-scale battery facilities. [22]

RESEARCH ACCOMPLISHMENT

Industry-led Assessment Shows that a Large-scale Hydrogen Production Plant Integrated with Nuclear Power can be Profitable

With DOE cost-share through the Nuclear Energy Office Industrial Funding Opportunity Announcement, [23] Xcel Energy and Arizona Public Services completed technical and economic assessments using the computation tools and capabilities developed jointly by the LWRS and IES Programs. [24] The Xcel technical and economic assessment addressed the potential hydrogen market analysis of the greater Minneapolis region and lifecycle CO_2 emissions analysis of various hybrid product options that can be integrated with a light water reactor (LWR) and produced using carbon-free nuclear energy. Figure 7 illustrates the hydrogen users that were evaluated in the region surrounding the Prairie Island nuclear power plant see Figure 8.

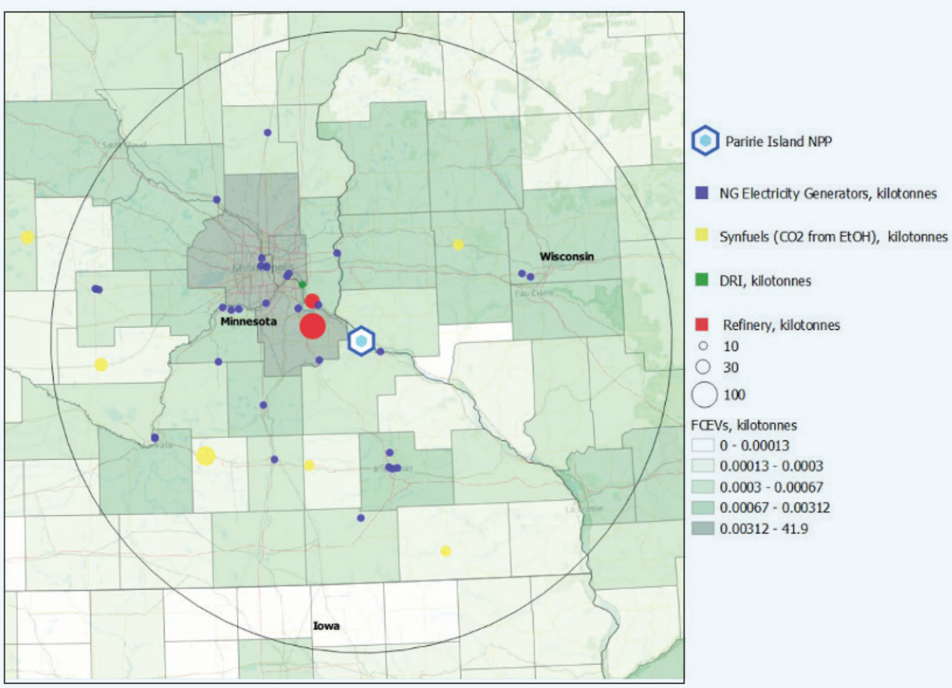


Figure 7. Future potential hydrogen demand near the Prairie Island Generating Plant. Points and colors show the type of demand and the size—NG- natural gas, EtOH- ethanol, DRI- direct reduced iron, FCEVs- Fuel cell electric vehicles.

Figure 8. Prairie Island Nuclear Generating Plant in Welch, Minnesota

This is the first comprehensive assessment of hydrogen production for a nuclear power plant in a regulated grid environment where capital expenses and electricity market prices are controlled by a public commission. The value of a potential production tax credit now realized under the Inflation Reduction Act was also evaluated in the study. The results of this analysis show that with a production tax credit, achievable improvements in electrolysis technology, and scale-up of electrolysis manufacturing capacity, the profitability of a large-scale hydrogen production plant integrated with nuclear power is achievable.

A technical and economic assessment for Arizona Public Service is in progress and will be completed early in 2023. This effort focuses on hydrogen production and storage to shift generation to the late afternoon and evening as sunset approaches and nightfall brings a spike in power demand in the Phoenix and surrounding metropolitan area.

RESEARCH ACCOMPLISHMENT

Preliminary Study Shows that Clean Synfuels can be Produced with Nuclear Hydrogen Market at a Reasonable Cost

In 2022, an evaluation of the business case for producing synthetic fuels (synfuel) via Fischer-Tropsch was undertaken. The Fisher-Tropsch process makes use of the hydrogen produced by an LWR combined with CO produced from CO_2 that can also be captured from an industrial source. In this assessment, the CO_2 was also collected and delivered to the synfuels plant using the nuclear reactor energy. A process model and assessment were completed by Argonne National Laboratory under the IES Program. [25] Analysis was performed by LWRS Program to determine the cost of collecting and transporting CO_2 from distributed sources to the centralized fuel synthesis plant as a function of the synfuel plant capacity and corresponding CO_2 demand. The energy from the nuclear power plants was used to provide power to the electrolysis plant and the fuels synthesis plant.

The technical and economic assessment compared the cost of synfuels production at various scales for four separate nuclear power plants that are in proximity to several corn ethanol plants that currently release CO_2 as a by-product. [26] The nuclear plants provide electricity to pump the CO_2 that is collected at near-by ethanol plants to a hydrogen plant located by the respective nuclear plant. This study shows that it is feasible to convert the nuclear hydrogen and the biogenic CO_2 into clean synthetic diesel fuel for under \$4 per gallon when hydrogen can be produced for under \$2 per kilogram, as shown in and Figure 10.

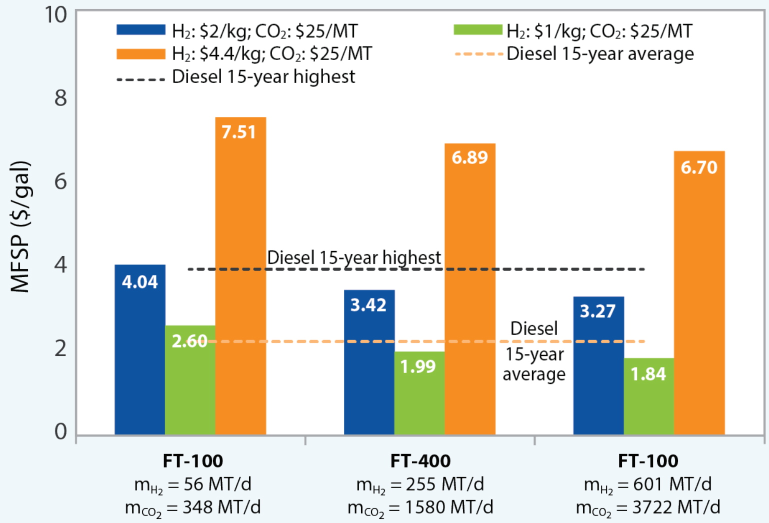


Figure 9. The production cost of Fisher-Tropsch (FT) fuel at different plant scales and H_2 prices. Minimum fuel selling price (MFSP).

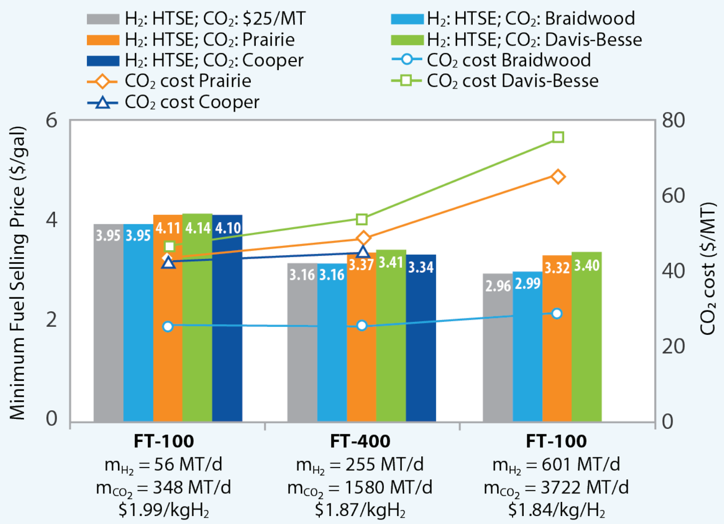


Figure 10. Influence of nuclear power plant location and CO_2 price on the production of FT synfuel.

2.1.1.4 Industry Engagement and Demonstration Projects

The LWRS Program and other DOE Program offices are conducting and sponsoring research to support the demonstration and deployment of scalable hydrogen (H_2) generation coupled to operating nuclear power plants. Through 2020, 2021, and 2022, four projects have been funded under DOE-FOA-0001817 to demonstrate the production of H_2 at U.S. nuclear power plants; Constellation, Energy Harbor, Xcel Energy, and PNW Hydrogen (see Figure 11).

Constellation: Nine-Mile Point Plant

- H_2 production beginning in 2023
- NEL Hydrogen proton electrolyte membrane electrolysis module

Energy Harbor: Davis-Besse Plant

- H_2 production beginning in 2024
- 2 MW_{eDC} Cumins Proton Electrolyzer Membrane electrolysis module

Xcel Energy: Prairie Island Plant

- H_2 production beginning in 2024
- Bloom Energy high-temperature solid-oxide electrolysis module

PNW Hydrogen

- Award under negotiation
- 20 MW_{eDC} electrolysis

Figure 11. Overview of the plans and schedule of the four demonstration projects.

Each of the projects has complementary but unique benefits to the individual utilities and their associated hydrogen electrolysis technology industries. For example, they will establish an understanding of how to connect the nuclear plant electricity transmission substations to the hydrogen plant power converters. The Xcel Energy project will demonstrate hydrogen production with high temperature (steam) electrolysis which requires a thermal energy offtake and delivery system. The projects establish institutional awareness of the steps that will be required to scale-up to full-scale plants. They help develop operating concepts at a small scale without any significant risk to current plant operations.

In 2022, Constellation held a ribbon-cutting ceremony for the installation of a NEL Hydrogen electrolysis unit and, as of February 2023, hydrogen production is now underway. Energy Harbor completed the installation of an auxiliary power transformer to relay power to a Cummins low-temperature electrolysis unit. Xcel Energy completed a competitive bid request before selecting Bloom Energy to supply high-temperature electrolysis modules to their project. The PNW Hydrogen Project was selected for funding in 2021 and is currently under negotiations.

In summary, the demonstration projects are indispensable to commercializing hydrogen production at nuclear power plants. These first projects are key to realizing large-scale projects and regional clean hydrogen hubs. The Bipartisan Infrastructure Law will cost-share at least one qualifying nuclear-source hydrogen hub up to $1.25 billion to build a commercial project. The FPOG Pathway 2022 Technical Program Plan [27] outlined an approximate schedule for associated R&D supporting the first commercial projects. The goal is to help stakeholders execute commercial deployment of the most promising options.

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

- Demonstrate hydrogen production using direct thermal and electrical power offtake from a nuclear power plant.
- Develop monitoring and control procedures for scale-up to large commercial-scale hydrogen plants.
- Evaluate the feasibility of dynamic operations of an electrolyzer coupled with nuclear plant operations and transmission system needs.
- Produce hydrogen for captive use by nuclear power plants and first movers of clean hydrogen.

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

To support extended plant life, U.S. nuclear power plants need to modernize. Modernizing the aging technology currently used in nuclear power plants is understandably complicated. Plant modernization technology is available, but the difficulty mostly lies in how to implement them safely and cost-effectively in a working nuclear power plant. In addition to addressing technology application challenges, a major consideration is economics. As evidenced by recent plant closures, the decision to continue operations needs a clearly sustainable business model to justify investments in long-term operations.

The LWRS Program plant modernization research provides the nuclear industry with practical guidance on both technology modernization and business model transformation to enable the U.S. nuclear industry to remain cost competitive. Research results validate to nuclear energy industry leaders, stakeholders, and companies that new operating models and technologies will provide meaningful improvements. Therefore, the LWRS Program provides a clear path forward for nuclear energy generated by existing nuclear power plants to be competitive while maintaining the highest safety standards.

Through safe and successful modernization, the nuclear industry is positioned to transform its business into a long-term, cost-competitive solution for the U.S. to achieve its environmental goals to halve greenhouse-gas emissions by 2030 and reach net-zero emissions by 2050 [28]. Though there is not a simple one-size-fits-all solution to modernize nuclear power plants, researchers have developed highly customizable and unique solutions that are publicly accessible to support industry modernization.

The LWRS Program will continue to emphasize obtaining industry collaboration and leadership perspectives, through the maturation and deployment of plant modernization technologies at operating plants. As technologies and partnerships with the industry continue and broaden, these perspectives will verify that plant modernization research priorities address long term industry needs. Future interactions will provide the data needed to refine program objectives and activities.

2.1.2.1 Integrated Operations for Nuclear (ION) Business Operations

The nuclear energy industry has been a mainstay contributor to the U.S. electrical grid since the 1960s. Today, nuclear energy provides about 50% of the carbon-free electricity in the United States. However, the heritage of almost continuous operation in energy's most highly regulated industry is that revolutionary changes to technologies and business practices can seem out of reach for commercial nuclear energy utilities.

Over time, nuclear plant organizational structures have been molded by an emphasis on safety and reliability, resulting in a highly successful safety record. At the same time, plant staffing and operational costs have risen and industry initiatives (e.g., NEI's Delivering the Nuclear Promise [DNP]) have been undertaken to reduce costs and increase operational efficiencies.

Based on the information provided by nuclear industry organizations' cost estimates, nuclear power needs to lower its operating costs in some markets to be or remain competitive. To identify opportunities to reduce costs and improve efficiencies in the operating fleet, the LWRS Program adapted methods for modernization and cost-reduction from the North Sea Oil and Gas industry's development and implementation of 'Integrated Operations.' Integrated Operations identifies the critical capabilities necessary to achieve strategic objectives and develop solutions integrating these capabilities. LWRS Program researchers took lessons learned and best practices from that major industrial sector initiative and adapted them for the nuclear industry, terming the resulting method 'Integrated Operations for Nuclear' (ION). Figure 12 depicts the ION approach used by Xcel Energy at Monticello and Prairie Island nuclear power plants. By applying the ION methodology Xcel significantly reduced their operating costs while maintaining production and safety goals. LWRS Program researchers are continuing to work with other utilities to apply ION methodology. The ION methodology uses plant-specific market analysis to identify goals for operating costs necessary for long-term commercial viability. Based on the results of these modeling and cost goals, a plant or organization-specific transformation strategy is developed to identify the needed technology and process modifications, including goals for staffing to achieve the targeted sustainability goals.

Figure 12. Integrated Operations for Nuclear (ION) at Xcel Energy

In 2021 the ION business model was developed to lay out the steps that industry could use to achieve more efficient operations through interlocking technology, organization, cultural, and process changes. Using ION, changes can be streamlined, extraneous work tasks can be eliminated or automated, and industry activities and practices optimized. Ultimately, the ION team working with industry partners has validated that nuclear energy utilities committed to strategic digital and efficiency upgrades, can save up to 30% in operating costs. These savings translate into substantial opportunities overall to remain competitive in the electricity market.

RESEARCH ACCOMPLISHMENT

Demonstration that Nuclear Power Plants Could Save 30% of Operation Costs Through Modernization

In 2022, the ION research team validated previously estimated 30% cost saving by establishing a net present value for modernization projects in a focused analysis [29]. Working with industry collaborators including Xcel Energy, Southern, and Dominion, researchers estimated capital costs and projected savings to show a business case for modernization projects that not only identify and detail the scope of technology modernization efforts but also lays out the long-term economics.

Four specific areas where nuclear power plant work efforts and costs could be reduced have been highlighted (Figure 13). These each have a high degree of confidence of producing a positive net present value. These cost-reduction opportunities involve transitioning to condition-based monitoring; automated planning and scheduling; developing programs for state-of-the-art advanced training; and implementing the technology to automate remote troubleshooting in nuclear power plants. The ION research team found other opportunities to reduce, automate, or re-organize work, recognizing that each operating plant's needs and potential to achieve similar harvestable savings are unique.

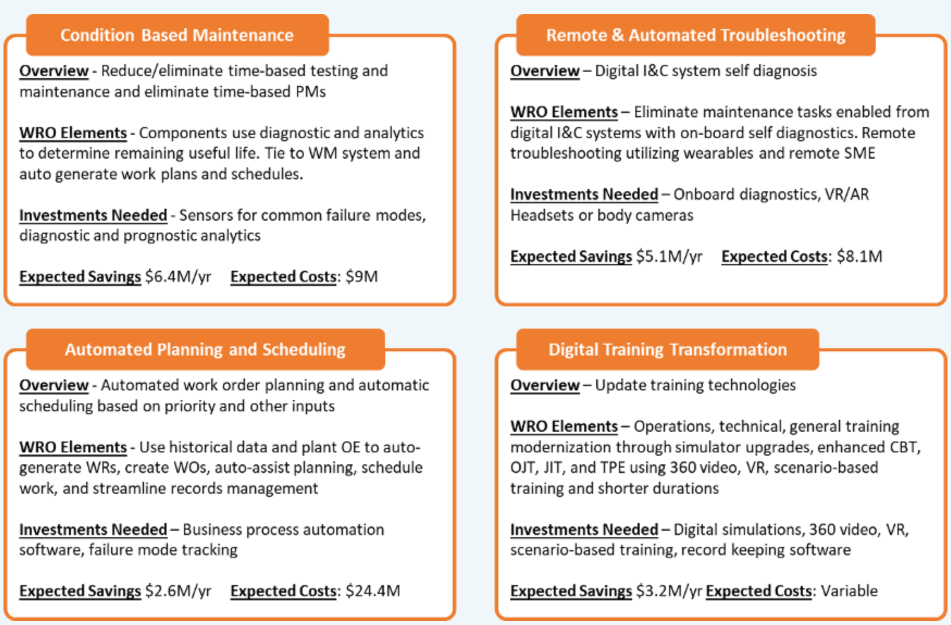


Figure 13. ION Top Cost-Reduction Opportunities.

These results confirm both the wide variety of plant modernization solutions and the potential to achieve positive economic impacts. Together, ION's sophisticated economic model and the researched and freely available technologies from the LWRS Program can be used by plant operators to modernize approaches used in the operating fleet to achieve cost reductions and maintain its competitiveness. Moving forward, the ION research team will continue to work with industry partners to demonstrate and validate these approaches to achieve cost reductions.

2.1.2.2 Machine Learning-Assisted Compliance Activities Using a Data Portal and Advanced Analytic Tools

In the business of operating light water reactors today, compliance with laws, regulations, and standards has big implications for day-to-day costs to plant owners. Activities to manually check, record, and report the various required data are time-consuming, expensive, and can be a source of errors. Researchers are developing solutions to streamline compliance activities through innovative integration of data collection, data storage, and data analytics.

In 2022, researchers worked to show how automating aspects of compliance activities at nuclear power plants could reduce costs and improve performance metrics [30]. They focused on three efforts to help meet the objectives to modernize plants while cutting costs. These included: (1) developing methods to streamline access to plant data for compliance activities, (2) demonstrating improved utility compliance processes, and (3) creating compliance analysis tools that evaluate plant performance.

RESEARCH ACCOMPLISHMENT

A Digital Platform to Deal with Nuclear Power Plant Data and Manage Compliance Activities More Efficiently

To streamline compliance data collection and analysis, researchers working with industry developed a data portal (see Figure 14), to automate data collection and integration. The data portal rapidly provides plant staff with relevant data, along with a method for applying performance analytics. This results in a much more efficient approach to conducting some compliance activities.

Since plants support many kinds of inspections, researchers focused the demonstration of their data-driven machine learning (ML) solutions around a regularly performed problem identification and resolution inspection [31]. This specific set of regulatory inspection criteria gave the researchers the details they needed to ensure data access automation worked as expected, streamline their evaluations based on utility-specific criteria, then run custom performance tracking and appraisals to find and resolve compliance issues before or during inspections.

Leveraging the corrective action program issues tracking repository that documents most inspections at nuclear power plants, researchers designed a tool to automate compliance-related analysis and decision-making. Natural language processing is a branch of computer science within artificial intelligence that enables computers to interpret and analyze text data generated by an organization. The analytic tool, Machine Intelligence for Review and Analysis of Condition Logs and Entries (MIRACLE) was developed through LWRS Program research and uses advanced natural language processing and custom ML tools to automate the analysis of condition reports. MIRACLE can scan through condition reports and analyzes the information by incorporating multiple screening functions that are performed manually today.

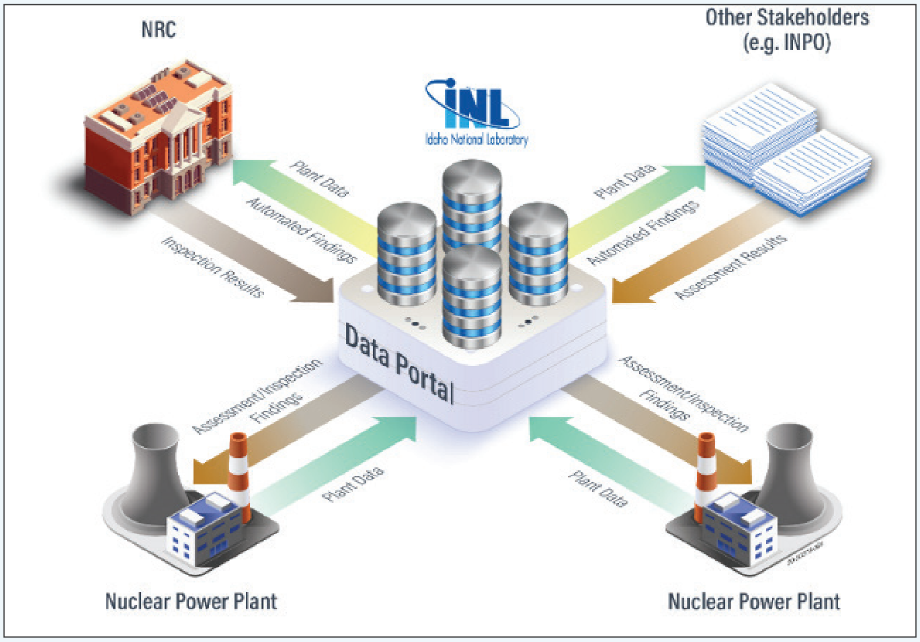


Figure 14. A data portal stores and processes data from nuclear power plants to enable efficient collection and analysis of data to streamline compliance activities.

For this research, MIRACLE used condition reports from more than three dozen nuclear power reactors across the U.S. Using decades of operations data, researchers created a standard set of corrective actions, and a standard nuclear dictionary. By applying this standard set of corrective action topics, utilities can compare their performance over time more accurately, as well as benchmark their performance with others. This approach enables developing metrics for evaluating how an individual utility is performing compared to the rest of the industry.

The resulting data portal provides industry a clear modernization pathway to convert inspection procedures into data-driven decisions. Analytics software developed during this research is available now and free licenses have already been granted to industry. These utilities have already begun customizing methods to make and implement new compliance activity decisions.

2.1.2.3 Enhancing the Usability of Artificial Intelligence and Machine Learning in Nuclear Power Plants

The nuclear industry has traditionally relied on periodically scheduled maintenance (referred to as preventive maintenance) to inspect plant equipment. During these regularly scheduled inspections, utilities take the opportunity to perform routine maintenance. While this may seem like a practical approach, there is a significant cost associated with performing unnecessary maintenance and a risk of human error during maintenance later causing equipment to malfunction. A key cost savings opportunity is transitioning to a predictive maintenance strategy instead. This necessitates maintenance only when there is evidence a component requires attention. Evaluating the risk of accurately identifying degraded component conditions and responding in time to avoid unplanned equipment outages is vital to transition to a predictive maintenance program.

LWRS Program researchers working with industry have developed and demonstrated risk models and technology to monitor and successfully predict component health. Even with positive results, there is a reluctance to broadly adopt these technologies mainly due to the perceived complexity of the ML algorithms used by the analytics. To help plant maintenance teams and system engineers better understand the bases for the analytics predictions and the algorithms used, researchers are developing methods that clearly explain the reasoning behind the AI/ML recommendations. The terms explainability and trustworthiness used by data scientists refer to the reasonable ease for users to understand the analytic predictions and ascertain their validity. Explainability and trustworthiness measures are being developed and validated by LWRS Program research.

RESEARCH ACCOMPLISHMENT

A Visual Interface that Provides Clear Information to Predict and Prevent Plant Equipment Failures

In 2022, in collaboration with Public Service Enterprise Group (PSEG) Nuclear, LLC, researchers showcased how AI and ML can provide monitoring and diagnostic (M&D) center operators relevant information about plant component health using a simplified visual interface. The interface also allows the M&D center operator to monitor the status of the plant/system with AI/ML engine performing analytics in the background and when alerted, allows them to navigate to critical parameters as faults develop in plant components. It provides visual information that is straightforward that can be used to predict and prevent plant many types of equipment failures before they happen.

Specifically, researchers conducted an experiment to predict (i.e., hypothetically simulate) circulating water system waterbox fouling at a nuclear plant. In day-to-day operations, a fouled waterbox in the circulating water system can trigger unplanned and expensive power production outages. The manual process of diagnosing a fouled waterbox and taking actions to mitigate the condition typically requires many hours of data collection, processing, and analysis to determine the source and type of pending failures.

The researchers demonstrated to M&D center operators how AI/ML technology can automate data processing by using different measurements and other objective inputs associated with the circulating water system waterbox fouling problem. This provided relevant information associated with the circulating water system health (measurements indicating system state: healthy vs. degraded) and recommendations of actions to be performed in a clear and easy-to-understand visual display. The prototype computer interface identifies component degradation, also providing the likelihood of the prediction and its potential for concern. This visual display alerts operators rapidly whether they have a healthy system or a potential problem. The M&D center operators can use this information to confirm analytic predictions quickly and independently, before a significant likelihood for loss of electric production occurs, saving time, manpower, and costly unplanned outages.

The prototype interface (see Figure 15) provides M&D users with component degradation information as it continually assesses the overall health of the circulating water system. The interface shown in Figure 15 provides relevant circulating water system measurements used to diagnose waterbox fouling when compared to healthy conditions. Operators can interact with the prototype interface and enhance the display of the ML model into a usable and interpretable format.

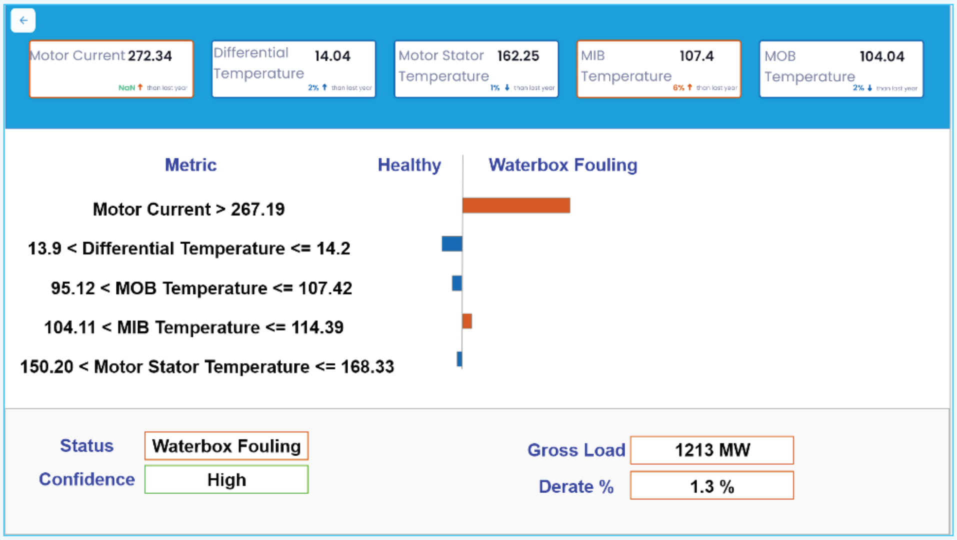


Figure 15. User Interface with Important Parameters Identified, Key Metrics, and Outcome Predicted.

Trust in new technologies is paramount when plant safety and reliable operations are at stake. In this demonstration of AI/ML applications for monitoring and predicting component health, researchers demonstrated that this technology can accurately monitor system performance, predict the need for maintenance, and communicate complicated data in a simple, explainable way that operators can trust to make accurate and timely decisions. Going forward, this technology will be extended to other component monitoring applications and a wide user verifiability study. The research will continue to focus on verifying and validating the explainability and trustworthiness of AI/ML technology in real-world plant scenarios.

2.1.2.4 Automation and Risk-Informing Performance Trends

Condition reports and other information are used to monitor plant performance and to create performance trends, extract information on improving or worsening conditions, and communicate findings to plant management. This information is used by many plant organizations, including operations, maintenance, licensing, and upper management to make informed decisions regarding day-to-day operations and long-term planning. For instance, a declining trend for motor-operated valve performance may indicate that the maintenance strategy is no longer adequate to keep up with degradation mechanisms and must be reconsidered to avoid unexpected failures. Utilities also use this information to support external oversight activities. Performance trending processes currently used at nuclear power plants are based on manual effort to extract and sort data and they rely on subject matter experts for analyzing input and producing output from analyses. As the result, generated performance trends are often dependent on the person's interpretation of what is important. Given the importance of performance trends, it is important to establish trending processes that are consistent, reliable, repeatable, and have the capabilities to systematically prioritize performance issues.

To address these issues, the LWRS Program is conducting research in the automation of performance tracking at nuclear power plants. Researchers have developed and together with utilities are using a new AI tool termed MIRACLE, to automate condition report handling. MIRACLE reads through tens to hundreds of information fields, including free-form fields, sifts through text, and evaluates incidents against historical performance records. It rapidly performs multiple functions that are typically performed by plant staff over days of work. The workflow of the automated tool is presented in Figure 16:

- the incident report text is sent through the MIRACLE Topic Assignment process following a standardized set of coding rules,
- the MIRACLE Decision Making algorithm assigns labels to the reported issues, such as safety significance, priority, severity, etc.,
- as a result, the performance trend is produced showing an increase, decrease, or no change in the specific area of performance (in Figure 16 industrial safety is the selected area of performance with the trend showing fewer incidents meaning an improving performance trend over the last six years).

The automation by MIRACLE provides enhancements in terms of improved efficiency, reliability, consistency, and transparency of the incident report processing.

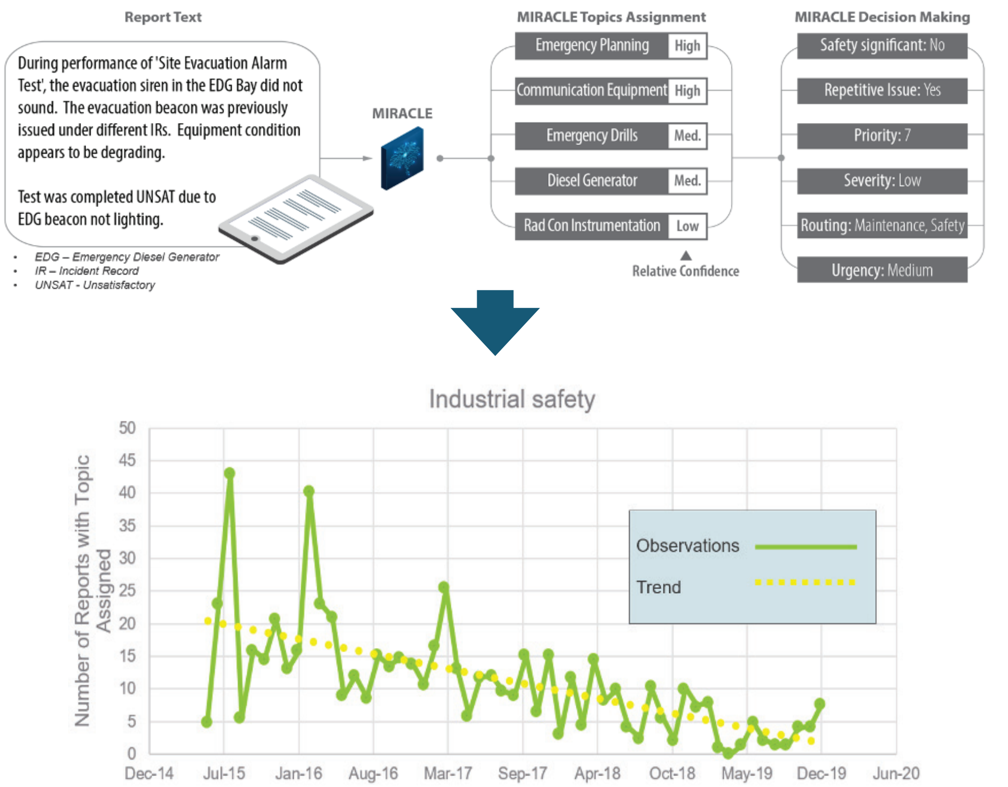


Figure 16. Workflow of trend generation automation.

RESEARCH ACCOMPLISHMENT

Automate the Identification of Issues to Enhance Safety andd Efficiency in Nuclear Power Plants

MIRACLE's development started in 2020, continued in 2021, and in 2022 it has been expanded by developing a novel approach to identify topics of high priority based on risk metrics. This improvement was used to extract a set of safety-related topics, i.e., areas that a plant must focus on to prevent safety-related incidents, for individual utilities collaborating in this project. The utilities adopting MIRACLE are expected to realize benefits in terms of reduced labor to analyze incident reports, consistency in results, and automatic digitalization and distribution of the results to support enhanced decision-making for plant asset management.

Next, the researchers explored how utility-specific safety-related topics correspond to the overall industry topics by combining data from all the participating utilities and comparing outcomes. Data used in this research effort includes information from Constellation Energy, NextEra Energy, Xcel Energy, Tennessee Valley Authority (TVA), and Energy Northwest, representing 35% of the U.S. nuclear power fleet.

As a result, a list of the main contributors to potential plant incidents (i.e., topics that must be trended) has been generated. This approach to risk-informing performance trends offers the opportunity to reduce efforts associated with trending issues and ensure that risk-important trends are recognized and prioritized.

The MIRACLE-centered trend generation and prioritization process has been validated with industry subject matter experts by comparing the results of their assessment, including prioritization, with the computer-generated assessment. The comparison showed a good agreement between the two processes which provides basis for adoption of the automated approaches to assist plant operations. A single nuclear power plant enters multiple incidents to their database daily and each entry must be manually reviewed in terms of their importance and required corrective actions. Often, a single occurrence expands into dozens of additional records associated with post-incident processing. This can take several hours of reviews of multiple plant staff and is estimated to cost the industry an excess of $100M annually. The adoption of AI-based automation offers to significantly reduce this burden.

The research results have been shared with the collaborating utilities—Constellation, Xcel Energy, TVA, NextEra Energy, and Energy Northwest, most of which are interested in adopting this technology and approach. The LWRS Program team is planning a demonstration of risk-informed trending generation with industry participants in 2023.

2.1.2.5 Advancing Human reliability Analysis to Enhance Modern Systems Design and Support Optimized Plant Operations

U.S. nuclear power plants rely on PRA in day-to-day operations, for long-term planning, for demonstration of compliance with licensing, and for many other processes. PRA has for a long-time been used to inform many aspects of plant operation from a safety perspective and the industry has increased the reliance on PRA following the NRC policy statement in 1995 (emphases added):

> *"**the use of probabilistic risk assessment (PRA) technology should be increased in all regulatory matters** to the extent supported by the state-of-the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy." [32]*

The use of PRA has increased even more in the last decade to support the Delivering the Nuclear Promise industry initiative focused on making operations of nuclear power plants more efficient [33]. An essential part of PRA is a human reliability analysis (HRA) which is a systematic assessment of human performance under specific conditions important to plant safety. HRA methods were developed to address the behavior of control room crews using technology for plant operation that are aging and being replaced with newer technologies. New HRA methods are needed to address operations of modernized plants and can also be used to inform normal operation, novel systems design, and performance of plant operators in using modernized systems. This provides a valuable source of safety and reliability inputs to a broader set of plant activities than just for design basis accidents and supports informed decision-making and optimized plant operations.

The currently used HRA methods were developed after the inception of PRA in the 1980s [34, 35]. Given that PRAs became dramatically more complex, and the use of PRA expanded well beyond the original applications, there is a need to modernize HRA methods and tools. Additionally, HRA is being used beyond traditional PRA such as to risk-inform plant modernization activities including digitalization and new operational processes. Current HRA methods do not directly support these new uses.

The LWRS Program undertook this R&D aiming to support the industry with development of an easy-to-use tool assisting HRA practitioners in performing assessments of risks in novel plant system designs as well as in complex scenarios accurately and efficiently. As the result researchers have developed Human Unimodel for Nuclear Technology to Enhance Reliability tool (HUNTER). HUNTER explicitly accounts for three facets of operator performance: performing an action (i.e., task), the conditions under which the action is performed (i.e., environment), and aspects of human psychology that may affect performance (i.e., individual). These are shown in Figure 17.

The novelty of HUNTER stems from the integration of these three aspects. This allows automated modeling and analysis of performance factors instead of manually selecting and analyzing the factors by the analyst as done in other HRA approaches. HUNTER also explicitly considers cognitive processes which are an important part of human performance.

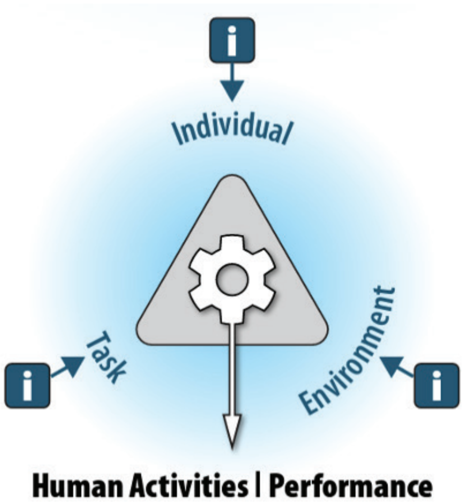


Figure 17. The HUNTER Conceptual Framework addresses aspects of human performance, the performance environment, and relevant aspects of psychology that may affect performance of the action in the conditions of interest.

RESEARCH ACCOMPLISHMENT

Easy-to-Use Framework to Assess Human Performance and Risks in Nuclear Power Plants

The HUNTER software features a graphical user interface to simplify HRA model development. HUNTER integrates three core modules (task, environment, and individual) into a simple-to-use interface where the individual activities of a task can be analyzed. This is based on information in procedures that operators and other workers in nuclear power plants use to guide work activities.

HUNTER was developed as an easy-to-use computation-based HRA modeling method to provide enhanced HRA capabilities. It provides the ability to create a digital human performance model to be used in simulations of plant normal operating conditions and accident conditions. Analysis of variants of task performance can be simulated in a repeated fashion, allowing what-if modeling for novel contexts. For example, the range of human activities involved in deploying portable equipment under a variety of situations could be simulated automatically. A similar effort using conventional HRA methods would typically require extensive manual analyses, proving labor and time intensive. In addition to standard HRA outputs (e.g., human error probabilities), HUNTER uniquely models task time. This functionality is not covered in other HRA methods and represents a significant milestone for realizing the added value of dynamic HRA.

In March 2022, the first version of the HUNTER software was released [36]. With the release of the software, HUNTER provides a uniquely accessible entry point into the power of computation-based risk modeling for HRA. In September 2022, RISA researchers documented an extensive set of human performance data from simulator runs used for building and validating industry-relevant scenarios in HUNTER [37]. In November 2022, RISA researchers coupled HUNTER to a nuclear power plant simulator, enabling faster and more extensive scenario modeling [38]. HUNTER offers unique capabilities to the industry in terms of risk-informed optimization of modern plant systems, assessment of operators' performance in using the modernized systems, and a systematic, consistent, reliable assessment of operators' performance under novel operating conditions such as a nuclear plant coupled with a hydrogen production facility.

2.1.2.6 Risk-Informed Asset Management

Operations and maintenance costs are the significant expenses for operating nuclear power plants. To reduce these costs, nuclear power plants are moving from corrective and periodic maintenance to predictive maintenance strategies to maximize component availability and minimize maintenance costs. Such a transition requires novel computational tools and data assessment techniques.

RESEARCH ACCOMPLISHMENT

Use Artificial Intelligence to Analyze Plant Record Databases, Prevent Future Failures and Reduce Operation and Maintenance Costs

LWRS Program has developed an approach to employ AI technologies to analyze plant records and extract quantitative information. The data retrieved from massive plant record textual databases are a potentially valuable input to equipment reliability assessments. Currently, plant records are used in a limited capacity due to the significant manual effort required to process them. The AI-assisted approach allows users to extract valuable information and use it to support equipment reliability assessments that inform strategies for equipment maintenance, both preventive and emergent. Figure 18 illustrates the general process: an equipment failure is documented in a plant incident report, and plant personnel are assigned with tasks of (1) determining the cause of failure and (2) establishing measures to prevent future similar failures. Given multiple possibilities of failure causes, this could be labor-intensive and time-consuming. Historical records, either plant-specific or industry-wide, could be valuable in finding causes of failure based on similar occurrences in the past, but the search through thousands of records is a daunting task. In this case, AI is a valuable assistant since it can analyze a large amount of data in minutes. By employing AI, plant personnel can identify the cause of failure in a matter of hours instead of weeks.

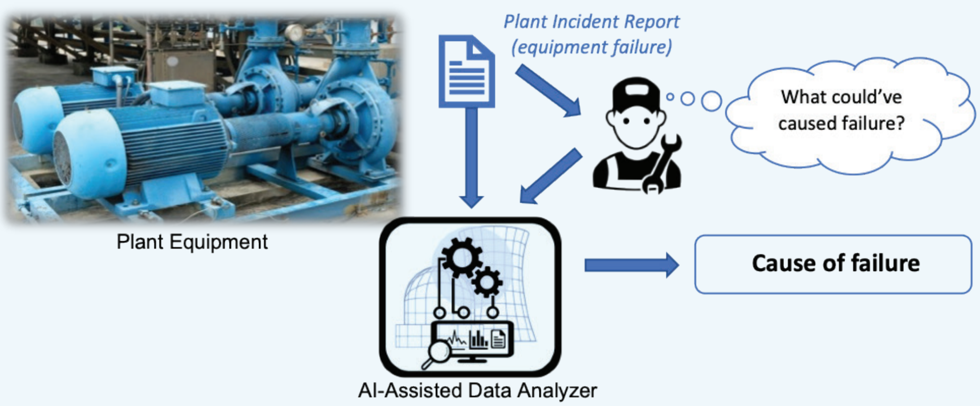


Figure 18. Schematic of AI-Assisted Causal Reasoning Approach.

RESEARCH ACCOMPLISHMENT

Novel Method to Model Equipment Reliability, Optimizing and Reducing the Cost of Plant Management

The project researchers also developed and demonstrated a creative, novel, and unconventional method to conduct equipment reliability modeling. Instead of using a traditional probability of failure metrics, equipment reliability is expressed as available margin (i.e., remaining useful life). The margin here is defined as the "distance" between the present status of a component and an undesired event (e.g., component failure). The two perspectives on maintenance are presented in Figure 19.

For the corrective maintenance, the margin is estimated based only on historical records of similar component failures without a consideration of the current condition of a given component. For condition-based maintenance, the margin is calculated based on both historical failure data and the actual state of the component of interest. The actual state is important because it allows to schedule maintenance more accurately before failure occurs but not too early if equipment conditions do not warrant it. The margin-based reliability is an intuitive way to express system health and convey this information to plant engineers and management. It supports various plant operations such

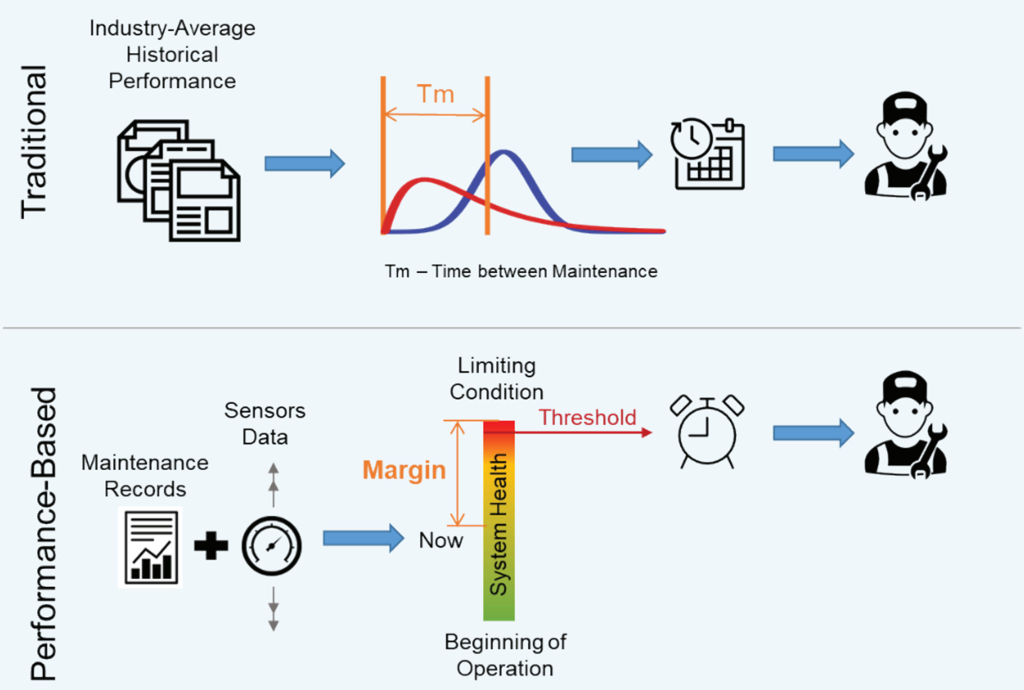


Figure 19. Margin in Equipment Performance under corrective and condition-based maintenance.

as planning routine equipment maintenance, optimization of crew schedule and spare part inventory, selecting between equipment replacement or refurbishment, and other cost-significant activities.

The methodologies developed as part of this project have been demonstrated in collaboration with industry partners, the most recent being through the partnership with PSEG and Westinghouse. The multiple modules developed as plug-ins have been released as open-source and are ready for industry use.

2.1.2.7 Advanced Technologies for Physical Security

The events of September 11, 2001, and subsequent regulatory guidance resulted in significant increases in physical security at nuclear power plant sites. It is estimated that roughly 20% of a nuclear power plant site's staffing is dedicated to physical security. During an LWRS Program stakeholder meeting on physical security [39], optimizing the physical security posture without impacting regulatory requirements was identified as a priority for near-term research and development. This research area provides an economic and technical evaluation of response force technologies, and the development of a deployable remote operated weapon systems (ROWS) capability for installation at nuclear utility sites that meets regulatory requirements for inclusion in their security posture. It is also intended to support a potential future cooperative private-public implementation of a ROWS at a candidate nuclear utility site.

The objective of this research is to leverage an operationally deployed ROWS solution for external (see Figure 20 inside red circle) [40] and internal (see Figure 21 for indoor deployment only) deployment at domestic nuclear power plant sites as a force multiplier that will reduce manpower requirements and increase the survivability of the overall security force. This research activity will assist the current nuclear power fleet in addressing the challenges of optimizing ROWS deployment within a 5-year timeframe. This research is being performed in collaboration with Xcel Energy, Entergy, Constellation, and coordinated through regular industry stakeholder engagement activities.

Figure 20. Single Sentry-II ROWS Configuration.

Figure 21. Single Inverted T-360 ROWS Configuration.

RESEARCH ACCOMPLISHMENT

Optimizing a Site's Physical Security Posture using a Remote Operated Weapons System

Through engagements with nuclear utilities, ROWS is viewed as a technical solution to reduce manpower requirements and enable the nuclear utilities to operate nearer the staffing requirements of 10 CFR 73.55. In 2022, LWRS Program researchers collaborated with nuclear utilities and the U.S. NRC to evaluate an existing operationally deployed ROWS through reviews of documentation (e.g., Safety Basis and Cybersecurity Basis), considerations of force-on-force exercise assumptions, and application of a phased approach for ROWS deployment:

- Phase 1: Conduct modeling and simulation of external and internal ROWS placement.
- Phase 2: Develop and use a full-scope ROWS simulator for training, and verification of modeling and simulation of ROWS placements.
- Phase 3: Leverage the full-scope ROWS simulator for limited-scope force-on-force exercises to validate the modeling and simulation of ROWS placements.
- Phase 4: Support a full-scope ROWS deployment.

In 2022, research efforts identified external ROWS deployments, which included considering NRC assumptions, and completed a review of upgraded armored solutions for external ROWS configurations. Candidate ROWS technologies, such as the Precision Remotes Sentry II platform (Figure 22), are being considered. 2022 efforts included updating the command-and-control software evaluations for safety, security, and performance of a ROWS deployment at domestic nuclear power plant sites. The research included conducting live fire testing of the M240-SLR rifle (see Figure 22) [41] to support updating and increasing the accuracy of the ROWS modeling and simulation.

Figure 22. M240-SLR Semiautomatic Rifle.

The modeling and simulation efforts used the Dante™ software and Scribe3D© software to identify preliminary ROWS placement (Phase 1) with two collaborating nuclear utilities. The Dante software is used to inform decision-makers and security professionals about the system effectiveness of existing and future physical protection system designs. The Dante software is the only approved software for the operationally deployed ROWS, and it is used for this research. Scribe3D is a three-dimensional tabletop recording and scenario visualization software that creates, records, and plays back scenarios developed during tabletop exercises and can be used as a planning tool for performance testing, force-on-force, or other security analysis-related applications. Collaborating nuclear utilities are using Scribe3D to provide feedback on ROWS placement (see Figure 23) and input to the Dante software. These security software tools help facilitate open discussions, capture subject matter expert input, visualize consequences, leverage performance data, and record adversary scenarios to compare events with current security force personnel locations versus proposed ROWS placements. The Dante analysis shows that for comparative adversary scenarios, the ROWS based security force generally has a higher success rate against an adversary force than a non-ROWS-equipped security force. Modeling and simulation refinements will be made to finalize Phase 1 of the graded approach in 2023 with at least one collaborating nuclear utility.

Figure 23. Notional Visualization for Modeling External ROWS Placements using Scribe3.

The following accomplishment are planned for the deployment of ROWS:

- In 2023, complete modeling and simulation of external and internal ROWS placement.
- In 2024, complete the development and use a full-scope ROWS simulator for training and verification of modeling and simulation of ROWS placements.
- In 2025, complete a full-scope ROWS simulation for limited-scope force-on-force exercises to validate modeling and simulation of ROWS placements.
- In 2026, complete the implementation of a full-scope ROWS deployment.

This graded approach to ROWS deployment allows each nuclear utility to reduce its financial and regulatory risks as they evaluate the feasibility of deployment at each site.

2.1.2.8 Risk-Informing Physical Security

This research focuses on performance-based, risk-informed physical security to help establish methods for developing an integrated risk-informed solution for security. One goal of such methods is to develop a structured approach that can simultaneously support consistency in security-related decision-making and address the unique security-related concerns of each nuclear power facility. Ultimately, insights from advances in risk assessment and complex systems analysis provide framing to leverage the advantages of various cutting-edge risk-informed approaches to help improve physical security for modernizing and expanding nuclear facilities against a 21st century threat environment. This research enhances and demonstrates risk-informed methodologies for physical security by integrating dynamic risk methods, physics-based modeling and simulation, operator actions, and onsite equipment, which will extend the radiological sabotage timelines for response force success and explores the expansion of existing risk-informed methods for nuclear security.

The objective of this research area is to enable the use of risk-informed processes for use by LWR stakeholders, including the regulator, for making physical security decisions that reduce uncertainties, optimize physical security postures, and supports processes for making changes to a nuclear utility's physical security plans. Physical security has demonstrated limited use of quantitative risk assessment (or other risk-based approaches) due to the dynamic human variables associated with a well-resourced and motivated attacker. This is, in part, because an attacker can change an attack plan or sabotage target set in the middle of an attack based on how the attack is going. Today the physical security community relies on limited empirical data and subject matter experts to inform physical security plans. This results in large uncertainties in traditional analyses and perhaps overly conservative security plans to account for these uncertainties. A performance-based, risk-informed approach to physical security can enable improvements to physical security postures without negatively impacting the required overall physical security system effectiveness.

RESEARCH ACCOMPLISHMENT

A New Approach to Better Assess the Security of Unattended Openings – Such as Pipes – and Protect Nuclear Facilities Against Intrusions

In 2022, LWRS Program researchers collaborated with nuclear utilities, the Nuclear Energy Institute (NEI), and the NRC regarding the smallest opening that a person can fit through under several spatial scenarios to provide further understanding regarding the delay characteristics (e.g., crawling rates) of engineered openings (pipes) as well as potential breach points. All test results are focused about a U.S. Government-wide unattended opening area size, which is currently considered the minimum opening area that must be protected. While unattended openings have an NEI policy document [42], it required additional input into this high-priority issue using a performance-based risk-informed approach. The goal of conducting this research was to establish empirically derived information regarding person passable opening sizes and rates to inform approaches to better manage unattended openings.

In 2022, the research produced a first-of-a-kind approach for performance-based, risk-informed assessments of physical security; NRC provided a peer review. The data and conclusions generated from the test series and risk-informed analyses can be used to help evaluate unattended openings (pipes) and potential breach points of physical security systems and inform security policy changes for nuclear power plant sites. Figure 24 provides an example of the test setup for three dimensional openings (pipes) and Figure 25 and Figure 26 provide an example of the test setup for two-dimensional openings (breach point).

The test results and risk-informed insights differentiate between the minimum area that will allow a person to pass through in two-dimensional rectangular, square, and circular apertures and three-dimensional pipe openings. This answers a basic question of what the minimum breach or unattended opening size one must use to evaluate a physical security system perimeter or potential adversary path, and ultimately enabled the study to evaluate and answer the following questions:

- Can a particular opening geometry, including its shape, aspect ratio, depth, and so on, pose a potential risk or offer an advantage to an adversary,

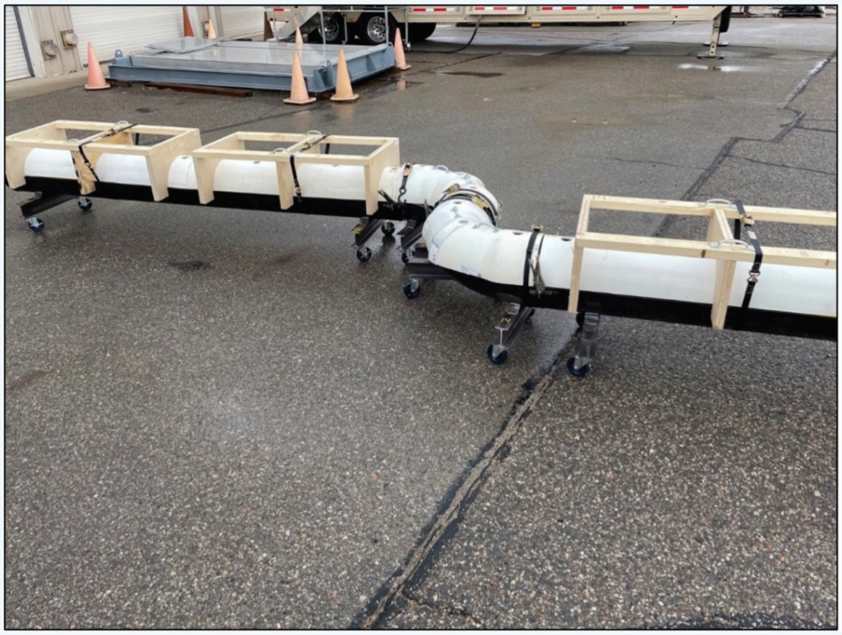


Figure 24. Three-Dimensional Piping Structure in an S-shape Configuration.

Figure 25. Two-Dimensional Rectangular Frame.

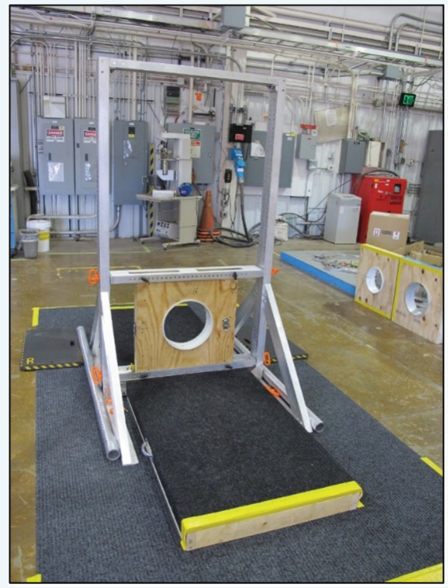


Figure 26. Two-Dimensional Circle Frame.

- If a given opening increases the risk or provides an opportunity to an adversary, how can this opening be exploited,
- How much time does it take for the opening to be exploited in various scenarios; and
- What are the limitations of this exploitation?

Further, this study sought to correlate the minimum opening size that a person can successfully traverse with various measured body dimensions spanning the normal curve of human physiology from approximately the 5^{th} percentile through the 75^{th} percentile adult.

The primary results of this effort can define the conditions in which an adversary could successfully pass through a potentially complex opening, as well as define the conditions in which an adversary would not be expected to successfully traverse a complex opening. This rigorously produced data can be used to provide the basis for risk-informed decision-making. At its inception, this effort intended to investigate openings that could be found to intersect security boundary layers, but through careful experimental design, the testing has also yielded insights to understand the delay characteristics of engineered openings, as well as potential breach points. From the design of the experiment, performance testing series, risk-informed analyses, and detailed writeup, this first-of-a-kind approach for performance-based, risk-informed assessments of physical security provides a framework for future evaluations of access/delay technologies and security barrier concerns. This effort focused on understanding the risk associated with a U.S. Government unattended opening requirement and thus, it is understood that any opening has some level of associated security risk. Further, any analysis of nuclear facility security risk should consider other attributes such as:

- Traversal and exit strategies of the opening which are based on site conditions, and
- Attack tools required to achieve the adversary's objective(s).

2.1.2.9 Advanced Sensors and Barrier Systems for Physical Security

This research aims to develop low-cost, rapidly deployable detection, assessment, and delay technologies that could be used at nuclear power plant sites. Those technologies will improve performances and increase the time necessary for an external adversary to intrude or commit a sabotage action. For example, this research is investigating technologies that can be used to create an integrated sensor and advanced barrier systems - Technical Embroidery (i.e., Sensors and Textiles Innovatively Tailored for Complex, High-Efficiency Detection - STITCHED) an emerging technology that can be used to attach wire, fiber optics, and tubes to various substrate materials used in delay barriers (e.g., a ballistic barrier incorporating integrated detection and delay attributes). Additionally, this research explores advances in sensor and barrier technologies, including available commercial-off-the-shelf sensors and barrier materials, for novel use in security applications.

The objective of this research is to develop advanced security sensors and barrier systems that 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 will increase the likelihood of defending against an attack and enhance the economics of doing so. This work will leverage technology to develop advanced security sensor capabilities such as those shown in Figure 27. This figure provides a notional sensor

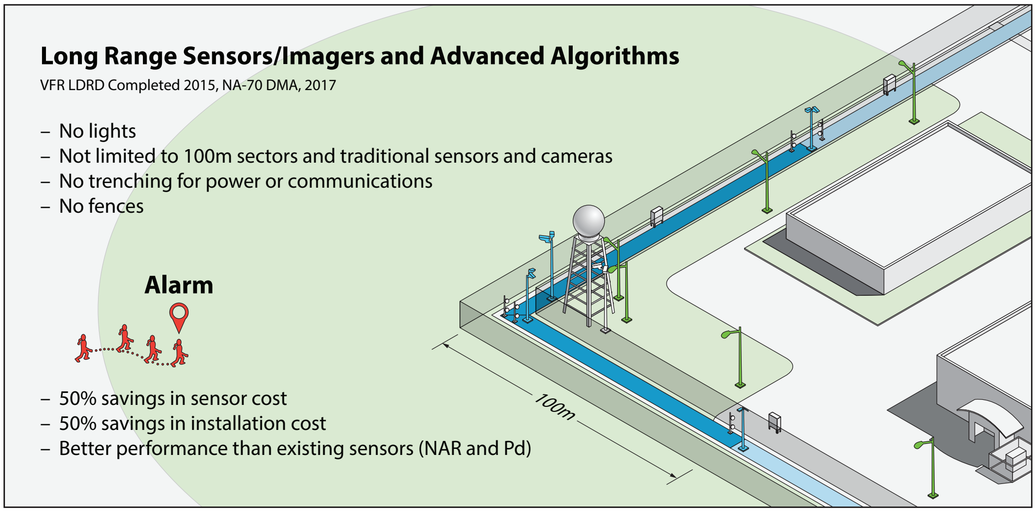


Figure 27. Example of LWRS Program Security Sensor Technologies for Nuclear Power Plant Applications.

improvement beyond the perimeter intrusion detection and assessment system (PIDAS) through advancement in U.S. Government security technologies. These U.S. Government technologies could be leveraged by domestic nuclear power sites to assist in overall cost reductions, reduced nuisance alarm rates, and increases in adversary probability of detection (Pd). Such a deployment of advanced security sensor technologies will also increase the site's early response, increase the probability of interdiction (PI), the probability of neutralization (PN) of an adversary, and raise the overall physical security system effectiveness.

RESEARCH ACCOMPLISHMENT

A Technology Analyzing Inputs from Multiple Sensors of Different Types to Reduce False Alarms and Improve Intruder Detection

The LWRS Program has been researching deliberate motion analytics (DMA) to leverage previous efforts with other U.S. Government organizations and to enable the LWR fleet to leverage the concept of complementary sensor fusion. DMA can take input from multiple, complimentary sensors of different types (including radar and optical devices), analyze the data, and determine if an adversary is approaching a facility; see Figure 28 as an example. In Figure 28, the blue and yellow dots that form a similar straight-line path create a complementary sensor fusion approach which greatly increases the difficulty for an adversary to avoid detection.

The goal of developing DMA is to create improved low-cost, rapidly deployable detection and assessment technologies for nuclear utility sites which could also be used as an early warning system in un engineered terrain. The application of DMA and sensor fusion into LWR physical security postures potentially provides a significant reduction in nuisance and false alarms for the industry and enables an optimized physical security posture without negatively impacting required physical security capability.

The 2022 research focused on conducting pilot deployment of DMA and sensor fusion at nuclear power plant sites with different terrain, weather patterns, and wildlife. Using DMA and sensor fusion, this effort collected multiple days of continuous performance data at candidate nuclear power plant sites without connecting to the site's security systems. Nuisance alarm rate collection considered wildlife, wind, rain, and blowing snow; DMA declared very few nuisance alarms (approximately one nuisance alarm per 24 hour period). Also, the 2022 efforts considered un-engineered terrain (owner-controlled area), and the pilot deployed DMA system integrated a long-range radar, a short-range radar, visible wavelength pan-tilt-zoom imagers, and a bi-spectral pan-tilt-zoom imager. Additionally, this work introduced the "virtual sector" DMA concept, allowing the creation of continuous lines of detection or discontinuous isolated trip wires at critical adversary pathways. Through the 2022 pilot studies, the DMA system showed it could provide reliable detection of NRC-specified intruders in a "beyond the fence environment," while producing significantly fewer nuisance alarms from wildlife and weather.

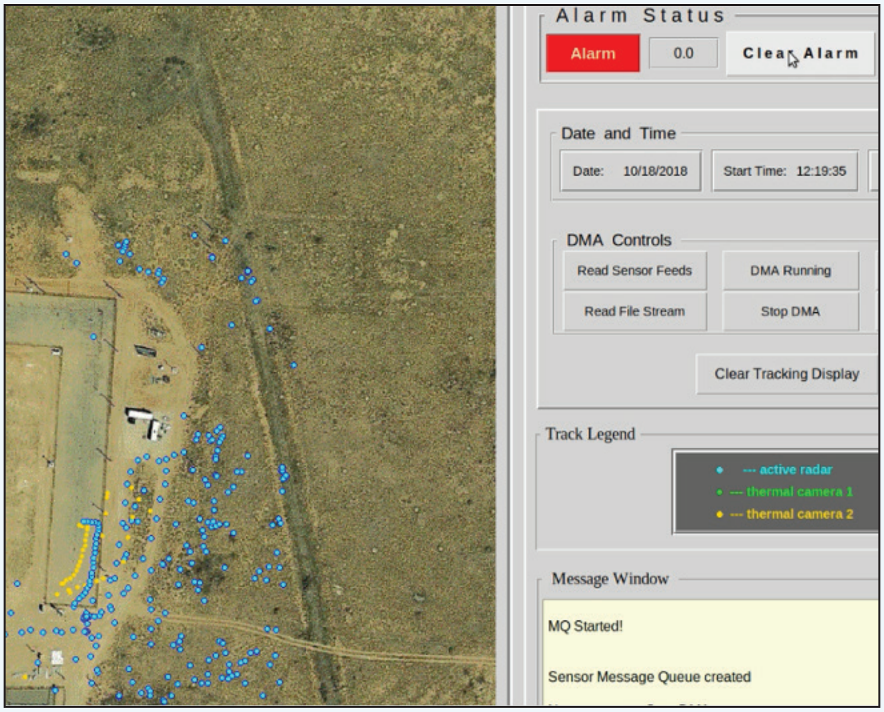


Figure 28. Active Radar (blue) and Thermal Camera (yellow) fused through DMA showing both Nuisance data and Adversary track data.

The result of this research effort is security sensor fusion linked with DMA that can take input from multiple sensors of different types, analyze the data, and determine if an adversary is approaching a facility. Sites using current commercial-off-the-shelf sensor technologies typically experience elevated nuisance alarm rates not caused by an intruder. Thru sensor fusion and DMA, a nuclear utility site can maintain a low nuisance alarm rate while being able to detect intruders and has the potential to decrease the cost of security by crediting early warning zones (secured owner-controlled area) for NRC-specified intruders. Future research on DMA technology will include testing the sensors and algorithms in more nuclear plant settings having differing terrain types, gathering data over longer test periods to assess system performance, and supporting deployment activities into plant physical security operations.

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 found in nuclear power plants. 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 (The primary system consists of the reactor vessel, the steam generators, the reactor coolant pumps, a pressurizer, and the connecting piping whereas the major secondary systems of pressurized-water reactor are the main steam system and the condensate/feedwater system.), along with additional materials in concrete, the containment vessel, Instrumentation and control (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, Figure 29 illustrates that many variables have complex and synergistic interactions that affect materials performance in ways that can impact plant operation or reduce safety and performance. 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 plants 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 the 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 by the LWRS Program Materials Research Pathway and described here is intended to provide data, models, methods, and techniques to inform industry on long-term materials performance.

The Materials Research Pathway's research activities focus on the following materials and novel mitigation strategies to address aging and degradation: (1) reactor metals, (2) concrete, (3) cables and (4) mitigation.

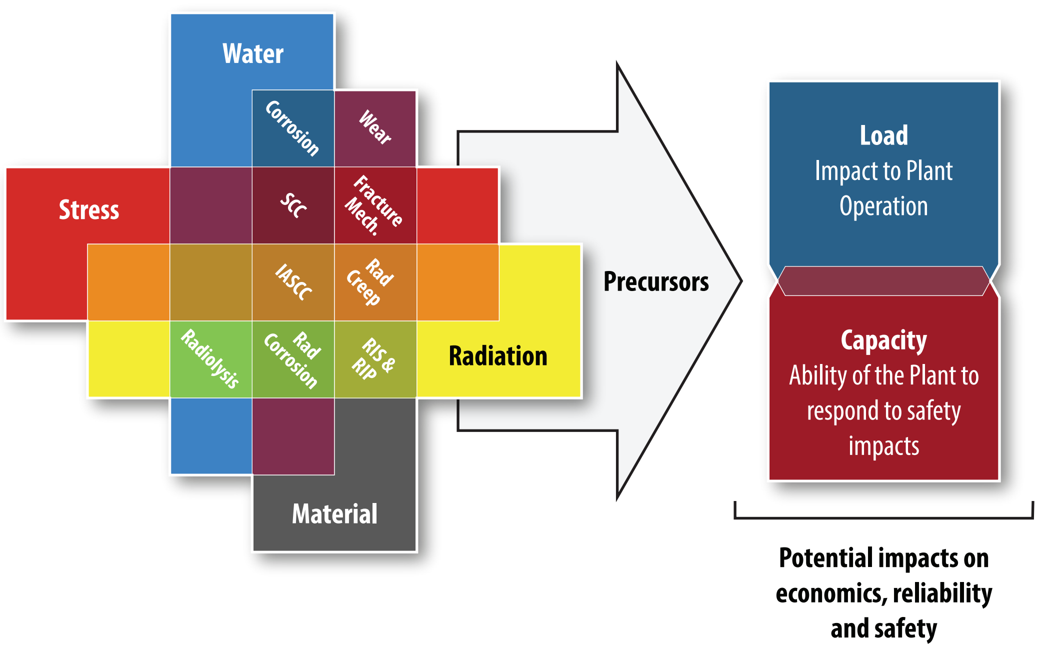


Figure 29. Complexity of interactions between materials, environments, and stresses in a nuclear power plant. SCC: stress corrosion cracking, IASCC: irradiation-assisted stress corrosion cracking, RIS: radiation-induced segregation, RIP: radiation-induced precipitation.

2.2.1.1 Ensuring the Long-Term Performance of Reactor Materials

The challenging operating environment faced by metal alloys in the primary and secondary systems of nuclear power reactors creates degradation mechanisms in the materials that are unique to reactors. Research programs in this area provide the technical foundation to understand and account for the degradation mechanisms of those metals in aging management programs to support the extended operation of the U.S. nuclear fleet.

Researchers hope to underpin the mechanisms of irradiation-assisted stress corrosion cracking (IASCC) in stainless steels for PWR internal material aging management. They aim to understand the role of material composition, history, and environmental conditions on IASCC, and to develop models based on a strong mechanistic understanding of various degradation modes.

IASCC is widely recognized as an important degradation mode for reactor core structural materials and applies to nuclear power reactors that may operate for 60 to 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 of certain alloying elements on material grain boundaries), that can enhance stress corrosion cracking susceptibility. This research employs a multifaceted approach, including crack initiation experiments, microstructure analysis, advanced mechanical tests, and corrosion studies, to provide a complete understanding of IASCC.

RESEARCH ACCOMPLISHMENT

A Better Understanding of Materials Behavior in Nuclear Reactors to Reduce the Risk of Cracks and System Failures

In 2021, the research team at the University of Michigan, funded by the LWRS Program, proved grain boundary (GB) oxidization as the precursor damage for IASCC. In 2022, the separation of oxidation and straining approach confirms that GB oxidation is both a necessary and sufficient condition to initiate IASCC. As shown in Figure 30, exposure to irradiated stainless steel in a PWR water environment resulted in oxidized GB. When the oxidized material was subjected to straining in high-temperature Argon, cracks would initiate in the material. In contrast, a pristine sample without GB oxides could sustain higher load and deformation in high-purity Argon without any intergranular cracking. The decrease in stress needed to initiate cracking with long-term exposure substantiates the role of GB oxidation on IASCC.

The results establish that GB oxidation in a PWR water environment is a key factor in the intergranular cracking of irradiated 304 stainless steel. This finding advances the current understanding of the mechanism by which IASCC initiates. In addition, it sheds light on future research directions to mitigate IASCC, such as developing materials more resistant to PWR water environment corrosion or modifying the current PWR water chemistry to reduce reactor internal oxidation. This research is conducted in close collaboration with the EPRI to coordinate the research efforts and exchange information with the industry and regulatory authorities.

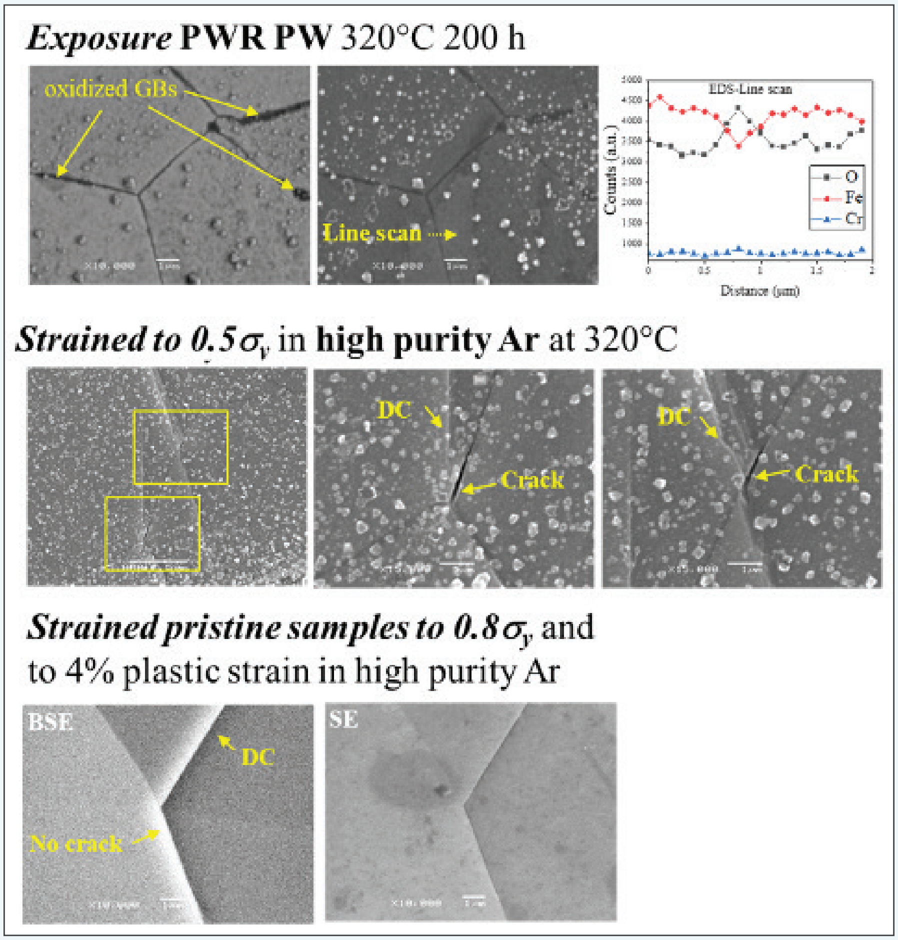


Figure 30. Separation of GB oxidation from intergranular cracking of 304 stainless steel irradiated to 69 dpa in BOR-60 reactor at 320°C. EDS: Energy-dispersive X-ray spectroscopy, DC: dislocation channeling.

Figure 30 confirms that exposure to PWR primary water resulted in GB oxidation from which cracking developed. In contrast, a pristine sample without GB oxidation was able to sustain a higher load without cracking. The results establish a critical link between GB oxidation and IASCC and will inform aging management activities and research needs for mitigating IASCC for PWR internal materials.

2.2.1.2 Crack Initiation in Nickel-Based Alloys

This research is investigating the long-term stress corrosion cracking (SCC) behavior of nickel-based alloys in PWR primary water to enable better lifetime performance predictions, safety assessments, and risk management during the extended operation of the nation's existing LWR fleet. In addition, research is directed at understanding the microstructural changes occurring in a high-chromium, nickel-based alloy and its weldment during long-time exposure to reactor operating temperatures and the effect of these changes on their service performance. The research focus was developed with input from regulatory and industry groups and employs state-of-the-art laboratory testing and microscopic characterizations.

Recently, research has expanded to support the U.S. nuclear industry's effort to evaluate options to replace 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 SCC response of nickel-based alloys in a KOH environment to ensure that SCC susceptibility is not enhanced by KOH water chemistry. In collaboration with an ongoing EPRI-led KOH qualification program, this research is performing SCC evaluations on selected materials in both LiOH and KOH-containing PWR primary water chemistries.

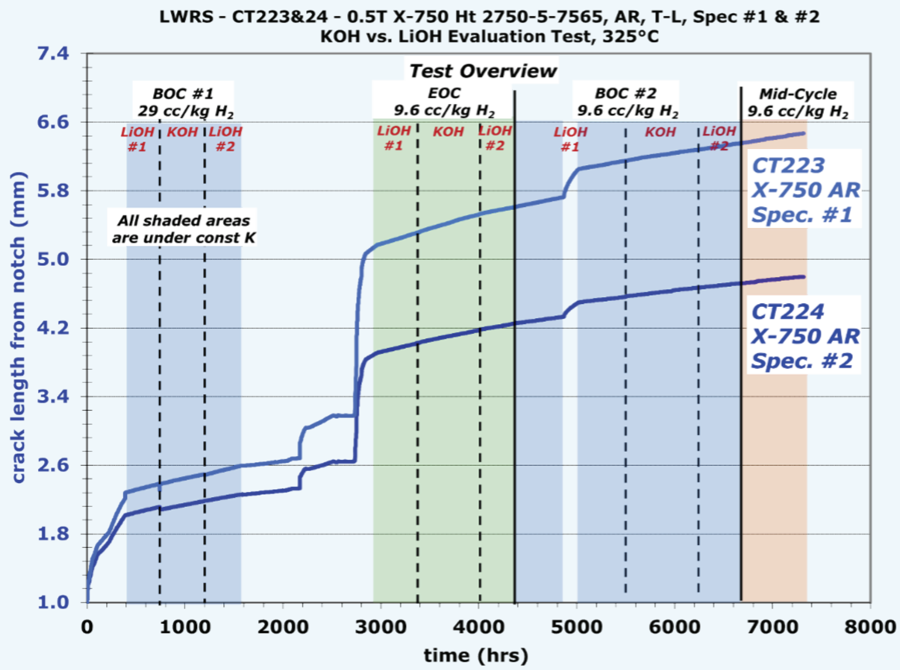
RESEARCH ACCOMPLISHMENT

An Evaluation of Crack Growth in Reactors Metal Alloys to Improve Plant Management and Economics

In 2022, the LWRS Program research team at Pacific Northwest National Laboratory completed the SCC growth rate evaluation of some metal alloys (namely, Alloy X-750 and Alloy 718) in KOH versus LiOH, an effort initiated in 2021. The team applied in-situ measurement of crack extension in PWR primary water chemistries with on-the-fly changes between KOH and LiOH, allowing uninterrupted, direct comparison of SCC growth rates of KOH versus LiOH. As shown in Figure 31, switching to KOH did not affect the SCC growth behavior of these two alloys in beginning-of-cycle, end-of-cycle, and mid-cycle water chemistry, nor on shifting between these water chemistries. This is manifested by no apparent slope change for the crack length versus time curves in Figure 31. These results indicate that replacing LiOH with KOH would not adversely impact the SCC growth susceptibility of these materials in PWR primary water. By the end of 2023, this task will be completed with additional SCC growth rate evaluation of another alloy frequently found in reactors (Alloy 82), in KOH vs. LiOH environments. The results from this task will be crucial in supporting industry decisions about whether to replace LiOH with KOH, a more cost-effective option, in pilot PWR plants.

During the water chemistry switch indicated by the dashed vertical lines, the light and dark blue crack growth versus time curves did not show any change in the slope which confirms replacing LiOH with KOH would not adversely impact the SCC growth susceptibility of the two materials in PWR primary water. Specimen ID: CT223 and CT224 for Alloy X-750 in (a) and CT226 and CT227 for Alloy718 in (b). Tests were performed under constant stress intensity (K).

(a)



(b)

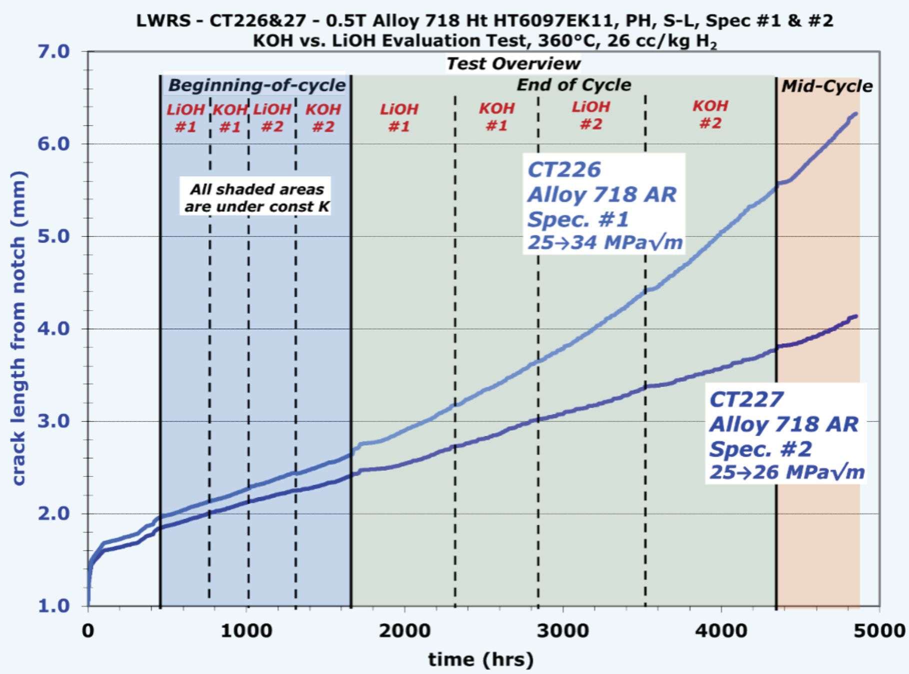


Figure 31. SCC growth behavior of Alloy X-750 in (a) and Alloy 718 in (b) in the beginning-of-cycle, end-of-cycle, and mid-cycle water chemistry with on-the-fly switching between KOH and LiOH.

2.2.1.3 Weld Repair Techniques

Welding is widely used for repair, maintenance, and upgrade of nuclear reactor components. As a critical technology to extend the service life of nuclear power plants beyond 60 years, weld technology must be further developed to meet new challenges associated with the aging of the plants, such as control and mitigation of the detrimental effects of weld residual stresses and repair of highly irradiated materials. To meet this goal, a fundamental understanding of welding effects is needed to develop new and improved welding technologies.

This research, a joint effort of LWRS Program researchers at Oak Ridge National Laboratory (ORNL) and EPRI, is aimed at developing advanced welding technology for reactor repair and upgrades. It focuses on welding repair of irradiated materials that are extremely challenging and require long-term R&D. Multiple weld campaigns have been completed on irradiated stainless steels with different helium levels between 2018 and 2021. In stainless steel under intense neutron irradiation and under the influence of high temperatures and high tensile stresses during welding, rapid formation and growth of helium bubbles can occur at grain boundaries, resulting in intergranular cracking in the heat-affected zone – the so-called helium-induced cracking. Microstructural characterizations demonstrated the feasibility to use advanced auxiliary beam stress-improved laser welding and friction stir welding to mitigate the formation of helium-induced cracking.

RESEARCH ACCOMPLISHMENT

New Welding Technique Reducing the Risk of Cracks and Enabling to Repair Irradiated Materials in Nuclear Reactors

One nickel alloy irradiated with different helium levels was successfully laser welded in a specially designed hot cell at Oak Ridge National Laboratory. The laser welding process, the final welded patches, and the preliminary surface quality survey are highlighted in Figure 32. Various laser welding parameters, including weld speed, effective heat input, and wire feed speed, with and without the auxiliary beam stress-improved technique, were applied to study the influence on the formation of helium-induced cracking. This is the first time the ORNL and EPRI team performed the repair welding on irradiated nickel-based alloys. Surface inspection based on an in-cell camera revealed that uniform and smooth weld beads were produced, and no macroscopic cracking (i.e., greater than a millimeter size) was observed. More detailed microstructural evaluations using optical and electric microscopes will be performed in 2023. The significant ongoing effort to weld irradiated alloys with high helium concentrations and comprehensively analyze the results will eventually yield validated repair techniques and guidelines for use by the nuclear industry in extending the operational lifetimes of nuclear power plants.

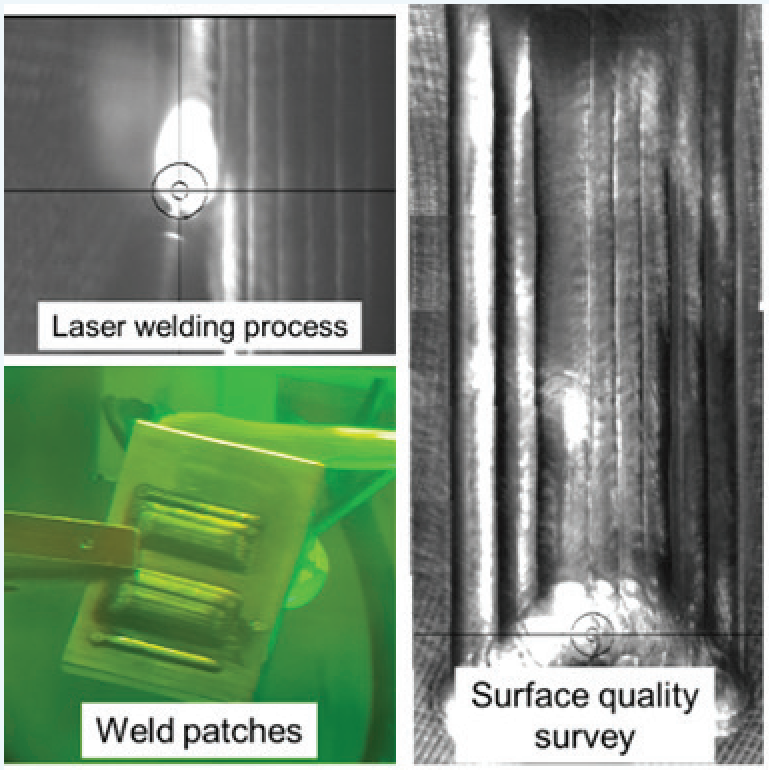


Figure 32. Laser repair welding of irradiated nickel Alloy 182.

2.2.1.4 Experimental Characterization and Modeling of Aging and Degradation of Concrete in In-service Environments

The long-term performance of concrete in nuclear power plants varies with environmental and operational conditions (temperature, humidity, in-service mechanical loading, and irradiation). 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 including temperature, stress, moisture, and radiation. 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.

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

Novel Simulations of Irradiation Damage in Concrete Components and New Methods to Detect Cracks and Porosity in Nuclear Power Plant's Concrete Components

Several characterization techniques were used by the LWRS Program research team at ORNL to study mineralogy and the porosity and cracks generated by neutron radiation in concrete aggregates of varied mineralogical origin. The samples were provided by the Japan Concrete Aging Management Program (JCAMP) team under the Civil Nuclear Working Group (CNWG) framework. To produce maps accounting for the locations of different minerals in the samples (mineral phase maps), a combination of energy-dispersive spectroscopy (EDS) with micro-X-ray fluorescence was used (Figure 33 top left). The mineral phase maps were informed by analyzing optical microscopy images to account for grain size distributions, providing a realistic interpretation of grain boundaries. The maps were used as input for 2D simulations of expansion and damage performed with MOSAIC, a software developed in-house to model irradiation damage in concrete. The simulation results were close to experimental data provided by the JCAMP team (Figure 33, bottom left). The results suggest that the larger the quartz content, the larger the damage.

In addition, investigations of radiation-generated porosity at the micro and nanoscale on the same rock specimens using highly energetic X-ray techniques (synchrotron light source at Argonne National Laboratory) have shown that the porosity of rocks containing silicates increases with neutron irradiation, but this is not the case for rocks composed primarily by calcite. The presence of radiation-induced micro-cracks has also been investigated by electron microscopy and linked to the minerals present around the cracks using spectroscopy. Cracks along grain boundaries and through grains have been observed (see Figure 33). It has

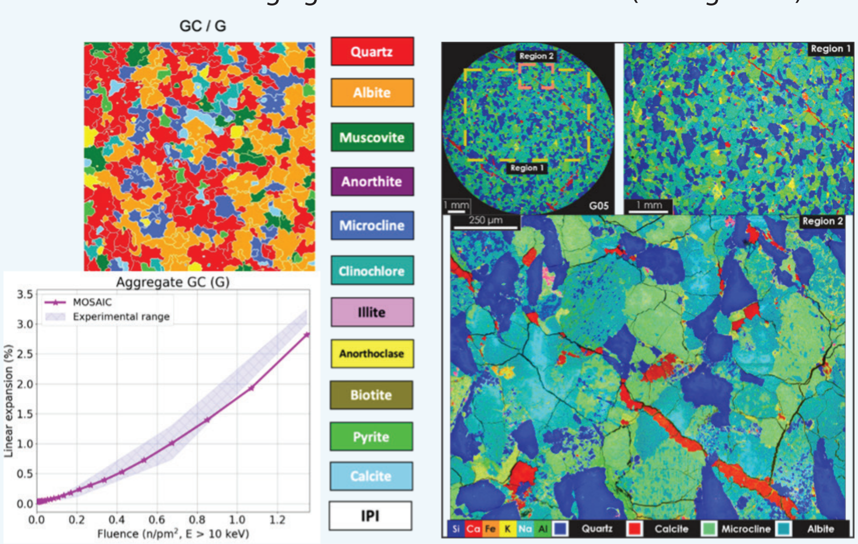


Figure 33. Mineral phase map for a sandstone Japanese aggregate (top left), MOSAIC simulation of aggregate expansion with neutron dose (bottom left), and micro-crack observation through microscopy and spectroscopy showing cracks along grain boundaries and through mineral grains. Note no cracks are observed through quartz grains (dark blue particles).

been found that for rocks containing various silicates, quartz drives the formation of radiation-induced cracks, as no cracks were observed in the interior of quartz grains (blue particles in Figure 33), but rather originating at the boundaries of quartz grains.

The results of this research highlight the importance of characterizing the mineralogy of the aggregates in any nuclear power plant concrete structure to accurately model and predict radiation damage after prolonged exposure to neutrons. Industry can apply similar characterization and modeling techniques to estimate the radiation damage in their concrete structures.

2.2.1.5 Human and Technology Integration

Existing U.S. nuclear power plants were originally designed and constructed using analog systems for monitoring and control. Over time, this technology has become obsolete: systems have become expensive to maintain; are not readily available through common supply chains; and are unfamiliar to a new workforce. This underscores the need for nuclear power plants to adopt digital solutions for plant monitoring and control. Due to the perceived complexity and costs to modernize, industry has largely avoided large control room upgrade projects. Upgrades to the control room are also not a simple case of buying newer computers and upgrading software since almost all operating U.S. nuclear power plant control rooms pre-date the digital age. In fact, before 2022 the NRC had not approved any substantial LAR to add digital technology to a LWR control room safety system for 20 years. To support extended plant operations of 60 years and beyond plants will modernize and many have already begun. Digitalizing I&C applications will improve the operability of control rooms while offering broad economic benefits.

RESEARCH ACCOMPLISHMENT

Providing Practical Guidance to the Industry on How to Implement Digital Upgrades

LWRS Program human factors engineers have for the past decade focused their efforts on studying the safest and most effective methods to make meaningful change through digital I&C system upgrades to nuclear power plant control rooms. These proven human factors methods were applied to Constellation Energy's LAR submittal effort, providing the NRC with the necessary information to begin the LAR review process. In May 2022, Limerick staff gathered at Idaho National Laboratory's Human Systems Simulation Laboratory (HSSL) to work through function, allocation, and task analysis in a 3-D digital mock-up of Constellation Energy's Limerick Generating Station's control room (see Figure 34). This critical LWRS Program support in partnership with Constellation Energy, Westinghouse, and Sargent & Lundy provides direct assistance to industry in their efforts for large-scale digital modifications.

Figure 34. LWRS Program Researchers host Limerick Safety System Modernization Analysis at the INL Human Systems Simulator Laboratory.

A key effort in assessing the impact of modernization is functional analysis and allocation planning. This process evaluates human and technology integration and identifies the optimum allocation of human and digital technologies to meet industry requirements. The team examined new tools and technologies to ensure the final control room design reduced redundancy and wasted efforts while ensuring no compromise in safety or reliability. This planning process allowed Limerick station staff to reimagine aspects of nuclear power plant operations.

The results from this multidisciplinary workshop's activities and the data collected were compiled into a practical industry guidance explaining how to apply human-technology and human factors engineering to digital function analysis and allocation planning. The guidance includes instruction and lessons learned captured during the workshop and provides industry with examples of how to effectively apply these techniques in large-scale safety-related digital I&C upgrades on a wider scale. This guidance shows other nuclear power plants and even other industries how digital upgrades can be planned and executed, while reducing regulatory uncertainty, and ensuring safe and reliable operations. Leveraging information generated from the workshop, Constellation Energy's safety-related digital I&C upgrade LAR was submitted on September 26, 2022, using the streamlined NRC LAR Alternate Review process. Utilizing the information provided by Limerick and LWRS Program planning, design, and analysis reports, the NRC issued a letter on December 9, 2022, accepting Constellation Energy's LAR for docketing. Constellation Energy and LWRS Program researchers continue the activities necessary to support NRC's LAR approval that will ultimately enable the replacement of Limerick's existing safety-related analog control systems with a single digital plant protection system.

LWRS Program researchers have, over the course of the past decade, studied a multitude of human factors engineering approaches to thoroughly understand requirements and constraints for all plant and work functions so they can be modernized and revitalized nuclear power's strategic business objectives. The accomplishment this year of successfully initiating the LAR acceptance review is a critical first step in securing regulatory approval for the activities described in the Human Factors Engineering Program Plan developed for the Limerick I&C Upgrade. NRC's approval of this effort and its implementation will help provide industry with a proven approach and the confidence to engage in similar digital I&C upgrades. The impact of the years of Plant Modernization Pathway-funded Human Factors Engineering research, and now, its applications at the Limerick Generating Station will comprehensively reimagine industry guidance and prove that digital I&C technologies work and can save nuclear power plants money.

Moving forward, researchers will continue to work with Constellation Energy and the Limerick Generating Station staff to assist in design and implementation activities supporting control room upgrades by continuing to apply human and technology integration advice and guidance, including generating detailed design activities and validating the integrated systems as they develop.

2.2.1.6 Risk Assessment of Digital Instrumentation and Control Systems

The advancements in digital I&C technology in the last two decades have been revolutionary and many industries have successfully transitioned to digital I&C systems which are proven to be reliable, less expensive, less expensive, and easier to maintain. However, the transition involves more than replacement for the nuclear industry especially when dealing with systems that must be qualified to perform safety-related functions. While digital systems have proven to have some advantages over analog systems, they introduce a new concern: the possibility of system failure caused by software. Since this concern is not applicable to analog systems, it must be uniquely evaluated to obtain approval for installation of a safety-related digital I&C system at a nuclear power plant.

The LWRS Program has undertaken a R&D project to develop a risk assessment method for digital I&C upgrades that addresses requirements for system performance, including software system performance, to assure availability and reliability of the system for anticipated operational conditions. The method provides a systematic, verifiable, and reproducible approach. The method is shown in Figure 35. It supports the identification and quantification of software failures, including CCFs, and evaluates the system's capabilities to perform its safety functions given identified and analyzed potential failures. This assessment allows the identification of system vulnerabilities as well as provides suggestions for risk reduction and design optimization.

As shown in Figure 36, the proposed method has as a modularized structure supporting effective interactions between various reliability analysis phases. Among those modules, RESHA (Redundancy-guided Systems-theoretic Hazard

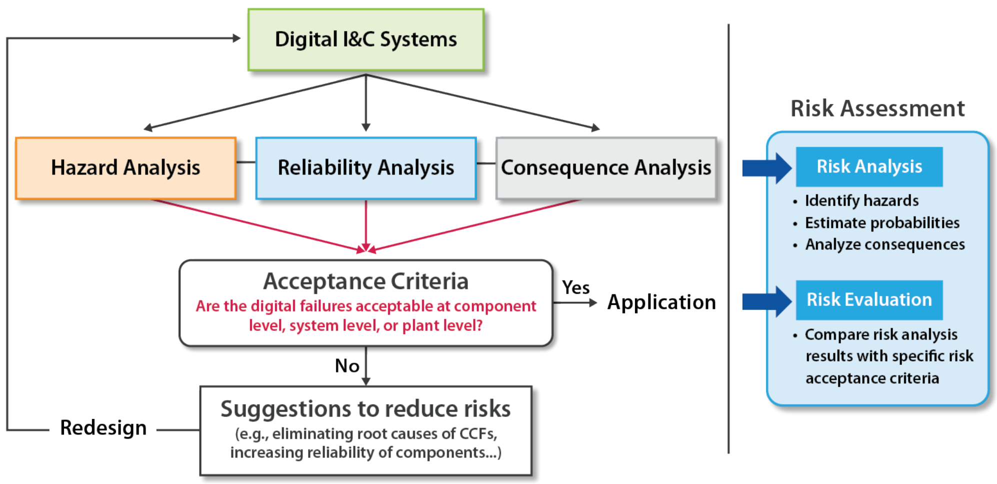


Figure 35. Schematic of Digital I&C System Risk Assessment Framework.

Analysis), provides a top-down approach to analyze important hazards and potential system failures. Bayesian and HRA-Aided Method for the Reliability Analysis of Software (BAHAMAS) and Orthogonal-defect Classification for Assessing Software reliability (ORCAS) quantify the probability of the postulated failures. Lastly, a PRA determines potential consequences.

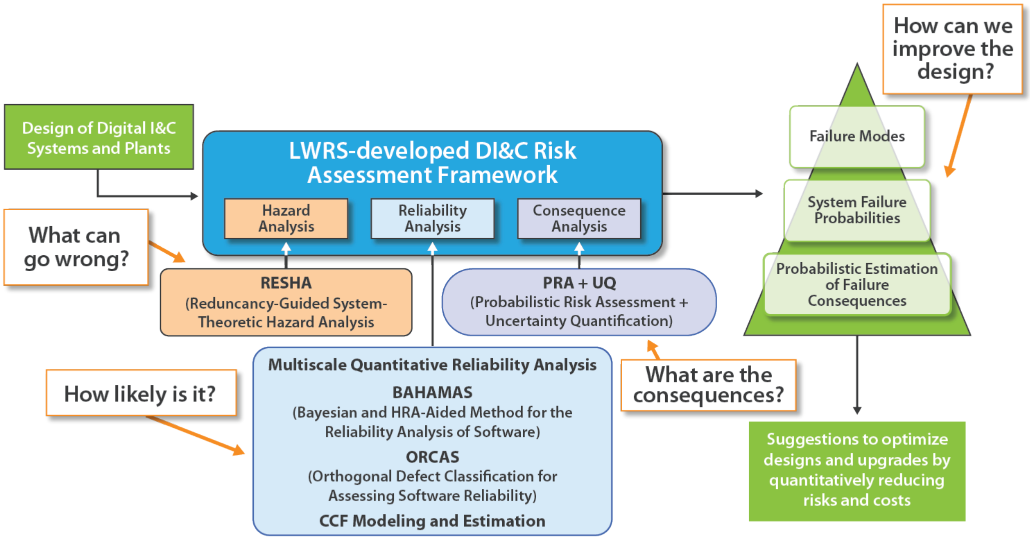


Figure 36. Modularized Structure of Digital I&C System Risk Assessment Framework.

RESEARCH ACCOMPLISHMENT

A New Framework to Detect and Address Software Failures in a More Efficient, Cost-Effective Way

The method development is intended to support the latest advancement in the NRC policy for addressing potential CCFs in digital I&C systems. As shown in

Figure 37, NRC is expanding the existing policy SECY-93-087 [43] to allow risk-informed approaches in addressing digital I&C CCFs. The draft of the new policy (SECY-22-0076 [44]) was issued for the Commission review and approval.

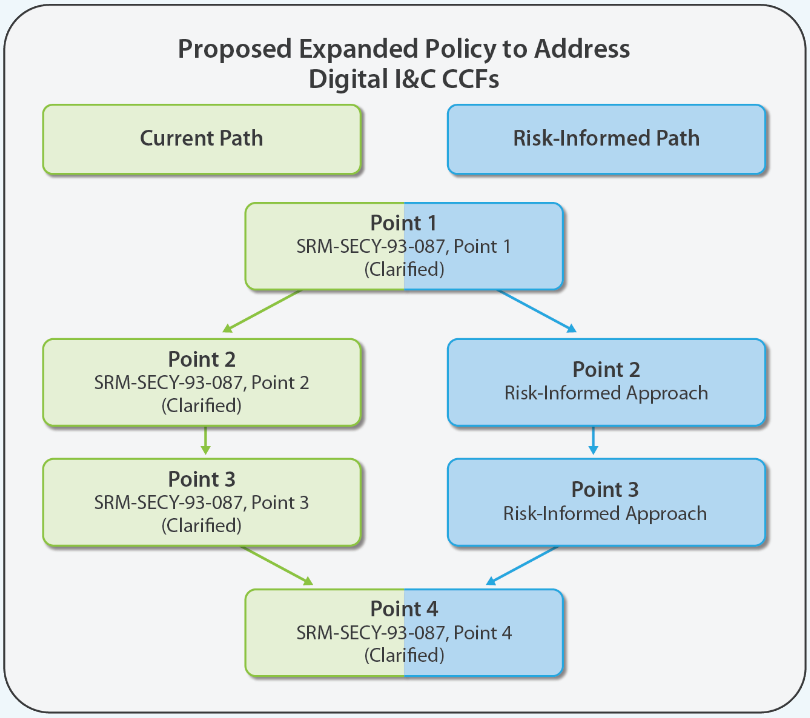


Figure 37. Proposed Expansion of Policy on Addressing Digital I&C CCFs.

Diversity (i.e., multiple measures built-in to ensure redundancy) at a system and/or component level is currently the only solution for addressing potential software CCF. Additional levels of diversity can also increase system complexity. The method is intended to provide a capability to implement risk-informed approaches allowed by the expanded policy to address digital I&C CCFs in an efficient, cost-effective way compared to the reliance on diversity alone.

Case studies conducted in 2022 demonstrated the ability to use the method to successfully identify various failure mechanisms, single points of failure, and key CCFs. The team also developed and demonstrated an innovative approach to quantify probabilities of software failures, including software CCFs.

The research in this project has progressed from methodology development to demonstration in 2022. The researchers tested the developed methodologies via collaboration with academia using the Virginia Commonwealth University smart sensor platform [45]. The results showed that the framework is capable of successfully identifying, classifying, and quantifying software CCFs.

The latest work is focused on demonstration of the framework using industry data. The LWRS Program team is currently working on a joint project with the Pressurized-Water Owners Group (PWROG). Internationally, this work is coordinated with the Halden HTO Project [46] supporting their digital systems research program. Halden researchers are developing a safety assurance framework that is expected to support nuclear utilities in their efforts to efficiently demonstrate the safety of digital systems. In 2023, researchers will be conducting a peer review to collect feedback from the industry subject matter experts on the techniques developed through this research. The results of the peer review will be used to improve the method in order to ready it for industry use.

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23-50332