Plenary Lecture

Risk and Reliability Research at Idaho National Laboratory

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1. RISK-INFORMED SYSTEMS ANALYSIS

The U.S. nuclear industry is facing strong challenges in terms of maintaining regulatory-required levels of safety while also ensuring economic competitiveness in current and future electricity markets. Safety remains a key parameter in all aspects related to the operation of light water reactor (LWR) nuclear power plants (NPPs), and it can be achieved more economically by employing a risk-informed ecosystem such as that being developed by the Risk-Informed Systems Analysis (RISA) Pathway under the U.S. Department of Energy (DOE) Light Water Reactor Sustainability Program (LWRS). The LWRS Program is promoting a wide range of research and development (R&D) activities to maximize both the safety and economic efficiency of NPPs via improved scientific understanding, especially given that many plants are considering second license renewals.

The LWRS Program focuses on two objectives for maintaining long-term operation of the existing U.S. LWR fleet: (1) provide industry with science-and-technology-based solutions for implementing technology that can outperform the current business model, and (2) manage the aging of structures, systems, and components (SSCs) to extend lifetimes of NPP and continue their operation safely and efficiently. The RISA Pathway has the objective of performing R&D to optimize safety margins and minimize uncertainties to achieve economic efficiencies while maintaining high levels of safety. This objective is achieved in two ways: (1) by deploying methodologies and technologies that enable better representation of safety margins and the factors that contribute to cost and safety, and (2) by developing advanced modeling and simulation tools that enable cost-effective plant operation.

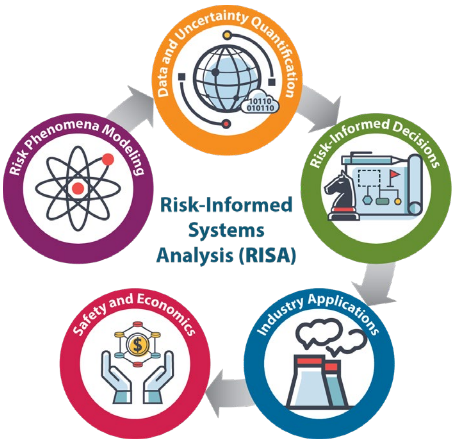

Figure 1. RISA Framework

Safety is central to the design, licensing, operation, and economics of the U.S. commercial nuclear power generating fleet. As the current LWR NPPs age beyond 60 years, they face the possibility of amplified degradation and an increased frequency of SCC failures that initiate safety-significant events, thus reducing existing accident mitigation capabilities or creating new failure modes. Plant modifications such as plant modernization (via the installation of new systems or the inclusion of power uprates) or hydrogen generation introduce new risks and uncertainties. This makes it important to understand the potential hazards associated with NPP aging and modifications and to develop appropriate strategies that enable safe, long-term operation of the existing NPPs.

1.1. Safety Margins

The demonstration of adequate safety margins has been a cornerstone objective in nuclear reactor design and operation ever since the earliest days of commercial nuclear power. While safety margins were expressed only in physics-based terms (e.g., temperature and pressure) back when the existing fleet of NPPs was designed, risk-informed safety margins became a prominent part of the regulatory policy and operational culture of the U.S. nuclear industry in the 1990s. Both physical and safety margins significantly influence many facets of NPP operations, making economic aspects even more important in regard to enabling large industry initiatives such as power uprates and plant modernization. A safety margin can be defined as the distance between the load imposed on the system and system’s capacity, as illustrated in Figure 2.

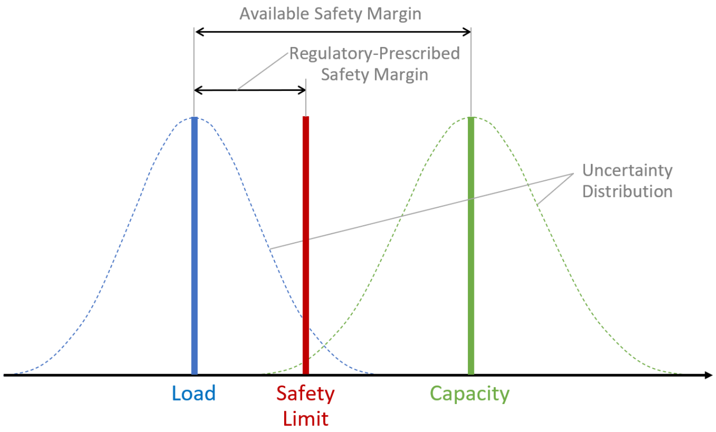

Figure 2. Graphical representation of safety margin.

NPPs in the U.S. were designed based on intentionally conservative safety margins to overcome knowledge limitations in terms of both the phenomenology of potential accidents and the plant responses to those accidents. The techniques for modeling physical phenomena were also limited, introducing further uncertainties. Finally, no operational history was available for comparing predicted vs. actual plant performance. Thus, plant designers commonly “overdesigned” portions of NPPs to add robustness in the form of redundant and diversely engineered safety features to ensure that even in well-beyond-design-basis accident scenarios public health and safety remained protected with a very high degree of assurance.

Modern computer technologies enable us to create more precise models and simulations of physical processes. When combined with comprehensive data analytics and uncertainty quantification, we gain a clearer understanding of physical conditions and associated uncertainties. This improved understanding allows us to more accurately assess risk and demonstrate larger safety margins. The increased safety margins are important because they can justify adjustments to the originally prescribed regulatory safety limits, thus allowing for flexibility in plant operations and enabling important initiatives such as power uprates. In short, a better understanding and more detailed modeling of plant physical processes and associated uncertainties leads to better representation of risks.

2. RISA RESEARCH AREAS

Multiple R&D activities conducted under RISA Pathway are discussed below.

2.1. Sizable Power Uprates

One of the most recent initiatives for the U.S. commercial nuclear industry is the opportunity to increase power production by the operating fleet, a process called power uprates. Recently performed feasibility studies [2] demonstrated economic feasibility of power uprates especially given the incentives offered in the Inflation Reduction Act (IRA) [3]. The research project developed a financial modeling tool to inform plant-specific models supported by a case study which demonstrated the value of implementing the IRA tax incentives and provided the U.S. nuclear fleet with insights and information usable to support site-specific power uprate business cases.

The uprate benefits are significantly amplified if the added power is used to generate clean hydrogen. The concept of hydrogen generation via energy produced by a NPP is relatively new, and initial pilot efforts are underway. However, there is growing interest in zero-carbon hydrogen production and the use of hydrogen as an alternative energy carrier to displace fossil fuels for applications that cannot be easily electrified or decarbonized, and as a cost-effective approach for bulk long-term energy storage [2, 4].

2.2. Risk-Informed Asset Management

The project is aimed at developing/deploying methods and tools that help decrease NPP operational costs. This project targets the development of more effective and efficient analytical methods and tools for supporting risk-informed decisions related to NPP equipment reliability and asset management programs. As commercial NPPs pursue extended operations they encounter opportunities to make capital investments for ensuring long-term safe and economic performance.

The outcomes of this research will enhance the short- and long-term safety and economics of NPPs by providing a structured risk-informed approach for evaluating and prioritizing plant capital investments made in preparation for—and during the period of—extended plant operation. This framework combines classical PRA tools, risk and reliability evaluation methods, advanced data analytics, degradation models for plant SSCs, and plant cost models into a unified analysis environment [5-6].

The latest focus of this project is the development of methodology to automate knowledge extraction from numerical and textual data for integrated knowledge base intended to support informed decision making for equipment maintenance [7]. This artificial knowledge base enables plant staff to identify precursors to equipment failures faster and take mitigating actions to preclude failures. The artificial knowledge base also directly supports knowledge retention and transfer, an important benefit given the nuclear industry workforce shortage. The tool, Digital Analytics, Causal Knowledge Acquisition and Reasoning for Technical Language Processing (DACKAR) is available as open-source [8].

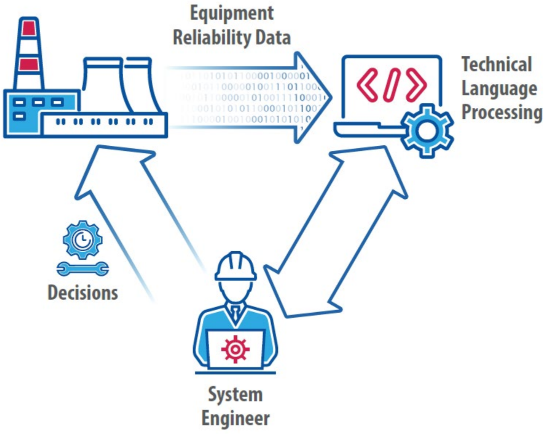

Figure 3. Connecting data to decisions.

2.3. Risk Assessment of Digital Instrumentation and Control Systems

The focus of the project is on the development of a risk assessment strategy for delivering a strong technical basis to support effective, licensable, and secure digital instrumentation and control (DI&C) technologies for digital upgrades to NPPs [9-11].

An integrated risk assessment technology for the DI&C aims to:

- provide a best-estimate, risk-informed capability to quantitatively and accurately estimate the safety margin obtained from plant modernization, especially for the high safety-significant safety-related DI&C systems;
- support and supplement existing advanced risk-informed DI&C design guides by providing quantitative risk information and evidence;
- offer a capability for evaluating the design architecture of various DI&C systems to support system design decisions and diversity and redundancy applications;
- ensure the long-term safety and reliability of DI&C systems; and
- reduce cost uncertainty and support the integration of DI&C systems in the plant.

2.4. Enhanced Fire Probabilistic Risk Assessment

Implementation and management of fire PRAs is very expensive. Many fire scenarios are modeled using unrealistic conservatisms, leading to overestimated fire risks. NPPs would benefit from refining these overly conservative fire scenarios, but this is usually cost prohibitive due to very intensive labor efforts required for any scenario modification. This project encompasses R&D for streamlining fire PRA modeling processes, thus affording NPPs the opportunity to gain safety margins in terms of reduced fire risks [12, 13].

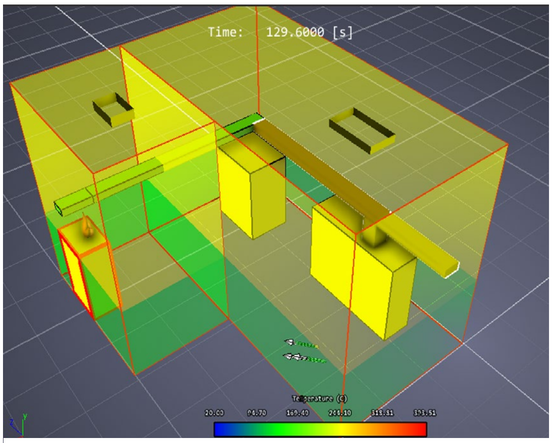

Figure 4. FRI3D Simulation.

The R&D 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 methods of modeling complex scenarios, as opposed to the highly conservative simplified methods currently in use.

The Fire Risk Investigation in 3D (FRI3D) modeling and simulation software was developed under this project and is now available for industry use: https://centroidlab.com/project/fri3d/.

2.5. Optimization of Reactor Core Design

The optimization of the fuel loading pattern is one of the most important considerations in reducing the amount of new fuel used in the core. However, the loading pattern cannot be optimized by itself. Fuel performance analysis and system safety analysis (i.e., thermal-hydraulics) results must also be considered to determine the most appropriate loading patterns.

Due to thousands of possible core configuration options, finding optimal solutions is unachievable for humans. This is where modern artificial intelligence (AI) techniques come into play. In this research, the genetic algorithm method was integrated with physics-based assessments using RAVEN as a main controller.

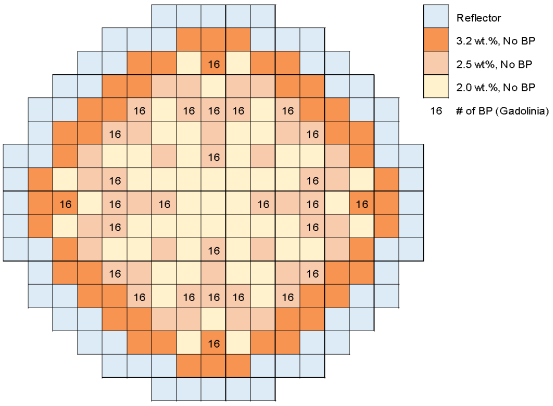

Figure 5. Randomly generated PWR core.

The optimization methodology allows for handling multiple objectives, such as reduced volume of new fuel and longer operation between refueling outages, and many constraints. The framework was successfully demonstrated on the real-life Pressurized Water Reactor (PWR) in collaboration with a U.S. utility [14, 15].

2.6. Dynamic Risk Assessment

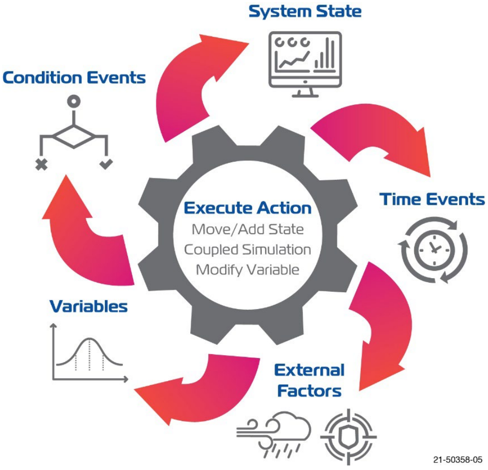

Figure 6. Conceptual framework of dynamic risk assessment.

Dynamic PRA was introduced a few decades ago, but it is still relatively immature compared to the traditional (static) PRA even though it offers multiple benefits. Dynamic PRA, just as with static PRA, evaluates risk of adverse scenarios, their likelihoods, and the consequences stemming from those scenarios. The major difference between dynamic and static PRA lies in the evaluation and application of time and physics—dynamic PRA is capable of explicitly integrating time and physical phenomena into risk considerations.

We have developed a dynamic risk assessment tool, Event Modeling Risk Assessment Using Linked Diagrams (EMRALD), which uses discrete event simulation to calculate system failure probabilities during various stages of the event progression [16-18].

The dynamic approach to risk assessment necessitates similar capabilities in human reliability analysis (HRA). HUNTER, Human Unimodel for Nuclear Technology to Enhance Reliability, tool satisfies this need—it evaluates performance of humans during the progression of an abnormal event [19-22]. HUNTER explicitly incorporates principles of human psychology to for a better-refined evaluation of human cognitive performance.

While the static PRA and HRA models satisfy current industry needs, both from a utility and a regulator perspective, these models are becoming increasingly difficult to use for novel operating conditions and hazard scenarios. Researchers should tackle cutting-edge methods and tie them into advances in fields such as psychology and AI. Dynamic PRA/HRA research is a way to address the range of phenomena ignored by static methods.

2.7. Risk-Informed Aging Management

According to the latest Nuclear Energy Institute (NEI) industry survey [23], more than 90% of the 80 units surveyed anticipate receiving approval to operate for at least 80 years. As part of the application process for license renewal and SLR, nuclear utilities must perform an evaluation to confirm that the renewal scope appropriately considers aging's effects on plant SSCs.

LWRS team conducted research [24] to identify opportunities to risk-inform aging management with the goal to reduce associated costs. The focus of the project was on buried piping, components that are difficult and costly to inspect and replace. Modern in-service inspection technologies could assist in data collection for the condition of passive components like buried pipes and cables. Advanced modeling and simulation tools, like Multiphysics Object-Oriented Simulation Environment (MOOSE), can then evaluate the fit-for-service of the component given collected and analyzed data offering accurate predictions of the failure rates and times.

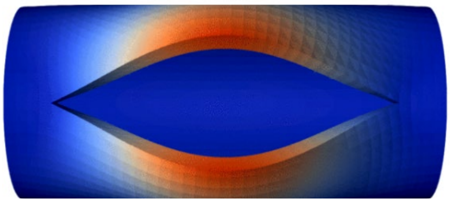

Figure 7. Pipe crack propagation modeled in MOOSE.

3. RISK ASSESSMENT OF ADVANCED NPPS AND NOVEL OPERATIONAL STRATEGIES

In addition to risk assessment of traditional operation of NPPs, Idaho National Laboratory (INL) conducts research to understand other risks relevant to novel operational strategies of existing NPP, risks of new advanced NPPs, as well as hazards and risks for critical infrastructure systems and facilities.

3.1. Risk Assessment of NPP Coupled with Hydrogen Generation Facility

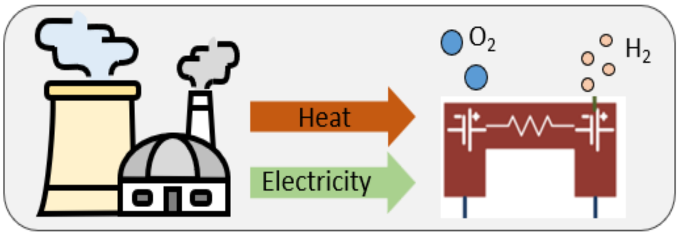

Figure 8. NPP provides heat and electricity to HTSE facility

Nuclear energy is exceptionally positioned to support clean hydrogen generation via electrolysis since a NPP can provide thermal energy and electricity. However, this coupled operation introduces unique hazards such as close proximity of potentially explosive hydrogen and plant modification required to extract steam and redirect electricity to support hydrogen generation.

The LWRS team evaluated hazards associated with the NPP modifications necessary to support the placement of a co-located high temperature electrolysis hydrogen production facility (HTEF). The identified hazards provided input to the PRA model of the generic NPP and HTEF facilities. The fragility of the NPP SSCs combined with deterministic consequence analysis were used to risk-inform the safe separation distance of the HTEF from the NPP's most fragile SSC, the switchyard transmission tower. Both the deterministic and probabilistic results support the licensing case for the proposed changes to the NPP and safe siting distance of the HTEF.

The research demonstrated, with high confidence, that a HTSE facility could be located as close as 200 meters from the NPP transmission towers, the most vulnerable SSCs [25]. The PRA results support the use of risk-informed approach to justify placement of hydrogen generation facility close to the NPP without a license amendment request due to very low increase in risk [25, 26].

3.2. Probabilistic Risk Assessments of Advanced Nuclear Reactors

INL leads R&D for new advanced nuclear reactors, including risk assessments which are an essential part of nuclear reactor development, licensing, and later operation. INL researchers perform risk assessments of several novel reactor technologies (see reference [27] as an example), to inform reactors design and demonstrate their safety in support of licensing applications.

3.3. Site Integration and Regulatory Considerations for a Nuclear Power Plant Co-located with Industrial Facilities

Multiple advanced nuclear reactor technologies are well-positioned to support various industrial processes many of which are hard to electrify with the goal of substantial reduction of CO_2 emissions. However, such coupled operation introduces unique challenges in terms of additional hazards and risks for both NPP and the industrial facility which warrants comprehensive analyses.

The INL researchers explored co-locating NPPs with industrial applications [28]. Three existing industrial sites were considered to demonstrate the siting process and illuminate technological gaps for future work. The three applications demonstrated for co-location were a petroleum refinery, a methanol production plant, and a pulp and paper plant. The study used siting criteria to explore the geological and demographic characteristics of the location of the current industrial site, as well as exploring external hazards from the industrial plant and its surrounding land use. The study assessed how the site characteristics may impact the ability to co-locate an NPP with an industrial application and performed hazard analyses to determine how co-location may impact reactor safety. The project identified additional needs for future research on placing NPPs alongside petroleum refineries, methanol, and pulp and paper plants which should consider a more comprehensive review of local industrial hazards and pipeline networks. It should also examine the softer soil conditions that could lead to higher site preparation costs, assess the risks of coastal flooding and hurricanes, and explore the possibility of using existing natural gas pipelines for hydrogen delivery when direct NPP heat use is impractical. The opportunity for resource sharing with nearby industrial plants could lead to additional co-location possibilities.

4. INFRASTRUCTURE RESILIENCE ASSESSMENT

With impacts from natural disasters and human-caused incidents on the rise, resiliency—the ability to withstand impacts and rapidly recover from different degrees of disruption— has become a top priority. National defense, economic prosperity and quality of life have long depended on critical infrastructures such as energy, water, transportation and telecommunications. INL is conducting extensive R&D to improve the understanding of critical infrastructure vulnerabilities and develop mitigating strategies. Several areas targeting risk reduction for critical infrastructure are discussed below.

4.1. Resilience Optimization Center

INL established Resilience Optimization Center (IROC), an innovation center for system resilience and risk management [29]. The center draws from INL's extensive track record as a world leader in critical infrastructure systems analysis and security, as well as its unique, large-scale test ranges. Resilience planning should be scaled and bound to an operation's criticality, risk profile and budget. Forming a plan to enhance the resilience of critical infrastructures requires owners/operators to determine the ability of the system to withstand specific threats and then return to normal operations following degradation. Thus, a resilience methodology requires comprehensive consideration of all parts of critical infrastructure systems—from threats to consequences. The methodology must generate reproducible results that can support decision making in risk management, disaster response, and business continuity.

IROC can organize multi-disciplinary teams and laboratory-wide lifeline-infrastructure capabilities that are scalable to any asset, system or network, regardless of function or geography. Its experts also can analyze the resilience impacts posed by cyber-physical relationships and infrastructure dependencies and interdependencies. In short, IROC is a highly collaborative center that employs tools and resources from across multiple resources. By leveraging existing expertise, tools, test infrastructures and other partner capabilities, IROC can comprehensively analyze the state of stakeholder resilience and provide optimized solutions that will yield observable results.

4.2. All Hazard Analysis

All Hazards Analysis (AHA) [30], is a dynamic framework for dependency analysis, empowering the discovery of critical infrastructure insights and facilitating decision making. Developed by Idaho National Laboratory, AHA identifies dependencies and associated risks, offering decision-makers and emergency managers a holistic perspective on interconnected infrastructure systems.

Employing an optimized framework, AHA efficiently collects, stores, analyzes and visualizes critical infrastructure data. Its function-based approach organizes information into nodes (representing infrastructure) and links (depicting dependency relationships). Continuously learning, AHA integrates general and facility dependency profiles with new data and evolving network structures, enabling more comprehensive sector analysis and consequence assessment compared to other infrastructure modeling systems.

4.3. Electrical Substation Configuration Effect on Substation Reliability

It is crucial that the electrical grid is reliable due to its critical role in all the areas of everyday life. Many common tasks and industrial operations rely on proper electrical power distribution. In designing new systems or evaluating existing ones, the system configuration affects risk, reliability, maintenance, and costs. Electrical utility companies are seeking ways to numerically analyze reliability of the grid. Such analysis is essential for ensuring reliable electrical power distribution.

The INL tram conducted research where PRA was used to evaluate sensitivity of substation reliability to different configurations as discussed in [31].

Acknowledgements

The work described here is funded primarily by the U.S. Department of Energy, Office of Nuclear Energy, though the Light Water Reactor Sustainability Program and Integrated Energy Systems Program.

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