

Light Water Reactor Sustainability Program

Risk-Informed Systems Analysis (RISA) Pathway Industry Application Pilot Demonstration Projects - Edition 2019



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**Risk-Informed Systems Analysis (RISA) Pathway
Industry Application Pilot Demonstration Projects
- Edition 2019**

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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 margins, 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 (RIMM).

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 (SSC) of a NPP.

The RISA tools will be demonstrated through industry application pilot demonstrations projects, which are identified through in-depth discussions and participation from leading U.S. nuclear industries. The pilot projects are developed following three RISA R&D focus areas based on current industry challenges: (1) enhanced resilient NPP concepts, (2) cost and risk categorization applications, and (3) margin recovery and operation cost reduction. Current pilot projects are:

- RISA Enhanced Resilient Plant Systems
- Enhanced Operation Strategies for System Components
- Risk-Informed Asset Management
- Plant Health Management
- Enhanced Fire Probabilistic Risk Assessment (PRA)
- Modernization of Design Basis Accidents Analysis with Application on Fuel Burnup Extension
- Digital Instrumentation and Control (I&C) Risk Assessment
- Plant Reload Process Optimization.

This report summarizes the progress of each project as of May 2019, future works, feedback and comment from industry collaboration partners, and new pilot project idea for upcoming years.

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ACRONYMS

3D	three-dimensional
AOO	Anticipated Operation Occurrence
ATF	Accident Tolerant Fuel
BEPU	Best Estimate Plus Uncertainty
BWR	Boiling Water Reactor
DBA	Design Basis Accident
DNC	Dynamic Natural Convection
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
ER	Equipment Reliability
ESFAS	Engineered Safety Feature Actuation System
FLEX	Diverse and Flexible Coping Strategy
FY	Fiscal Year
GOTHIC	Generation of Thermal-Hydraulic Information for Containment
I&C	Instrumentation and Controls
INL	Idaho National Laboratory
IR	Incident Report
LOCA	Loss Of Coolant Accident
LWR	Light Water Reactor
LWRS	Light Water Reactor Sustainability
MAAP	Modular Accident Analysis Program
MOOSE	Multiphysics Object-Oriented Simulation Environment
MP-BEPU	Multi-Physics Best Estimate Plus Uncertainty
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Program
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
PDF	Probability Density Function
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
R&D	Research and Development
RAVEN	Risk Analysis in a Virtual Environment
RCIC	Reactor Core Isolation Cooling

RD&D	Research, Development, and Demonstration
RIA	Reactivity Initiated Accident
RIMM	Risk-Informed Margin Management
RI-MP-BEPU	Risk-Informed Multi-Physics Best Estimate Plus Uncertainty
RISA	Risk-Informed Systems Analysis
RISC	Risk-Informed Safety Categorization
RPS	Reactor Protection System
SLR	Second License Renewal
SNL	Sandia National Laboratories
SSC	System, Structure, and Component
TTEXOB	Terry Turbine Expanded Operating Band

1. INTRODUCTION

The United States (U.S.) nuclear industry faces challenges to remain economically competitive in electricity markets for many reasons. Safety is key to all aspects of light water reactor (LWR) operation, including the cost of operations. In the context of extending the operating periods of nuclear power plants (NPPs), traditional deterministic safety concepts may not guarantee the most economic results. One of the approaches to achieve greater cost efficiencies is to identify and optimize plant safety margins. In the Light Water Reactor Sustainability (LWRS) Program, the Risk-Informed Systems Analysis (RISA) Pathway focuses on optimizing safety margins and minimizing uncertainties to achieve high levels of safety and economic efficiencies. 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 (RIMM).

The RISA Pathway aims to improve economics and reliability and sustain safety of operating NPPs over periods of extended operation. The goals of the RISA Pathway are twofold: (1) deploy the RISA toolkit of technologies that enables better representation of safety margins and the 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 methods and tools provided by the RISA Pathway support effective margin management for both active and passive system, structure, and components (SSCs).

The RISA toolkit will be applied in industry-application pilot projects. These pilot projects were developed through discussions with U.S. nuclear utilities. The projects affect the following focus areas that correspond to key industry challenges: (1) enhanced resilient NPP concepts, (2) cost and risk categorization applications, and (3) margin recovery and operating cost reduction. The pilot projects represent studies using selected applications of the RISA toolkit. The research will also address the needed verification and validation of the tools and methods that are used in pilot projects.

On May 15, 2018, Idaho National Laboratory (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. Eight projects were identified based on comprehensive analysis on rising issues from the U.S. nuclear industry. Table 1 shows how each pilot demonstration project relates to each RISA research and development (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.

Table 1. Pilot demonstration projects related to RISA R&D focus areas.

RD&D Focus Areas	Pilot Demonstration Projects
Enhanced resilient NPP concepts	RISA-Enhanced Resilient Plant Systems Enhanced Operation Strategies for System Components.
Cost and risk categorization applications	Risk-Informed Asset Management Plant Health Management.
Margin recovery and operation cost reduction	Enhanced Fire Probabilistic Risk Assessment (PRA) Modernization of Design Basis Accidents Analysis with Application on Fuel Burnup Extension Digital Instrumentation and Control (I&C) Risk Assessment Plant Reload Process Optimization

Each of these pilot projects addresses one or more issues of critical importance to ensuring the safety and economic operation of the U.S. commercial NPPs. It should be noted that because these pilot projects can address a wide range of issues, they are not mutually exclusive. Consequently, it is expected that applications identified by NPP operating utilities may have aspects that address more than one of these pilot projects.

At the workshop in May 2018, the participants agreed on the selection principal for the pilot projects. The project should meet both demand from NPP operators and goal of LWRS Program: (1) maintaining operation of the current fleet to provide reliable, economic, carbon-free electricity; and (2) providing a pathway for transition to deployment of advanced reactor technologies. The project should be accomplished in appropriate timeframe so that deployment of the application could support enhancing economics of current operating U.S. NPPs. This is one of most important parameters for pilot project selection and performance.

In the evaluation of pilot projects, following six criteria were developed to support review of proposed projects with collaborators:

1. The pilot project should consistent with the RISA scope and mission.
2. Participation of utility, stakeholders, and university collaborators.
3. A “Minimum Viable Product” should be defined for benefits to NPPs.
4. The pilot project is scalable and adaptable to larger scope, more users, or other applications.
5. The pilot project employs technology innovation or demonstrates technology readiness.
6. Results of the pilot project address a critical near-term need of NPPs.

Details of workshop outcomes, candidates of pilot projects, selection criteria, and initial plan of pilot projects are described in INL/EXT-18-51012, “RISA Industry Use Case Analysis”[1]. Note that the “Pilot Project” is equivalent to “Use Case.”

For conduct of the applications, a broad suite of computational tools will be used within the RISA Pathway. These include both mature codes and advanced simulation codes being developed by the Nuclear Energy Advanced Modeling and Simulation program and the Consortium for Advanced Simulation of Light Water Reactors.

The goal of this report is to provide current status of RISA industry application pilot projects, feedback from collaborators, future work plan, and additional pilot projects proposal.

2. RESEARCH, DEVELOPMENT PURPOSE AND GOALS

2.1 Work Scope and Strategies

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.

The 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 1. In actual applications, both probabilistic and mechanistic analysis will be combined to support decisions.

Figure 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 demonstration project”, in-short "pilot project").

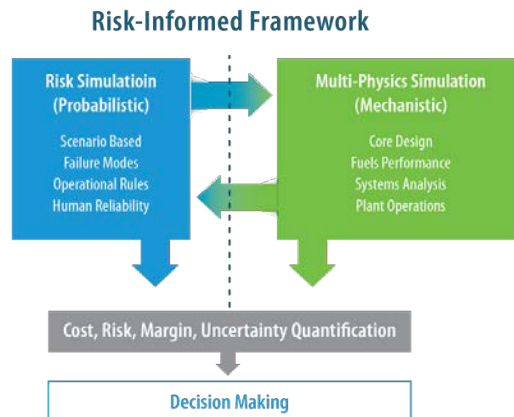


Figure 1. Types of analysis that are used in the RISA Pathway

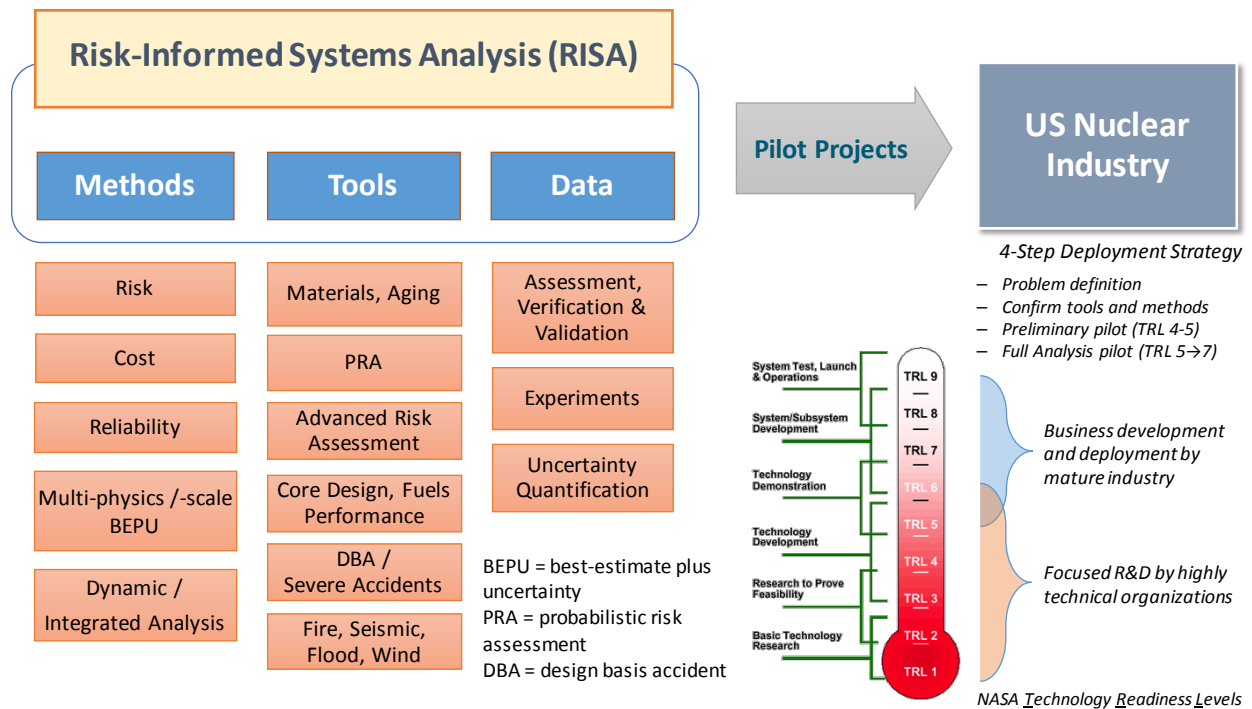


Figure 2. The RISA Pathway programmatic structure

2.2 Research and Development Focus Areas

The RISA Pathway research is performed within the framework of specific focus areas that represent key challenges identified by NPP owner-operators. The focus areas represent groups of applications of risk-informed technology to assist operating NPPs reduce costs and otherwise adapt to the changing economic and generating-mix environment. The RISA Pathway focus areas are (1) enhanced resilient NPP concepts, (2) cost and risk categorization applications, and (3) margin recovery and operating cost reduction. Scalable industry application pilot projects are being conducted in each of these focus areas, coordinated with industry collaborators. Upon successful demonstration, a larger community of users may implement scaled-up technology to support own applications.

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

2.2.1 Enhanced Resilient Nuclear Power Plant Concepts

The “Enhanced Resilient Plant Systems” concept is to use of enhanced safety features in NPPs to improve self-resiliency of the systems during any severe accidents. Current effort includes combinations of innovative safety features such as accident tolerant fuel (ATF), implementing a diverse and flexible coping strategy (FLEX), enhancements to plant components and systems, improved fuel cycle efficiency, and the incorporation of augmented or new passive cooling systems. The key metrics that 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 and Large Early Release Frequency, 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.

The research objective of this focus area is to use the risk-informed methods and tools in industry applications to enhance existing reactors’ safety features (both active and passive) and to substantially reduce operating costs. The work will use risk-informed approaches to plant design modifications to enhance plant resiliency. High-value evaluations of proposed ATF, together with enhanced resilient plant system concepts, will be performed to identify both the technical (e.g., benefits to risk, safety, and operational margins) and the economic (e.g., 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.

2.2.2 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. 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:

- 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.

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 risk-informed 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.

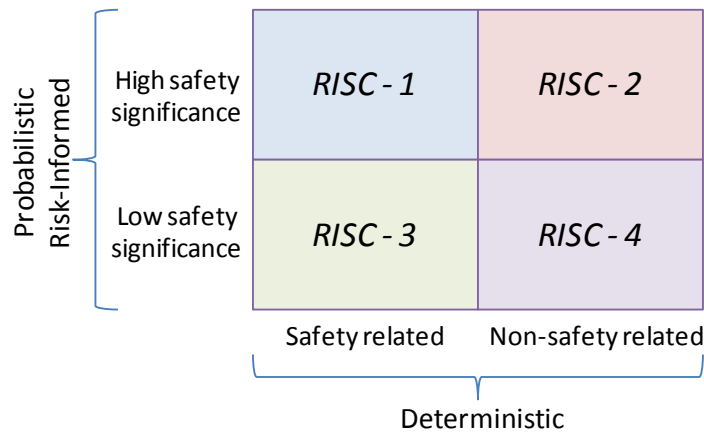


Figure 2. Risk-Informed Safety Categorization (RISC) (courtesy of 10 CFR 50.69).

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. 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 works scope includes employment of multiple tools using testing and maintenance data from existing NPPs.

2.2.3 Margin Recovery and Operation Cost Reduction

The goal of this area is to perform related research that develops risk-informed, multi-scale, and multi-physics high-fidelity tools and methods. This research supports the industry by conducting 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 work scope includes development of an integrated evaluation approach that combines plant PRA methods with Multi-Physics Best Estimate Plus Uncertainty (MP-BEPU), thus Risk-Informed Multi-Physics Best Estimate Plus Uncertainty (RI-MP-BEPU), methods.

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.

3. STATUS OF PILOT 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:

1. 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.
2. Advanced:
 - Analyze multi-physics, multi-scale, complex systems
 - Use of a modern computational framework
 - Utilize a variety of methods, tools, and data (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.
3. Risk-informed decision-making capabilities:
 - Use of an integrated decision process
 - Provide integrated consideration of both risks and deterministic elements of safety.

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 fiscal year (FY) 2019, the entire pilot project has been successfully initiated. The RISA Pathway team has been continuously put highest effort to communicate with their collaborators, U.S. nuclear industry, stakeholders, and universities. In June 2019, the RISA Pathway team collected feedback from pilot project collaborators.

In this section, each pilot project is summarized by providing following information:

1. Description of the project: Issues to be researched, work scope and plan, and outcome of the pilot project and their benefit to U.S. nuclear industry.
2. Work status: Work progress summary as of May 2019.
3. Future works: Project plan for upcoming years.
4. Deliverables: List of deliverables by years.

3.1 RISA Enhanced Resilient Plant Systems

3.1.1 Description of the Project

This study focuses on the combined effect evaluation of different plant resilience enhancing technologies to give better synergy and benefit from available and new plant systems and components.

For instance, utilities strategically look forward to improving both safety and economics even under the current high-operating cost environment. The deployment of ATF, along with the optimal use of diverse and FLEX equipment, is a good example of such an effort. The study will also 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 Risk Analysis in a Virtual Environment (RAVEN) controller software. The study will also combine with the FLEX equipment to optimize risk assessment and enhance resiliency under beyond design basis accidents. In parallel, augmented cooling systems will be evaluated, such as the Reactor Core Isolation Cooling (RCIC) system extended operating band in boiling water reactors (BWRs) or the installation of new passive cooling systems in pressurized water reactors (PWRs).

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 methods and combinations. The results will give clear long-term vision to the U.S. nuclear industry in deploying ATF to existing NPPs.

3.1.2 Work Status (as of May 2019)

FY 2019 work focuses on scenario-based risk analysis of a near-term ATF concepts study, which gives a basic approach to enhanced resilient plant application. The project is performing PRA evaluation of FLEX systems to achieve enhanced resilience of a PWR. A BWR will be covered in the future. The main collaborators on this project are the Electric Power Research Institute (EPRI) and Jensen Hughes. Other collaborators include the U.S. Department of Energy's (DOE) Nuclear Energy University Program (NEUP) and DOE's other fuel programs.

The project completed ATF risk analysis scenarios for loss of feedwater, a PWR locked rotor, and an Anticipated Transient without a Scram. The ongoing analysis includes a steam generator tube rupture, a main steam line break, and other transients. Research on FLEX will include Human Reliability Analysis and PRA modeling issues. Future activity will focus on passive cooling analysis by RELAP5-3D for the Dynamic Natural Convection (DNC) design to perform risk analysis. The RISA Pathway will organize a dedicated meeting on "Enhanced Resilience Plant Workshop" on July 30–31, 2019 at Idaho Falls, Idaho, hosted by INL.

3.1.3 Future Works

In FY 2020, the project will focus on resilient plant application to BWR types. The scenario will be covered for near-term ATF concept combination with FLEX systems applications. The pilot project will be extended to long-term ATF deployment scenario and followed by demonstration of the enhanced passive cooling system for resilient plant system analysis. The project will be continued until first plant reload of near-term ATF concept.

3.1.4 Deliverables

(2019) Plant-level scenario-based risk analysis for an enhanced resilient plant model based on an existing PWR, with near-term ATF concepts and FLEX operations for risk significant accidents.

(2019) Evaluation of combined benefits of FLEX, ATF, and DNC under limiting licensing basis accidents for an enhanced resilient PWR mode.

(2020) Plant-level scenario-based risk analysis for an enhanced resilient plant model based on an existing BWR, with near-term ATF concepts and FLEX operations for risk significant accidents.

- (2020) Plant specific PRA and human reliability analysis for FLEX in plant risk management.
- (2021) Detailed data analysis for FLEX in collaboration with Pressurized Water Reactor Owners Group/Boiling Water Reactor Owners Group to perform reliability studies for FLEX.
- (2021) Investigation of crediting non pre-deployed FLEX in plant risk management and utilizing FLEX in beyond Station Black Out (SBO) scenarios.
- (2021) Using risk-informed approaches to comprehensively investigate plant-specific risk profiles and optimize potential plant enhancements for resilience.
- (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.

3.2 Enhanced Operation Strategies for System Components

3.2.1 Description of the Project

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, 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 the first stage of theory and experimental study from the ongoing TTEXOB Project, the work will cover a specific area for beyond Design Basis Accident (DBA) 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 system and other safety issues.

3.2.2 Work Status (as of May 2019)

The project focuses on integral full-scale experiments for long-term low-pressure operations and full-scale modeling, as well as long-term low-pressure case experiments and modeling. The main collaborators of this project are the Boiling Water Reactor Owners Group – RCIC Operation Band Committee; Pressurized Water Reactor Owners Group – Procedures Committee; EPRI's Nuclear Maintenance Advanced Center's Terry Turbine Group, and the Institute of Applied Energy (Japan).

Significant efforts were dedicated to experiment work in FY 2019. Air and air/water tests were completed for 10% scaled ZS-1 Terry turbine to identify the dimensionless parameter, which predicts Terry turbine behavior under two-phase flow conditions. The scaling results were verified and will be used in a surrogate of a GS-series Terry turbine. The air and air/water tests underway on a GS-2 Terry turbine at Turbine-Driven Auxiliary Feedwater pump system at the Crystal River NPP. The initial data are under review to support the dimensionless parameter identified in the ZS-1 test.

The heated oil tests are completed. Initial analysis shows expanding the oil temperature limits (e.g., 180°F) can be expanded to 250°F and possibility to 310°F. The oil was heated to higher temperatures and held for at least 72 hours.

The integral oil and bearing tests were started in March, which include both 3- and 7-day cases. The results will be used in the ZS-1 and GS-1 (Clinton RCIC training skid) turbines case studies.

Free jet testing is also underway to confirm performance under 0–100% steam quality. The test achieved sonic velocity (e.g., ~1.1Ma) and will be refined to 1.2–2 Ma. High-speed video recording for single-phase tests will be done in June 2019.

3.2.3 Future Works

The modeling of nozzle shock physics for full-scale component and Terry Turbine experiments will be done in upcoming years. The test planning for integral full-scale experiments for long-term low-pressure operations will be also set. The project will be extended to uncertainty quantification and validation of two-phase flow across a steam nozzle. An experiment will be conducted for integral full-scale experiments for long-term low-pressure operations. The final modeling and experiment will cover scaling study on Fukushima Daiichi Unit 2.

3.2.4 Deliverables

(2019) Experimental results of the full-scale component and Terry Turbine nozzle experiments.

(2019) Extension of the efficient modeling capability of RELAP5-3D to simulate the reactor core isolation systems.

(2019) Initial scoping analyses of the integral full-scale long-term low-pressure operations for Terry turbo-pump systems.

(2020) Nozzle shock physics modeling for full scale component and Terry Turbine experiments.

(2020) Test planning for Integral full-scale experiments for long-term low-pressure operations.

(2021) Uncertainty quantification and validation of two-phase flow across a steam nozzle.

(2022) Integral full-scale experiments for long-term low-pressure operations.

(2023) Test planning for integrated scaled experiments replicating Fukushima Daiichi Unit 2 self-regulating feedback.

3.3 Risk Informed Asset Management

3.3.1 Description of the Project

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 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 in 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 that 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.

3.3.2 Work Status (as of May 2019)

For FY 2019, the project will conduct R&D to combine data analytics and risk analysis tools for long-term capital SSC refurbishment and replacement for an existing plant. The main participants for this work include Dominion, Jensen Hughes, Northwestern University, Texas State University, and EPRI.

Recent work includes a technical approach on explicit considerations of data uncertainties; an integration of different models such as economic models, PRA information, and plant health models; an evaluation of margins for real-time applications; an ability to deal with multiple and heterogeneous constraints; and perform multi-level optimization problems and solution validation.

3.3.3 Future Works

The research will be extended to the enterprise multi-risk framework to include plant revenue forecast. The work will use the data driven enterprise risk analysis optimization toolkit for SSC maintenance and testing using plant SSC and enterprise cost data from an existing plant. The final phase will be integration of both risk-informed plant asset and health management to model an enterprise multi-risk framework. The data driven enterprise risk analysis framework will be extended from an individual plant to a fleet for a candidate SSC refurbishment or replacement. The final work will be demonstration and deployment of enterprise multi-risk framework.

3.3.4 Deliverable

(2019) Demonstrate a combined data analytics and risk analysis tool for long-term capital SSC refurbishment and replacement for an existing plant.

(2020) Data driven risk analysis optimization toolkit for SSC maintenance and testing.

(2021) Full-scale data driven risk analysis for SSC refurbishment and replacement.

(2022) Demonstration of enterprise multi-risk framework.

(2023) Deployment enterprise multi-risk framework to support maintenance and license renewal.

3.4 Plant Health Management

3.4.1 Description of the Project

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 strategy as a pathway to implementing fully integrated advanced monitoring systems into plant ER programs is refined.

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 all 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 transferrable 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.

3.4.2 Work Status (as of May 2019)

The project is working to apply the plant health management system of emergency diesel generators and main feedwater systems of the Exelon fleet health management and Limerick Generating Station. The goal of this task is to integrate several Exelon data sources with risk-informed applications such as Engage-Health – ER, Passport – maintenance database, CAFTA – PRA, and Predix – data analytics. Other subtasks include the characterization of risk-informed applications, the identification of links between system health program and risk-informed applications, the development of requirements for system health programs and risk-informed applications, the review of system health information provided by the host plant, and the development of an advanced risk-informed system health program.

3.4.3 Future Works

In FY 2020, the project will complete the integration of the equipment failure data/model with existing plant system health program to optimize testing, maintenance, and replacement of the components. Next phase will be integration of both risk-informed plant asset and health management to model an enterprise multi-risk framework. The real-time equipment monitoring data will be integrated to system health program. The final work will be the demonstration and deployment of enterprise multi-risk framework.

3.4.4 Deliverable

(2019) Risk-informed systems health management automation tools integrated with an existing plant system health program.

(2020) Integration of data analytics and SSC aging models with plant system health program.

(2021) Integration of real-time equipment monitoring data to system health program.

(2022) Demonstration of enterprise multi-risk framework.

(2023) Deployment enterprise multi-risk framework to support maintenance and license renewal.

3.5 Enhanced Fire PRA

3.5.1 Description of the Project

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.

3.5.2 Work Status (as of May 2019)

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 will be delivered in June 2019 to a utility for evaluation. This tool will process actual plant data and add spatial information for 3D viewing. The FRI3D will provide 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 to publish a follow-on report.

3.5.3 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.

3.5.4 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 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.

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

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

3.6.1 Description of the Project

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 6wt% 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., loss of coolant accident [LOCA] and reactivity-initiated accident), which should be thoroughly studied and assessed.

The study will use 6wt% enriched fuel with a 24-month 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 distribution 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 transferred immediately to the U.S. nuclear industry since burnup extension is one of the largest ongoing efforts to reduce cost. The study will include licensing and issues analysis for optimized fuel enrichment and burnup extension, as well as economic benefits.

3.6.2 Work Status (as of May 2019)

Currently, the project performs core design to achieve burnup extension with an enrichment exceeding current limit of 5wt% and a fuel discharge burnup exceeding the current burnup limit by 20%. The work also includes the application of risk-informed high-fidelity multi-physics methodology to evaluate fuel rod non-burst potential under LOCA conditions for extended burnup fuel. The main

collaborators of this project include EPRI, Xcel Energy, South Texas Projects, and Texas A&M University.

3.6.3 Future Works

Future work will focus on completing the comprehensive uncertainty quantification and sensitivity analysis to inform the experiments. The experiment will be conducted at INL's Transient Reactor Test Program (TREAT) reactor for high burnup fuel to study the fuel fragmentation and relocation issues, which will be in collaboration with a NSUF project. The project will then progress to demonstrate the feasibility of extended fuel burnup designs for all prescribed plant transient scenarios and the cost/benefits analyses of optimal combinations of enrichment, burnup, and cycle length.

3.6.4 Deliverable

(2019) Fuel rod non-burst potential evaluation under LOCA conditions for an existing plant with extended burnup.

(2020) Demonstration of machine learning-assisted optimization of 2-year cycle core design for an existing PWR with burnup and enrichment extension.

(2021) Feasibility study on of extended fuel burnup designs and cost benefit optimization.

3.7 Digital I&C Risk Assessment

3.7.1 Description of the Project

The 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 and installed using the advanced Reactor Protection System (RPS) and Engineered Safety Feature Actuation System (ESFAS) due to 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. A technology gap identification will also be performed, which may support solving the 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.

3.7.2 Work Status (as of May 2019)

FY 2019 activity includes the development of risk assessment strategy for digital I&C upgrades using current digital technology information, which will perform a conceptual digital design RPS reliability study. Applying risk-informed tools to address common cause failure for digital I&C technology will be done this FY. Collaborators include Technology Resources, Duke Energy, Nuclear Energy Institute, and the LWRS Plant Modernization Pathway.

3.7.3 Future Works

FY 2020 activity will cover application of the risk-informed tools to address common cause failure modes that may be induced by a candidate digital I&C technology. This work will be done in

collaboration with LWRs Plant Modernization Pathway and a participating NPP operators. In FY 2021 the project will conduct plant-level scenario-based simulations of unanalyzed transients concurrent with common cause failures to demonstrate plant safety with digital I&C upgrades.

3.7.4 Deliverable

(2019) Risk assessment strategy for digital instrumentation and control upgrades using current digital technology information.

(2020) Perform hazard and reliability studies on a digital RPS (reactor protection systems) and ESFAS (engineered safety features actuation systems).

(2021) Demonstration of enhanced safety by using ungraded digital I&C during transient accidents.

3.8 Plant Reload Process Optimization

3.8.1 Description of the Project

The optimization of plant reloading reactor core thermal limits has been requested from U.S. NPPs, which can help reduce significant amounts of fuel costs. 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 evaluations. The assessment will also include peak cladding temperature during LOCA analysis and departure from nucleate boiling 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 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 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 and RAVEN for the management of the model optimization, risk assessment, and data 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.

3.8.2 Work Status (as of May 2019)

Work to identify a coherent and feasible development/deployment plan and early demonstration of the tool infrastructure on a selected accident sequence is the focus of this stage of the project. The reactor coolant pump shaft seizure (Locked Rotor) sequence has been selected for an early demonstration of the software and methodology infrastructure. Main collaborators are FPoliSolutions, Exelon and Southern Company (TBD).

3.8.3 Future Works

Future works include perform risk-informed reload licensing calculations to demonstrate the margin and costs benefits for the pilot plant and extended study on the reload licensing risk-informed framework to the existing fleet. In FY 2020 the work will focus of analysis method development based on Design Basis Accident (DBA) scenario. Main thermal limit evaluation scenario will be determined that will be

simulated by using classical deterministic method for licensing DBA scenario. This simulation will demonstrate plant reload process could be evaluated through NUREG-800 Chapter 19, which is risk-informed licensing analysis area. The Locked Rotor Event Scenario will be used for optimizing existing PWR reloading license process and plant cycle management scenario.

The project will be extended to apply risk-informed model to fuel reloading thermal limit optimization for FY 2021. The research will propose risk-informed modeling scenario for U.S. NPPs Final Safety Analysis Report licensing evaluation. This will support development of risk-informed methods to optimize plant reloading thermal limit.

In FY 2022, the project will perform full-scale demonstration of plant reloading thermal limit optimization by using risk-informed method. The outcome will quantify number for fuel assemblies could be reduced for reloading and cost benefits. Innovative reactor core fuel loading pattern will be suggested based on risk-informed fuel reloading thermal limit, Peak Cladding Temperature, Departure from Nucleate Boiling Ratio, and hydrogen/oxide limitations.

3.8.4 Deliverable

(2019) Development plan for optimize the existing reload licensing process and plant cycle management for an operating PWR.

(2020) Development and demonstration of fuel reloading model based on DBA scenario.

(2021) Application of risk-informed model to fuel reloading thermal limit optimization.

(2022) Full-scale demonstration on plant reloading thermal limit optimization and cost benefit.

4. FEEDBACK AND COMMENTS

4.1 Stakeholder Engagement Review Meeting

On January 17–18, 2019, the LWRS Program Stakeholder Engagement Review Meeting was organized in Rockville, Maryland. The purpose of the meeting is to meet related U.S. nuclear stakeholders and to collect their feedback on LWRS Program, which will help identifying future R&D priorities. The meeting was held with more than 130 participants from U.S. nuclear industries, vendors and suppliers, regulators and research institutes. A panel discussion entitled, “Industry Challenges and Perspectives for Long-Term Operation,” was organized. The breakout session for each Pathway was followed by to discuss gaps and opportunities for each R&D area of LWRS Program. More detail is available at LWRS webpage [2].

Nineteen participants were attended at the RISA Pathway break session. Follow by the presentation on accomplishment summary of the Pathway to describe goals, objectives, and current pilot projects in the RISA pathway. The meeting then progressed to discuss industry needs in the area of risk-informed applications and recommendations for the direction of the RISA pathway research. Following areas were identified as need from industries:

- Use existing reliability data to demonstrate limited benefit from 10 CFR 50.69 requirements and support evaluation by using risk-informed tools and methods
- Identify “non-traditionally risk informed” processes where risk insights may reduce time/cost for regulatory activities such as physical security, aging analysis, or tools to support engineering walk downs
- Use methods to reduce cost of conservatism and PRA analysis for industry use.

To help better support industry through the RISA program, the following suggestions for future pathway activities were provided:

- Identify correct industrialized tools as the PRA tools used industries are not unified
- Evaluate new PRA tools and methods against PRA standards and U.S. Nuclear Regulatory Commission (NRC) RegGuide 1.200 requirements
- Develop time reliability models for real-time risk analysis, taking advantage of big data methods
- Involve the U.S. regulatory body to the Pathway and early deployment of risk-informed tools and method to ease acceptance of current risk-informed tools and methods
- Ensure continued involvement and feedback from RISA Pathway collaborator and expert group through various methods including annual review meeting
- Engage with Risk-Informed Steering Committee support group (Nuclear Energy Institute [NEI]/NRC) and other standards committees to support awareness of new methods (e.g., ASME and ANS)
- Harvest available data from decommissioned or decommissioning plants to validate risk-informed tools and methods
- Continue communicate with entire U.S. nuclear industry for effective dissemination of the Pathway accomplishment and future involvement to current and new pilot projects
- Ensure all efforts related to risk-informed tools and methods are coordinated with external stakeholders including government, institutes and industries.
- Provide training and better information about how to use or apply new risk-informed tools and methods developed within the pathway.

4.2 Feedback and Comment from Collaborators

In May 2019, the RISA Pathway collected feedback and comment from current pilot project collaborators to listen their opinion and to identify arising issues to be considered as new pilot projects. A summary report was provided to collaborators including work progress and questionnaire [3]. Table 2 is the example of questionnaire for feedback and comments. The answer of each questions will be transferred to the point, thus, strongly agree is 5 and strongly disagree is 1 point. The average point will be calculated to measure the degree of quality. Collected feedback and comments are summarized in following section.

Table 2. Example of questionnaire for feedback

Pilot Project Questionnaire						
No.	Specific Questions	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
1	Pilot application scope and work plan addresses the right issues.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2	Pilot application goal is appropriate and understandable.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	Pilot application outcome will help LWR sustainability.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4	Pilot application plan is suitable and progresses as planned.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5	Pilot application uses correct tools and methods.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6	Pilot application communication is timely and effective.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Pilot application collaboration is effective and productive.	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Comments:						

4.2.1 General Feedback

General feedback and comments are as follows:

- Additional collaboration with universities will improve academic background and credibility of pilot project. This includes NEUP projects and other related DOE sponsored research
- Longer term (i.e., annual basis) research agreement with academic institutions will improve research qualities and can enhance communication. Number and quality of the research publications will be also increased by long term research collaboration with universities.
- Voluntary contribution from utilities decreases motivation to the pilot project involvement and may delay scheduled milestones. The pathway should find appropriate solution to support utility experts to make them to provide the resources necessary and get alignment on the project and then subsequently in assigning resources to achieve the objectives.

4.2.2 Enhanced Resilient Plant Systems

The comment addresses that the benefit from combination of ATF, FLEX, and DNC will give maximum benefit to U.S. nuclear industry. Collaboration quality could be improved by having more frequent engagement with industry groups working on these issues such as NEI Safety Benefits Task Force. Tools for the demonstration need to be identified and verified.

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	4
2	Pilot application goal is appropriate and understandable.	4.5
3	Pilot application outcome will help light water reactor (LWR) sustainability.	4
4	Pilot application plan is suitable and progresses as planned.	4.5
5	Pilot application uses correct tools and methods.	4
6	Pilot application communication is timely and effective.	4.5
7	Pilot application collaboration is effective and productive.	4.5

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.3 Enhanced Operation Strategies for System Components

This activity has broad collaboration within the industry and science areas as well as international participation. Progress in the past year has been acceptable. The remaining steps for system validation has the potential to tie the results together for the benefit of the industry

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	5
2	Pilot application goal is appropriate and understandable.	5
3	Pilot application outcome will help light water reactor (LWR) sustainability.	5
4	Pilot application plan is suitable and progresses as planned.	5
5	Pilot application uses correct tools and methods.	5
6	Pilot application communication is timely and effective.	4
7	Pilot application collaboration is effective and productive.	5

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.4 Risk-Informed Asset Management

The ongoing NEUP project (RC-9 #17-12614) has complementary work scope which focuses on in-depth causality for physical degradation phenomena (e.g., stress corrosion cracking and human performance) associated with operations and maintenance of the plant. The RISA Pathway pilot project scope includes specifying the optimal conditions and timing for replacement/refurbishment based on anticipated conditions with appropriate assessments performed to address uncertainties. It would be beneficial to explore the complimentary nature of these two projects and integrate this work using a common computational platform such as RAVEN.

Collaboration with industry partners should be more effective and productive. Correct selection and effective participation of the industry expert will increase product quality and avoid potential delay of the milestone. Voluntary contribution from industry could limit effective participation.

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	4
2	Pilot application goal is appropriate and understandable.	4
3	Pilot application outcome will help light water reactor (LWR) sustainability.	4.5
4	Pilot application plan is suitable and progresses as planned.	2
5	Pilot application uses correct tools and methods.	4
6	Pilot application communication is timely and effective.	2
7	Pilot application collaboration is effective and productive.	2

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.5 Plant Health Management

The collected comments are summarized as follows:

- Similar to the pilot project on the risk-informed asset management, the ongoing NEUP project (RC-9 #17-12614) could provide complementary research outcome by using common computational platform such as RAVEN.
- The industry participation is effective and productive. The RISA Pathway should endorse strong participation from industry to avoid any potential delay of the schedule.
- Work scope and overall goals are valuable and timely for improving economics and long-term viability of U.S. NPPs and to the related industries.
- Should consider of providing the process data such as the plant health management history.
- Existing tool (e.g., COTS in the Predix platform) should be verified for the quality purpose and other tools could be considered.
- Fully validated power generation risk assessment tool will provide higher confidence in current pilot project.

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	4.7
2	Pilot application goal is appropriate and understandable.	4.3
3	Pilot application outcome will help light water reactor (LWR) sustainability.	4.7
4	Pilot application plan is suitable and progresses as planned.	3.7
5	Pilot application uses correct tools and methods.	4
6	Pilot application communication is timely and effective.	4.3
7	Pilot application collaboration is effective and productive.	4

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.6 Enhanced Fire PRA

The feedback and comments from collaborators are as follows

- Ongoing collaborative activity between University of Illinois at Urbana Champaign and South Texas Project will be a complementary research to the RISA Pathway fire PRA pilot project. The collaborative work has been published with the title of “An integrated methodology for spatio-temporal incorporation of underlying failure mechanisms into fire probabilistic risk assessment of NPPs,” *Reliability Engineering & System Safety*, Vol. 169, pp. 242–257, 2018.
- With added capability of simulating fire with Consolidated Model of Fire and Smoke Transport (CFAST) and Fire Dynamics Simulator (FDS) directly connected to spatial and logical relationships, FRI3D will become even more useful and powerful tool for fire PRA analysis.
- By using FRI3D, building the 3D model in Physical Analysis Unit became easier.
- Use of 3D scanning tool for FRI3D modeling will help simulating plant level analysis.
- FRI3D will support validation of existing fire PRA scenarios and identification of unrealistic conservative fire scenarios. Realistic fire PRA scenario model will economize plant modification or regulatory risk assessment.
- Use of existing 3D structure models (i.e., Vogtle 3,4) could improve credibility of FRI3D model.
- The project has been receiving high interest and support from related industry area. To produce quality outcome long term collaboration with academic institute is proposed.

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	4.5
2	Pilot application goal is appropriate and understandable.	4
3	Pilot application outcome will help light water reactor (LWR) sustainability.	4.5
4	Pilot application plan is suitable and progresses as planned.	3.5
5	Pilot application uses correct tools and methods.	4
6	Pilot application communication is timely and effective.	4
7	Pilot application collaboration is effective and productive.	4

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.7 Modernization of DBA analysis with Application on Burnup Extension

Following feedback and comments are collected:

- Early deployment of the ATF with enhanced enrichment and extended burnup will support industry’s objectives.
- Type of the NPP (e.g., 3 or 4-loop Westinghouse PWR) that can show different accident scenario boundary conditions, should be evaluated to determine if this plant type is sufficient to provide general industry results. For example, 3-loop Westinghouse PWR will show limited scenario compare to 4-loop PWRs for Small Break LOCA.
- Need to identify type of Burnable Poison for scenario (Integral Fuel Burnable Absorber, Gadolinium, etc.).
- Recommend communicate with various operators (e.g., Westinghouse and Framatome) to compare boundary conditions, scenarios, plant type, burnable poison, etc., to confirm applicability of output to different type of NPPs.

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	4.5
2	Pilot application goal is appropriate and understandable.	4.5
3	Pilot application outcome will help light water reactor (LWR) sustainability.	4.5
4	Pilot application plan is suitable and progresses as planned.	4.5
5	Pilot application uses correct tools and methods.	3.5
6	Pilot application communication is timely and effective.	4
7	Pilot application collaboration is effective and productive.	4.5

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.8 Digital I&C Risk Assessment

The pilot application and lessons learned and documented will help follow on units to reduce their risk exposure during the design, licensing, installation, and operations of advanced digital protection, control, and monitoring systems.

The average point of questions are as follows:

No.	Specific Question	Avg. Point*
1	Pilot application scope and work plan addresses the right issues.	5
2	Pilot application goal is appropriate and understandable.	5
3	Pilot application outcome will help light water reactor (LWR) sustainability.	5
4	Pilot application plan is suitable and progresses as planned.	5
5	Pilot application uses correct tools and methods.	5
6	Pilot application communication is timely and effective.	5
7	Pilot application collaboration is effective and productive.	5

* Strongly agree: 5 point, Strongly disagree: 1 point

4.2.9 Plant Reload Process Optimization

No specific comment was received.

5. PROPOSAL FOR NEW PROJECTS

5.1 Supporting R&D Activities

Two supporting R&D activities are proposed for upcoming years.

5.1.1 Implementation of Risk-Informed Multi-Physics Best Estimate Plus Uncertainties (RI-MP-BEPU) Application

Most of RISA Pathway pilot demonstration projects are aiming to provide risk-informed solution to issues in the U.S. NPP systems to optimize uncertainties and eventually to improve economics by applying risk-informed tools and methods. The risk-informed approach basically uses classic and dynamic PRA methods for application tools, which are selected by pilot project such as RELAP5-3D. Many ongoing pilot projects are aiming to use RELAP5-3D for risk-informed analysis of issues to be solved couple with PRA (risk-informed) and uncertainty analysis, notably, Risk-Informed Multi-Physics Best Estimate Plus Uncertainties (RI-MP-BEPU) approach. The risk-informed analysis will be covered by RAVEN and SAPHIRE software, which has been used for various PRA applications. However, the RELAP5-3D lacks the uncertainty analysis capabilities to perform full Best Estimate Plus Uncertainty (BEPU) analysis. The BEPU method requires the application of Uncertainty Quantification methods, the input parameter Probability Density Functions (PDFs) determination, and the propagation of these PDF the 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 (e.g., closure laws) still need to be developed for RI-MP-BEPU application.

The objectives of this activity are as follows:

- Implement full BEPU analysis capability to RELAP5-3D
- Improve RAVEN to perform risk-informed analysis by using classical/dynamic PRA
- Demonstrate and benchmark RI-BEPU capability through selected Anticipated Operation Occurrence (AOO) and DBA scenarios
- Develop and validate Multi-Physics BEPU model
- Support existing and future industry pilot projects, which plan to employ the RI-MP-BEPU model.

The Uncertainty Quantification method will be based on the application of order statistics, which is widely used by nuclear-related facility license processes. The RELAP5-3D will be modified to allow a direct perturbation of selected closure laws/correlations. In this way it would be possible to have a consistent application of the order statistics methods. Then, the tight coupling with RAVEN will be implemented to access RELAP5-3D output binary files directly. The final product will allow extend of RELAP5-3D control logic for dynamic PRA applications, and to control and manage RELAP5-3D calculations status.

The developed capability will be validated through Organization for Economic Co-operation and Development/Nuclear Energy Agency's activity on "Benchmark for Uncertainty Analysis in Best-Estimate Modeling," which aims to perform comprehensive benchmark study of various nuclear systems to implement uncertainty analysis method.

Work scope and plan are as proposed as follows:

FY-2020

- Develop initial perturbation model for selected closure laws such as interfacial friction correlations and coefficients, which are key parameters to predict risk-informed AOO and DBA scenarios
- Identify suitable probability distribution functions for the interfacial friction correlations coefficients

- Demonstrate risk-informed transient scenarios with RAVEN (e.g., Large Break LOCA coupled with PRA model) to study perturbation of the interfacial friction correlation coefficients.

FY-2021

- Develop extended perturbation model to cover system level analysis of LWR AOO and DBA scenario
- Initiation of PDF database to support uncertainty quantification
- Improvement of RAVEN to allow RELAP5-3D control logic.

FY-2022

- Expansion to Multi-Physics BEPU model development
- Validation of developed model for RI-MP-BEPU application
- Establish PDF database.

5.1.2 Development of Risk-Informed Reactor Containment Thermal-hydraulics Analysis Framework

Nuclear power plant reactor containment is the final barrier, which prevents release of radioactive contamination to the environment during severe accident. Since the Three Mile Island accident, considerable research has been performed to understand containment thermal-hydraulics behavior to remove potential hydrogen fire risk. However; it is the hydrogen explosion was occurred during Fukushima accident and R&D effort has been dramatically increased around the world. The performance of Passive Autocatalytic Recombiners (PARs) has been improved and installation number are increased in Europe and Asia. Early deployment ATF is main goal in U.S. to remove potential hydrogen risk.

The main goal of the project is to establish extended capability of risk-informed reactor containment thermal-hydraulics analysis, which will support ongoing RISA Enhanced Resilient Plant pilot project. According to 10 CFR 50.44, “Combustible gas control for nuclear power reactors,” the hydrogen and containment atmosphere should be monitored, evaluated, and controlled during normal operation and (beyond) DBA to mitigate potential hydrogen risk and to maintain containment and system integration. However, the complexity of hydrogen behavior and detonation characteristics increases analysis resource; thus, the safety margin was set with over-conservatism.

The scenario-based containment thermal-hydraulics will be analyzed by GOTHIC (Generation of Thermal-Hydraulic Information for Containment) code and RAVEN will support PRA modeling. The GOTHIC is a computer code for thermal hydraulic and combustion calculations in multi-dimensional modeling. Precise risk-informed analysis on containment thermal-hydraulics will improve economics of NPP license and maintenance.

The proposed work scope and plan are as follows:

FY-2020

- GOTHIC-RAVEN coupling
- Development of P/BWR accident scenario for method application

FY-2021

- Validation of GOTHIC-RAVEN coupling
- Demonstration of P/BWR scenario-based GOTHIC-RAVEN analysis.

6. REFERENCES

- [1] R. Szilard, et al., *RISA Industry Use Case Analysis*, INL/EXT-18-51012, 2018.
- [2] https://lwrs.inl.gov/Newsletter%20Articles/Issue%2028/Issue_28-Article_01.pdf
- [3] C. Smith, et al., *LWRS Risk Informed Systems Analysis (RISA) Pathway Pilot Demonstration Projects FY-2019 Work Progress and Feedback*, INL/MIS-19-53993, 2019.