INL/RPT-24-76758
Revision 0

Light Water Reactor Sustainability Program

Overview and Accomplishments Report – 2023

April 2024

U.S. Department of Energy

Office of Nuclear Energy

INL/RPT-24-76758
Revision 0

Overview and Accomplishments Report – 2023

April 2024

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Light Water Reactor Sustainability Program

FROM THE LWRS PROGRAM TECHNICAL INTEGRATION OFFICE DIRECTOR

Bruce Hallbert, Director,
LWRS Program
Technical Integration Office

The United States (U.S.) Department of Energy's (DOE's) Office of Nuclear Energy (NE) 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 technology.
5. Enable a high-performing organization.

The Light Water Reactor Sustainability (LWRS) Program is the primary programmatic activity that addresses DOE-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.

LWRS Program Organization

Federal Program Management

Sujata Goetz
Federal Program Manager
Office of Nuclear Energy
U.S. Department of Energy
Sujata.Goetz@nuclear.energy.gov

Daniel Warner
Safeguards and Security Federal Lead
Office of Nuclear Energy
U.S. Department of Energy
Daniel.Warner@nuclear.energy.gov

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

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

Technical Integration Office

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

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

Research and Development Pathway Leads

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

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

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

Xiang (Frank) Chen, Ph.D.
Materials Research
Oak Ridge National Laboratory
chenx2@ornl.gov

Commie R. Byrum
Physical Security Lead
Sandia National Laboratory
crbyru@sandia.gov

CONTENTS

FIGURES

TABLES

ACRONYMS

AI	artificial intelligence
ALARM	Automated Latent Anomaly Recognition Method
ALWR	Advanced Light-Water Reactor
BCA	Business Case Analysis
BOC	beginning-of-cycle
CAP	corrective action program
CBS	concrete biological shield
CCF	common-cause failures
CCS	carbon capture and storage
CFR	Code of Federal Regulations
DBT	design basis threat
DCPD	direct current potential drop
DMA	deliberate motion analytics
DOE	Department of Energy
EDS	energy-dispersive spectroscopy
EFPD	effective full power day
EFPY	effective full power years
EMDA	Expanded Materials Degradation Assessment
EMRALD	Event Model Risk Assessment using Linked Diagrams
EPDM	ethylene propylene diene monomer
EPM	Engineering Planning and Management, Inc.
EPR	ethylene-propylene-rubber
EPRI	Electric Power Research Institute
EQ	environmental qualification
ETC	embrittlement trend curves
FDS	Fire Dynamics Simulator
FLEX	flexible mitigation capability
FoF	force-on-force
FORCE	Framework for Optimization of ResourCes and Economics
FPOG	flexible plant operation and generation
FT	Fisher-Tropsch
GB	grain boundary
HERON	Holistic Energy Resource Optimization Network
HFE	human factors engineering
HSSL	Human Systems Simulation Laboratory
HTE	high-temperature electrolysis
HTI	Human and Technology Integration
HTO	Human Technology Organization
HUNTER	Human Unimodel for Nuclear Technology to Enhance Reliability

H3RG	Hydrogen Regulatory Research Review Group
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
IRA	Inflation Reduction Act
ITC	investment tax credit
ITE	inverse temperature effect
JCAMP	Japan Concrete Aging Management Program
KOH	potassium hydroxide
LAR	License Amendment Request
LCOE	levelized cost of electricity
LCOH	levelized cost of hydrogen
LCOS	levelized cost of storage
LiOH	lithium hydroxide
LOCA	loss-of-coolant accident
LTE	low-temperature electrolysis
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
MOSAIC	Microstructure Oriented Scientific Analysis of Irradiated Concrete
NAR	nuisance alarm rates
NE	nuclear energy
NEA	Nuclear Energy Agency
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NG	natural gas
NLP	natural language processing
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Co-operation and Development
ORCAS	Orthogonal-defect Classification for Assessing Software
ORNL	Oak Ridge National Laboratory
P2MP	point-to-multipoint
PEM	proton electrolyte membrane
PI	probability of interdiction
PI&R	Problem Identification and Resolution

PIDAS	perimeter intrusion detection and assessment system
PN	probability of neutralization
PNGS	Palisades Nuclear Generating Station
PNNL	Pacific Northwest National Laboratory
PPS	Plant Protection System
PRA	probabilistic risk assessment
PRLO	plant reload optimization
PSEG	Public Service Enterprise Group
PTC	production tax credit
PTP	point-to-point
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Owners Group
R&D	research and development
RAVEN	Risk Analysis and Virtual Environment
RF	radio frequency
RIP	radiation-induced precipitation
RIS	radiation-induced segregation
RISA	Risk-Informed Systems Analysis
RIVE	radiation-induced volumetric expansion
ROWS	remote operated weapon systems
RPV	reactor pressure vessel
SAPHIRE	Systems Analysis Programs for Hands-on Integrated Reliability Evaluations
SCC	stress corrosion cracking
SMR	steam methane reforming
SSC	structures, systems, and components
STPNOC	South Texas Project Nuclear Operating Company
TEAL	Tool for Economic AnaLysis
WEC	Westinghouse Electric Company
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin
XRD	X-ray diffraction

OVERVIEW AND ACCOMPLISHMENTS REPORT 2023

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 production credits 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, extending the benefits of nuclear power operation in and around their surrounding areas. [2]
- Power uprates, increasing the rated electrical output of an existing nuclear plant, is seeing great interest by U.S. industry and the owner-operators of operating nuclear power plants. Data from the Nuclear Energy Institute shows that U.S. plants have already added over 8,000 MW_e during their operations, though some of that additional clean energy is no longer available due to early plant retirements. Considering added incentives from the Inflation Reduction Act, more plants are again voicing interest in pursuing power uprates, some in addition to those they have already completed. Collaborative research by the LWRS Program with industry and other stakeholders is supporting these efforts to add clean power through power uprates.
- New plant commissioning at the Vogtle site has added two additional operating power reactors to the U.S. fleet and plans to return the Palisades nuclear plant to service will add additional clean energy to our nation's electrical grids. 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 has been shown to be tied to an increase in carbon emissions. [3]
- 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] In October 2023, the Biden-Harris administration together with Energy Secretary Granholm announced selection of clean energy hubs slated to receive $7 billion in funding to establish these hubs. In doing so, these hubs will catalyze over $40 billion in private investment, contributing substantially to a clean energy economy. Nuclear power plants figure prominently in several of these hubs, and announced discussions are underway with nuclear plants in others. LWRS Program research supports these hub activities and some of the early projects demonstrating integrating hydrogen production with operating nuclear power plants. Progress in these areas achieved through research sponsored by LWRS Program are key to achieving the achieving the Secretary of Energy's Earthshot Hydrogen initiative. [5]
- The Civil Nuclear Credit Program provides a new national strategic investment in the operating fleet of nuclear power reactors. [6] 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 January 2024, the Department of Energy formalized its decision to award Pacific Gas and Electric Co. $1 billion in financial aid to keep the Diablo Canyon Nuclear Power Plant running. [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]

- 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. [8] Research by the LWRS Program is initiating activities between the offtake market for industrial heat and existing operating nuclear power plants, following a model for technical, economic, and safety assessments that were piloted in industrial integration of commercial hydrogen production. That research will continue and the LWRS Program anticipates future industrial partnerships in this area.

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 R&D 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 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.

1.2 Program Research and Development Interfaces

The LWRS Program will continue to refine its R&D pathways based on industry needs and emerging technologies. An increased focus will be placed on demonstrating and deploying developed technologies across the nuclear fleet. Continued engagement with stakeholders, regulators such as Nuclear Regulatory Commission (NRC), industry, will be crucial for ensuring program effectiveness and long-term success in U.S. national energy goals.

Planning, execution, and implementation of the LWRS Program are done in coordination with the nuclear industry, 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. [9]

1.2.2 Nuclear Regulatory Commission

The NRC employs a memorandum of understanding [10] 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. [11] 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, some nuclear power plants are facing the need to throttle operations or pay others to curtail generation. [12]

Flexible Plant Operation and Generation (FPOG) is a new operating concept in which a nuclear power plant directs thermal energy and electricity to a secondary user to produce a non-electric energy product or service. The range of FPOG concepts is illustrated in Figure 12. The main objective is to continuously maintain the output of energy from the nuclear power plant near the plant's full production capacity. With flexible operations, the thermal energy can either be converted into electrical power with the plant's primary generator, or it can be stored and recovered for peak power supply later; or it may be transported to a nearby industry that uses heat to produce a non-electric product. Similarly, electrical power can either be immediately sold to the grid or to industrial users that are directly coupled to the power plant; or it can charge electric storage batteries for recovery during periods of peak demand. Another option is hydrogen production by an electrolysis plant that requires electricity to split water into hydrogen and oxygen. One type of electrolysis, referred to as high-temperature electrolysis (HTE), can use both thermal and electrical energy provided by the nuclear plant to split steam into hydrogen and oxygen. HTE achieves higher overall efficiency compared to low-temperature electrolysis, which splits water by utilizing the thermal energy to produce the steam that is sent to the electrolysis units.

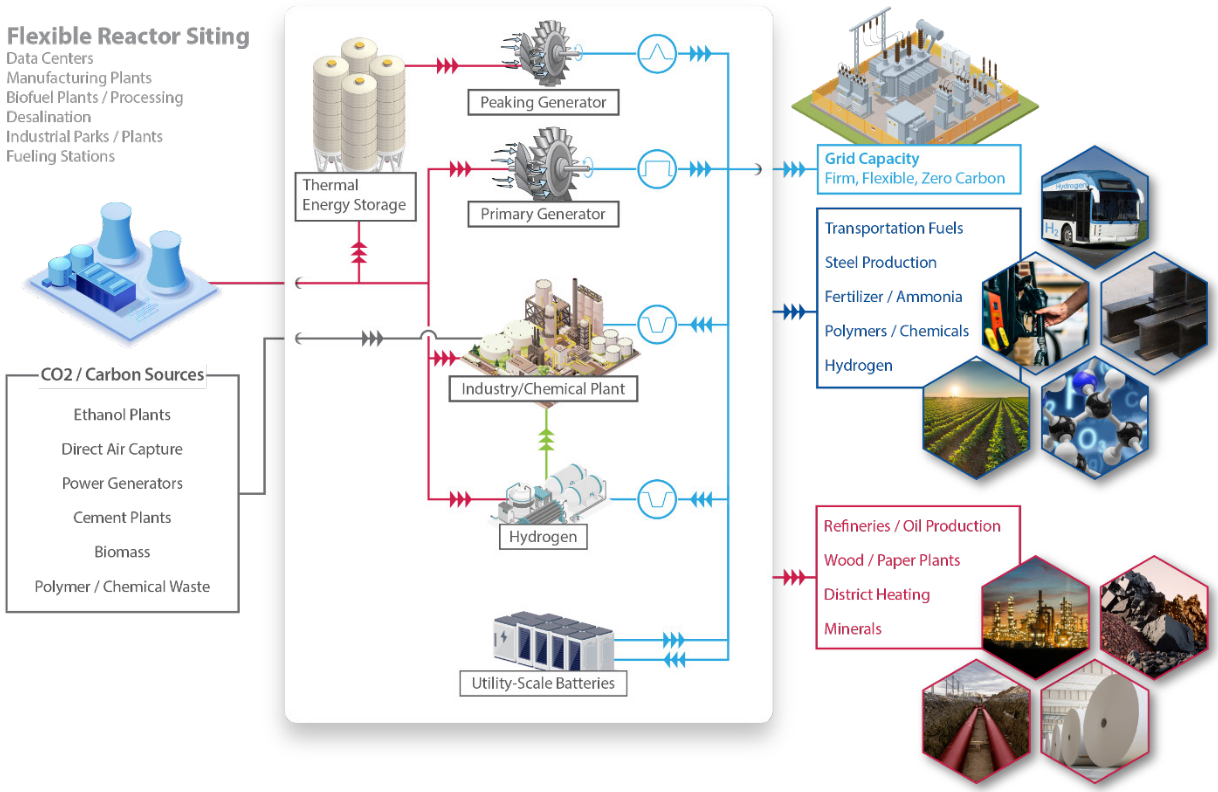


Figure 2. FPOG options for utilizing the full capacity of nuclear power plants.

Hydrogen is particularly noteworthy as an FPOG option because it is widely used by industry. The hydrogen produced using nuclear power does not result in carbon dioxide (CO_2) emissions and can help decarbonize industries shown on the right side of Figure 2, in the blue box and hexagons. When combined with the non-fossil carbon sources indicated on the left side of Figure 2. it can be converted into clean fuels and urea fertilizer. This can significantly reduce the buildup of greenhouse gases in the atmosphere. Additionally, hydrogen can be stored in tanks or underground caverns for use in power generation when demand is high and the price of electricity on the grid is relatively high.

In 2023, the LWRS Program completed technical and economic assessments for most of the options depicted in Figure 2. This included a comparison of three utility-scale energy storage options for power production: namely, thermal energy, batteries and hydrogen. Energy storage allows nuclear plants to firm up the electricity transmission grid by providing reliable capacity when wind and solar energy are not producing power. It also allows nuclear plants to provide reserve capacity during peak power demands periods.

The LWRS Program focuses on three R&D activities:

1. Complete technical and economic assessments.

Technical and economic assessments address the business case for directly coupling a nuclear power plant to a nearby existing industry or a new manufacturing plant.

2. Design, develop and test new thermal and electrical offtake systems for the secondary users.

The delivery of heat, generally in the form of steam, and new connections to the power transmission switch yard requires an engineering design. In addition, new operator controls concepts need to be developed and proven to dispatch power between the electricity grid and the industrial plant.

3. Identify, characterize, and evaluate safety hazards and licensing considerations for FPOG applications.

Safety hazards analysis and risk assessments support operating license reviews. These assessments can also support potential amendments of the physical modifications and new operating concepts under the regulatory process for nuclear power plants.

In addition to the three R&D activities, the LWRS Program engages industry to help advance FPOG technology development and experience through industry-led projects. Three projects are demonstrating hydrogen production at actual nuclear power plants. Other projects are developing and testing control logic and human factors to effectively dispatch energy to the industry direct heat and power user.

Figure 3 summarizes the R&D progress toward the technical and economic assessment of hydrogen production. The team is also developing physical interfaces and operator controls, as well as interfaces engineering designs to provide quantitative analysis of potential failure modes and their effects. These combined efforts contribute to an increasingly rigorous probabilistic risk assessment (PRA) of a generic commercial hydrogen plant located as close as 500 meters from the nuclear reactor.

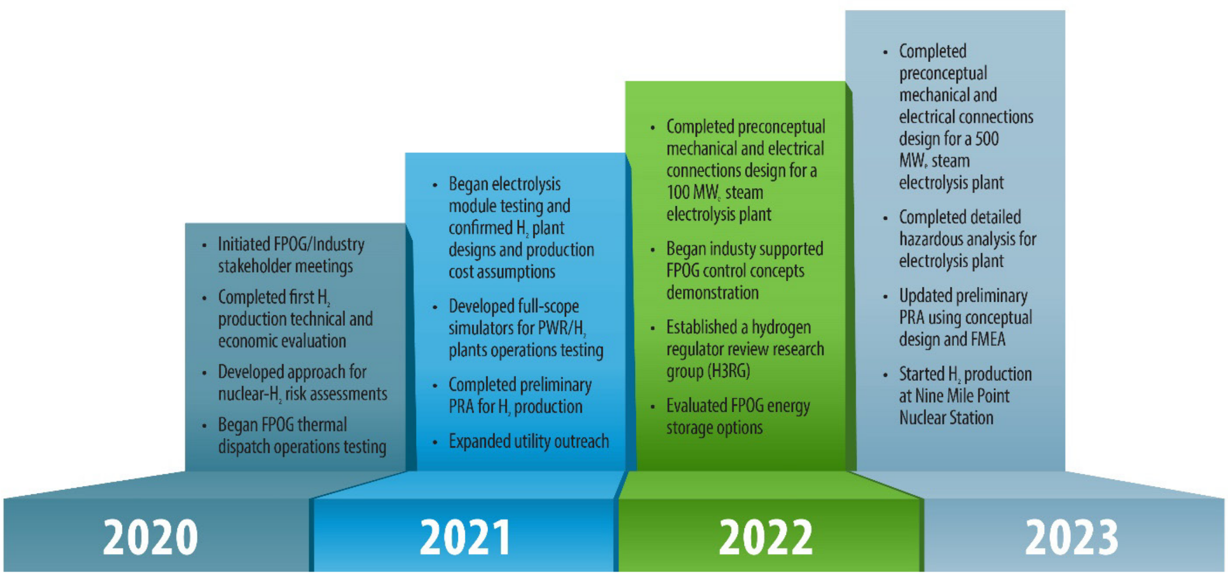


Figure 3. Progressive R&D leading to FPOG with hydrogen production. (PWR – Pressurized Water Reactors; PRA; FMEA – Failure Modes and Effects Analysis; H_2 – Hydrogen).

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.

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. [12] 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. [13] This work was foundational in establishing a set of bounding generic hazard conditions associated with coupling HTE hydrogen technology with an existing nuclear power plant.

Research Accomplishment:

Completed a Probabilistic Risk Assessment of Hydrogen Production near a Nuclear Power Plant

Using the preconceptual design for the physical connections and operating concepts provided by the architecture-engineering firm funded study for commercial-scale nuclear power plants, a preliminary safety and hazards analysis was performed and used to expand a preliminary PRA for a generic nuclear plant. This expanded effort considered various spatial layouts for the hydrogen plant with input from the leading HTE vendors.

The safety analysis was completed by Sandia National Laboratory using HyRAM - a computation model developed by the Department of Energy Hydrogen and Fuel Cell Technology Office for hydrogen fires and explosions. The hydrogen safety analysis and associated risks of the appurtenant thermal energy delivery systems and electrical connection were next used as inputs for a rigorous safety preliminary PRA using SAPHIRE (Systems Analysis Programs for Hands-on Integrated Reliability Evaluations) – a code that is often used by the NRC for nuclear power plant safety analysis. This work was also translated into CAFTA (Computer-Aided Fault Tree Analysis) for the nuclear power utilities that commonly use this tool to complete risk assessments. The overall approach for the safety analysis/risk assessment is illustrated in Figure 4.

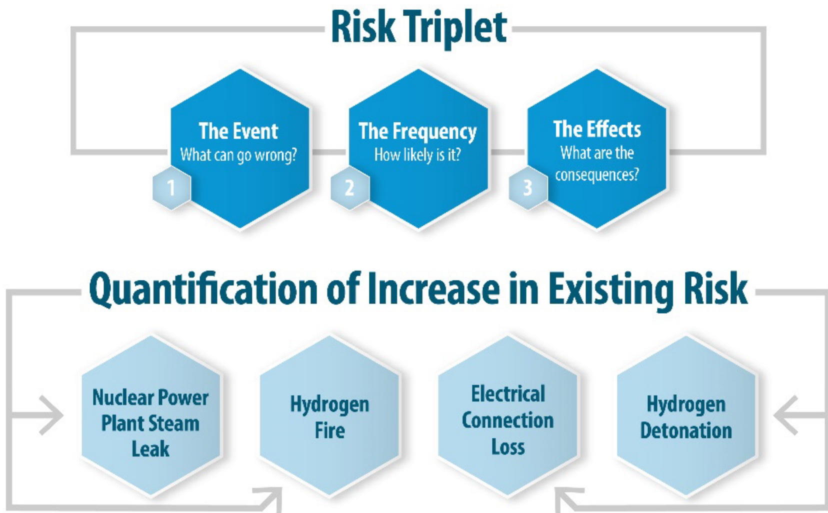


Figure 4. Elements of the risk analysis for nuclear supported hydrogen production.

Figure 5 shows an example layout for one of the cases considered in this exemplary work. Here, a notional 500 MW_e scale hydrogen plant is placed near a lake-side nuclear power plant. The position of the hydrogen plant and its gas collection headers, compressors and storage tanks are positioned in the best location to mitigate fire and explosion impacts on the nuclear power plant. For example, the concentric distance for an unobstructed pressure wave created by a hydrogen explosion to drop below 1.0 psi (pounds-per-square-inch) is determined. This is the distance where the blast would not likely result in significant physical damage to critical infrastructure. Depending on the hydrogen plant size and geographical constraints, physical barriers, such as a blast fence or earthen berm, can be used to attenuate the pressure wave created by an explosion at the hydrogen plant. The use of blast shields have not been evaluated at this point; but, if necessary, they can be evaluated on a case-by-case basis. reduce the impact of potential explosions on the fragile equipment of the power plant as well as critical infrastructure, businesses and dwelling of the community.

Figure 5. Illustrative safe boundaries surrounding hydrogen explosions for a 500 MW_e electrolysis plant connected to a nuclear power plant.

This research provides a strong basis for nuclear utilities and hydrogen project developers to conduct plant-specific safety hazards analysis and risk assessments that will ensure the safety of the nuclear power plant. The preliminary analysis considered a commercial-scale hydrogen plant located within 500 meters of a nuclear power plant and attempted to apply the safety criteria set forth by NRC "conditions of licenses" under 10 CFR 50.59 [14] using a risk-informed decision approach consistent with NRC RG 1.174, [15] recognizing that this is not an actual facility as presumed by the referenced requirements. This work was performed in a manner to comply with RG 1.91, which deals with safety in the presence of flammable and potentially explosive gas containers located near nuclear power plants.

This work is intended to provide exemplary information on the method, tools, and general approach of potential projects and studies that may be conducted by the nuclear hydrogen projects that are associated with the Regional Clean Hydrogen Hubs that were recently selected by the Department of Energy[a]. The matching risk analysis codes, SAPHIRE and CAFTA, are available and can be readily adopted for broad use by nuclear utilities and industry.

This research activity was reviewed by the Hydrogen Regulatory Research Review Group (H3RG) that was initially established in 2022 to obtain input and recommendations from a broad spectrum of nuclear utility and industry stakeholders. Relevant input from the utilities and nuclear power plant owners has routinely been provided to the H3RG. In fact, many of the H3RG contributors are the same utilities considering nuclear-source hydrogen as an alternative market for their plants.

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

a https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs/

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 may be required to curtail power generation or pay other generators to curtail generation to avoid down powering the nuclear plants. Some nuclear power plants have already curtailed their full electrical generation capacity in response to congestion of power transmission systems or due 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. [17] 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 MW_e 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:

Completed a Preconceptual Engineering Design and Operating Recommendations for 100 and 500 MW_e electrolysis hydrogen plant coupled to Nuclear Power Plants

In 2023, the LWRS Program released preconceptual engineering design documents developed by an architecture-engineering firm for thermal and electrical power connections to a 100 MW_e and to a 500 MW_e hydrogen plant. This study confirms steam can be easily extracted and transported from nuclear power plants at the levels needed to operate commercial hydrogen plants. A reboiler can be placed on the existing power turbines deck to transfer steam to heat a demineralized water supply located a safe distance away for the hydrogen plant. This is illustrated in Figure 6.

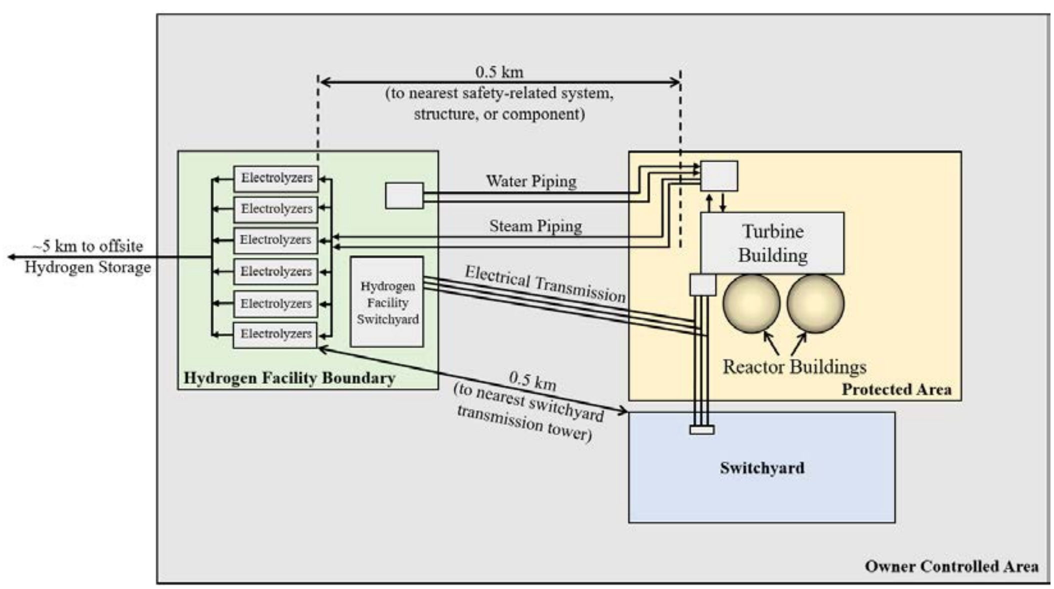


Figure 6. Architecture-engineering firm preconceptual site layout for a 500 MW_e hydrogen facility design.

Electrical power is taken off the high-voltage side of the station power transmission transformer, where it is then connected via a 345-kV transmission line to the hydrogen facility. A sketch for the electrical power connection is shown in Figure 7. Control capabilities for the steam interfacing equipment and electrical dispatch are accessible from the nuclear power plant main control room, while protective relays for the transmission line are located inside the relay room.

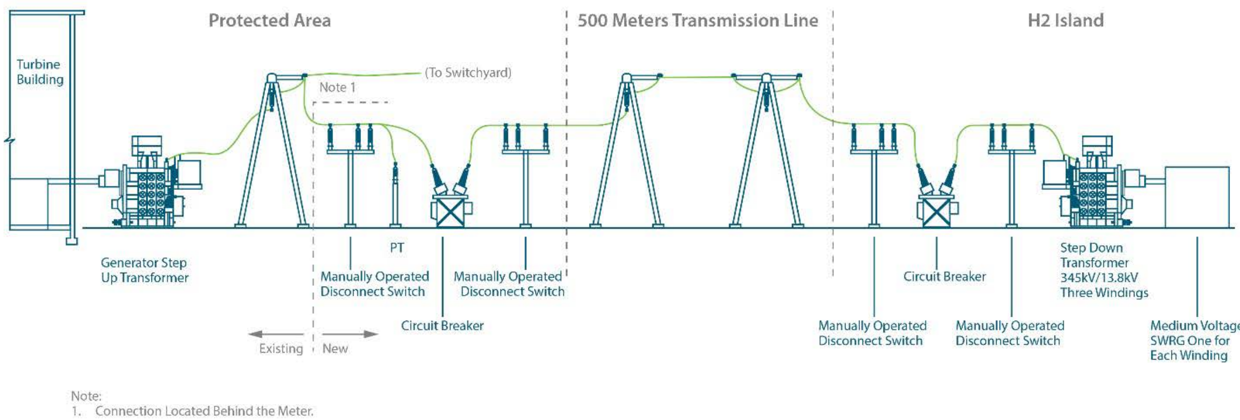


Figure 7. Main power line from a nuclear power transmission station to a close-coupled hydrogen plant.

The architecture-engineering firm study serves several purposes, including providing a credible cost estimate for the energy delivered to the hydrogen plant as well as providing design details to address all new safety hazards. The preconceptual design provides a starting basis for the engineers of the nuclear power plant to complete detailed designs for their plants. Nuclear plant simulator models are being updated with the preconceptual design connection. These models in turn are being used to develop the human-machine interfaces and control panels that are needed for nuclear reactor operators to efficiently dispatch the plant's energy to the hydrogen plant.

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.

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 requires holistic assessments of energy markets. To address these issues, the FPOG Pathway is conducting technical and economic assessments of alternatives that may be competitive with current market positions.

Hydrogen production and energy storage continue to receive strong interest from all stakeholders, given the increasing market demand for clean hydrogen (hydrogen produced without the emission of CO_2). 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:

Helping Decision Makers in Understanding the Financial Benefits of Producing Hydrogen

To better assist decision makers in understanding the financial benefits of producing hydrogen, an Excel program calculator has been developed. This tool allows decision parameters such as the wholesale price of electricity to be input into the calculator to compute the production cost of hydrogen. Other user-adjustable parameters include the size of the electrolysis plant, the value of federal or state production tax credits (often referred to as PTCs), and other financial terms for a capitalized project - such as project life and the interest rate on borrowed money. The tool then displays the levelized cost of hydrogen production and other financial indicators that can help guide the decision makers.

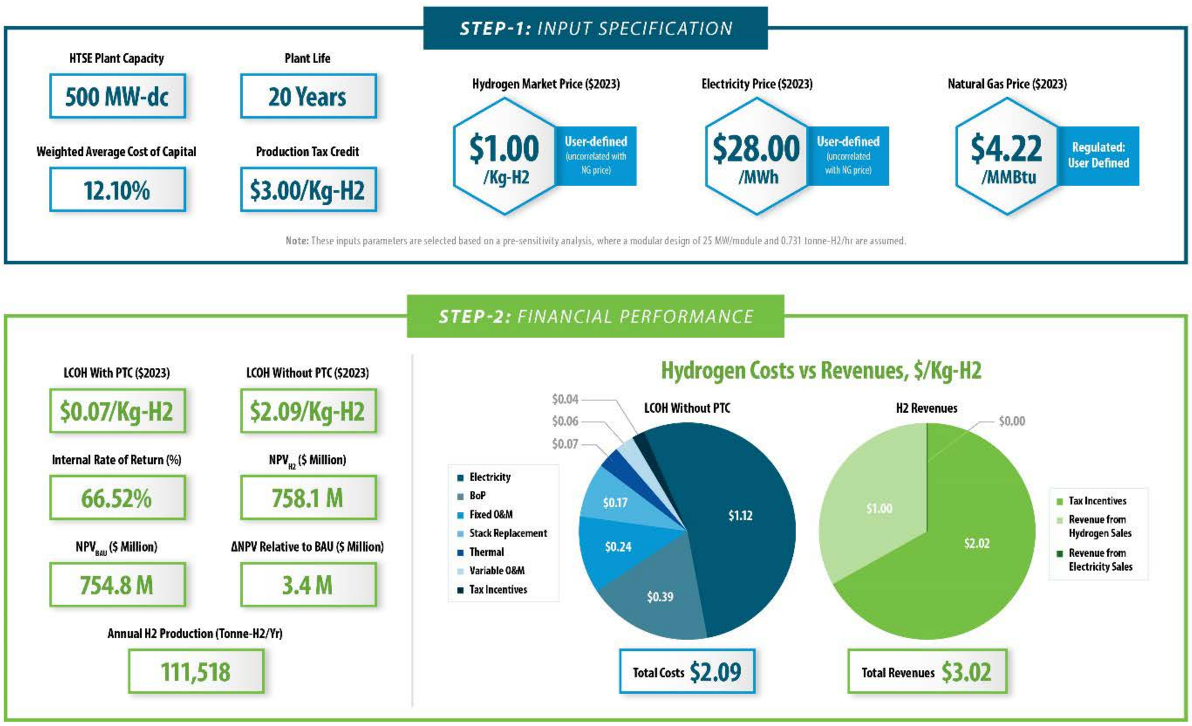


Figure 8 shows an image of the main dashboard of this new calculational tool. The program also prints graphics on the screen that indicate the value of switching to hydrogen production versus continuing the usual business of selling power to the grid (see Figure 9).

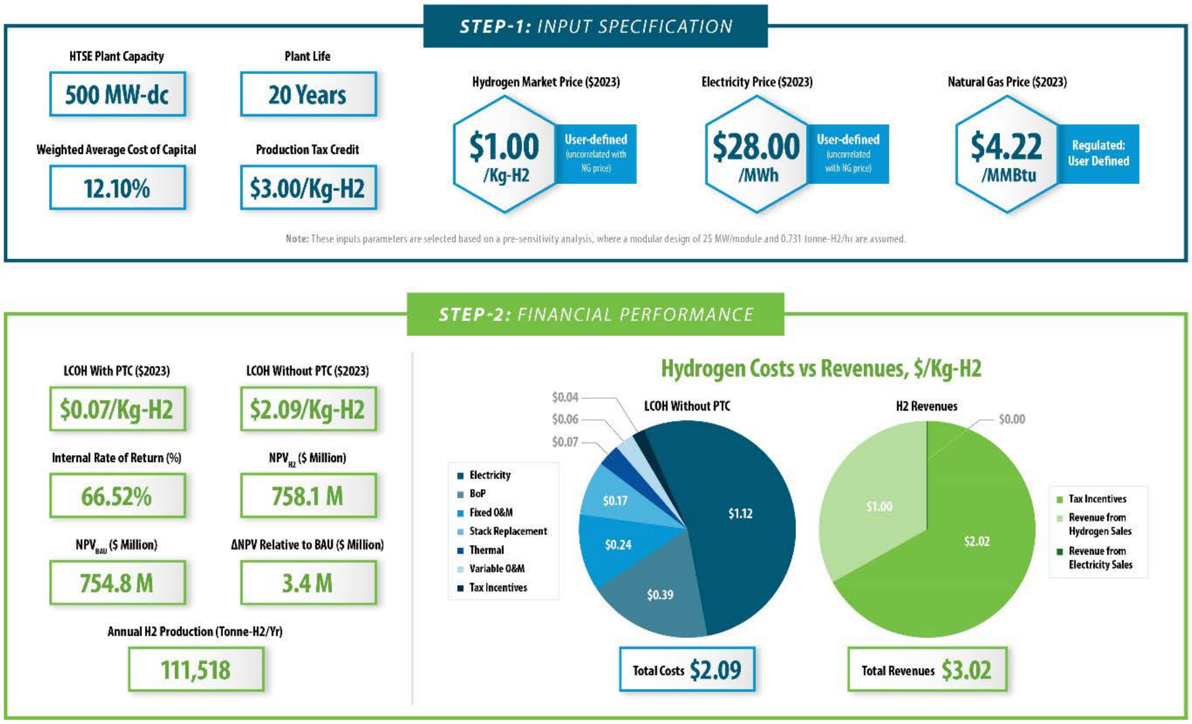


Figure 8. Input specification dashboard for financial performance estimation of nuclear supported hydrogen production costs.

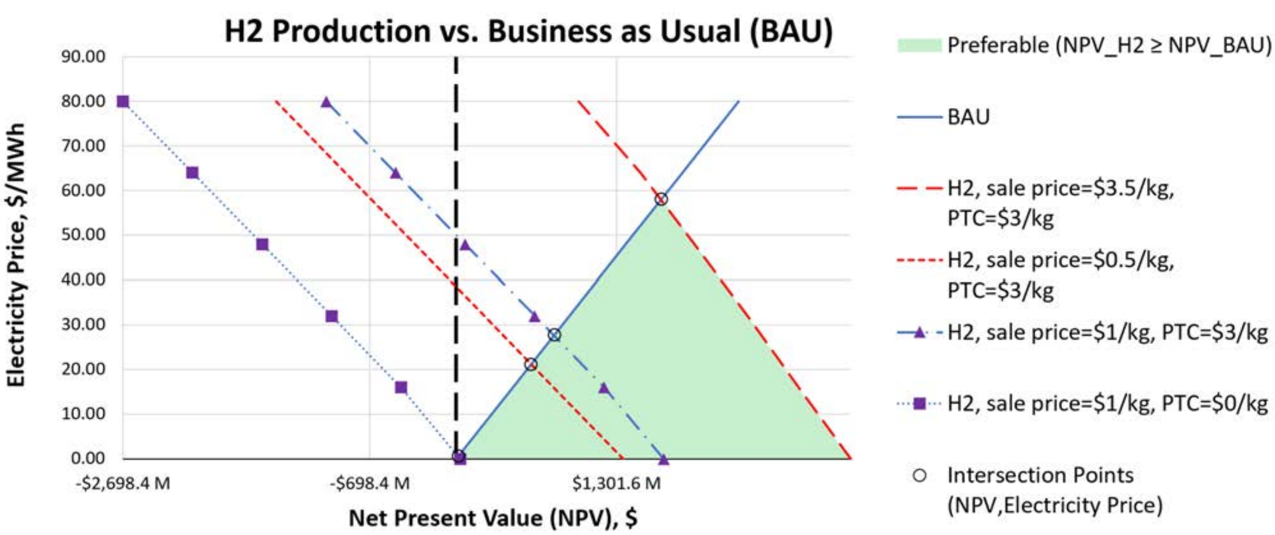


Figure 9. Graph of decision points for choosing hydrogen production versus selling power to the electricity grid with and without production tax credits.

Simple instructions are provided to help users quickly become familiar with the tool and the output fields and charts.

Once users have a better understanding of the value of hydrogen production, a deeper analysis of location and region-specific markets can be evaluated using a more sophisticated suite of computational tools that have been developed by the LWRS Program and the Integrated Energy Systems Program[b]. These computational programs include TEAL (Tool for Economic AnaLysis) and HERON (Holistic Energy Resource Optimization Network) that are solved under a systems optimization computation framework know as FORCE (Framework for Optimization of ResourCes and Economics).

2.1.1.4 Industry Engagement and Demonstration Projects

Research Accomplishment:

Demonstrating Hydrogen Production at Actual Nuclear Power Plants through Industry-Led Projects

The LWRS Program and other DOE program offices are conducting cost-sharing research to support the demonstration and deployment of scalable hydrogen production coupled to operating nuclear power plants. Three projects have been funded under DOE-FOA-0001817 (see Figure 10), Constellation, Energy Harbor and Xcel Energy. These projects have been highlighted at various public conferences and workshop meetings.

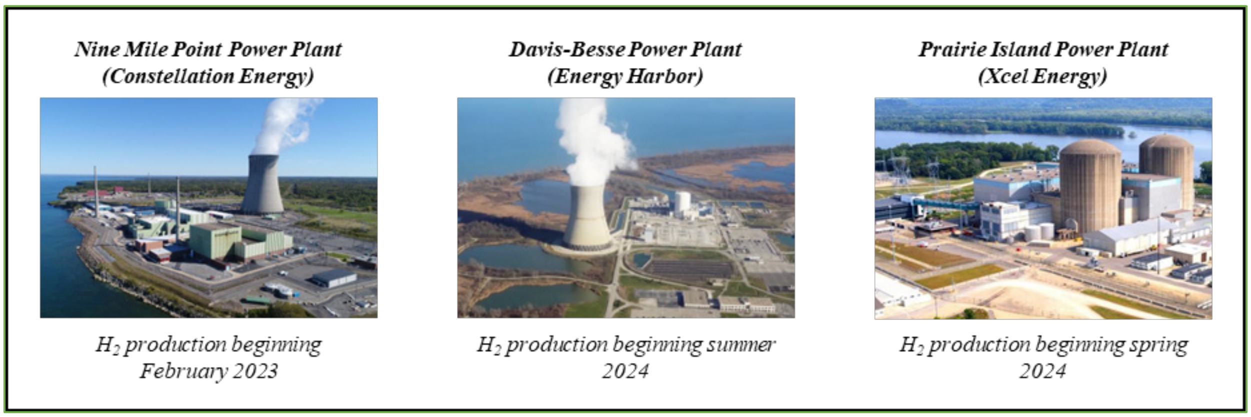


Figure 10. Overview of the plants and schedule of the three hydrogen production demonstration projects.

These projects have complementary but unique benefits to the individual utilities and their associated hydrogen electrolysis technology partners. For example, the projects help understanding how to connect nuclear power 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.

In February 2023, Constellation had initiated hydrogen production at their Nine Mile Point power plant using the Nel proton electrolyte membrane (PEM) water electrolysis pilot plant module shown in Figure 11. Nel is a Norwegian company that built a PEM electrolysis plant in the United States. A hydrogen compressor is used for high pressure hydrogen storage for use by the power plant for water treatment and turbine cooling. This project provides Constellation with operating experience and local hydrogen management within the power plant boundaries. This experience is valuable for Constellation to scale up hydrogen production using several modules that can be ganged together. This demonstration

[b] The Integrated Energy Systems Program is supported by the U.S. Department of Energy's Office of Nuclear Energy. It maximizes the use of nuclear energy by developing technologies to support chemical, thermal and electrical energy pathways that deliver clean nuclear energy to the industrial, transportation and commercial sector. https://ies.inl.gov/.

benefits nuclear-source hydrogen and proposed renewable hydrogen projects that have been proposed at various locations throughout the country.

Figure 11. Nel PEM water electrolysis stack, pilot plant electrolysis module and hydrogen compressor.

The project led by Energy Harbor completed site preparations and installation of new power supply switch gear and power relays at the Davis-Besse Nuclear Power Plant (see Figure 12. This will support upwards of 60 MW_e water electrolysis. This project is currently planning on installing a low-temperature, PEM electrolysis module that will be like the Nel module. However, the project leads are also considering demonstration of a high-temperature [steam] electrolysis module. Each of these locations have potential for large hydrogen markets using nuclear and renewable energy inputs.

Figure 12. Installation of power switch gear for hydrogen pilot plant demonstration at the Davis-Besse Nuclear Power Plant.

The Xcel Energy project will demonstrate high-temperature steam electrolysis by extracting steam from the Prairie Island power plant. The engineering design for extracting steam from the power plant turbine deck was completed. This steam will be directly split into hydrogen and oxygen using two pilot plant modules provided by Bloom Energy (see Figure 13). This demonstration will mark the first-ever electrolysis of nuclear plant secondary-side steam.

Figure 13. Examples of Bloom Energy high-temperature steam electrolysis modules that will be used at the Xcel Energy hydrogen production demonstration.

The Bloom electrolysis modules are scalable units that have been patterned after their fuel cell modules which are operating worldwide. A protype of the Bloom electrolysis units has been under testing at the Idaho National Laboratory throughout 2023, logging almost 6,000 hours of run time without any problem under weather conditions ranging from -30°F in the winter to 90°F in the summer. This module has been cycled numerous times, demonstrating that it is possible to quickly ramp-up and down the electrolysis units. This will effectively allow the hydrogen plant to throttle operations, while sending the electricity generated by the power plant to the electricity grid.

The Xcel Energy demonstration tests will provide valuable experience to the plant operators. An understanding of how the Prairie Island plant can flexibly operate while building out clean energy, mainly utility-scale wind turbines, is of paramount importance to Xcel Energy and other utilities that expect to increase renewable energy.

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. Together with other research activities the LWRS Program is helping stakeholders execute commercial deployment of hydrogen production plants.

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. It is important that new technology enable business and operational innovation that leads to more efficient and cost-effective performance, rather than adding to overall costs. 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 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 an approach for energy generated by operating 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. [18] Though there is not a simple one-size-fits-all solution to modernize nuclear power plants, the LWRS Program has developed customizable solutions that are publicly available and support industry modernization.

The LWRS Program will continue to emphasize 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 research priorities address industry needs. Regular interactions will provide the feedback and information needed to refine research objectives and activities.

2.1.2.1 Integrated Operations for Nuclear (ION) Business Operations

The LWRS Program identified the North Sea Oil and Gas industry's '*Integrated Operations'* model as a proven method to significantly drive down operational costs through strategic modernization. Responding to similar cost pressures on operating and production expenses, the North Sea Oil and Gas industry developed this model to improve performance, reduce costs, and maintain safe operation. Integrated Operations identifies the critical capabilities necessary to achieve strategic cost objectives and develops solutions integrating these capabilities. LWRS Program researchers working with Xcel Energy took lessons learned and best practices from that major industrial sector and adapted them to the nuclear industry, terming the resulting method 'Integrated Operations for Nuclear' (ION). Figure 14 shows how Xcel Energy used ION at the Monticello Nuclear Generating Plant and Prairie Island Nuclear Power Plant. This approach involved identifying activities that could be relocated to centralized locations. By applying ION, Xcel Energy significantly reduced their operating costs while maintaining production and safety goals. This consolidated enterprise-wide functions is just one step in the ION approach, though vital in minimizing redundancy, increasing efficiency, and streamlining business and operational support activities.

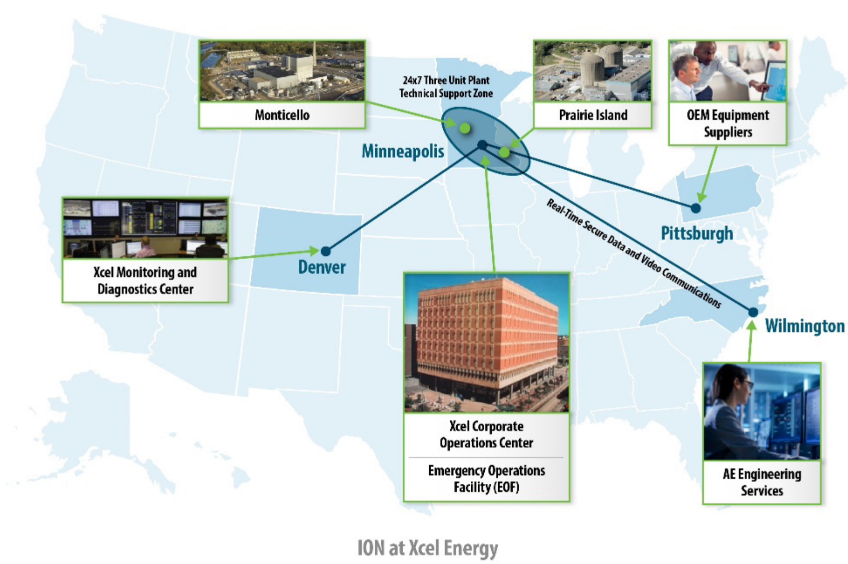


Figure 14. ION at Xcel Energy.

The LWRS Program, through ION, worked with U.S. nuclear utilities to develop site specific strategic modernization plans for their long-term commercial viability. Using plant-specific analysis, ION develops these transformation strategies, identifying the needed technology and process modifications, including operational cost objectives and staffing levels, to achieve the targeted sustainability goals.

ION represents a paradigm shift for the nuclear industry and provides a transition from the conventional site-centric nuclear business model to one that leverages technology and remote support.

This top-down approach to nuclear plant innovation and strategic modernization paved the way for more efficient operations. In collaboration with industry partners, LWRS Program estimated savings of up to 30% in operating costs year over year. By integrating technology, organization, cultural, and process modernization, changes can be streamlined, and inefficient work tasks optimized. Ultimately, these savings translate into substantial opportunities to remain competitive in the electricity market.

In 2022, the ION research team, working with industry collaborators including Xcel Energy, Southern Nuclear, and Dominion, validated estimated modernization capital costs and projected savings, showing a positive business case for ION modernization projects. The research results validated the previously estimated 30% cost savings, providing strong evidence for the project's economic potential. [19] The report detailed the scope of technology modernization efforts needed to achieve these savings and lays out the long-term economics to assist industry adoption.

Research Accomplishment:

Achieving Substantial Change Through Innovation and Modernization

In 2023, leveraging the previous year's cost savings analysis, LWRS Program researchers continued collaborating with industry to pilot the implementation of the ION business model change process. To provide the nuclear industry with examples of this change process, the LWRS Program together with the South Texas Project Nuclear Operating Company (STPNOC) plant, demonstrated the ION approach to evaluate and prioritize ongoing modernization efforts at STPNOC (see Figure 15). This demonstration included evaluating opportunities to integrate STPNOC's modernization efforts with relevant ION work reduction opportunities.

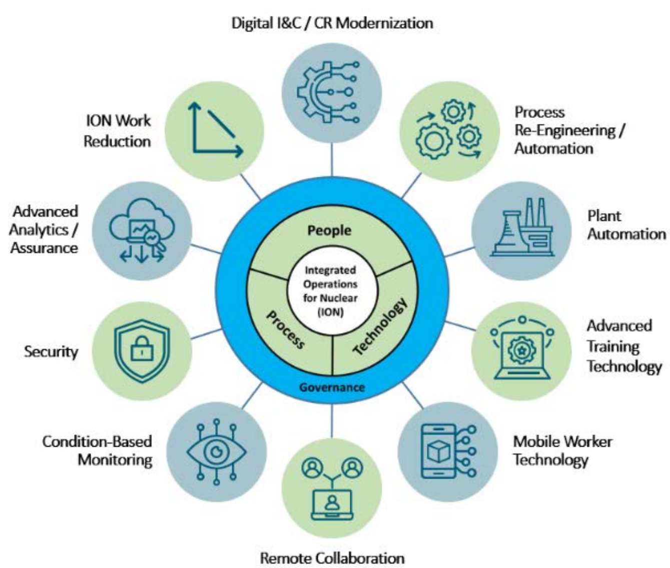


Figure 15. ION Work Reduction Opportunities Areas.

ION work reduction opportunities had been developed and validated through prior research efforts. As shown in Figure 15, work reduction opportunities covered a broad range of modernization areas. During 2023, the evaluation of ongoing STPNOC modernization activities coupled with ION work reduction opportunities enabled researchers and STPNOC staff to create a comprehensive strategic modernization plan that included an analysis of net present value for each significant modernization effort and a phasing schedule to achieve positive economic value.

ION uses four different assessments to identify and prioritize modernization opportunities: business, market, labor, and obsolescence. This business model change represented in Figure 16. process starts by evaluating business objectives and confirming through business and market analysis the critical station objectives necessary to achieve sustainability. ION uses these analysis outcomes as inputs to establish operational cost targets along with recommended staffing levels. Equipment obsolescence analysis identifies and prioritizes the necessary plant modernization opportunities. A key element to achieving significant cost savings through the application of ION is leveraging modernization to not just replace analog equipment with digital equivalents but also, through an enterprise-wide assessment of data infrastructure, developing solutions that support broad work automation and remote plant support. As part of the analysis, a customized ION transformation roadmap is developed for the plant. The business model change process provides and effective method to evaluate plant modernization already undertaken and develops a plant-specific digital infrastructure and data modernization plan.

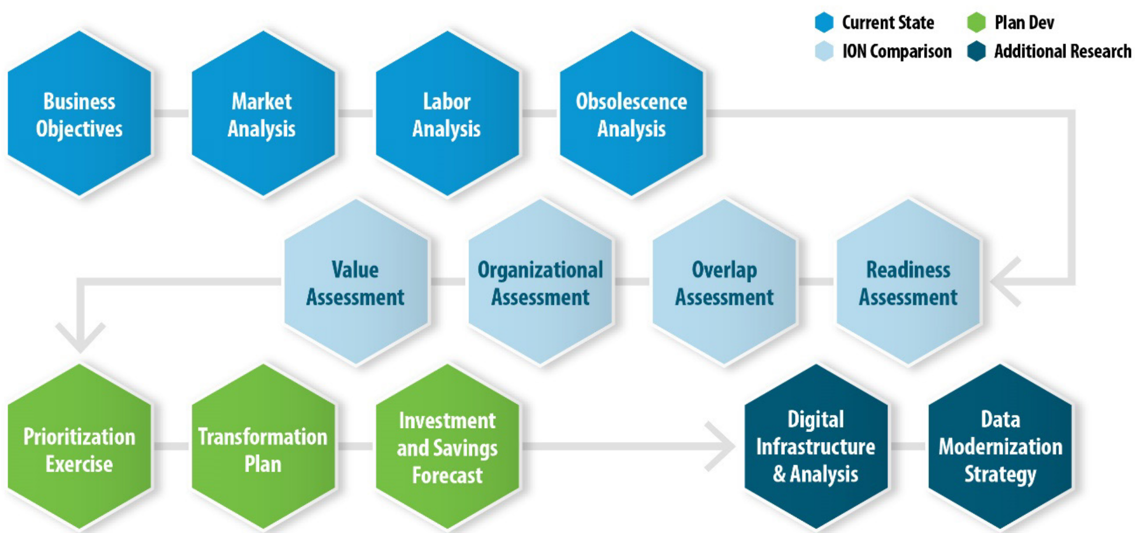


Figure 16. ION assessment and business model change process.

These analysis methods developed by the LWRS Program are described in the report *Applying the ION Business Model to a Domestic Nuclear Plant: Assessment and Transformation Plan* (INL/RPT-23-73942). [20] and leverage select ION work reduction opportunity business cases. The full list of work reduction opportunities and business case analysis are described in *Pilot Business Case Analysis (BCA) for Digital Infrastructure* (INL/RPT-23-74393). [21] This strategic approach drives 2024 Digital Infrastructure research toward a more mature process for pinpointing specific and viable technologies and techniques to implement these work reduction opportunities. The work reduction opportunity research is intended to produce sufficient technical and business case information to enable a utility to approve specific work reduction-related project(s) for implementation. This effort provides industry a demonstrated approach for modernization and enables nuclear power plants to maintain market competitiveness in the U.S. electricity market.

2.1.2.2 Digital Architecture for an Automated Plant

In the business of operating light-water reactors today, compliance with laws, regulations, and standards has significant cost implications for plant owners. Asking workers to manually check, record, and report the various required data into various parts of large physical structures is time-consuming, expensive, and can be a source of errors. LWRS Program researchers are developing solutions to streamline compliance activities through innovative integration of data collection, data storage, and data analytics.

Natural language processing (NLP) is a branch of computer science within artificial intelligence that enables computers to interpret and analyze text data generated by an organization and can be useful in automating compliance activities. In previous years, LWRS Program researchers developed an analytic tool using advanced NLP and custom machine learning tools. The software named, "Machine Intelligence for Review and Analysis of Condition Logs and Entries," or MIRACLE, is capable of scanning through nuclear plant condition reports and analyzing the information. It uses multiple screening functions, improving performance and significantly reducing costs.

Research Accomplishment:

Successful Digital Platform Demonstration of an Improved Approach to Manage Nuclear Power Plant Compliance Activities

LWRS Program research is showing how automating aspects of compliance activities at nuclear power plants could reduce costs and improve performance metrics. This research focuses on three efforts to meet the program goals of modernizing plants while cutting costs. These included:

- Developing methods to streamline access to plant data for compliance activities;
- Demonstrating improved utility compliance processes; and
- Creating analysis tools that evaluate plant performance.

The efforts were integrated into a single data platform that was demonstrated in July 2023 with the collaborating nuclear utility (Xcel Energy), the U.S. NRC, and the Nuclear Energy Institute (NEI).

LWRS Program researchers and industry collaborators developed a data portal (see Figure 17). It is a digital platform developed to automate data collection and integration. The data portal rapidly provides plant staff with access to needed data along with tools for applying performance analytics. This results in a much more efficient approach to managing compliance activities.

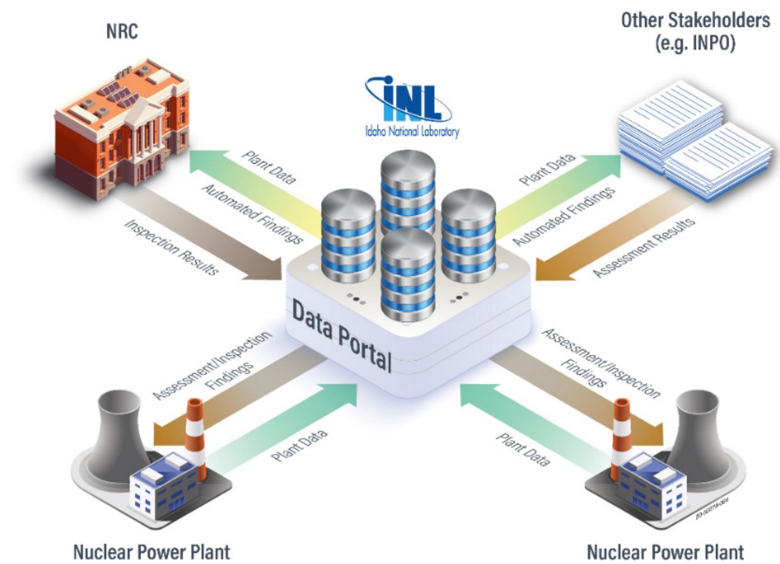


Figure 17. A data portal stores and processes data from nuclear power plants to enable efficient regulation by the NRC and assessment by other stakeholders.

To demonstrate managing and automating power plant compliance activities in this new way, researchers selected the NRC’s Problem Identification and Resolution (PI&R) inspection to validate the approach and impact of applying these technologies. Researchers used the specific set of regulatory inspection criteria for the PI&R. It gave them the details needed to validate that data access automation worked as expected, streamline their evaluations based on utility-specific criteria, and then run custom performance tracking and appraisals to find and resolve compliance issues before or during inspections.

Leveraging the information available from the corrective action program (CAP) issue tracking repository that documents most inspections at nuclear power plants, researchers used and advanced MIRACLE to automate compliance-related analysis and decision-making. Drawing on the data-rich CAP repository, MIRACLE was trained using historic human decisions. It also enabled the machine to apply the training to new and complex decisions and provide insight into the organization that is not currently available.

The resulting data portal and the R&D 100 award-winning[c] MIRACLE analytic tool provide an approach to convert inspection procedures into data-driven decisions. MIRACLE is available now, and free licenses have already been granted to industry partners. These utilities have already begun customizing MIRACLE methods to make and implement new compliance activity decisions.

Researchers who built these free tools held a workshop in the summer of 2023 at Idaho National Laboratory, attended by Xcel Energy, the NRC and the NEI, to demonstrate how these tools can streamline compliance activities. The demonstration went through various functions and demonstrated how they are used to meet inspection requirements and provide insight into plant performance in an automated and timely manner. Demonstration findings were generated and documented for further development in preparation for using the data portal in an actual inspection’s self-assessment at Xcel Energy in 2024.

---

[c] MIRACLE received an R&D 100 Award in 2022: https://www.rdworldonline.com/rd-100-2022-winner/machine-intelligence-for-review-and-analysis-of-condition-logs-and-entries-miracle/

2.1.2.3 Assisting Operators to Detect Plant Anomalies

One of the numerous responsibilities of nuclear power plant operators is to monitor and respond to plant anomalies. Plant alarms are generated when plant process anomalies occur and are significant enough to exceed some monitoring threshold. Due to the scale and complexity of nuclear power plants, subtle plant anomalies may go undetected until they become more obvious or exceed alarm threshold setpoints. Industry recognizes the benefits of early detection, that provides more time to efficiently plan and execute repairs, especially for expensive components or for conditions that could affect operations. To assist operators in monitoring plant systems to detect subtle anomalies, dedicated monitoring and diagnosis (M&D) centers are collecting and analyzing plant data. These centers use algorithms to monitor and process large amounts of data coming in from sensors throughout the plant. M&D centers use the information to produce assessments of plant, system, and component performance for the purposes of maintaining safety and ensuring the operability of plant systems.

To advance the U.S. nuclear industry's capabilities for monitoring and detecting subtle anomalies, LWRS Program researchers are collaborating with industry to create a suite of anomaly detection tools. These applications are based on data-driven methods that correlate sensors and processes using historical data. ALARM (Automated Latent Anomaly Recognition Method) is software developed through this effort (Figure 18) and provides an integrated suite of advanced monitoring capabilities needed to identify subtle anomalies earlier and more reliably than manual monitoring. ALARM software is available to utilities through a no-cost license from INL.

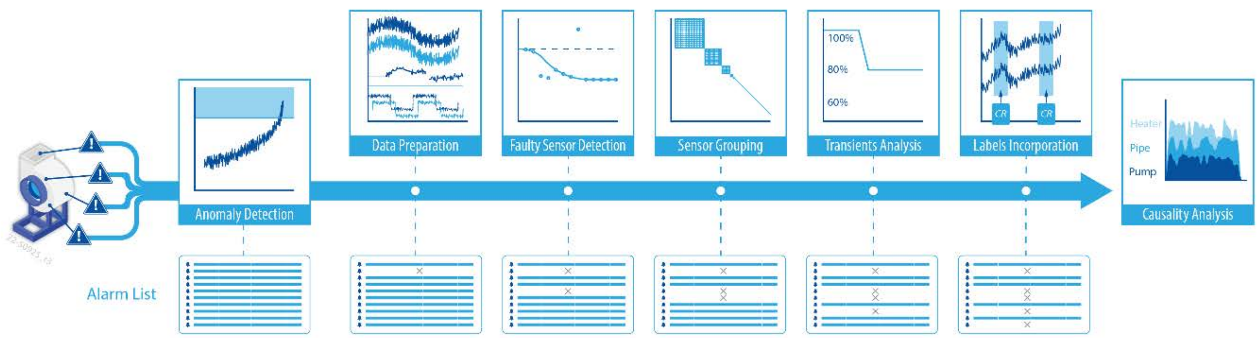


Figure 18. Methods developed to enhance anomaly detection while minimizing false alarms.

In 2023, research was conducted to expand the anomaly detection capability of ALARM. Historically, nuclear power plants have operated predominantly at or near full power, meaning that most of the data collected are in this operating regime. Therefore, data-driven anomaly detection methods that are developed using this data can perform well at full power operations. However, this presents a challenge when the power drops (referred to as a "transient") and may result in false alarms due to the lack of historical data at those transient power levels. The current approach to handling this challenge is to turn the anomaly detection algorithms off during transients, causing missed detections of anomalies during plant transients. In 2023, LWRS Program researchers developed solutions to extend these data-driven methods to transient conditions, thereby increasing both monitoring uptime and the likelihood of detecting anomalies in their earliest phase.

Research Accomplishment:

Improved Anomaly Detection Methods for Safer Operation During Plant Transients

This effort demonstrated that anomaly detection methods can be modified and used during transient conditions, improving overall plant M&D capabilities.

Researchers focused on two common types of approaches to anomaly detection: prediction-based and feature-based. Prediction-based anomaly detection is performed by either withholding some data from the complete dataset and predicting that withheld data or compressing the complete data to some smaller set and using the compressed data to predict the full data. An anomaly is detected if the prediction error between the real measurement and the prediction is large. In contrast to prediction-based methods, feature-based methods try to extract data features that are small during normal operations and larger during anomalies.

To evaluate these detection methods in a controlled environment, a synthetic data generator was created and used. Initial results showed that the anomaly detection methods were extremely sensitive to nonlinearity. Nonlinear systems are systems where inputs and outputs do not correlate in a proportional manner. Instead, they have complex correlations that can be difficult to capture and explain. Nuclear systems usually exhibit predominantly proportional correlation (linear behavior) when operating within their normal parameters. To develop detection methods that included both linear and nonlinear data, the nonlinearity of the data was quantified, and the methods (which included both linear and nonlinear versions) were tested. An example of linear and nonlinear system responses is shown in Figure 19, where flow rate through a valve can be linearly proportional to the valve position in ideal situations but could be nonlinear during transients.

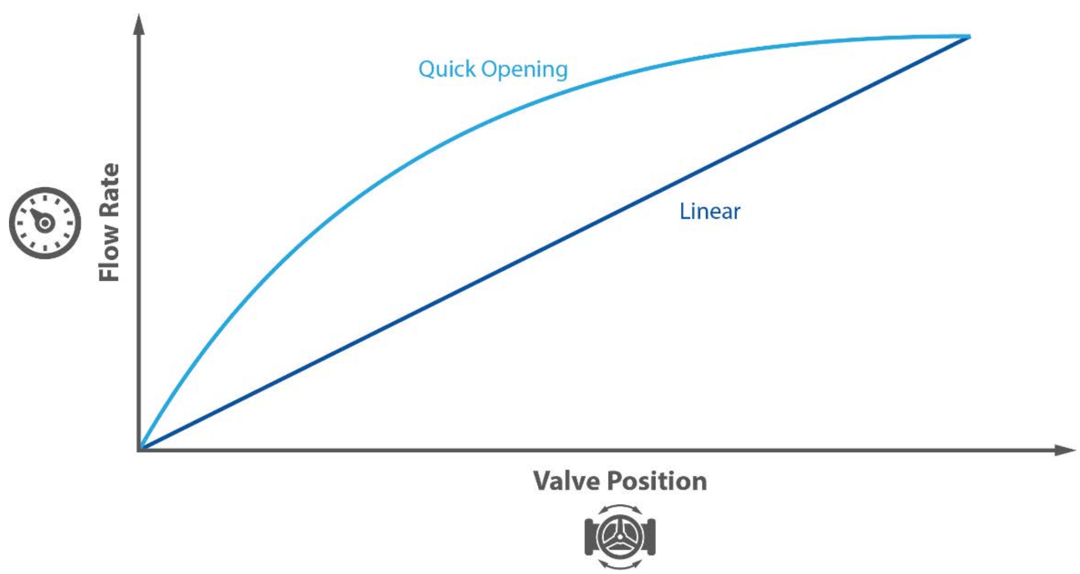


Figure 19. Example of linear and nonlinear flow behavior in a valve system.

Research results indicate that feature-based methods appear to perform better than the prediction-based methods when given very small amounts of transient data, although this advantage was not seen as more data were added. One possible explanation for this is that the methods are finding just the features that are linear and ignoring the other effects, while the prediction-based methods may not be able to extract the linear features as accurately.

It appears that, for linear datasets, the transient problem is solvable and multiple methods can achieve good results. For nonlinear datasets, the transient problem is much more difficult and, for very limited transient datasets, may only be solvable when some linear patterns exist that can be extracted. While there is still work to be done with regards to systems exhibiting nonlinear responses during transients, the result of this research shows promise for providing systems with complex and nonlinear interactions in different operating regimes, such as nuclear power plants, with new capabilities to identify anomalies during transient conditions.

2.1.2.4 Advanced Artificial Intelligence and Machine Learning in Nuclear Power Plants

The nuclear industry is taking advantage of artificial intelligence (AI) and machine learning (ML) to study ways to automate aspects of manually performed operations and maintenance activities. Traditionally, the industry has relied on periodically scheduled maintenance (referred to as preventive maintenance) to inspect plant equipment. During these regularly scheduled inspections, utilities use the opportunity to perform routine maintenance. While practical, it is costly to perform unnecessary maintenance (i.e., when it might not be required by the condition of the equipment) not to mention the added risk associated with potential human errors. A key cost savings opportunity is transitioning to a predictive maintenance strategy. This strategy recommends maintenance to be performed when there is evidence a component requires attention.

The predictive maintenance approach may be enhanced through the application of AI and ML technologies to analyze and predict the need for maintenance. Evaluating the risk of accurately identifying degraded component conditions and responding in time to avoid unplanned equipment downtime is critical to successfully transition to a predictive maintenance program. Researchers are developing ways to effectively explain AI/ML results and how to provide the industry with the needed level of trustworthiness. The historical barriers to achieving these results encompass things such as the lack of instrumentation and control (I&C) digitalization and modernization, as well as nuclear safety events which have slowed down technological advancement. The results of this AI/ML explainability research assists industry addressing these technological adoption barriers including such things as data quality, governance around the use of AI/ML, perceived complexity, lack of transparency in how AI/ML outcomes are achieved, and concerns to develop individual AI/ML technology for each piece of equipment in the plant.

Research Accomplishment:

Developed a Visualization Approach that Builds Trust Between Operators and Artificial Intelligence

The LWRS Program working with industry has developed and demonstrated risk models and technologies to monitor and successfully predict component health using AI/ML technologies. Even with very positive results and a valid business case for using predictive maintenance programs, there is a reluctance to broadly adopt these technologies. Several challenges associated with the adoption of AI/ML technologies can be categorized as historical, technical, business, regulatory, nuclear plant stakeholder readiness, experience, and end-user acceptance.

It is essential to overcome these AI adoption barriers to enable wider use of AI/ML technologies in the nuclear industry. Addressing this need, LWRS Program researchers are developing a novel approach to effectively explain AI/ML results and recommendations by developing solutions on three aspects of AI technologies, i.e., performance, explainability, and trustworthiness (Figure 20). It uses specific metrics, user-centric visualization, and human-in-the-loop evaluation to assess user confidence. To evaluate the three aspects of AI technologies, LWRS Program researchers are collaborating with Public Service Enterprise Group (PSEG) Nuclear, LLC. Data and fault modes from the PSEG-owned plant circulating water system were used. Specifically, researchers conducted an experiment to predict a plant site's circulating water system waterbox fouling, which on day-to-day operations caused unplanned and expensive power production outages. The manual process of diagnosing a fouled waterbox and taking actions to mitigate the threat typically requires many hours of data processing. AI/ML solutions have reduced manual processing time significantly and provide ahead of time warning of developing waterbox fouling issues with recommended actions.

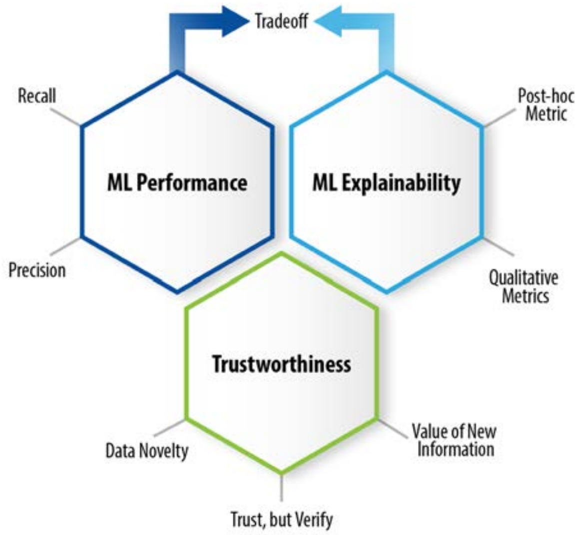


Figure 20. Balancing performance explainability and trustworthiness.

Copyrighted user-centric visualization software was developed (Figure 21) to promote trust between operators and AI/ML technology recommendations for decision-making. The user-centric visualization presents performance results along with explainability objective metrics for the human-in-the-loop This explains what data the AI/ML approach (under the hood of the visual) used to arrive at the results (i.e., diagnosis and prognosis) and which data or combination of data are salient in making the recommendations and increases confidence in the diagnosis. The user-centric visualization was tested with a large audience to ascertain how the application appealed to a general audience of people with varying levels of AI/ML experience.

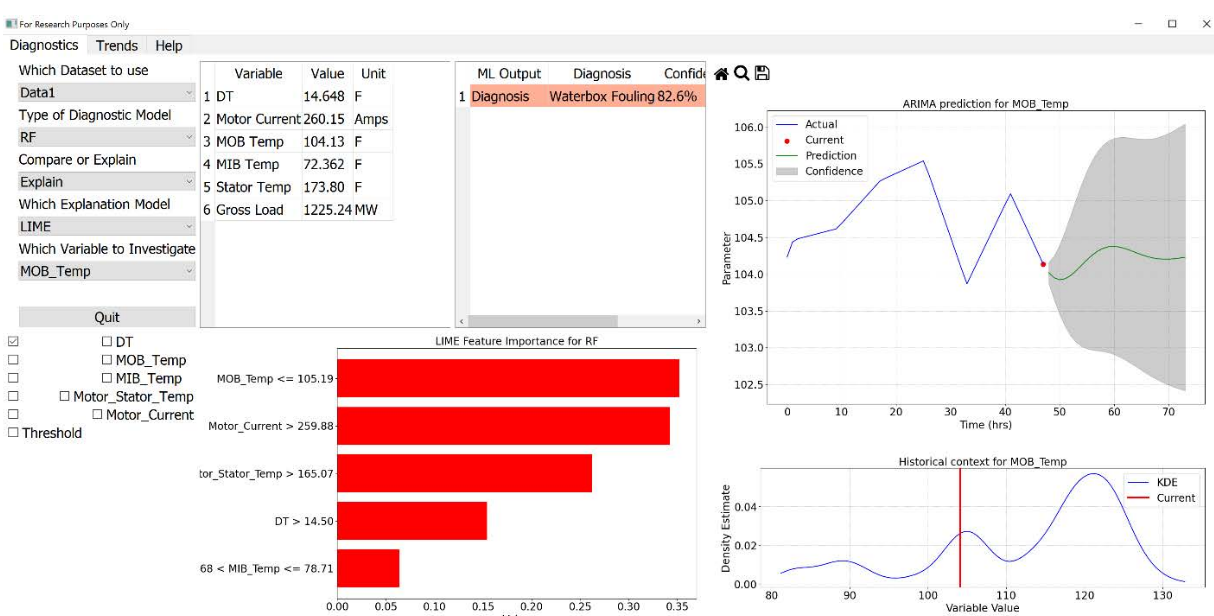


Figure 21. User-centric visualization with performance and explainability metrics.

The research outcomes will assist industry in addressing these technological adoption barriers, addressing issues such as data quality, governance around the use of AI/ML, perceived complexity, lack of transparency in how AI/ML outcomes are achieved, and concerns to developing individual AI/ML technology for each plant's equipment. The user-centric visualization with additional improvements will be available to deploy at scale by plant sites and at monitoring and diagnostic centers, via a no-cost, non-exclusive licensing agreement.

2.1.2.5 Analyzing the Sizable Power Uprate Potential for Existing Fleet to Diversify Revenue Sources and Increase Economic Sustainability

The LWRS Program 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. The recently enacted law, the Inflation Reduction Act (IRA), enables an additional pathway to strengthen the sustainability of operating nuclear power plants by offering incentives for generating new low-carbon electricity, (i.e., added capacity to the electric grid).

The IRA includes incentives to promote investment in new carbon-free power generation and the sustainable operation of existing carbon-free assets. Specifically, the IRA includes both a production tax credit (PTC, in section 45Y of the IRA) and an investment tax credit (ITC, in section 48E). Utilities may leverage these to offset the power uprate costs. Furthermore, the IRA includes a provision (Section 45V) for a PTC associated with carbon-free hydrogen cogeneration. These tax credits, along with recent decarbonization-related legislation, reemphasize the importance of maintaining the nuclear power plants and its optimized operation in which nuclear energy is categorized into zero-emission energy source.

Existing nuclear power plants could produce extra power via a process called a power uprate. The increase in power generation could range anywhere from 1% up to 20%. To put this in perspective, the addition of 8% to 12% of power for a 1,000 MWh capacity operating plant equates to 80 to 120 MWh of electricity added to the grid. This corresponds to the size of a small nuclear reactor. Given the aggressive national decarbonization goal, deployment of new clean electricity before new nuclear reactors begin operations is critically important.

The power uprate is viewed as a great opportunity to increase sustainability of operating nuclear power plants by many U.S. utilities. A recent NEI industry survey [22], found over 50% of utilities are interested in a power uprate. Power uprate is also seen as the "stepping stone" in the deployment of new nuclear reactors. The large plant modifications required to support sizable power uprates will indeed naturally reengage or establish "building blocks" that will be necessary in the future to build and operate new reactors. This includes, but it not limited to, workforce development, supply chain of both nuclear-grade and commercial grade materials and components, efficient review and approval processes with the NRC and other regulatory agencies, and improvements in the project management practices. Large scale new nuclear power plants will greatly benefit from the lessons learned and supply chains established during smaller-scale power uprates.

Researchers from the LWRS Program performed a feasibility assessment of sizable power uprates. This included evaluation of economics, market conditions and capabilities of the plant systems, and provided evaluation of several business cases for power uprates. Such assessment is a must for utilities to proceed with the power uprate since it supports understanding of the business case to justify the investments.

Research Accomplishment:

Demonstrated Feasibility of Near-Term Increase of Clean Energy Generation via Power Uprates

With this study, the objective was to:

1. Understand if the IRA incentives support the business case of power uprates to justify the investments.
2. Expand the business case to evaluate the opportunity to use added power to produce hydrogen as an alternative revenue source and compare the benefits of electricity versus hydrogen generation.

Most hydrogen produced in the U.S. is via steam methane reforming (SMR) of natural gas, a process that entails a very high level of greenhouse emissions. Transitioning from almost sole reliance on SMR-based hydrogen over to carbon-free hydrogen is one of DOE's top priorities to support decarbonization goals. According to the DOE's Pathways to Commercial Liftoff report [23] "hydrogen can play a role in decarbonizing up to 25% of global energy-related carbon emissions, particularly in industrial/chemicals uses and heavy-duty transportation sectors." While the zero-carbon hydrogen market is still emerging, forecasts are extremely favorable, with a large market being anticipated in which nuclear utilities can sell hydrogen. Per [23], "Clean hydrogen production for domestic demand has the potential to scale from < 1 million metric ton per year (MMTpa) to ~10 MMTpa in 2030." The economics of nuclear-based hydrogen look very promising thanks to substantial advancements in electrolysis technologies. The cost of electrolysis-based hydrogen is projected to decline by about 50% by 2030. These metrics demonstrate a potentially significant market and business opportunity for carbon-free hydrogen generation and the nuclear industry is interested in understanding the details of the business case to identify investment strategies.

To support industry needs, the project collaborated with the industry and NEI to assess the IRA tax credits of operating nuclear power plants as documented in [24]. Specifically, a Microsoft™ Excel-based financial modeling tool was developed for use in supplementing plant-specific models. Its overall functioning is summarized in Figure 22. Also, a case study was documented that was intended to (1) demonstrate the value of implementing the IRA tax incentives and to (2) provide the domestic nuclear fleet with insights and information usable to support site specific power uprate business cases.

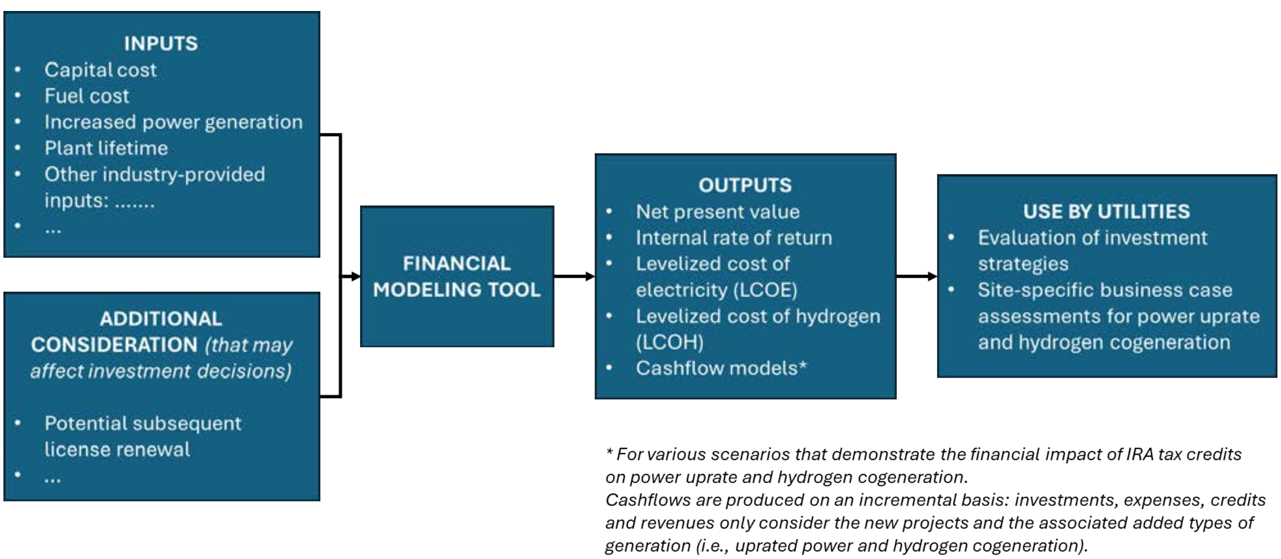


Figure 22. Overall functioning of the LWRS Program financial modeling tool.

The project was conducted in close collaboration with industry. NEI facilitated engagement of utilities and fuel vendors to provide inputs into the business case model and feedback. After the model was developed, industry subject-matter experts reviewed it to ensure the input values were realistic, and the output results were reasonable.

The results of the research supported by the model demonstrated significant benefits of IRA incentives for the business case of power uprates. Figure 23 presents the levelized cost of electricity (LCOE)s for power uprate for different scenarios.

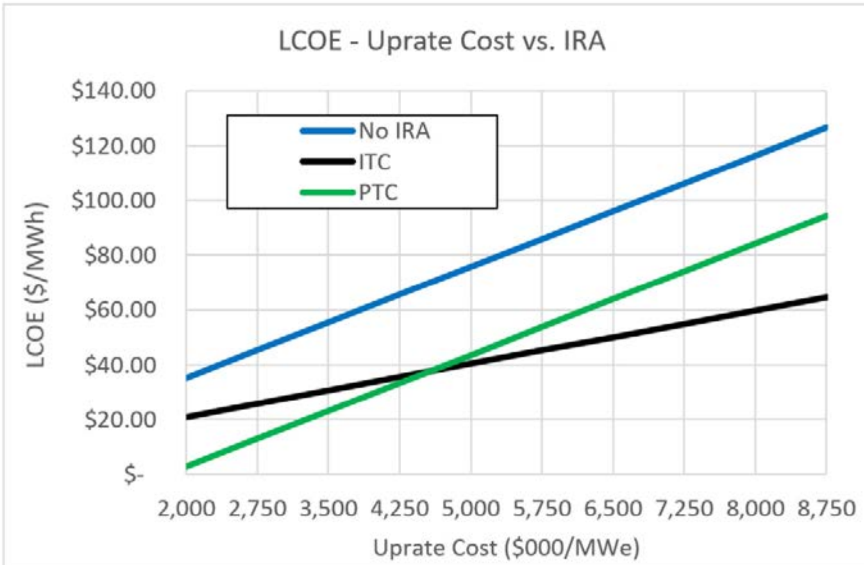


Figure 23. LCOE at various power uprate levels, both with and without IRA tax credits. ITC: investment tax credit; PTC: production tax credit.

The LCOE for the baseline uprate (i.e., with no IRA credits), varying from $35 to $120/MWh, shows that the cost of new power from power uprates is still significantly lower than the LCOE of added nuclear power from new nuclear plants, which ranges from $141 to $221/MWh, from the 2023 Levelized Cost of Energy report [25]. The IRA incentives make a significant difference by lowering the LCOE even further.

The business case of power uprates becomes even stronger when added power is used for carbon-free hydrogen generation. Figure 24 presents the levelized cost of hydrogen (LCOH) produced via either low-temperature electrolysis (LTE) or HTE and compares the cost with LCOH produced via SMR, the predominant industrial approach today, with and without carbon capture and storage (CCS). The LTE and HTE electrolysis-based hydrogen is already competitive with SMR-based hydrogen, which is the most prevalent type of hydrogen on the market. The electrolysis-based hydrogen is even more competitive when requirements for carbon capture sequestration (via CCS) are imposed on SMR processes.

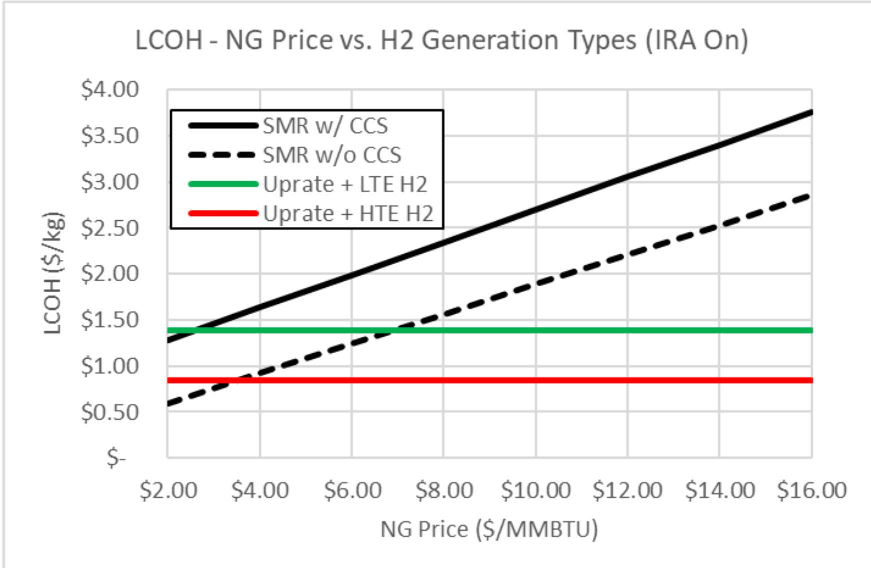


Figure 24. LCOH for electrolysis- and SMR-based hydrogen, depending on the price of natural gas (NG).

The case study and corresponding sensitivity analyses demonstrated that the IRA tax credits would have a significant positive impact on the business case for implementing uprates to existing nuclear power plants. Furthermore, the study results provide insights into the key drivers and sensitivities of various inputs (e.g., capital costs, power pricing, hydrogen sales price, and power plant lifetime), thus helping inform overall decision-making throughout the power uprate and/or hydrogen cogeneration process. Other considerations crucial to evaluating the overall business case and the impact of the tax credits include financing approach, direct payment, credit transfer and implementation timeframe.

The project also evaluated the safety assessments required to support sizable power uprates. Historically, power uprates mostly relied on the already available safety margins to demonstrate that plant modifications due to power uprate do not affect overall plant safety. For most plants, the remaining safety margins, as currently assessed, are too small to support additional power uprate on a scale larger than a few percent. However, the latest developments in computational resources and technologies, including modern data analytics technologies such as AI and ML, allow for dramatically improving the modeling and simulation of plant operations and their underlying physics-based processes. This results in a much better understanding and representation of scenarios that may occur at a nuclear power plant. The advanced, more detailed modeling and simulation of nuclear power plant scenarios remove unnecessary conservatisms typically imbedded in most of the analyses and demonstrate improved (i.e., larger) safety margins that directly support larger power uprates.

2.1.2.6 Optimizing Plant Fuel Load to Improve Performance and Fuel Utilization

Nuclear fuel costs represent approximately 20% of the total cost to generate electricity, a substantial expense for a nuclear utility. As such, fuel reload optimization continues to be one of the industry's high-priority interests. The research aims to optimize reactor core thermal limits by implementing state-of-the-art computational and modeling techniques. Optimization of core thermal limits allows a smaller fuel batch size to produce the same amount of electricity. This reduces new fuel costs and significantly reduces the cost of processing spent fuel, by reducing the volume of spent fuel.

The optimization of the nuclear reactor core fuel loading pattern when refueling is one of the most important considerations in reducing the amount of new fuel usage in the core. Due to millions of possible core configuration options, finding optimal solutions is unachievable for humans. However, it is achievable by use of modern AI techniques. To enable the optimization of reactor core design, research develops an integrated, comprehensive platform offering an all-in-one solution for reactor core reload evaluations with a special focus on finding the best solutions for core design considering feedback from system safety analysis (i.e., thermal-hydraulics) and fuel performance. [26]

The goal of this research is to develop and demonstrate a unified and thorough AI-powered plant reload optimization (PRLO) platform that provides a complete solution for reload assessments, particularly emphasizing fuel optimization. The PRLO platform is an enhanced arrangement for the reactor core, meticulously designed based on critical safety parameters that are essential to fulfill regulatory standards.

The PRLO platform was developed using the Risk Analysis and Virtual ENvironment (RAVEN) computer software that allows great flexibility in using modern AI techniques such as genetic algorithm. This technique is a proven technology for fuel reload optimization. RAVEN's capability is not just limited to optimization. It can also provide input decks to other physical codes and perform post-processing of simulation results. This extensibility of RAVEN facilitates coupling with other physical codes for core design, fuel performance and systems analysis, which can lead to a unified framework that considers physical phenomena. The PRLO platform can set multiple objectives and constraints such as fuel cycle length (e.g., an extension from 18 to 24 months), fuel enrichment, burnable poisons, core design limits (e.g., peaking factors and boron concentration), as well as safety parameters (e.g., peak cladding temperature and departure of nucleate boiling rate).

Research Accomplishment:

AI-based Optimization Technology Applied to Nuclear Reactor Design and its Economics Offers a Measurable Reduction of Operating Costs Through Optimization of Fuel Utilization

In 2023, the PRLO platform was improved to handle many objectives and constraints by applying augmented objectives methodology in non-dominated sorting genetic algorithm (NSGA-II). [27] The NSGA-II algorithm specifically allows specification of several objectives for a problem being optimized instead of a single objective.

The demonstration was performed with constrained multi-objective optimization of a PWR core loading pattern with the objectives to minimize fuel cost and maximize fuel cycle length. The coupling interface between RAVEN and the core design code SIMULATE[d] was built and tested for the NSGA-II optimizer. Figure 25 shows the set of potential loading pattern solutions (i.e., search space), feasible solutions, and 11 optimized solutions shows as the Pareto frontier. As observed in the figure, the optimization algorithm reduced the number of potential solutions, which is in this case a particular core design configuration, from a very large set to just a few most optimal core design alternatives. These optimal alternatives meet all the constraints and are the best options in terms of postulated objectives. The optimized core pattern showed fuel cycle length range between 364.1 to 383.5 effective full power day (EFPD) and the fuel cost range from $499,450,000 to $520,920,000.

[d] Studsvik SIMULATE, https://www.studsvik.com/key-offerings/nuclear-simulation-software/software-products/simulate5/

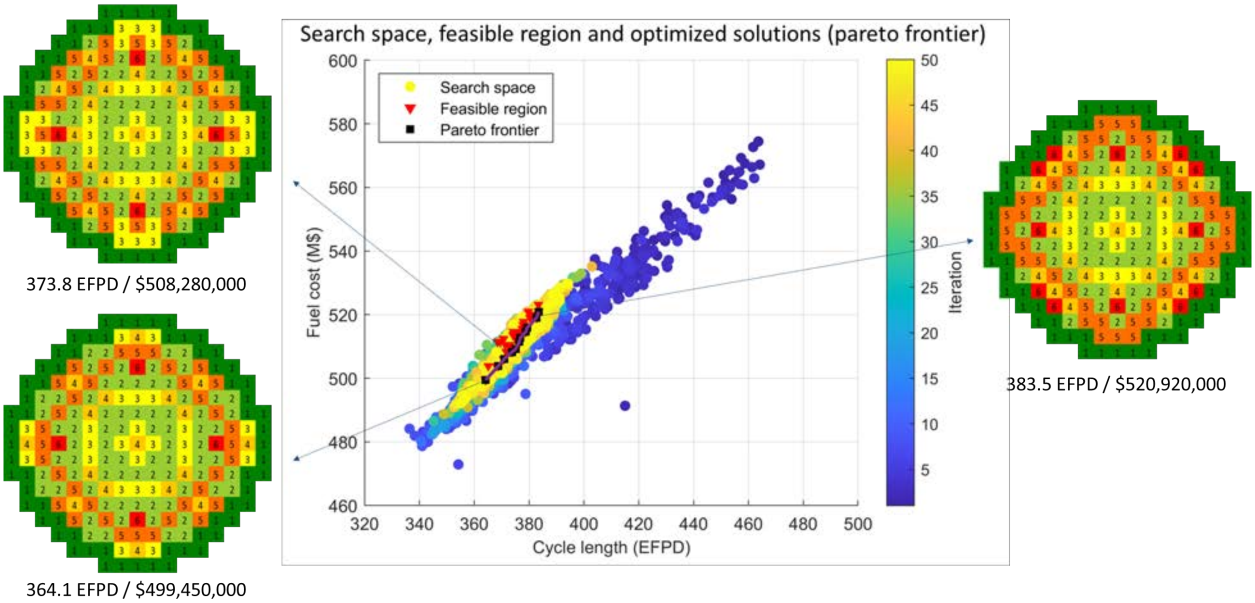


Figure 25. Optimized core designs from potential core loading patterns.

This demonstration is the first kind of research that showed optimized fuel cost and associated fuel cycle length using AI technology. The optimization generated realistic core loading patterns, with the optimized core design showing a substantial reduction in the fuel volume and associated costs.

The outcome of this LWRS Program R&D is an integrated platform that combines multiple tasks required for fuel reload analyses. This integration removes manual data transfer between tasks—thus eliminating human errors—and significantly reducing analyses time.

This is very timely, considering that almost the entire fleet of operating plants intends to increase their power output. Fuel performance and reactor core performance are the most important factors for determining power uprate scales. This project focuses on the optimal core design and system performance and will be able to provide insights and solutions to enable larger-scale power uprates.

2.1.2.7 Providing Better Tools for Utilities to Assess and Anticipate Fire Hazards in Nuclear Plants

Implementation and management of fire PRA is very expensive -- in the order of $1M to $3M for a plant for the initial development and $100K to $500K per year after the model is developed. Many decisions affecting nuclear plants operation, maintenance strategies, investment strategies and regulatory oversight are made using risk insights provided by the plant PRA model. Any plant modification is evaluated using PRA and evaluations of fire risks are the most complicated and resource consuming. As such, there is a need to improve the effectiveness and reduce the cost of fire risk analyses.

In addition, fire is the dominating hazard for many plants. This is attributed to fire scenarios typically being modeled using unrealistic conservatisms, leading to overestimated fire risks. Nuclear power plants would benefit from refining these overly conservative fire scenarios, but this is usually cost prohibitive by the labor required to modify any scenario. The project encompasses R&D for streamlining fire PRA modeling processes, thus affording nuclear power plants the opportunity to gain safety margins in terms of reduced fire risks.

This project has two main objectives: (1) develop effective methods and tools to significantly reduce the resources required by current fire PRAs, and (2) research and outline new time-based methods of modeling complex fire scenarios, as opposed to the highly conservative methods currently in use.

The objectives were achieved via development and demonstration of the fire analysis tool, Fire Risk Investigation in 3D (FRI3D). [28] FRI3D is in the process of deployment to industry partners for commercial use.

Research Accomplishment:

Improved the Effectiveness and Reduced the Cost for Fire Risk Analyses

The final stages of FRI3D development were completed in 2023 [29] with the tool updated to meet industrial standards. Figure 26 is an example of smoke visualization in FRI3D based on Fire Dynamics Simulator (FDS) simulation.

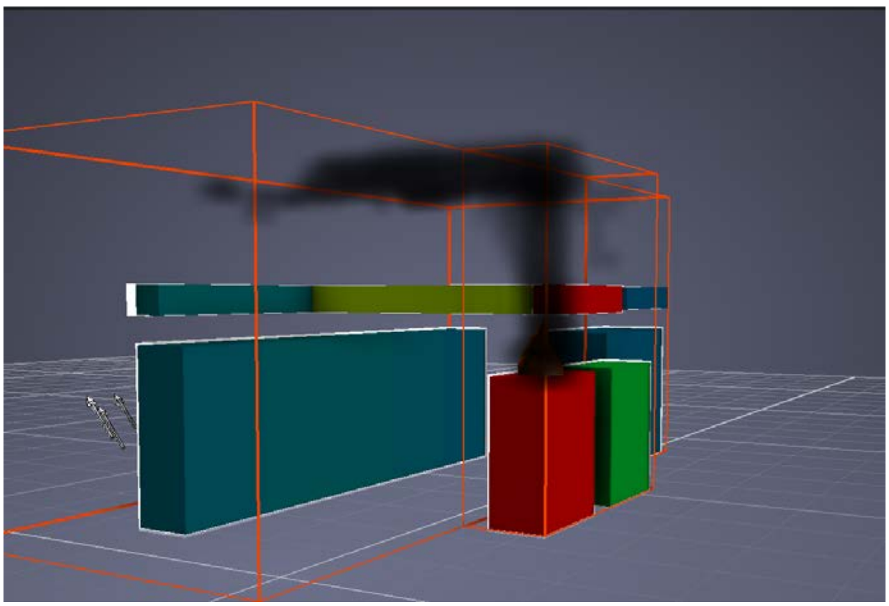


Figure 26. Smoke visualization in FRI3D based on FDS results.

A pilot study conducted in 2023[29] compared the durations needed by fire assessment experts to perform analyses using traditional methods vs. using the FRI3D tool. The FRI3D software carries significant potential as a cost savings tool for nuclear industry fire analyses, as it can reduce the initial evaluation time by up to 50% and subsequent changes by over 90%. The greatest potential for cost savings is for a full-plant fire PRA analysis.

FRI3D offers valuable features such as fire modeling from scratch, time- and space-dependent fire simulation, automated PRA workflow and 3D visualization. The software imports existing plant models and then combines required tools and methods in a 3D visualization environment. This coupled approach automates tasks that are then carried out in one system, reducing the overall maintenance costs and human errors entailed by fire modeling. The FRI3D platform also maintains all necessary information in one place, allowing analysts to evaluate scenarios without searching through numerous plant drawings and databases.

This integrated fire modeling and visualization software promises to reduce efforts needed for fire hazard modeling by up to 50%, turnaround time by up to 50%, and decrease user errors by 90% or more, thus optimizing the cost and time devoted to fire scenario analyses yet still increasing the accuracy. The fast turnaround and ability to refine critical scenarios are invaluable during NRC significance determination process evaluations. In addition, FRI3D affords valuable decision-making support during design phases, as it allows risk-informed insights pertaining to multiple what-if scenarios for a component replacement type or the best location for the new component.

The benefits of FRI3D utilization vs the traditional approaches to fire risk analyses have been recognized by both domestic and international industry experts. Engineering Planning and Management, Inc. (EPM) is one of the major consulting companies providing fire risk assessment services to the U.S. nuclear utilities. EPM is now offering advanced capabilities in fire analysis and simulation by performing them in FRI3D. The European main provider of risk assessment and PRA services, Risk Spectrum, is in the process of signing the contract to offer advanced risk evaluations and fire PRAs by using FRI3D as part of their portfolio. Lastly, Canadian utilities were introduced to FRI3D at the international conference on fire risk assessments and they strongly consider incorporation of FRI3D in their fire PRAs.

2.1.2.8 Advanced Technologies for Physical Security

The events of September 11, 2001, and the subsequent responses, including guidelines for maintaining physical security, resulted in increases in physical security measures at nuclear power plant sites. During an LWRS Program stakeholder meeting on physical security in September 2019, optimizing postures for physical protection at nuclear power plants through advanced technologies was prioritized for near-term research. This research is developing a deployable remote operated weapon systems (ROWS) capability, which meets regulatory requirements for inclusion in a nuclear power plant's physical security posture. Since 2019, LWRS Program researchers have been evaluating a ROWS that uses thermal imaging and optical cameras to identify intruders. ROWS allows a security officer in a control room, outside the line of fire, to actively engage and defend against physical threats. The system would enable a single system operator to switch from one ROWS vantage point to another almost instantly, by control from within a protected room.

The objective of this research is to deploy operational external (see Figure 27 – inside red circle) and internal (see Figure 28 for indoor deployment only) ROWS solutions at domestic nuclear power plant sites. The LWRS Program intends to initiate and carry out a cooperative private-public implementation of such solutions at an existing candidate nuclear utility site by 2026. As envisioned, a ROWS may optimize physical security by serving as a force multiplier and by increasing survivability of the overall security force. This research activity will assist the current nuclear power fleet in addressing the challenges in optimizing ROWS deployment within a 5-year timeframe. This research is being performed in collaboration with Xcel Energy, Entergy, and Constellation.

Figure 27. Single Sentry-II ROWS Configuration.

Figure 28. Single Inverted T-360 ROWS Configuration.

Research Accomplishment:

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

In 2023, LWRS researchers collaborated with nuclear utilities and the U.S. NRC to develop and document the technical basis to support deployment of ROWS at nuclear power plant sites (e.g., Safety Basis and Cybersecurity Basis). The researchers observed force-on-force exercises, conducted a series of ballistic performance tests, and finalized a graded approach for ROWS deployment following four phases:

- 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: Implement full-scope ROWS deployment.

In 2023, Phase 1 research efforts identified external and internal ROWS deployments placements and configurations, considering regulatory requirements, and conducted initial evaluations of an upgraded armor solution for external ROWS configurations. A solution like that shown in Figure 27 was used as a reference system for this research. Additionally, 2023 efforts included updating the command-and-control software evaluations for safety, security, and performance tests of a simulated ROWS deployment at domestic nuclear power plant sites. It included the ballistic testing of various attack scenarios (see Figure 29 as an example) to support ballistic data updates and increasing the accuracy of the ROWS modeling and simulation.

Figure 29. Ballistics testing.

The modeling and simulation efforts used the Dante™ software and Scribe3D© software to identify ROWS placement (Phase 1) with a collaborating nuclear utility. The Dante software is used to inform decision-makers and security professionals on the system effectiveness of existing and future physical protection system designs. Scribe3D is a three-dimensional tabletop recording and scenario visualization software that creates, records and plays back scenarios developed during tabletop exercises. Scribe3D can be used as a planning tool for performance testing, force-on-force, or other security analysis related applications.

Researchers modeled the performance of ROWS against the design basis threat; the characteristics that the authorities presume an attacking force will have. The ROWS-based security force generally has a higher success rate against the adversary force over a traditional security team. The current research being conducted with the nuclear power utility uses tabletops and high-fidelity modeling and simulation which are the main basis of the research. The tabletop exercises are conducted where security personnel make decisions with visualization software tools that allows them to explore states and decisions over the course of an attack with a responder-in-the-loop. The modeling and simulation is conducted using high-fidelity physics, behavior engines, path planning and other data libraries that are melded together to evaluate several thousand iterations of different scenarios of adversary and security force tactics in a Monte Carlo batch analysis.

The collaborating nuclear utility uses Scribe3D to conduct tabletop exercises and provides feedback on ROWS placement (see Figure 30) 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.

Figure 30. Notional visualization for modeling external ROWS placements using Scribe3D.

In 2024, the LWRS researchers plan to complete Phase 1 modeling and simulation for external and internal ROWS placements at an existing candidate nuclear utility site and start Phase 2 efforts to develop a full-scope ROWS simulator prototype which will be used for training and verification of the modeling and simulation of ROWS placements. The expectation for outyears is in 2025 to complete Phase 2 and start Phase 3 limited-scope force-on-force exercises to validate the modeling and simulation of ROWS placement. In 2026, Phase 4 will be initiated with the implementation of a full-scope ROWS deployment. The demonstration of this graded approach to ROWS deployment will allow each nuclear utility to reduce their financial and regulatory risks as they evaluate the feasibility of deployment at each site.

2.1.2.9 Risk-Informing Physical Security

This research is developing performance-based methods to support the use of risk-informed solutions for physical security at nuclear sites. The goal is to develop a structured, risk-informed approach supporting security-related decision-making and addressing the unique security-related concerns for each nuclear power facility.

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. This can potentially extend the radiological sabotage timelines for response force success. It also investigates the expansion of existing risk-informed methods for nuclear security.

The objective of this research is to enable the use of risk-informed processes by light water reactor (LWR) stakeholders for making physical security decisions that reduce uncertainties, optimize physical security postures and plans, and enable a predictable process for managing and modifying a nuclear utility’s physical security plans. Physical security has made 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 in the middle of an attack based on their progression. The result is that the physical security community relies heavily on limited empirical data and subject-matter experts to inform physical security plans. This results in large uncertainties in traditional analyses and potentially a conservative security plan to account for these uncertainties. A performance-based, risk-informed approach to physical security has the potential to enable improvements to physical security postures without negatively impacting the required overall effectiveness of the physical security system.

Research Accomplishment:

A New Approach to Better Assess the Holistic Nature of Safety and Security at a Nuclear Power Facility

In 2023, LWRS Program researchers collaborated with a nuclear utility and the Pressurized Water Reactor Owners Group (PWROG) to apply a dynamic computational framework that links results from a commercially available force-on-force simulation tool, a commercially available thermal-hydraulic analysis tool, and INL's Event Model Risk Assessment using Linked Diagrams (EMRALD) software[e]. The resulting framework includes the use of plant-specific operating and security procedures, safety analysis results, and is called Modeling and Analysis for Safety-Security using Dynamic EMRALD Framework, or MASS-DEF (see Figure 31). This framework is used to identify opportunities to optimize security by applying the MASS-DEF computational framework to the collaborating nuclear utility's security scenarios and timelines, which could result in significant savings in security costs.

The early 2023 MASS-DEF proof-of-concept demonstrates that, even in the extreme case of a hypothetical successful adversarial attack, the application of a modified flexible mitigation capability (FLEX) equipment strategy[f] has a high likelihood of preventing core damage and radiological release. The modeling and simulation framework of integrating onsite, mobile safety equipment with force-on-force modeling enables a site to credit portable safety equipment within the plant security posture. This results in more efficient, balanced, and optimized physical security. Preliminary results from the 2023 case study with a collaborating nuclear utility have led to the concept of 'security-designated portable equipment.'

The results obtained provide valuable insights about the potential effectiveness of crediting security-designated portable equipment in security scenarios and showed about a 20% potential reduction in response force personnel requirements. Feedback from the utility regarding both the process and the analyses of the results indicated they would consider the implementation of a "Physical Security Response Pump." This mobile pump is identical to the plant FLEX pump but would be pre-staged inside the plant's protected area and include physical security delay features, adjustments to response force strategies, or both to reduce the ease of radiological sabotage. The pump placement leverages guard positions, maximizing the benefits of crediting this additional pump in most scenarios. The utility also proposed alternative and more economical options for pump cooling hookup, along with adjustments to guard requirements and defense strategies. Additional regulatory and cost analysis still need to be performed before deciding on proceeding with the project.

The lessons learned from this 2023 study will be used in planned 2024 research with the nuclear power industry to create guidance outlining the detailed process to perform this type of analysis. Additionally, the data created through this phase of research identify potential post modifications (e.g., the need for and type of physical security response to specific threats and attack pathways) that could be reasonably justified by including the "physical security response pump" into the physical security plan. However, the overall cost savings of these potential modifications will need to be analyzed. They indeed imply the need to purchase equipment, train staff, install additional delay features, perform engineering analyses, and address regulatory issues related to changes in the physical security plan.

---

[e] https://emrald.inl.gov

[f] Nuclear Energy Institute, "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," NEI 12-06.

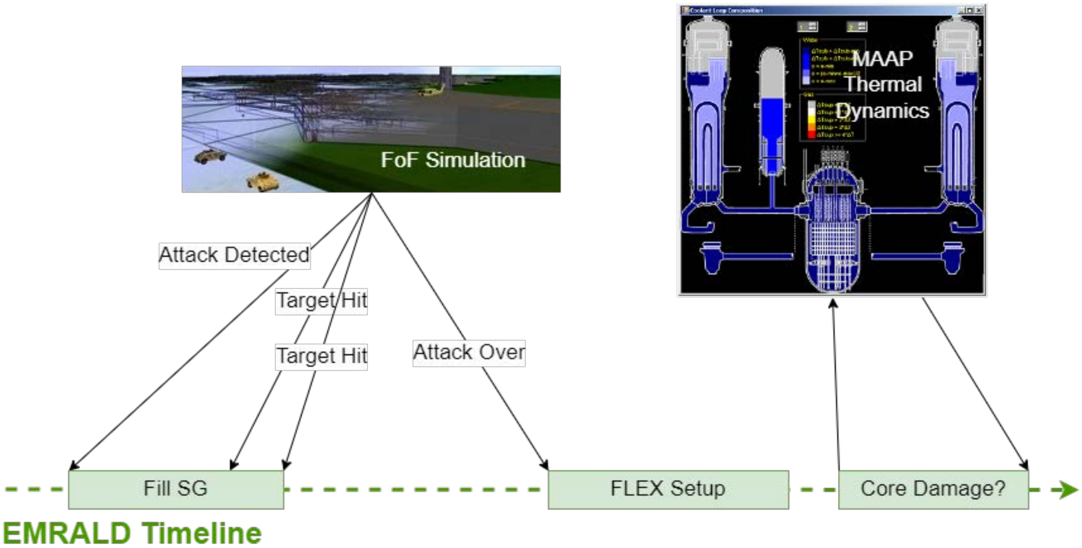


Figure 31. Combined security and safety inputs for the MASS-DEF Computation Framework (Force-on-force [FoF], steam generator [SG], MAAP: severe accident code)

2.1.2.10 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 applied at nuclear plant sites. Another objective is to develop advanced sensors and barrier systems that have the potential to significantly quicken onsite security response time to a design basis threat (DBT) adversary earlier within the attack phase. Figure 32 shows a current type of perimeter intrusion detection and assessment system (PIDAS). Advanced sensor technologies within this research area are looking to assist in overall cost reductions, reduced nuisance alarm rates (NARs), and increased adversary probability of detection (P_d) when fielded in a PIDAS arrangement. Such a deployment of advanced security sensor technologies will also increase the site's early response, increase the probability of interdiction (P_I), the probability of neutralization (P_N) of an adversary, and raise the overall effectiveness of the physical security system (P_E).

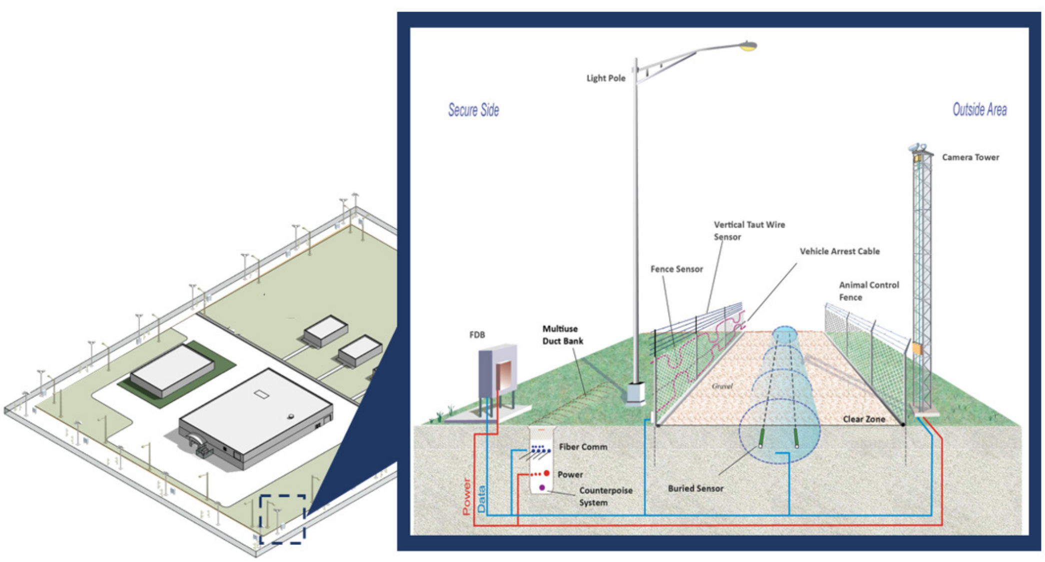


Figure 32. Example of a high security facility with the traditional two fence lines and intrusion detection system.

The research into barrier system technologies is expected to improve system effectiveness and increase the time necessary for an external adversary to intrude or commit a sabotage action. For example, a technology that can be used to integrate both advanced sensors and barrier systems is technical embroidery (i.e., Sensors and Textiles Innovatively Tailored for Complex, High-Efficiency Detection – [STITCHED]). STITCHED is an emerging technology which can, for example, be used to attach wire, fiber optics, and tubes to various substrate materials for use in delay barriers (e.g., a ballistic barrier which has integrated detection and delay attributes); see Figure 33 for examples. This research explores advances in sensor and barrier technologies to include available commercial-off-the-shelf sensor and barrier materials, for novel use in security applications at nuclear power plant sites. Where technology has not been developed to support security needs, R&D is being performed to develop these needed sensors and barrier systems. This research is being performed in collaboration with Xcel Energy, Arizona Public Service, Entergy, Constellation, and American Electric Power.

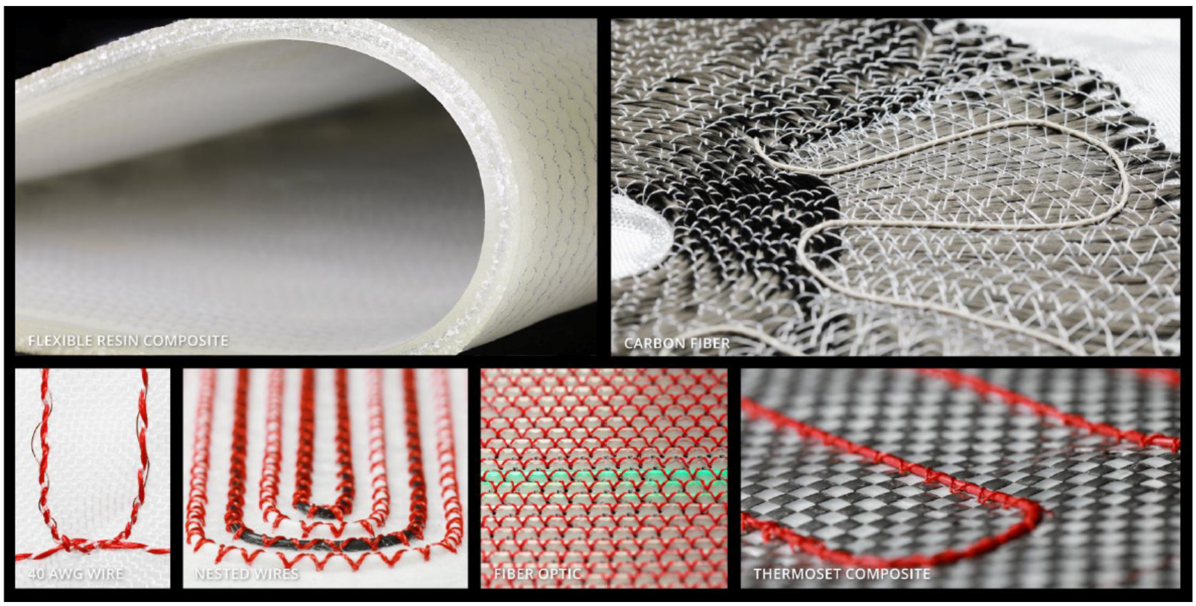


Figure 33. Examples of STITCHED technologies; flexible resin composite, carbon fiber, 40 AWG wire, nested wires, fiber optic and thermoset composite.

Research Accomplishments:

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

The LWRS Program has been conducting research on deliberate motion analytics (DMA) with the goal of developing an improved, low-cost, rapidly deployable detection and assessment technology for nuclear utility sites. It could also be used as an early warning system in unengineered terrain. DMA leverages the concept of complimentary sensor fusion, which can take input from multiple sensors of different types (including radar and optical devices), analyze the data, and determine if an adversary is making an approach toward a facility; see Figure 34 as an example. In this figure, the blue and yellow dots are active radar and thermal cameras, respectively, where the motion path is tracked from the perimeter towards the protected area; the alarm is issued (red dots) after the active radar and thermal camera detect enough deliberate motion towards the protected area. Additionally, the application of DMA with sensor fusion for application in LWR physical security postures potentially provides reductions in nuisance and false alarms for the industry.

The 2023 research focused on a pilot study of a DMA sensor system at the Waterford-III nuclear power plant site in Killona, Louisiana. This site was selected because of the different terrain, foliage, weather patterns, and wildlife compared to the high desert environment where DMA was initially tested at Sandia National Laboratories (New Mexico), and the cold winter environment of the DC Cook nuclear power plant site at Bridgman, Michigan, which participated in a pilot study in 2022. The system tested at Waterford-III integrates a long-range radar, a short-range radar, visible wavelength pan-tilt-zoom imagers and a bi-spectral pan-tilt-zoom imager. This research introduced the "Virtual Sector" DMA concept, allowing for the creation of continuous lines of detection or discontinuous isolated trip wires at critical adversary pathways. Additionally, the research effort also identified the anticipated steps necessary to commercialize the DMA technology and evaluates the concept of a "High Security Technology Readiness Level" model that can be used to assess the maturity of the DMA technology against requirements for commercial use.

The impact of this research effort is that security sensor fusion linked with DMA can take input from multiple sensors of different types, analyze the data, and determine if an adversary is making an approach toward a facility. Sites using current commercial-off-the-shelf sensor technologies typically experience elevated NARs not caused by an intruder. Through sensor fusion and DMA, a nuclear utility site can maintain a low NAR while being able to detect intruders and has the potential to decrease the cost of security by crediting early warning zones (a secured owner-controlled area) for NRC-specified intruders.

Figure 34. Active radar (blue) and thermal camera (yellow) fused through DMA showing both nuisance data and adversary track data; the red dots are the alarm indication.

Research Accomplishment:

A Cyber-hardened, Jam-resilient Wireless Communications Technology – CARBON Wireless

This research is creating state-of-the-art, cyber-hardened, jam-resilient wireless communication technologies to provide an alternative or adjunct to trenched or buried fiber and/or copper transmission lines for robust wireless communications in nuclear security applications. Buried transmission lines, while suitable for secure communications and data transfer, can be costly and lack flexibility for any temporary or permanent site reorientations. While wireless technologies have been maturing in recent years to the point that offers a cost-effective and viable alternative to trenched or buried communication lines, there are additional security objectives to consider. Because wireless signals are available in the open air, adversaries could potentially eavesdrop on wireless signals, allowing them access to physical security information to which they would not otherwise have access. While hardwire lines are not impervious to eavesdropping, they do represent more of a challenge to access. Additionally, encryption of both buried and wireless signals may offer sufficient protection against eavesdropping adversaries, yet wireless signals may be held to a higher level of protection.

Availability was another key issue addressed for wireless information systems. A buried transmission line remains a reliable means of transmission unless the line is either broken, intentionally or unintentionally, or becomes otherwise unavailable due to aging and degradation or other environmental factors. Wireless systems, on the other hand, may be prone to wireless interference issues such as radio frequency (RF) noise, interference from other systems that share the RF spectrum, or intentional RF jamming. While there are several factors that could result in a lack of availability for wireless transmissions, certain wireless architectures, such as mesh radio systems, allow for multiple paths that wireless data could take, but they are by no means 'jam proof.' If enough 'noise' is found at a radio location, that radio may find no available path for which to route its data in the wireless network, resulting in data loss. To resolve the availability issue, multiple and diverse frequencies can be utilized to create independent radio pathways for data to flow. This is basically the hard-wired equivalent of multiple, redundant lines that are required for the wired transmission of critical nuclear security data. In addition to frequency, independent pathways can be obtained through differing radio architectures mesh, point-to-point (PTP), point-to-multipoint (P2MP) or differing polarizations, beam steering, and others; see Figure 35 as an example.

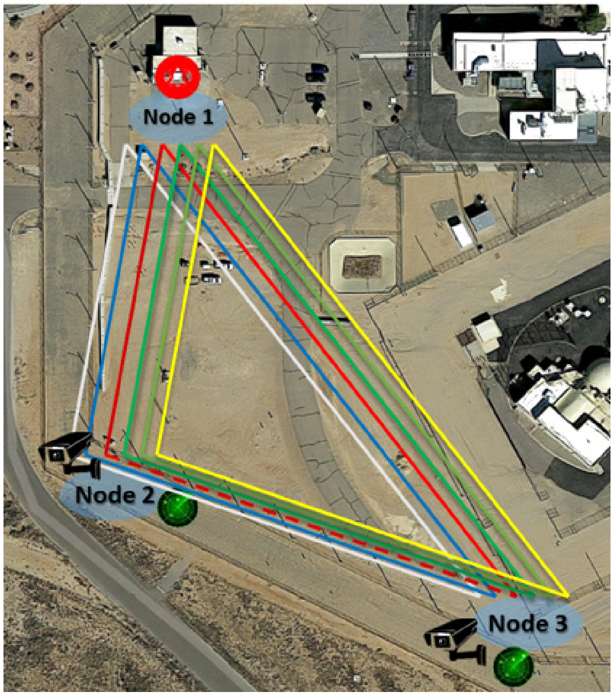


Figure 35. Example of CARBON Wireless Nodes using multiple, diverse underlay networks to transmit the same data streams.

In 2023, CARBON research conducted the initial evaluation of various radio options for the secure wireless transport of communications. It considers current requirements for nuclear power plant site physical security wireless communications systems and performs preliminary assessments on existing hard-wired communication requirements as they translate over to wireless environments. Keeping these security requirements in mind, CARBON Wireless solutions identify either wireless radios and/or wireless networking solutions, that could provide site wireless communication at much lower price points than trenching and burying hard-wired communication cables. The research aim is that, when applied properly, the CARBON Wireless solutions can approach the reliability and security of a nuclear utility site's wired-systems counterparts for the system is intended to provide secure, highly available, and jam and interference resistance communications while offering significant price reductions compared to existing systems.

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

During periods of long-term operation, it is vital to understand aging and degradation processes that affect key SSC that are vital to the safe operation of nuclear power plants. The materials used in nuclear power plants face many challenges due to the harsh environment of the operating reactor. They must withstand high-temperature water, stress and vibration, and a high level of neutron radiation. These factors can cause the materials to degrade over time, affecting their performance and reliability. If the degradation is not predicted or prevented, it can result in unexpected and costly repairs or failures of the components during service.

The primary and secondary systems of the reactor contain more than 25 different metal alloys, as well as other materials such as concrete, containment vessels, I&C equipment, cabling, and other support structures. Material degradation in a nuclear power plant represents the effects of complex phenomena that depend on the type of material, the environmental conditions, the stress states, and other factors. In a simplified form, Figure 36 shows the phenomena that can affect the performance of materials in complex and synergistic ways, which can have implications for plant operation, safety, and performance. Moreover, unexpected failures or the unnecessary repair of components due to overly conservative estimates of degradation can increase operational costs.

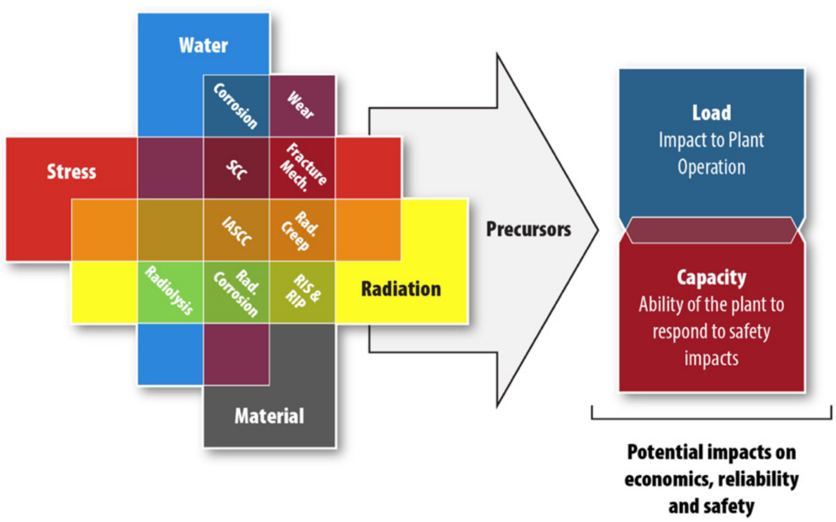


Figure 36. Complexity of interactions between materials, environments, and stresses in a nuclear power plant. Stress corrosion cracking (SCC), irradiation-assisted stress corrosion cracking (IASCC), radiation-induced segregation (RIS), radiation-induced precipitation (RIP).

To ensure the safe and reliable operation of existing nuclear power plants beyond 60 years, it is essential to understand how these materials and components behave over time and how their performance affects the different SSCs. The LWRS Program Materials Research Pathway conducts research to provide data, models, methods, and techniques that can help industry assess and manage long-term materials performance. In 2023, this Pathway focused on the following areas to address materials aging and degradation: (1) SCC of metal alloys, (2) reactor pressure vessel surveillance capsule harvesting, (3) concrete degradation modeling, and (4) cable aging and gap analysis.

2.2.1.1 Evaluating the Feasibility of Replacing pH-control Agent in Pressurized Water Reactors with Cheaper and More Available Alternatives

Materials in primary systems of western-designed PWRs contain Lithium Hydroxide (LiOH). Lithium is present in its isotope lithium-7 (Li-7) form, a component that controls pH to mitigate corrosion and minimize in-core crud deposition. Replacing LiOH with Potassium Hydroxide (KOH) has been considered by both domestic and international PWR utilities and vendors due to the high cost and low availability of Li-7 isotope. However, the impact of KOH on the structural materials used in the reactor internals is a concern, especially since it is not well known how nickel-based (Ni-based) alloys react to KOH water chemistry. LWRS Program researchers at Pacific Northwest National Laboratory (PNNL) are collaborating with the EPRI to support its KOH Qualification Program. They assess the materials degradation risk of KOH PWR water chemistry compared to LiOH PWR water chemistry. As part of this program, PNNL is performing SCC tests to evaluate the effect of KOH on the SCC behavior of Ni-based alloys. The test materials and water chemistries were selected in consultation with EPRI to fill the gaps in EPRI's KOH Qualification Program. Two high-strength Ni-based alloys, Alloy X-750 and Alloy 718, are commonly used in PWR structural support applications such as springs and fasteners. They were evaluated in 2021–2022 and the results were reported in two previous milestone reports. [30, 31] In 2023, the SCC initiation and crack growth tests were completed on the final material evaluated in this task, Alloy 82, which is commonly used as the compatible weld metal in various pressure boundary components in PWRs.

Research Accomplishment:

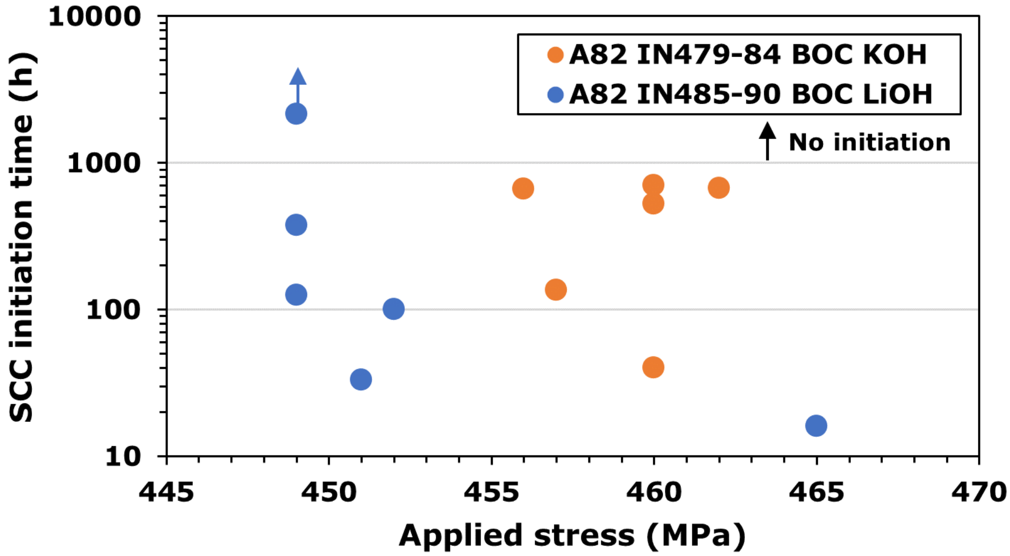
Demonstrated that KOH is a Safe, Cheaper, and More Available Alternative to LiOH for pH- Control in Pressurized Water Reactors

A 2023 study examined the SCC behavior of a first-generation, Ni-based weld metal, Alloy 82. Six Alloy 82 specimens were exposed to 360°C PWR primary water with 1,500 parts per million (ppm) boron and either 2.2 ppm lithium or 12.4 ppm potassium and loaded at yield stress. A direct current potential drop (DCPD) technique was applied to detect SCC initiation time in these specimens.

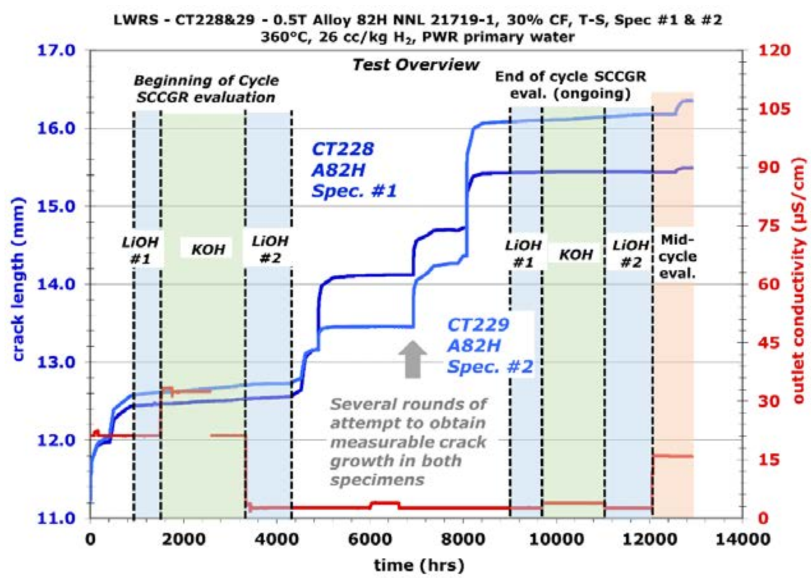
As shown in Figure 37a, except for one specimen that did not show SCC initiation after 2,152 hours of exposure, all specimens showed similar SCC initiation time within ~700 hours, whether tested in KOH- or LiOH-containing PWR primary water. SCC growth behavior was also investigated on two 30% cold forged Alloy 82 compact tension specimens. SCC crack growth rates on the two specimens were obtained during transitions between LiOH and KOH.

The data shown in Figure 37b showed no significant difference in SCC crack growth rate in KOH vs. LiOH in each water chemistry, nor on changing among the three water chemistries. The findings of the LiOH vs. KOH SCC comparison study support the EPRI's KOH Qualification Program. Combining with data collected previously on Alloy X-750 and Alloy 718 with the current observations on Alloy 82, it is determined that switching LiOH with KOH would not negatively affect the SCC initiation or growth behavior of these materials in PWR primary water.

This research supports the PWR industry initiative of replacing LiOH with a safe, cheaper, and more available pH-control agent, i.e., KOH. In fact, the Sequoyah Unit 1 reactor is scheduled to commence an industrial trial for such replacement in 2025, marking the first-ever attempt for a western PWR plant.



(a)



(b)

Figure 37. SCC initiation time comparison for Alloy 82 in LiOH vs. KOH in (a) and SCC crack growth rate evaluation of Alloy 82 in LiOH vs. KOH in (b).

2.2.1.2 High Fluence Surveillance Capsule Harvesting at Palisades Nuclear Power Plant to Support Accessing the Integrity of Reactor Pressure Vessels for Long-term Operation

One of the main challenges in extending the lifespan of U.S. nuclear power plants is to assess the integrity of the reactor pressure vessel (RPV), which is exposed to radiation and thermal stresses. To obtain reliable data on the degradation of RPVs, different approaches are employed. This includes irradiating specimens in test reactors, installing surveillance capsules inside the RPV, measuring the variation of properties across the RPV wall, accounting for the differences in neutron flux between surveillance and harvested materials, and correcting the bias between test methods and actual conditions. These approaches help to calibrate transition-temperature-shift models and PRA models (i.e., pressurized thermal shock), which are essential for predicting the safety margins of RPVs. Among these methods, harvesting and testing of ex-service and surveillance materials provide a unique opportunity to address scientific knowledge gaps and validation of predictive degradation models.

Research Accomplishment:

Completed the Retrieval of a Unique and Highly Valuable Surveillance Capsule from Decommissioned Palisades Nuclear Power Plant to Assess Reactor Pressure Vessel Embrittlement Behavior

The Palisades Nuclear Generating Station (PNGS) was an operating nuclear power plant located in Covert Township, Michigan. Equipped with a single pressurized water reactor, the plant served as a crucial source of electricity for the surrounding region. After more than four decades of active service, PNGS ceased operations in 2022 and transferred the plant ownership to Holtec International for the purposes of decommissioning. However, Holtec is actively working with the Michigan state government and other power generation cooperatives to restart the shuttered Palisades plant. As part of its comprehensive surveillance program, PNGS incorporated a dedicated surveillance capsule, denoted as A-60. The capsule housed specimens of welded metal characterized by a nickel content of approximately 1.36 wt% (weight percentage) and a copper content of around 0.20 wt%. Originally positioned within the surveillance system, the A-60 capsule was removed from its surveillance position in 1995 and has since resided in the onsite spent fuel pool. Subjected to irradiation at a fluence of 1.87×10^{20} n/cm^2 (E > 1MeV), equivalent to over 120 effective full power years (EFPY) for the U.S. RPV fleet, the material within the A-60 capsule is of particular interest. Its distinguishing features include an exceptionally high nickel content and the potential for the development of NiMnSi (nickel-manganese-silicon) precipitates which contribute to RPV embrittlement. Given the unique combination of very high fluence and elevated nickel and copper content, the material in the A-60 capsule holds significant importance as a benchmark for the ongoing development of embrittlement trend curves (ETC). These curves aim to predict embrittlement at high fluences, making the A-60 capsule a valuable resource in this research endeavor.

In 2019, recognizing its potential, the LWRS Program initiated negotiations with Entergy (the utility company that operated PNGS) to harvest the A-60 capsule. Despite lacking regulatory interest for PNGS, the capsule was deemed crucial for LWRS Program's efforts in developing ETC for very long-term operation, since this will be the only surveillance data point that corresponds to more than 120 EFPY and thus providing a unique benchmarking opportunity for any long-term ETC model. Following the transition of PNGS ownership to Holtec International in June 2022, which proved supportive of LWRS Program initiatives, negotiations resumed. Consequently, a contract was established with the Westinghouse Electric Company (WEC) to retrieve the A-60 capsule from the PNGS site. The capsule was transported to the WEC Churchill hot cell facility, where it was opened, and all surveillance specimens within the capsule were sent to Oak Ridge National Laboratory (ORNL) for future characterization. Figure 38 highlights several key steps for the surveillance capsule harvesting process. ORNL staff will perform mechanical testing of these surveillance materials after such high neutron fluence exposure. This includes the following tests: tensile, Charpy impact, fracture toughness, hardness, and state-of-the-art microstructural characterization using Atom Probe Tomography..

Figure 38. (a) View of Palisades nuclear power plant, (b) operation inside the spent nuclear fuel pool, (c) retrieve the cask loaded with the surveillance capsule, (d) specimen sorting and inventory inside the hot cell.

2.2.1.3 Modeling Concrete Degradation

In the context of LWRs, the concrete biological shield (CBS) refers to the concrete structure positioned directly opposite the RPV. The primary purpose of the CBS is to shield equipment and personnel from the neutron and gamma radiation emanating from the RPV. Additionally, many CBSs in operation in the U.S. serve the dual function of providing structural support to the RPV. Ensuring the long-term structural integrity of the CBS involves considerations for transferring in-service passive loads to the foundation, dynamic loading during seismic events, and thermal loading during a loss-of-coolant accident (LOCA). Long-term structural analyses are conducted to verify these functions. Test reactor data indicates that the mechanical properties of irradiated concrete are notably affected when exposed to neutron fluence higher than approximately 10^{19} n/cm^2 (E > 0.1 MeV). For CBS, this would result in irradiation-induced cracks and spalling on the concrete surface. After 80 years of operation, fluence estimates at the CBS surface range between 1×10^{19} and 7×10^{19} n/cm^2 (E > 0.1 MeV). Despite the attenuation of fluence through the CBS due to the shielding properties of concrete, approximately 5% to 10% of the CBS wall depth is impacted by high fluence. The primary degradation mechanism observed is known as radiation-induced volumetric expansion (RIVE). It induces significant deformations and diminishes the structural properties of concrete.

The LWRS Program developed the Microstructure Oriented Scientific Analysis of Irradiated Concrete (MOSAIC) software[g] to perform long-term irradiation damage modeling on CBS. MOSAIC elucidates the response of concrete and its components to a spectrum of factors, including temperature, moisture, constraint, radiation, creep, and composition variations over an extended irradiation period. It integrates extensive datasets, including compositional and phase microscopy, materials properties, and evolving versions of constitutive models. MOSAIC can simulate concrete damage induced by RIVE. The materials considered in this modeling endeavor are heterogeneous, encompassing both the paste and aggregates (rocks), comprising multiple minerals and various phases of the same minerals. This diversity introduces complexity to the constitutive model. Furthermore, MOSAIC is equipped to tackle dimensional challenges on the micron scale, addressing both 2D and 3D issues. This capability adds an additional layer of intricacy to the combined constitutive model, allowing for a comprehensive understanding of long-term irradiation damage on CBS due to RIVE.

Research Accomplishment:

Developed and Published a Guideline on How to Model Concrete Degradation and a Software Tool Called MOSAIC for Industry Use

The outcomes of this modeling and simulation endeavor offer the industry a user-centric procedural guide for determining RIVE in concrete exposed to fast-neutron irradiation. This is achieved using the MOSAIC code and the characterization of aggregate materials. The estimated RIVE for concrete can be derived by multiplying the aggregate RIVE by the volume fraction of aggregate in the mix, a value typically around 0.70.

The comprehensive methodological steps are succinctly presented in the flowchart depicted in Figure 39. Ideally, this methodology is designed to be executed using advanced characterization techniques, including electron microscopy and X-ray devices (indicated in the left branch of the flowchart). However, acknowledging potential limitations such as restricted access to these instruments or harvested material, an alternative approach utilizing only mineral composition information is also permissible (outlined in the right branch of the flowchart). The primary output of this guideline is to procure dependable RIVE properties for both aggregate and concrete, specifically tailored to the chemical composition of the concrete under investigation.

The results of this modeling and simulation effort will provide industry with a tool to assess potential concrete degradation at extended lifetimes and is expected to reduce uncertainty in regulatory safety margins. In addition, this methodology can be used as a part of an aging management program and evaluation methods in the context of subsequent license renewal.[h]

[g] Software link: https://code.ornl.gov/MOSAIC/mosaic

[h] For example, the EPRI’s report 3002011710 on “Irradiation Damage of the Concrete Biological Shield: Basis for Evaluation of Concrete Biological Shield Wall for Aging Management”, https://www.epri.com/research/products/3002011710

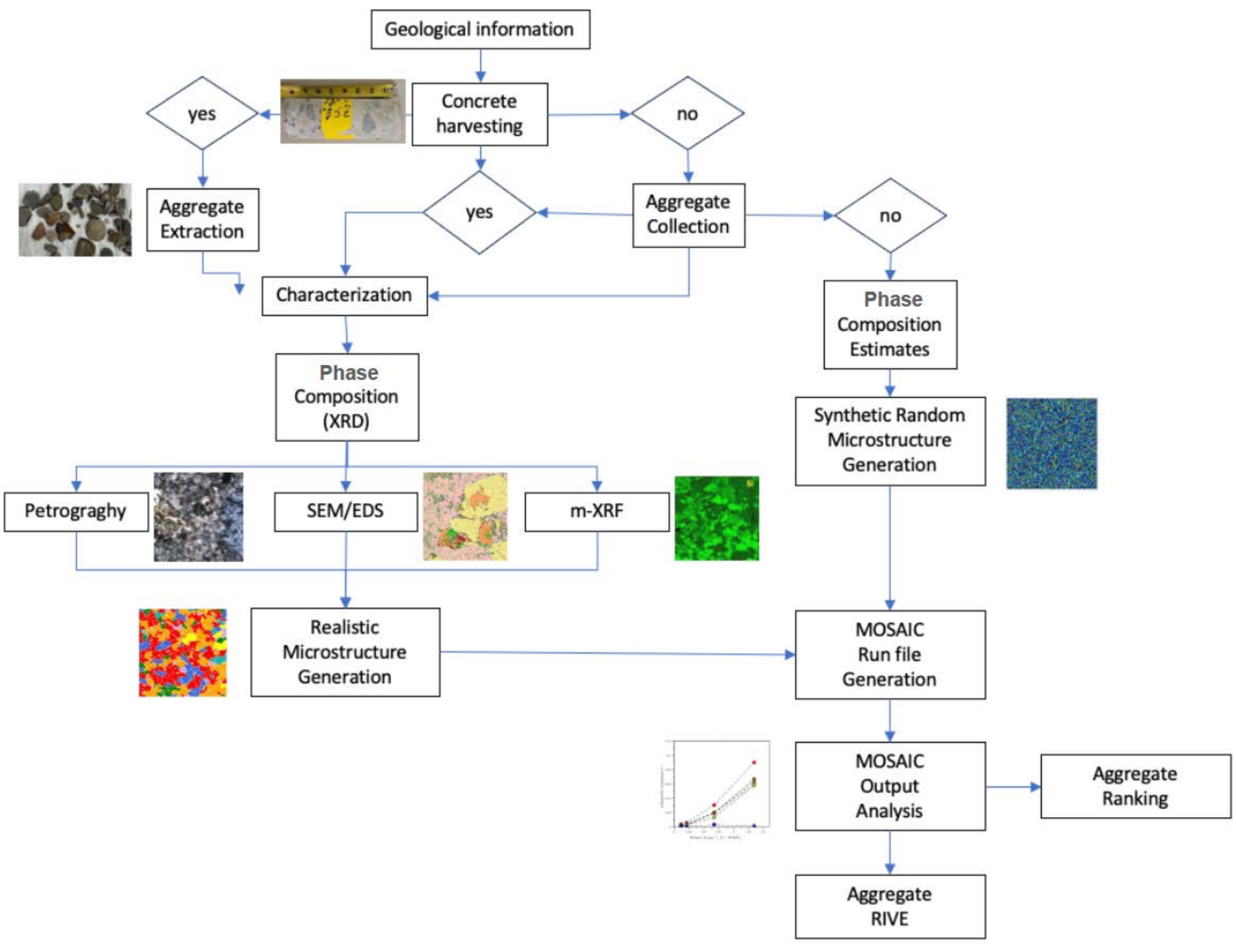


Figure 39. Guidelines on irradiation degradation assessment based on predictive models. X-ray diffraction (XRD), Scanning Electron Microscopy/energy dispersive X-ray spectroscopy (SEM/EDS), micro-X-ray fluorescence (m-XRF), MOSAIC, RIVE.

2.2.1.4 Analyzing Cable Aging in Nuclear Facilities

This research initiative is dedicated to the thorough testing and characterization of both naturally aged nuclear electrical cables and cables deliberately subjected to accelerated aging. The overarching goal is to enhance our understanding of the material changes that occur in cables because of aging, and to discern the implications of these changes on the long-term performance of cable systems. By gaining a predictive understanding of degradation behavior, the research aims to provide the foundation for informed cable aging management strategies. This includes offering guidance on the direction and interpretation of cable inspections, as well as facilitating optimized decisions regarding cable repair and replacement. A key focus of this LWRS Program study is on specific cable insulation materials, with particular attention given to cross-linked polyolefin (XLPO) and ethylene-propylene-rubber (EPR). These materials have been identified as the highest priority for in-depth analysis due to their widespread usage in nuclear electrical cables. Through this comprehensive exploration, the research seeks to contribute valuable insights into the aging dynamics of these materials, ultimately supporting the development of robust cable aging management practices within the nuclear electrical infrastructure.

Research Accomplishment:

Completed Assessment of Knowledge Gaps to Better Understand the Aging of Cables and Cable Systems in Nuclear Power Plants

The Expanded Materials Degradation Assessment (EMDA) is a comprehensive materials degradation assessment conducted by NRC examining a wider scope of SSCs, such as core internals, piping systems, the RPV, electrical cables, and concrete and civil structures covering an analytical timeframe of 80 years operation of LWRs. The identified knowledge gaps within EMDA Vol. 5 (Aging of Cables and Cable Systems) highlight concerns about the assumptions underpinning the 40-year environmental qualification (EQ) of cables. These concerns encompass the potential weakness of these assumptions, the suggestion that pre-aging of cables prior to LOCA testing might not truly represent a 40-year equivalence, and the resulting possibility that the EQ process may lack conservatism, potentially leading to an overestimation of cable useful lifetime. Although cable failures were relatively scarce during the initial 40-60 years of plant operation, the apprehension is that the lack of conservatism in the 40-year qualification may become a more significant issue when extending licensing to 80 years. Subsequent research, conducted by the LWRS Program and others following the publication of EMDA Vol. 5, indicates that the assumptions related to the Arrhenius and equal dose/equal damage principles of thermal and radiation aging behavior—upon which the historical qualification process was based—hold true for certain cable materials, accelerated aging conditions, and performance metrics, but not for others (e.g., Figure 40 shows that cross-linked polyethylene (XLPE) material clearly exhibited an inverse temperature effect (ITE) while an ethylene propylene diene monomer (EPDM) material did not show significant ITE).

These findings support the understanding that the concerns identified with historical cable qualification do not represent generic concerns for continued safe use of existing qualified cables into the subsequent license renewal period. Qualification was indeed conservative for many of the cable materials and conditions considered. The research by the LWRS Program and others on EMDA knowledge gaps does, however, emphasize inherent limitations in long-term cable performance prediction-based on accelerated aging alone.

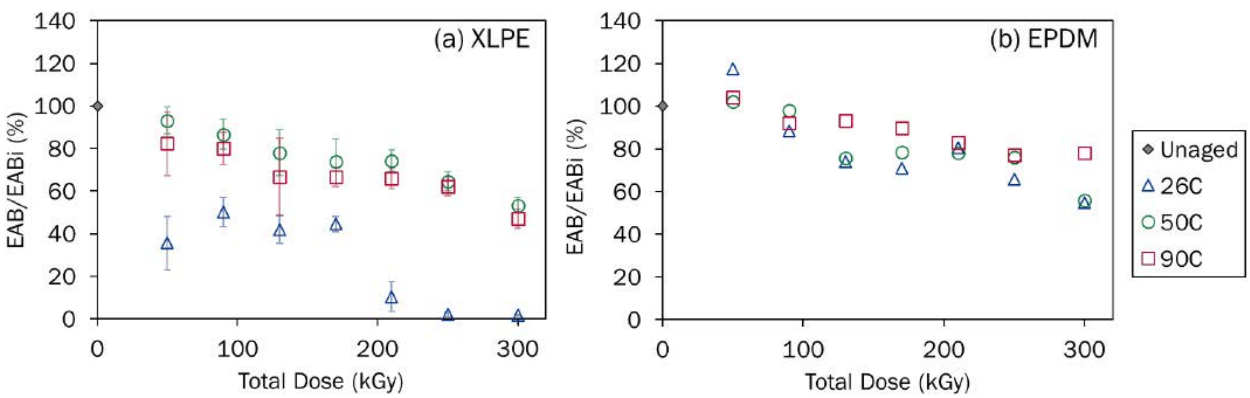


Figure 40. Normalized elongation at break of (a) XLPE and (b) EPDM aged at 100 Gy/h and 26°C, 50°C, 90°C. [32]

Cable performance has a complex dependence not only on cable insulation material class and service environment history, but also on manufacturer formulation, batch, cable treatment history and other factors. Considering this observation and these results, several paths forward toward ensuring continued safe operation of existing cables during prolonged operation present themselves:

1. Continued research into the effects of individual and combined environmental stresses of cable insulation performance through accelerated aging and characterization of harvested materials. Targeted efforts in accelerated aging and analysis of harvested materials will continue to be needed but must be evaluated in the context of the inherent limitations of the results.
2. Improved predictive understanding of the effects of environmental exposure on cable material properties by using modeling and simulation to anticipate future performance from current state. Considering progress in efforts in recent years to understand aging of concrete with similar challenges, modeling and simulation of cable material aging is worth pursuing but will take time to develop.
3. Condition-based rather than time-based decision-making in which testing is widely used to ensure continued cable performance. Basing repair, replace and test again decisions on cable diagnostics has the potential to overcome limitations of accelerated aging qualification-based assumptions and reduce costs associated with unnecessary testing and replacement.

2.2.1.5 Human and Technology Integration

A significant barrier to digital safety-related digital I&C upgrades has been the lack of practical guidance addressing human factors engineering (HFE) implementation. HFE is the process of evaluating and optimizing the introduction of technology while ensuring safety and reliability are not negatively impacted. This is critical to obtaining regulatory approval of an operating license amendment request for such upgrades. Collaborating with Constellation Energy, LWRS Program researchers addressed this barrier by developing and executing a first-of-a-kind HFE method enabling regulatory approval for safety-related digital I&C upgrades.

Research Accomplishment:

Completed First-of-a-kind Human Factors Engineering Methods to Enable U.S. Regulatory Approval for Safety-Related Digital I&C Upgrades

One of the key challenges for modernization is ensuring modernization efforts do not negatively impact plant performance. Human and Technology Integration (HTI) research delivers methods and tools for ensuring effective modernization and providing validated methods for work optimization. In 2023, LWRS Program researchers working with multiple utility partners (Dominion, Southern Nuclear Co., Constellation Energy, Westinghouse, and Sargent & Lundy) effectively demonstrated this type of HFE control room modernization guidance. One of the key research activities included LWRS Program researchers and Constellation Energy demonstrating a method to execute HFE-related verification and validation efforts. The successful outcome enabled Constellation Energy to use the NRC's alternate review process for Limerick Generating Station's safety-related I&C upgrades (Figure 41) in alignment with the NRC Digital I&C Interim Staff Guidance (DI&C-I&C-06). This method was demonstrated through the careful planning and execution of a conceptual verification in December 2022 and a preliminary validation in February 2023, both of which were conducted at INL's Human Systems Simulation Laboratory. Notably, the NRC audited the preliminary validation activity, further underscoring its significance.

Key:

1 – Upgraded Distributed Control System Annunciator Panels

2 – New Distributed Control System Group View Display Visual Display Units (also referred to as Head-Up Displays)

3 – Reactor Operator '5-Pack' Workstation, including four divisionalized Safety Visual Display Units and one Distributed Control System Visual Display Unit

4 – Plant Reactor Operator '5-Pack' Workstation

Figure 41. Limerick Generating Station Main Control Room Layout Used in Preliminary Validation.

The successful completion of these activities, accompanied by the production of accessible reports, served to fulfill commitments made by Constellation to the NRC, reinforcing the appropriateness of the proposed Licenses Amendment Request approach. Importantly, non-proprietary versions of the conceptual verification and preliminary validation reports from both activities have been made available to the public. Additionally, a related research report detailing the demonstration and evaluation of human-technology integration guidance for plant modernization was generated, along with an all-encompassing lessons learned report to disseminate the knowledge gained (see Table 1). These remarkable efforts have not only set a new industry standard in this domain but have also provided invaluable support for the Department of Energy's $50 million cost-sharing initiative for control room modernization. This collection of accomplishments represents a key step in the transformation of commercial nuclear energy.

Table 1. Technical and Lessons Learned Reports Associated with the Limerick Safety-Related Digital I&C Upgrade.

Technical and Lessons Learned Reports Associated with the Limerick Safety-Related Digital I&C Upgrade	
Technical Reports	
Document ID	Title
INL/EXT-20-61079	Vendor-Independent Design Requirements for a Boiling Water Reactor Safety System Upgrade Vendor-Independent Design Requirements for a Boiling Water Reactor Safety System Upgrade (S&T Accomplishment Report) | OSTI.GOV
INL/EXT-20-59371	Business Case Analysis for Digital Safety-Related Instrumentation & Control System Modernizations Business Case Analysis for Digital Safety-Related Instrumentation & Control System Modernizations (Technical Report) | OSTI.GOV
INL/RPT-22-68693	Human Factors Engineering Program Plan for Constellation Safety-Related Instrumentation and Control Upgrades. Starting at.pdf page 780 at the following link: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML23255A095

Technical and Lessons Learned Reports Associated with the Limerick Safety-Related Digital I&C Upgrade	
Technical Reports	
Document ID	Title
INL/RPT-22-68995	Human Factors Engineering Combined Functional Requirements Analysis, Function Allocation, and Task Analysis for the Limerick Control Room Upgrade: Results Summary Report. Starting at.pdf page 831 at the following link: https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML23255A095
INL/RPT-23-71063	Limerick Safety-Related Instrumentation and Control Upgrade Human Factors Engineering Conceptual Verification Report Limerick, Units 1 and 2, Supplement to License Amendment Request to Revise the Licensing and Design Basis to Incorporate the Replacement of Existing Safety-Related Analog Control Systems with a Single Digital Plant Protection System (PPS)- Human Factors (nrc.gov)
INL/RPT-23-71903	Limerick Safety-Related Instrumentation and Control Upgrade Human Factors Engineering Preliminary Validation Report Limerick Generating Station, Units 1 and 2 - Supplement to License Amendment Request to Revise the Licensing and Design Basis to Incorporate the Replacement of Existing Safety-Related Analog Control Systems with a Single Digital Plant Protection..... (nrc.gov)
Lessons Learned Reports	
Document ID	Title
INL/EXT-20-59809	Safety-Related Instrumentation and Control Pilot Upgrade: Initial Scoping Phase Implementation Report and Lessons Learned Safety-Related Instrumentation & Control Pilot Upgrade Initiation Phase Implementation Report (S&T Accomplishment Report) | OSTI.GOV
INL/RPT-23-72105	Safety-Related Instrumentation and Control Upgrade: Conceptual – Detailed Design Phase Report and Lessons Learned Safety-Related Instrumentation and Control Pilot Upgrade: Conceptual - Detailed Design Phase Report and Lessons Learned (Technical Report) | OSTI.GOV
INL/RPT-23-71395	Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques Demonstration of the Human and Technology Integration Guidance for the Design of Plant-Specific Advanced Automation and Data Visualization Techniques (Technical Report) | OSTI.GOV

3. REFERENCES

1. U.S. Department of Energy (DOE), 2021, *Office of Nuclear Energy: Strategic Vision*. Available at: https://www.energy.gov/sites/default/files/2021/01/f82/DOE-NE%20Strategic%20Vision%20-Web%20-%2001.08.2021.pdf (accessed 28 February 2024).
2. Huff, K., 2021, "Saving Existing Nuclear Fleet Brings Net-Zero Future Closer," Energy.gov website, 6 December 2021. Available at: https://www.energy.gov/articles/saving-existing-nuclear-fleet-brings-net-zero-future-closer (accessed 28 February 2024).
3. Hallbert, B. P., and K. D. Thomas, 2020, "Sustaining the value of the U.S. nuclear power fleet," *The Bridge: Nuclear Energy Revisited*, Fall 2020, 50(3), 15 September 2020. Available at: https://www.nae.edu/239486/Sustaining-the-Value-of-the-US-Nuclear-Power-Fleet (accessed 28 February 2024).

4. Derr, E., 2021, "Bipartisan Infrastructure Package Includes Major Investments in Nuclear Energy," Nuclear Energy Institute, 9 November 2021. Available at: https://www.nei.org/news/2021/infrastructure-package-major-investments-nuclear (accessed 28 February 2024).

5. U.S. Department of Energy (DOE), 2021, "Secretary Granholm Launches 'Hydrogen Energy Earthshot' to Accelerate Breakthroughs Toward a Net-Zero Economy," DOE website, 7 June 2021. Available at: https://www.energy.gov/articles/secretary-granholm-launches-hydrogen-energy-earthshot-accelerate-breakthroughs-toward-net (accessed 28 February 2024).

6. U U.S. Department of Energy (DOE), 2024, "Civil Nuclear Credit Award Cycle 1," DOE website, 17 January 2024. Available at: https://www.energy.gov/gdo/civil-nuclear-credit-first-award-cycle (accessed 28 February 2024).

7. World Nuclear Association, 2024, "California's Electricity," World Nuclear Association, January 2024. Available at: https://world-nuclear.org/information-library/country-profiles/others/californias-electricity.aspx (accessed 28 February 2024).

8. U.S. Department of Energy (DOE), 2023, "Industrial Heat Shot," DOE website. Available at: https://www.energy.gov/eere/industrial-heat-shot (accessed 28 February 2024).

9. Kelly J. E., and N. Wilmshurst, 2015, "Memorandum of Understanding between the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI) on Cooperative Nuclear Power Research," 15 December 2015.

10. Furstenau, R. V., and A. Caponiti, 2021, "Addendum No. 4 to the Memorandum of Understanding between the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission on Cooperative Nuclear Safety Research Related to Light Water Reactor Sustainability,"30 March 2021.

11. U.S. Energy Information Administration (EIA), 2022, "Renewable Energy Requirements and Incentives," EIA website, 30 December 2022. Available at: https://www.eia.gov/energyexplained/renewable-sources/incentives.php (accessed 28 February 2024).

12. Jenkins, J.D., Zhou, Z., Ponciroli, R., Vilim, R.B., Ganda, F., de Sisternes, F., & Botterud, A. (2018). The benefits of nuclear flexibility in power system operation with renewable energy. Applied Energy, 222, 872-884.Glover, A. M., D. M. Brooks, and A. R. Baird, 2020, *Final Report on Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting near Nuclear Power Plants*, 1 October 2020, SAND2020-10828, Sandia National Laboratories, Albuquerque, NM, USA, and Livermore, CA, USA. Available at: https://doi.org/10.2172/1678837 (accessed 28 February 2024).

13. Vedros, K. G., R. Christian, and C. Rabiti, 2020, *Probabilistic Risk Assessment of a Light Water Reactor Coupled with a High-Temperature Electrolysis Hydrogen Production Plant*, 12 October 2020, INL/EXT-60104, Idaho National Laboratory, Idaho Falls, ID, USA. Available at: https://doi.org/10.2172/1691486 (accessed 28 February 2024).

14. U.S. Nuclear Regulatory Commission, 2021, "Conditions of licenses," USNRC 10 CFR 50.54(i), 18 December 2023, NRC.gov website. Available at: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0054.html (accessed 28 February 2024).

15. U.S. Nuclear Regulatory Commission, 2018, "An approach for using probabilistic risk assessment in risk-informed decisions on plant-specific changes to the licensing basis," USNRC Regulatory Guide 1.174, Revision 3, January 2018, NRC.gov website. Available at: https://www.nrc.gov/docs/ML1731/ML17317A256.pdf (accessed 28 February 2024)

16. U.S. Department of Energy (DOE) Nuclear Energy University Program (NEUP), 2022, "FY 2022 Integrated Research Projects Awards," DOE NEUP website, 31 December 2022. Available at: https://neup.inl.gov/SitePages/FY22_IRP_Awards.aspx (accessed 20 February 2023).

17. Frick, K., D. Wendt, P. Talbot, C. Rabiti, and R. Boardman, 2021, “Technoeconomic assessment of hydrogen cogeneration via high-temperature steam electrolysis with a light-water reactor,” *Appl. Energy*, Vol. 306, Part B, Art. 118044. https://doi.org/10.1016/j.apenergy.2021.118044.

18. Boardman, R. D., T. L. Westover, S. J. Remer, and L. T. Knighton, 2022, FPOG Technical Program Plan for FY 2023, October 2022, INL/RPT-22-69013, Revision 0, Idaho National Laboratory, Idaho Falls, ID, USA. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_63657.pdf (cited 20 February 2023).

19. Remer, Sherman Jason. 2022. “Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation”. INL/RPT-22-68671United States. https://www.osti.gov/servlets/purl/1894935.

20. Remer, J., Hansen, J., Kovesdi, Casey, Spielman, Z. (2023) Applying the ION Business Model to a Domestic Nuclear Plant: Assessment and Transformation Plan (INL/RPT-23-73942). Idaho National Laboratory, Idaho Falls, ID, USA. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/ION_BusinessModel.pdf#search=INL%2FRPT%2D23%2D73942%20%20%29.

21. Hunton, P.J., England, R.T., Lawrie, S., Martin, L., Pilot Business Case Analysis (BCA) for Digital Infrastructure INL/RPT-23-74393 Idaho National Laboratory, Idaho Falls, ID, USA. https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/PilotDigitalInfrastructureBCA.pdf#search=INL%2FRPT%2D23%2D74393].

22. Nuclear Energy Institute (NEI). (2023). The Future Of Nuclear Power: 2023 Baseline Survey. https://www.nei.org/CorporateSite/media/filefolder/advantages/The-Future-of-Nuclear-Power-2023-Baseline-Survey.pdf.

23. U.S. Department of Energy (DOE). (2023, March). Clean hydrogen: Pathways to commercial liftoff. https://liftoff.energy.gov/.

24. Larsen, L.M., Lawrence, S, Josek, F., Choi, Y-J, Wendt, D. S., Greschuk, M., Price, W., Federline, E., Carlone, P., Dame, C., and Womble, M.. 2023. “Assessing the Impact of the Inflation Reduction Act on Nuclear Plant Power Uprate and Hydrogen Cogeneration, INL/RPT-23-74681. https://lwrs.inl.gov/RiskInformed%20Safety%20Margin%20Characterization/HydrogenUprate.pdf#search=INL%2FRPT%2D23%2D74681.

25. Lazard. (2023, April). 2023 Levelized cost of energy. https://www.lazard.com/media/2ozoovyg/lazards-lcoeplus-april-2023.pdf.

26. Kim, J., Abdo, M., Choi, Y.-J., Gutierrez, J. C. L., Hou, J., Gosdin, C. and Valeri, J. “Pressurized-Water Reactor Core Design Demonstration with Genetic Algorithm Based Multi-Objective Plant Fuel Reload Optimization Platform,” Light Water Reactor Sustainability Program, INL/RPT-23-74498, September 2023.

27. S. Prescott, R. Christian, R. Sampath, J. Biersdorf and S. Lawrence, “Industry Level Integrated Fire Modeling Using Fire Risk Investigation in 3D (FRI3D),” Light Water Reactor Sustainability Program, INL/EXT-21-604079, 2021.

28. S. Prescott, R. Christian and R. Sampath, “FRI3D Fire Simulation Options and Verification Tasks,” Light Water Reactor Sustainability Program, INL/RPT-23-70843, January 2023.

29. S. Prescott, S. Schiavo, R. Sampath and R. Christian, “FRI3D Industry Adoption and Verification Tasks,” Light Water Reactor Sustainability Program, INL/RPT-23-74213, August 2023.

30. Zhai, Z., Toloczko, M. B., Cintron-Colon, F., & Bouffioux, R. A. (2021, September). Evaluation of stress corrosion cracking behavior of Ni-base alloys in PWR primary water containing KOH vs. LiOH (Technical Milestone Report M2LW-21OR0402036). Pacific Northwest National Laboratory: Light Water Reactor Sustainability Program, DOE Office of Nuclear Energy

31. Zhai, Z., Toloczko, M., Cintron-Colon, F., & Bouffioux, R. A. (2022). Stress corrosion cracking of Ni-base alloys in PWR primary water containing KOH vs. LiOH (Technical Milestone Report M3LW-22OR0402033). Pacific Northwest National Laboratory, Light Water Reactor Sustainability Program, DOE Office of Nuclear Energy. https://lwrs.inl.gov/Materials%20Aging%20and%20Degradation/StressEorrosionCrackInitiation2022.pdf.

32. Fifield, L. S., Ni, Y., Li, D., Sriraman, A., Guzman, A., Ortiz, A., Spencer, M. P., Murphy, M. K., & Zwoster, A. J. (2022). Inverse temperature effects in nuclear power plant electrical cable insulation (PNNL-33296). Pacific Northwest National Laboratory.