Light Water Reactor Sustainability Program

Risk-Informed Systems Analysis (RISA) Pathway Technical Program Plan

September 2019

U.S. Department of Energy
Office of Nuclear Energy
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Risk-Informed Systems Analysis (RISA) Pathway
Technical Program Plan

Hongbin Zhang
Yong-Joon Choi
Curtis Smith
Steven Prescott
Diego Mandelli
Andrea Alfonsi

September 2019

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U.S. Department of Energy
Office of Nuclear Energy
EXECUTIVE SUMMARY

The United States nuclear industry is facing a strong challenge to ensure maximum safety while enhancing economic benefit. Safety is a key parameter to all aspects related to light water reactor (LWR) nuclear power plants (NPPs), especially cost savings. Since the goal is to extend the lifetimes of these NPPs, the traditional deterministic safety concept may not guarantee a current economic asset. The Light Water Reactor Sustainability (LWRS) Program has been promoting a wide range of research and development (R&D) in this field to maximize the safety, economics, and performance of these NPPs through improved scientific understanding.

One of the best practices to achieve this goal is to identify and optimize safety margin, which can lead to cost reduction. To do this, under the LWRS framework, the Risk-Informed Systems Analysis (RISA) Pathway will focus on the optimization of safety margin and minimization of uncertainties to ensure both safety and economics at the highest level. The RISA Pathway will provide enhanced capabilities for analyzing and characterizing LWR systems performance by developing and demonstrating methods, tools, and data to enable risk-informed margins management.

The main purpose of the RISA Pathway is to support the U.S. nuclear industry with the aim to improve economics, reliability, and sustain safety of current NPPs over periods of extended plant operations. The goals of the RISA Pathway are twofold: (1) deploy the risk-informed tools and methods that enable better representation of safety margins and factors that contribute to cost and safety; and (2) conduct advanced risk-assessment applications with industry to support margin management strategies that enable more cost-effective plant operation. The tools and methods provided by the RISA Pathway will support effective margin management for both active and passive safety systems, structures and components of a NPP.

The RISA tools will be demonstrated through industry application pilot demonstrations, which are identified through in-depth discussions and participation from leading organizations in the U.S. nuclear industry. These pilot demonstrations are developed following three RISA R&D focus areas based on the industry current challenges: (1) enhanced resilient NPP concepts; (2) cost and risk categorization applications; and (3) margin recovery and operation cost reduction. Pilot demonstration projects have been identified in order to use the selected RISA toolkit along with the industry partners. Further, the verification and validation status of tools and methods will be evaluated. The RISA Pathway will continue communication with related U.S. nuclear industries and institutes to assess emerging issues and demands, and to promote effective deployment of the risk-informed tools and methods for the benefit of the existing fleet.

This report summarizes the program plan, milestones, and deliverables of the RISA Pathway.
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<tr>
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<th>Full Form</th>
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<tbody>
<tr>
<td>1D</td>
<td>one-dimensional</td>
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<tr>
<td>2D</td>
<td>two-dimensional</td>
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<tr>
<td>3D</td>
<td>three-dimensional</td>
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<tr>
<td>ALWR</td>
<td>Advanced Light Water Reactor</td>
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<td>API</td>
<td>Application Programming Interface</td>
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<tr>
<td>ATF</td>
<td>Accident Tolerant Fuel</td>
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<tr>
<td>ATWS</td>
<td>Anticipated Transients without Scram</td>
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<tr>
<td>BDBA</td>
<td>Beyond Design Basis Accident</td>
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<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
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<tr>
<td>CASL</td>
<td>Consortium on Advanced Simulation of LWRs</td>
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<tr>
<td>CDF</td>
<td>Core Damaged Frequency</td>
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<tr>
<td>CFAST</td>
<td>Consolidated Model of Fire and Smoke Transport</td>
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<tr>
<td>CNWG</td>
<td>Civil Nuclear Energy Research and Development Working Group</td>
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<td>CSARP</td>
<td>International Cooperative Severe Accident Research Program</td>
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<td>CSNI</td>
<td>Committee on the Safety of Nuclear Installations</td>
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<tr>
<td>DBA</td>
<td>Design Basis Accident</td>
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<tr>
<td>DNB</td>
<td>Departure of Nucleate Boiling</td>
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<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
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<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
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<tr>
<td>ER</td>
<td>Equipment Reliability</td>
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<tr>
<td>ESFAS</td>
<td>Engineered Safety Feature Actuation System</td>
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<tr>
<td>ESSAI</td>
<td>Energy Systems, Strategies, Assessments, and Integration</td>
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<tr>
<td>FDS</td>
<td>Fire Dynamics Simulator</td>
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<tr>
<td>FF</td>
<td>Functional Failure</td>
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<tr>
<td>FLEX</td>
<td>Diverse and Flexible Coping Strategy</td>
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<td>HEP</td>
<td>Human Error Probability</td>
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<td>HWR</td>
<td>Heavy Water Reactor</td>
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<td>I&amp;C</td>
<td>Instrumentation and Controls</td>
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<td>ILCM</td>
<td>Integrated Life Cycle Management</td>
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<tr>
<td>INL</td>
<td>Idaho National Laboratory</td>
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<tr>
<td>IR</td>
<td>Incident Report</td>
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<tr>
<td>ISO</td>
<td>Independent System Operators</td>
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<tr>
<td>LERF</td>
<td>Large Early Release Frequency</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>LOCA</td>
<td>Loss Of Coolant Accident</td>
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<td>LWR</td>
<td>Light Water Reactor</td>
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<td>LWRS</td>
<td>Light Water Reactor Sustainability</td>
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<tr>
<td>MAAP</td>
<td>Modular Accident Analysis Program</td>
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<tr>
<td>MOOSE</td>
<td>Multiphysics Object-Oriented Simulation Environment</td>
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<tr>
<td>MP-BEPU</td>
<td>Multi-Physics Best Estimate Plus Uncertainty</td>
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<tr>
<td>MPFF</td>
<td>Maintenance Preventable Functional Failure</td>
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<tr>
<td>MSPI</td>
<td>Mitigating Systems Performance Index</td>
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<tr>
<td>NEA</td>
<td>Nuclear Energy Agency</td>
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<td>NEAMS</td>
<td>Nuclear Energy Advanced Modeling and Simulation</td>
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<td>NEET</td>
<td>Nuclear Energy Enabling Technologies</td>
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<td>NEUP</td>
<td>Nuclear Energy University Program</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<tr>
<td>NLSSI</td>
<td>Non-linear Soil-Structure Interaction</td>
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<td>NOEP</td>
<td>Notice Of Enforcement Discretion</td>
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<tr>
<td>NPP</td>
<td>Nuclear Power Plant</td>
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<tr>
<td>NRC</td>
<td>U.S. Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>OECD</td>
<td>Organization for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCT</td>
<td>Peak Cladding Temperature</td>
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<td>PNNL</td>
<td>Pacific Northwest National Laboratory</td>
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<tr>
<td>PRA</td>
<td>Probabilistic Risk Assessment</td>
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<tr>
<td>PSF</td>
<td>Performance-Shaping Factor</td>
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<td>PSM</td>
<td>Plant “Super” Model</td>
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<tr>
<td>PWR</td>
<td>Pressurized Water Reactor</td>
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<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
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<tr>
<td>RAVEN</td>
<td>Risk Analysis in a Virtual Environment</td>
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<tr>
<td>RCIC</td>
<td>Reactor Core Isolation Cooling</td>
</tr>
<tr>
<td>RD&amp;D</td>
<td>Research, Development, and Demonstration</td>
</tr>
<tr>
<td>RELAP-5</td>
<td>Reactor Excursion and Leak Analysis Program-5</td>
</tr>
<tr>
<td>RHR</td>
<td>Residual Heat Removal</td>
</tr>
<tr>
<td>RIA</td>
<td>Reactivity Initiated Accident</td>
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<tr>
<td>RIMM</td>
<td>Risk-Informed Margin Management</td>
</tr>
<tr>
<td>RI-MP-BEPU</td>
<td>Risk-Informed Multi-Physics Best Estimate Plus Uncertainty</td>
</tr>
<tr>
<td>RISA</td>
<td>Risk-Informed Systems Analysis</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>RISC</td>
<td>Risk-Informed Safety Categorization</td>
</tr>
<tr>
<td>RISMC</td>
<td>Risk-Informed Safety Margins Characterization</td>
</tr>
<tr>
<td>RPS</td>
<td>Reactor Protection System</td>
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<tr>
<td>RPV</td>
<td>Reactor Pressure Vessel</td>
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<tr>
<td>RTO</td>
<td>Regional Transmission Organization</td>
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<tr>
<td>SAMG</td>
<td>Severe Accident Management Guideline</td>
</tr>
<tr>
<td>SDP</td>
<td>Significance Determination Process</td>
</tr>
<tr>
<td>SLR</td>
<td>Second License Renewal</td>
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<tr>
<td>SNL</td>
<td>Sandia National Laboratories</td>
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<tr>
<td>SSC</td>
<td>System, Structure, and Component</td>
</tr>
<tr>
<td>SVVP</td>
<td>Software Verification and Validation Plan</td>
</tr>
<tr>
<td>TCD</td>
<td>Thermal Conductivity Degradation</td>
</tr>
<tr>
<td>TRISO</td>
<td>Tristructural Isotropic</td>
</tr>
<tr>
<td>TTEXOB</td>
<td>Terry Turbine Expanded Operating Band</td>
</tr>
<tr>
<td>V&amp;V</td>
<td>Verification and Validation</td>
</tr>
<tr>
<td>WGEV</td>
<td>Working Group on Natural External Hazards</td>
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</table>
Risk-Informed Systems Analysis (RISA) Pathway Technical Program Plan

1. BACKGROUND

Safety is central to the design, licensing, operation, and economics of the United States light water reactor (LWR) nuclear power plant (NPP) fleet. As the current LWR NPPs age beyond 60 years, there are possibilities for increasing frequency of degradations or failures to the structures, systems, and components (SSCs) that initiate safety-significant events, reducing existing accident mitigation capabilities, or creating new failure modes. Plant designers commonly “over-design” portions of NPPs and provide robustness in the form of redundant and diverse-engineered safety features to ensure that, even in the case of well-beyond design basis accident (BDBA) scenarios, public health and safety will be protected with a very high degree of assurance. This form of defense-in-depth concept is a reasoned response to uncertainties and is often referred to generically as a “safety margin.” Historically, specific safety margin provisions have been formulated primarily based on “engineering judgment.” Further, these historical safety margins have been set conservatively (for example in design and operational limits) in order to compensate for uncertainties.

The Light Water Reactor Sustainability (LWRS) Program is focused on ensuring the safety and performance of the nuclear fleet to enhance operational efficiencies of existing NPPs, support long-term operation, and provide confidence for subsequent license renewals. Within this program, the Risk-Informed Systems Analysis (RISA) Pathway is solving technical issues for several of the “sustainability” dimensions that exist, as illustrated in Figure 1-1.

Since safety is important to successful operation of the NPPs, there are strong motivations to better manage safety and its associated “margin.” These motivations include having improved knowledge of both the qualitative and quantitative aspects of safety margins in order to provide for enhancements and improvement in NPPs, including support for applications such as:

- **Plant design changes**: During the lifetime of the NPP, design changes could be implemented to follow appropriate application of regulatory and licensing processes. For example, extension of power generation will promise a significant amount of profits.

![Figure 1-1. The sustainability aspects that exist for near- and long-term NPP operation](image-url)
- **Operability issues:** During NPP operations, a variety of off-normal situations may arise, such as licensing issues (e.g., nearing a limit for an allowable outage time) that may cause potential SSC failure. Having an improved safety technical basis may provide an enhanced operation durability (e.g., not having to shut down the plant) and reduced regulatory actions.

- **Addressing BDBAs:** As a result of the Fukushima event, the U.S. Nuclear Regulatory Commission (NRC) established a task force to conduct a review of NRC processes and regulations to determine if the agency should make additional improvements to its regulatory system. This task force, known as the Near-Term Task Force gave recommendations to the Commission in report SECY-11-0137 [1]. Currently, the deterministic analysis method is used for design basis requirements for NPPs related to hazards such as flooding and earthquake. However, the licensees are obliged to provide in-depth analysis on BDBAs to the NRC. The advanced safety margin evaluation method will give better insights to BDBA analysis.

- **Plant life beyond 60 years:** The ability to better characterize (i.e., describe and quantify) safety margins will give clear vision to improved decision-making on LWR design, economics, and long-term operation.

- **Economic efficiencies by leveraging risk information:** Through regulations such as 10 CFR 50.69, the RISA methods and tools can provide flexibility to reduce cost and improve plant operations and safety margins. 10 CFR 50.69 has two parts—the first is to use risk analysis to categorize plant components, while the second is for “low safety significant” components to determine “relaxed requirements” for those components. This process of risk-informed engineering program provides several possible areas for investigation:
  - Using the existing probabilistic risk assessment (PRA) to categorize components is challenging and time-consuming. By using advanced RISA tools, automation of the analyses could be realized and may provide an additional technical basis for categorization purposes.
  - RISA methods could supply a “50.69 limit surface,” where the simulation method uses data mining to explore regions around the safety margin threshold for the low safety significant components.
  - Determining what to do under the “relaxed requirements” is not always straightforward. RISA simulation-based data mining can be used to more fully understand margins and possible changes to components, such as extending testing and inspection intervals. These quantitative analyses can be used to strengthen the technical basis to support these applications and complement the engineering and licensing elements of 10 CFR 50.69.
  - Within the process of fulfilling 10 CFR 50.69, the risk assessment must have both internal events (e.g., initiators such as transients, loss of key systems, loss-of-coolant-accidents [LOCAs]) and internal flooding. The RISA advanced flooding models are less conservative than static models and may provide additional components classified as low safety significant and will provide a more comprehensive technical basis for this specific hazard type.

Within the RISA Pathway, the application of “risk” is intended to focus not only on safety, but also on potential shortfalls important to plant reliability, safety, and economics. Thus, the R&D that is applied through the Pathway is not just centered on PRA. Instead, we take a broader view of risk that encompasses integrated models that can better understand plant margins in terms of operational efficiencies, safety, and economics; we also strive to provide associated improvements in performing these analyses.

The RISA methodology can optimize plant safety and performance by incorporating plant impacts, physical aging, and degradation processes into the safety analysis. A systematic approach to the characterization of safety margins and subsequent margins management options represents a vital input to the involving licensee and regulatory analysis and decision-making. In addition, as R&D in the LWRS
Program and other collaborative efforts yield new data and improved scientific understanding of physical processes governing the aging and degradation of plant SSCs (and concurrently support technological advances in nuclear reactor fuels and plant instrumentation and control systems), opportunities to better optimize plant safety and performance will be realized. This interaction of improved scientific understanding and potential impacts to plant margins is shown in Figure 1-2. To support decision-making related to economics, reliability, and safety, the RISA Pathway will provide tools and methods via the RISA toolkit, that enable mitigation options known as risk-informed margin management (RIMM) strategies.

![Figure 1-2](image)

Figure 1-2. Representation of the interaction of degradation mechanisms that may impact plant operations and safety barriers if left unmitigated [23]
2. RESEARCH, DEVELOPMENT AND DEMONSTRATION

2.1 Purpose, Goals, and Strategy

The RISA Pathway provides enhanced capabilities for analyzing and characterizing LWR systems performance by developing and demonstrating methods, tools, and data to enable RIMM.

The purpose of the RISA Pathway R&D is to support plant owner-operator decisions with the aim to improve the economics, reliability, and maintain the high levels of safety of current NPPs over periods of extended plant operations. The goals of the RISA Pathway are twofold:

1. Deploy the RISA toolkit of technologies that enable better representation of safety margins and the factors that contribute to cost and safety.
2. Conduct advanced risk-assessment applications with industry to support margin management strategies that enable more cost-effective plant operation.

A strategy to accomplish the above RISA Pathway goals employs the following:

1. Conduct research to develop and demonstrate industry applications in pilot projects that employ the RISA methodology collaboratively with organizations from the U.S. commercial nuclear power industry.
2. Leverage industry pilot demonstration projects to address needs of the entire industry, demonstrating how the use of risk-informed techniques can improve plant efficiency and increase confidence in their use.

The RISA Pathway has two primary elements to guide R&D activities. The first element involves developing a set of tools and methods that can be used to develop the technical basis for plant safety margins and support their use in applications of risk-informed decision-making. The second element is on industry pilot demonstrations using modern software and associated tools to quantify safety margins that can be used for commercial deployment. This set of tools, collectively known as the “RISA toolkit,” will enable a risk analysis capability that currently does not exist.

To better understand the approach to characterize and employ safety margins in risk-informed engineering, two types of analyses are used in this Pathway—probabilistic and mechanistic analysis, as shown in Figure 2-1. In actual applications, both probabilistic and mechanistic analysis will be combined to support decision.

Figure 2-2 shows the RISA Pathway program structure. The main R&D program focuses on methods, tools, and data areas. The RISA R&D results will be applied to challenging industry-demanded programs (i.e., the so called “industry application pilot demonstrations”, in-short “pilot project”).

Figure 2-1. Types of analysis that are used in the RISA Pathway

Figure 2-2. The RISA Pathway programmatic structure
2.2 Safety and Economic Impacts

The RISA Pathway provides tools and methods to inform NPP margin management decisions, with a focus on improved economics and reliability. These tools and methods were developed throughout the last seven years with a focus on coupling (a) risk-assessment (probabilistic) and (b) systems margin quantification (deterministic) to achieve very accurate modeling and representation of margins for the long-term benefit of NPPs. Figure 2-3 shows the strategy to achieve the stated goals. The issues were addressed by major U.S. nuclear industries. The RISA Pathway then selected the “High Value RISA Pilot Demonstration Projects”, which is the most urgent and impactful issue to address both safety and cost savings. Demonstration of a select pilot project using the RISA methods tools will deliver the maximum positive economic impact to the NPPs (quadrants to the right) while sustaining high levels of safety (top right quadrant). The implementation strategy of the risk-informed tools and methods focuses on industry organizations participation in pilot demonstration projects addressing key issues relevant to NPPs.

Figure 2-3. Safety and economic benefit from the RISA Pathway

To successfully accomplish the goals described in Section 2.1, the RISA Pathway will define and demonstrate the risk-informed safety margin approach. The determination of the degree of a safety margin requires an understanding of risk-based scenarios. Within a scenario, an understanding of plant behavior (i.e., operational rules such as technical specifications, operator behavior, and SSC status) and associated uncertainty will be required to interface with system codes (i.e., RELAP5-3D as currently coupled with the Risk Analysis in a Virtual Environment [RAVEN]). Then, to characterize safety margin for a specific safety performance metric of consideration (e.g., peak clad temperature), the plant simulation will determine time- and scenario-dependent outcomes for both the load and capacity. Specifically, the safety margin approach will use the physics-based plant results (the “load”) and contrast these to the capacity (for the associated performance metric) to determine if the safety margins have been exceeded (or not) for a family of accident scenarios. Engineering insights will be derived based on the scenarios and associated outcomes.

---
a. Safety performance metrics may be application-specific, but in general are engineering characteristics of the NPP, for example, as defined in 10 CFR 50.36, “safety limits for nuclear reactors are limits upon important process variables that are found to be necessary to reasonably protect the integrity of certain of the physical barriers that guard against the uncontrolled release of radioactivity.”
In addition to the safety impacts represented in the probabilistic scenarios, the RISA Pathway is also able to address economic impacts. As shown in Figure 2-4, two alternatives could be considered:

Alternative #1 – retain the existing, but aging, component as-is
Alternative #2 – replace the component with a new one.

Each of these alternatives has an economic impact associated with it. However, the type of costs associated with each is complicated and falls into two general types—direct costs (typically with small uncertainties) and indirect costs (typically with large uncertainties). Examples of these costs are:

- **Alternative #1:**
  - Direct costs: Inspection or maintenance of the aging component now and in the future.
  - Indirect costs: The cost associated with pre-cursor events in the future; the cost associated with accidents in the future; and the cost to replace the component in the future.

- **Alternative #2:**
  - Direct costs: The cost to replace the component now.
  - Indirect costs: The cost associated with pre-cursor events in the future; and the cost associated with accidents in the future.

For the two alternatives, the direct costs would typically be modeled and quantified by the owners/operators of the specific facility. It is the other costs, those that occur probabilistically (i.e., in the future), that is of interest to the RISA Pathway since our methods and tools can represent and quantify those costs directly as part of the simulation.
2.3 RD&D Risk-Informed Approach

2.3.1 Methodology

Central to this Pathway is the concept of a safety margin. In general engineering terms, a “margin” is usually characterized in one of two ways:

- A *deterministic* margin, defined by the ratio (or, alternatively, the difference) of an applied capacity (i.e., strength) to the load. For example, we test a pressure tank to failure where the tank design is rated for a pressure \( C \), it is known to fail at pressure \( L \), thus the margin is \((L - C)\) (safety margin) or \( L/C \) (safety factor).

- A *probabilistic* margin, defined by the probability that the load exceeds the capacity. For example, we model failure of a pressure tank where the tank design capacity is a distribution \( f(C) \), its loading condition is a second distribution \( g(L) \), the probabilistic margin would be represented by the expression \( \Pr[L > C] \).

In practice, actual loads \( (L) \) and capacities \( (C) \) are uncertain and, consequently, most engineering margin evaluations are (or should be) of the probabilistic type (in cases where deterministic margins are evaluated, the analysis is typically conservative in order to account for uncertainties). The RISA Pathway uses the probability margin approach to quantify impacts to economics, reliability, and safety in order to avoid conservatism (where possible) and treat uncertainties directly. Further, this approach is used in RIMM to present results to decision-makers as it relates to margin evaluation, management, and recovery strategies. The types of margins that can be characterized vary according to the “system” of interest and the performance metrics being evaluated. Examples of these metrics are listed in Table 2-1.

<table>
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<tr>
<th>“System”</th>
<th>Performance Metric</th>
<th>Example of Margin Contributors</th>
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| Nuclear Power Plant           | Safety margin      | \( L \) = scenarios are modeled that represent component failures/successes leading to an increased core coolant temperature.  
\( C \) = ability of the fuel/clad to withstand elevated core coolant temperature. |
| Structures such as the Core Internals | Economic margin | \( L \) = scenarios are modeled that account for potential costs of off-normal conditions and replacement due to core internal degradation issues.  
\( C \) = ability of the core internals to withstand radiation embrittlement and corrosion. |
| Component such as an Emergency Diesel Generator | Seismic margin | \( L \) = scenarios are modeled that estimate the energy transferred from an earthquake using non-linear soil-structure interaction analysis.  
\( C \) = ability of a diesel generator to withstand the energy transferred from the earthquake. |
Figure 2-4 illustrated a type of approach that can be taken by the RISA method and tools. For this example, the main hypothesis is that the NPP decision-maker has two alternatives to consider:

- Alternative #1 – retain an existing, but aging, component as-is
- Alternative #2 – replace the component with a new one.

Using simulation-based risk analysis methods and tools, 30 simulations were performed where this component plays a role in plant response under off-normal conditions. For each of the 30 simulations, the outcome was calculated based on a selected safety metric – in this example, peak clad temperature – and compared against a capacity limit (assumed to be 2200°F). However, these simulations should run for both alternative cases, resulting in a total of 60 simulations.

The results of these simulations are then used to determine the probabilistic margin:

- Alternative #1: \( \Pr[L > C] = 0.17 \)
- Alternative #2: \( \Pr[L > C] = 0.033 \)

If the safety margin characterization were the only decision factor, then Alternative #2 would be preferred, since it has a better margin than Alternative #1 as its safety characteristics are better. However, these insights are only part of the information that would be available to the decision-maker. For example, the costs and schedules related to the alternatives would also need to be considered. In many cases, multiple alternatives will be available to the decision-maker, due to level of redundancy and several barriers for safety present in current NPPs. If one focuses on a specific scenario shown in Figure 2-4, the details of the scenario could be evaluated from the determined failure or success (i.e., failure is defined as scenarios resulting in a peak cladding temperature in the core greater than 2200°F). Each “box” embodies a single simulation representing a single scenario. This scenario could be determined by RAVEN, where scenarios are set via stochastic simulation. For example, “inside” the first blue box labeled “1580” under Alternative #1, the scenario that is captured could produce the information shown in Figure 2-5.

![Figure 2-5. Example of the details available from a scenario characterization via simulation](image)

### 2.3.2 RISA Toolkit

While simulation methods in risk and reliability applications have been proposed for several decades, the availability of advanced mechanistic and probabilistic simulation tools have been limited. But, as noted by researchers such as Zio [2], “…simulation appears to be the only feasible approach to quantitatively capture the realistic aspects of the multi-state system stochastic behavior.” Consequently, the approach we are using for the RISA Pathway is to use a set of simulation tools to model plant behavior and determine safety margins, which include:

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b. Note that in this example, the capacity is represented by a single value (i.e., 2200°F), rather than be a distribution. In general, for a performance metric such as safety, the capacity would be represented by a distribution representing the possible variation in the behavior of fuel/clad performance under various plant scenarios and conditions.
• **BISON:** BISON is a finite element-based nuclear fuel performance code applicable to a variety of fuel forms including LWR fuel rods, tristructural isotropic (TRISO) particle fuel and metallic rod and plate fuel. It is an advanced fuel performance code being developed at Idaho National Laboratory (INL) and offers distinctive advantages over FRAPCON/FRAPTRAN, such as three-dimensional (3D) simulation capability, etc. BISON solves the fully-coupled equations of thermomechanics and species diffusion, for either one-dimensional (1D) spherical, two-dimensional (2D) axisymmetric, or 3D geometries.

• **CFAST:** Developed by National Institute of Standards and Technology (NIST), the Consolidated Model of Fire and Smoke Transport (CFAST) is a computer program that fire investigators, safety officials, engineers, architects, and builders can use to simulate the impact of past or potential fires and smoke in a specific building environment. CFAST is a two-zone fire model used to calculate the evolving distribution of smoke, fire gases, and temperature throughout compartments of a building during a fire. The CFAST package includes NIST’s Smokeview program, which visualizes with colored, 3D animations, the results of the CFAST simulation of a specific fire’s temperatures, various gas concentrations and growth and movement of smoke layers across multi-room structures.

• **CRAFT:** CRAFT is a stochastic analysis framework that has been designed to evaluate the risk of SSCs of complex systems, including NPPs. The risk is evaluated from both a financial and a safety perspective by explicitly considering aging of SSCs and their impact on the overall plant risk. CRAFT applications range from plant asset management to plant risk diagnostics and prognostic.

• **EMRALD:** EMRALD is a state-based discrete event simulation tool that can calculate system failure probabilities, couple multiple simulations, and perform dynamic PRA. A key part of the EMRALD tool is to develop an object-oriented model that is flexible enough to support the varied dynamic simulation models (e.g., fails to operate, fails on demand). By having a state-based approach, it can integrate different hazards into a single comprehensive model. For example, a single model can include fire-, flooding-, transient-, and seismic-initiating events. Each of these events becomes a trigger into the state-based approach that tells the model to make a transition based upon the specific initiator.

• **FDS:** NIST developed the computational fluid dynamics Fire Dynamics Simulator (FDS) code to perform computational fire modeling and simulation. The code has been extensively validated for the types of fire scenarios encountered in both standard buildings, as well as nuclear environments. FDS facilitates the simulation of combustion, including fire migration, of an arbitrary number of materials in geometrically complex environments.

• **FRAPCON/FRAPTRAN:** FRAPCON/FRAPTRAN is a suite of codes developed by Pacific Northwest National Laboratory (PNNL) for the NRC for the purposes of performing fuel performance analyses under steady state (FRAPCON) and transient (FRAPTRAN) conditions. FRAPCON is a computer code that calculates the steady-state response of LWR fuel rods. The code calculates the temperature, pressure, and deformation of a fuel rod as functions of time-dependent fuel rod power and coolant boundary conditions. FRAPTRAN calculates the transient performance of LWR fuel rods during reactor transients and hypothetical accidents such as LOCAs, anticipated transients without scram, and reactivity-initiated accidents. FRAPTRAN calculates the temperature and deformation history of a fuel rod as a function of time-dependent fuel rod power and coolant boundary conditions.

• **GRIZZLY:** GRIZZLY is a simulation code being developed to simulate the progression of aging mechanisms and SSCs in LWRs and to assess their ability to safely perform their intended engineering functions after being subjected to aging. GRIZZLY is ultimately planned to have capabilities for modeling a variety of structures, but current development is focused on reactor
pressure vessels (RPVs) and concrete structures because of the essential functions and extreme
difficulty of mitigating degradation or replacement of those components. For RPVs, GRIZZLY has a modern and flexible architecture for multidimensional engineering fracture mechanics analysis, which allows it to compute the probability of fracture in the presence of a population of pre-existing flaws that can serve as fracture initiation sites under a given transient event. It also has a set of models being developed to predict microstructure evolution under irradiation, which will be used to provide improved predictive models of embrittlement that can be applied for long-term operation scenarios. For concrete structures, GRIZZLY has coupled physics models to predict expansive mechanisms, including alkali-silica reaction and radiation-induced volumetric expansion, and their effects on the mechanical response of the structure.

- **HUNTER**: HUNTER is a flexible hybrid approach that functions as a framework for dynamic modeling, including a simplified model of human cognition—a virtual operator—that produces relevant outputs, such as the human error probability (HEP), time spent on task, or task decisions based on relevant plant evolutions. HUNTER is the human reliability analysis counterpart to the RAVEN framework used for dynamic PRA. Although both RAVEN and HUNTER are under various stages of development, there has been a successfully integrated and implemented RAVEN-HUNTER initial demonstration. The demonstration centers on a station blackout scenario, using complexity as the sole virtual operator performance-shaping factor (PSF). The implementation of RAVEN-HUNTER can be readily scaled to other nuclear power plant scenarios of interest and will include additional PSFs in the future.

- **LOTUS**: LOTUS is a Multi-Physics Best Estimate Plus Uncertainty (MP-BEPU) analysis approach being developed at INL, which establishes the automation interfaces among the various disciplines in NPP systems analysis, such that uncertainties can be propagated consistently in multi-physics simulations. LOTUS integrates existing computer codes, as well as the advanced computer codes still being developed under various U.S. Department of Energy (DOE) programs, to provide feedback and guide development of advanced tools. Regardless of the specific codes used to model the physics involved, the methodology developed in LOTUS is a paradigm shift in managing the uncertainties and assessing risks. LOTUS is essentially a workflow engine with capability to drive physics simulators, model complex systems, and provide risk assessments.

- **MASTODON**: MASTODON is a tool that will have the capability to perform stochastic Nonlinear Soil-Structure Interaction (NLSSI) in a risk framework coupled with virtual NPP. These NLSSI simulations will include structural dynamics, time integration, dynamic porous media flow, hysteretic nonlinear soil constitutive models (i.e., elasticity, yield functions, plastic flow directions, and hardening softening laws), hysteretic nonlinear structural constitutive models, and geometric nonlinearities at the foundation (i.e., gapping and sliding) [3].

- **MELCOR**: MELCOR is a computational code developed by Sandia National Laboratories (SNL) for the NRC, DOE, and the International Cooperative Severe Accident Research Program (CSARP). MELCOR simulates the response of LWRs during severe accidents. Given a set of initiating events and operator actions, MELCOR predicts the plant’s response as the accident progresses. MELCOR also includes containment transient analysis capabilities to model thermal hydraulic phenomena (within a lumped-parameter framework) for existing containment designs for boiling water reactors (BWRs) and PWRs.

- **Neutrino**: Neutrino is a mesh-free, smooth particle hydrodynamics-based solver developed by Centroid Lab, which also uses advanced boundary handling and adaptive time stepping. Neutrino is an accurate fluid solver and is being used to simulate coastal inundation, river flooding, and other flooding scenarios. Neutrino code can model friction and adhesion between solid/fluid boundaries and various adhesive hydrodynamic forces between fluid/fluid particles [4].
RAVEN: RAVEN is a flexible and multi-purpose uncertainty quantification, regression analysis, probabilistic risk assessment, data analysis and model optimization framework, designed to perform parametric and stochastic analyses based on the response of complex systems codes. It can communicate directly with the system codes described above and below (e.g., RELAP5-3D, Neutrino, BISON, MAAP, etc.), which are currently used to perform plant safety analyses. Depending on the tasks to be accomplished and on the probabilistic characterization of the problem, RAVEN perturbs (e.g., Monte-Carlo, Latin hypercube, reliability surface search) the response of the system under consideration by altering its own parameters. The data generated by the sampling process is analyzed using classical statistical and more advanced data mining approaches. RAVEN also manages the parallel dispatching (i.e. both on desktop/workstation and large High-Performance Computing machines) of the software representing the physical model. RAVEN heavily relies on artificial intelligence algorithms to construct surrogate models of complex physical systems in order to perform uncertainty quantification, reliability analysis (limit state surface) and parametric studies.

RELAP5-3D: The RELAP5-3D code has been developed for best-estimate transient simulation of LWR coolant systems during postulated accidents. Specific applications of the code have included simulations of transients in LWR systems, such as LOCA, Anticipated Transients without Scram (ATWS), and operational transients, such as loss of feed water, loss of offsite power, station blackout, and turbine trip. RELAP5-3D, the latest in the series of RELAP5 codes, is a highly generic code that, in addition to calculating the behavior of the reactor coolant system during a transient, can be used for simulation of a wide variety of hydraulic and thermal transients in both nuclear and nonnuclear systems involving mixtures of vapor, liquid, non-condensable gases and nonvolatile solutes.

RELAP-7: The RELAP-7 code is the next generation nuclear reactor system safety analysis code being developed at INL. The code is based on INL’s modern scientific software development framework, Multi-Physics Object Oriented Simulation Environment (MOOSE). The overall design goal of RELAP-7 is to take advantage of the previous thirty years of advancements in computer architecture, software design, numerical integration methods, and physical models. The result will be a reactor system analysis capability that retains and improves upon RELAP5-3D’s capabilities and extends the analysis capability for all reactor system simulation scenarios.

SAPHIRE: SAPHIRE is a software application developed for performing a complete PRA using a personal computer (PC) running the Microsoft Windows operating system. SAPHIRE enables users to supply basic event data, create and solve fault and event trees, perform uncertainty analyses and generate reports. For NPP PRAs, SAPHIRE can be used to model a plant’s response to initiating events, quantify core damage frequencies, and identify important contributors to core damage (Level 1 PRA). The program can also be used to evaluate containment failure and release models for severe accident conditions given that core damage has occurred (Level 2 PRA). In addition, SAPHIRE can be used to analyze both internal and external events and, in a limited manner, to quantify the frequency of release consequences (Level 3 PRA).

VERA-CS: VERA-CS is a core simulator tool developed by the Consortium on Advanced Simulation of LWRs (CASL) and includes coupled neutronics, thermal-hydraulics, and fuel temperature components with an isotopic depletion capability. The neutronics capability is based on MPACT, a 3D whole core transport code. The thermal-hydraulics and fuel temperature models are provided by the COBRA-TF (CTF) subchannel code. The isotopic depletion is performed using the ORIGEN code system.

The RISA toolkit currently used to perform RISA-specific applications is shown in Figure 2-6.
In addition to the RISA tools, industry codes such as CAFTA (i.e., a PRA tool), Modular Accident Analysis Program (MAAP) (i.e., a systems analysis tool), and GOTHIC (i.e., a containment response tool) will be used in the pilot demonstration projects:

- **CAFTA**: Developed by the Electric Power Research Institute (EPRI), CAFTA is an integrated tool to perform PRA, incorporating linking event tree/fault tree methodology. The code is a fault tree analysis tool, utilizing the full power of today’s PCs and providing the ability to effectively model and analyze complex systems. As fault tree analysis assumes a greater importance in many industries, the need to develop models in a logical and efficient manner has increased. CAFTA code addresses this need by providing a set of interactive editors, databases, and model evaluation tools. This interactive environment promotes the smooth flow of information throughout the model development, quantification, and results interpretation process.

- **MAAP**: MAAP is a fast-running computer code that simulates the response of LWR and heavy water reactor (HWR) moderated NPPs for both current and Advanced Light Water Reactor (ALWR) designs. It can simulate both LOCA and non-LOCA transients for PRA applications as well as severe accident sequences, including actions taken as part of the Severe Accident Management Guidelines (SAMGs).

- **GOTHIC**: GOTHIC is a versatile, general purpose thermal-hydraulics software package, which solves the conservation equations for mass, momentum, and energy for multi-component, multi-phase compressible flow in lumped parameter and/or multi-dimensional (i.e., 1D, 2D, or full 3D) geometries. The ability to combine these different nodalization options in a single model allows GOTHIC to provide computationally efficient solutions for multi-scale applications.

### 2.3.3 Verification, Validation, Uncertainty Quantification, and Data

Verification, validation, and uncertainty quantification is essential to producing tools that can (and will) be used by industry. Evaluation of existing data for validation is done in parallel with RISA toolkit development; verification is done as part of the software development process. If additional data are
needed, experiments will be designed and carried out to meet the validation needs. As the development and capabilities of the RISA toolkit progress, the LWRS Program will work with industry to determine how to transition the tools to a user-supported community of practice, including planning for lifecycle software management issues, such as training, software quality assurance, and development support. The general approach to toolkit development is that the tools will be validated to the extent that industry can then take the tools and use data specific to their design to create a validated model for their specific application.

The RISA toolkit overall quality assurance process includes the activities of verification, independent validation, assessment, and related documentation to facilitate reviews of these activities. To support activities such as validation, a variety of experimental results will be identified and collected specific to each tool/application by a team independent of the software development. These validation results include data from facility operation, integral effects test, separate effect tests and fundamental tests including experiments on individual components, as shown in Figure 2-9. Separate effect test results are used to validate and quantify uncertainty for specific physics models while component test results are used to identify and represent key parameters for component models. For example, tests related to component performance during flooding conditions represent a separate effects test. Integral effects tests are performed on large-scale experimental facilities and can be used to validate how well the code(s) represents typical scenarios that may be found for off-normal conditions.

Figure 2-7. Information types and sources that will be used for validation

INL has facilitated quality software by implementing modern software management processes (including the use of tools such as source code version control), conducting NQA-1 audits, and creating a Software Verification and Validation Plan (SVVP). The SVVP identifies software requirements and the associated tests that will be used to validate specific tools. For long-term applications, validation-data support will be a community-scale effort. For each tool in the RISA toolkit, an independent SVVP will be performed based on developed SVVP method throughout the RISA Pathway. Table 2-2 shows an example of SVVP contents, which will provide better understanding and communicating the software development process and outcomes for a specific tool.
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<td>7.</td>
<td>User Documentation</td>
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3. RESEARCH AND DEVELOPMENT FOCUS AREAS

The RISA Pathway is being performed within the framework of specific “Focus Areas” that are applied by NPP owners/operators. The goal of the RISA industry focus areas is to identify and demonstrate industry applications of risk-informed technology to assist operating NPPs to reduce costs, and otherwise adapt to the changing economic and generating-mix environment. The industry Focus Area demonstrations of interest are in the areas of margins and risk assessment and asset management. The focus area strategy emphasizes the identification and selection of a scalable pilot application for the RISA methodology and technology with a partnering utility that participates in order to both validate the feasibility of the approach and to demonstrate the value of the approach. An interest group of other utilities and industry stakeholders will provide input to the project. When demonstrated successfully, the technology may be scaled up to support applications by a larger community of users and stakeholders. To ensure producing impactful research outcomes by the RISA Pathway that supports the current and near-term needs of the operating U.S. NPP fleet, these focus areas are designed to be conducted in areas where cost and risk assessment methods/tools can help address issues that, if solved, support closing the economic gap in NPP performance. To achieve this objective, three focus areas have been identified for the RISA Pathway.

- Demonstrate the safety benefits associated with enhanced resilient nuclear power plant concepts.
- Identify, prioritize, and apply the RISA methodology and tools to assess alternative margin recovery strategies and operating costs reduction.
- Apply the RISA methodology and tools to support cost and risk categorization.

These focus areas are intended to provide a pathway for rapid technology development, deployment and dissemination throughout the operating U.S. NPPs to address issues of pressing economic, operational, or safety significance.

While simulation methods in risk and reliability applications have been previously proposed, the availability of advanced mechanistic and probabilistic simulation tools used to be limited. However, with advanced tools and modern computational resources, simulation is now a viable approach to represent complex scenarios. Consequently, the RISA Pathway approach is to use a set of existing and advanced simulation tools to model plant behavior, determine safety margins and evaluate cost-saving strategies to plant performance.

Computational codes used within the RISA Pathway include both mature codes and advanced simulation codes being developed by NEAMS, CASL and other institutions.

The following subsections have detailed description of the three focus areas.

3.1 Enhanced Resilient Nuclear Power Plant Concepts

Several initiatives are underway in the commercial nuclear power industry to enhance the safety and improve the economic competitiveness of existing nuclear power plants. These initiatives include efforts on developing accident tolerant fuel (ATF), implementing a diverse and flexible coping strategy (FLEX), which provides additional mitigation capability in the unlikely occurrence of a BDBA, and an industry-wide initiative entitled, “Delivering the Nuclear Promise: Advancing Safety, Reliability, and Economic Performance.” The collective changes resulting from these separate initiatives have the potential to produce greater contributions in the aggregate to plant efficiency and resiliency, especially if integrated through systematic efforts and analyses.

While the R&D on ATF is still ongoing, the main attributes of ATF include improved fuel and cladding properties, improved clad reaction with steam, slower hydrogen generation rates, better fission product retention, and improved fuel cladding interactions. These attributes are intended to lead to higher melting temperature of the fuel/cladding, longer-term windows (i.e., coping time) for the performance of
operator mitigating actions with higher likelihoods of successful completion (i.e., improved human
reliability), lower hydrogen (or other combustible gas) generation, and fewer fission products released
during severe accident conditions. The “Enhanced Resilient Plant Systems” concept includes
combinations of ATF, optimal use of FLEX, enhancements to plant components and systems, and the
incorporation of augmented or new passive cooling systems, as well as improved fuel cycle efficiency.

The key metrics that will be used to evaluate the resiliency enhancements for the NPP include:

- Increased coping time as compared to the current state of fuel/plant systems.
- Decreased Core Damage Frequency (CDF) and Large Early Release Frequency (LERF), as compared
to the current state of fuel/plant systems.
- Increased safety margins, such as more margins on fuel/clad temperature or reduced hydrogen gas
generation, as compared to the current state of fuel/plant systems.
- Improved plant economics during normal operations.

Plant resiliency enhancements can be demonstrated by meeting one or more metrics described above.
For the first metric, the definition of “coping time” has evolved over time. In the NRC’s Regulatory
Guide 1.155, “Station Blackout,” the coping time is defined as “the limited time the batteries are capable
of providing electrical power for the essential safety systems.” In evaluating the risks and benefits of ATF
and enhanced resilient plant systems, the definition of coping time may also include the following:

*Coping time is the available time for nuclear power plant operators to mitigate an event that has the
potential to result in significant core damage or a large early release of radioactive materials to the
environment.*

In addition to providing more time to implement specified mitigation measures to address the event,
increased coping time would also be expected to reduce HEPs and enable better utilization of the FLEX
equipment combined with ATF and enhanced resilient plant systems configurations. As a result of these
improvements, the plant CDF and LERF are expected to be reduced, which could bring direct economic
benefits to NPPs with the potential to reduce costs and regulatory burden associated with mitigating
systems performance index (MSPI), significance determination process (SDP), notices of enforcement
discretion (NOEDs), and plant maintenance and refueling outages.

The objective of this research effort is to use the RISA methods and toolkit in industry applications,
including methods development and early demonstration of technologies, in order to enhance existing
reactors safety features (both active and passive) and to substantially reduce operating costs through risk-
informed approaches to plant design modifications to the plant and their characterization. High-value
evaluations of proposed ATF, together with enhanced resilient plant system concepts, will be performed
to identify both the technical (i.e., benefits to risk, safety, and operational margins) and the economic (i.e.,
business and cost) elements associated with industry adoption of the technologies. This research will
develop an integrated approach to complement the development, testing, qualification, licensing, and
deployment of ATF and enhanced resilient plant systems technologies that can achieve substantial safety
and economic improvements, as well as timely widespread adoption by the U.S. nuclear industry.

### 3.2 Cost and Risk Categorization Applications

The objective of this research is to develop and test methods to decrease operational costs of NPPs.
Two plant cost-sensitive areas have been identified as initial targets—component reclassification-
repurpose (see 10 CFR 50.69) and component testing-maintenance.

The first area of interest is component re-categorization based on 10 CFR 50.69. In current
deterministic regulations, the SSCs are categorized as “safety related” or “non-safety related.” Safety
related SSCs need “special treatment,” such as additional quality assurance program and specific
regulations. While all safety features are linked to each other, those linked SSCs to certain safety features
will be treated as being in the “safety related” category under deterministic method; consequently, this will increase the cost of SSC design, licensing, and operation. By using the probabilistic risk-informed method under 10 CFR 50.69, both safety and non-safety related SSCs could be re-categorized into following Risk-Informed Safety Categorization (RISC), as shown in Figure 3-1:

- RISC–1: Safety-related SSCs that perform high safety-significance
- RISC–2: Non-safety-related SSCs that perform high safety-significance
- RISC–3: Safety-related SSCs that perform low safety-significance
- RISC–4: Non-safety-related SSCs that perform low safety-significance.

Figure 3-1. Risk-Informed Safety Categorization (RISC) (courtesy of 10 CFR 50.69)

Safety-significance means the function that can result in significant adverse effect on defense-in-depth, safety margin, or risk in case of degradation or loss of performance. Under 10 CFR 50.69 risk-informed categorization, SSCs in the “safety related” category could be re-categorized into the “high (RISC–1)” or “low (RISC–3)” safety significance categories. Then the SSCs in category RISC–3 could avoid “special treatment,” which can enhance plant economics. By using the RISA tools and methods, the technical basis of the SSC categorization will be enhanced, and could be linked to observable engineering margin metrics, such as core temperatures and pressures.

The second area of interest is to optimize component testing and maintenance costs, while maintaining plant safety and plant performance. A large portion of the cost in U.S. NPPs comes from maintenance and testing, which is driven by regulatory and reliability requirements to ensure safe and continuous operation. Cost reduction could be achieved by optimizing plant safety incorporating with plant dynamics, physical aging, and degradation processes into the safety analysis in a single consistent analysis framework.

Given these two areas of interest, the objective of this focus area is to develop an innovative framework on risk categorization to enhance economics. Figure 3-2 provides a schematic diagram of this framework structure. The idea is to combine physics, risk, and cost information to enable a risk-and-cost-based decision-making process for optimizing maintenance activities and achieving the greatest cost-efficiency. Research will be performed by employing multiple tools using testing and maintenance data from existing NPPs:

- Classical PRA tools (such as SAPHIRE), which can determine risk associated to NPPs
• Dynamic PRA tools (such as RAVEN), which employ system simulation tools to more accurately model plant dynamics
• Plant cost modeling
• Plant operation data
• Data analysis tools in order to extract information and knowledge to be employed in the decision-making process.

Figure 3-2. Integrated framework for optimizing maintenance activities

### 3.3 Margin Recovery and Operation Cost Reduction

Existing U.S. NPPs are designed and constructed based on the defense-in-depth safety principle. Design basis safety analyses have been performed using deterministic approaches, which normally employ conservative models and assumptions to provide tolerances to account for uncertainties. The conservatisms associated with the current design basis safety analysis process provide enough margin such that the probability of damage to the plant should be negligible even under the worst considered plant conditions. However, culminations of conservatisms in the current process may reflect unrealistic operating situations, which limit the operating flexibility of the current fleet and can result in adverse effects on plant economics. Additionally, while the deterministic approaches use prescribed enveloping design basis accident scenarios, NPP operating experience has shown that more complicated scenarios, such as those that resulted from out of design basis accident sequences during the Three Mile Island and Fukushima accidents, need to be considered with support from PRA approaches.

Research tasks are initiated to develop risk-informed, multi-scale, and multi-physics high-fidelity tools and methods to support the industry to conduct a comprehensive investigation of design basis accident process requirements and implementation to assess and recover margins associated with the conservatisms of legacy licensing, design, and analysis such that existing NPPs can operate more efficiently and with more operational flexibility. The general objective of this research is the development of an integrated evaluation approach that combines plant PRA methods with MP-BEPU, or the so-called Risk-Informed MP-BEPU (RI-MP-BEPU), analyses in a seamless fashion. The integrated evaluation framework enables plant system configuration variations to be studied with speed and precision, including detailed risk and benefit assessments associated with the adoption of advanced nuclear technologies by the operating LWR plants in their pursuit of both safety and operational performance enhancements.
The RI-MP-BEPU framework will take advantage of modern high-fidelity probabilistic and best estimate modeling and simulation tools with consistent uncertainty propagation and rigorous uncertainty quantification and sensitivity analysis in a multi-scale and multi-physics environment. RI-MP-BEPU will integrate various simulation tools across the full spectrum of plant analysis activities including core design, fuels performance, component aging and degradation, systems analysis, containment response, radionuclide transport, and release and risk assessment. This will allow complex multi-physics and risk-informed approaches to be implemented so that NPP systems problems can be solved with high-efficiency and speed. This approach is used to identify the actual margins that are available for the accident scenarios so that decision-makers, both plant owners and regulators, can identify areas of excess margin. This will provide the potential for NPPs to reallocate that margin to higher priority applications and provide commensurate operational cost reductions.

The RISA Pathway mainly uses RELAP5-3D for thermal-hydraulics and system accident analysis in on-going pilot project. However, the RELAP5-3D lacks the uncertainty analysis capabilities to perform full BEPU analysis. The BEPU method requires the application of Uncertainty Quantification (UQ) methods, the input parameter Probability Density Functions (PDFs) determination, and the propagation of these PDF to RELAP5-3D. This will derive the PDF of the Figure of Merits (FOMs). Current RELAP5-3D allows the possibility to perturb few relevant parameters, but most important parameters for perturbation capabilities (e.g., closure laws) still need to be developed for RI-MP-BEPU application. The RISA Pathway will therefore support developing full RI-MP-BEPU analysis capability to RELAP5-3D coupled with RAVEN code.
4. INDUSTRY APPLICATION PILOT DEMONSTRATION PROJECTS

One of the primary avenues for collaboration with industry is through the application of the RISA methods and tools on specific industry issues. The end goal of these activities is the full adoption of the RISA tools and methods by industry applied to their decision-making process. The elements of the above proposition are further explored below:

(a) Demonstrate:
- Provide confidence and technical maturity in the RISA Pathway (essential to broad industry adoption)
- Strong stakeholder interaction required
- Address a wide range of current relevant issues.

(b) Advanced:
- Analyze multi-physics, multi-scale, complex systems
- Use of a modern computational framework
- A variety of methods, tools, and data can be utilized (e.g., use of legacy tools and state-of-the-art tools as they become available for use)
- Be as realistic as practicable (with the use of appropriate supporting data)
- Consider uncertainties appropriately and reduce unnecessary conservatism when warranted.

(c) Risk-informed decision-making capabilities:
- Use of an integrated decision process
- Integrated consideration of both risks and deterministic elements of safety.

As described in the previous section, each of the RISA focus area may address a broad range of relevant plant technical issues. Because of their broad range of applicability, each focus area may spawn one or more industry pilot demonstration projects, each depending on stakeholder interest on different aspects of a given focus area.

In May 2018, INL organized a special workshop with delegations from major U.S. nuclear utilities to discuss and develop the “Pilot Demonstration Projects” under the RISA Pathway. A total of eight projects were identified based on comprehensive analysis on rising issues from the U.S. nuclear industry. Table 4-1 shows how each pilot demonstration project relates to each RISA R&D focus area.

These are the most relevant industry topics that can potentially impact plant operations in a significant way making them interesting and relevant applications for the RISA toolkit. The RISA Pathway will continue to communicate with various U.S. nuclear industries to collect issues and develop additional pilot demonstration projects. The currently identified eight pilot demonstrations are summarized in the following sections. More details are addressed in the RISA Pathway Industry Application Pilot Demonstration Projects – Edition 2019 (INL-EXT-19-54449).
Table 4-1. Pilot demonstration projects related to RISA R&D focus areas

<table>
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<th>RD&amp;D Focus Areas</th>
<th>Pilot Demonstration Projects</th>
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<td>Enhanced Operation Strategies for System Components.</td>
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<td>Cost and risk categorization applications</td>
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<td>Plant Health Management.</td>
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<td>Margin recovery and operation cost reduction</td>
<td>Enhanced Fire Probabilistic Risk Assessment (PRA)</td>
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<td>Plant Reload Process Optimization.</td>
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4.1 RISA Enhanced Resilient Plant Systems

This study will focus on the combined effect evaluation of different plant resilience enhancing technologies to give better synergy and benefit from limited resources. For instance, the utility always strategically looks forward to improving both safety and economics even under current high-operating cost environment. The deployment of ATF, along with the optimal use of the FLEX equipment, is a good example of such an effort. The study will evaluate the safety and economic benefits from the deployment of strategic investments, either stand-alone or in combination. The work will focus on ATF concepts combined with optimization of FLEX equipment and development, as well as possible deployment of new passive cooling systems.

The main goal of the study will be to evaluate the maximum benefits of safety and economics from applying the ATF concepts to risk-informed NPP operation. The analyses will use both deterministic (e.g., RELAP5-3D, TRACE, MELCOR, MAAP) and probabilistic (e.g., SAPHIRE, HUNTER) tools, as well as the LOTUS and RAVEN controller software. The study will also combine with the FLEX equipment to optimize risk assessment and enhance resiliency under BDBAs. In parallel, augmented cooling systems, such as the Reactor Core Isolation Cooling (RCIC) system extended operating band in BWRs or the installation of new passive cooling systems in PWRs, will be evaluated.

The outcome of this study will evaluate the degree of safety and risk control enhancement by combining different advanced technologies and propose the most efficient and optimized method and combinations. The results will give clear long-term vision to the U.S. nuclear industry in deploying ATF to existing NPPs.

4.2 Enhanced Operation Strategies for System Components

The Terry turbine is widely used in various NPPs around the world, including the Fukushima Daiichi (Units 2 and 3) NPP. Extended knowledge of the maximum operating limit of this type of turbine will enhance emergency core cooling, thus enabling a clear identification of turbine operation margin that will in turn reduce plant accident risk and provide additional time to transition to other core cooling equipment, such as FLEX, in order to prevent core damage.

The research will be done by advanced modeling methods and full-scale experimental testing to propose the overall Terry turbine expanded operating band (TTEXOB). Based on first stage of theory and experimental study from the on-going TTEXOB Project, the work will cover a specific area for BDBA Terry turbine performance evaluation, such as pump function modeling, oil and bearing characteristics, and turbine operation behavior under two-phase flow condition.

The outcome will provide a technical basis of extended operation of TTEXOB under accident conditions, and will support a PRA application on accident analysis, as well as the turbine maintenance
plan. As a long-term vision, this study will give high credit on Terry turbine reliability and identification of operation margin, which may help utility cost economics. The study could be extended to a BWR application, such as improving residual heat removal (RHR) system and other safety issues.

### 4.3 Risk Informed Asset Management

The goal of this research is to enhance the long-term safety and economics of NPPs during the Second License Renewal (SLR) period of operation by providing a structured risk-informed approach to evaluate and prioritize plant capital investments made in preparation for and during the period of extended plant operation. The risk informed analysis to the capital improvements for SLR that includes assessment of the expected useful life of the SSCs and the likelihood and impacts of unanticipated occurrences that could impact their performance during this operating period. The scope of the work will specify the optimal conditions and timing for replacement/refurbishment based on anticipated probabilistic conditions with appropriate assessments performed to address uncertainties.

From previous studies, the list of potential capital improvements to support plant operation throughout the SLR period is suggested. These SSCs will be used to develop and apply methods to cope with failure during this operating period. The research will then continue to identify an optimal allocation of the capital expenditures and management of these expenditures (via re-optimization) as circumstances change from initial approval through the end of the SLR operating period. The Integrated Life Cycle Management (ILCM) method and software (developed by EPRI, for example see EPRI Report "Program on Technology Innovation: An Optimization Approach for Life-Cycle Management Applied to Large Power Transformers") as well as INL’s RAVEN software, will be investigated to address management and optimization of large capital expenditures for the purposes of extended plant operation.

The outcome of the research will demonstrate the pilot application can be scaled up with reasonable cost and effort to support periodic evaluations and optimizations. The application also will be directly deployed to utilities who are considering SLR. As a long-term vision, providing an integrated process and suite of support tools will support executive planners and decision-makers in the planning and selection of capital investment for plant SLR.

### 4.4 Plant Health Management

Industry Equipment Reliability (ER) programs are an essential element that supports safe and economic plant operation and are well-addressed in several industry-wide and regulatory programs. However, these programs are labor intensive and expensive. Leveraging advanced monitoring technology can significantly reduce costs and improve engineering effectiveness and can improve the performance of critical SSCs. The main goal of this study is to provide an initial step in the process of deploying these technologies while the integrated approach as a pathway to implementing fully integrated advanced monitoring systems into plant ER programs.

The overall objective of this effort is to develop and deploy an integrated Plant System Health program that maximizes automation and advanced data analytics to minimize cost and enhance performance. This will be accomplished by providing timely high-quality information to decision makers that characterizes all aspects of system health, including uncertainties and risks. The goal of this research is to retrieve equipment performance and monitoring data to update the existing models and processes to support risk-informed decision making. It should be noted that in the context of the RISA approach, risk-informed decision making incorporates a broad interpretation of risks to include not only the traditional focus on nuclear safety (as evaluated in a plant PRA), but also broader elements of risk such as financial aspects.

Since entire existing NPPs in the U.S. have formal ER, Maintenance Rule, and Mitigating Systems Performance Index programs, the technology developed from this research will be directly transferable across the industry. This study also is intended to demonstrate that the approach can be scaled up with
reasonable cost to develop and implement integrated monitoring in NPP ER programs. The future work includes the development of an advanced approach to perform integrated system health management, which will leverage a variety of data sources to effectively manage system health.

4.5 Enhanced Fire PRA

Fire PRA models have been receiving high interest recently in the nuclear industry, which has led to the conclusion that better characterization of uncertainty could significantly improve both safety and cost savings. Based on previous studies, this project will develop efficient methods and tools to help reduce labor costs in building and analyzing basic fire model scenarios, and in reducing conservatism in critical sequences.

The research is focused on two main areas: tools and data. First is the modification and integration of tools to reduce the manual effort required by improving and analyzing existing models for daily plant use. This will enable further research of using advanced PRA tools with the capability to identify key relationships and timing that can support improving current PRA models. This research will target the reduction of the costs for current fire PRA activities. This will be done with the modification and development of a visualization tool to enable users to manage spatial relationships of components in fire zones and their failure properties, execute fire simulations (e.g., with Consolidated Model of Fire and Smoke Transport (CFAST) or Fire Dynamics Simulator (FDS) software) to determine component and cable failures, and easily analyze subsequent component failures or basic events due to cable failures. The PRA modeling capabilities will be coupled with fire simulation and visualization tools. This will also evaluate the margins gained from the use of the fire PRA analysis results used to modify an initial static model.

The second area involves analyzing the current data used in modeling methods. Experiments were performed from 2001 to 2016 using a range of methodologies and available equipment. These results were used to determine inputs like heat release rates and cable failure times. Often, conservative methods were used to perform these tests and have compounding results in the plant models. In some areas, they do not reflect what is being seen in actual events. This data research involves determining the parameters used to do the experiments, quantifying the uncertainty for those parameters, and evaluating the possible effect on plant models if that uncertainty is reduced. In other words, where would better data provide the most benefit to improving the models? This would allow for better decision-making of which experiments could be reconsidered for testing and the development of new data for plant use.

This project will develop effective methods for using enhanced PRA analysis for fire accidents, which could then be expanded to other natural hazard events. Then using those results, the project will develop more generally applicable concepts or modeling techniques that can be used in current PRA methods to more realistically model external hazard events. This will also help industry to reduce potential risk model conservatism associated with fire and other external events, allowing facilities to focus resources on high-priority events scenarios.

4.5.1 Current Work Status

The work in FY 2019 started by leveraging an advanced visualization tool to combine existing fire PRA models with three-dimensional (3D) spatial information to develop a framework for efficient analysis of key fire PRA scenarios to reduce conservatism. Main collaborators of this work include Southern Nuclear Co., Jensen Hughes, and EPRI.

A visualization tool called the “Fire Risk Investigation in 3D (FRI3D)” is under development and the beta version was delivered in June 2019 to a utility for evaluation. This tool processes actual plant data and adds spatial information for 3D viewing. FRI3D provides the following capabilities:
• 3D model locations for items included in both the FRANX database and a plant model located in a defined area.
• Index data between model sources for automated linking and searches.
• Visually show equipment failures for a given fire scenario.
• Allow additions/modifications of scenarios and generate a new quantification model.

The data analysis work is a collaborative effort between Sandia National Laboratory (SNL), the University of Illinois, and EPRI. Initial parameters for the experimental data from SNL have been identified and the University of Illinois has begun implementing the algorithms and setting up fire simulation tools to develop uncertainty data. They are leveraging INL’s high-performance computing center to perform these quantifications and simulations. EPRI has performed some related uncertainty analysis work on the facility modeling parameter's inconsistencies. By close collaboration with EPRI, the gaps of experimental data input uncertainties and present results will be covered in a similar manner. A path for publication of EPRI report is currently in progress and we will provide a related report for input data uncertainties.

4.5.2 Future Works

The FY 2020 work will be application of the physics-based fire simulations with fire PRA data to demonstrate methods to reduce risk using a participating utility’s selected high-consequence fire scenarios. This will include completing the integration between physics simulation tools and advanced PRA methods for full analysis of a demo model and evaluation of an existing plant scenario. The work will be extended to demonstrate use and develop a strategy for adoption of dynamic fire PRA tools by the existing fleet.

4.5.3 Deliverables

(2019) Improvements in plant analysis and the reduction of manual efforts with routine fire analysis using improved models for an existing participating plant.

(2019) An initial analysis report on fire experiment data to identify gaps and data needs to reduce uncertainties and conservatisms to enhance NPPs PRA models.

(2020) Apply physics-based fire simulations with fire PRA data to demonstrate methods to reduce risk using a participating utility's selected high consequence fire scenarios.

(2020) Importance measure analysis of experiments parameters of fire data and the impact on fire PRA modeling.

(2021) Demonstrate use and develop a strategy for adoption of fire PRA enhancement tools by the existing fleet.

4.6 Modernization of Design Basis Accidents Analysis with Application on Fuel Burnup Extension

Increase of fuel enrichment and discharge burnup will promise significant cost reduction through the nuclear fuel cycle for any type of NPP around the world. Past studies showed that a combination of up to 6 w/o of U-235 enriched fuel with an extended batch cycle can result in high resource usage and further overall cost savings. However, additional risks and regulatory issues may arise along with suggested higher burnup operation, and these issues should be clearly identified and analyzed. Main licensing challenges for high burnup fuel are design basis accident condition analyses (e.g., LOCA and Reactivity Initiated Accident [RIA]), which should be thoroughly studied and assessed.
The study will use 6 w/o enriched fuel with a 24 months fuel cycle for a 4-loop Westinghouse-designed PWR. The RI-MP-BEPU framework will be used for the licensing and deployment study. VERA-CS code will be used to study pin-resolved power distributions for the core design followed by detailed fuel performance calculations for individual fuel rods in the core using the FRAPCON and BISON fuel performance analysis codes. The analyses will apply both deterministic (e.g., VERA-CS, FRAPCON/FRAPTRAN, BISON, RELAP5-3D, MELCOR) and probabilistic (e.g., SAPHIRE, RAVEN) methods using the LOTUS controller. Uncertainty quantification and sensitivity analysis technologies will be integrated into the RI-MP-BEPU framework to alleviate concerns on extrapolating experimental data.

It is expected that the outcomes from this research will be immediately transferred to the U.S. nuclear industry since burnup extension is one of the largest on-going efforts to reduce cost. The study will include licensing and issues analysis for optimized fuel enrichment and burnup extension, as well as economic benefits.

4.7 Digital I&C Risk Assessment

Deployment of digital I&C systems to safety-related NPP instruments will increase long-term reliability and reduce uncertainties of system performance. However, only one U.S. NPP has been successfully licensed using the advanced Reactor Protection System (RPS) and Engineered Safety Feature Actuation System (ESFAS) due to high replacement cost and unclear solution of regulatory uncertainties. The main objective of this study is to develop and demonstrate reliability and risk assessment of the safety-related digital I&C system to support system licensing and enhance qualification work.

The work scope includes a conceptual design of a proposed I&C system modeled at the channel logic level with a detailed design and functional specification followed by a risk and reliability evaluation to support the analysis of integrated RPS and ESFAS replacement using the risk-informed and graded approach to safety significance. The identification of technology gap will be also performed, which may support solving engineering and licensing issue of the digital I&C system.

The risk assessment will start from a channel-level conceptual design to validate the chosen evaluation process as a table-top exercise first, followed by an in-depth study on a selected case to achieve a quality feasibility demonstration. The research will then expand to support the digital I&C modeling, data, and modular analysis software development to facilitate design, licensing, and operation activities of U.S. nuclear utilities.

4.8 Plant Reload Process Optimization

Optimization of plant reloading reactor core thermal limit is one of the highest requests from U.S. nuclear plant utilities, which can help reduce significant amounts of fuel cost. The optimization of safety margins could be proposed by developing independent methods for design basis accident analysis, including LOCA and non-LOCA events that will be compliant with the new 10 CFR 50.46c regulations and thermal conductivity degradation (TCD) evaluations. The assessment will also include peak cladding temperature (PCT) during LOCA analysis and departure of nucleate boiling (DNB) analysis associated with non-LOCA events. The research scope includes an analysis of core design, safety margins, fuel performance, and modern data management. The project will focus on customizing the thermal limits for each NPP based on the core physics at certain reload cycles by applying the risk-informed method to optimizing safety margin.

Three work phases have been proposed. Phase-I will focus on studying a concept of application by using a fixed core loading pattern to evaluate recoverable margin during plant reloading, Phase-II will develop the methods to optimize the thermal limit, and Phase-III will conclude with plant reloading using a management method developed using optimized safety limits. The Plant “Super” Model (PSM) will be used for plant reloading risk assessment to reduce long-term maintenance costs for existing licensing
bases, while increasing the modeling fidelity and accuracy in the PRA modeling analysis. This model will provide risk-informed safety analysis on non-LOCA/LOCA events. The project will use RELAP5-3D for the thermal-hydraulics modeling of the design basis accidents and risk informed analysis.

Since cost reduction from plant reloading is an immediate demand from utilities, the outcome of this research will give high impact on the current fuel market, as well as the utility cost reduction plan. Though regulation issues still need to be solved, positive changes are foreseen in the future fuel supply chain.
5. COLLABORATIONS

Strong collaboration and support are required to meet the goals of the RISA Pathway. Since the outcome of the pathway will directly benefit the existing U.S. NPP fleet, high interest has been received from many utilities, vendors, national institutes, and the Federal government.

Motivations for DOE involvement in supporting the RISA Pathway include:

- The need to better characterize and quantify safety margin when considering near-term operation and plant life extension of more than 60 years.
- The need of data, models, and information integration from parallel activities, such as materials research and I&C development. From these complementary activities, the RISA Pathway can assimilate potential safety implications in order to better predict NPP viability and to support decision-makers.
- The need to create confidence in a verified and validated approach and tool set that will be applicable in NPP operation and licensing activities. The DOE national laboratory system has broad experience in independent validation, verification, and uncertainty quantification, which are essential components for successful development of the RISA toolkit.
- The need to provide relevant economic information as it pertains to off-normal scenarios, including the incorporation of aging concerns.
- The need to enhance and expand on the existing body of methods and tools. Many of the legacy safety tools used in the U.S. nuclear industry were designed and created 30 to 40 years ago.
- The need to better understand BDBAs. As a result of the Fukushima event, NPPs are being asked for information on hazards, such as seismic and floods, and to characterize the safety impact of these hazards.
- The need to move NPP analysis onto modern high-performance computational architectures, methods, and cloud computing approaches, and move away from more-limited technologies.
- The need to use science-based models for NPP performance prediction, rather than parametric- or correlation-based mechanistic models that are prevalent.
- The need to proactively respond to future NPP changes over extended lifetimes, such as aging, or for desired plant changes, such as increasing the economic viability by extended power uprates.
- The need to better describe uncertainties with a focus on improved decision-making.

One result of the approach in the RISA Pathway is the use of RIMM strategies. These strategies will be informed by the risk and economics assessment and will focus on desired and measurable outcomes, rather than prescriptive processes, technologies, or procedures, with the aim of identifying performance quantification that ensures the adequate safety margin maintenance over the NPP lifecycle. The RISA Pathway will be working collaboratively with industry partners, LWRS Materials Research, and the Plant Modernization Pathway, other DOE Programs, universities, and the U.S. NRC to provide solutions to the issues identified above.

A variety of avenues are being followed in order to foster collaborations within the RISA Pathway, including:

- The RISA methodology and toolkit being jointly developed with EPRI.
- Research results are disseminated via a variety of technical meetings, conferences, and are made available in program reports.
- Industry is the targeted user group for the RISA toolkit.
• Code “testers” are being actively sought. The RISA toolkit will be made available to industry volunteers who will use the tools and provide feedback to the LWRS Program.

• An “Industry Working Group” is also being considered for maintenance, application information, and updates as necessary.

5.1 Industry Interactions

Industry is significantly engaged in the RISA Pathway, and the level of engagement is increasing. Up to now, industry engagement in RISA has taken place at two levels: (1) input into program planning; and (2) active participation in the RISA activities. One effect of this collaboration has been strengthening RISA team consensus that RISA developments should be driven by “Pilot Demonstration Projects” (i.e., explicitly planned eventual applications that are used to formulate requirements on development of the next-generation capability) and “case studies” (i.e., actual applications that scope particular developments and, once completed, support assessment of the current phase of development). EPRI and other industry representatives are becoming increasingly involved in detailed technical planning of “industry applications” that now drive development activities and are expected to continue to support actual execution. This has two effects: (1) it helps to ensure the program moves in a direction that addresses practical industry concerns; and (2) it provides the RISA team with access to engineering expertise that is needed in development of enabling methods and tools.

Coordination of RISA activities include the following:

EPRI: As an independent R&D organization, EPRI may provide guidance and input on the technical requirements for advanced technologies to be commercially viable in operating NPPs. Within this perspective, EPRI may assist as an interface between NPP owners/operators and other key stakeholders, including U.S. DOE, fuel vendors, and engineering services providers. As part of this collaboration, EPRI may be a valuable contributor to the technical evaluation and cost/benefit assessment associated with the industry pilot demonstrations. Through its access to its members, EPRI can also sponsor relevant analyses at operational NPPs to assess and demonstrate the benefits of advanced technology deployment.

Owners Groups: Interactions will continue with groups such as the BWR and PWR Owners Groups through information exchange and evaluations of specific topics via case studies.

Other industry partners: Involvement of engineering and analysis support from industry is presently foreseen in the performance of case studies to drive next-generation analysis development and in formulation of component models for implementation in next-generation analysis capability. The individuals prospectively involved are either industry consulting firms or currently independent consultants who have working relationships with current licensees. All individuals are experts in applying traditional safety analysis tools and are conversant with risk-informed analysis.

Multilateral International Collaboration: A variety of international researcher interactions are of potential interest to the RISA Pathway, including:

NEA Working Groups under Committee on the Safety of Nuclear Installations (CSNI)

This Nuclear Energy Agency (NEA) committee aims to assist member countries in maintaining and further developing the scientific and technical knowledge base required to assess the safety of nuclear reactors and fuel cycle facilities. The NEA is under the framework of the Organization for Economic Cooperation and Development (OECD). The U.S. is a member of both organizations. One of the task groups in CSNI is primarily working on safety margin applications and assessment: Working Group on Risk Assessment (WGRISK), which advances the understanding and use of PRA tools. Another working group in CSNI, Working Group on Analysis and Management of Accidents (WGAMA) addresses safety analysis research including the uncertainty and sensitivity evaluation of best-estimate methods program. Various benchmarking activities and international collaborative programs are organized through the Working Groups.
Since 2013, NEA is organizing dedicated expert group on natural hazards: CSNI Working Group on Natural External Hazards (WGEV). The mission of the WGEV is to improve the understanding and treatment of external hazards that would support the continued safety performance of nuclear installations and improve the effectiveness of regulatory practices. Dr. Curtis Smith (INL) is member of this Working Group. One of the active areas of research within the WGEV is a CSNI Activity Proposal for a science-based approach to screening for external events. The objective of the CSNI Activity Proposal is to build on the existing experience base within member countries and identify best practices and any gaps. Currently, there are three types of screening processes: (1) deterministic screening based on standard practice; (2) absolute frequency (or probability) screening; and (3) relative probabilistic considerations conditional upon plant design (e.g., conditional core damage probabilities for potential initiating events). The CSNI Activity Proposal is focused on absolute frequency screening, factoring in physical conditions that limit the frequency or magnitude of a natural hazard.


Under guidance of NEA Nuclear Development Committee, a new NEA Ad Hoc Expert Group on Maintaining Low-Carbon Generation Capacity through LTO of Nuclear Power Plants: Economic, Technical and Policy Aspects (EGLTO) was formed in April 2018. Dr. Ronaldo Szilard (INL) is the member of the expert group. The expert group will review the technical and economic aspects of long-term operation (LTO) of existing NPPs and their interactions. Considering the following items:

- The need for major investments in maintenance and refurbishment, including those brought about by regulatory changes, as well as additional safety requirements due to the Fukushima Daiichi accident
- Changes in operation and maintenance (O&M) costs (e.g., higher personnel costs or similar)
- Changes in market conditions, e.g. decline in wholesale electricity or decreasing capacity factors due to competing technologies (subsidized renewable, cheap fossil fuels), tax regimes, absent or ineffective carbon pricing
- The impact of the operational lifetime on the costs and funding of waste management and decommissioning.

The expert group will also analyze NPP life extension and its impact under de-carbonization policy perspectives.

**NEA Expert Group on Uncertainty Analysis Method (EGUAM)**

Under guidance of NEA Nuclear Science Committee, NEA Expert Group on Uncertainty Analysis Methods (EGUAM) has been performing a comprehensive benchmark study of various nuclear systems to implement uncertainty analysis method. Through the “Benchmark for Uncertainty Analysis in Best-Estimate Modeling,” the goal of the activity is to determine modelling uncertainties for reactor systems under steady-state and transient conditions, quantifying the impact of uncertainties for each type of calculation in the multi-physics analysis for neutronics, thermal-hydraulics and nuclear fuel performance.

**Sustainable Nuclear Energy Technology Platform (SNETP)**

Established in September 2007 with the backing of the European Commission (EC), the SNETP promotes and coordinates research activities in the field of nuclear fission. Over 100 members are drawn from industry, research and safety organizations, universities, and non-governmental bodies based in Europe, sharing a common interest in developing safe and sustainable nuclear power.

**NUGENIA: Nuclear Generation II&III Association**
NUGENIA is an international non-profit association supported by SNETP dedicated to the R&D of nuclear fission technologies, with a focus on Gen II & III nuclear plants. It provides scientific and technical basis to the community by initiating and supporting international R&D projects and programs. The association gathers stakeholders from industry, research, safety organizations and academia, committed to develop joint R&D projects in the field.

Civil Nuclear Energy Research and Development Working Group (CNWG)

The CNWG is bilateral agreement established by DOE and Japan’s Ministry of Economy, Trade, and Industry (METI) and Japan’s Ministry of Education, Culture, Sports, Science, and Technology (MEXT). In addition, participants from Japan included the Japan Atomic Energy Agency (JAEA) and Japan’s Central Research Institute of Electric Power Industry (CRIEPI). The goal of the group is to foster cooperative efforts and collaboration on nuclear R&D in various fields, including fast reactors, high-temperature gas reactors, nuclear fuel cycle and waste management, and LWRs. DOE, JAEA, and CRIEPI also jointly launched a new project to conduct safety analysis on metal-fueled fast reactors. Related to the RISA Pathway, CNWG has shown high interest on risk-informed and advanced seismic PRA applications.

The RISA research team has engaged in collaboration activities with a variety of international stakeholders, including joint activities with the Korea Atomic Energy Research Institute (KAERI), the India-U.S. Civil Nuclear Energy Research and Development Working Group (CNEWG) bilateral working group, and the Japan Nuclear Risk Research Center (NRRC).

5.2 DOE Collaborations

5.2.1 Nuclear Energy Advanced Modeling and Simulation (NEAMS)

The NEAMS Program is developing a simulation tool kit that will accelerate the development and deployment of nuclear power technologies that employ enhanced safety and security features, produce power more cost-effectively, and utilize natural resources more efficiently. The overall objective of NEAMS is to develop and validate predictive analytic computer methods for the analysis and design of advanced reactor and fuel cycle systems. The LWRS Program intends to take advantage of the detailed, multi-scale, science-based modeling and simulation results developed by the NEAMS Program. The modeling and simulation advances will be based on scientific methods, high dimensionality, and high-resolution integrated systems. The simulations will use the most advanced computing programs and will have access to the most advanced computation platforms that are available to DOE. These tools will include fully 3D, high-resolution representation of integrated systems based on physical models. Included in these tools will be safety codes integrated predictive physics for nuclear fuels, reactor systems, and separations processes.

In FY-2018, NEAMS provided development support for the RELAP-7 software. RELAP-7 is the new generation nuclear reactor system safety analysis code based on MOOSE, a finite-element, multi-physics framework primarily developed by INL. [5]

5.2.2 Consortium on Advanced Simulation of LWRs (CASL)

CASL is the first DOE Energy Innovation Hub established in July 2010, for the purpose of providing advanced Modeling and Simulation (M&S) solutions for commercial nuclear reactors. The focus is on ultra-high fidelity of reactor core physics. CASL is developing a detailed model of the LWR core; if investigations in the LWRS Program warrant it, the LWRS Program-developed models can couple with the CASL-developed models. CASL has an interest in using RELAP-7 for one or more of their challenge problems. The RISA Pathway will be collaborating with CASL on aspects of technology transfer to industry related to methods and tools being developed in the respective programs.
5.2.3 Nuclear Energy Enabling Technologies (NEET)

The NEET Program is developing crosscutting technologies that directly support and complement the DOE advanced reactor and fuel cycle concepts, focusing on innovative research that offers the promise of dramatically improved performance. It coordinates research efforts on common issues and challenges that confront the LWRS, Advanced Reactor Technologies (ART), and Small Modular Reactors (SMR) to advance technology development and deployment.

5.3 University and Regulatory Engagement

Universities participate in the LWRS Program in at least two ways: (1) through the Nuclear Energy University Program (NEUP); and (2) via direct contracts with national laboratories that support the Program’s R&D objectives. NEUP funds nuclear energy research and equipment upgrades at U.S. colleges and universities and provides scholarships and fellowships to students. In addition to contributing funds to NEUP, the LWRS Program provides descriptions of research activities important to the LWRS Program, while the universities submit proposals that are technically reviewed. The top proposals are selected, and those universities then work closely with the LWRS Program in support of key LWRS Program activities. Universities also are engaged in the LWRS Program via direct subcontracts where unique capabilities and/or facilities are funded by the program.

Recent and current NEUP- or IRP-funded projects that interact with the RISA Pathway are:

- NEUP-13-5142 with Professor Halil Sezen at The Ohio State University. The focus of this research is on the creation of an approach to external events PRA for structures and components and the associated integration into an existing risk assessment. Case studies are being evaluated in order to implement new external events approaches (for example, for seismic events) into the MOOSE platform.

- NEUP-14-6442 with Professor Klein at Oregon State University. The focus of this research is on probabilistic economic valuation of safety margin management. The goal of the project is to use the RISA toolkit to perform probabilistic assessment of accident scenario consequences and costs avoided by safety margin upgrades and to compare to costs of safety margin upgrade installation for cost/benefit analysis. This work will provide risk-informed, data-driven decision making, for both plant owners and regulatory bodies.

- NEUP-15-8000 with Professor Sant at the University of California–Los Angeles. Influences of Neutron Irradiation on Aggregate Induced Degradation of Concrete.


- NEUP-16-10630 with Professor Brooks at the University of Illinois–Urbana Champaign. Validation of RELAP-7 for forced convection and natural circulation reactor flows.


- NEUP-16-10402 with Professor Dean at the Ohio State University. RELAP-7 Application and Enhancement for FLEX Strategies and ATF Behavior under Extended Loss of AC Power Conditions.

- NEUP-17-12723 with Tunc Aldemir at the Ohio State University. Integrating Static PRA Information with RISA Simulation Methods.

- NEUP-17-12614 with Zahra Mohaghegh at the University of Illinois at Urbana–Champaign. Systematic Enterprise Risk Management by Integrating the RISA Toolkit and Cost-Benefit Analysis.

• NEUP-18-15270 with Karen Vierow Kirkland at Texas A&M University. Use of Accident Tolerant Fuels (ATF) with the RCIC System to Enhance Passive Safety of Commercial LWRs.


DOE’s mission to develop the scientific basis to support both planned lifetime extension up to 60 years and lifetime extension beyond 60 years, and to facilitate high-performance economic operations over the extended operating period for the existing LWR NPP operating fleet in the U.S., is the central focus of the LWRS Program. Therefore, more and better coordination with industry and NRC is needed to ensure a uniform approach, shared objectives, and efficient integration of collaborative work for the LWRS Program. This coordination requires that articulated criteria for the work appropriate to each group be defined in memoranda of understanding that are executed among these groups. NRC has a memorandum of understanding in place with DOE, which specifically allows for collaboration on research in these areas. Although the goals of the NRC and DOE research programs may differ, fundamental data and technical information obtained through joint research activities are recognized as potentially of interest and useful to each agency under appropriate circumstances. Accordingly, to conserve resources and avoid duplication of effort, it is in the best interest of both parties to cooperate and share data and technical information and, in some cases, the costs related to such research, whenever such cooperation and cost sharing may be done in a mutually beneficial fashion.

5.4 Collaborations with LWRS R&D Pathways

In addition to the case study collaborations, the RISA Pathway works with the other LWRS Pathways, including:

• Collaboration with the Materials Research Pathway on incorporating the insights gained through the pathway R&D, focusing on material degradation modeling. The primary interaction is through the development of the GRIZZLY code. GRIZZLY is a MOOSE-based tool for simulating component aging and response of aged components that is being developed within the Materials Research Pathway.

• Collaboration with the Plant Modernization Pathway on human reliability modeling and non-destructive research on concrete aging predictive modeling.
6. PRODUCTS AND SCHEDULES

In order to give clear vision on risk-informed margin recovery to U.S. nuclear industry and decision makers, the RISA Pathway will focus on the pilot demonstration projects and the RISA toolkit deployment to the industry. The RISA Pathway will deliver following two main areas of products:

1. Industry application pilot demonstrations
2. RISA toolkit deployment.

The industry application pilot demonstration projects will study specific scope of phenomena, components, and simulation capabilities needed to address the given issue area. As a part of these applications, refinement of the associated methods and tools would continue at a reduced level of effort compared to the effort associated with the RISA toolkit development. As the development and capabilities of the RISA toolkit progresses, INL will collaborate with industry to determine how to transition the RISA Tools to a user-supported community of practice, including planning for lifecycle software management issues such as training, software quality assurance, and development support.

The RISA Pathway proposes five years project plan as shown in Figure 6-1. In FY-2019, the RISA Pathway will focus on the initiation of selected pilot demonstration projects and will deliver preliminary results on the case studies. The feedback on selected pilot demonstration projects will be communicated with industry through a specific RISA Pathway working group. Based on the preliminary studies, the pilot demonstration projects will be extended to full scale analysis during FY-2020 and FY-2021. The validation and verification of associated the RISA toolkit will be done in this period. For the last two years of the project, the RISA Pathway will develop optimized methods of R&D results implementation to industry as well as long-term support plan by research institutes for U.S. nuclear industry to provide sustainable benefit from RIMM.

It is noted that the project timeline could be different to the technical maturity and development status of using the tool and method.

![Figure 6-1. Notional 5-year plan of a RISA Pathway Industry Application](image-url)
6.1 RISA Toolkit Deployment Plan

The RISA Toolkits are a set of computer software that will be used through the industry application pilot demonstrations and deployed to U.S. nuclear industry to support RIMM analysis. As shown in Section 2.3.2 and Figure 2-8, various computer codes are included in the RISA toolkit and could be added or removed as necessary. Since not all software has been fully verified and validated, the RISA Pathway will perform appropriate degree of software Verification and Validation (V&V) in order to give clear understanding to future RISA toolkit users in US nuclear industry. The industry will engage to the selected pilot demonstration projects. The RISA Pathway will continuously communicate with industry to develop issues and to collect feedback. The RISA toolkit deployment will have the following four process steps:

1. Select tools and methods.
2. Confirm verification and validation status.
3. Pilot demonstrations using selected tools and methods.
4. Industry deployment and feedback.

6.1.1 Selection of RISA Toolkit

The tools and methods used in the RISA Pathway should have high-confidence and enough technical maturity and ability to cover a wide RIMM area range. Advanced technologies should be applied to the RISA Toolkits, such as multi-physics and multi-scale analysis, and cutting-edge computational proficiency as well as capability of uncertainty control if necessary. The toolkit should also have the capability to support risk-informed decision-making for both probabilistic and deterministic elements of safety. As listed in Section 2.3.2, the current RISA toolkit includes various computer simulation tools that can cover wide range of work scope. Many of tools are currently available in related industry, and well validated with mature technology level. However, there are still many tools under development or needing to be verified and/or validated to confirm the technical maturity and suitability for the RISA Pathway framework.

6.1.2 Verification and Validation (V&V) of the RISA Toolkit

In order to provide confidence during industry deployment, the selected tools and methods should be address quality-assurance levels appropriate for industry use. Well-known methods such as V&V and uncertainty quantification of the produced result will enhance credibility of the selected tools and enable industry to use them with confidence. The selected RISA Toolkits will be examined to confirm V&V status to show its Technology Readiness Level (TRL) and to assure quality of the outcomes. The RISA Pathway will deliver the annual report of V&V examination and confirmation data for the selected RISA toolkit. The deliverable will include specific information of the tool such as capability and features, quality assurance program, developer/independent V&V record, separation/integral tests history, user documents, and feedback.

6.1.3 Pilot demonstration using RISA Toolkit

As of the end of FY-2018, a total of eight RISA pilot demonstration projects are proposed during comprehensive discussion with U.S. nuclear industries and related institutes. Each project has its own selected tools and methods to show optimum RIMM, which aims to enhance both safety and economics. The RISA Pathway will maintain strong engagement with the U.S. nuclear industry to perform each pilot demonstration project. Direct participation of industry will provide better understanding on arising issue and can facilitate promoting innovative solutions, as well as smooth deployment of RISA toolkit in the future.
6.1.4 RISA Toolkit Industry Deployment and Feedback

Successful deployment of the RISA Toolkits to the U.S. nuclear industry is the one main goal of the entire RISA Pathway. The industry has been involved in the RISA Pathway from its initiation and will support the pilot demonstration project by using the selected RISA toolkit. During the pilot demonstration project phase, industry will have enough time to experience selected tools and methods. The RISA Pathway will organize its annual meeting with leading U.S. nuclear industries to develop additional pilot demonstration projects, collect feedback to upgrade on-going projects, and discuss an effective RISA toolkit implementation strategy. Licensing and regulation issues will be also addressed. The result of this meeting will be published and shared for long-term maintenance of the RISA toolkit.

6.2 Deliverable List by Fiscal Years (2020-2023)

Deliverables list by fiscal years (2010-2023) is as follows:

**FY-2020:**
- Update on RISA technical program plan
- Evaluation of combined benefits of FLEX and ATF licensing basis accidents for an enhanced resilient BWR model
- Reactor Core Isolation Cooling (RCIC) modeling and Terry turbopump testing
- Design basis accident methods for plant reload license optimization
- Integration of the design basis analysis with the plant reload activity
- Risk analysis toolkit for plant resources optimization
- Integration of data analytics and SSC health models with plant system health program
- Apply physics-based fire simulations with fire PRA data to demonstrate methods to reduce risk using a participating utility's selected high consequence fire scenarios.
- Importance measure analysis of experiments parameters of fire data and the impact on fire PRA modeling.
- Hazard analyses and reliability studies for a digital reactor protection systems and engineered safety features actuation systems
- Assessment of validation and verification (V&V) status for PRA tools EMRALD and HUNTER

**FY-2021:**
- Update on RISA technical program plan
- RISA Pathway industry working group – Industry applications implementation strategy and feedback on pilot demonstrations
- RISA toolkit software verification and validation
- Human reliability analysis using FLEX in accident management and risk-informed analysis on passive cooling design
- Full scale data driven risk analysis for SSC refurbishment and replacement
- Integration of real-time equipment monitoring date to system health program
- Demonstrate use and develop a strategy for adoption of fire PRA enhancement tools by the existing fleet
- Feasibility study on of extended fuel burnup designs and cost benefit optimization
• Full scale demonstration on plant reloading thermal limit optimization and cost benefit
• Demonstration of enhanced safety by using ungraded digital I&C during transient accidents
• Expansion on risk-informed resilience to include cyber-, physical-, and weather-based scenarios
• Application of physics-based models and tools to flooding hazard analysis
• Real-time co-simulation of thermal and electrical systems for the evaluation of thermal and rotational inertia in power plants.

FY-2022-2023
• Update on RISA technical program plan
• RISA Pathway industry working group – Industry applications implementation strategy and feedback on pilot demonstrations
• RISA toolkit software verification and validation
• Development of enhanced resilient plan system analysis framework for long-term ATF concept
• Demonstration of enhanced resilient plant concepts including passive cooling systems
• Support first plant reloading of near-term ATF concept.
### 6.3 Deliverable List by R&D Focus Areas

Table 6-1 shows a list of the deliverables sorted by the following three R&D focus areas described in Chapter 3:

2. Cost and Risk Categorization Applications.

Supporting the technical tasks above is a project management activity. This activity provides the project management aspects to support accomplishing the pathway objectives and other DOE requirements related to project reporting and oversight.

Table 6-1. RISA Pathway activities list by R&D focus area

<table>
<thead>
<tr>
<th>Descriptive Activity Title</th>
<th>Activity Description and Major Deliverables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Management and Industry Engagement</strong></td>
<td>Support routine project management activities and new program development tasks, report generation, travel, meetings, and benchmarking</td>
</tr>
</tbody>
</table>
| **RISA toolkit Deployment and Industry Application Pilot Demonstration Projects** | Continuous identification and update on RISA industry application pilot demonstration projects. Active communication with leading US nuclear industry by regular working group meeting:  
  - (All years) Update on RISA technical program plan  
  - (All years) Assessment of verification and validation (V&V) status of RISA toolkit |
| **Enhanced Resilient Nuclear Power Plant Concepts** | Apply RISA methods and toolkit in industry applications, including methods development and early demonstration of technologies, in order to enhance existing reactors safety features (both active and passive). Reduce on operating costs through risk-informed approaches to design modifications and their characterizations:  
  - (2020) Plant-level scenario-based risk analysis for an enhanced resilient plant model based on an existing BWR  
  - (2020) Full-scale Terry turbine testing under beyond-design basis conditions  
  - (2021) Human reliability analysis using FLEX in accident management and risk-informed analysis on passive cooling design  
  - (2022) Development of enhanced resilient plan system analysis framework for long-term ATF concept  
  - (2023) Demonstration of enhanced resilient plant concepts including passive cooling systems  
  - (2025) Support first plant reload of a near-term ATF concept. |
<table>
<thead>
<tr>
<th>Descriptive Activity Title</th>
<th>Activity Description and Major Deliverables</th>
</tr>
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| **Cost and Risk Categorization Applications** | Develop an innovative framework by combining physics, risk and cost information to enable a risk-and-cost-based decision-making process for optimizing maintenance activities and achieving the maximum cost-efficiency:  
  • (2020) Data driven risk analysis optimization toolkit for SSC maintenance and testing  
  • (2020) Integration of equipment failure data and models to system health program  
  • (2021) Full scale data driven risk analysis for SSC refurbishment and replacement  
  • (2021) Integration of real-time equipment monitoring date to system health program. |
| **Margin Recovery and Operation Cost Reduction** | Develop methods and demonstrate approaches to conduct a comprehensive investigation of design basis accident process requirements and implementation that can benefit from risk-informed, multi-physics, multi-scale, high-fidelity tools and methods to recover margins associated with uncertainties and conservatisms of legacy licensing design and analysis:  
  • (2020) Apply physics-based fire simulations with fire PRA data to demonstrate methods to reduce risk using a participating utility’s selected high consequence fire scenarios  
  • (2020) Importance measure analysis of experiments parameters of fire data and the impact on fire PRA modeling  
  • (2020) Comprehensive uncertainty quantification and sensitivity analysis for high burnup fuel test in TREAT  
  • (2020) Development of risk-informed method to optimize plant reloading thermal limit  
  • (2020) Demonstration of risk-informed tools for digital I&C upgrade and plant modernization  
  • (2021) Demonstrate use and develop a strategy for adoption of fire PRA enhancement tools by the existing fleet  
  • (2021) Feasibility study on of extended fuel burnup designs and cost benefit optimization  
  • (2021) Full scale demonstration on plant reloading thermal limit optimization and cost benefit  
  • (2021) Demonstration of enhanced safety by using ungraded digital I&C during transient accidents |
7. REFERENCES


APPENDIX A – Bibliography of Recent RISA Reports

The current list of reports can be found at:

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

- Enhancements to Engineering-scale Reactor Pressure Vessel Fracture Capabilities in Grizzly, B. Spencer, W. Hoffman, W. Jiang, INL_EXT-17-43427, September 2017.
- Additional Model Datasets and Results to Accelerate the Verification and Validation of RELAP-7, INL/EXT-16-40577, J. Yoo, Y. Choi, November 2016.
• Lower Length Scale Model Development for Embrittlement of Reactor Pressure Vessel Steel, INL/EXT-16-40011, Y. Zhang, P. Charkraborty, X. Bai, D. Schwen, September 2016.
• RELAP-7 Software Verification and Validation Plan, INL/EXT-16-40015, J. Yoo, Y. Choi, C. Smith, September 2016.


• Light Water Reactor Sustainability Program Seismic Data Gathering and Validation, J. Coleman, Idaho National Laboratory, February 2015.
• 3D J-Integral Capability in Grizzly, B. Spencer, M. Backman, P. Chakraborty, and W. Hoffman, INL/EXT-14-33257, September 2014.
• Case Study for Enhanced Accident Tolerance Design Changes, S. Prescott, C. Smith, T. Koonce, and T. Yang, Idaho National Laboratory, INL/EXT-14-32355, Rev. 1, September 2014.
• Enhanced Severe Transient Analysis for Prevention Technical Program Plan, H. Gougar, Idaho National Laboratory, INL/EXT-14-33228, September 2014.
• Prototype Consequence Modeling Tool Based Upon the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) Software, C. Pope, B. Byambadorj, C. Hill, E. Lum, B. Nield, and J. Swanson, Idaho State University, September 2014.
• Survey of Models for Concrete Degradation, B. Spencer and H. Huang, INL/EXT-14-32925 Rev. 0, August 2014.
• Grizzly Year-End Progress Report, B. Spencer, Y. Zhang, P. Chakraborty, S.B. Biner, M. Backman, B. Wirth, S. Novascone, J. Hales, INL/EXT-13-30316, Revision 0, September 2013.


• Technical Approach and Results from the Fuels Pathway on an Alternative Selection Case Study, R. Youngblood and C. Smith, INL/EXT-13-30195 Rev. 0, September 2013.


• Implementation of Changes to the EONY Model to Account for Extended Service Conditions and Late Blooming Phases for Reactor Pressure Vessel Steels, J.T. Busby and B.D. Wirth, ORNL, May 2013.