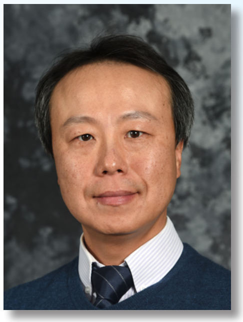
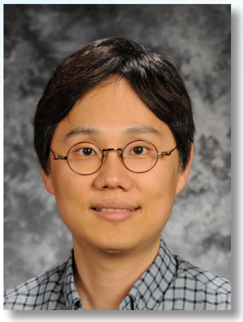
LWRS
LIGHT WATER REACTOR SUSTAINABILITY

Issue 30
March 2020

Validation of Risk-Informed Tools and Methods: NEUTRINO Flooding Analysis Tool

Yong-Joon Choi and Jun Soo Yoo
Risk-Informed Systems Analysis Pathway

An assessment of technical maturity and a credible validation of the risk-informed tools and methods being developed through Light Water Reactor Sustainability (LWRS) Program research will facilitate interest, confidence, and transfer of risk-informed technologies to the nuclear industry. These "tools" are comprised of computer software platforms to perform risk-informed analyses to a variety of nuclear power plant applications. The Risk-Informed Systems Analysis (RISA) Pathway is validating risk-informed tools to develop an appropriate approach to be applied to risk-informed activities. The goals of a validation include the assessment of the validation status and to quantify the technical maturity, identify technical gaps, propose improvements for verification and validation, and develop dedicated validation methods for risk-informed systems analysis. This article summarizes the validation status assessment activity of the flooding analysis computational software NEUTRINO, which is being used in the RISA Pathway (see Figure 1).

Continued on next page

Table of Contents

U.S. DEPARTMENT OF ENERGY

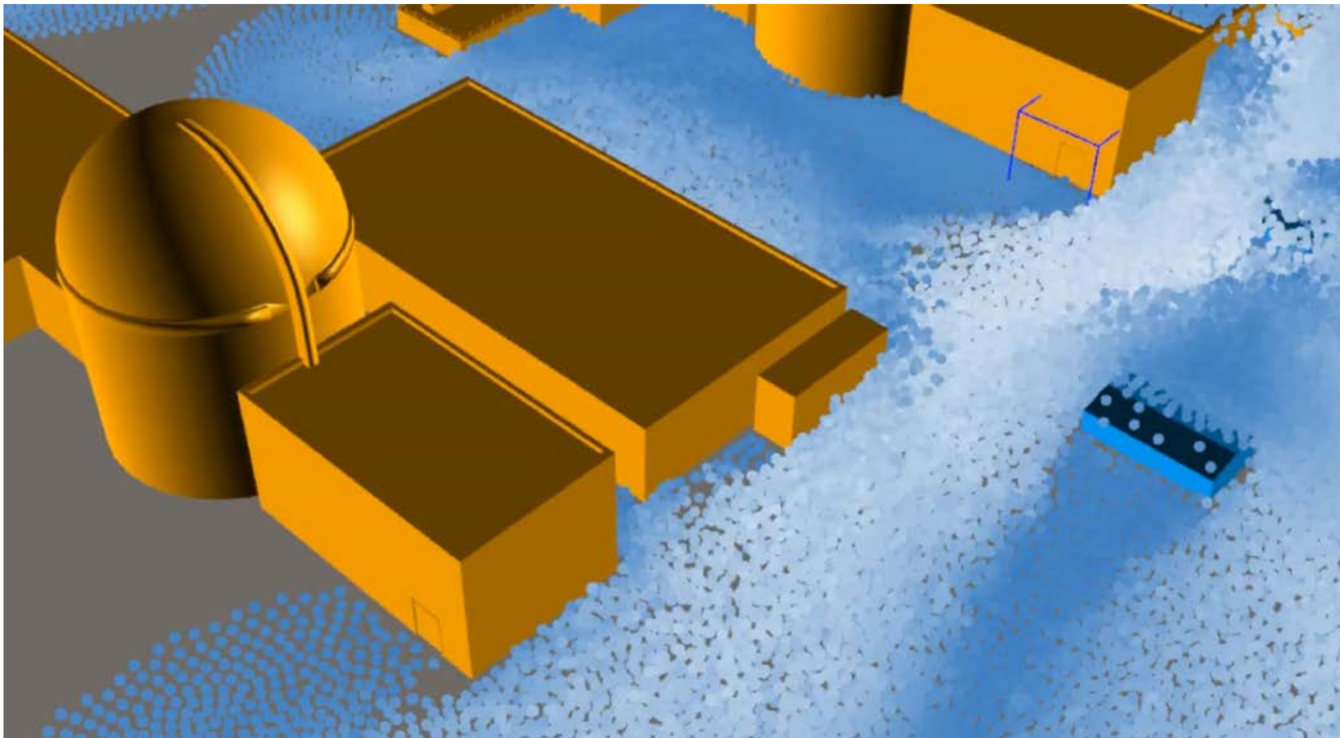


Figure 1. Example of high-fidelity flood representation at a site-level resolution.

Continued from previous page

Validation status assessment of flooding analysis tool NEUTRINO

The NEUTRINO [1] tool is a general-purpose simulation and visualization computational fluid dynamics code that uses a smoothed particle hydrodynamics (SPH) mesh-free, particle-based solver. SPH has the advantage of accurate visualization and, along with component fragility experiments, has been used in various RISA Pathway flooding hazard analysis programs [2], as observed in Figure 1.

The validation status assessment of NEUTRINO focused on examining the simulation capability for flooding hazards analysis and identifying the need for improvements. In order to assess simulation capability, the applicable nuclear power plant flooding hazard scenarios were investigated based on the: hazard source; hazard mode; associated physics; regulatory/industry concerns; and potentially impacted system, structure, and components (SSCs) of the nuclear power plant. The investigated flooding hazard phenomena were re-categorized into three hazard types: (1) water rising; (2) pressure and wave; and (3) debris migration and related physical phenomena.

The degree of importance for each flooding-related phenomena was then ranked by the Phenomena Identification and Ranking Technique (PIRT) [3]. Developed by the U.S. Nuclear Regulatory Commission (NRC), the PIRT method has been used in the nuclear industry to help in determining the priority of relevant physical phenomena for nuclear reactor regulations and safety analysis. Extension of the PIRT method allows identifying and prioritizing research needs, and supports cost-effective experiments and simulations. A three-level scale was used for phenomena importance ranking:

- High: Dominant impactful phenomena. Requires high accuracy experiments and modeling.
- Medium: Moderate impactful phenomena. Requires medium accuracy experiments and modeling.
- Low: Small or no impactful phenomena. Exhibits a basic level of experiment or modeling.

Table 1 shows the assessment results for the importance ranking exercise, as well as the NEUTRINO code development status for flooding hazard analysis. The major phenomena considered are identified as critical areas that a flooding analysis tool should have for a demonstrated simulation capability.

As evaluated, the NEUTRINO code has good capabilities for the visualization of fluid movement and water buoyancy. However, in order to use it in risk-informed analysis in nuclear power plant accident scenarios, additional validation activity may be needed for fluid-solid impact and fluid-fluid/-solid interaction phenomena, which can contribute to safety impacts to nuclear power plants during flooding hazard events. Potential future applications of NEUTRINO that would include these specific phenomena may need to perform validation to understand the limits of the software. However, other phenomena representation appears to be at a medium- to high-level of modeling maturity.

References

1. http://www.neutrinodynamics.com.
2. C. Smith, et al., Risk-Informed External Hazards Analysis for Seismic and Flooding Phenomena for a Generic PWR, INL/EXT-17-42666, 2017.
3. D.J. Diamond, Experience using Phenomena Identification and Ranking Technique (PIRT) for Nuclear Analysis, Brookhaven National Laboratory, 2006.

Table 1. Ranking of importance and NEUTRINO code development status for flooding hazard analysis.

Hazard Type	Major Phenomena	Importance	NEUTRINO Code	
			Capability	Validation
Water rising	Water level / wetting area – most common in flooding scenarios and gives significant consequences, such as SSC failure, during a flooding event.	High	High	High
Pressure and wave	Velocity profile (wave propagation and dissipation) – Improvement is needed for artificial compressibility test and viscosity formulation. The code uses an advanced numerical model to avoid the particle size influence during simulations.	High	High	High
	Vortex (turbulence) – Since the flooding hazard is dominated by large-scale flow, the importance of vortex is relatively low.	Low	Medium	Medium
	Fluid-solid impact (impact forces, spray) – Despite a continuous effort to improve numerical models for accurate simulations, experiment and validation activities are limited.	High	Medium	Low
Debris migration	Buoyancy – The code has a good ability to simulate the effect and is highly validated through floating scenarios and the falling of solids in water.	Medium	High	High
	Fluid-solid interaction (debris travelling) – The code has a medium level of simulation capability and the validation status is insufficient.	High	Medium	Low
	Solid-solid interaction (collision, force impact) – The code shows low capability in this area and no direct validation has been performed.	High	Low	Low

Enhanced Resilient Plant 2019 Workshop Summary

Hongbin Zhang, Curtis L. Smith, and Shawn W. St. Germain
Risk-Informed Systems Analysis Pathway

Ongoing initiatives in the nuclear industry seek to enhance the safety and improve the economics of existing nuclear power plants. These initiatives include efforts to develop Accident Tolerant Fuels (ATF), to optimize the implementation of Diverse and Flexible Coping Strategies (FLEX), to extend the response time of Terry Turbine-related systems, and to develop passive cooling systems (e.g., the Dynamic Natural Convection system being developed by NuVision Engineering and DYNAC Systems). All of these have the potential to offer

Figure 2. Enhanced Resilient Plant Workshop.

longer coping time for operator mitigating actions during plant abnormal operations or severe accident conditions. Longer coping time, for example, will support the enhanced use of FLEX equipment and accompanying mitigating strategies in design basis and beyond design basis events. The collective changes to plant response capabilities and safety margins that may result from these types of technologies may contribute to nuclear power plants that are more resilient to off-normal events. The benefits of enhanced resilient plants are envisioned to be safety enhancements, risk reduction, and economic improvements.

The safety and risk benefits of these technologies have to be quantified and monetized such that the investment of these technologies can be justified. Since different approaches, assumptions, data, and computer codes are being used by different stakeholders, the evaluation of these technologies may result in varied conclusions. Consequently, there is a need to "harmonize" the analysis methods wherever possible. To that end, the RISA Pathway organized an Enhanced Resilient Plant workshop in Idaho Falls, Idaho, on July 30 and 31, 2019. There were over 40 attendees from 19 different domestic and international organizations who participated and contributed to the workshop (a photo from the workshop is shown in Figure 2). The primary topics of this workshop were to:

1. Discuss technologies that can contribute to the enhanced resilience of nuclear power plants.
2. Present approaches being used to analyze and evaluate these technologies.
3. Benchmark approaches and identify opportunities to coordinate activities.
4. Develop a schedule of efforts and outcomes that may contribute to the needed capabilities to support the deployment of resilient plant technologies and the means for evaluating their impact on plant safety and economics.

After two days of intensive presentations and discussions, several key points emerged from the meeting and discussions, and are summarized as follows:

1. Business conditions require the nuclear industry to change its practices. It is a prerequisite to identify how advanced technologies will be able to realize economic benefits before their adoption. It is imperative to have solutions implemented within the next 3 to 5 years.
2. Key industry priorities to achieve cost reductions:
    a. Near-term ATF deployment (coated claddings) with batch reloads in 2023
    b. Widespread deployment of digital I&C to replace obsolete analog systems
    c. Risk-informed licensing and security
    d. Flexible plant operations (e.g., "load following").
3. Major areas where research is needed to support industry directions:
    a. Human Reliability Analysis – particularly to obtain more realistic credit for the use of FLEX
    b. Common cause failures that drive risk insights.
4. Successful industry deployment of ATF will require a comprehensive change management plan. To meet the goal of batch reloads in 2023, this needs to be addressed starting now.
5. Dynamic Natural Convection systems have significant potential for plant safety improvements. An assessment is needed as to whether (and if so, how) this system can provide economic benefits.
6. Engage the regulator at an early stage so critical issues can be identified and resolved and the NRC can allocate resources appropriately.
7. Any future use of dynamic probabilistic risk assessment tools will need to address constraints from end-users. It is recommended to focus on how the analyses can be performed in a timeframe in which the utilities/NRC need to make decisions using computational capabilities that are available to these end-users.

This workshop provided participants with a better understanding of methods and modeling approaches, as well as a vision for future research and development directions, which would contribute to the enhanced resilience of nuclear power plants and permit plant operators to enhance safety and economic performance. The "Enhanced Resilient Plant (ERP) Workshop Presentations and Summary" report INL/MIS-19-55260) was developed from the Enhanced Resilient Plant workshop and is available on the LWRS Program website under the following link:

https://lwrs.inl.gov/SitePages/EnhancedResilientPlantWorkshop.aspx.

Nuclear Digital Transformation Strategy

Paul J. Hunton, Craig A. Primer, Kenneth D. Thomas, and Jeffrey C. Joe
Plant Modernization Pathway

The Plant Modernization Pathway and industry collaborators are developing a Nuclear Digital Transformation Strategy to minimize nuclear power plant total cost of ownership. This strategy will allow nuclear utilities to:

- Replace the "like-for-like" replacement approach for obsolete electronic equipment, holistically leverage the modern capabilities of digital platforms, and reduce human workload and equipment costs.
- Plan for foundational digital platforms to be implemented with lifecycle support strategies already in place. This allows technology investments to be executed, maintained, and refreshed continuously and deliberately; retains intellectual property investments; manages digital obsolescence; and lowers lifecycle costs.

The Advanced Concept of Operations Model shown in Figure 3 establishes requirements and constraints for all plant and work function modernization efforts ensuring strategic business objectives are achieved. Nuclear power plant budgets are created using a market-based electricity price point to derive total operating, maintenance, and support costs to support this price (top-down). Work is also analyzed for opportunities to aggressively focus workload on essential functions that can be resourced within budget (bottom-up). Work functions are then configured into the operating model. Process innovations and enabling Plant Modernization Pathway research technologies are then applied as an integrated set by using Systems and Human Factors Engineering. This promotes a business-driven Digital Transformation Strategy that reformulates the traditional labor-centric model to one that is technology-centric. This transformation lends itself to fewer on-site staff that are focused on daily operations, with maintenance and support functions centralized or outsourced to on-demand service models.

The Digital Transformation is realized by the tiered digital system infrastructure depicted in Figure 4.

The integrated infrastructure shown in Figure 4 supports the Advanced Concept of Operations in its full range of activities to directly operate and support nuclear power plants in the following ways:

Instrumentation and Control (I&C) Systems Category

Current plant I&C functions are transformed by: (1) transitioning current safety-related I&C functions to one digital, safety-related platform, (2) transitioning current non-safety/balance-of-plant I&C functions to one digital, non-safety-related platform, and (3) implementing a fully digital Main Control Room and eliminating remote operating stations.

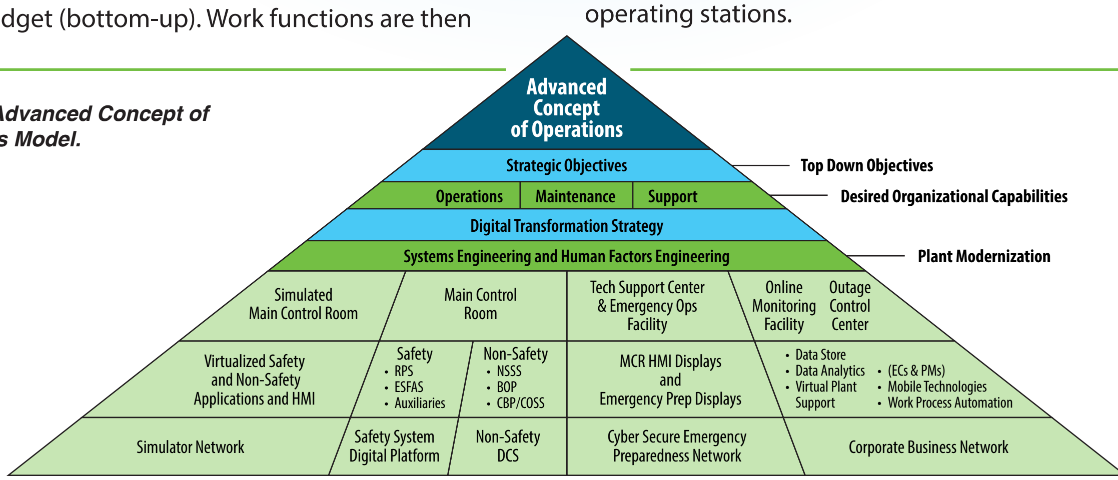


Figure 3. Advanced Concept of Operations Model.

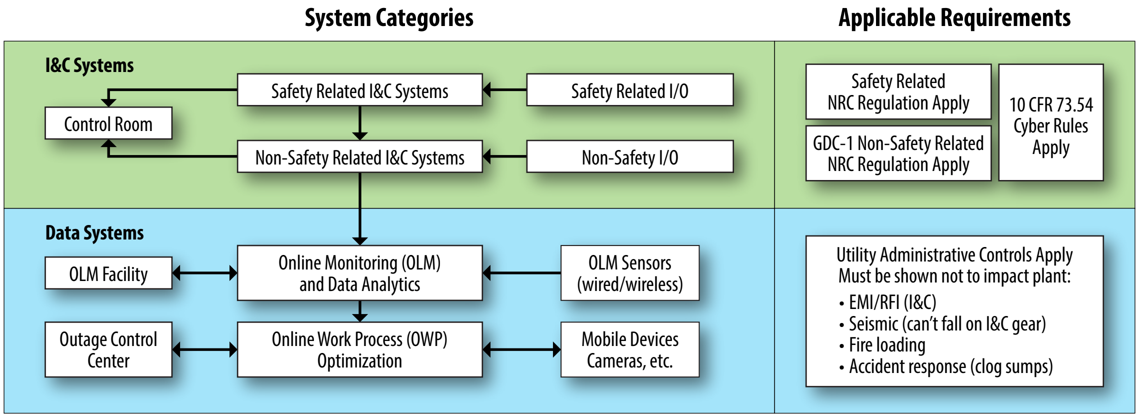


Figure 4. Digital Transformation System Infrastructure.

Together, these changes minimize investment costs while still complying with all technical and regulatory requirements. The digital transformation simplifies maintenance and engineering support, and reduces operations workload and operator training requirements by using only two I&C platforms (i.e., safety-related and non-safety-related). The coordinated design of these foundational elements vastly improves digital upgrades performed individually, following a "bottom-up" approach.

The same control and human machine interface (HMI) software developed for plant use are directly leveraged as shown in Figure 5. No separate design effort is needed. This improves simulator performance for training and enables simulator use as a design tool for developing control system changes, HMI changes, and procedures. It also allows validation of final system software and HMI designs prior to plant installation.

Data Systems Category

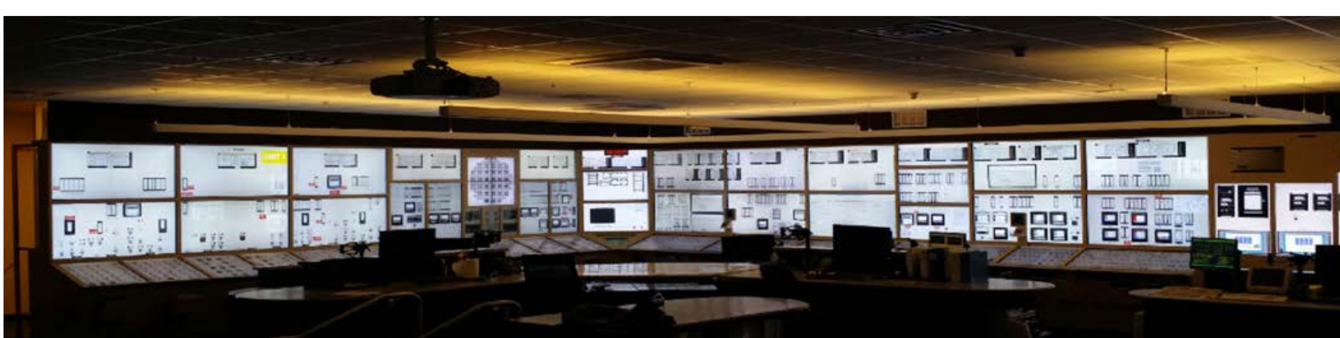
Data capture and analytics for plant support are transformed by: (1) capturing vast quantities of digital plant data directly from the safety and non-safety I&C platforms, (2) adding non-process control sensors to the data systems to fill I&C systems data gaps for plant health monitoring, (3) reducing maintenance workload through condition-based maintenance and predictive maintenance, and (4) performing condition-based maintenance and predictive maintenance analysis in a non-I&C environment, enabling monitoring, diagnosis and maintenance tracking in remote facilities.

Total costs are further reduced through work process optimization, achieved by coupling the condition-based maintenance and predictive maintenance functions with data systems technology. Such technologies include automatic generation and scheduling of electronic work packages and use of mobile technologies to promote correct and timely maintenance.

These data capture and data analytics tools enhance decision-making. I&C operating display facsimiles are provided across the data systems. Multi-disciplined performance dashboards are also created at the plant, site, and/or fleet level. These improve the understanding of the operating status of a plant across the enterprise and improve operational and emergency response decision-making by management.

The modern digital infrastructure shown in Figure 4 does more than enable like for like upgrade of obsolete analog I&C and other electronic system replacements. This sustainable, technology-centric solution delivers an approach that drastically reduces total cost of ownership while improving plant operation and maintenance capabilities.

Figure 5. "Digital twin" of I&C systems in a nuclear power plant control room glasstop simulator.



Evaluation of Stress Corrosion Crack Initiation in Nickel-Base Alloys and Implications for PWR Components

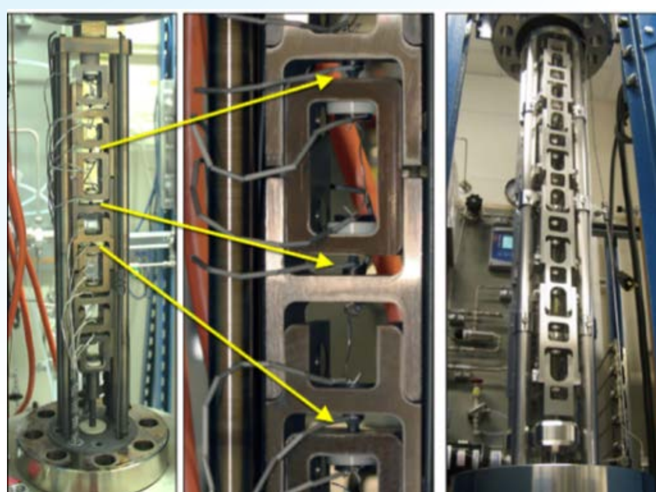
Ziqing Zhai, Mychailo B. Toloczko, Karen Kruska, Matthew J. Olszta, and Stephen M. Bruemmer
Materials Research Pathway

Stress corrosion cracking (SCC) of Ni-base alloys used in light water reactor (LWR) pressure boundary components is a critical issue to the long-term viability of the nation's nuclear fleet. SCC of the originally selected low-Cr Ni-base Alloy 600 and its weld metals used in steam generators and to join piping and instrumentation nozzles to the reactor vessel began to significantly impact pressurized water reactor (PWR) performance in the 1980s and 1990s, which led to their progressive replacement in these components [1]. Although the service performance has been restored through either application of mitigation techniques or replacement with high-Cr Ni-base Alloy 690 and its weld metals, Alloy 600 and its weld metals remain in use in certain regions of the reactor where viable mitigation techniques are still being developed. Meanwhile, SCC susceptibility has been identified in the laboratory for Alloy 690 [2], prompting a need for further assessment of SCC susceptibility for both materials.

This Materials Research Pathway project addresses one of the least understood aspects of SCC for LWR pressure boundary components—crack initiation. Our focus is to investigate important material (e.g., composition, processing, microstructure, strength) and environmental (e.g., temperature, water chemistry, stress) effects on SCC initiation susceptibility of Alloys 600 and 690. The primary objectives are to identify mechanisms controlling crack nucleation, investigate the transition from short to long crack growth under realistic LWR conditions, and establish the framework to effectively model and mitigate SCC initiation.

Three state-of-the-art multi-specimen SCC initiation testing systems were designed and built at Pacific Northwest National Laboratory (PNNL), as shown in Figure 6. The successful implementation of these advanced test systems and methods under the Materials Research Pathway has provided a foundation for SCC initiation studies at the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) [3], as well as helping to establish the standard for LWR SCC initiation testing around the world [4]. To date, SCC initiation tests have been performed in simulated PWR environments on both Alloy 600 and 690 to evaluate the effects of key material and environmental factors on crack precursor development. For cold-worked (CW) Alloy 600, SCC initiated at the specimen surface following intergranular (IG) attack and grew into the bulk material. In contrast, CW Alloy 690 exhibited internal IG damage in the form of grain boundary cavities, which eventually led to cracks

Figure 6. Small SCC initiation test system with instrumented specimens (left side) and the large SCC initiation test system (right side) located at PNNL.



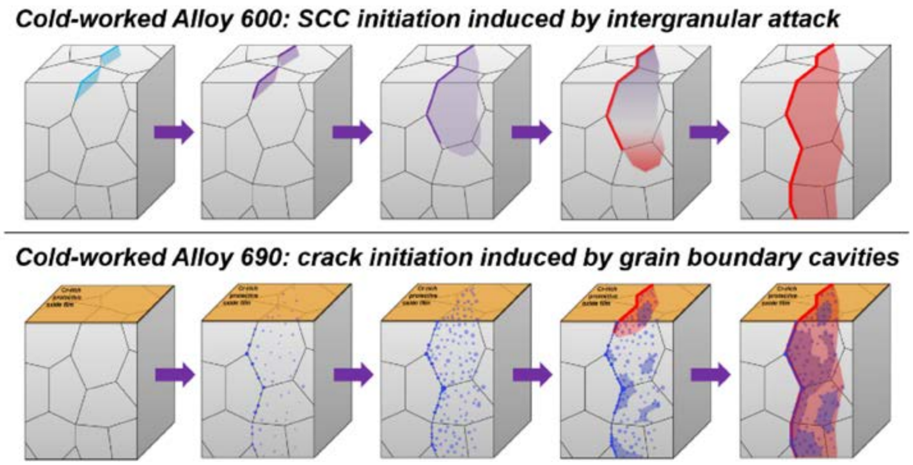
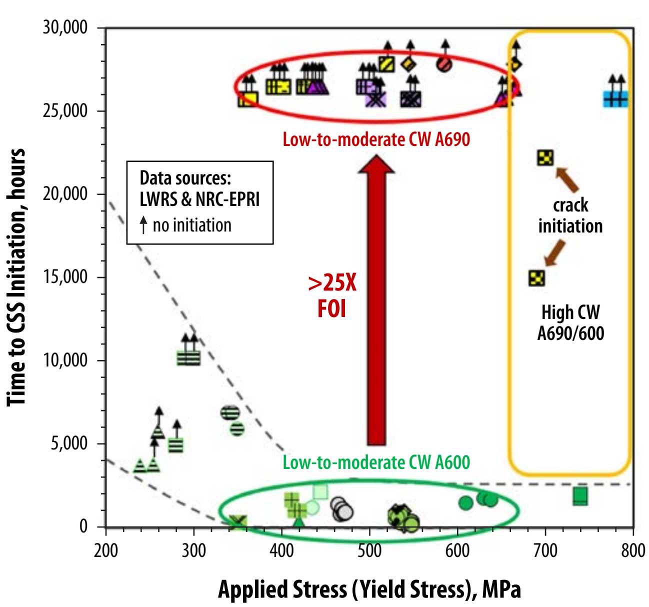


Figure 7. Proposed crack initiation and growth mechanism for CW Alloy 600 (top) and Alloy 690 (bottom) based on experimental observations.

connected to the specimen surface. The different crack initiation and growth mechanisms for Alloys 600 and 690 are illustrated in Figure 7.

SCC initiation data generated for this project and another at PNNL [3] have enabled an estimation of the factor of improvement (FOI) for Alloy 690 versus Alloy 600 in 360°C PWR primary water, as shown in Figure 8. SCC initiation time of less than 1,000 hours was frequently detected in all CW Alloy 600 materials, most of which are in the 15% CW condition. In comparison, SCC initiation has not

Figure 8. Measured SCC initiation time as a function of applied stress for CW Alloy 600 and Alloy 690.



been detected in any of the low-to-moderate CW Alloy 690 materials surpassing 27,000 hours of exposure at constant load. This suggests the Alloy 690 initiation FOI is greater than 25 times and is still increasing with continued testing. However, crack initiation has been detected in a highly CW Alloy 690 heat after approximately 15,400 and 22,240 hours. All of this information is of critical importance for material degradation prediction and plant life management for existing PWR systems.

In summary, the ongoing SCC initiation research combining advanced testing and characterization techniques is providing unique insights into the mechanisms and precursor states for SCC initiation in Ni base alloys. This knowledge is enabling the FOI assessment for replacement Alloy 690 and the development of quantitative models to assess the performance of existing Alloy 600 and 690 components. In addition, the basis for improved SCC-resistant alloys and mitigation strategies are being evaluated, all of which are of high interest to the nuclear industry.

References

1. P. M. Scott, P. Combrade, Journal of Nuclear Materials 524, 2019, p. 340-375.
2. S. M. Bruemmer, M. J. Olszta, et al., Corrosion, 69 (10), 2012, p. 953-963.
3. M. B. Toloczko and Z. Zhai, SCC Initiation Testing 2017 Report, PNNL-27011, October 2017.
4. Z. Zhai, M. B. Toloczko, and S. M. Bruemmer, Stress corrosion crack initiation behavior of Alloy 600 and Alloy 690 in PWR primary water, September 2018.

BWROG Feedwater System Improvement Committee Meeting

Mehdi Asgari, Thomas M. Rosseel, Douglas M. Osborn, Mitchell T. Farmer, and Christian Rabiti
Materials Research Pathway

The LWRS Program program hosted the Boiling Water Reactor Owners Group (BWROG) Feedwater System Improvement (FWSI) Committee Meeting from July 30 to August 1, 2019, at Oak Ridge National Laboratory (ORNL). The meeting, with 33 attendees (see Figure 9) including staff from four U.S. Department of Energy (DOE) national laboratories—Oak Ridge National Laboratory, Argonne National Laboratory, Idaho National Laboratory, and Sandia National Laboratories; BWROG FWSI committee utility members; General Electric employees; and a Pressurized Water Reactor Owners Group (PWROG) representative to discuss current boiling water reactor (BWR) and pressurized water reactor (PWR) feedwater system issues and challenges, as shown in Figure 10. The discussions focused on identifying component failures and evaluating applicable DOE resources that could be utilized to address design improvements that may reduce lost power generation caused by feedwater system outages. (An estimated 30-60 MW_e is lost within the BWR or PWR feedwater system.)

Feedwater system component failures have a long history of being the number one cause of lost electrical generation for BWRs and PWRs. The economic costs associated with lost generation range up to $150 million per year for the fleet with a potential loss of additional income of up to $10 million per reactor per year due to original system design inefficiencies (based on 1960s/1970s technology). An analysis of the lost generation data suggests that improving the performance of heat-exchangers, valves, pumps, and valve operators would mitigate much of these lost generation trends. For example, Table 1 shows the major causes of lost generation in 2018 for BWR feedwater systems. It should be noted that these numbers are representative of the components causing lost generation; however due to how lost generation is reported, the total lost generation is higher than the sum of each component.

Figure 9. Utility, industry, and DOE national laboratory FWSI Committee Meeting attendees (July 30 – August 1, 2019, ORNL).

In addition to system component issues, feedwater systems were designed more than 50 years ago and have generally not been updated to improve performance based on the latest technologies, except for instrumentation and control (I&C). Furthermore, the BWR feedwater system is complicated with multiple stages of

Component	Generation Loss Events	MW-Hrs Lost	Percent
Heat exchanger, condenser, steam generator	6	555,833	40%
Valves, dampers	9	385,737	28%
Pumps, eductors	6	322,776	23%
Valve operators	2	46,190	3%
Turbines (steam, gas)	1	38,988	3%
Motors (electric, hydraulic, pneumatic)	2	26,096	2%
Instrument controllers	3	17,405	1%
Integrator/computation module	1	2,627	0%
Transmitters, detectors, elements	1	109	0%
Total	31	1,395,761	

Table 2. Summary of BWR Feedwater Component Failures in 2018 and Lost Generating Capacity. (Data provided courtesy of the BWROG)

heat-exchangers, pumps, steam jets, and flow diversions in which all components of the system must operate within design limits and respond predictably to the plant controllers.

Meeting attendees acknowledged that a multi-disciplinary subject matter expert team comprised of DOE national laboratories and industry personnel may be able to improve plant reliability and economic competitiveness with an initial focus on feedwater systems. This could be accomplished by analysis and assessments of the historical and current causes of BWR/PWR feedwater system failures and current maintenance practices along with the utilization and application of DOE's capabilities and resources.

It was estimated that a 30 MW_e improvement obtained at each BWR plant due to system configurations changes, could yield approximately 1,000 MW_e of new generation capacity in the U.S. BWR fleet. An additional 2,000 MW_e fleet-wide could be achieved if the reliability of existing feedwater systems were improved.

Figure 10. Participants discussing FWSI issues at the FWSI Committee Meeting

The following items were identified as the key areas in which DOE has unique technologies and R&D expertise to facilitate opportunities for improving feedwater performance:

- Commercialization of DOE technologies, such as advanced water level sensors
- Analytical techniques that identify common cause failures
- Adaptive control systems
- Artificial intelligence for sensor systems
- Improved inspection techniques (e.g., feedwater heaters)
- Active sensors for crack detection
- Peel and stick sensors connected to plant WiFi systems
- Standard instrument packages for data collection
- Radiation hardened equipment/remote mobile equipment
- System modernization of components nearing end of life
- Standardized fleet Knowledge Transfer and Retention (KT&R) processes.

The subject matter experts across the LWRS Program research and development pathways plan to continue their engagement with the BWROG FWSI committee and will explore opportunities to improve feedwater system performance issues.

Sustaining the Industrial Sector with Nuclear Energy

Richard D. Boardman
Flexible Plant Operation and Generation Pathway

The Light Water Reactor Sustainability (LWRS) Program has added the Flexible Plant Operation and Generation (FPOG) Pathway to its portfolio of research to address new markets for the United States' (U.S.) nuclear reactor fleet. This Pathway is currently applying process modeling and systems optimization tools to evaluate the technical feasibility and economic benefits of dynamically sending a portion of a nuclear power plant's electricity and thermal energy to nearby industries producing non-electrical products. Flexible operations can maximize the plant's revenue by providing reserve, load-balancing capacity to the grid when the localized marginal price for selling electricity is relatively high. On a holistic level, flexible nuclear power plant operations can help stabilize the grid in regions where the percentage of non-dispatchable, variable solar and wind power generation is becoming significant.

The U.S. transportation sector and manufacturing industries currently expend over 70% of the total energy used by the nation. This amount of energy includes one-fourth of retail electricity provided by the electrical grid. Flexible nuclear plant operations will help sustain U.S. industries and the transportation sector by providing low-cost, low-emissions energy to industries for decades. Several LWR connections to large U.S. industries are shown in Figure 11, where a nuclear power plant is the primary source of energy for producing fuels, ammonia, steel, polymer, and hydrogen. Hydrogen is a key energy currency and can effectively incorporate nuclear energy into existing or new U.S. industries.

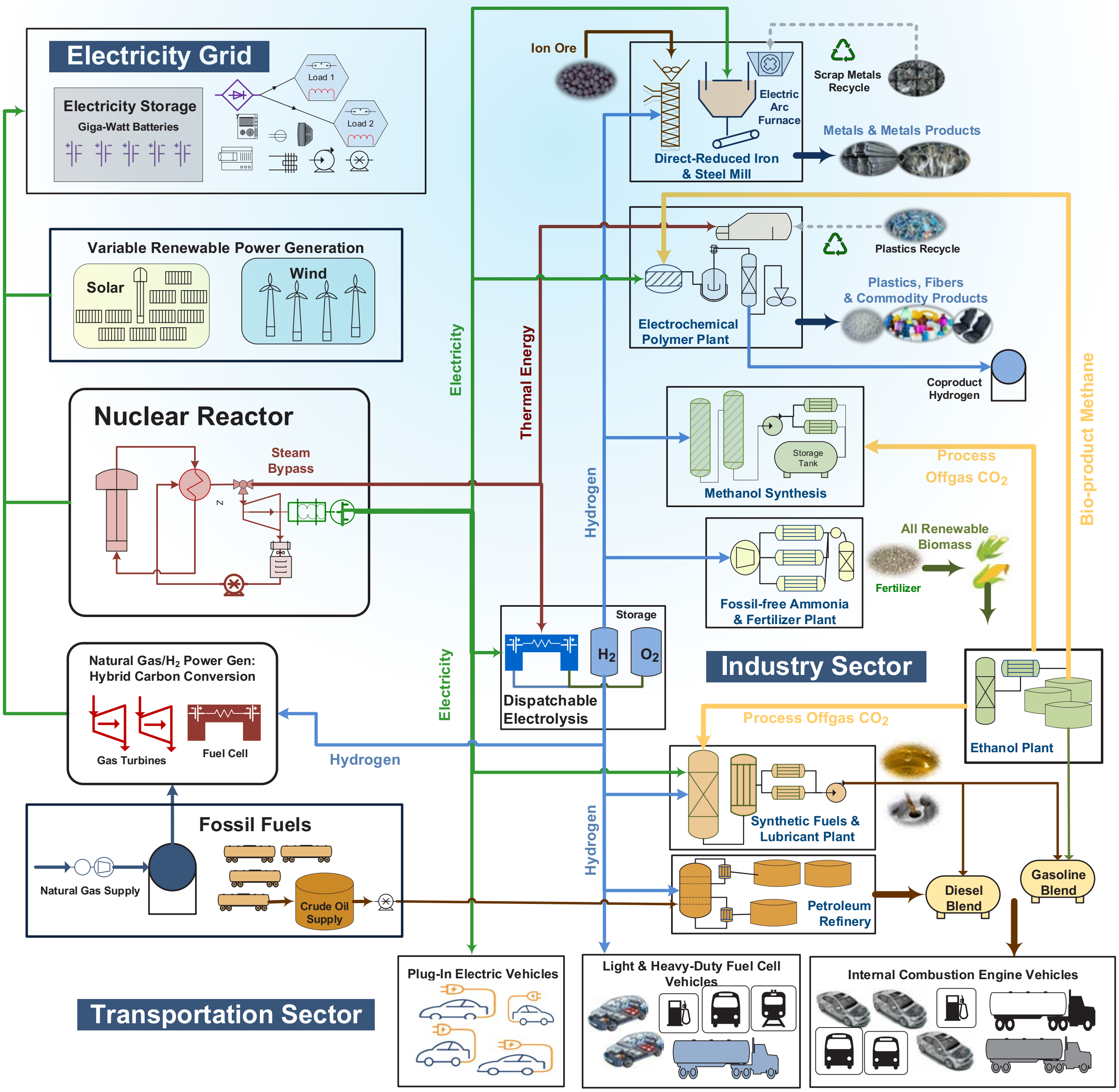
Each of the processes featured in Figure 11 is reaching a high technology commercialization readiness level and is benefiting from the interests of technology developers, industrial gas supply companies, and industry associations. For example, manufacturers of heavy-duty trucks, passenger vehicles, and forklifts, have started building hydrogen fuel cell-powered drive systems. Over the past decade, dozens of ethanol plants and biodigesters have been established throughout the Midwest. Nuclear plants in this region can increase the yield of biofuels produced by ethanol and biodigesters when their CO_2 by-product is diverted to a process that makes synthetic motor fuels. These synthetic fuels would be compatible with existing gasoline and diesel fuel supply systems. As domestic and global demand for steel continues to rise, nuclear power plants can provide electricity and hydrogen to produce direct-reduced iron briquettes and to operate electric arc furnaces. With nuclear power, steel making emissions can be reduced 95% as compared to traditional integrated blast-furnace and open-hearth steel plants.

Table 3. Plausible FPOG Market for LWRs.

New Market	Market Size by Indicated Applications	Number of LWRs (nominally 1,000 MWe)
Heavy-Duty Fuel-Cell Trucks	500,000 trucks 10% of U.S. Fleet	8-11
Synthetic Fuels	280,000 barrel/day 2.5% of Market	15-18
Fertilizer-Grade Ammonia	10,000 tonnes/day 25% of U.S. market	2-3
Finished Steel Production	10 Mtonnes/yr (direct reduced iron) 30 Mtonnes/yr (new electric arc furnaces) 10% of market	7-9
Combustion of Hydrogen with Gas	0.1 Quad BTU hydrogen 1% of the total use for power generation	3-4
Ethylene	4 Mtonnes/yr 10% of U.S. market	2-3

The FPOG Pathway plans to address the business case for each of these options, based on the location of individual plants, the surrounding industries, and new market opportunities. FPOG research activities will also help LWR owners prepare their plants for flexible plant operation, that is, alternating between electricity and non-electric product generation, by developing, testing, and implementing the crucial interfaces that will couple LWR plants with the industrial processes. The number of LWRs that could be committed to these new process concepts is summarized in Table 3.

Figure 11. Products made with nuclear energy as a primary input.



What's the Lifespan for a Nuclear Reactor? Much Longer Than You Might Think

Office of Nuclear Energy
November 19, 2019

U.S. nuclear plants are proving that age is really just a number. As the average age of American reactors approaches 40 years old, experts say there are no technical limits to these units churning out clean and reliable energy for an additional 40 years or longer.

Thanks to research performed over the last decade by the U.S. Department of Energy (DOE) and the Electric Power Research Institute (EPRI), utilities now have the confidence and data they need to apply for a second 20-year operating license with the Nuclear Regulatory Commission (NRC).

Five utilities already announced plans to extend their operating licenses and the first approvals could come by the end of this year.

That would keep nearly a quarter of the nation's fleet online beyond 2050.

Extending the Life of Reactors

Eighty-eight of America's 96 reactors have received approval of their first 20-year extension. The majority of these will expire in the 2030s. Due to the amount of time it takes to prepare for regulatory reviews, utilities are now determining if they should apply for an additional 20 years of service.

In preparation for this uncharted territory, DOE proactively established the Light Water Reactor Sustainability (LWRS) program in 2010 to research areas that would support the long-term operation of the nation's reactors.

DOE, EPRI, NRC, and other stakeholders identified a list of key materials and parts used at the plants. This ranged from the reactor core (and much of the equipment inside of it) to the cabling and concrete around the plant. They then measured the performance of each material to determine how they function over time.

Most of these materials met the desired performance standards expected for long-term operation. The materials that did show signs of normal aging and degradation were identified so that plants could proactively monitor and maintain them over time.

Figure 12. Turkey Point Units 3 and 4 could be the first reactors cleared to operate for up to 80 years. Florida Power and Light.

The 80-Year Club

Six reactors are already using this research to apply for a second 20-year extension.

Florida Power and Light's Turkey Point Units 3 and 4 became the first reactors cleared by the NRC to operate for up to 80 years.

The NRC is also reviewing applications from Dominion Energy and Exelon Corporation. Several other utilities, including Duke Energy, have announced plans to apply. Xcel Energy is also considering an extension.

To date, 20 reactors, representing more than a fifth of the nation's fleet, are planning or intending to operate up to 80 years. More are expected to apply in the future as they get closer to the end of their operating licenses.

Why It's Important

America has the largest fleet of reactors in the world. Nuclear energy generates more than 800 billion kilowatt hours of electricity each year and makes up more than half of the nation's clean energy.

It operates at full power more than 92% of the time and has provided roughly a fifth of the nation's power since the mid-90s.

Despite this performance, 9 reactors have retired before their licenses expired since 2013 due to challenging market conditions, and an additional 8 units are slated to retire by 2025.

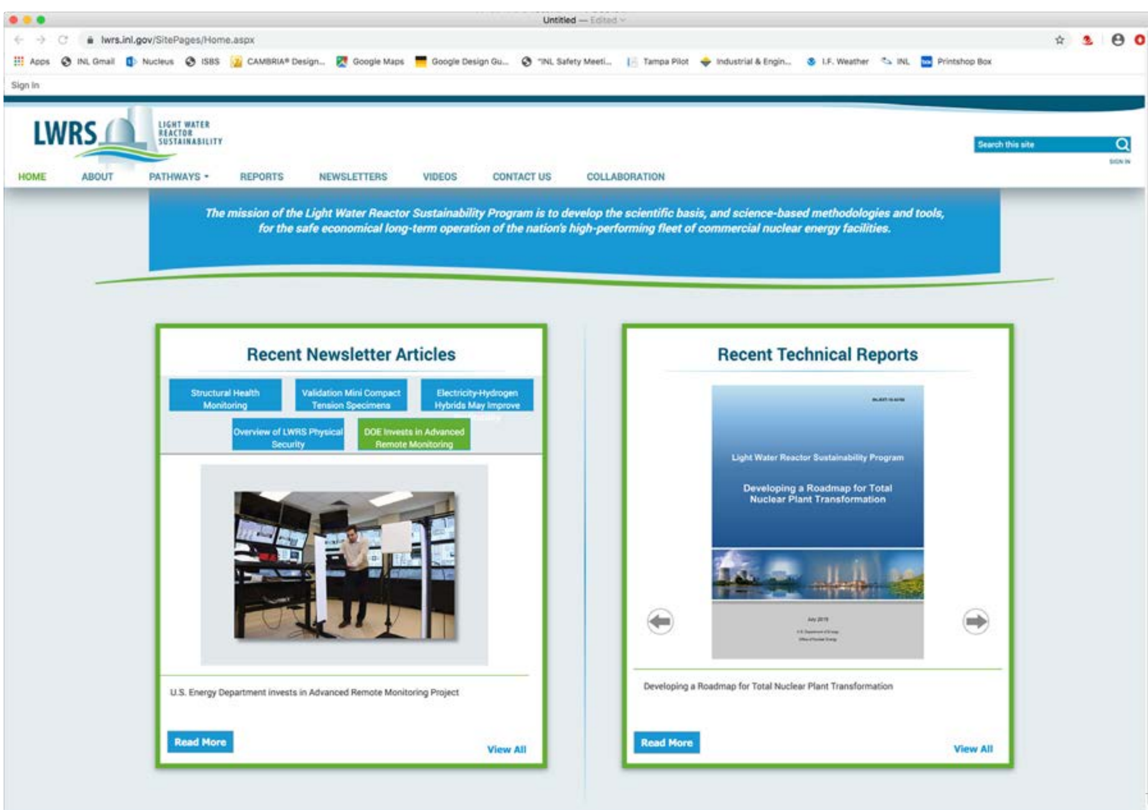
Losing these reactors would ultimately reduce America's large-scale supply of affordable and dependable clean power, as well as deplete the expertise, knowledge, and supply chain that goes along with the entire U.S. nuclear industry.

What's Next?

In addition to materials research, the LWRS program is working on modernizing plant systems to reduce operation and maintenance costs, while also looking to diversify plant products through non-electric applications such as desalination and energy for hydrogen production.

This article was originally added to the Energy.gov website on November 19, 2019 at:
https://www.energy.gov/ne/articles/whats-lifespan-nuclear-reactor-much-longer-you-might-think

Figure 13. LWRS Program Website (lwrs.inl.gov).



Recent LWRS Program Reports

Technical Integration Office

- *LWRS Program Stakeholder Engagement Meeting Summary*

Materials Research

- *Progress on Grizzly Development for Reactor Pressure Vessels and Reinforced Concrete Structures*
- *Irradiation Assisted Stress Corrosion Cracking of Highly Irradiated 300-Series Stainless Steels in PWR Primary Water Environment*
- *Elucidating the Grain-Orientation Dependent Oxidation Rates of Austenitic Stainless Steels*
- *Grain Boundary Microstructure Effects on Stress Corrosion Crack Initiation Mechanisms in Alloy 600 And Alloy 690*
- *A System-Level Framework for Fatigue Life Prediction of a PWR Pressurizer-Surge-Line Nozzle under Design-basis Loading Cycles*
- *Develop Parameters and Characterize the Quality of Friction Stir and Laser Weld-Repaired, Irradiated Structural Materials Representative of Extended Reactor Service Life M2LW-19OR0406014*
- *Analysis of Localized Deformation Processes in Highly Irradiated Austenitic Stainless Steel through In Situ Techniques*
- *Post-Irradiation Examination of High Fluence Baffle-Former Bolts Retrieved from a Westinghouse Two-Loop Downflow Type PWR*
- *Comparative Analysis of Nondestructive Examination Techniques of Enhanced Model Based Iterative Reconstruction (MBIR) and Frequency-banded Synthetic Aperture Focusing Technique (SAFT) Reconstructions*
- *Two-modulator Generalized Ellipsometry Microscope (2-MGEM) Examination of Concrete Aggregates*
- *Report on Initial Evaluations of Effects of Diffusion Limited Oxidation (DLO) Testing*
- *Evaluation of Inverse Temperature Effects on Cable Insulation Degradation in Accelerated Aging of High Priority Cable Insulation Materials*
- *Dielectric Spectroscopy for Bulk Condition Assessment of Cable Insulation*
- *Recent Technological Advances in Welding Irradiated Austenitic Steel with Helium M3LW-19OR0406015*
- *Steam Oxidation of Alloy 718A and Tensile Properties of Select Advanced Replacement Alloys for LWR Core Internals*

Plant Modernization

- *Report for 2.2.1 Task 4: Software-Based Tools to Support Human-System Evaluation Studies*
- *Nuclear Power Plant Modernization Strategy and Action Plan*
- *Automating Fire Watch in Industrial Environments through Machine Learning-Enabled Visual Monitoring*
- *Data Integration Aggregated Model and Ontology for Nuclear Deployment (DIAMOND): Preliminary Model and Ontology*
- *Preliminary Results of a Bounded Exhaustive Testing Study for Software in Embedded Digital Devices in Nuclear Power Applications*
- *Automating Surveillance Activities in a Nuclear Power Plant*
- *Subtle Process-Anomalies Detection Using Machine-Learning Methods*
- *Utilizing FLEX Equipment for Operations and Maintenance Cost Reduction in Nuclear Power Plants*
- *Determination of Sensor Quality of Calibration Using Advanced Data Analytics and Machine Learning Methods*
- *Addressing Nuclear I&C Modernization Through Application of Techniques Employed in Other Industries*
- *Modeling and Simulation – Introducing Hardware-in-the-Loop Capabilities to the Human Systems Simulation Laboratory*

Risk-Informed Systems Analysis

- *Risk-Informed Analysis for an Enhanced Resilient PWR with ATF, FLEX, and Passive Cooling*
- *Combined Data Analytics and Risk Analysis Tool for Long Term Capital SSC Refurbishment and Replacement*
- *Plant Integral Risk-informed System Health Program*
- *Fuel Rod Burst Potential Evaluation under LOCA Conditions for an Existing Plant with Extended Burnup Exceeding the Current Limit by 20%*
- *Risk-Informed Systems Analysis (RISA) Pathway Industry Application Pilot Demonstration Projects - Edition 2019*
- *Fire Modeling Enhancement Tools and Methods*
- *An Integrated Risk Assessment Process for Digital Instrumentation and Control Upgrades of Nuclear Power Plants*
- *Risk-Informed Systems Analysis (RISA) Plant Reload Process Optimization Technical Plan*
- *Evaluation of the Benefits of ATF, FLEX, and Passive Cooling System for an Enhanced Resilient PWR Model*
- *Assessment of verification and validation status - RELAP5-3D and RAVEN*
- *Terry Turbopump Expanded Operating Band Modeling and Full-Scale Test Development Efforts in Fiscal Year 2019 – Progress Report*

Flexible Plant Operation and Generation

- *Technoeconomic Analysis on an Electrochemical Nonoxidative Deprotonation Process for Ethylene Production from Ethane*
- *HERON as a Tool for LWR Market Interaction in a Deregulated Market*

Physical Security

- *Modeling for Existing Nuclear Power Plant Security Regime.*
- *LWRS Program – September 2019 Physical Security Stakeholder Working Group Meeting*

(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-GA50624-30