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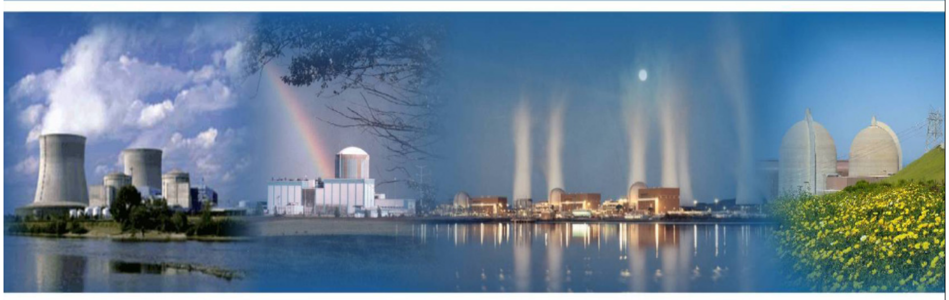
Light Water Reactor Sustainability Program

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

November 2012



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Light Water Reactor Sustainability Program

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

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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 and quantify safety margin is important to improved decision making about LWR design, operation, and plant life extension. A systematic approach to characterizing 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 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 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 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. Included in this Toolkit are the next generation reactor systems-analysis code (RELAP-7), a probabilistic-based scenario simulation code (RAVEN), and a component aging and damage evolution mechanism simulation application (Grizzly).

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. The deliverables provided by the Pathway include: (1) Technical Basis Guides for Risk-Informed Margins Management and (2) the RISMC Toolkit. These deliverables will serve to provide a comprehensive approach and software to support safety-, reliability-, and economic-decisions needed for long term NPP operation.

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ACRONYMS

DOE	Department of Energy
EPRI	Electric Power Research Institute
HPC	High Performance Computing
INL	Idaho National Laboratory
LWR	light water reactor
MOOSE	Multiphysics Object-Oriented Simulation Environment
NPP	nuclear power plants
NRC	U.S. Nuclear Regulatory Commission
PRA	probabilistic risk assessment
R&D	research and development
RIMM	Risk-Informed Margin Management
RISMC	Risk Informed Safety Margins Characterization
SSC	systems, structures, and component
T-H	thermal-hydraulics

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.

Since safety is important to successful operation of the NPP fleet, there are strong motivations to better characterize and 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. [US NRC, 2011] 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 and quantify safety margin provides a mechanism to improved decision making about LWR design, operation, and plant life extension.

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 degradation understanding and potential impacts to plant margins is shown in Figure 1-1. To support decision making related to economics, reliability, and safety, the RISMC Pathway will provide methods and tools that enable mitigation options known as margins management strategies.

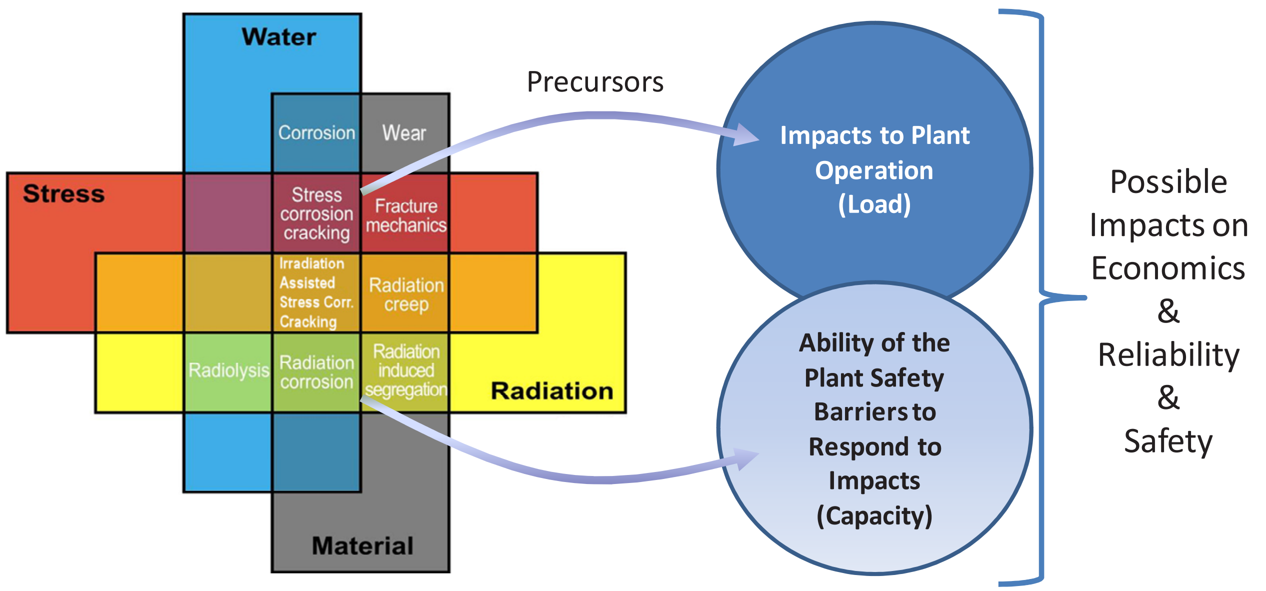

Figure 1-1. Representation of the interaction of degradation mechanisms that may impact plant operations and safety barriers if left unmitigated (adapted from INL 2012).

2. RESEARCH & DEVELOPMENT

2.1 Purpose and Goals

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 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.

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 key 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 key 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, (Zio, 2009) "…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 simulation tools to model plant behavior and determining safety margins. Specifically, we are developing the simulation components of the "RISMC Toolkit" which include:

- **RELAP-7:** The next generation nuclear reactor system safety analysis code is RELAP-7. The code is based upon the High Performance Computing (HPC) development and runtime framework – MOOSE (Multi-Physics Object-Oriented Simulation Environment). RELAP-7 will become the main reactor systems simulation toolkit for LWRS/RISMC and the next generation tool in the RELAP reactor safety/systems analysis application series (the replacement for RELAP5). The design goal of RELAP-7 development is to leverage 30 years of advancements in software design, numerical integration methods, and physical models.

- **RAVEN:** Based upon the MOOSE HPC framework, RAVEN (Reactor Analysis and Virtual Control Environment) is a multi-tasking application focused on RELAP-7 simulation control, reactor plant control logic, reactor system analysis, uncertainty quantification, and performing probability risk assessments (PRA) for postulated events. RAVEN is being developed to drive RELAP-7 (and other MOOSE-based reactor applications) for which the following functional capabilities are provided:

  - Front-end driver for RELAP-7:
    - ✓ Input a plant description to RELAP-7 (component, control variable, and control parameters)
    - ✓ Runtime environment
    - ✓ Parallel distribution of RELAP-7 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 accident-sequence based analysis
  - Control of Graphical User Interface (GUI) to:
    - ✓ GUI capability provided by NiCE (a NEAMS product) and 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

- **Peacock:** A graphical user interface for MOOSE that can be used to create, control, and interact with the various tools in the RISMC Toolkit.

- **Grizzly:** A MOOSE-based tool is being constructed for simulating component ageing and damage evolution events for LWRS specific applications. This new simulation tool, called Grizzly, will in the future have implicit time simulation capabilities for component damage evolution concerning LWR pressure vessel, core internals, and concrete support and containment structures subjected to a neutron flux, corrosion, and high temperatures and pressures.

The RISMC Toolkit is being built using MOOSE, a computer simulation framework that simplifies the process for modeling complicated physics as represented by mechanistic models.(Gaston, Hansen, & Newman, 2009) The MOOSE framework was developed by INL by using existing computer code and numerical libraries from proven scalable numerical tools developed at universities and DOE. The result is a framework with a number of high-level features that includes built-in parallelization and advanced geometry meshing capabilities. The constituent pieces of the overall RISMC Toolkit are shown in Figure 2-1.

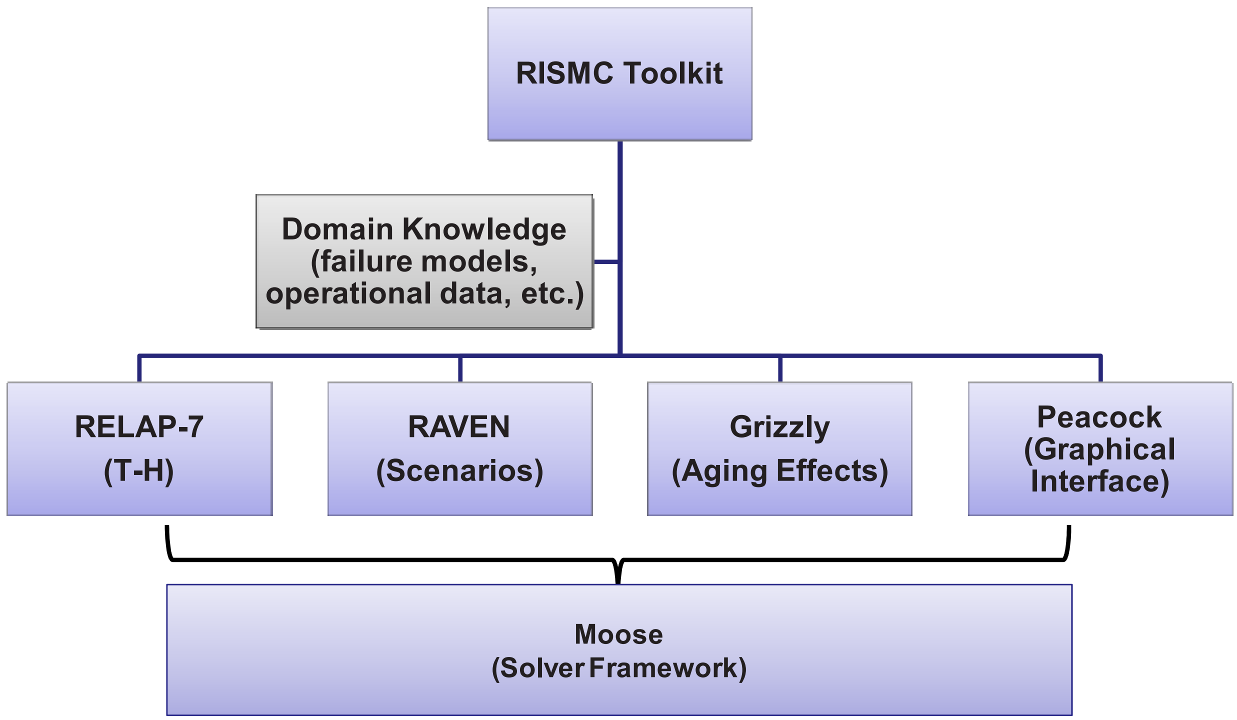

Figure 2-1. The major software modules present in the RISMC Toolkit.

2.2 Details of the R&D Approach

Central to this pathway is the concept of a safety margin. In general 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 f(**L**), the probabilistic margin would be represented by the expression Pr[f(**L**) > f(**C**)].

In practice, actual loads (**L**) and capacities (**C**) are uncertain and, as a consequence, most engineering margin evaluations are of the probabilistic type (in cases where deterministic margins are evaluated, the analysis is typically very 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.

Probabilistic Safety Margin

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

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 has two alternatives to consider: Alternative #1 – retain the existing, but aging, component as-is or Alternative #2 – replace the component with a new one. Using risk analysis methods and tools (described in Section 3), we run 30 simulations where this component plays a role in plant response under accident 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). 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(Load exceeds Capacity) = 0.17

Alternative #2: Pr(Load exceeds Capacity) = 0.033

If the safety margin characterization were the only decision factor, then Alternative #2 would be preferred (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.

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 2-3 illustrates that safety, as represented by a load distribution, is a complex function that varies from one type of accident 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 and material properties (which are common across a spectrum of accidents) or regulatory safety limits (such as the 10 CFR 50.46 limit in the Figure 2-2).

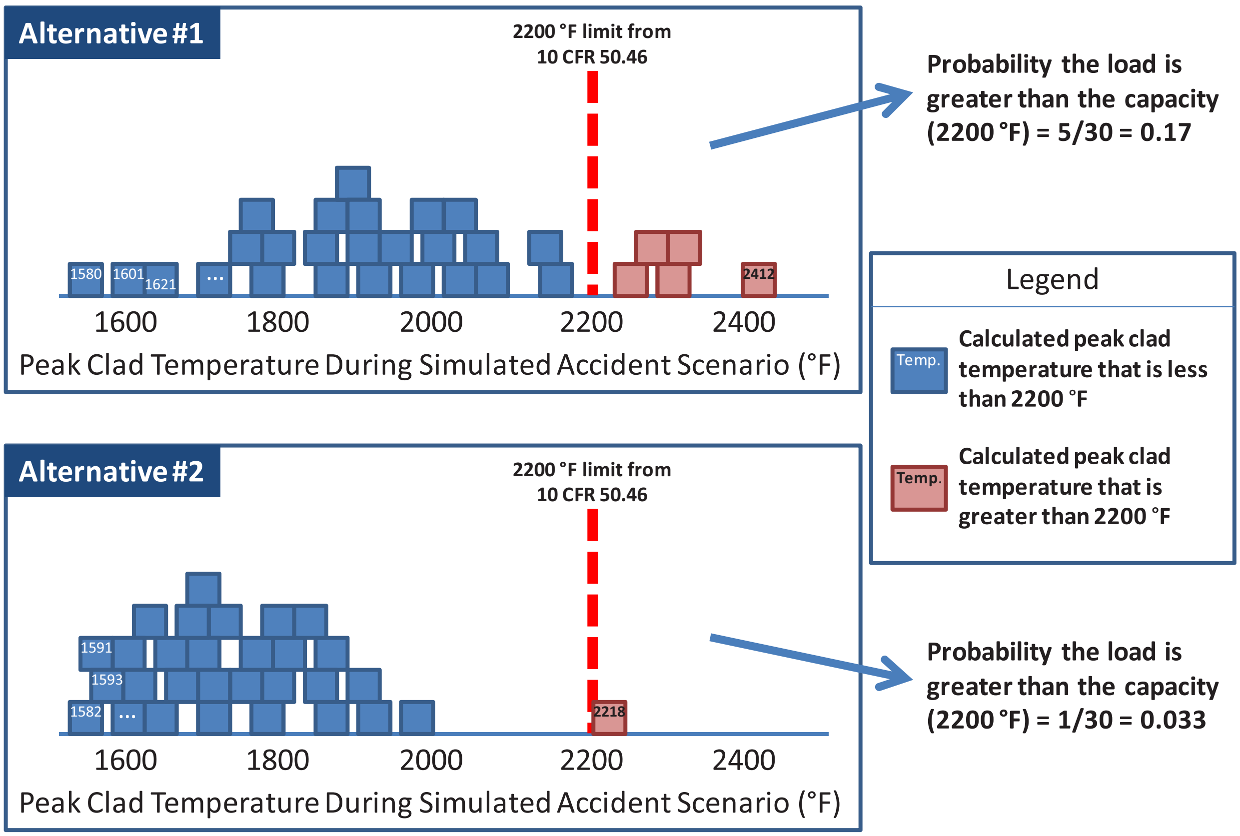

Figure 2-2. RISMC example when evaluating alternatives for risk-informed margins management.

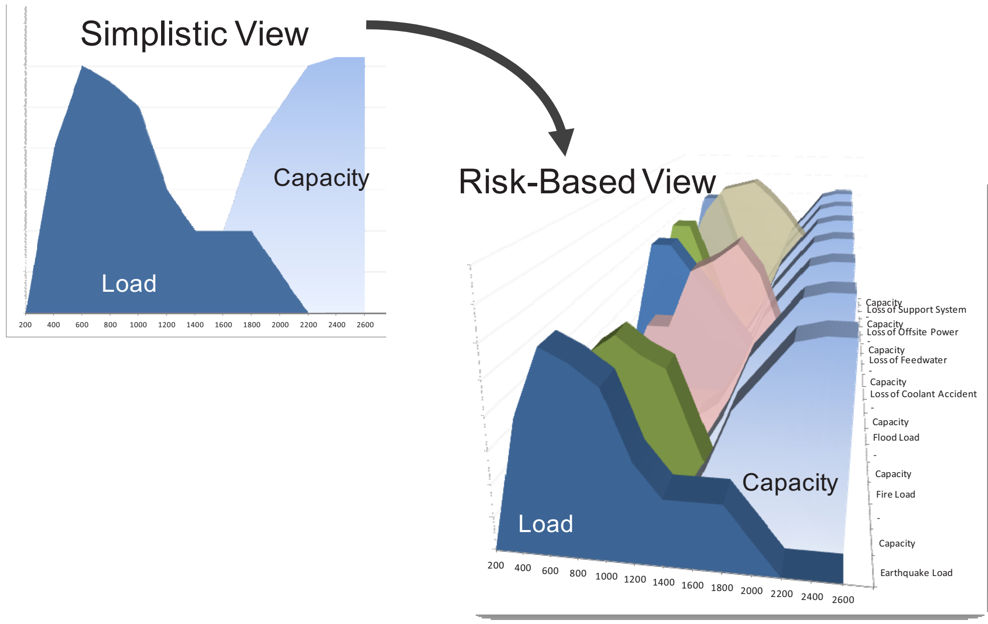

Figure 2-3. Family of load and capacity distributions representing different accident conditions.

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-7 as part of the RISMC Toolkit). Then, to characterize safety margin for a specific safety performance metric[a] of consideration (e.g., peak clad temperature), the plant simulation will determine time and scenario-dependent outcomes for both the load and capacity. Specifically, the safety margin approach will use the physics-based plant results (the “load”) and contrast these to the capacity (for the associated performance metric) to determine if 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.

The RISMC Pathway will also develop a significantly improved plant physics code (i.e., RELAP-7) and a suite of control/probability methods contained in RAVEN for driving RELAP-7 to analyze safety margin as part of the RISMC Toolkit. These tools will use advanced computational techniques to simulate the behavior of NPPs in a way that develops more comprehensive safety insights and enables a more useful risk-informed analysis of plant safety margin than can be done using existing tools. RELAP-7 is a systems code, meaning it will simulate behavior at the plant level (i.e., it will address a broad range of phenomena at a level of detail that is feasible and appropriate for a plant scale of modeling) as opposed to analyzing highly localized phenomena in great detail at every point in the plant (which is still infeasible today). However, as a systems code, RELAP-7 will function as an environment within which user-

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a. Safety performance metrics may be application-specific, but in general are engineering characteristics of the NPP, for example as defined in 10 CFR 50.36, “safety limits for nuclear reactors are limits upon important process variables that are found to be necessary to reasonably protect the integrity of certain of the physical barriers that guard against the uncontrolled release of radioactivity.”

supplied, highly detailed models of selected subsystems [e.g., via linkage to the Consortium of Advanced Simulation of Light Water Reactors (CASL) model of the reactor core] can be applied as needed.

The type of "plant physics" represented in the RELAP-7 software will include both T-H and neutronics. Specifically, RELAP-7 has both neutronics physics (via a point kinetics model) and T-H physics (through a variety of models covering single- and two-phase flow). However, the Pathway is also planning on coupling RELAP-7 to other INL-developed neutronics software (e.g., Rattle$S_N$ake, a S_N transport code being developed using the MOOSE framework) when needed for the spatially-dependent neutronics models. Consequently, for scenarios only requiring "simple" neutronics (which are most accident scenarios) one would just use RELAP-7 and use the built-in neutronics module. More complicated problems (from a neutronics standpoint) would require neutronics from a more sophisticated module, such as the Rattle$S_N$ake transport code [Frederick et al, 2012] or linkage to higher-fidelity models such as those being developed by CASL.

2.3 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. Motivations for DOE involvement in supporting the RISMC Pathway include:

- The need to better characterize and quantify safety margin when considering 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 validation, verification, and uncertainty quantification, which are essential components for successful development of the RISMC Toolkit.
- The need to provide demonstration cases that represent the viability of the Pathway methods and tools.
- The need to enhance and expand on the existing body of methods and tools. For example 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 be able 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 of plants by extended power uprates.

- The need to better describe uncertainties with a focus on improved decision-making.

- The development of tools such as RELAP-7 is high-risk, requiring multiphysics modeling capabilities developed in the DOE national laboratory system. Moreover, RELAP-7 is highly multi-disciplinary, making RELAP-7 development a good match for the institutional conditions at DOE.

- Government and industry are sharing work on methods and tools for characterizing safety margin.

    - The DOE role is to lead the development of advanced techniques, including building on uncertainty analysis methodology that has been under development for years at government laboratories and internationally.

    - Industry, under EPRI's Long-Term Operation Program, is carrying out simplified case studies to better understand the issues and to provide feedback and comparative results to DOE on both RELAP-7 development and the methods and tools for analysis of safety margin.

One result of a risk-informed approach in the RISMC Pathway is the use of "performance-based" Margins Management Strategies. These strategies will be informed by the risk 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, Advanced Light Water Reactor Nuclear Fuels, and the Advanced Instrumentation and Control Systems Technologies Pathways.

3. PATHWAY RESEARCH & 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 may be 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. Because probabilities are not observable quantities, we rely on models to estimate probabilities for certain specified outcomes.	Mechanistic analysis (also called "deterministic") uses models to represents situations where the observable outcome will be known given a certain set of parameter values.
An example of a probabilistic model is the counting of *k* number of failures of an operating component in time *t*: Probability(k=1) = $\lambda e^{-\lambda t}$.	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.

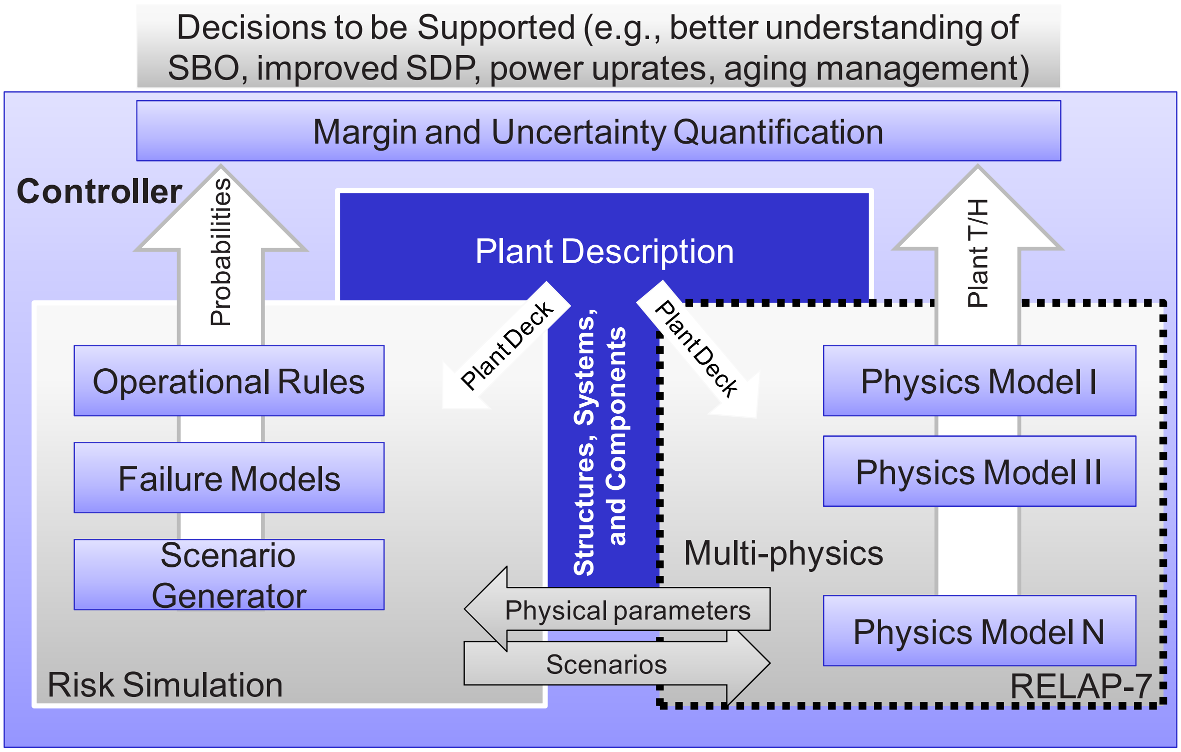

Figure 3-2. Attributes of the RISMC approach for supporting decision-making.

The RISMC Pathway has two primary focus areas to guide the R&D activities. First, the Pathway is developing the methods that will be used to obtain the technical basis for safety margins and their use in the support of the risk-informed decision making process. These methods are to be described in a set of documents called the Technical Basis Guides for Risk-Informed Margins Management (RIMM). Second, 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 Guides for Risk-Informed Margins Management

Technical Basis Guides

A set of technical documents providing the details for analysis and evaluation protocols related to safety margin characterization and risk-informed margins management.

The RISMC methodologies are captured in a set of Technical Basis Guides. 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 Guides are intended to be companion documents to EPRI-produced reports. The guides will be developed to support industry use in their 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.(Bishop & Bloomfield, 1998)*

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, in practice, 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. As noted by Youngblood and Smith [2011]:

> *Arguably, then, in providing a design or even a system, we may know its technical capability… and cost and so on, but we do not know its "safety" in the same sense as we know the observable technical capability or cost. That is, safety cannot be observed, photographed, weighed, or objectively measured, although a lack of safety may be manifested by accidents. Instead of "measuring" safety, we marshal evidence that safety claims are true; this is the safety case.*

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 Guides will address 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. Formulate an "issue space" that describes the safety figures of merit to be analyzed.

2. Quantify the decision-maker and analyst's state-of-knowledge (uncertainty) of the key variables and models relevant to the issue. For example, if long-term operation is a facet of the analysis, then potential aging mechanisms that may degrade components should be included in the quantification.

3. Determine issue-specific, risk-based scenarios and accident timelines (as shown in Figure 3-4). The scenarios will be able to capture timing considerations that may affect the safety margin and plant physical phenomena, 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, technical specifications, maintenance schedules) 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 (plant procedures), the probabilistic plant representation will account for the possibility of failures.

5. Represent plant physics mechanistically. The plant systems level code (e.g., RELAP-7) will be used to develop distributions for the key plant process variables (i.e., loads) and the capacity to withstand those loads for the scenarios identified in Step 4. 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.

6. Construct and quantify probabilistic load and capacity distributions relating to the figures of merit that will be analyzed to determine the probabilistic safety 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 aware of limitations in the analysis and adhere to protocols of "good engineering practices" to augment the analysis. This step relies on effective communication from the analysis steps in order to understand the risks that *were* characterized.

8. Identify and characterize the factors and controls that determine the relevant safety 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) safety control is justified.

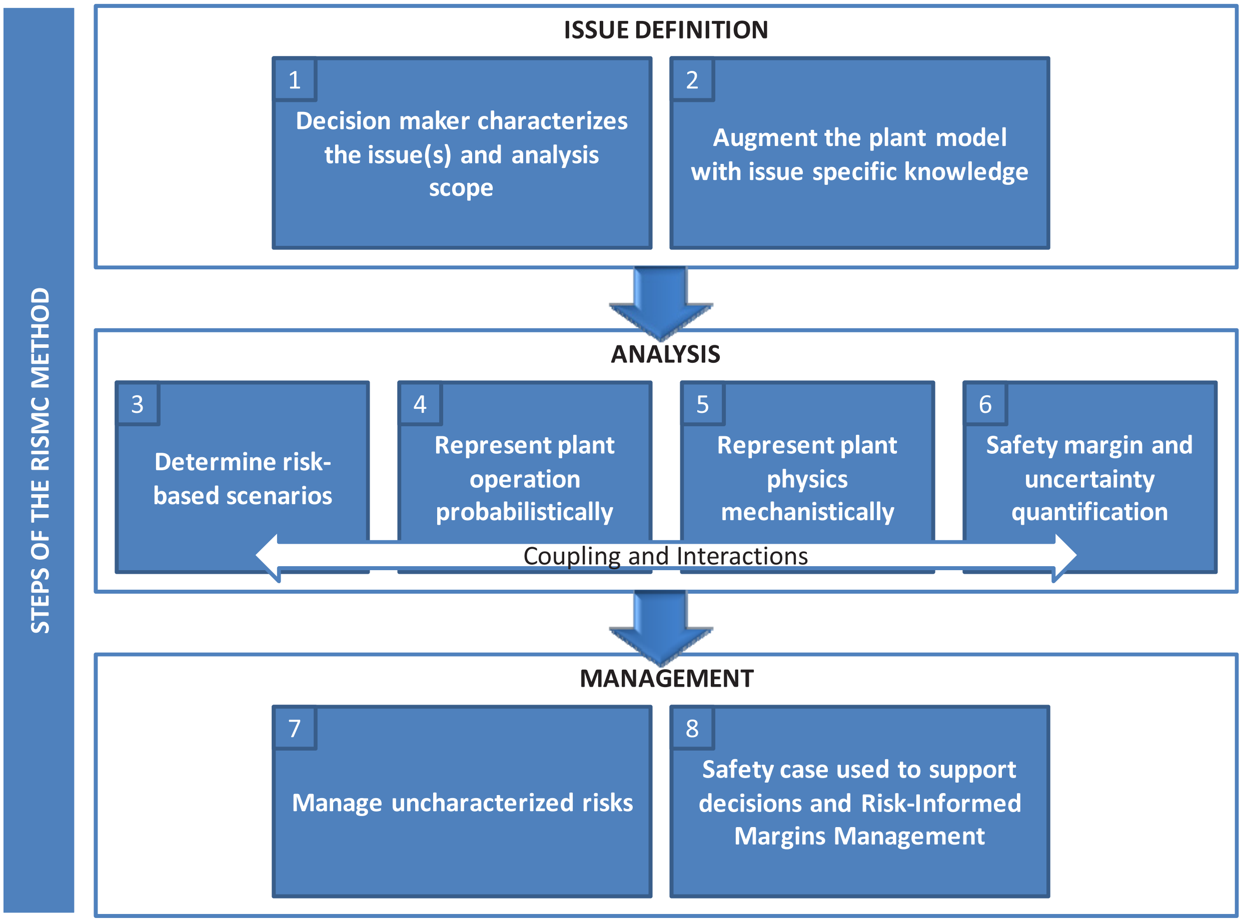

Figure 3-3. Depiction of the high-level steps required in the RISMC method.

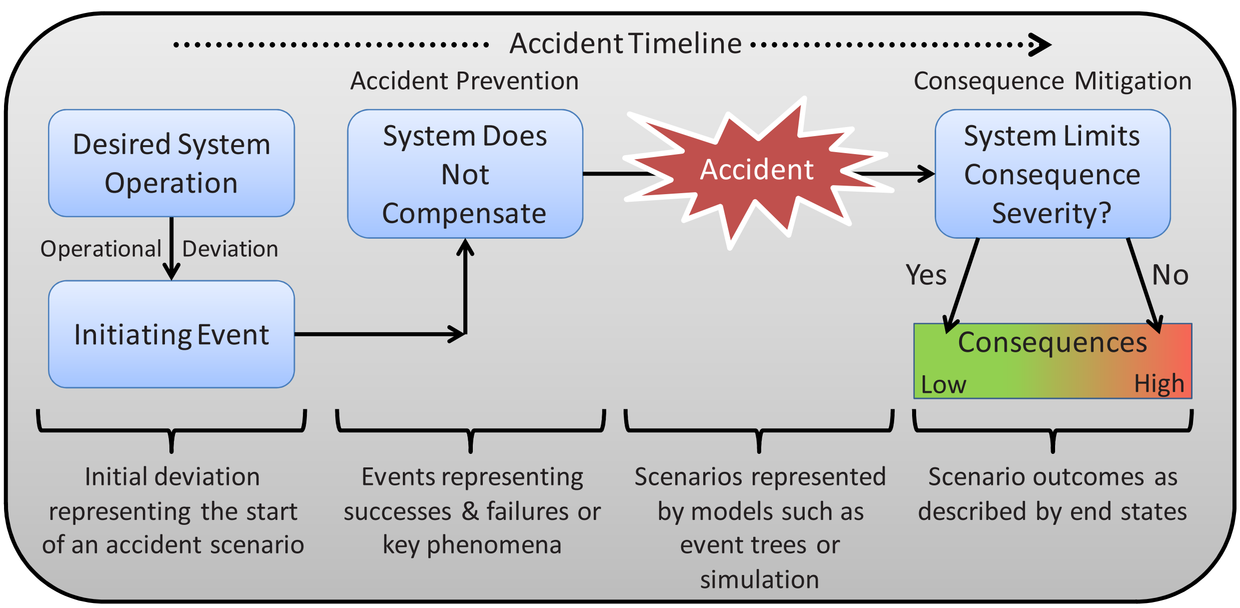

Figure 3-4. Accident scenario representation.

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. In FY2013, the team will be collaborating on a boiling water reactor extended power uprate case study. 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. A second case study of interest to industry is the task to develop a Technical Basis Guide that will describe 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 for th second case study will focus on how the safety-margin approach may be used to determine risk levels as different plant configurations are considered.

3.2 The RISMC Toolkit

The RISMC Toolkit is being built using the INL's Multi-physics Object Oriented Simulation Environment (MOOSE) HPC framework. MOOSE is the INL development and runtime environment for the solution of multi-physics systems that involve multiple physical models or multiple simultaneous physical phenomena. The systems are generally represented (modeled) as a system of fully coupled nonlinear partial differential equation systems (an example of a multi-physics system is the thermal feedback effect upon neutronics cross-sections where the cross-sections are a function of the heat transfer). Inside MOOSE, the Jacobian-Free Newton Krylov (JFNK) method is implemented as a parallel nonlinear solver that naturally supports effective coupling between physics equation systems (or Kernels). The physics Kernels are designed to contribute to the nonlinear residual, which is then minimized inside of MOOSE. MOOSE provides a comprehensive set of finite element support capabilities (libMesh) and provides for mesh adaptation and parallel execution. The framework heavily leverages software libraries from DOE SC and NNSA, such as the nonlinear solver capabilities in either the Portable, Extensible Toolkit for Scientific Computation (PETSc) project or the Trilinos project.

The RISMC Toolkit provides the foundation for the analysis steps found in the RISMC method. In Figure 3-5, we show the roles that each of the four tools support as part of safety margin analysis.

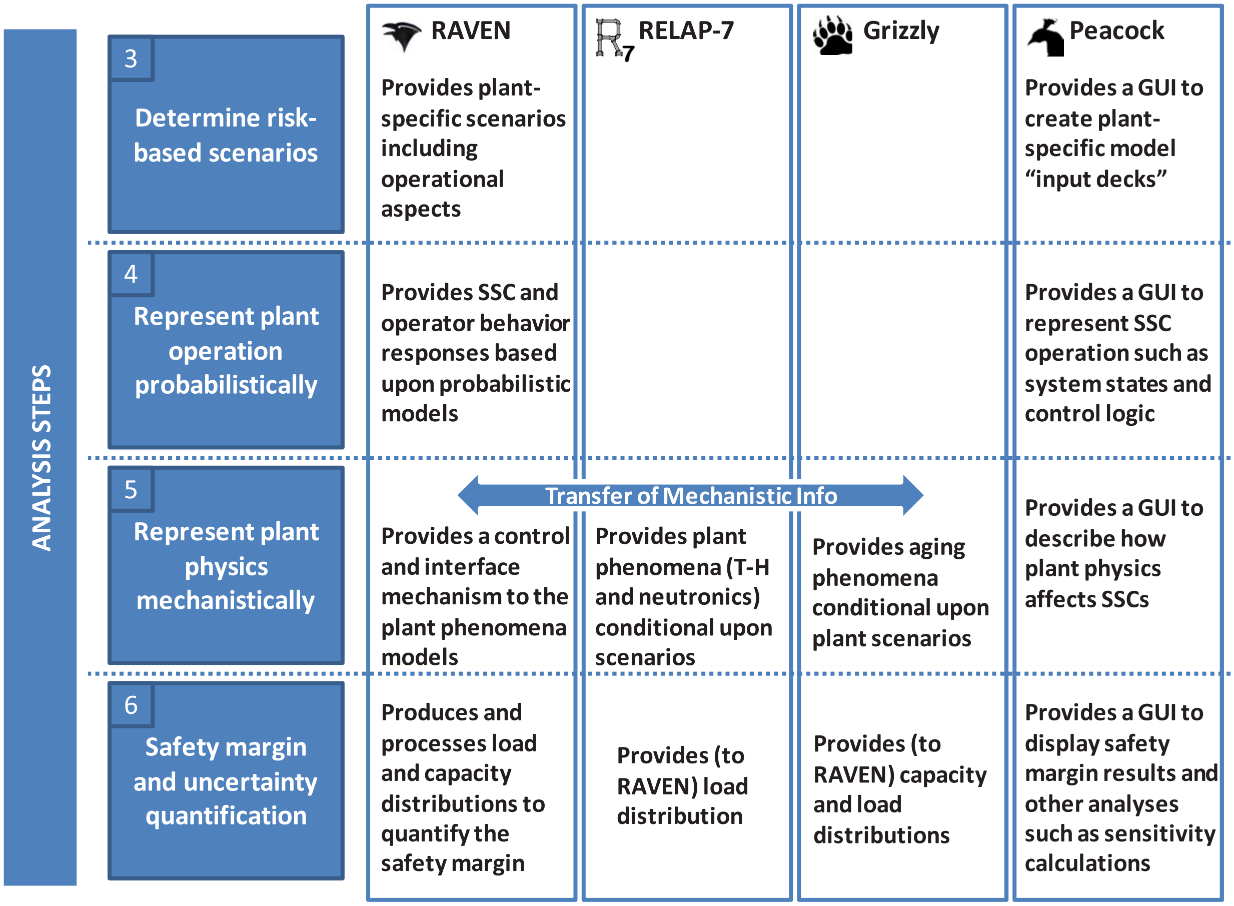

Figure 3-5. The RISMC Toolkit roles in the analysis steps.

3.2.1 RELAP-7

The next generation nuclear reactor system safety analysis code is RELAP-7. The code is based upon the INL's HPC development and runtime framework, MOOSE. RELAP-7 will become the main reactor systems simulation toolkit for LWRS/RISMC and the next generation tool in the RELAP reactor safety/systems analysis application series (the replacement for RELAP5). The design goal of RELAP-7 development is to leverage 30 years of advancements in software design, numerical integration methods, and physical models. Specifically, the RELAP-7 design is based upon:

- Modern Software Design:
  - ✓ Object-oriented C++ construction provided by the MOOSE framework
  - ✓ Designed to significantly reduce the expense and time of RELAP-7 development
  - ✓ Designed to be easily extended and maintain
  - ✓ Meets NQA-1 requirements

- Advanced Numerical Integration Methods:
  - ✓ Multi-scale time integration, PCICE (operator split), JFNK (implicit nonlinear Newton method), and a point implicit method (long duration transients)
  - ✓ New pipe network algorithm based upon Mortar FEM (Lagrange multipliers)
  - ✓ Ability to couple to multi-dimensional reactor simulators
- State-of-the-Art Physical Models:
  - ✓ All-speed, all-fluid (vapor-liquid, gas, liquid metal) flow
  - ✓ Well-posed 7-equation two-phase flow model
  - ✓ New reactor heat transfer model based upon fuels performance

RELAP-7 simulates behavior at the plant level with a level of fidelity that will support the analysis and decision-making necessary to economically and safely extend and enhance the operation of the current NPP fleet.

3.2.2 RAVEN

Based upon the MOOSE framework, RAVEN (Reactor Analysis and Virtual Control Environment) is a multi-tasking application focused on RELAP-7 simulation control, reactor plant control logic, reactor system analysis, uncertainty quantification, and performing probability risk assessments (PRA) for postulated events. RAVEN is being developed to drive RELAP-7 (and other MOOSE-based reactor applications) for which the following functional capabilities are provided:

- o Front end driver for RELAP-7:
  - ✓ Input a plant description to RELAP-7 (component, control variable, and control parameters)
  - ✓ Runtime environment
  - ✓ Parallel distribution of RELAP-7 runs (adaptive sampling)
- o Control logic required to:
  - ✓ Simulate the reactor plant control system
  - ✓ Simulate the reactor operator (procedure guided) actions
  - ✓ Perform Monte Carlo sampling of random distributed events
  - ✓ Perform event tree based analysis
- o Control of Graphical User Interface (GUI) to:
  - ✓ GUI capability provided by NiCE (NEAMS product) and Peacock (see below)
  - ✓ Concurrent monitoring of control parameters
  - ✓ Concurrent alteration of control parameters
- o Post Processing data mining capability based on:
  - ✓ Dimensionality reduction
  - ✓ Cardinality reduction
  - ✓ Uncertainty quantification and propagation

3.2.3 Grizzly

Grizzly is a MOOSE-based tool for simulating component ageing and damage evolution events for LWRS specific applications. Grizzly will in the future have implicit time simulation capabilities for component damage evolution concerning LWR pressure vessel, core internals, and concrete support and containment structures subjected to a neutron flux, corrosion, and high temperatures and pressures. Grizzly will heavily leverage the thermo-mechanics physics found in the BISON fuels performance application as a starting point. [Williamson et al, 2012] Grizzly will be able couple with RELAP-7 and RAVEN to provide aging analysis in support of the RISMC methodology.

3.2.4 Peacock

The Peacock software is a general Graphical User Interface (GUI) for MOOSE based applications. Peacock has been built in a very general fashion so to allow specialization of the GUI for different applications via an Application Programming Interface (API). The specialization of Peacock for RELAP-7/RAVEN allows both a graphical input of the RELAP 7 input file, online data visualization and is moving forward to provide a direct user control of the simulation and data mining capabilities in support of PRA analysis.

More in details, the underlining software infrastructure is built in PyQt. PyQt is an interface between python language and Qt. Qt is a GUI library in C++. These choice allow a quick deployment of new features while retaining a high level of reliability and flexibility.

The Peacock realization for RAVEN has four main tab: Input File, Execute, Postprocess, Visualize. A short description of each tabs is below reported:

- Input File – This option (Figure 3-6) provides the interface for creating the input for a typical PWR plant. On the far left a tree menu allows creating the input for each component of the plant as also for the general simulation setting. On the right the whole plant is pictured, components are shown as soon as added to the input. A last addiction to this visualization is the capability to access to the input description of a component already created selecting (double click) its visual representation.

- Execute – This is the windows running and monitoring the simulation. In the RAVEN specialization it shows buttons that open the capability to set up also the parameters for parallel sampling and parallel running of the simulation. The large central box is used to collect the input coming out directly from the simulation. For a single run this input is directly the RELAP-7 output while for multiple runs is the output from the RAVEN simulation control.

- Postprocess – This option is used to visualize every variable exported by the simulation in CVS format (comma separated value). The variable that could be exported in this format are: monitored, controlled, and auxiliaries.

- Visualize – This option (Figure 3-7) allows visualization of the RELAP-7 solution field while the simulation is running. The solution field (e.g. temperature, pressure, velocity) are projected on a plant like drawing and the time changes are visualized in movie fashion. The movie visualization allows to move to any point in time already simulated to re-examine the time evolution.

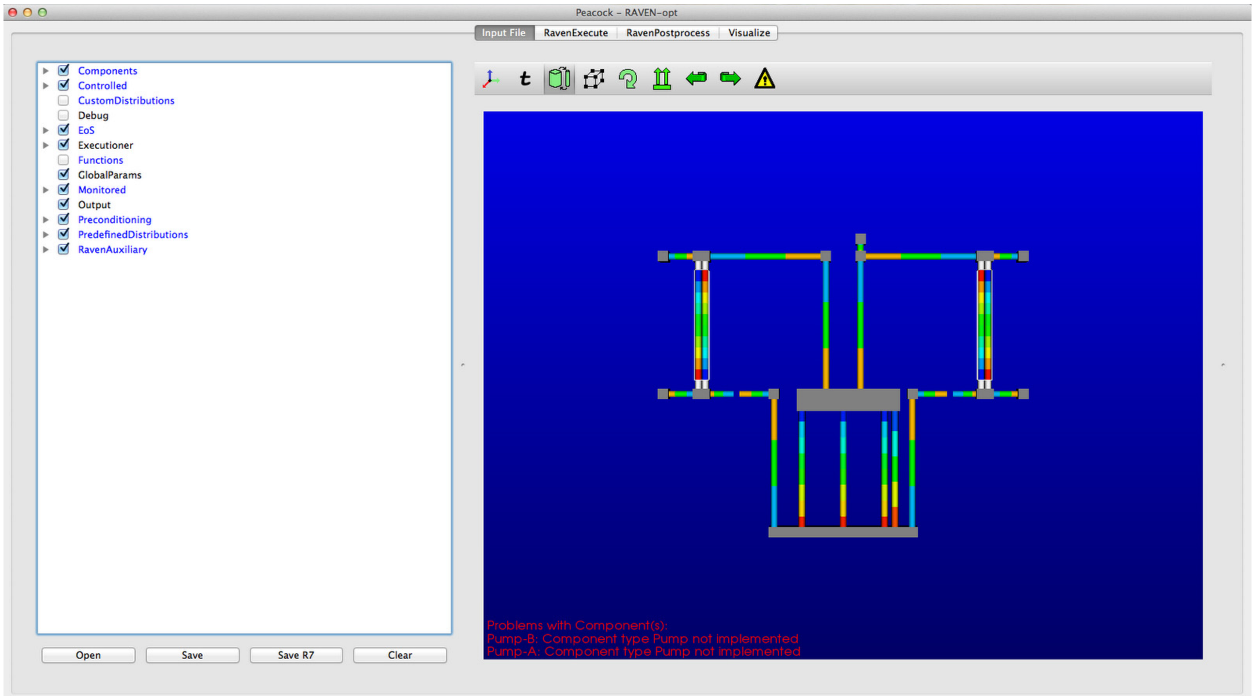

Figure 3-6. Representation of the Peacock graphical user interface for input.

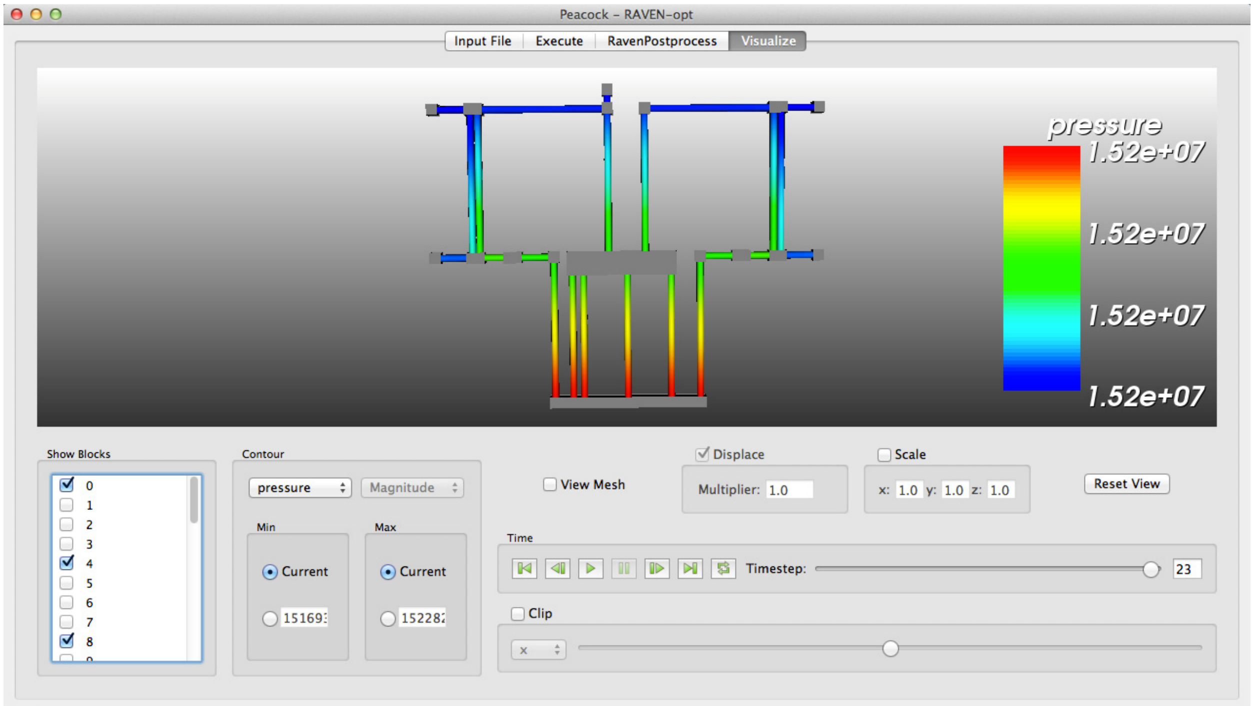

Figure 3-7. Representation of the Peacock results visualization

3.3 R&D Collaborations

3.3.1 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 (MOU) 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.

3.3.2 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.

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.

4. RESEARCH AND DEVELOPMENT COOPERATION

4.1 Nuclear Energy Advanced Modeling and Simulation.

A critical interaction of the LWRS Program is with the DOE Nuclear Energy Advanced Modeling and Simulation Program. The LWRS Program intends to take advantage of the detailed, multiscale, science-based modeling and simulation results developed by the DOE Nuclear Energy Advanced Modeling and Simulation 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.

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 Working Group 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 the case studies 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 BWR and PWR Owners Groups through information exchange and evaluations of specific topics via case studies.

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

- **Multilateral International Collaboration**: A variety of international researcher interactions are of potential interest to the 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 (NEA). One of the task groups in CSNI was focused on Safety Margin Applications and Assessment (SM2A). The Working Group on Risk Assessment (WGRISK) advances the understanding and use of PRA tools. The Working Group on Analysis and Management of Accidents (WGAMA) addresses safety analysis research including the uncertainty and sensitivity evaluation of best-estimate methods program. Various benchmarking activities are organized. Meetings are held twice a year in Paris in June and December. DOE (Rich Reister) is a member. Currently, RISMC has no collaborative projects with CSNI.

  - 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.

5. RESEARCH AND DEVELOPMENT PRODUCTS AND SCHEDULES

The RISMC Pathway will deliver the following products:

1. Technical Basis Guides for Risk-Informed Margins Management
2. Completion of the RISMC Toolkit

It has been agreed upon with industry that the focus in the near term will be on NPP case studies that specify a scope of phenomena, components, and simulation capabilities needed to address the given issue space. It is expected that development of the safety margins analysis techniques will be largely complete in 2013, including illustrations of margin characterization and methods for driving RELAP-7 to assess margin within the scope of initial case studies. Refinement of the associated methods and tools would continue thereafter at a reduced level of effort compared to the effort associated with RISMC Toolkit development.

In the first round of development, RELAP-7-compatible models of passive SSCs also will be created. As other pathways develop models and results to be input to margins assessments, they will be addressed beginning in the first round and continuing more intensively in the second and subsequent rounds. Application of test and operating data to RELAP-7 calibration and model testing will begin in the first round with data used to validate existing safety analysis codes. As newer data become available to address issues not covered by the old data, comparison with those data will support RELAP-7 refinement.

Assuming a funding profile commensurate with that in the current program plan, RELAP-7 development is expected to be substantially complete early in FY2015. This does not mean that RELAP-7 would be frozen as of FY2015, any more than previous-generation safety analysis codes have been frozen, but its development would be more evolutionary in nature.

Beginning in 2013 and continuing thereafter, increasing effort will be devoted to training a broader user community of practice and supporting their applications. As the development and capabilities of the RISMC Toolkit progresses, INL will collaborate with industry to determine how to transition tools such as RELAP-7 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:

FY2013

- Upgrade and document in a report the RELAP-7 capabilities through implementation of seven-equation two-phase flow model, including selected major physical components for BWR primary and safety systems. To support the planed demonstration case of the RISMC methodology studies (see below), this version will provide two-phase flow capabilities.

- Perform and document in a report the RELAP-7 simulation resolving a station blackout scenario on a simplified geometry of a BWR.

- Complete a partial-scope demonstration of RELAP-7 and RAVEN capabilities using the BWR station blackout case study, the industry-recommended case study for systems code development and methodology/ framework development.

- Demonstrate and document in a report the integration of reactor pipe network and components for two-phase flow model for ideal BWR reactor loop.

- Complete the Technical Basis Guide describing how to perform safety margin-based configuration risk management.

- Using the Grizzly tool, demonstrate and document in a report the modeling of late blooming phases and precipitation kinetics in aging reactor pressure vessel (RPV) steels.

FY2014

- Assess leading accident resistant fuel technologies to understand potential changes in safety margins that could be achieved by adoption of the technology using the RISMC methodology.

- Complete the software structure of the coupled RAVEN/RELAP-7 portion of the RISMC Toolkit.

- Demonstrate RISMC approach using LWR Case Study for Enhanced Accident Tolerance design changes using Risk-Informed Margins Management approaches.

- Demonstrate current margins analysis techniques on selected case studies using the completed software structure. The case studies will be selected in consultation with external stakeholders and will be chosen based on their potential to address an issue important to LWR sustainability and/or to achieve widespread stakeholder acceptance of the RISMC approach.

- Initial Grizzly development will be complete and version 1.0 will be finished

FY2015

- The margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including using RELAP-7/RAVEN/Grizzly (component aging module)/others (multiscale system analysis of plant performance, such as coupling to localized fuel behavior for a boiling water reactor station blackout and other defined LWR scenarios).

- RELAP-7 will be validated against an accepted set of data.

FY2016-2018

- Complete the Technical Basis Guides for Risk-Informed Margins Management.

- Complete a full-scope margins analysis of a commercial reactor power uprate scenario using RELAP-7/RAVEN. Use margins analysis techniques, including use of RELAP-7/RAVEN/Grizzly (component aging module)/others, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of life extension or assessment of the safety benefit of advanced fuel forms). Test cases will be chosen in consultation with external stakeholders.

- Validation and benchmarking of Grizzly for concrete aging will be completed.

FY2019-2020

- Ensure development and validation to the degree that by the end of 2020 RELAP-7 and the margins analysis techniques are the generally accepted approach for safety analysis support to plant decision-making, covering analysis of design-basis events and events within the technical scope of internal events 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:

1. RELAP-7 Development
2. RAVEN Development
3. RISMC Applications
4. EPRI Collaboration
5. Grizzly Development
6. QA and V&V of Tools
7. Code Maintenance
8. University and Regulatory Engagement

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
RISMC Management	Support routine project management activities and new program development tasks, report generation, travel, meetings, and benchmarking
RELAP-7 Development	(FY2013) Upgrade and document in a report the RELAP-7 capabilities through implementation of seven-equation two-phase flow model, including selected major physical components for BWR primary and safety systems. (FY2013) Perform and document in a report the RELAP-7 simulation resolving a station blackout scenario on a simplified geometry of a BWR. (FY2013) Demonstrate and document in a report the integration of reactor pipe network and components for two-phase flow model for ideal BWR reactor loop. (FY2014) Complete software structure, allowing rapid and scalable development. At this time, RELAP-7 can be fully controlled by RAVEN for complete systems analysis. RELAP-7/RAVEN will have the capability to be coupled to other applications (e.g., aging and fuel modules) and perform as a balance-of-plant capability for the multidimensional core simulators under development in other DOE programs such as CASL.
RAVEN Development	(FY2013) Demonstrate RELAP-7 capability to simulate boiling water reactor station blackout with the RAVEN system controller. (FY2014) Complete software structure, allowing rapid and scalable development. At this time, RELAP-7 can be fully controlled by RAVEN for complete system analysis. RELAP-7/RAVEN will have the capability to be coupled to other applications (e.g., aging and fuels modules) and perform as a balance-of-plant capability for the multidimensional core simulators under development in other DOE programs such as CASL.

Descriptive Activity Title	Activity Description and Major Deliverables
RISMC Applications	(FY2013) Complete a partial-scope demonstration of RELAP-7 and RAVEN capabilities using the BWR station blackout case study. (FY2013) Support the Fuels Pathway in an alternative selection case study. (FY2013) Complete the Technical Basis Guide describing how to perform safety margin-based configuration risk management. (FY2014) Demonstrate current margins analysis techniques on selected case studies using the completed software structure. The case studies will be selected in consultation with external stakeholders and will be chosen based on their potential to address an issue important to LWR sustainability and/or to achieve widespread stakeholder acceptance of the RISMC approach. Currently it is anticipated that this will apply RELAP-7/RAVEN to a margins evaluation of an extended power uprate on a BWR plant. (FY2015) The margins analysis techniques will be sufficiently mature to enable industry to conduct margins quantification exercises for their own plants, including using RELAP-7/RAVEN/Grizzly (component aging module)/others (multiscale system analysis of plant performance, such as coupling to localized fuel behavior for a boiling water reactor station blackout and other defined LWR scenarios). (FY2016) Complete full-scope analysis of a power uprate using RELAP-7/RAVEN (test case will be chosen in consultation with external stakeholders). In FY2016, use margins analysis techniques, including use of RELAP-7/RAVEN/Grizzly (component aging module)/others, to analyze an industry-important issue (e.g., assessment of major component degradation in the context of life extension or assessment of the safety benefit of advanced fuel forms). Test case will be chosen in consultation with external stakeholders.
EPRI Collaboration	(FY2013) Assist EPRI in application of Significant Determination Process (SDP) modeling (e.g., common-cause failure adjustments) and data. (FY2013) Assist EPRI in the boiling water reactor station blackout case study. (FY2014-2016) Assist EPRI in collaboration activities related to RISMC case studies and emergent issues.
Grizzly Development	(FY2013) Demonstrate and document in a report the modeling of late blooming phases and precipitation kinetics in aging reactor pressure vessel (RPV) steels. (FY2014) Initial development will be complete and version 1.0 will be finished.
QA and V&V of Tools	(FY2013) Deliver the RELAP-7 verification and validation plan. (FY2014) RELAP-7 validation underway. (FY2015) RELAP-7 will be validated against an accepted set of data. (FY2015) Validation and benchmarking of Grizzly will be conducted for reactor metal applications. (FY2016) Validation and benchmarking of Grizzly for concrete aging will be completed.
Code Maintenance	Support RISMC toolkit including bug fixes and minor updates.
University and Regulatory Engagement	Coordinate collaboration (e.g., IDPSA, NRC, Universities) activities.

5.3 Research and Development Activity Schedule

For each of the activities and deliverables identified in the previous section, we show the schedule including the start time in the respective FY and its duration in Figure 5-1 and Figure 5-2. Note that only activities from FY12 to FY16 are shown in the figure.

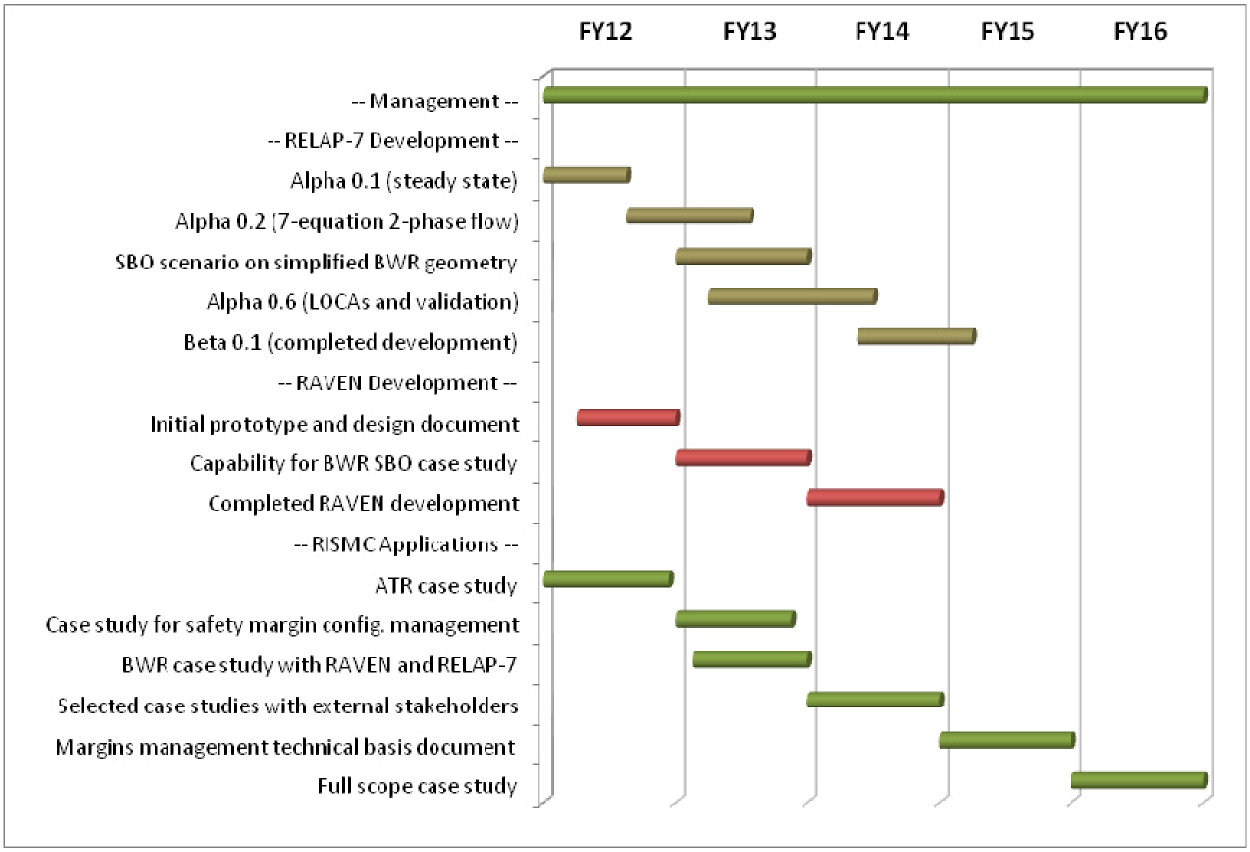

Figure 5-1. Activity schedule (priority activities 1-4).

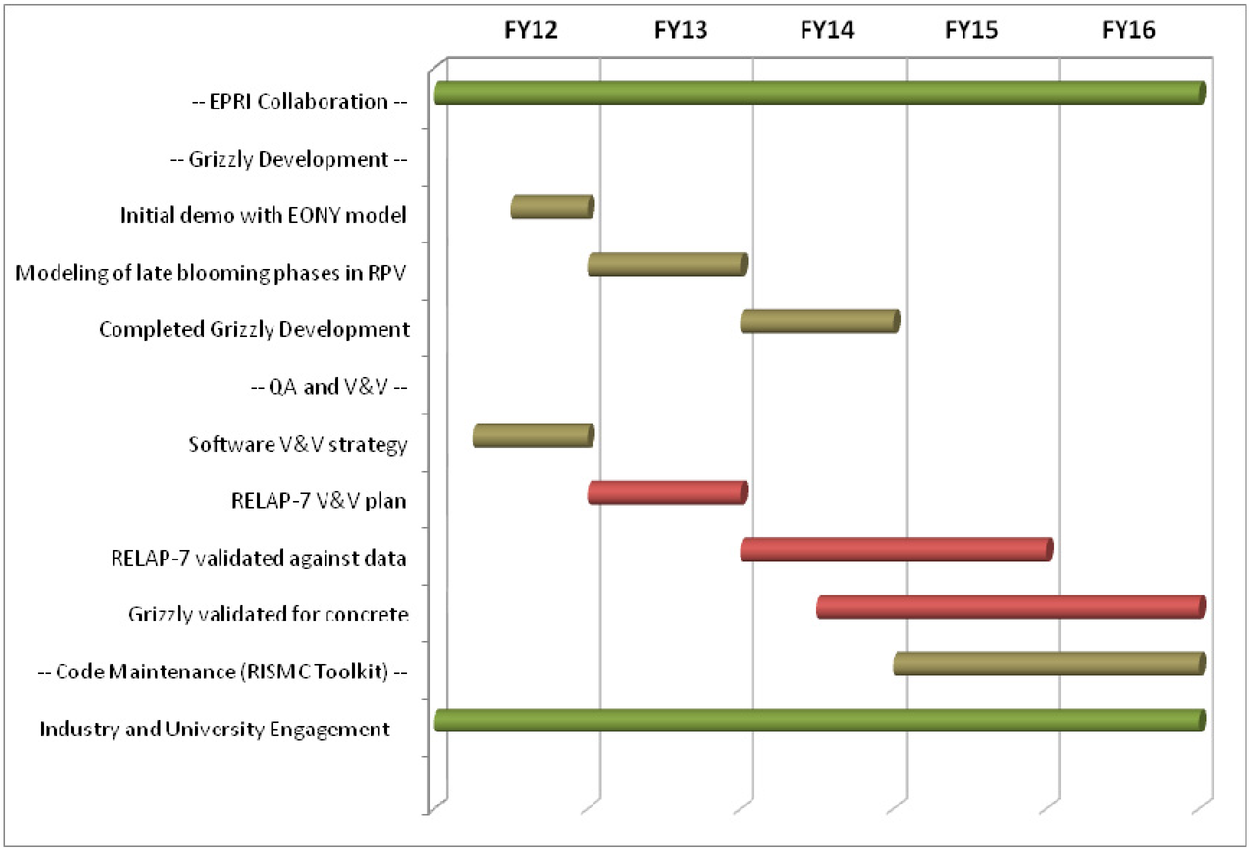

Figure 5-2. Activity schedule (priority activities 5-9).

6. REFERENCES

Bishop, P., & Bloomfield, R. (1998). *A Methodology for Safety Case Development*. Safety-Critical Systems Symposium. Birmingham, UK.

Frederick N. Gleicher II, Yaqi Wang, Derek Gaston, and Richard Martineau (2012). "The Method of Manufactured Solutions for Rattle$S_N$ake, A S_N Radiation Transport Solver Inside the MOOSE Framework," *Transactions of American Nuclear Society*, Vol. 106:1, p. 372 - 374.

Gaston, D., Hansen, G., & Newman, C. (2009). MOOSE: A Parallel Computational Framework for Coupled Systems for Nonlinear Equations. International Conference on Mathematics, *Computational Methods, and Reactor Physics*. Saratoga Springs, NY: American Nuclear Society.

Idaho National Laboratory (2012), *Light Water Reactor Sustainability Program Integrated Program Plan,* INL/EXT-11-23452, January.

US Nuclear Regulatory Commission (2011). Prioritization of Recommended Actions to be Taken in Response to Fukushima Lessons Learned, SECY-11-0137.

Williamson, R. L., J.D. Hales, S.R. Novascone, M.R. Tonks, D.R. Gaston, C.J. Permann, D. Andrs, and R.C. Martineau (2012). "Multidimensional Multiphysics Simulation of Nuclear Fuel Behavior," *Journal of Nuclear Materials*, Vol. 423, p. 149.

Youngblood, R. W. and C. L. Smith (2012), "On the Significance of the "Safety Case," submitted for publication in *Risk Analysis*.

Zio, E. (2009). "Reliability engineering: Old problems and new challenges." *Reliability Engineering and System Safety* , 94(2), 125-141.