INL/EXT-17-43243
Revision 0

Light Water Reactor Sustainability Program

Risk-Informed Safety Margins Characterization (RISMC) Pathway Technical Program Plan

September 2017

DOE Office of Nuclear Energy

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Risk-Informed Safety Margins Characterization (RISMC) Pathway Technical Program Plan

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September 2017

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

EXECUTIVE SUMMARY

Safety is central to the design, licensing, operation, and economics of nuclear power plants (NPPs). As the current Light Water Reactor (LWR) NPPs age beyond 60 years, there are possibilities for increased frequency of systems, structures, and components (SSCs) degradations or failures that initiate safety-significant events, reduce existing accident mitigation capabilities, or create 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 scenarios, public health and safety will be protected with a very high degree of assurance. This form of defense-in-depth is a reasoned response to uncertainties and is often referred to generically as "safety margin." Historically, specific safety margin provisions have been formulated, primarily based on "engineering judgment."

The ability to better characterize (i.e., describe and quantify) safety margin is important to improved decision making about LWR design and long-term operation. A systematic approach to characterizing safety margins and the subsequent risk informed margins management options represents a vital input to the licensee and regulatory analysis and decision making that will be involved. In addition, as research and development (R&D) in the LWRS Program and other collaborative efforts yield new data and improved scientific understanding of physical processes that govern the aging and degradation of plant SSCs (and concurrently support technological advances in nuclear reactor fuels and plant instrumentation and control systems), needs and opportunities to better optimize plant safety, economics, and performance will become known.

The purpose of the Risk-Informed Safety Margins Characterization (RISMC) Pathway R&D is to support plant decisions for risk-informed margins management with the aim to improve economics, reliability, and sustain safety of current NPPs. The goals of the RISMC Pathway are twofold: (1) develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by NPP decision makers as part of risk-informed margin management strategies; (2) create an advanced RISMC Toolkit that enables more accurate representation of NPP safety margins. The methods and tools provided by RISMC are essential to a comprehensive and integrated risk-informed margin management approach that supports effective preservation of margin for both active and passive SSCs.

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ACRONYMS

ASAMPSA_E	Advanced Safety Assessment Methodologies: Extended PSA
AFT	accident tolerant fuel
BWR	boiling water reactor
CASL	Consortium on Advanced Simulation of LWRs
CNWG	Civil Nuclear Energy Research and Development Working Group
CRA	computational risk assessment
CSNI	Committee on the Safety of Nuclear Installations
CWO	core-wide oxidation
DG	diesel generator
DOE	Department of Energy
ECR	equivalent cladding reacted
EPRI	Electric Power Research Institute
FLEX	Diverse and Flexible Coping Strategies
GUI	graphical user interface
IA	Industry Applications
INL	Idaho National Laboratory
LOCA	loss-of-coolant accident
LWR	light water reactor
MOOSE	Multiphysics Object-Oriented Simulation Environment
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEET	Nuclear Energy Enabling Technologies
NEUP	Nuclear Energy University Program
NPP	nuclear power plants
NRC	U.S. Nuclear Regulatory Commission
OECD	Organization for Economic Co-operation and Development

PCT	peak cladding temperature
PRA	probabilistic risk assessment
PSA	probabilistic safety assessment
PWR	pressurized water reactor
R&D	research and development
RAVEN	Risk Analysis in a Virtual Environment
RELAP-5	Reactor Excursion and Leak Analysis Program-5
RIMM	Risk-Informed Margin Management
RISMC	Risk-Informed Safety Margins Characterization
SBO	station black out
SSC	systems, structures, and component
T-H	thermal-hydraulics
WGEV	Working Group on Natural External Hazards

Risk-Informed Safety Margins Characterization (RISMC) Pathway Technical Program Plan

1. BACKGROUND

Safety is central to the design, licensing, operation, and economics of nuclear power plants (NPPs). As the current light water reactor (LWR) NPPs age beyond 60 years, there are possibilities for increased frequency of systems, structures, and components (SSC) degradations or failures that initiate safety-significant events, reduce existing accident mitigation capabilities, or create 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 scenarios, public health and safety will be protected with a very high degree of assurance. This form of defense-in-depth is a reasoned response to uncertainties and is often referred to generically as "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 LWR Sustainability program is focused on ensuring the safety and performance of the nuclear fleet to enhance operation efficiencies of existing plants, support long term operation of these plants, and provide confidence for subsequent license renewals. Within this Program, the Risk-Informed Safety Margins Characterization (RISMC) Pathway is solving technical issues for several of the "sustainability" dimensions that exist, as illustrated in Figure 1-1.

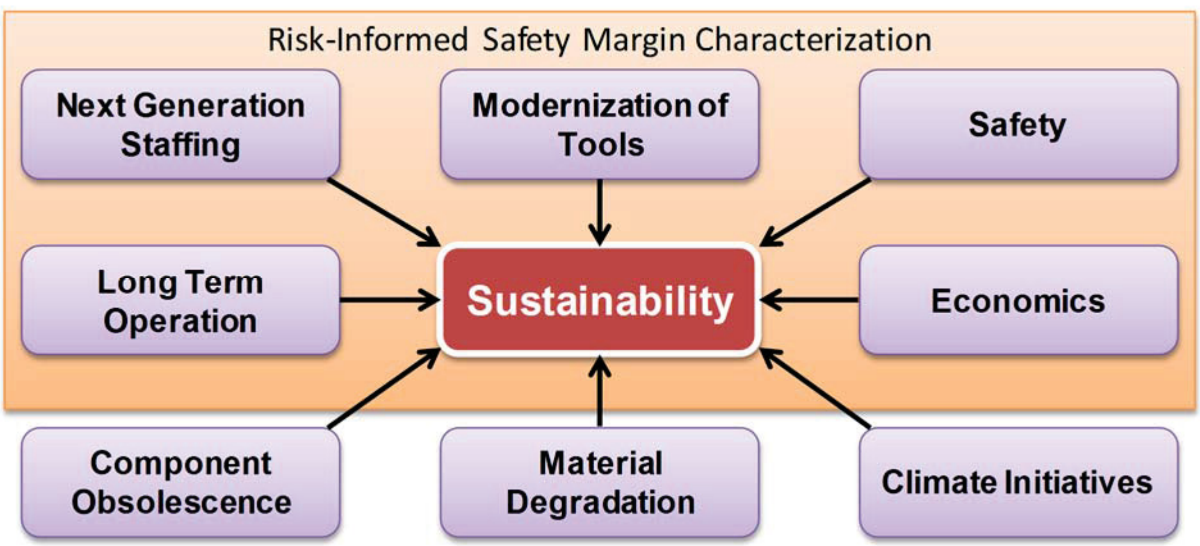

Figure 1-1. The sustainability aspects that exist for near and long term NPP operations.

Since safety is important to successful operation of the NPP fleet, 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 NPP lifetime, plant changes are implemented following appropriate application of regulatory and licensing processes. For example, NPP extended power uprates may increase the plant production of power by a significant amount.

- **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) to failures of SSCs. Having an improved safety technical basis may provide an enhanced operational record (e.g., not having to shut down the plant) or a reduction in regulatory actions.

- **Addressing beyond design basis accidents**. As a result of the Fukushima event, the 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 its recommendations to the Commission in its report SECY-11-0137. [1] Currently, design basis requirements for NPP related to hazards such as flooding and seismic are primarily deterministic. However, the NRC's requests to the licensees may require insights both within and outside their design bases, thereby prompting the NRC to evaluate this information using improved methods such as safety margins in order to determine whether the design basis must be changed.

- **Plant life beyond sixty years**: The ability to better characterize (i.e., describe and quantify) safety margin provides a mechanism to improved decision making about LWR design, economics, operation, and long-term operation.

- **Economic efficiencies by leveraging risk information:** Through initiatives such as 10CFR 50.69, we can use RISMC methods and tools to provide flexibility to reduce cost and improve plant operations and safety margins. The regulation 10 CFR50.69 has two parts, first is to use risk analysis to categorize plant components and then, for "low safety significant" components, determine "relaxed requirements" for those components. This process of Risk Informed Engineering Program provides several possible areas for investigation:

    - Using the existing PRAs to categorize components is challenging and time consuming. By using advanced RISMC tools, automation of the analyses could be realized and may be able to provide an additional technical basis for categorization purposes.

    - RISMC 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. RISMC 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 10CFR 50.69.

    - Within the process of fulfilling 10CFR 50.69, the risk assessment must have both internal events (e.g., initiators such as transients, loss of key systems, loss-of-coolant-accidents) and internal flooding. The RISMC 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.

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

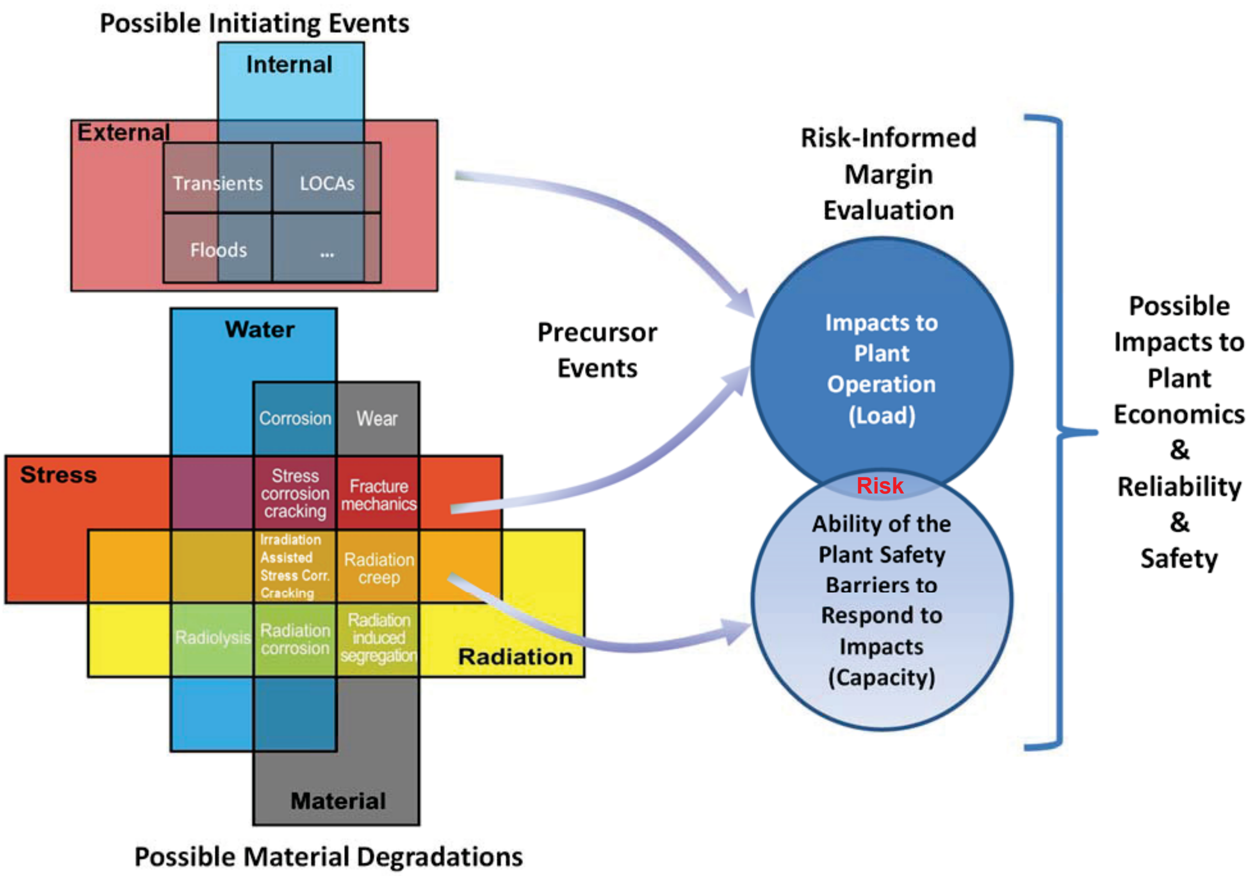

Figure 1-2. Representation of the interaction of degradation mechanisms that may impact plant operations and safety barriers if left unmitigated (adapted from INL 2012).

2. RESEARCH AND DEVELOPMENT

2.1 Purpose and Goals

The purpose of the RISMC Pathway R&D is to support plant decisions for Risk-Informed Margins Management with the aim to improve economics, reliability, and sustain safety of current NPPs over periods of extended plant operations.

The goals of the RISMC Pathway are twofold:

1. Develop and demonstrate a risk-assessment method that is coupled to safety margin quantification that can be used by NPP decision makers as part of risk-informed margin management strategies.

2. Create an advanced RISMC Toolkit that enables more accurate representation of NPP safety margins and their associated impacts on operations and economics.

One of the primary items inherent in the goals of the Pathway is the ability to propose and evaluate margin management strategies. If a situation exists that causes margins associated with one or more safety functions to become degraded, the methods and tools developed in this Pathway will serve to model and measure margins for active and passive SSCs for normal and off-normal conditions. These evaluations will then support development and evaluation of appropriate alternative strategies for consideration by decision makers to maintain and enhance the impacted margins as necessary. When alternatives are proposed that mitigate reductions in the safety margin, these changes are referred to as margin *recovery* strategies. Moving beyond current limitations in safety analysis, the Pathway will develop techniques to conduct margins analysis using simulation-based studies of safety margins.

Margin Management Strategies

Proposed alternatives (i.e., changes to SSCs or plant procedures) that work to control margin changes due to aging or plant modifications. Alternatives that off-set, or mitigate, reductions in the safety margin are known as margin recovery strategies.

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 RISMC Pathway is to use a set of simulation tools to model plant behavior and determining safety margins which include:

- **RAVEN:** RAVEN (Risk Analysis in a Virtual Control Environment) is a multi-tasking application focused on simulation control, plant control logic, system analysis, uncertainty quantification, and scenario-generation for computational risk assessment (CRA) of postulated events. RAVEN is a probabilistic code and has the capability to "drive" RELAP-7 (and other MOOSE- and non-MOOSE based applications) for which the following functional capabilities are provided:

    - Driver for thermal-hydraulics codes such as RELAP-5 and MAAP

        - Input a plant description (component, control variable, and control parameters)
        - Runtime environment to control scenario evolution
        - Parallel distribution of thermal-hydraulics runs (adaptive sampling)
    - Control logic required to:
        - Simulate the reactor plant control system
        - Simulate the reactor operator (procedure guided) actions
        - Perform Monte Carlo sampling of stochastic events
        - Perform off-normal and accident-sequence based analysis
    - Control of Graphical User Interface (GUI) to:
        - GUI capability provided by Peacock (see below)
        - Concurrent monitoring of control parameters
        - Concurrent alteration of control parameters
    - Post-processing data mining capability based on:
        - Dimensionality reduction
        - Cardinality reduction
        - Uncertainty quantification and propagation

- **EMRALD:** EMRALD is a state-based discrete event simulation tool that can calculate system failure probabilities, couple multiple simulations, and perform dynamic CRA. A key part of the EMRALD tool has been 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 tell the model to make a transition based upon the specific initiator.

- **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 (elasticity, yield functions, plastic flow directions, and hardening softening laws), hysteretic nonlinear structural constitutive models, and geometric nonlinearities at the foundation (gapping and sliding). [3]

- **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 simulate coastal inundation, river flooding, and other flooding scenarios. Neutrino models friction and adhesion between solid/fluid boundaries and various adhesive hydrodynamic forces between fluid/fluid particles. [4]

The parts of the RISMC Toolkit currently used to perform CRA are shown in Figure 2-1. Note that additional details on the HUNTER human reliability modeling approach can be found in [5] while application of the open-source DualSPHysics code can be found in [6].

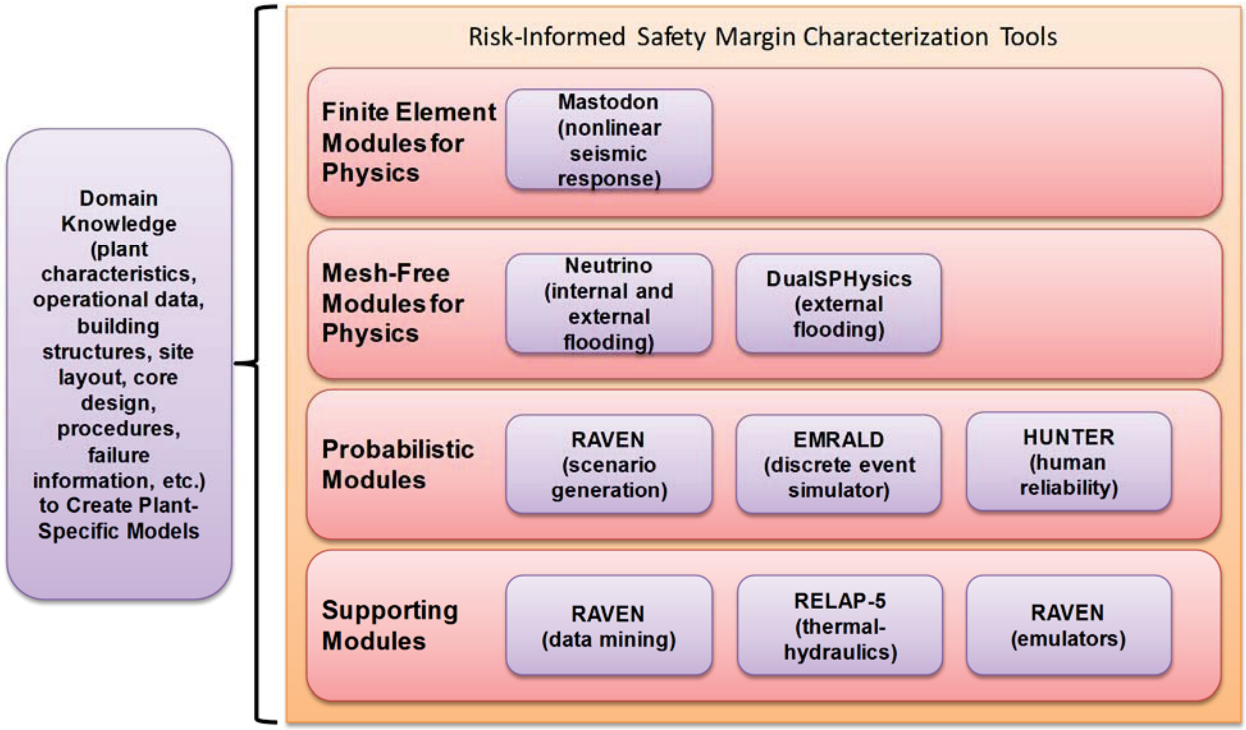

Figure 2-1. Current software modules used to perform RISMC-specific analyses.

2.2 Details of the R&D Approach

2.2.1 Probabilistic Safety Margin

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, as a consequence, 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 RISMC Pathway uses the probability margin approach to quantify impacts to economics, reliability, and safety in order to avoid conservatisms (where possible) and treat uncertainties directly. Further, we use this approach in risk-informed margins management 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.

Probabilistic Safety Margin

A numerical value quantifying the probability that a safety metric (e.g., for an important process variable such as clad temperature) will be exceeded under simulated scenario conditions.

Table 2-1. Examples of different types of margins that can be characterized.

"System"	Performance Metric	Example of Margin Contributors
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

As a simplified illustration of the type of approach taken by the RISMC method and tools, we show a hypothetical example in Figure 2-2. For this example, we suppose that a NPP decision-maker has two alternatives to consider: Alternative #1 – retain an existing, but aging, component as-is or Alternative #2 – replace the component with a new one. Using simulation-based risk analysis methods and tools (described in Section 3), we run 30 simulations where this component plays a role in plant response under off-normal conditions. For each of the 30 simulations, we calculate the outcome of a *selected* safety metric – in this example peak clad temperature – and compare that against a capacity limit (assumed to be 2200 F)[a]. However, we have to run these simulations 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

[a] Note that in this example, the capacity is represented by a single value (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.

If the safety margin characterization were the *only* decision factor, then Alternative #2 would be preferred (it has a better margin than Alternative #1 since its safety characteristics are better). But, these insights are only part of the decision 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.

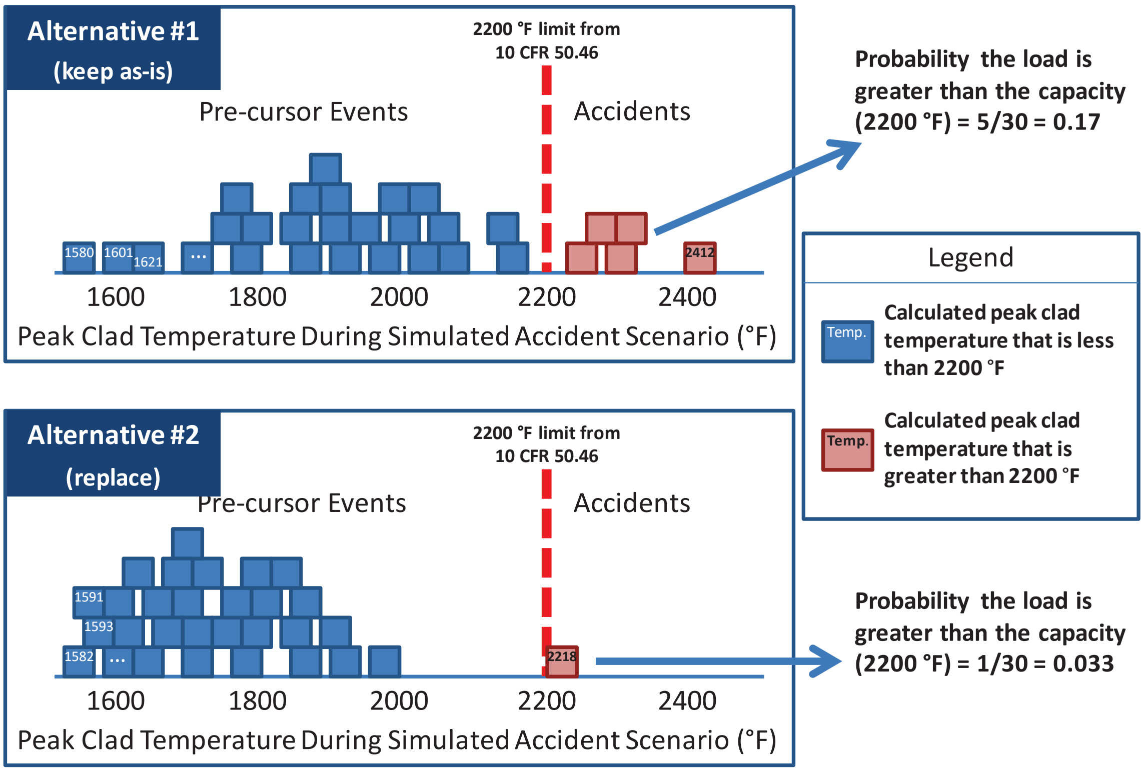

Figure 2-2. RISMC example when evaluating alternatives for risk-informed margins management.

If one focuses on a specific scenario shown in Figure 2-2, we can determine the details of the scenario that 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 is determined by RAVEN, where we produce scenarios 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 2-3.

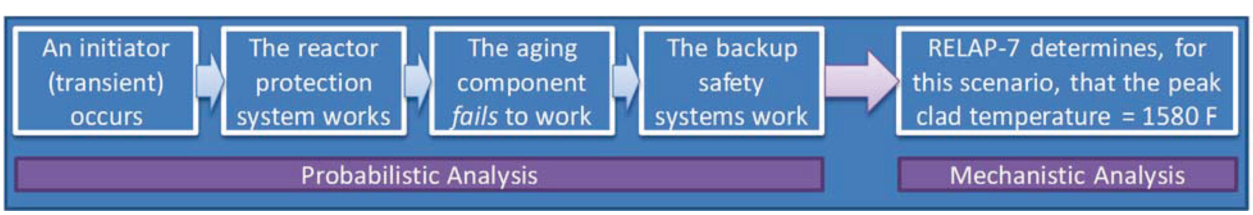

Figure 2-3. Example of the details available from a scenario characterization via simulation.

Because one LWRS Program objective is to develop technologies that can improve the reliability, sustain safety, and extend the life of the current reactors, any safety margin focus would need to consider more realistic load and capacity implications for operating NPPs. For example, the notional diagram shown in Figure 2-4 illustrates that safety, as represented by a load distribution, is a complex function that varies from one type of off-normal scenario to the next. However, the capacity part of the evaluation may not vary as much from one accident to the next because the safety capacity is determined by physical design elements such as fuel/clad and material properties (which are common across a spectrum of off-normal scenarios) or regulatory safety limits (such as the 10 CFR 50.46 limit in the Figure 2-2).

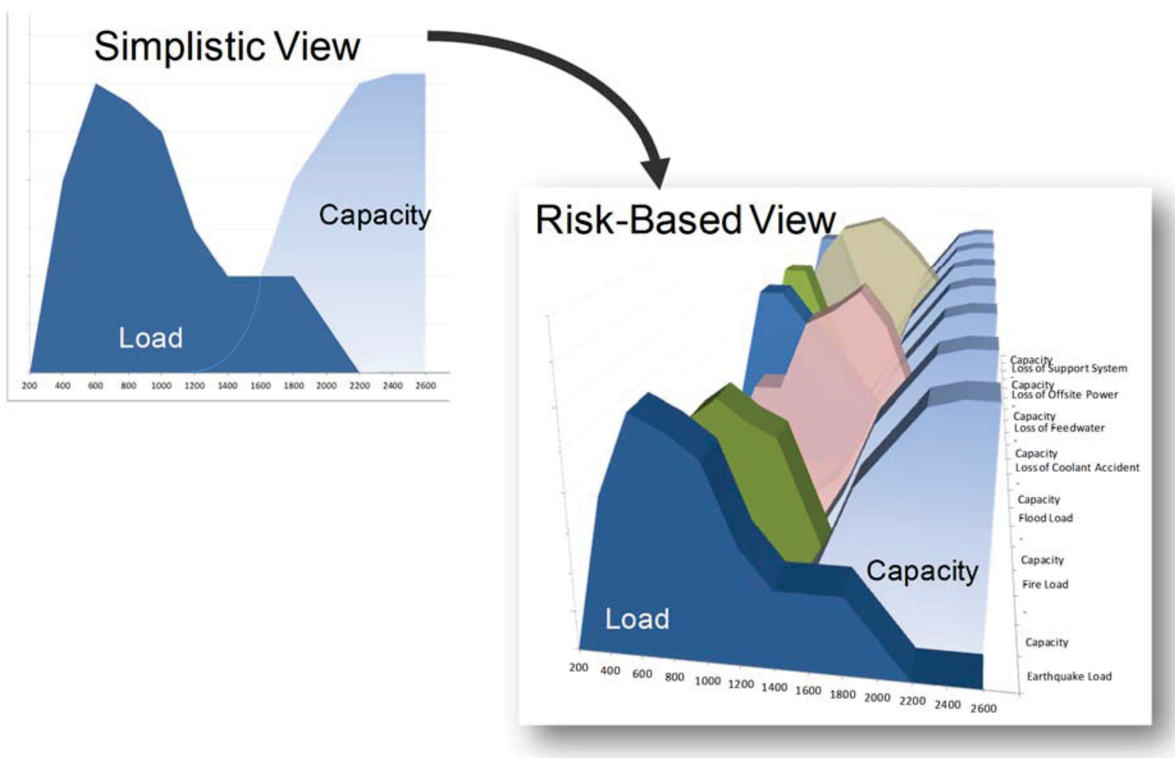

Figure 2-4. Family of load and capacity distributions representing different off-normal conditions.

2.2.2 Safety and Economic Impacts

To successfully accomplish the goals described in Section 2.1, the RISMC 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 a systems code (i.e., RELAP-5 as currently coupled with the RAVEN code). Then, to characterize safety margin for a specific safety performance metric[b] of consideration (e.g., peak clad temperature), the plant simulation will determine time and

[b] 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

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 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.

In addition to the safety impacts that are represented in the probabilistic scenarios, the RISMC Pathway is also able to address economic impacts. In the example previously illustrated in Figure 2-2, we considered two alternatives:

Alternative #1 – *retain* the existing, but aging, component as-is

Alternative #2 – *replace* the component with a new one

Each one 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; 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; the cost associated with accidents in the future

For the two alternatives, the direct costs would typically be modeled and quantified by the owner/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 RISMC Pathway since our methods and tools can represent and quantify those costs directly as part of the simulation. For example, Figure 2-5 shows, for a specific simulated outcome, how costs would be represented (for both pre-cursor and accident events). Note that even in cases where a peak clad temperature outcome does *not* exceed the 2200F limit, an impact could be that a degraded component can cause an outage (say a pipe ruptures causing damage). In this hypothetical case, the plant would require an outage to repair the damage, which had an economic penalty due to replacement components and lost power generation.

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necessary to reasonably protect the integrity of certain of the physical barriers that guard against the uncontrolled release of radioactivity."

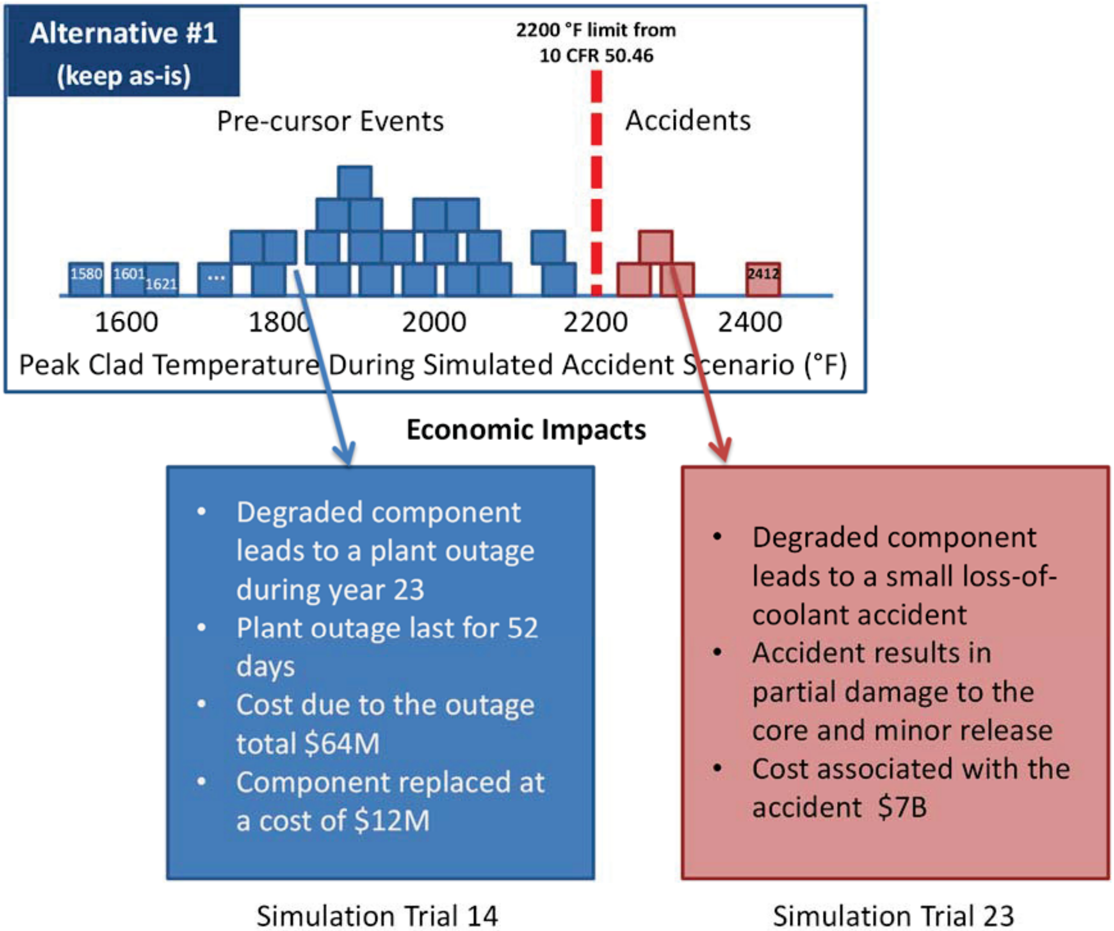

Figure 2-5. Hypothetical example of economic considerations of probabilistic costs as part of risk-informed margins management.

2.3 The Federal Role

In order to better manage the successful operation of the NPP fleet for current- and extended-lifetimes, there are needs to characterize and manage safety margin. Using a risk-informed approach, issues such as what are off-normal conditions, how likely are they, and what are the consequences, are all questions that must be addressed. The RISMC method and associated Toolkit provide answers to NPP operational questions related to safety margins and plant economics. Motivations for DOE involvement in supporting the RISMC Pathway include:

- The need to better characterize and quantify safety margin when considering near-term operation and plant life extension beyond 60 years.

- The need to better integrate data, models, and information from parallel activities such as materials research and instrumentation and controls development. From these complementary activities, we 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 RISMC 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 in use in the US nuclear power industry were designed and created 30 to 40 years ago.

- The need to better understand beyond design-basis events. 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 techniques.

- The need to use science-based models for prediction of NPP performance rather than parametric- or correlation-based mechanistic models that are prevalent.

- The need to pro-actively respond to future NPP changes over extended life-times (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 RISMC Pathway is the use of risk informed margins management strategies. These strategies will be informed by the risk and economics assessment and will focus on desired, measurable outcomes, rather than prescriptive processes, techniques, or procedures, with the aim of identifying performance measures that ensure an adequate safety margin is maintained over the lifecycle of a NPP. In addition to the activities identified above in this pathway, RISMC will be working with the Materials and the Advanced Instrumentation and Control Systems Technologies Pathways. In addition, the RISMC Pathway will be collaborating with the DOE Advanced Fuels Campaign on risk informed case studies for issues such as accident tolerant fuel design and testing.

3. RISMC RESEARCH AND DEVELOPMENT AREAS

The purpose of this section is to describe those R&D areas that are the focus for the RISMC Pathway.

To better understand the approach to determine safety margins, we first describe the two types of analysis used in this pathway (see Figure 3-1), probabilistic and mechanistic quantification. Note that in actual applications, a blended approach is used where both types of analysis are combined to support any one particular decision.

Types of Analysis Used in Safety Margin Evaluations	
PROBABILISTIC	MECHANISTIC
Pertaining to stochastic (non-deterministic) events, the outcome of which is described by a probability.	Pertaining to deterministically predictable events, the outcome of which is known with certainty if the inputs are known with certainty.
Probabilistic analysis uses models representing the randomness in the outcome of a process. Probabilities are not observable quantities, we rely on models to estimate them for certain specified outcomes such a failure of a component.	Mechanistic analysis (also called "deterministic") uses models to represent situations where the observable outcome will be known given a certain set of parameter values.
An example of a probabilistic model is related to counting of *j* number of failures of an operating component in time *t*: Probability(j>0) = $1-e^{-\lambda t}$.	An example of a mechanistic model is the one-dimensional transfer of heat (or heat flux) through a solid: $q = -k \, \partial T / \partial x$.

Figure 3-1. Types of analysis that are used in the RISMC Pathway.

The use of both types of analysis, probabilistic and mechanistic, is represented in Figure 3-2. Probabilistic analysis is represented by the risk analysis while mechanistic analysis is represented by the plant physics calculations. Safety margin and uncertainty quantification rely on plant physics (e.g., thermal-hydraulics and reactor kinetics) coupled with probabilistic risk simulation. The coupling takes place through the interchange of physical parameters (e.g., pressures and temperatures) and operational or accident scenarios. Together, the analysis methods can be used to support a variety of safety margin decisions, including recovery of or increasing safety margins:

- If the nominal core power levels are increased (power uprate)
- If a different type of fuel or clad is introduced
- If aging phenomena becomes more active over long periods of plant operation
- If plant modifications are taken to increase resiliency for hazards such as flooding and seismic events
- If systems, structures, or components are degraded or failed

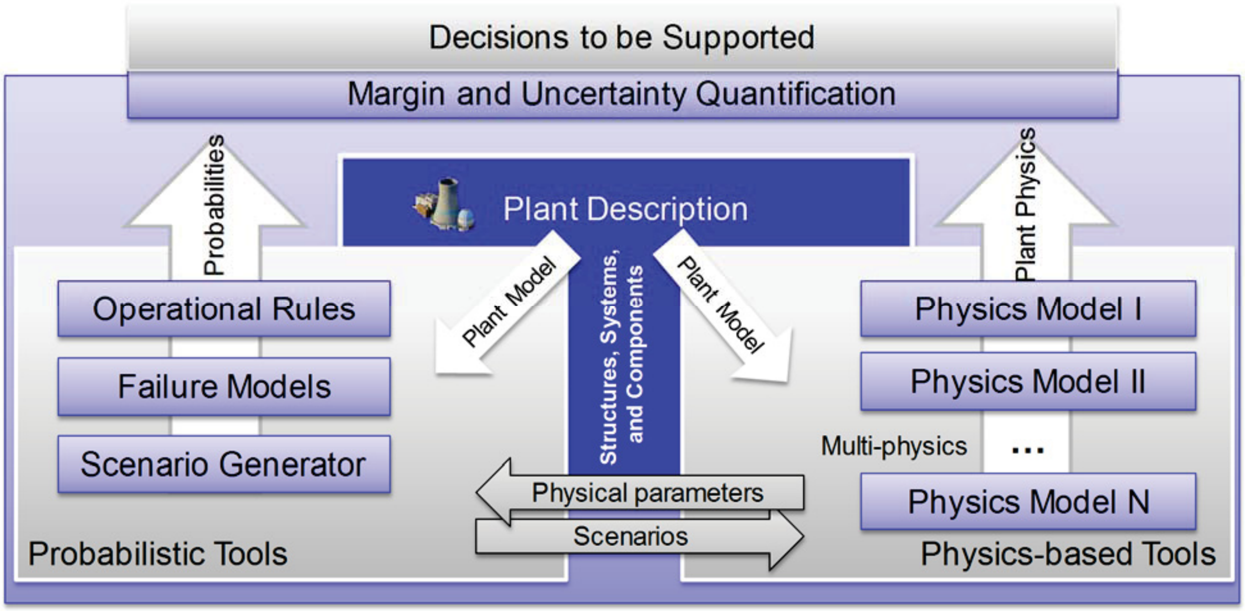

Figure 3-2. Attributes of the RISMC approach for supporting decision-making.

The RISMC Pathway has two primary focus areas to guide the R&D activities.

1. The Pathway is developing the technical basis of methods for safety margins quantification in support of the risk-informed decision making process.

2. The Pathway is producing an advanced set of software tools used to quantify safety margins. This set of tools, collectively known as the RISMC Toolkit, will enable a risk analysis capability that currently does not exist.

3.1 Technical Basis for Risk-Informed Margins Management

The RISMC methodologies are captured in a set of technical basis reports. These guides are technical documents that describe how the RISMC Pathway captures the protocols for analysis and evaluation related to safety margin characterization. The technical basis reports are intended to be companion documents to EPRI-produced reports. The guides will be developed to support industry use in their Risk-Informed Margins Management (RIMM), plant analysis, and licensing activities.

3.1.1 The Safety Case

The technical basis for risk-informed margins management is captured in what is known as the "safety case." While definitions may vary in detail, the safety case essentially means the following:

> *A structured argument, supported by a body of evidence that provides a compelling, comprehensible and valid case that a system is adequately safe for a given application in a given environment. [7]*

The realization of a safety case for RISMC applications will be an output when applying the Pathway methods. The safety-margin claims will do the following:

1. Make an explicit set of safety margin claims about the facility and its constituent SSCs.

2. Produce qualitative and quantitative evidence that supports the claims from #1.

3. Provide a set of safety margin management strategies that link the claims to the probabilistic and mechanistic evidence.

4. Make clear the assumptions, models, data, and uncertainties underlying the arguments

5. Allow different viewpoints and levels of detail in a graded fashion to support decision making.

The safety case of a facility or particular SSCs should be regarded as having fundamental significance as opposed to being mere documentation of facility or SSC features. For practical purposes, "safety margin" is not observable in the way that many other operational attributes are (e.g., core temperature or embrittlement of pressure vessels). However, in decision-making regarding the facility or SSC margin management strategies, the safety case is a proxy for a set of safety attributes of interest. And, regardless of context, the formulation of a safety case is about developing a body of evidence and marshaling that evidence to inform a decision.

Since safety margins are inferred (not directly observable) unlike how cost, power output, pipe thickness, water temperature, radiation level, etc., are observed, we rely on a combination of models (probabilistic and mechanistic) to make safety margin predictions. These models also rely on unobserved elements such as failure rates and probabilities. Consequently, the characterization of a safety margin requires the treatment and understanding of uncertainty in order to effectively manage margins in a risk-informed decision making approach. Further, the decision of what is adequate margin resides with the NPP decision-makers and is informed by our models, sensitivity cases using those models, and other information in an integrated approach.

3.1.2 Margins Analysis Techniques

One aspect of the technical basis that is addressed is the mechanics of techniques to conduct margins analysis, including a methodology for carrying out simulation-based studies of safety margins, using the following process steps (as shown in Figure 3-3) for RISMC applications.

1. Characterize the issue to be resolved in a way that explicitly scopes the modeling and analysis to be performed, including delineating the performance metrics to be analyzed (e.g., safety, economics).

2. Quantify the relevant state-of-knowledge (i.e., uncertainty) of the key variables and models for the issue at hand. For example, describe parametric uncertainties to be sampled during the analysis in later steps.

3. Determine issue-specific, risk-based scenarios and associated timelines (as depicted in Figure 3-4). The scenario simulation captures timing considerations that may affect plant physical phenomena and margins, as described in Steps 4 and 5. As such, there will be strong interactions between the analysis Steps 3-5. Also, in order to "build up" the load and capacity distributions representing the safety margin (as part of Step 6), a large number of scenarios will be needed to be evaluated.

4. Represent plant operation probabilistically using the scenarios identified in Step 3. For example, plant operational rules (e.g., operator procedures, where we include the possibility for human-caused failures) are used to provide realism for scenario generation. Because numerous scenarios will be generated, the plant- and operator-behavior cannot be manually created like in current risk assessment using event- and fault-trees. In addition to the *expected* operator behavior, the probabilistic plant representation will account for the possibility of failures.

5. Represent plant physics mechanistically. The plant systems level code will be used to develop time and/or space distributions for the key plant process variables (i.e., loads). Other codes such as fuel/clad performance codes will be used to develop capacity distributions. Because there is a coupling between Steps 4 and 5, they each can impact the other. For example, a calculated high loading (from pressure, temperature, or radiation) in an SSC may disable a component, thereby impacting an accident scenario that challenges fuel performance.

6. Construct and quantify the load and capacity distributions (obtained from Steps 4 and 5) relating to the performance metrics that will be analyzed to determine the margin.

7. Determine how to manage *uncharacterized* risk. Because there is no way to guarantee that all scenarios, hazards, failures, or physics are addressed, the decision maker should be made aware of limitations and uncertainties in the analysis. This step relies on effective communication from the analyst in order to understand the risks that *were* characterized.

8. Identify and characterize the items that determine the relevant margins within the issue being evaluated to in order to develop appropriate RIMM strategies. Determine whether additional work to reduce uncertainty would be worthwhile or if additional (or relaxed) controls are justified.

One of the unique aspects of the RISMC approach compared to traditional PRA is how it couples probabilistic approaches (the scenario) directly with mechanistic phenomena representation (the physics) through simulation. This simulation-based modeling allows decision makers to focus on one or more safety, performance, or economic metrics. For example, while traditional risk assessment approaches attempt to quantify core damage frequency (CDF), RIMM approaches may instead wish to consider other metrics such as:

- Magnitude of the hazard – for example, when evaluating external hazards, the height of water on buildings, or the height of water inside strategic rooms. The "magnitude" might be measured (during the simulation) by metrics such as water height, seismic energy, water volume, water pressure, etc.
- Damage to the plant (but not core damage) – for example, we may be interested in scenarios in which the facility does not see core damage, but would still experience extensive (or even minor) damage. The "damage" might be measured (again during the simulation) by metrics such as total number of components failed, cost of components destroyed, structures rendered unusable, the length of time the facility is impacted (hours versus months), etc.

The defining difference between these new RIMM metrics and traditional ones such as CDF is that they represent observable quantities (e.g., the number of components failed, the costs related to the event, the height of water in a room, the duration of the event) rather than just a statistical average of an event frequency. We believe these new metrics that are provided by the RISMC simulation yield enhanced decision-making capabilities for nuclear power plants.

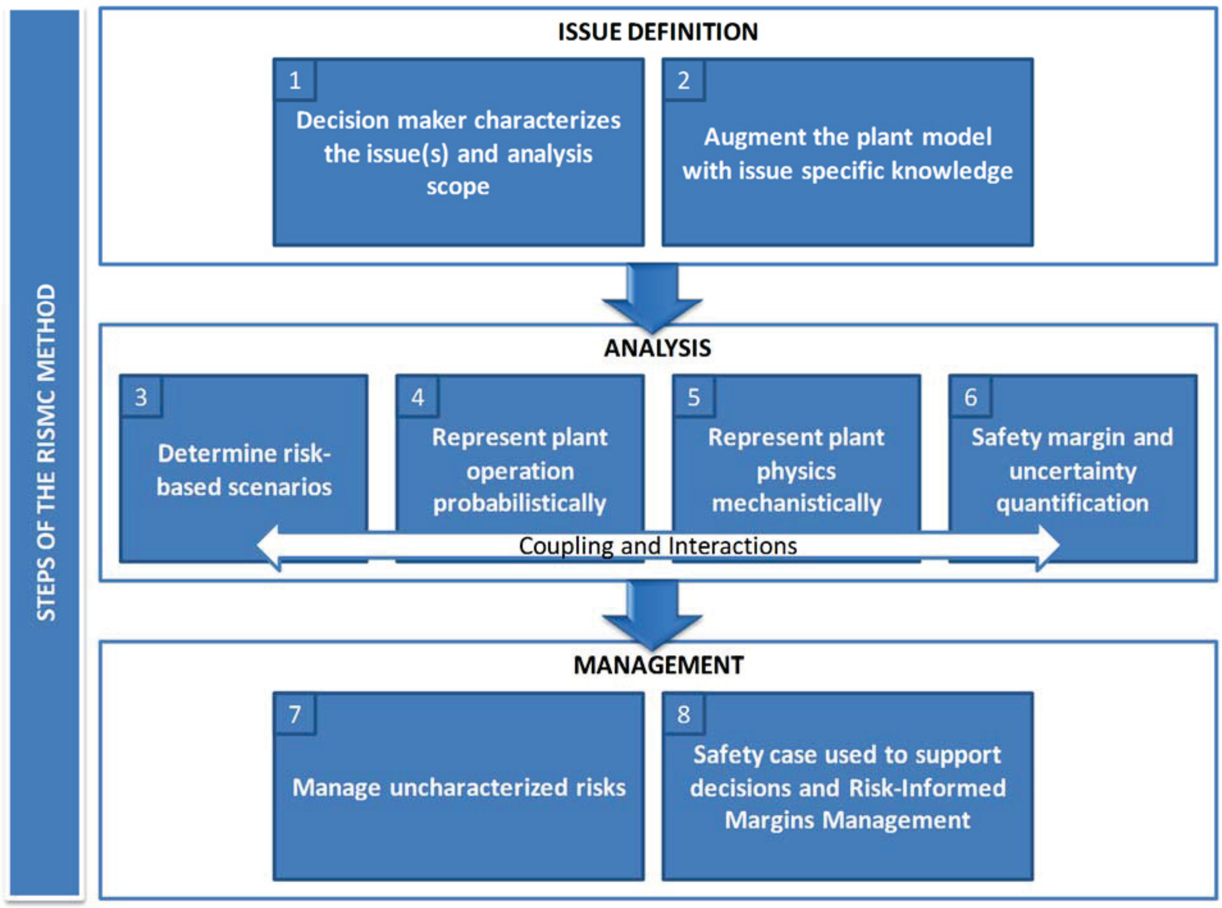

Figure 3-3. Depiction of the high-level steps required in the RISMC method.

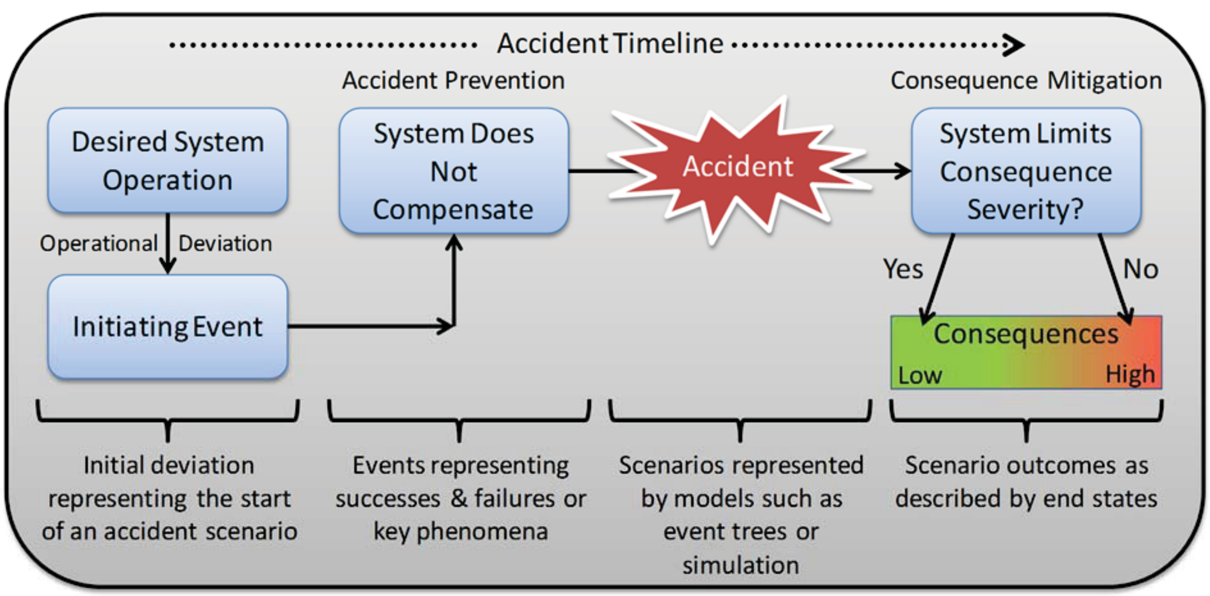

Figure 3-4. Accident scenario representation.

3.1.3 Case Study Collaborations

Jointly with EPRI, the LWRS RISMC Pathway is working on specific case studies of interest to the NPP industry. During FY2013 through FY2016, the team performed multiple case studies including a demonstration using the INL's Advanced Test Reactor, a hypothetical pressurized water reactor, a boiling water reactor extended power uprate case study, a pressurized thermal shock scenario, seismic modeling, and river-, tsunami-, and precipitation-types of flooding simulations. Safety margin recovery strategies will be determined that will mitigate the potential safety impacts due to the postulated increase in nominal reactor power that would result from the extended power uprate. An additional task was to develop a technical report that describes how to perform safety margin-based configuration risk management. Configuration risk management currently involves activities such as the Significance Determination Process which traditionally uses core damage frequency as the primary safety metric – the research will focus on how the safety-margin approach may be used to determine risk levels as different plant configurations are considered. The results for the recent case studies are briefly described here.

3.1.3.1 Advanced Test Reactor Case Study

Constructed in 1967, ATR is a pressurized water test reactor that operates at low pressure and low temperature. It is located at the Advanced Test Reactor Complex on the INL site. The reactor is pressurized and is cooled with water. As part of the RISMC demonstration, we successfully coupled the risk assessment simulation to the thermal-hydraulics analysis in order to integrate probabilistic elements with mechanistic calculations. With the knowledge of plant response, we needed to determine whether or not a particular outcome is "success" (meaning no fuel damage) or "failure" (meaning fuel damage). For our analysis, we assumed that any event that saw a peak cladding temperature of 725°F (658 K) was a fuel damage outcome.

The purpose of the RISMC ATR case study was to demonstrate the RISMC approach using realistic plant information, including both real PRA and thermal-hydraulics models. As part of this case study, we evaluated emergency diesel generator issues. Historically, ATR has had a continually running emergency diesel generator as a backup power supply, which is different than all commercial nuclear power plants in the United States (commercial plants have their emergency diesel generators in standby). Margin recovery strategies under consideration include the following:

- Keep the emergency power system as is (emergency diesel generator running, one in standby, and commercial power as backup)
- Redundant commercial power as primary backup, single new emergency diesel generator as backup
- Redundant commercial power as primary backup, two existing emergency diesel generators as backup.

For the different strategies, we simulate the plant behavior both probabilistically and mechanistically. To perform this simulation, we used the existing PRA and thermal-hydraulics information. We then defined the simulation for different scenarios and different strategies and ran a large number of iterations to determine overall safety margins. The results vary for each alternative (the margins are different), but are used to determine preferential strategies.

3.1.3.2 Boiling Water Reactor Station Blackout

The scope of the boiling water reactor (BWR) station blackout (SBO) case study is to show the RISMC capabilities in order to assess performances of the power uprates using a simulation-based environment. Such assessment cannot be naturally performed in a classical PRA-based environment since the thermal-hydraulics (T-H) is not integrated with the probabilistic modeling. In our analysis, we used RELAP-5 and RAVEN as tools to perform a simulation-based stochastic analysis. [8] [9]

The focus of the analysis was to investigate the (possible) impact of power uprate on the safety margin of a BWR. The case study considered is a loss of off-site power followed by the possible loss of all diesel generators, i.e., a station black-out (SBO) event. We created the necessary inputs file for the mechanistic T-H codes that models system dynamics under SBO conditions. We also interfaced RAVEN with these codes so that it would be possible to run multiple RELAP simulation runs by changing specific portions of the input files. We employed classical statistical tools, i.e. Monte-Carlo, and more advanced machine learning based algorithms to perform uncertainty quantification in order to determine changes in system performance and limitations as a consequence of power uprate. We also employed advanced data analysis and visualization tools that helped us to correlate simulation outcomes such as maximum core temperature with a set of input uncertain parameters.

Results obtained give a detailed overview of the issues associated to power uprate for a SBO accident scenario. For example, we were able to quantify how the timing of specific events was impacted by a higher reactor core power. Such safety insights can provide useful information to the decision makers to perform risk-informed margins management.

As an example of the RIMM insights gained from the RISMC analysis, Figure 3-5 shows the limit surface for two different core power levels where variations in either off-site (i.e., AC power) recovery time or the time at which the diesel generators fail (i.e., DG failure time) can affect the outcome of core damage (failure) or not (success). As can be seen in the figure, as the core power level is increased, it becomes more likely to see core damage. In the nominal case, if off-site power is recovered in less than 7 hours (approximately 25,000 seconds) then core damage is always averted. However, in the 120% power uprate case, in scenarios where the diesel generators fail early (in less than 2 hours) and off-site power is recovered in less than 7 hours, some of those cases result in core damage.

Limit Surface

The boundary in the input space between two simulated outcomes, for example, failure or success.

Further, the limit surface is determined by understanding the outcomes of specific scenarios (shown as the red and green points in Figure 3-5). These individual points (or scenarios) provide information to the decision maker for use in RIMM. For example, in the case of the power uprate to 120% power, the new points/scenarios that result in core damage may be investigated to determine what at the plant may be changed in order to mitigate the core damage risk while still maintaining an economic enhancement of the power uprate.

Note that in order to characterize the limit surface, the concept of "margin" has already been resolved. In order to define a specific point around the limit surface, we had to determine, during the simulation, if the load exceeded the capacity for the performance metric of interest (e.g., safety). For cases where the load exceeded the capacity, we classify these scenarios as a "failure" (the red points). Thus, over a large number of simulation cases, we are able to quantify the margin probabilistically by determining the expression $Pr[L > C]$. One interesting fact is that the limit surface itself is the location where the margin is equal to zero – it represents cases where the load equals the capacity.

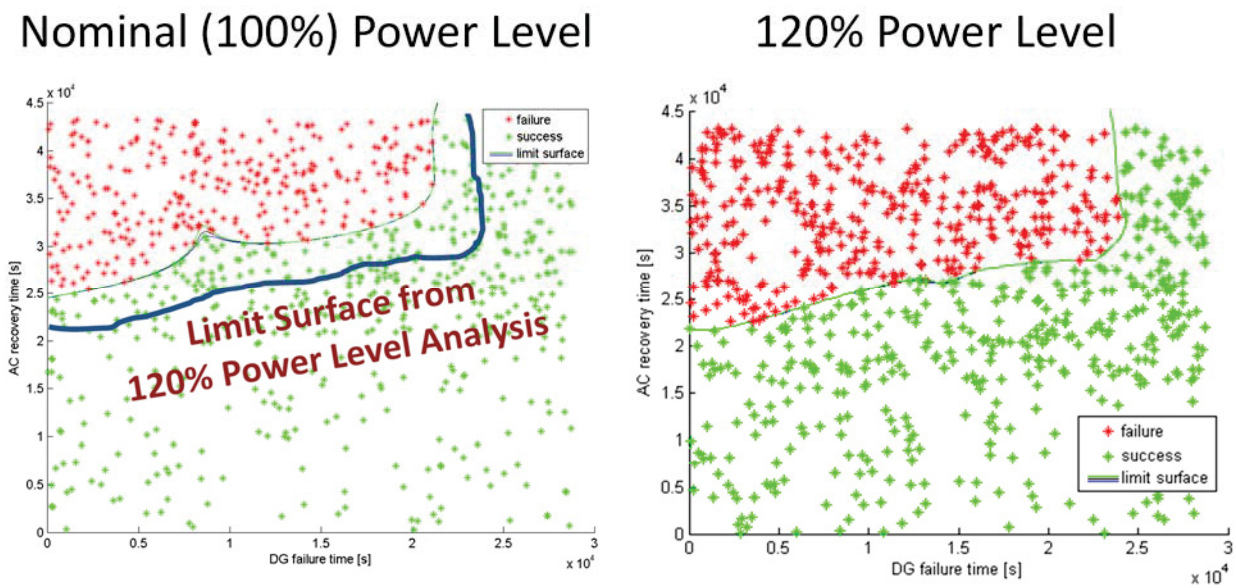

Figure 3-5. Limit surface plots from the BWR SBO analysis.

3.1.3.3 Safety Margin Configuration Risk Management

Configuration risk management is an important process that evaluates testing and maintenance activities that are proposed while the reactor is at full power. Performing these activities while at full power provide many benefits to the plant owner/operators, improving both economics and safety. Configuration risk management helps identify if these activities should be allowed while at power based on their risk impact. The proposed configuration is evaluated and if the increase in the risk metric of choice does not exceed a predefined safety threshold then the planned activities can proceed. Different plant configurations, depending upon safety system and duration, can have different impacts on risk.

Configuration risk management is also used to evaluate degraded conditions that have occurred at plants. This evaluation is based on the plant configuration during the degraded condition to assess what the increase in risk was observed. Given this information, management changes can be implemented to decrease the future likelihood of being in these degraded conditions.

R&D on configuration risk management using the RISMC approach showed how improved accuracy and realism can be achieved by simulating changes in risk – as a function of different configurations – in order to determine safety margins as the plant is modified. [10] In order to carry out configuration risk management, a coupling of mechanistic and probabilistic calculations is performed. Within this process, several technical issues are encountered and addressed so that future applications can take advantage of the analysis benefits while avoiding the technical pitfalls that are found for these types of calculations. The technical areas that were addressed: common cause failure treatment, human error probability determination, incorporation of plant physics, how to perform delta risk calculations, accuracy related to convolution factors, and resolving success states as part of the modeling. For each technical issue, specific recommendations were provided with the intention of improving the safety margin analysis and strengthening the technical basis behind the analysis process. By following the overall RISMC approach described and applying the recommendations, a technically-sound safety margin characterization for configuration risk management can be realized.

3.1.3.4 External Events Analysis

In FY14, the RISMC Pathway extended its analysis capabilities into additional initiating events including external events (primarily focusing on seismic and flooding events). The approach used to treat an event such as flooding is illustrated in Figure 3-6 and follows:

1. *Initiating event modeling*: modeling characteristic parameters and associated probabilistic distributions of the event considered

2. *Plant response modeling*: modeling of the plant system dynamics

3. *Components failure modeling*: modeling of specific components/systems that may stochastically change status (e.g., fail to performs specific actions) due to the initiating event or other external/internal causes

4. *Scenario simulation*: when all modeling aspects are complete, (see previous steps) a set of simulations can be run by stochastically sampling the set of uncertain parameters.

5. Given the simulation runs generated in Step 4, a set of statistical information (e.g., margin, core damage probability) can be generated. We are also interested in determining the limit surface.

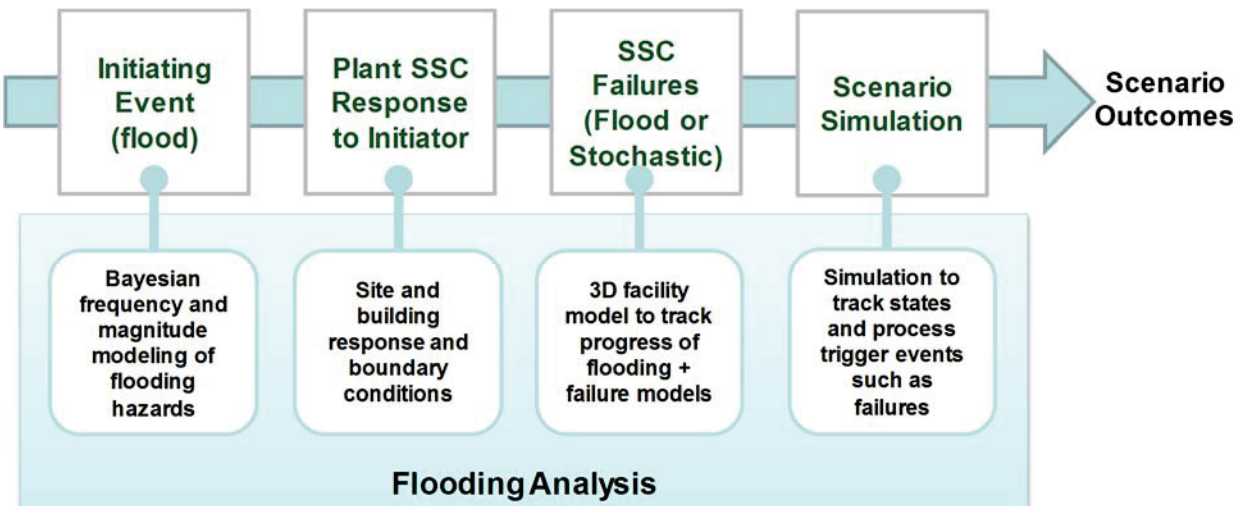

Figure 3-6: Overview of the RISMC approach to simulate initiating event and plant response using the RISMC toolkit

To demonstrate the RISMC approach for flooding, a generic 3D facility model (see Figure 3-7) with conditions similar to the Fukushima incident was created and used to simulate various tsunami flooding examples. For initial testing only, a slice of the entire facility (containing just a single unit) was used, this includes:

- Turbine building
- Reactor building
- Offsite power facilities and switchyard
- Diesel generator (DG) building

The 3D model is used as the collision geometry for any simulations. For the initial demonstration all objects are fixed rigid bodies – our later analysis explored the possibility of moving debris (cars moving caused by the flood) and possible secondary impacts due to this debris. [11]

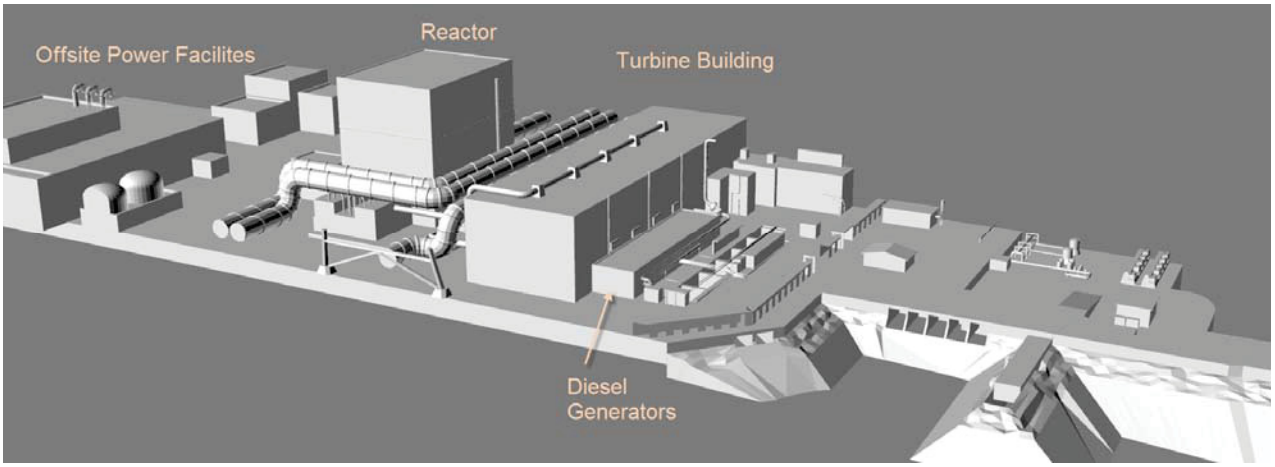

Figure 3-7: 3D plant model developed to simulate flooding

To mimic a tsunami entering the facility, a bounding container was added around the perimeter of the model and for the ocean floor. Then, for this demonstration, over 12 million simulated fluid particles were added for the ocean volume. A wave simulator mechanism was constructed by having a flat planar surface that moves forward and rotates, pushing the water and creating a wave in the fluid particles. Once the wave is "started," the fluid solver handles all of the remaining physics calculations in order to simulate the moving wave through the facility.

As the particles of a simulation move, they interact with the rigid bodies of the 3D model. The simulated fluid flows around buildings, splashes, and interacts in a similar manner to water. Measuring tools can also be added to the simulation to determine fluid contact information, water height, and even flow rates into openings at any given time in the simulation. This dynamic information can be used in two ways: (1) a static success or failure of components or structures depending on wave height or (2) a dynamic result based on time for use in more detailed analysis. As shown in Figure 3-8, the fluid particles are penetrating both air intake vents for an 18 m wave. Evaluating this scenario in more detail, we can determine that at simulation time (or frame) 1,275 DG1 fails from splash particles and DG2 fails at 1,375. Additional detail on this flooding analysis can be found in [12].

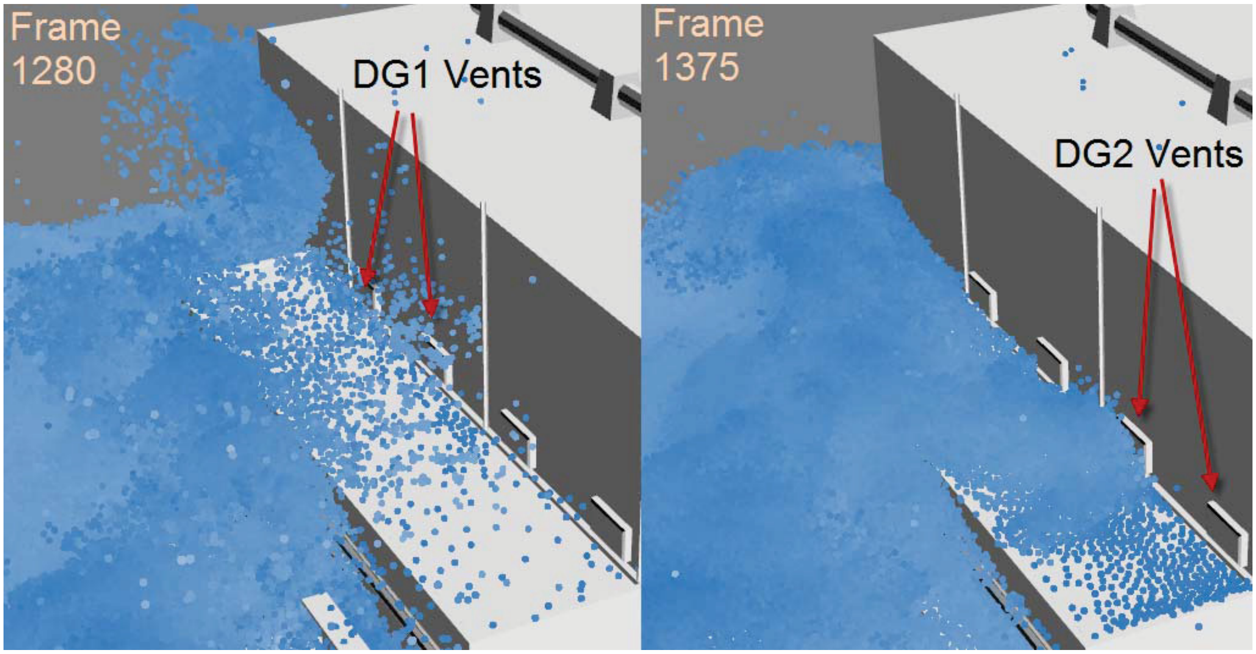

Figure 3-8: Time spacing between failures of generators due to fluid in the air intake vents of the generator room.

In addition to the flooding research, the RISMC Pathway is also investigating advanced methods, tools, and data for seismic hazards. Currently, the nuclear industry is addressing the Fukushima Near-Term Task Force recommendations. One specific recommendation that is of interest is recommendation 2.1 which states, “Order licensees to reevaluate the seismic and flooding hazards at their sites against current NRC requirements and guidance, and if necessary, update the design basis and SSCs important to safety to protect against the updated hazards.” On February 15, 2013 the NRC provided its endorsement of the EPRI-1025287 document that serves as a response to the recommendation 2.1. This document provides a process to meet the recommendation 2.1 and includes a screening process that evaluates updated site-specific seismic hazard. One of the items is to evaluate updated site-specific hazard curves, which have the potential for higher magnitude and higher frequency content accelerations.

The NRC requires ten sites to submit their detailed risk analysis by June 30, 2017, while an additional ten sites to submit their detailed risk analysis by December 31, 2019. They are also considering detailed submittals for another 23 sites (by 2020 if needed). And there may be additional requirements “in the near future” related to evaluations of spent fuel pools at some sites. These activities over the next five years are related to the seismic hazard reevaluation and detailed risk evaluation initiatives. In addition to these initiatives, the Near Term Task Force recommendation 2.2 requires plants to perform an update of seismic modeling every 10 years. As part of RISMC, we are bringing a risk-informed picture to seismic analysis by performing evaluations in an integrated fashion, for example through our seismic and flooding work. We are also looking to improve our methods, tools, and data for seismic simulation in order to reduce conservatisms (where they exist) and make the analysis process itself more efficient. Our research and development on seismic analysis will not only improve the safety state-of-the-practice related to seismic analysis, it is timely (by fitting well within the NRC’s 2020 time window and 10 year update cycle).

The earthquakes that have been seen recently seem to indicate that traditional seismic models might be conservative since very few systems or structures have failed during these events. Three recent earthquakes (Kashiwazaki-Kariwa in 207, Fukushima in 2011, and North Anna in 2011) have demonstrated events that exceeded the plant design basis earthquake values. Yet for all of these events, it appears that little damage actually occurred to safety (and most non-safety) related components or structures. By reevaluating these events using a modern analysis approach, we have the opportunity to determine if conservatisms exists in traditional seismic PRA and, if possible, how these conservatisms might be reduced.

3.1.3.5 Collaborations with other LWRS Pathways

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

- Collaboration with the Materials Aging and Degradation 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 tool. Grizzly is a MOOSE-based tool for simulating component aging and response of aged components that is being developed within the Materials Aging and Degradation Pathway.

- Collaboration with the Advanced Instrumentation, Information, and Control Systems Technology Pathway on human reliability modeling and non-destructive research on concrete aging predictive modeling.

- Collaboration with the Advanced Reactor Safety Technologies Pathway on leveraging the RISMC Toolkit for use on safety analysis techniques.

3.1.4 Methodology Research Impact

Already, the RISMC R&D is having impacts that are being seen in the industry:

- At the 2012 American Nuclear Society Winter Meeting (in San Diego), one of the RISMC researchers (Diego Mandelli) presented a paper co-authored with Curtis Smith describing the implementation of adaptive sampling algorithms to identify boundaries between system failure and system success. Following the Winter Meeting, Dr. Mandelli and Dr. Smith were recognized for the publication of this paper with an Honorable Mention Award by the Nuclear Installations Safety Division. The paper described an artificial-intelligence based algorithm that is able to drastically reduce the number of simulation needed in order to identify boundaries between important system characteristics such as failure/success. The paper presented both the mathematical background and test cases. In addition, it also demonstrated the algorithm validity for a station blackout analysis. Such sampling analysis allowed the state of the test system to be readily identified (thereby speeding up calculations) when parameters of interest are varied as part of the scenario simulation.

- The RISMC team had a second award winning paper at the American Nuclear Society Probabilistic Risk Assessment 2013 conference. The paper was titled "Adaptive Sampling Algorithms for Probabilistic Risk Assessment of Nuclear Simulations" and was coauthored by Diego Mandelli of the INL.

- The RISMC team had a third award winning paper; a paper written by the RISMC team has been selected among the top 40 papers at the NURETH conference (held in Chicago in September, 2015) as a candidate for best paper. Since there were almost 800 papers at the conference, this places the paper in the top 5% of papers at the conference. The paper was titled "10 CFR 50.46c Rulemaking: A Novel Approach in Restating the LOCA Problem for PWRs" and was authored by Cesare Frepoli, Joseph Yurko, Ronaldo Szilard, Curtis Smith, and Robert Youngblood.

- The RISMC Pathway has collaborations ongoing with the 2016 Idaho State University College of Science and Engineering Outstanding Student Award winner, Emerald Ryan. Emerald received the College of Science and Engineering Outstanding Student Award, in part, for her work supporting the LWRS program in the area of smoothed particle hydrodynamics (SPH) for simulation of flooding scenarios. She has contributed to several technical LWRS-related deliverables within the Risk Informed Safety Margin Characterization Pathway, including progress on Industry Applications (external events) and modeling and simulation on river-based flooding scenarios. Emerald is continuing her work supporting LWRS under the research led by Professor Chad Pope. Her research focus will be on the application and validation of SPH-based methods for advanced computational risk analysis.

- The RISMC Pathway lead provided an invited plenary speech on September 25th, 2017, at the American Nuclear Society Probabilistic Safety Assessment PSA-2017 Conference. The speech, *Computational Risk Assessment*, describes the Idaho National Laboratory (INL) advanced risk activities through the Risk-Informed Safety Margins Characterization (RISMC) project. The talk outlined the next-generation reliability- and risk-assessment methods that supports decision-making by combining mechanistic physics-based models with probabilistic quantification approaches. This talk was attended by almost 200 risk, reliability, and NPP decision-makers from the international nuclear community.

- In March 2017, the Risk-Informed Safety Margins Characterization (RISMC) Pathway released the Risk Analysis and Virtual Environment (RAVEN) software as INL's latest open-source software on the GitHub website (https://github.com/idaholab/raven). The software is available for nuclear plant safety collaboration and for other researchers to expand the feature set. RAVEN is a unique and powerful tool for dynamic risk analysis using simulation, offering capabilities not currently available in other software.

- The RISMC RAVEN development team supported and is in collaboration with the FPoliSolutions company on a $1M SBIR award funded through the DOE. Based upon the RISMC-development technology, FPoliSoultions has been awarded a Phase II SBIR award, which is the first SBIR to be won out the RISMC-developed software. FPoliSolutions is developing and commercializing an integrated data and simulation management framework to reduce nuclear power plant operating costs, building upon the current RAVEN technology developed by the Idaho National Lab.

- In collaboration with INL, Westinghouse has performed dynamic fire risk analysis modeling using the RAVEN code. They successfully completed switchgear room fire scenarios using the industry code CFAST by developing a working RAVEN-CFAST interface and have run several thousand fire simulation scenarios.

- The RISMC RAVEN team conducted four RAVEN workshops. These workshops were attended by industry, National Laboratory, and academic researchers. Workshops were held at North Carolina State University (March 29-31, 2017), Idaho State University (July 18-20, 2017), Idaho National Laboratory (May 4, 2017), and PSA 2017, Pittsburgh (September 24, 2017).

- The RISMC Pathway research on flooding experiments received the 2017 ANS Student Conference award where the Idaho State University (ISU) student Mr. Tahhan was awarded the "Best in Track" recognition for the presentation. The presentation provided an overview of the flooding fragility experiments being carried out at ISU for the RISMC Pathway.

- In September 2017, the release of the seismic MASTODON software was accomplished bringing this unique seismic analysis tool to the nuclear community. This software is equipped with numerical material models of dry and saturated soils including a nonlinear soil model, a model for saturated soil, as well as structural materials such as reinforced concrete. It is also equipped with models that simulate gapping, sliding and uplift at the interfaces of solid media such as the foundation-soil interface of structures. MASTODON recently had an internal SQA assessment that showed its development is effective and highly successful in implementing DOE O 414.1D and an ASME NQA-1 compliant program.

- In September 2017, the RISMC Grizzly development team released a version of Grizzly providing the capability of performing deterministic engineering fracture analysis of reactor pressure vessels containing flaws, including multiple improvements to the crystal plasticity models. The purpose of this release is to make the code and associated documentation available for pilot users for testing purposes. It has been made available to a limited set of users and developers for the purposes of obtaining feedback, testing and additional feature development.

In addition to the award-winning papers and students, publications in nuclear industry trade journals have been realized, including feature articles in both the ANS Nuclear News and Nuclear Engineering International.

3.1.5 Experimentation

One of the technical gaps that have been identified related to the external events analysis is the lack of fragility models, especially in the area of flooding analysis. Historically, rudimentary conservative methods for conducting flooding risk assessment fall short because they fail to sufficiently characterize both the fragility of components and the risk from the hazards. In short, current risk analysis methodology assumes that many components simply fail if contacted by water. As part of the RISMC Pathway, we propose to test representative nuclear power plant components and structures to failure (and, potentially, to the point of recovering after failure) and develop a science-based approach to flooding risk analysis. We will conduct wave impact, rising water, and top-down water spray testing as part of this experimentation for both mechanical and electrical components. The experimental laboratory will also integrate flood simulation computer codes with the experimental work in order to conduct modeling-informed experimental design. The experimental data obtained will ultimately be used in conjunction with the simulations to create more accurate flooding risk assessment. An example of the type of failure information that will be collected as part of the RISMC flooding experimentation is shown in Figure 3-9 and Figure 3-10. These types of fragility information is needed for flooding in order to have failure models that are equivalent (approximately) in scope and fidelity as those found for other failure modes (e.g., seismic analysis, “random” failures).

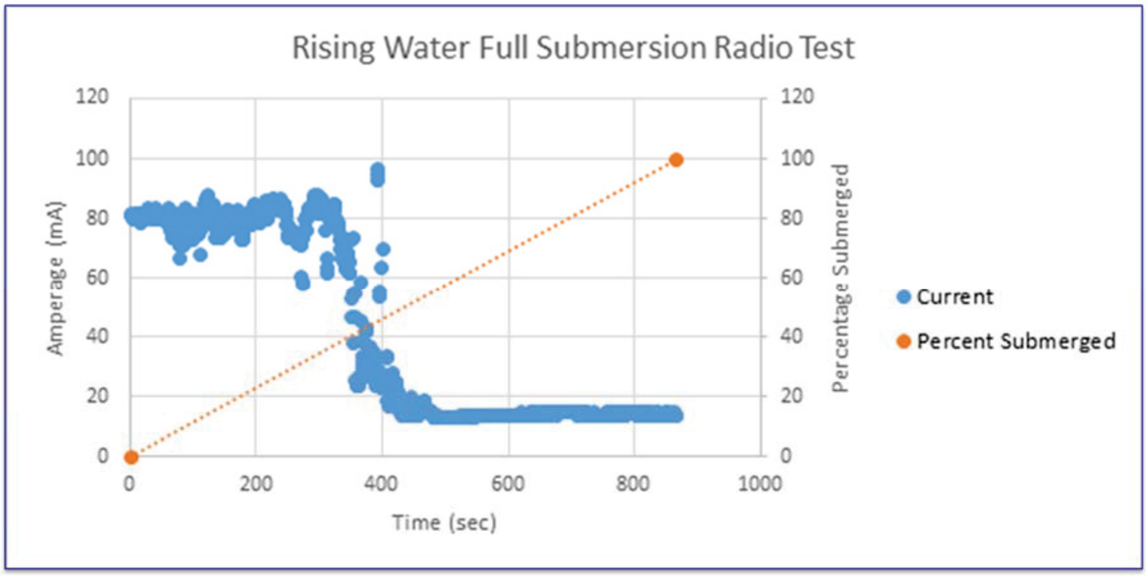

Figure 3-9: Operability, as measured by current draw, of a radio as a function of water inundation.

Figure 3-10: Experimental results of door flooding fragility tests.

3.1.6 Fragility Modeling

The approach to use the seismic or flooding experimental data is through what are called fragility models. Historically, fragility models have been used primarily within the seismic community to represent the probability that a structure or component will fail as a function of the earthquake level. Typically, these fragility models have been simple monotonically-increasing functions that give the probability of failure of a single structure or component as a function of the earthquake severity as measured by a single metric such as the acceleration (g) level. Limitations found in these traditional fragility models include: expert opinion, to simplistic (one single parameter), and excessive conservativism. For the RISMC flooding fragility modeling, we are avoiding these issues by moving to a more flexible, data-informed approach – Bayesian fragility modeling through phenomena-driven regression modeling.

In the simple fragility models, a single parameter is used to completely characterize the failure probability. However, in reality, other observables may be better indicators for the potential of failures. For example, these observables could include the detailed characteristics of an earthquake such as the X, Y, and Z parts of the ground motion or the frequency of the wave; the age of the component; the anchorages of the component; or the specifics of the component type (or all of the above). Fortunately, there are advanced modeling techniques that are able to capture these types of modeling characteristics in a systematic and technically defensible fashion. Instead of a single "driving" parameter in a simple model, it is possible to represent affects by observable quantities such as energy level, age, inundation level, pressure, mass, temperature, etc., on the failure probability for a structure or component. For flooding fragility, a simple one-dimensional fragility model may be adequate for some flooding types (e.g., submersion depth for a slow-rising flood) and components, but other flooding scenarios (e.g., waves, spray) may require a more complicated regression fragility model to capture the phenomena adequately. [13]

3.1.7 Validation

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 RISMC 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 RISMC 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 particular design to create a validated model for their specific application.

The RISMC 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 (see Figure 3-11) results from facility operation, integral effects test, separate effect tests, and fundamental tests including experiments on individual components. 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.

The 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.

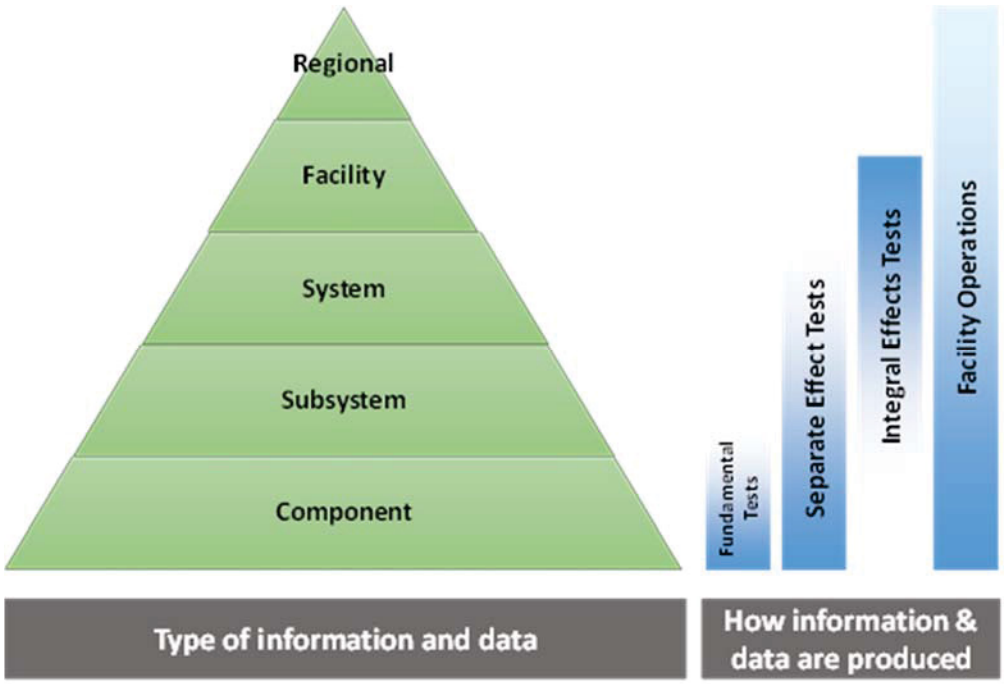

Figure 3-11: Information types and sources that will be used for validation.

For each tool in the RISMC Toolkit, we are in the process of creating a "development plan" (see Table 3-1) that will document a variety of information with the purpose of better understanding and communicating the software development process and outcomes for a specific tool.

Table 3-1. Information captured in the RISMC Toolkit Software Development Plan.

1.	Introduction		
	a.	Overview	
		i.	Purpose of software and/or tool
		ii.	Targeted users
	b.	Quality Assurance Requirements/Categorization	
2.	General Capabilities and Features		
3.	Development Requirements		
	a.	Software Design and Structure	
	b.	Numerical Methods	
	c.	Physics Implementation	
	d.	Graphical User Interface	
	e.	Data Storage and Retrieval	
	f.	Configuration Management	
4.	Verification and Validation Plan		
5.	Development Schedule		
	a.	Document when specific features are planned to be implemented	
	b.	Planned releases	
6.	Technology Transfer		
	a.	Deployment Plan	
	b.	Intellectual Property Plan	
7.	User Documentation		

3.2 R&D Collaborations

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

- RISMC Methodology and Toolkit is being developed together with EPRI
- Research results are disseminated via a variety of technical meetings, conferences, and are made available in program reports
- Industry is the targeted users group for RISMC Tools
- Code "testers" are being actively sought, the RISMC tools will be made available to industry volunteers who will use the tools and provide feedback to the LWRS Program
- A "User's Group" is being considered for maintenance and application information

3.2.1 EPRI Collaboration

EPRI has established the Long-Term Operations Program, which complements the DOE LWRS Program. EPRI's and industry's interests include applications of the scientific understanding and the tools to achieve safe, economical, long-term operation of the operational fleet of NPPs currently in service. Therefore, the government and private sector interests are similar and interdependent, leading to strong mutual support for technical collaboration and cost sharing. The interface between DOE-NE and EPRI for R&D work supporting long-term operation of the existing fleet is defined in a memorandum of understanding between the two parties. A joint R&D plan defining the collaborative and cooperative R&D activities between the LWRS Program and the Long-Term Operations Program has been developed. Also, contracts with EPRI or other industrial organizations may be used as appropriate for some work.

Recently, the Risk & Safety Management group within EPRI provided to DOE a list of priority items that they felt best meets the needs of industry related to risk and safety. This list of research topics identified are (1=highest priority):

1. Fire Analysis
2. Multi-Unit Analysis
3. External Flooding Barrier Testing
4. Dynamic Probabilistic Risk Assessment

These topical areas will be considered for investigation as the Pathway R&D proceeds.

3.2.2 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 the 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 (see www.neup.gov). In addition to contributing funds to NEUP, the LWRS Program provides descriptions of research activities important to the LWRS Program and 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 RISMC Pathway are:

- 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.

- 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 RISMC 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

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

- 15-8258 with Professor Mosleh at the University of California, Los Angeles. Physics-Based Probabilistic Model of the Effects of Ionizing Radiation on Polymeric Insulators of Electric Cables

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

- IRP-16-10918 with Professor Dinh at North Carolina State University. Development and Application of a Data-Driven Methodology for Validation of Risk-Informed Safety Margin Characterization Models.

- 17-12723 Tunc Aldemir, The Ohio State University, Integrating Static PRA Information with RISMC Simulation Methods

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

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 operating fleet in the United States, 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 to 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.

3.3 RISMC Advisory Committee

The RISMC Pathway Advisory Committee consists of a collection of individuals with backgrounds (knowledge and skills) from academia, nuclear consultants, owner/operators, and vendors that can assist in providing:

- Technical review and guidance on the scientific methods and tools:
  - Being developed now and considered in the future as part of the RISMC Pathway
  - Being validated for use in industry applications
- Strategic guidance on the overall focus areas to be considered in the RISMC Pathway, including:
  - Recommendations on high-value applications of interest the RISMC stakeholders
  - Review and feedback on the RISMC Pathway Plan
  - Recommendations on communication of the RISMC value and technical achievements

In FY14, the initial structure and member selection began. The Committee was formally started in FY15 and held its initial kick-off meeting in July, 2015. Feedback from this Committee will be used to further modify and refine the Pathway Plan. Members (in FY18) of the Committee will be:

- George Apostolakis, Consultant
- Doug True, Consultant
- John Gaertner, Consultant
- Enrico Zio, Professor Politecnico di Milano, Italy
- Greg Krueger, Exelon Director of Risk Management
- Gabe Balog, Candu Owners Group Director of R&D
- Bret Boman, Areva

4. RESEARCH AND DEVELOPMENT COOPERATION

4.1 DOE Collaborations

4.1.1 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, multiscale, 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 three-dimensional, 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-18, NEAMS is providing the development support for the RELAP-7 software. RELAP-7 is the new generation nuclear reactor system safety analysis code which is based upon the MOOSE, a finite-element, multiphysics framework primarily developed by INL. [14]

4.1.2 Consortium on Advanced Simulation of LWRs (CASL).

The CASL Hub 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 main 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 RISMC Pathway will be collaborating with CASL on aspects of technology transfer to industry related to methods and tools being developed in the respective programs.

4.1.3 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.

4.2 Industry Interactions

Industry is significantly engaged in RISMC activities, and the level of engagement is increasing. Up to now, industry engagement in RISMC (primarily through EPRI) has taken place at two levels: (1) input into program planning and (2) active participation in RISMC activities. One effect of this influence has been strengthening the RISMC team consensus that RISMC developments should be driven by “use cases” (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 RISMC team with access to engineering expertise that is needed in development of enabling methods and tools.

Coordination of RISMC activities includes the following:

- **EPRI:** EPRI will continue to play an important role in high-level technical steering and in detailed planning and execution of RISMC case studies. EPRI also will play a critical role in engaging industry stakeholders (i.e. personnel form operational NPPs) to support pathway development, contribute technical expertise to use case development and evaluate technical results from case study applications. The RISMC Pathway R&D is coordinated with EPRI Long-Term Operation Program work.

- **Owners Groups:** Interactions will continue with groups such as the CANDU, BWR, and PWR Owners Groups through information exchange and evaluations of specific topics via case studies. Recent technical exchange meetings have included participants from both Westinghouse and GE Nuclear. In addition, staff from the CANDU Owners Group have been trained on the MOOSE Framework and will be interacting with INL analysts and developers that are working on the RISMC Pathway.

- **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 RISMC Pathway, including:

  - The Committee on the Safety of Nuclear Installations (CSNI). This committee is a Organization for Economic Co-operation and Development (OECD)-sponsored group that is part of the Nuclear Energy Agency. One of the task groups in CSNI was focused on Safety Margin Applications and Assessment. The Working Group on Risk Assessment (WGRISK) advances the understanding and use of PRA tools. The Working Group on Analysis and Management of Accidents addresses safety analysis research including the uncertainty and sensitivity evaluation of best-estimate methods program. Various benchmarking activities are organized. Meetings are held twice a year in Paris in June and December. DOE (Rich Reister) is a member. A second Working Group is the newly-formed 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. INL (Curtis Smith) is a 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 – deterministic screening based on standard practice, absolute frequency (or probability) screening and 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.

- The European Nuclear Plant Life Prediction (NULIFE) – A virtual organization funded by over 50 organizations and the European Union under the Euratom Framework Program. This organization is working on advancing safety and economics of existing NPPs.

- The Advanced Safety Assessment Methodologies: Extended PSA (ASAMPSA_E) organization is investigating challenging initiating events such as the combination of two correlated extreme external events (earthquake and tsunami). The consequences of these situations, in particular flooding, has the potential to go beyond what has been considered in some NPP designs. Such situations can be identified using probabilistic safety assessment (PSA) methodology that complements the deterministic approach for beyond design accidents. The ASAMPSA_E group aims at promoting good practices for the identification of such situations with the help of PSAs and for the definition of appropriate criteria for decision-making in the European context. It offers a new framework to discuss, at a technical level, how "extended PSA" can be developed efficiently and be used to verify if the robustness of Nuclear Power Plants (NPPs) in their environment is sufficient. The project has experts from 28 organizations in 18 European countries. Members of the RISMC project team have interacted with this organization, including attending the first End Users workshop in May 2014.

- Civil Nuclear Energy Research and Development Working Group (CNWG), which is a bilateral activity with Japan that is focusing on RISMC and advanced seismic PRA applications. Tasks included in the CNWG include participation in a PRA expert's roundtable wherein U.S. participants discussed how PRA is applied in the U.S. and the resulting benefits, and Japanese participants discuss the issues associated with PRA application in Japan. Also advanced seismic PRA and RISMC activities are being considered for additional activities.

- The RISMC 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-US Civil Nuclear Energy Research and Development Working Group (CNEWG) bilateral working group, and the Japan Nuclear Risk Research Center (NRRC).

4.3 Risk-Informed Design

One of the primary avenues for collaboration with industry is through application of the RISMC methods and tools on specific industry issues. The end goal of these activities is the full adoption of the RISMC 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 a technical maturity in the RISMC methodology (essential for 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

Each industry issue application may address a broad range of relevant plant technical issues. Examples of these issues are discussed in a prior report INL-EXT-14-32928 [15], where we selected, prioritized, and combined important plant issues into several Industry Application (IA) categories. These were the most relevant industry topics that can potentially impact plant operations in a significant way, in the near future, making them interesting, relevant, applications for the RISMC toolkit. Because of their broad range of applicability, each Industry Application may spawn one or more demonstration problems, each depending on stakeholder interest on different aspects of a given IA. Examples of the type of problems identified in the IA are described in the next subsections.

4.3.1 IA-LOCA-ECCS → Performance-Based ECCS Cladding Acceptance Criteria

The RISMC toolkit has sufficiently matured to offer a potential solution to the loss-of-coolant accident (LOCA) problem and provide to the plant operator a vehicle to manage the margins and inform decisions when compliance with 10 CFR 50.46 is challenged by changes in the operational envelope.

This compliance issue is the driver behind the RISMC Industry Application LOCA-ECCS, where margin is here relative to the 10 CFR 50.46 rule. A LOCA safety analysis involves several disciplines which are computationally (externally) coupled to facilitate the process and maintenance of legacy codes and methods. The key disciplines involved in a LOCA analysis are:

- Core physics (fuel and core design)
- Fuel rod thermos-mechanics
- Clad corrosion
- LOCA thermal-hydraulics

The proposed rule (10 CFR 50.46c) would replace the prescriptive analytical requirements of the previous rule [peak clad temperature (PCT)<2200°F, MLO<17%, etc.], with performance-based requirements. The US NRC Draft Regulatory Guide DG-1263 defines an acceptable analytical limit on peak cladding temperature and integral time at temperature for the zirconium-alloy cladding materials tested in the NRC's LOCA research program. This analytical limit is based on the data obtained in the NRC's LOCA research program.

Referring to DG-1263, the analytical limit presented in Figure 4-1 will substitute for the 17% embrittlement limit. The hydrogen content depends on the burnup value and material characteristic of the cladding, i.e. performance to embrittlement under irradiation for a specific cladding alloy. Note that the temperature limit (at least when the pre-transient hydrogen content is less than 400 weight-ppm) is still the same, i.e. 2200°F. However the margin to embrittlement significantly decreases as the fuel is irradiated in the core and the cladding hydrogen concentration increases.

As a result of local oxidation, a measure of time-at-temperature is anticipated to be the controlling figure-of-merit under the proposed rule. In general terms, the two criteria embrittlement oxidation limit and PCT should be treated jointly.

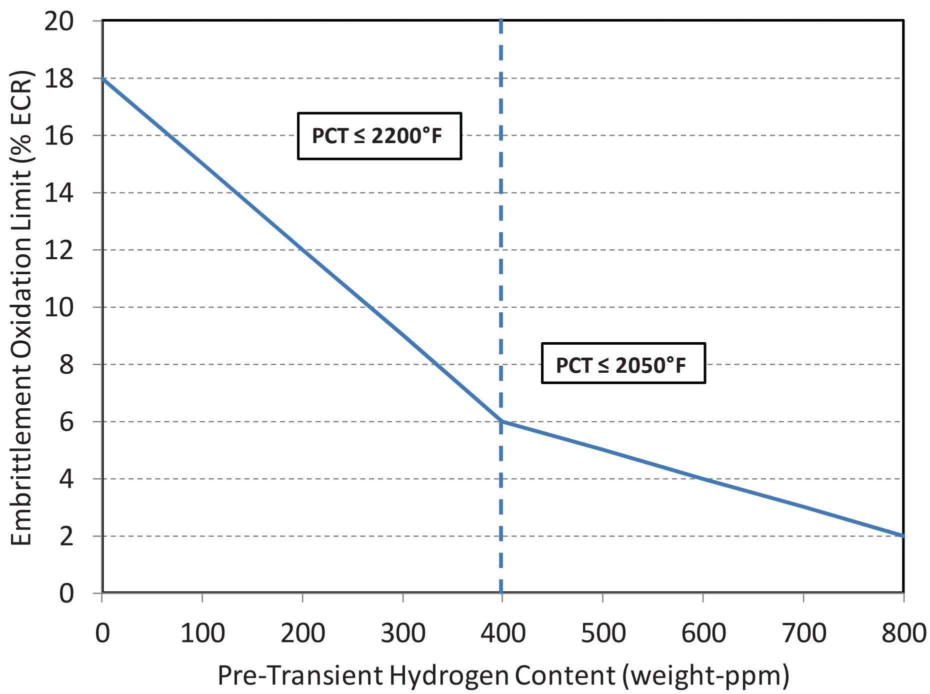

Figure 4-1. Proposed limit on peak cladding temperature and embrittlement oxidation limit [16].

4.3.2 IA-EE → Enhanced Seismic / External Hazard Analysis

Given that hazards external to a nuclear facility may negatively impact a variety of SSCs from direct damage (e.g., failure during a fire) or indirect damage (e.g., consequential failure from a flood following a pipe break), there is a possibility that initiating events, reduced redundancy levels, reduced reliability, or degraded safety barrier may be realized, thereby increasing the likelihood or severity of potential accident scenarios.

A class of hazards to nuclear facilities originates external to the plant. These external events are a class of initiating event that has the initial deviation caused by a hazard located outside the normal plant SSCs. Physical impacts such as fires, floods, and earthquakes are typically included in this group of initiating events. Additional detail on the modeling of external hazards was provided in Section 3.1.3.4.

4.3.3 IA-CONTAIN → Reactor Containment Analysis

One of the safety improvements mandated by the NRC following the accident at the Fukushima Daiichi nuclear facility is to have reliable, hardened containment venting systems capable of operating under beyond-design-basis (BDA) and severe accident (SA) conditions and installation of containment engineered vent filtration systems to reduce the release of radioactive materials should a SA occur for Mark I and Mark II containments. [17] Given the relatively small volumes of Mark I and II containments which depend on suppression pools and have no mitigation for hydrogen, ensuring the availability of reliable, hardened containment vents may provide plant operators with improved methods to vent containments during wide range of BDA accidents (but before core melt). However, the industry has stated that the addition of filters to hardened containment vents may require modifications to vent design. An EPRI study indicated that the containment venting alone is not effective. It has to be combined with active debris cooling to be effective. [18] Hence, accident sequences need to be better understood to determine under what conditions the filters are beneficial or non-beneficial.

4.3.4 IA-FLEX → Long Term Coping Studies

The "Diverse and Flexible Coping Strategies" (FLEX) [19] aim at increasing defense-in-depth for beyond-design-basis scenarios to address an extended loss of off-site power and loss of normal access to the ultimate heat sink occurring simultaneously at all units on a site. The objective of FLEX is to establish an indefinite coping capability to prevent damage to the fuel in the reactor and to maintain the containment function by using installed equipment, on-site portable equipment, and pre-staged off-site resources. The coping can be thought of as occurring in three phases:

Phase 1: Cope relying on installed plant equipment

Phase 2: Transition from installed plant equipment to on-site FLEX equipment

Phase 3: Obtain additional capability and redundancy from off-site equipment until power, water, and coolant injection systems are restored or commissioned.

The primary objective of establishing the FLEX analysis capability is to establish a RISMC framework which uses the system safety analysis tools to:

1. Better understand the accident sequence and recovery strategies
2. Search any vulnerability that might exist with FLEX.

The FLEX case study requires coordination with the external hazard analysis and containment analysis case studies. The external hazard analysis and containment analysis case studies emphasize more on the deterministic analysis tools development while the FLEX case study emphasizes on RISMC probabilistic methodology development and applications.

4.3.5 IA-RIEP → Risk-Informed Engineering Programs

When we apply the RISMC methodology to 10CFR 50.69, we can provide flexibility to reduce cost and improve plant operations and safety margins. Potential avenues for R&D will focus on two pieces, first to use enhanced risk analysis to categorize plant components and second to provide additional information for the technical basis of components undergoing "relaxed requirements."

4.4 Accident Tolerant Plant Design

The RISMC Pathway has proposed a two-phased plan that will focus on the risk-informed evaluation of accident tolerant fuel (AFT) and plant designs. Phase I will be a near term scoping study that has as the goal of determining the trade-off surface of coping time versus economic savings that includes:

- Determining the expected change in risk for postulated (or fixed) “coping times”, where coping time is defined as the extra time that ATF might provide during accident sequence conditions leading up to fuel damage of the fuel. This analysis will look at short, medium, and long fixed coping times (e.g., 6, 24, 72 hours) in order to characterize the changes in accident sequences that would result from these coping time(s). For example, suppose a plant with ATF could withstand a loss of cooling for 6 hours; this capability would imply a reassignment of some risk event sequences from "core damage" to "OK," enabling characterization of the benefit of ATF.

- Performing of risk analysis perturbations including potential changes in system success criteria, human actions, and component performance. These perturbations will be characterized according to their risk reduction. The evaluation of ATF benefits will be in terms of changes in metrics such as success criteria of systems, structures, and components (SSCs).

- Identification of potential regulatory implications of extended coping time within applications of 10CFR 50.69 such as economic enhancements and regulatory relaxations that might be possible.

- Characterization of specific SSCs that could be re-categorized based on 10CFR 50.69 for the different "fixed coping times." Potential systems or components that may be of interest including: auxiliary feedwater (pumps, valves, pipes, operator actions and associated batteries), diesel generators (and associate sequencers), operator recovery actions, reactor coolant pumps, service water (pumps, valves, etc.), and low pressure recirculation.

Phase II will be a longer term detailed assessment that will consider ATF accident sequences and postulate possible changes (e.g. improved success criteria, components no longer needed, and easier ways to prevent core damage) as part of an event-tree based risk assessment of reactor fuel and system performance. Within the event-tree analysis, specific minimal cuts sets (i.e. unique combinations of component failures that can cause system failure) will be evaluated for possible positive changes in risk against 10CFR50.69. This will enable an improved understanding of regulatory relaxations that are possible for specific SSC’s of interest. A key focus of Phase II will therefore be the building of plant models to study system configuration variations, including the ability to analyze inverse problem configurations that are not easily done with traditional sequential processes. Included in the detailed assessment will be a look into current LWR plants for design enhancements including consideration of ATF and other non-fuel/clad enhancements. Included in the enhancements items to consider during the evaluation are accident-tolerant core structures, backup safety systems such as FLEX, additional new passive cooling systems, improved operational control, and accident-tolerant instrumentation. This detailed evaluation approach becomes important when analyzing magnitude range and timeline of system responses for a given sequence of events, such as evaluating ATF composition, behavior, and characteristics under accident scenarios.

4.5 RISMC Toolkit Deployment

As part of the RISMC Tools development, we have created new software to incorporate critical insights and models from material-related testing in order to incorporate these material advances into risk-informed applications. This software is a combination of the RAVEN and Grizzly tools and they have been used to evaluate operational issues such as long-term radiation impacts to pressure vessels. Insights from these tools can help to inform operation of nuclear power plants and modernize the "legacy" analysis tools that are currently in use.

Helping to represent complex issues unique to nuclear power generation is also a focal point for the RISMC Tool product development. Being able to accurately model potential risks in a nuclear power plant is the first step in being able to manage these risks. Toward that end, the risk-informed analysis tool RAVEN is in the process of being released under a very flexible license for use by the U.S. nuclear industry. Currently, the researchers that created RAVEN are working with nuclear businesses such as Westinghouse, Studsvik, and Newport News Shipbuilding in order to transfer this technology to industry. In addition to the active collaborations, several of these companies have agreed to participate in USG Technology Commercialization where private funding is used to match DOE funds.

Another LWRS product that is targeted to fuel performance and reliability is the LOCA Toolkit for the US (LOTUS) integrated tools. This integrated tool is the result of industry engagement to demonstrate relevant, realistic solutions nuclear fuel behavior and operational safety for the current nuclear fleet. The LOTUS tool that was developed by RISMC researchers is an integrated evaluation model used to better understand risks and uncertainties for core and fuel reload licensing processes used in the South Texas Project (STP) plant. These enhancements are essential to future safety modeling and simulations using an integrated toolkit for core design automation, fuel/clad modeling, thermal-hydraulics, and risk analysis. This product is also being evaluated for additional applications such as higher utilization of fuel (with the EPRI Fuels Reliability Program) which is considered of high priority to the industry. Westinghouse is also interested in this application. Farther out in time, the LOTUS tool could be used to evaluate accident-tolerant fuel once the material properties of these advanced fuel designs are better understood.

5. RESEARCH AND DEVELOPMENT PRODUCTS AND SCHEDULES

The RISMC Pathway will deliver the following high-level products:

1. Technical-basis reports for RIMM
2. The RISMC Toolkit

It has been determined that the focus in the near term will be on NPP Industry Applications that study a specify scope of phenomena, components, and simulation capabilities needed to address the given issue space. As 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 RISMC Toolkit development.

As the development and capabilities of the RISMC Toolkit progresses, INL will collaborate with industry to determine how to transition the RISMC Tools to a user-supported community of practice, including planning for lifecycle software management issues such as training, software quality assurance, and development support.

5.1 Integrated Project Plan Milestones

The major project plan milestones are listed by FY below:

FY2018

- (2018) Complete the research required for including 10CFR 50.69 risk-prioritization approaches into the RISMC approach.
- (2018) Flooding fragility work to support flooding fragility door, penetration, and seal experimental results.
- (2018) Release version of the flooding simulation software package for use by industry.
- (2018) Deploy RISMC techniques by applying to advanced tools for performance-based Emergency Core Cooling System ECCS) Cladding Acceptance Criteria.
- (2018) Use of RAVEN surrogate models for RISMC applications.
- (2018) Perform advanced risk-informed validation for the flooding tool based upon smoothed particle hydrodynamics.
- (2018) Complete work on a Fire Technology Roadmap that supports the Electric Power Research Institute Fire Risk Analysis Research Plan
- (2018) Using the roadmap for enhanced accident tolerant nuclear power plant systems, perform plant-level scenario-based risk analysis for a proposed accident tolerant plant design.
- (2018) Extend human reliability analysis in representing critical operator safety-related activities for preliminary technical basis for crediting FLEX.

FY2019

- (2019) Flooding fragility models for mechanical components will be validated against an accepted set of data.
- (2019) Release version of flooding analysis tool suitable for storm-surge representation.
- (2019) Completion of embedded human reliability models into the simulation framework.
- (2019) Demonstrate margins analysis techniques for advanced accident tolerant fuel (ATF) under extended station blackout conditions.
- (2019) Support for the validation of the RAVEN adaptive surrogate emulator approach.

FY2020

- (2020) Flooding fragility models for electrical components will be validated against an accepted set of data.
- (2020) Support for the validation of the RAVEN Bayesian inference capabilities.• (2020) Completion of full-scope risk assessment model suitable for a multi-unit site using the RISMC Toolkit (generic PWR/BWR model).
- (2020) Flooding fragility experiments for electrical components.
- (2020) Develop advanced fragility models based upon the flooding fragility experimental information.
- (2020) Release version of fire analysis tool for dynamic fire analysis based upon simulation approaches.
- (2020) Completion of advanced user interface platform.
- (2020) Implementation of a Bayesian inference approach for uncertainty quantification.

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- (2021) Development of modules in RAVEN to support enterprise risk analysis.
- (2021) Release version of advanced seismic probabilistic risk assessment model.
- (2022) Completion of enterprise risk analysis into the RISMC framework.
- (2022) Develop flood mitigation approaches based upon the flooding fragility experimental information.
- (2022) Ensure development and validation to the degree that by the end of 2022, the margins analysis techniques and associated tools are an accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of probabilistic risk assessment.

5.2 Integrated Program List

This section provides additional detail into the Pathway subtasks. The Integrated Program List is separated into following technical task priority order (details are found in Table 5-1):

1. Safety Margin Methods
2. External Hazards Experiments
3. Physics Modeling for Hazards
4. Risk-Informed Design
5. RAVEN Development
6. Risk-Informed Validation of Tools

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 5-1. RISMC Pathway activities list.

Descriptive Activity Title	Activity Description and Major Deliverables
Project Management and Industry Engagement	Support routine project management activities and new program development tasks, report generation, travel, meetings, and benchmarking
Safety Margin Methods	Conduct margins analysis, including the methodology for carrying out simulation-based studies of safety margin. • (2018) Complete the research required for including 10CFR 50.69 risk-prioritization approaches into the RISMC approach. • (2018) Extend human reliability analysis in representing critical operator safety-related activities for preliminary technical basis for crediting FLEX. • (2019) Completion of embedded human reliability models into the simulation framework. • (2020) Completion of full-scope risk assessment model suitable for a multi-unit site using the RISMC Toolkit (generic PWR/BWR model). • (2022) Completion of enterprise risk analysis into the RISMC framework.
External Hazards Experiments	This activity provides needed experiments to better understand technical gaps in industry understanding related to high-priority physical phenomena related to external hazards. The external hazard experiments (e.g., determining failure probabilities for components during flooding conditions) will be used to provide data to validate physics-based external hazards numerical methods and tools. • (2018) Flooding fragility work to support flooding fragility door, penetration, and seal experimental results. • (2020) Flooding fragility experiments for electrical components. • (2020) Develop advanced fragility models based upon the flooding fragility experimental information. • (2022) Develop flood mitigation approaches based upon the flooding fragility experimental information.
Physics Modeling for Hazards	This activity provides the research needed to develop and employ advanced models representing the physics of high-priority hazards being considered within the RISMC Pathway. • (2018) Release version of the flooding simulation software package for use by industry. • (2018) Complete work on a Fire Technology Roadmap that supports the Electric Power Research Institute Fire Risk Analysis Research Plan • (2019) Release version of flooding analysis tool suitable for storm-surge representation. • (2020) Release version of fire analysis tool for dynamic fire analysis based upon simulation approaches. • (2021) Release version of advanced seismic probabilistic risk assessment model.

Descriptive Activity Title	Activity Description and Major Deliverables
Risk-Informed Design	RISMC Advanced Safety Analysis - Development and application of advanced safety analysis tools. • (2018) Deploy RISMC techniques by applying to advanced tools for performance-based Emergency Core Cooling System ECCS) Cladding Acceptance Criteria. • (2018) Using the roadmap for enhanced accident tolerant nuclear power plant systems, perform plant-level scenario-based risk analysis for a proposed accident tolerant plant design. • (2019) Demonstrate margins analysis techniques for advanced accident tolerant fuel (ATF) under extended station blackout conditions. • (2022) Ensure development and validation to the degree that by the end of 2022, the margins analysis techniques and associated tools are an accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of probabilistic risk assessment.
RAVEN Development	This activity will enhance RAVEN in order to support other modeling activity found in the RISMC Pathway. • (2018) Use of RAVEN surrogate models for RISMC applications. • (2020) Completion of advanced user interface platform. • (2020) Implementation of a Bayesian inference approach for uncertainty quantification. • (2021) Development of modules in RAVEN to support enterprise risk analysis.
Risk-Informed Validation of Tools	The activity provides risk-informed focus for validating tools being developed and used within the RISMC Pathway. • (2018) Perform advanced risk-informed validation for the flooding tool based upon smoothed particle hydrodynamics. • (2019) Flooding fragility models for mechanical components will be validated against an accepted set of data. • (2019) Support for the validation of the RAVEN adaptive surrogate emulator approach. • (2020) Flooding fragility models for electrical components will be validated against an accepted set of data. • (2020) Support for the validation of the RAVEN Bayesian inference capabilities.

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The current list of reports can be found at:

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

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- Software Requirements Specification for RELAP-7, H. Zhang, D. Andrs, R. Martineau, N. Kyle, H. Henry, S. McKirdy, INL/EXT-17-41891, April 2017.

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