LWRS
LIGHT WATER REACTOR SUSTAINABILITY

Issue 39
May 2024

Supporting the Industry Cost-Saving Initiative for Longer Operating Cycles: Accident Source Term Analysis of High-Burnup Operation

Svetlana Lawrence
Idaho National Laboratory

Benjamin R. Lindley
University of Wisconsin-Madison

Risk-Informed Systems Analysis Pathway

The amount of energy produced in a nuclear power plant depends on how much uranium is burned in the reactor, a measurement called "burnup" that is expressed in gigawatt-days per metric ton (GWd/MTU) of uranium. The burnup levels have changed throughout the history of nuclear fleet operation. It was around 35 GWd/MTU two decades ago and over 45 GWd/MTU today. The increased burnup means that utilities are now using fuel more efficiently and can extract more power from their fuel before replacing it.

Continued on next page

Table of Contents

U.S. DEPARTMENT OF ENERGY

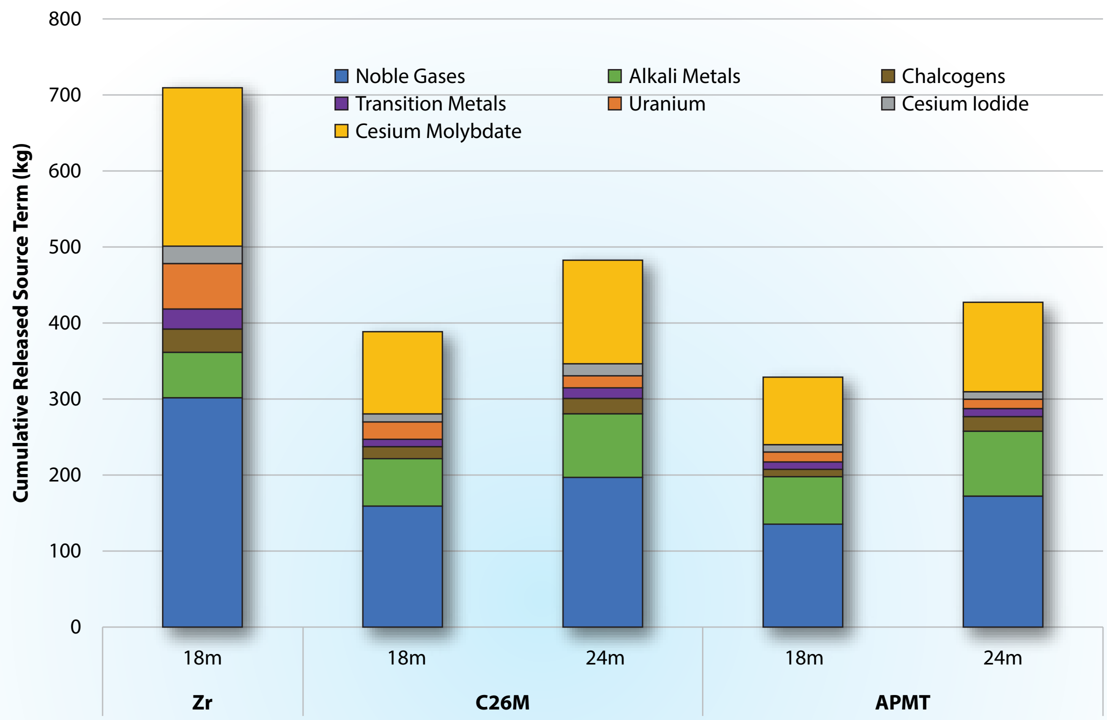


Figure 1. Cumulative released source term.

Continued from previous page

Operating nuclear power reactors at higher burnup (HBU) levels can significantly reduce costs associated with refueling and licensing, leading to substantial economic benefits for plant owners. The cost savings are twofold—first, they are due to longer operating cycles where reactors can operate longer between refueling outages, and second, because fewer fuel assemblies are subsequently required at each refueling.

HBU operation requires higher enriched uranium fuel that is more achievable with accident tolerant fuel (ATF) (e.g., Chromium [Cr] coated clad fuel compared to the traditional Zirconium [Zr] clad fuel). This is due to the more robust cladding characteristics of ATF, which allow them to cope better with postulated accident conditions. The deployment of ATFs with normal burnup is already underway in the industry, but HBU ATFs are still being evaluated to ensure their safety—especially under accident conditions. In particular, it is necessary to accurately evaluate the "accident source term," or the amount of radioactive materials that could be released from a nuclear power plant during an accident.

In this context, the LWRS Program Risk-Informed Systems Analysis (RISA) team is conducting research on the safety assessments of HBU ATF during a recovered large break loss of coolant accident of a pressurized water reactor. This topic is an urgent near-term industry initiative offering safety enhancements, as well as economic gains. The result could serve as a roadmap for the safety analyses that nuclear power plants must submit in their license amendment request to the U.S. Nuclear Regulatory Commission (NRC) when switching to new fuels [1].

Following Three Mile Island the accident in 1979, the NRC developed an extensive methodology for analyzing the consequence of a nuclear accident. This methodology considers both the timing and the chemical composition of the source term from coolant and fuel gap release to in- and ex-vessel of the source term [2]. The accident source term analysis for traditional Zr-clad fuel with HBU has been completed for burnup levels up to 62 GWd/MTU with a duration in the core from 14 to 18 months [3]. However, there is no publicly available assessment of source terms from HBU ATFs.

In the LWRS Program study, two different iron-chromium-aluminum alloy FeCrAl-clad materials (e.g., Kanthal APMT, Ironclad C26M) were selected as ATF, which have a lower high-temperature oxidation and hydrogen generation rate compared with Zr-clad fuel. Reactor cores were designed for 24-month burnup operation and compared with the 18-month case. A large break loss of coolant accident scenario as a postulated accident, with intentionally delayed activation of the emergency core cooling system, allowed reactor core damage and source term release to the reactor containment. This scenario is just one of the standard severe accident case studies from the NRC's state-of-the-art reactor consequence analysis report [4]. A reactor core was designed with a total of 193 fuel assemblies with a 17 × 17 lattice configuration for both the Zr- and FeCrAl-clad fuels and applied to a model of the Zion Nuclear Power Plant in Illinois using MELCOR, a severe accident simulation software. The decay heat and fission product inventories were calculated for both the 18- and 24-month cycle cases.

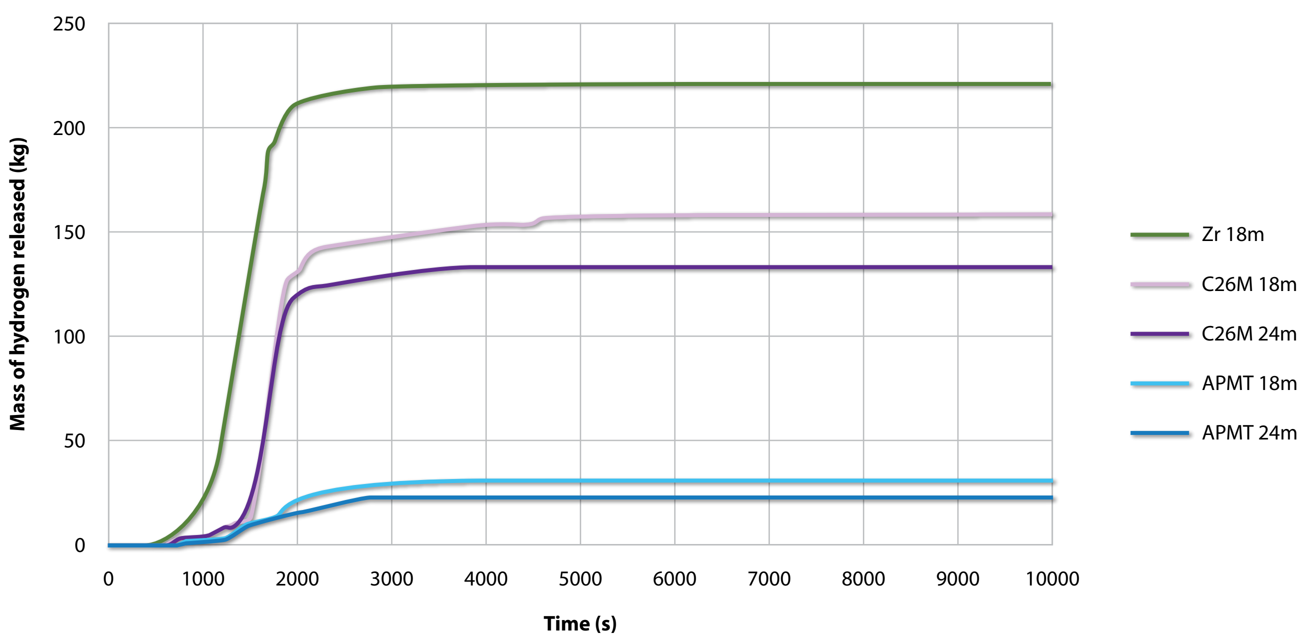
The Figure 1 shows the total mass of the cumulative released major source term during the recovered large break loss of coolant accident scenario. For all cases, noble gases (Xe, Kr, Rn, etc.) were the largest amount released from the source term, followed by cesium molybdate and alkali metals (Cs, Rb, Li, etc.). For the Zr-clad case, a large amount of uranium was found in the source term as compared with the ATF clad fuel cases.

This LWRS Program study showed the released accident source term from the ATF clad fuels is significantly smaller than from the Zr-clad fuel even in HBU operation for the accident scenario under consideration. In other words, the use of ATF clad fuels will be acceptable to current licensing requirements in terms of accident source term evaluation. In this scenario, ATF clad fuels (C26M 18m, C26M 24m, APMT 18m, APMT 24m) generate less hydrogen than Zr-clad fuel which can support mitigating hydrogen explosion risk (Figure 2). Future work will include safety analysis of a pressurized water reactor loaded with higher enriched Cr-coated Zr ATF during a recovered large break loss of coolant accident considering fuel deposition and impacts from the radioactivity release. Future work could also extend this analysis to other transients to determine whether these benefits generalize to an overall reduction in source term over a range of postulated scenarios.

References:

1. Choi, Y.-J., A. Whitmeyer, K. Franzese, and B. Lindley. 2023. "Safety Analysis of FeCrAl Accident-Tolerant Fuels with Increased Enrichment and Extended Burnup." INL/RPT-23-74731. Idaho National Laboratory, Idaho Falls, ID. https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_68267.pdf.
2. U.S. Nuclear Regulatory Commission (NRC). 1995. "Accident Source Terms for Light-Water Nuclear Power Plants." NUREG-1465. NRC, Washington, D.C. https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1465/index.html.
3. Gauntt, R. O., D. A. Powers, S. G. Ashbaugh, M. T. Leonard, and P. Longmire. 2010. "Accident Source Terms for Pressurized Water Reactors with High-Burnup Cores Calculated Using MELCOR 1.8.5." SAND2008-6664, Sandia National Laboratory, Albuquerque, NM. https://doi.org/10.2172/984120.
4. U.S. Nuclear Regulatory Commission (NRC). 2014. "MELCOR Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project." NUREG/CR-7008. NRC, Washington, D.C. https://www.nrc.gov/docs/ML1423/ML14234A136.pdf.

Figure 2. Hydrogen release over the transient.



An Approach to Performance-Based, Risk-Informed Evaluations of a Site's Physical Protection Strategy – the Vulnerability Assessment Process

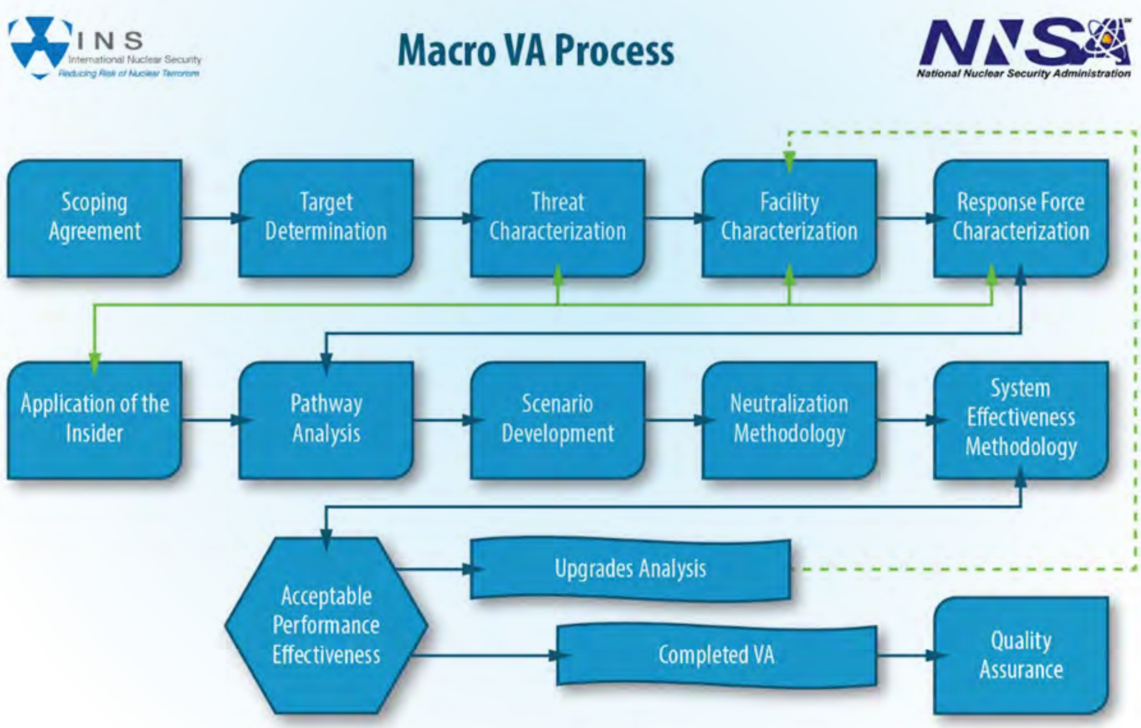
Commie R. Byrum
Physical Security Pathway

One of the most important aspects of any security program is the ability to analyze a facility's protective strategy to make cost-effective adjustments. It is critical for any type of facility with high-consequence assets to be able to take a multidisciplinary approach to self-identify and correct weaknesses.

The U.S. Department of Energy (DOE) and National Nuclear Security Administration (NNSA) have implemented a vulnerability assessment (VA) process that has standardized the security assessments of DOE/NNSA facilities across many of its sites. This process entails a systematic evaluation of threat risks and protection capabilities using a quantitative approach. A flow diagram of the DOE/NNSA VA process is shown in Figure 3.

At a high level, the VA process requires site operators and security teams to develop and document facility targets, threats, adversary and response force characteristics, insider threat mitigation programs and potential attack pathways. Using a common set of threats and boundary assumptions, it is used to develop realistic, peer-reviewed scenarios based on aspects of a site's design basis threat and evaluate these scenarios using modeling and simulation tools. This provides an overall physical security system performance effectiveness (PE) metric to assess the security readiness of the facility. One of these developed scenarios is then selected by the regulator to run as a force-on-force exercise to validate the assessment findings. The results are used for continuous improvement of security processes, technology implementation, and culture. This overall process is documented as a VA report, which is used as a single point of evaluation for both the peer-review team and the regulator.

Figure 3. DOE/NNSA VA process flow.



Currently, the domestic nuclear power fleet already conducts several of the steps included in a standard VA. However, a systematic process along with a PE number to evaluate the security program is not currently being used. One reason for this is because quantitative criteria for commercial activities have not been developed.

The LWRS Program has been conducting research in this area and is currently evaluating how the DOE/NNSA VA process could be adapted for commercial nuclear power plant sites. The LWRS Program has considered current practices for both the nuclear power industry and DOE/NNSA sites to evaluate where there is overlap and where differences exist for security program evaluation. Additionally, this research effort has conducted two technical exchanges with the nuclear power industry to describe the DOE/NNSA VA process and gather feedback from nuclear utilities regarding how they currently conduct evaluations. These exchanges supported the development of a crosswalk identifying similarities and differences.

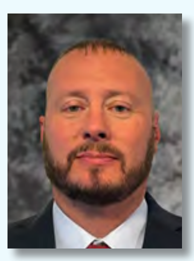
A prospective vulnerability analysis process has been developed from this research. It is a similar process to the DOE/NNSA VA, but, with adjustments to meet the specific needs of the nuclear power industry. The current plan for this research is to conduct VAs with collaborating nuclear power plant sites using an internally agreed upon PE number. These pilots inform the research and individual participants with lessons-learned and serve as a tool method refinement. These enhancements are intended to augment current insights and approaches to physical security self-assessments. The benefits for developing and implementing a VA process include:

- A potentially standardized VA process using a proven methodology
- The ability to quantify aspects of security assessments and establish formal metrics that are performance-based
- VA consistency improvement across assessments and sites
- Adversary characteristic and scenario realism improvement
- Enabling increased protective strategy information-sharing, lessons-learned and peer reviews
- The potential to reduce costs by increased efficiency and the elimination of redundant requirements.

Ultimately, this VA process will enable site personnel to assess protection strategies in its security program. Furthermore, a formal analysis program will support protective strategy decisions by using a performance-based, risk-informed process that is based on site-specific conditions. Understanding the site's risks would allow decision-makers to make investments to benefit the specific protection strategy being implemented and evaluate upgrades.

Welcome Commie Byrum, the New Physical Security Pathway Lead

Mr. Commie Byrum is the new Physical Security Pathway Lead for the LWRS Program. He works at Sandia National Laboratories (SNL) in the Global Security Analysis and Simulation department. During more than two decades of dedicated service within the U.S. Department of Energy National Nuclear Security administration, he has distinguished himself as a leader in security management.



Commie R. Byrum

Byrum has a broad range of expertise spanning various security disciplines including performance testing, vulnerability analysis, physical protection strategies, secure transportation of sensitive materials, insider threat countermeasures and protective force operations.

He holds Master of Arts (M.A.) and Bachelor of Science (B.S.) degrees in Organizational Management from Tusculum University and a Master of Arts (M.S.) degree in Security Management from Bellevue University.

Since joining SNL in 2022, Byrum has been instrumental in leading multidisciplinary teams to deliver critical systems analysis for physical protection and sabotage mitigation, supporting our nuclear/radiological security training and analysis programs. As the Physical Security Pathway Lead he will continue his commitment to enhancing our security initiatives and protecting our nation's critical assets and infrastructure.

Simple Calculator Evaluates Nuclear Hydrogen Market Opportunities

Currently, the U.S. generates around 10 million metric tonnes of hydrogen per year, but as the nation works to implement sustainable energy systems, the U.S. hydrogen market demand could increase to 96 million metric tonnes of clean hydrogen per year. Hydrogen is currently used in ammonia plants, petroleum refineries, and steel-making for iron ore reduction and for chemicals production such as methanol. In the future hydrogen could be combined with carbon sources to make bulk synthetic transportation fuels

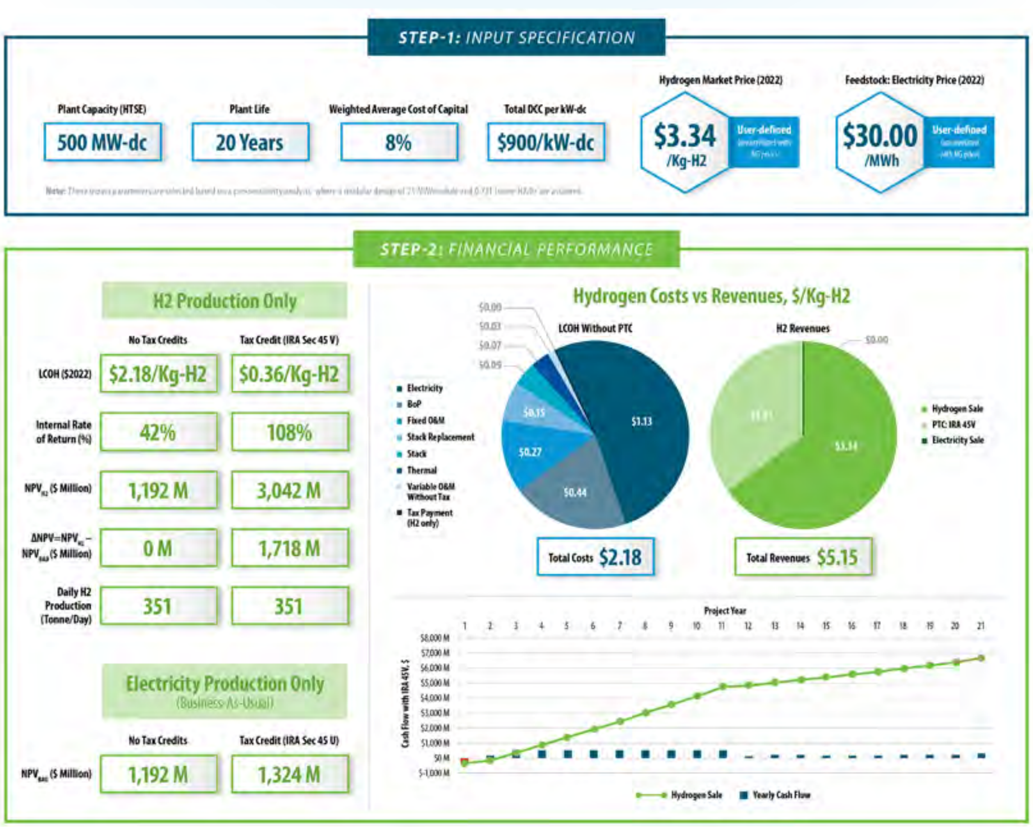
Wen-Chi Cheng, L. Todd Knighton
Flexible Plant Operation and Generation Pathway

Currently hydrogen is produced by reacting steam with natural gas, in a well-developed process called steam methane reforming, evolving carbon dioxide, a greenhouse gas, in the process. In addition, the extraction of natural gas from underground is often associated with fugitive greenhouse gas emissions. At increased cost, carbon dioxide from the steam methane reforming process could be captured and sequestered in underground geological formations to reduce the carbon intensity.

One alternative to steam methane reforming and carbon capture and sequestration is water or steam electrolysis. Low-temperature electrolysis requires water and electricity, while high-temperature electrolysis requires electricity, steam, and heat. High-temperature electrolysis is more efficient than low-temperature electrolysis because of its ability to use heat energy directly, avoiding electrical generation losses for some of the input energy. If the electricity used for electrolysis is provided by wind, solar, geothermal or nuclear energy, then the hydrogen product does not result in any significant level of greenhouse gas emissions.

Nuclear energy from existing U.S. light water reactors can efficiently vaporize water into steam for use in high-temperature electrolysis. U.S. LWRs provide a reliable source of energy that can operate reliably and continuously 24/7, all year without any interruption in hydrogen production.

Figure 4. Integrated Hydrogen Production Analysis 's (NIHPA) main dashboard is a graphical interface that displays input specifications and financial performance indicators.



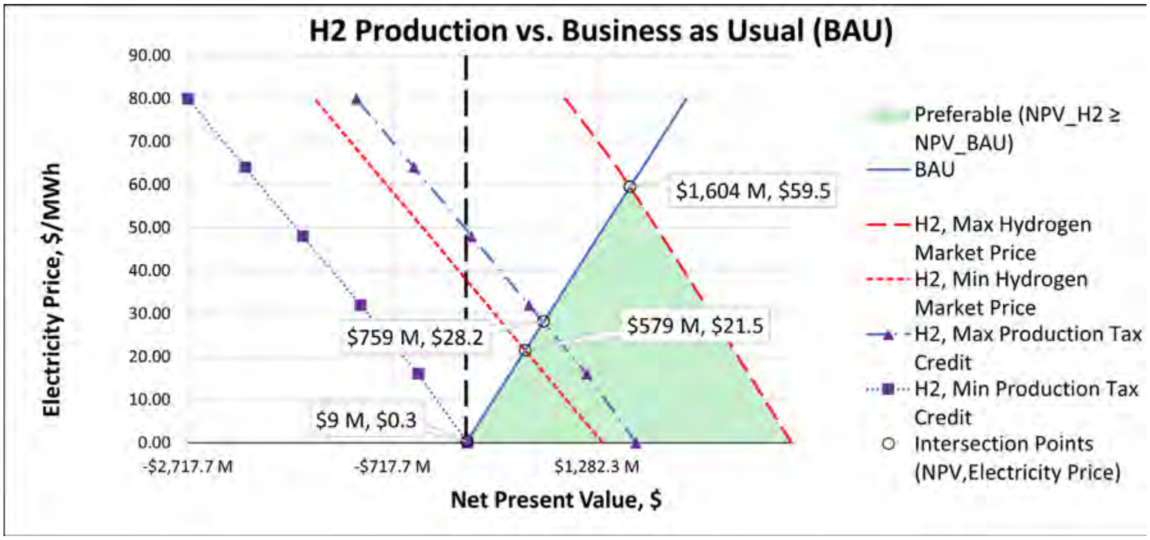


Figure 5. Decision points for choosing hydrogen production versus business-as-usual, showing a variety of potential hydrogen sale price points.

All or a portion of the energy from existing nuclear reactors' can be directed to hydrogen production throughout the year, and the amount can be optimized with local electricity market conditions.

The U.S. Congress passed the Bipartisan Infrastructure Law and the Inflation Reduction Act which provides significant incentives to build new hydrogen plants to produce clean hydrogen. These incentives also help drive down the costs of clean hydrogen production through funding research and development of electrolysis technology.

Nuclear power plants could technically switch from producing hydrogen to producing electricity as needed. However, the decision whether to produce electricity for the grid or to make clean hydrogen is not easy for utilities, grid operators or public utility commissions. If a nuclear plant is mostly dedicated to producing hydrogen, then a new source of power generation may be needed for producing electricity.

To better assist decision-makers in understanding the financial benefits of producing hydrogen, LWRS Program researchers at INL have developed a Microsoft Excel-based tool called Nuclear-Integrated Hydrogen Production Analysis. The tool allows decision-makers to input parameters such as the wholesale price of electricity to compute the cost of hydrogen production. Other user-adjustable parameters include the size of the electrolysis plant, the value of federal or state production tax credits, and other parameters for a capitalized project such as project life and the interest rate on borrowed money. The tool then displays the cost and other financial indicators with various graphical representations that make it easy for the user to interpret the results, as shown in Figure 4.

The NIHPA tool also automatically updates graphics and figures to show the value of switching to hydrogen production versus continuing the business-as-usual selling of electricity to the grid, as indicated in Figure 5.

This new calculator allows reactor operators, utility planners and industrial hydrogen users to evaluate hydrogen production costs and tradeoffs based on electricity, natural gas, and commodity market prices. While this tool has the flexibility to receive up to 50 different inputs, which can selectively be unveiled by the user, its more basic standard configuration provides utilities with enough information to compare two basic outputs—the revenue from hydrogen production and the revenue from electricity production—with a high degree of confidence.

Simple instructions are provided in the program to help users quickly become familiar with the tool and the output fields and charts. LWRS Program technical staff are also available to provide user assistance on an individual, group, or company basis.

Once users have a better understanding of the cost of hydrogen production, a deeper analysis of location- and region-specific markets can be evaluated using more sophisticated time-dependent statistical computational tools that have been developed by INL. These computational tools include Tool for Economic AnaLysis (TEAL) and Holistic Energy Resource Optimization Network (HERON), which are solved under a systems optimization computation framework known as Framework Optimization of ResourCes and Economics (FORCE). TEAL performs cash flow analysis while HERON provides optimized solutions with lowest costs and highest revenue for dispatching the electricity, steam and hydrogen depending on the customer's demand in a python-based environment.

Development of a Technical, Economic, and Risk Assessment Framework for the Evaluation of Work Reduction Opportunities





Ryan M. Spangler, Vivek Agarwal, Craig A. Primer
Plant Modernization Pathway

Jason Hansen
FPOG Pathway

Svetlana Lawrence
RISA Pathway






Christianna Howard, John McCague, Matthew Lohen, Pareez Golub
Sargent & Lundy, LLC

Jesse Budraitis, Raymond Herb
Southern Nuclear Company

To achieve operational efficiency and long-term economic sustainability, existing nuclear power plant stakeholders are identifying work reduction opportunities (WROs) as part of their approach to integrated operations for nuclear (ION) [1]. These WROs provide an opportunity to replace manually intensive activities with technology-enabled solutions to achieve cost savings. Executing these WROs at scale (i.e., system level to fleet level) is not a simple process and presents several challenges that include (but are not limited to) technical feasibility, performance uncertainty, organizational adoption of change, and others.

To alleviate these challenges, INL researchers have developed an evaluation framework in collaboration with Sargent & Lundy, LLC and Southern Nuclear Company to enable the successful implementation of new technological processes and WROs. This framework, known as the Technical, Economic, and Risk Assessment (TERA), is a method to systematically evaluate WROs. Through a series of interviews, process modeling, and an evaluation of technology integration into existing processes, TERA provides an understanding of the challenges and expected outcomes from potential WROs. The TERA framework is designed to ensure stakeholders can make informed decisions on modernization investments, overcoming challenges, and optimizing operations in the nuclear sector.

Technical, Economic, and Risk Assessment Framework

The TERA framework serves a twofold purpose when evaluating WROs. First, TERA screens and assesses WROs from technical, economic, and risk perspectives as shown in Figure 6. The screening is performed qualitatively in collaboration with stakeholders. A process map of the screened WRO is then developed and evaluated using quantitative models. Second, TERA results inform strategic development and implementation of modernized technologies, highlighting potential benefits to plant business.

TERA begins with a screening phase where the process is examined through a hybrid combination of Lean Six Sigma and ION guiding principles. This framework examines the current processes using the Lean Six Sigma Suppliers, Inputs, Process, Outputs, Consumers methodology but retains the key ION elements of people, technology, process, and governance as important factors to the nuclear decision-making process. By combining the principles of Lean Six Sigma and ION, the developed screening process provides a systematic evaluation methodology that is specific to the nuclear industry.

The output of TERA is an evaluation of WROs with the following perspectives:

- Technical – The technical assessment focuses on the process itself and the technical solution. This part of the assessment develops key performance indicators for measuring process performance. In addition, the technical assessment evaluates the feasibility and requirements of the potential solutions.
- Economic – The economic assessment focuses on the cost-benefit performance of the proposed solution which involves estimating the costs of the current process, the costs of developing and deploying the new solution, and the uncertainties in each. Through this assessment, the WRO will be evaluated for cost savings, break-even period, and the net present value of the investment.
- Risk – The risk assessment focuses on the identification and evaluation of potential consequences associated with the implementation of WROs. The risk assessment can also be used to evaluate any potential impacts on plant or personnel safety.

Once WRO solutions have been identified and scenarios analyzed, decision-making involves a careful weighing of benefits against the potential implementation risks. The TERA process develops an assessment of the various WROs in the form of key performance indicators, total cost of ownership, and risks. Using the insights from the TERA process, decision-makers can rank WRO solutions based on their business impact and potential risks. By doing so, the decision-making process becomes data-driven and risk-informed, thus ensuring that choices are backed by rigorous analysis and evaluation.

Real-world Application

LWRS Program collaborated with Sargent & Lundy, LLC and Southern Nuclear Company on a practical application of TERA. Through the analysis and screening conducted as part of the TERA process, five specific WROs were identified. These WROs were contained within two larger processes known as the work week planning and condition reporting process. Within the condition reporting process, one of the significantly beneficial WROs that was identified during the screening was the creation of a condition reporting research aid for system engineers.

The analysis of the conditioning research aid focused on the information-gathering process done by system engineers for equipment reliability-related research. Modeling and analysis predicted that a system engineering research aid could cut research process costs by 25% annually (approximately $570K in yearly cost savings). Assuming an initial cost of two million dollars and a full level of adoption (meaning all system engineers use the new process), the cost savings are overwhelmingly positive with a break-even date of less than four years. A full summary of the TERA framework and case study is detailed in "Development of a Technical, Economic, and Risk Assessment Tool for the Evaluation of Work Reduction Opportunities" INL/RPT-23-74724 [2].

References:

1. Remer, S. J., 2022, Integrated Operations for Nuclear Business Operation Model Analysis and Industry Validation, INL/RPT-22-68671, August 2022, Idaho National Laboratory, Idaho Falls, ID, USA. https://www.osti.gov/servlets/purl/1894935.
2. Spangler, R. M., V. Agarwal, C. A. Primer, J. K. Hansen, S. Lawrence, C. Howard, J. McCague, M. Lohens, P. Golub, R. Herb, and J. Budraitis, 2023, Development of a Technical, Economic, and Risk Assessment Tool for the Evaluation of Work Reduction Opportunities. INL/RPT-23-74724, September 2023, Idaho National Laboratory, Idaho Falls, ID, USA. https://doi.org/10.2172/2008364.

Figure 6. The technical, economic, and risk assessment is used to evaluate WROs.

Machine Learning Emerges as a New Tool for Assessing Reactor Pressure Vessel Embrittlement




Yu-chen Liu
National Cheng Kung University

Dane Morgan
University of Wisconsin-Madison

G. Robert Odette
University of California - Santa Barbara

Mikhail Sokolov
Oak Ridge National Laboratory

Materials Research Pathway

All light water reactors in the United States (U.S.) went into service with 40-year licenses to operate. 94 reactors have had their licenses extended to 60 years, 6 have completed applications and 14 are in the review process to operate to 80 years. An important issue for extended operations is the reactor pressure vessel steel embrittlement due to high-energy neutron exposure. The reactor pressure vessel is the "outer shell" of a nuclear reactor that combined with the concrete biologic shield provides a barrier against the release of radiation and radioactive material in the event of a core-damaging accident. Over years of operation, the reactor pressure vessel steel is exposed to high-energy neutrons which can change the characteristics of the steel. For long-term life extensions of nuclear reactors, improved predictions of reactor pressure vessel embrittlement are needed.

Commercial nuclear reactors use ferritic low alloy steels for construction of the reactor pressure vessel. Assuring structural integrity relies upon accurate knowledge of the change in the materials toughness over the time the nuclear reactor will be in operation. Surveillance programs, using small samples, have been designed to assess changes in fracture properties. Test reactor data also provide valuable information on embrittlement trends, often over a wider range of fluence, but with higher flux values. All the data can be examined with physics-based models that offer excellent insights and predictive power, but they are time consuming to build and require large parallel efforts to support their underlying physical assumptions.

This is where machine learning is coming into play. Embrittlement has been extensively studied in accelerated, higher flux test reactor irradiations, but the use of test reactor data naturally raises the question of flux effects. The September 2023 study published in Acta Materialia, "Characterizing the flux effect on the irradiation embrittlement of reactor pressure vessel steels using machine learning," details a machine learning approach [1]. This approach is trained on a set of hardening data covering a wide range of flux, fluence, and steel compositions to determine the interactive effects of both irradiation and material variables on the increase in yield stress, which is the natural outcome of embrittlement.

Support for this research came from a wide variety of sources. The "ATR2 experiment," which was conducted through the Light Water Reactor Sustainability (LWRS) Program, contributed greatly to the post-irradiation examination of samples irradiated in the advanced test reactor (ATR) at Idaho National Laboratory (INL). The ATR2 experiment is a critical part in developing machine learning-based embrittlement trend curves. Furthermore, the LWRS Program is involved in initiatives to integrate machine learning models into the American Society for Testing and Materials (ASTM) E900 standard and the American Society of Mechanical Engineers (ASME) code case N-914.

Machine learning provides an advanced "data-centered" alternative approach, which reveals flux effects, without any guidance from a priori assumptions about mechanisms and models. Machine learning establishes the empirical relations between features (independent variables) and outcomes (dependent variables) based on being trained by "adequate" sets of data. Combined with improved algorithms and exponential growth in computing power, high-dimensional input data from test reactors can provide insights into the effects of combinations of variables, which might not be otherwise recognized. These new insights not only lead to better embrittlement predictions within the domain of the data, but they also inform the mechanistic approaches to dealing with possible unmodeled physics as observed in Figure 7.

The success of any machine learning model relies primarily on the depth and quality of the training data. For the study, data from the University of California Santa Barbara were used to train the model that came from the Belgian Test Reactor 2, ATR and the Irradiation Variables facility, as designed by University of California Santa Barbara and the Heavy Section Steel Irradiation program at Oak Ridge National Laboratory. In addition to various machine learning statistical tests, the research team carried out extensive analysis that included comparisons to physical models, as well as cross plot analysis for a representative set of six core steels, with systematic and controlled combined variations in their copper and nickel contents.

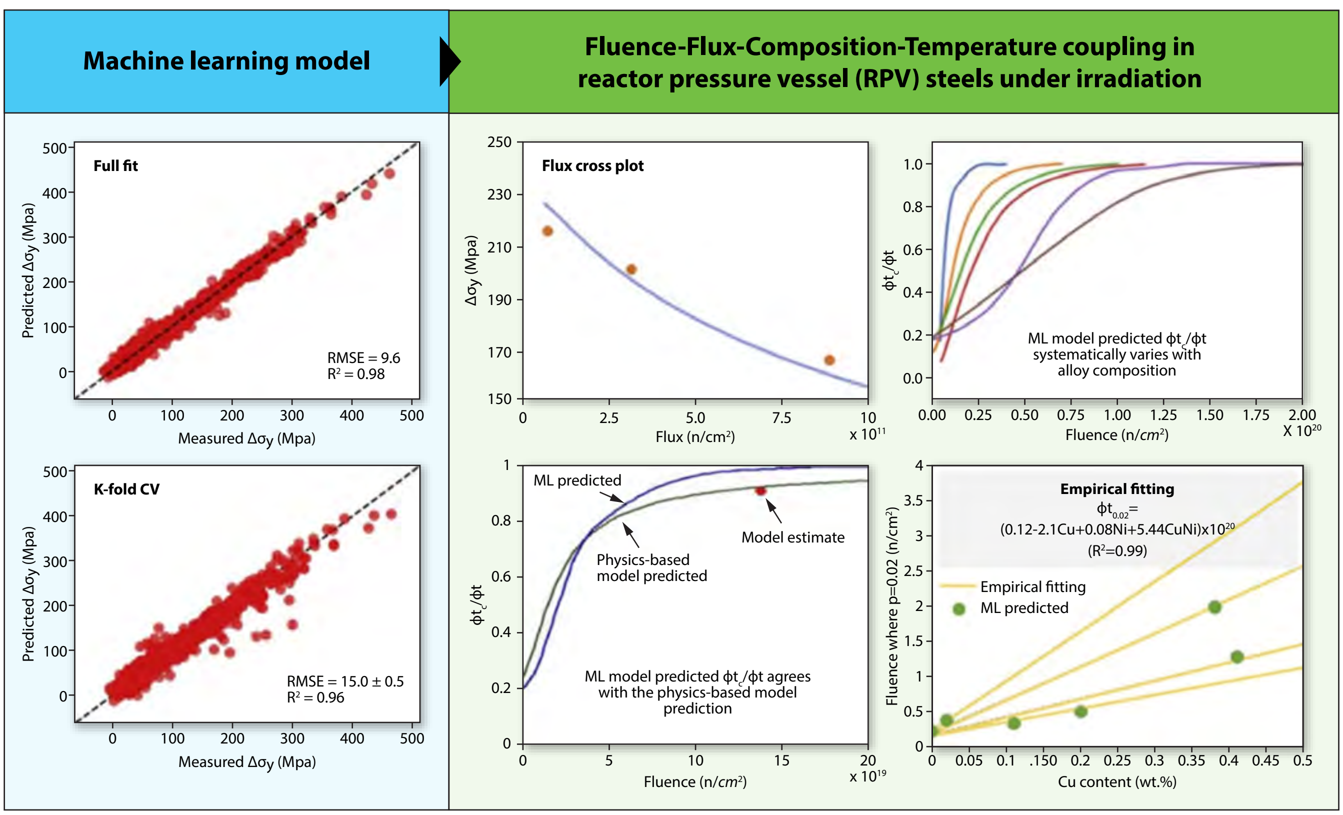
It is critical to emphasize that the two approaches are not an either/or issue. As noted by the authors, "The convergence of trends from both these very different approaches provides strong support for both of them." The authors point out that "Indeed, physics-based and machine learning methods are highly complementary. For example, the machine learning results provided a very useful, completely new, and quantitative insight regarding to the combined flux, fluence and alloy composition dependence of hardening."

This research holds significant practical importance and offers substantial insights into current efforts in physical modeling. Moreover, from an immediate practical standpoint, the results hold crucial significance for the life extension planning of LWR.

Reference

1. Liu, Y.-C., D. Morgan, T. Yamamoto, and G. R. Odette, 2023, "Characterizing the flux effect on the irradiation embrittlement of reactor pressure vessel steels using machine learning," Acta Mater., 256, 119144.

Figure 7. Machine learning model predicted trends are in good agreement with experiments and other physics-based models [1].



Recent LWRS Program Reports

Technical Integration

- *Light Water Reactor Sustainability Program Accomplishments Report*

Materials Research

- *Methodological guideline for industry focusing on characterization procedures to assess the risk of irradiation degradation of concrete in the biological shield*
- *Assessment of Machine Learning for Ultrasonic Nondestructive Evaluation of Alkali–Silica Reaction in Concrete*
- *Microstructure and In-Service Degradation of Baffle-Former Bolts – In-Core Components of Light-Water Reactors*
- *Spread Spectrum Time Domain Reflectometry (SSTDR) and Frequency Domain Reflectometry (FDR) for Detection of Cable Anomalies Using Machine Learning*
- *Extended Bandwidth Spread Spectrum Time Domain Reflectometry Cable Test for Thermal Aging*
- *The Mechanism of Irradiation Assisted Stress Corrosion Cracks in Stainless Steels*
- *Effect of thermal aging on microstructure and stress corrosion cracking behavior of Alloy 152 weldments*

Plant Modernization

- *Development of a Cloud-based Application to Enable a Scalable Risk-informed Predictive Maintenance Strategy at Nuclear Power Plants*
- *Digitalization Guiding Principles and Method for Nuclear Industry Work Processes*
- *Complete Evaluation of ION Cost Reduction Opportunities for LWRS Program Pathways*
- *Development of a Technical, Economic, and Risk Assessment Framework for the Evaluation of Work Reduction Opportunities*
- *Applying the ION Business Model to a Domestic Nuclear Plant: Assessment and Transformation Implementation Plan*
- *Development of Analysis Methods that Integrate Numeric and Textual Equipment Reliability Data*
- *Integrated Operations for Nuclear: Work Reduction Opportunity Demonstration Strategy*
- *Human and Technology Integration Evaluation of Advanced Automation and Data Visualization*
- *Pilot Business Case Analysis for Digital Infrastructure*
- *Optimizing Information Automation Using a New Method Based on System-Theoretic Process Analysis: Tool Development and Method Evaluation*
- *FY 23 ION-Based Approaches to Address Labor and Knowledge Retention*
- *Extending Data-Driven Anomaly Detection Methods to Transient Power Conditions in Nuclear Power Plants*
- *Explainable Artificial Intelligence Technology for Predictive Maintenance*

Risk-Informed Systems Analysis

- *Safety Analysis of Chromium-Coated Accident-Tolerant Fuels with Increased Enrichment and Extended Burnup for PWRs*
- *Assessing the Impact of the Inflation Reduction Act on Nuclear Plant Power Uprate and Hydrogen Cogeneration*
- *Safety Analysis of FeCrAl Accident-Tolerant Fuels with Increased Enrichment and Extended Burnup for PWR*
- *Novel Approaches and Technologies for Aging Management*
- *An Integrated Framework for Risk Assessment of Safety-related Digital Instrumentation and Control Systems in Nuclear Power Plants: Methodology Refinement and Exploration*
- *Pressurized-Water Reactor Core Design Demonstration with Genetic Algorithm Based Multi-Objective Plant Fuel Reload Optimization Platform*
- *Tools and Methods for Optimization of Nuclear Plant Outages*
- *Methods and Feature Enhancements for Industry Use of EMRALD*

Flexible Plant Operations & Generation

- *Design Basis for Control System Implementation in a PWR to Enable 30-100% Thermal Power Extraction*
- *Evaluation of the Technical Feasibility*
- *Preconceptual Designs of 50% and 70% Thermal Power Extraction Systems*
- *Preliminary Analysis and Evaluation of Thermal Stress Induced by High-Capacity Thermal Energy Delivery*
- *Evaluating Energy Storage Options and Costs for Consistent Energy Supply to Non-Electric Sectors*
- *Technical Economic Assessment of LWR-Supported Hydrogen Markets in Gulf Coast Regions*
- *Advancements in Development and Testing of Thermal Power Dispatch Simulators*
- *Comparison of Energy Storage and Arbitrage Options for Nuclear Power*

Physical Security

- *Plant-Specific Model and Data Analysis using Dynamic Security Modeling and Simulation*
- *Special issue on Nuclear Physical Security Risk and Uncertainty Analysis*

(Click on the report title to download the document.)

Editor: Gordon Holt
Designer: David Combs

To submit information or suggestions, contact Cathy J. Barnard at **Cathy.Barnard@inl.gov**.

10-GA50624-39