INL/EXT-13-28974

Small Modular Reactor (SMR) Probabilistic Risk Assessment (PRA) Detailed Technical Framework Specification

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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

Idaho National Laboratory

INL/EXT-13-28974
April 2013

Small Modular Reactor (SMR) Probabilistic Risk Assessment (PRA) Detailed Technical Framework Specification

Describing the framework to support the implementation of a state-of-the-art PRA to predict the performance of safety, security, and safeguards of SMRs

Curtis Smith
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Chapter 1 Introduction

1.1 Background

A key area of the Small Modular Reactor (SMR) Probabilistic Risk Assessment (PRA) strategy is the development of methodologies and tools that will be used to predict the safety, security, safeguards, performance, and deployment viability of SMR systems starting in the design process through the operation phase. The **goal of the SMR PRA activity** will be to develop quantitative methods and tools and the associated analysis framework for assessing a variety of risks. These risks will be focused on SMR designs and operational strategies as they relate to the technical basis behind safety and security characterization.

Development and implementation of SMR-focused safety assessment methods may require new analytic methods or adaptation of traditional methods to the advanced design and operational features of SMRs. We will need to move beyond the current limitations such as static, logic-based models in order to provide more integrated, scenario-based models based upon predictive modeling which are tied to causal factors. The development of SMR-specific safety models for margin determination will provide a safety case that describes potential accidents, design options (including postulated controls), and supports licensing activities by providing a technical basis for the safety envelope.

For the next generation of nuclear power plants (NPPs), it is imperative that safety analysis technologies evolve into an accepted, encompassing, validated, and integral part of the plant in order to reduce costs and to demonstrate safe operation. Further, while it is presumed that safety margins are substantial for proposed SMR designs, the depiction, understanding, and quantification of these margins needs to be better understood in order to validate them and to optimize the licensing process. Currently, a variety of stated (and unstated) and substantiated (and unsubstantiated) assumptions have been made for SMR plant designs, including:

- Greater safety margins
- Smaller exclusions zone (the traditional zone is too large)
- Simpler emergency planning
- Reliance on passive safety systems
- Smaller and delayed source term
- Accident doses will be lower

These and other statements may be accurate, but they will need to be substantiated as part of a risk-informed approach. In this document, INL is proposing an approach to expand and advance the state-of-the-practice in PRA, specifically we will:

> *Develop a framework for applying modern computational tools to create advanced risk-based methods for identifying design vulnerabilities in SMRs. This framework will require the fusion of state-of-the-art PRA methods, advanced 3D visualization methods, and high-performance optimization within a flexible open source framework. An initial effort will be to define the conceptual framework and a draft implementation plan.*

It is the **purpose of this document** to support the development and planning for a framework for applying modern computational tools to create advanced risk-based methods for identifying design vulnerabilities in SMRs.

1.2 Needs

In order to support an optimized licensing process, we need a framework and process that will provide:

- Support for existing and near-term regulatory approaches (for example, the Nuclear Regulatory Commission (NRC) is pursuing a risk-informed review approach for SMRs where risk-insights will enhance the safety focus for reviews).
- Support for the development of methods and tools to predict safety margins.
- Support for a demonstration of quantitative safety margins for specific technologies and designs.

Ultimately, we will need an analysis approach to predict, via a safety case, the technical basis behind margins that impact performance measures such as safety, security, and safeguards (note that other performance measures such as economics are important, but are not the focus here). In addition, the methods and tools must be able to support a graded approach for a spectrum of short- and long-term applications.

The SMR PRA framework described in this document focuses on the support for computational approaches and tools that will be used to conduct analysis of security and safety performance of the various SMR technologies. As a part of this approach, the use of PRA will be explored, where security- and safety-related scenarios will be described via probabilistic models with the intent to support risk-informed decision making. In this framework, the following areas are considered:

- Use of probabilistic models to provide information specific to SMR-applicable performance metrics.
- Representation of specific SMR design issues such as having co-located modules and passive safety features.
- Use of modern open-source or readily available analysis methods and software to support the probabilistic modeling.
- Emergency planning and management, including source term evaluation.
- Internal and external events resulting in impacts to safety.
- All-hazards considerations including the reactor core, storage/movement of spent fuel, and hazardous gases.
- Risks that may be present during low-power and shutdown conditions.
- Methods to support the identification of design vulnerabilities.
- Mechanistic and probabilistic data needs to support the modeling and tools development effort.

Currently, the quantitative risk and reliability aspects of nuclear power plant (NPP) operation are vital parts of safety management within the industry. For example, this risk aspect is reflected in the design and licensing requirements of new NPPs and in the operation of current plants [e.g., the U.S. NRC's Maintenance Rule, 10 CFR 50.65, and the Significance

Determination Process]. But, the current regime for quantitative risk and reliability assessment utilizes tools and techniques that are, in some cases, over thirty years old and limited by their analysis capabilities. Further, in many cases the risk analysis methods, models, and assumptions are inherently tied to (and limited by) the current NPP designs. Consequently, researchers and practitioners in the risk and reliability sciences for NPPs have not been able to effectively use the advances in areas such as:

- Parallel and advanced computation techniques
- Dynamic simulation
- Aging-degradation models for materials
- Embedded systems and advanced sensors
- Virtual environments
- Human cognition modeling
- Information technologies
- Parameter data analysis

The framework outlined in this document addresses the formulation and development of a risk/reliability platform for advanced SMR safety analysis. Since the task of measuring and managing risk of any complex, technological system is a multi-disciplinary endeavor; the objectives outlined for this project necessarily encompass a variety of sciences. As such, we describe various tools and techniques, ranging from computer science to mechanistic engineering calculations, that will be required as part of an integrated SMR PRA approach.

1.3 Overview of the Proposed Framework

The proposed framework will lead to an advanced risk-informed safety management approach that will maintain adequate safety in SMR facilities. An effective risk-informed management approach is one that balances costs with safety as illustrated in Figure 1.

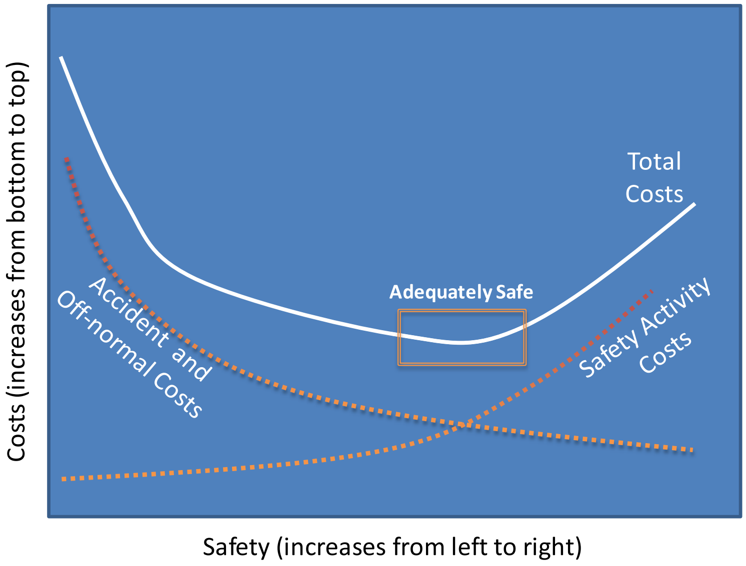

Figure 1. “Adequate safety” balances safety with the costs of too-much or too-few risk-informed activities.

The focus on risk-informed management provides a technical basis to understand and manage hazards. At a nuclear facility, a hazard is a condition that is or causes a deviation in the normal operation of something. Existence of a hazard implies that controls should be considered. Examples of the types of hazards that may exist (and will need to be represented) at a nuclear facility include different types of kinetic energy (e.g., motion from a seismic event) and potential energy (e.g., energy release during a chemical reaction). These types of hazards complicate the determination of safety in any complex facility. However, we propose to be able to measure (and thereby manage) these potential impacts to safety by developing the technology to incorporate physics (via probabilistic and mechanistic modeling) into SMR-specific scenarios. In addition, this risk-informed approach will be able to predict costs (such as those related to either off-normal or accident situations) in order to support safety decisions and assist in keeping a facility adequately safe.

In this proposal, the concept of a hazard precipitating a scenario is used to define the safety context. Adverse consequences occur when initiating events occur, system control responses (including operator actions) fail, and the consequence severity is not limited as well. Hazards may impinge on the system in several ways:

- They may provide enabling events (conditions that permit the scenario to proceed);
- They may affect the occurrence of initiating events (a departure from a desired operational envelope to a state where a control response is required);
- They may challenge system controls or safety functions;
- They may defeat mitigating systems.

The proposed advanced SMR PRA framework will focus on creating the risk-informed management approach to represent meaningful (i.e., realistic facility representation that is targeted to the metrics of interest) scenarios and consequences by using an advanced 3D SMR representation that will:

- Identify, model and analyze the appropriate physics (i.e., the physics that needs to be included to determine plant vulnerabilities) in an intelligent, scenario-based fashion.
- Manage the communication and interactions between different physics modeling and analysis technologies.
- Determine what facets of the problem are important for measuring and managing risk using this new application (which may require multiple safety metrics).
- Provide an analysis platform that can be used to "virtual stress-test" different risk-informed strategies.
- Integrate an ensemble of multiple physics models into a coherent predictive approach in order to best represent specific scenarios.
- Manage the computational infrastructure related to facility representation, scenario depiction, and physics prediction.
- Identify what behaviors the physics-models should simulate (i.e., hydrogen generation would be used to determine potential for deflagrations in containment; 3D particle tracking would be used to represent flooding impacts).

A notional depiction of these attributes of the proposed approach is shown in Figure 2 (focusing on just "motion" types of kinetic-energy hazards). The approach has several defining attributes focused within three general areas:

1. Models – A single 3D representation of all key systems, structures, and components (SSCs) will be defined for a particular facility. We will be able to simulate with these

models – by understanding how each SSC interacts with other parts of the facility (e.g., failure dependencies) – the hazard-induced susceptibilities of each SSC (e.g., energy from a seismic event may fail a component), and how to dial up model fidelity/resolution when needed (e.g., if flooding occurs in a room, the behavior of components related to water egress would become more important or enabled).

2. Phenomena – An approach to effectively representing hazards and their effect on physical behavior at a facility will need to be determined. In many cases, multiple models of a specific phenomenon may be available, but this ensemble of models will need to be intelligently managed. For example, how spatial effects may drive a scenario in an undesired fashion (e.g., a pipe break caused by a seismic event may flood a pump room) could be determined using several different methods – consequently we will need to be able to internally resolve and weight the variety of possible internal-analysis results.
3. Integration – Any advanced risk-informed decision support approach will rely on a variety of probabilistic and mechanistic information. The safety, security, and economic drivers will need to be integrated in order to determine the effectiveness of proposed mitigation strategies (e.g., should we install additional piping seismic restraints, should we install filtered vents on containment). We will need to be able to manage all (important) hazards for all (important) scenarios all of the time the facility is in operation.

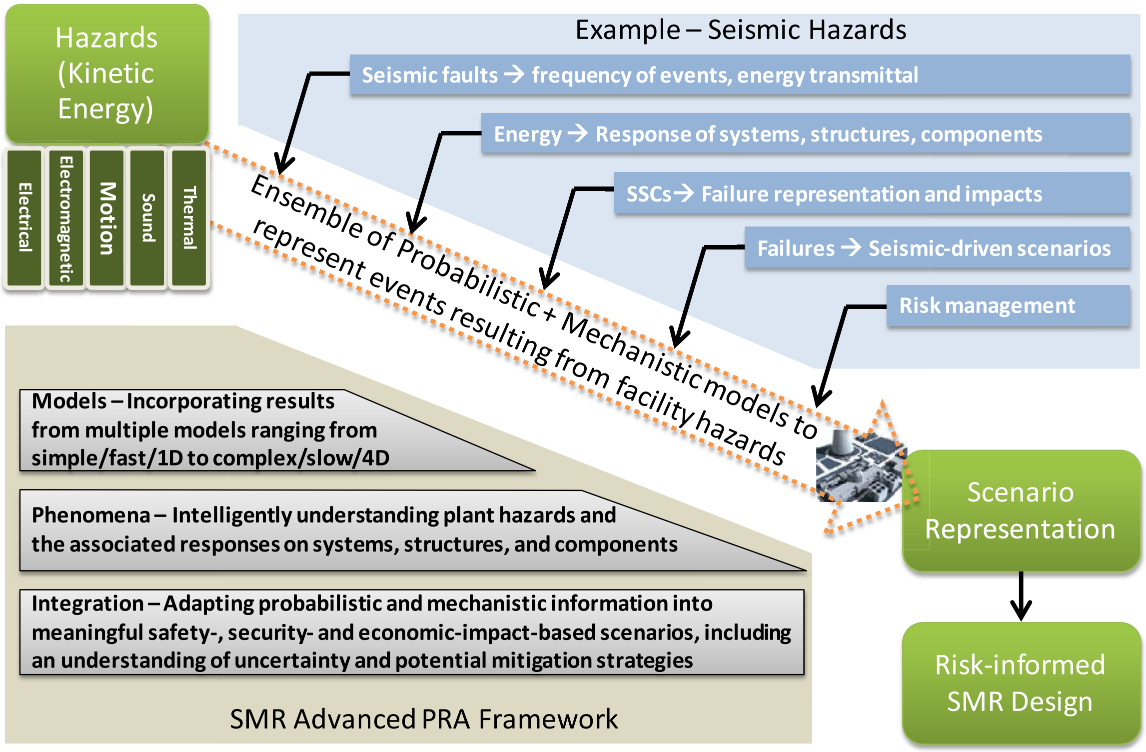

Figure 2. High-level features of the proposed advanced SMR PRA approach.

1.4 Benefits of the Proposed Approach

In later sections of this document, we describe the key parts and details of an enhanced PRA approach and toolkit. However, first we summarized the benefits of the proposed approach as compared to existing PRA methods and tools.

Capability	Existing PRA Limitations	Benefits of the Enhanced PRA
Simulation of Accident Scenarios	Limited treatment of dynamic sequence behavior (some discretization used, but this complicates modeling)	Able to capture timing considerations that may affect the safety margin and plant physical phenomena
Safety Margin Evaluation	Margin is not determined, instead discrete end states are decided upon during the model development	Safety margins will be determined directly by coupling mechanistic calculations with probabilistic calculations
Spatial Interactions	Very limited treatment of spatial interactions, mainly in select and simplistic flooding and fire models	Physics-based 3D environments will capture spatial interactions as part of accident scenarios
Failure Cause Representation	Traditionally, specific failure causes are rolled up into failure models such as fails-to-run or fails-to-start	A robust database of failure causes, mechanisms, and models will be plugged- into the component library such that analysts may pick-and-choose failure modes.
Cloud-based Creation, Analysis, and Storage of Safety Models	Traditionally, safety analysis has been performed by individual risk analysts (or a small team of analysts) with limited sharing and computational support	Multi-discipline, engineering focused teams will be able to share both models and computational resources in order to perform advanced analysis

Chapter
2

Analysis Framework

2.1 The General Modeling Approach

In order to enable probabilistic aspects of nuclear-based systems, we will be developing a variety of infrastructure methods/models **based upon simulation**. The INL has extensive capability in classical PRA, but for future applications, the proposed development is much superior to the static logic-based approaches used in existing accident risk analysis, in which simplifications and numerical approximations are necessary. Successfully linking probabilistic system simulation to system physics is a key facet of advanced SMR PRA methods and will directly address problems such as highly time-dependent scenarios in SMR risk analysis, where probability is a key aspect of the scenario.

Note that the science and engineering communities are increasingly moving to more sophisticated mechanistic models in order to better represent the complexities of "the real world." As part of this movement, we find an increasing reliance on or need for probabilistic approaches, including the elicitation of information. The use of probability concepts is needed to support the use of mechanistic models in a probabilistic world. Capturing what, why, and how one knows something related to science and engineering is important to realizing the potential of complex nuclear systems.

2.1.1 Safety Margins

In general terms, a "margin" is 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 failed 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**)].

The safety margin focus we need for advanced PRA activities must consider realistic "load" and "capacity" implications for operating NPPs for a large variety of scenarios. For example, the notional diagram shown in Figure 3 illustrates that a safety impact, as represented by a load distribution, is a complex function that varies from one 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 design elements such as fuel and material properties (which may be common across a spectrum of accidents).

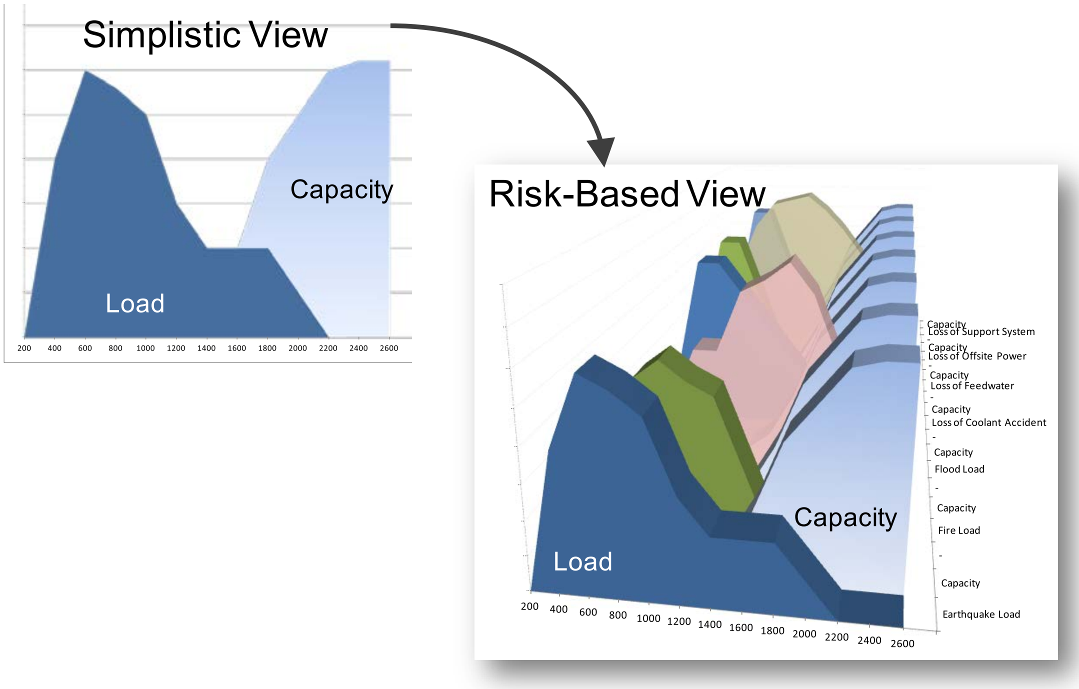

Figure 3. Family of load and capacity distributions representing different accident conditions.

2.1.2 Safety Margin Example

As an example of the type of results that are generated via probabilistic safety margins,[1] we show a simple hypothetical example in Figure 4. For this example, we suppose that a NPP has two alternatives to consider:

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

Using risk analysis methods and tools from the proposed framework, 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 – say 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 simulation results 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.

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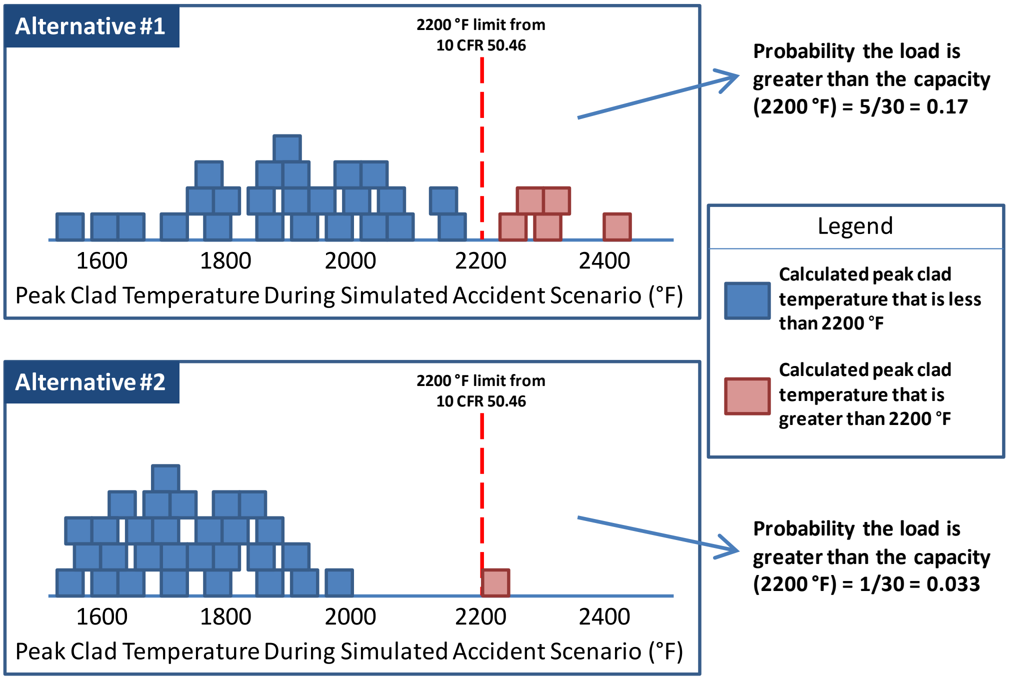
[1] A numerical value quantifying the probability that a key safety metric (e.g., for an important process variable such as clad temperature) will be exceeded under specified accident scenario conditions.



Probability the load is greater than the capacity (2200 °F) = 5/30 = 0.17

Probability the load is greater than the capacity (2200 °F) = 1/30 = 0.033

Figure 4. Safety margin example when evaluating changes to an SMR.

2.1.3 Types of Analysis to be used for the Safety Case

To better understand the approach to be used in the advanced SMR PRA approach, we need to describe the two types of analysis used (see Table 1). Note that in actual applications, a blended approach is used where both types of analysis are used to support any one particular decision. For example, the approach could be either mostly probabilistic, mostly mechanistic, or both in nature.

Table 1. Types of analysis that are used in an advanced PRA approach

Types of Analysis Supporting the Safety Case	
PROBABILISTIC	**MECHANISTIC**
Pertaining to stochastic (non-deterministic) events, the outcome of which is described by a probability.	**Pertaining to 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: $q = -k\partial T/\partial x$.**

The use of both types of analysis, probabilistic and mechanistic, is shown in Figure 5. Determining risk-based scenarios requires probabilistic considerations. Then, 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. These processes all support 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.*[2]

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[2] Bishop, P. and R. Bloomfield, "A Methodology for Safety Case Development," Safety-Critical Systems Symposium, Birmingham, UK. 1998.

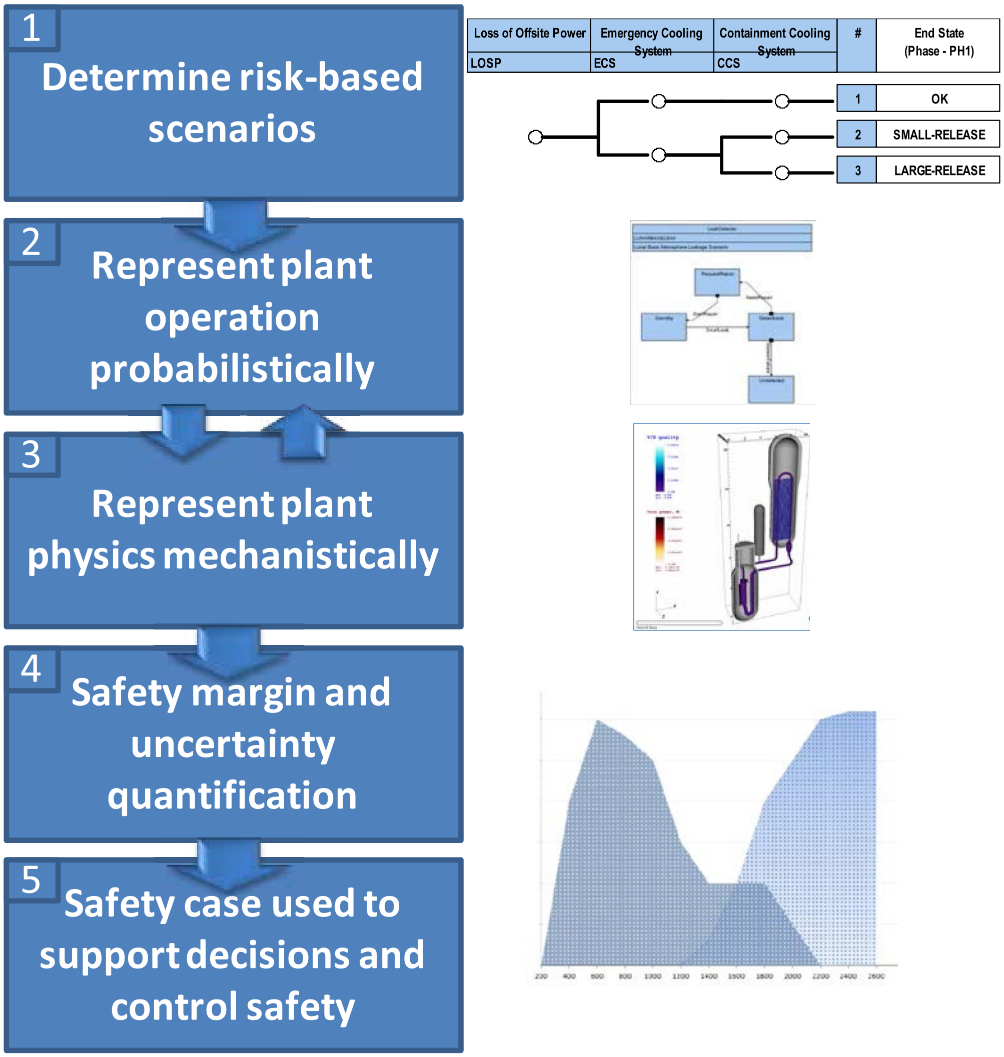

Figure 5. Attributes of the advanced PRA approach for supporting SMR decision-making.

The realization of a safety case will be an **output** of the SMR PRA framework. The safety-margin claims will do the following:

1. Make an explicit set of safety claims about the facility and SSCs
2. Produce evidence that supports the claims from #1 (e.g., representative operating history, redundancy in design, or results of analysis)
3. Provide a set of safety margin arguments that link the claims to the probabilistic and mechanistic evidence
4. Make clear the assumptions, models, data, and judgments underlying the arguments
5. Allow different viewpoints and levels of detail in a graded fashion for decision making.

The safety case 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., reactor core temperature). In decision-making regarding the facility or SSC, the safety case is, in practice, a proxy for the safety attribute. 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.

2.1.4 Proposed High-Level Architecture for the Advanced PRA Approach

The short description of the proposed approach is an Internet cloud-based PRA, where analysis modules (e.g., cut set solving of fault trees, simulation, mechanistic seismic calculations) are coupled to user-developed models in order to perform risk and vulnerability assessment. Since this approach uses Internet software advances, INL will be able to provide a scalable approach to PRA that is useable by a team of risk analysts – think of this as "the Google-Docs™" version of PRA.

The cloud-based PRA approach will allow for a well-controlled analysis process, whereby "process" we imply the seamless integration **of data + information + models + tools**. Features of this new approach to PRA would allow analysts to:

- Obtain the most current data (e.g., failure rates, CCF factors, etc.) and models from a single spot, including providing support for data-related queries (e.g., "what is the failure rate for a particular component," "show me the seismic events in Model X").

- Obtain the most current PRA models along with model revision information. If models are being updated or modified, they can be locked so no other changes can be performed on the same model (and changes can be tracked).

- Use centralized analysis tools to (via a browser) perform analysis such as a vulnerability search, determine component importance, or perform "what if" analyses similar to those done at the U.S. Nuclear Regulatory Commission as part of the Significance Determination Process. These analyses could be shared with associates and regulators on an as-needed (and read-only) basis, thereby alleviating the need to send multiple files/models between team members. This would streamline analysis and understanding and make sure everyone has access to the right information at the right time.

- Augment the existing analysis (e.g., SAPHIRE calculations) with additional tools/techniques such as Bayesian model checks and simulation. For example, we could embed Bayesian analysis as a wizard-like interface to allow for defensible inference calculations that support the safety case.

- Provide an easily accessible, but secure, repository for these kinds of risk-informed analysis so future generations of analysts, plant designers, and regulators can learn about best practices.

- Expand the power of safety analysis over current PRA approaches by providing increased functionality, faster decision-response times, less downtime (the model and tools are available anywhere), improved working environments (no longer needing to "install" software – the best version is always the available version), and an integrated collaboration with analysts.

- Provide access support to supercomputing resources, thereby bypassing the limitation of having to develop and run analysis on a single desktop computer.

The proposed SMR PRA framework will have specific features, including:

- **Import** → Ties to various modeling and analysis packages in an open-framework manner.

- **Access** → Access the model on- or off-line and be able to store copies locally and in the cloud.

- **Collaborate** → Modeling and analysis that is conducted and reviewed in teams of scientists and engineers.

- **Integrate** → Integrate model, data, and information in order to have a holistic risk analysis and to minimize the number of technical models in use.

- **Organize** → Finding the right information at the right time (for analysts, users, and reviewers).

- **Synchronize** → In order to keep everyone on the same page and up-to-date.

- **Share** → Communication for decision makers, where key insights and uncertainties in the safety case are provided.

- **Secure** → Security of information is both a safety and business issue.

- **Analysis** → Generating evidence for the safety case.

- **Verify** → Demonstrating satisfaction of safety goals and identifying plan vulnerabilities so that controls can be implemented.

A high-level depiction of the major modules that would be required in the cloud-based PRA approach is shown in Figure 6. As shown in the figure, analysts and reviewers would access the analysis tools and PRA models by using an Internet browser. The other modules provide the modeling and analysis capabilities for the user.

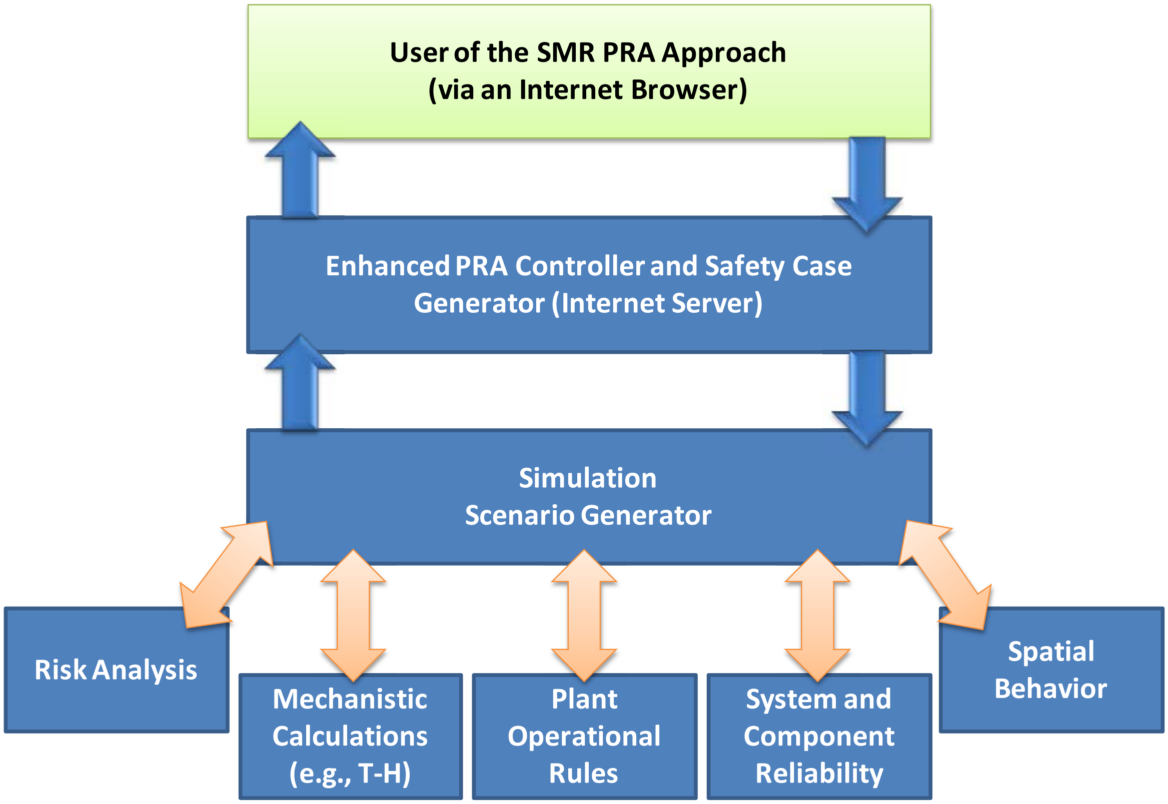

Figure 6. High-level architecture for the SMR advanced PRA framework.

The modules depicted above include:

- An overall PRA controller and module to produce (and store) the safety case. For each performance metric of consideration (e.g., peak clad temperature), this module will provide the time- and scenario-dependent results. These results (the "load") will be contrasted to the capacity in order to determine safety margins. Engineering insights will be derived based upon the scenario and associated outcomes (both load and capacity) and are used to document the safety case.

- Simulation for scenario generation. Individual SSCs will be simulated to determine their operability (or not) over time. Coupled to the scenario generator (which is a probabilistic calculation) will be a variety of mechanistic calculations as needed for the scenario.

- Risk analysis including system-level failure models such as simulation, event trees, and fault trees.

- Mechanistic calculations will be used as needed to determine impacts to safety margins. For example, during a seismic event, load and capacity responses to the ground motion may be used to determine component operability.

- Plant operational rules, for example, “rules” including operator procedures, technical specifications, maintenance schedules.

- Knowledge of plant physical properties including SSCs. These models represent component failure models – failure causes and associated info (failures on starting, failures to run, failure rates, etc.).

- Spatial behavior will be used to determine interactions within (and possibly between) the power plant being evaluated. For example, if a fire causes a pipe rupture, the flow of water will be tracked to determine other possible failures in the scenario.

- Uncertainty quantification of both model and parameter sensitivities and uncertainties will be evaluated as part of the overall approach.

2.1.5 Analysis Techniques for Scenarios and Safety Margins

One facet of the advanced PRA approach is to find vulnerabilities that affect margins. In general, a margins-analysis approach using simulation-based studies of safety follows the generic process steps:

1. Determine issue-specific, risk-based scenarios and accident timelines.

2. Represent plant operation probabilistically using the scenarios identified in Step 1.

3. Represent plant physics mechanistically.

4. Construct and quantify probabilistic load and capacity curves relating to safety to determine the safety margin.

5. Identify and characterize the factors and controls that determine safety margin within this issue to determine the safety case.

As we evaluate off-normal situations, the calculations that are required for plant simulation become more complex. For example, Figure 7 and Figure 8 show some of the types of probabilistic and mechanistic calculations (respectively) that would be required as part of the SMR PRA approach.

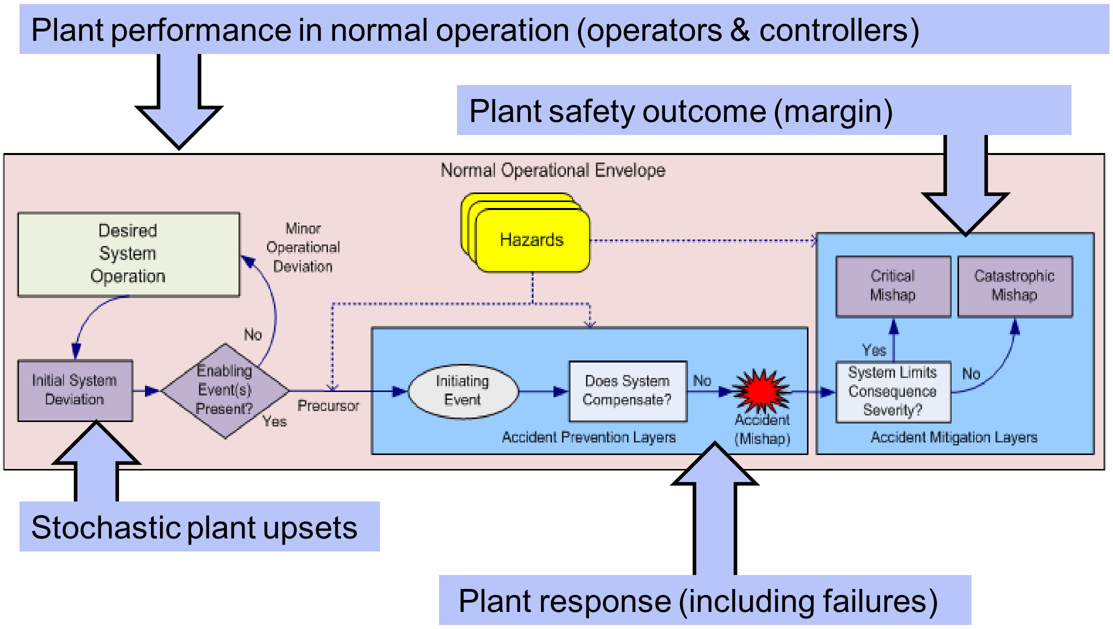

Figure 7. Characteristics of the accident scenario simulation for the probabilistic calculations.

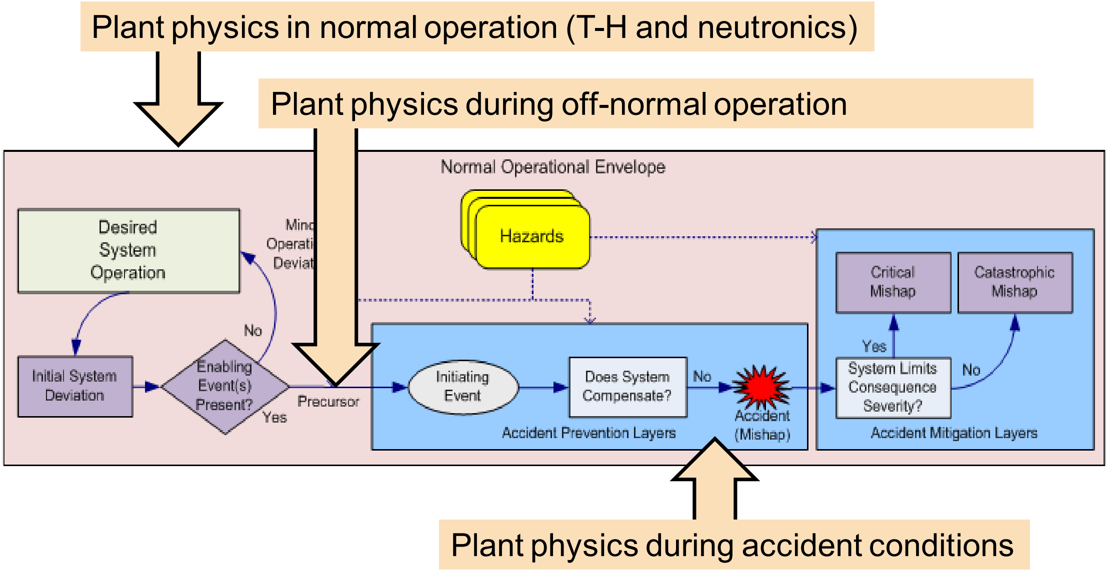

Figure 8. Characteristics of the accident scenario simulation for the mechanistic calculations.

As we simulate these accident scenarios depicted above, we will realize the need to simulate a large number of scenarios. Consequently, later in this report we also describe the required computational power – note that this computational power (while modest by “supercomputer” standards) will be able to be shared by many users since the cloud aspect of the PRA tool allows the computations to be centralized.

2.2 Modeling with Simulation

Since the SMR PRA approach is building upon existing PRA models such as fault trees, one question that may arise is why do we need to simulate failures and accident scenarios? The short answer is that we need to focus on safety margins, and in today's modern risk-informed analysis and operational environments, having accurate answers at the appropriate time is critical to having a defensibly safety case. Consequently, it is necessary for the SMR PRA approach to develop and use enhanced capabilities targeting accuracy and timeliness. The primary way to satisfy these targets is to use methods and tools related to simulation.

Simulation is a general modeling approach that can be used in many areas. However, simulation is more than just a methodology – using simulation approaches forces one to think holistically about complex system representations. Rather than focusing on how one can reduce a problem into a solution using existing approximate tools (like a fault tree), the evaluator is unencumbered and can, instead, focus on the problem (rather than the solution method). Consequently, simulation approaches can frequently provide relevant system insights that are simply not possible using older methods.

Further, simulation may be used to represent either mechanistic or probabilistic processes. For example, the analysis modules will include simulation to represent a variety of deterministic processes (e.g., fire environments, material damage, releases of material) during upset conditions. And, operability issues including reliability, risk, availability, maintainability, etc., have been evaluated using simulation in a variety of analysis-intensive private sector and government industries.

A common idiom is the phrase "the devil is in the details." While a cultural reference, this phrase is relevant when discussing capabilities targeting accuracy and timeliness. The conventional PRA approach (e.g., static logic-based models) is considered acceptable for answering select types of questions in select types of systems under select types of conditions. However, as industries such as nuclear power generation become more focused on risk-informed application, the nature of the questions change – sometimes dramatically. And the NPP types change, thereby complicating analysis being performed with outdated tools. Then, the details of these conventional approaches are raised in prominence, frequently to the dismay of decision makers when evaluating the safety case.

The details that are produced from simulation approaches have been criticized due to the analysis computational burden and the resulting volume of information that can be produced. While not readily apparent, we should view these criticisms as potentials for enhancing accuracy and timeliness. For example, the scenario detail that is obtained as part of simulation analysis may be (if we ask in the right way) viewed as providing information not just on failures (the typical question) but on degradations, operability issues, maintenance issues, and human performance. Further, these simulation information streams may be mined for positive aspects of performance (what works and why) since the bulk of these simulated realities will not result in undesired outcomes – the "insights" are in the details.

One insight from simulation would be the ability to evaluate different points in time where the SMR is considered to be safe. Current static event tree/fault tree approaches use a predetermined "mission time" (usually 24 hours) that dictates the cut-off for core damage or not. This limitation would be removed since the simulation is able to determine when (via physics) a safe condition has been reached and the simulation is stopped. This timing can have huge impacts when dealing with station blackout scenarios as demonstrated in the Fukushima accidents, which all occurred over extended (greater than 24 hours) periods of time.

While the static event-tree/fault-tree (ET/FT) approach has been used in the reliability modeling of systems for many years, numerous concerns have been raised about the capability of the ET/FT approach to handle dynamic and physical-based systems on a stand-alone basis. The ET/FT methodology does not treat the time-dependent interactions between physical processes and triggered or stochastic logical events as an accident evolves which may lead to coupling between these events through the control system. Even if these dynamic interactions are semi-quantitatively modeled through a classification of changes in process variables (e.g. "small", "moderate", "large), it may lead to the omission of some failure mechanisms due to inconsistencies in the definition of the allowed ranges for the process variables. Such limitations and inconsistencies of static PRA with respect to system dynamics would be particularly important for complex systems.

2.3 Physics-based Simulation

When simulating accident scenarios as part of a safety analysis, we will have the need of several physics-based simulations that must be run for one or more scenarios. A subset of these simulation modules might be run "offline" and their results stored in whatever format is native to that particular application. Alternatively, we may be able to translate these complicated mechanistic calculations into what are called “emulators” wherein the emulator mimics the more complicated analysis but is able to run orders of magnitude faster.

Let us describe a possible PRA scenario to better understand how physics-based simulation is used in the advanced PRA approach.

We construct a model representing the various structures at the SMR. Then, as part of the simulation, we are going to represent a seismic event (which occur stochastically and with different magnitudes) and look at implications to the on-site structures. For a given earthquake that is “produced” by the PRA, we query the results of the structural analysis (which could be a load-capacity calculation using stresses and strains, an emulator-based calculation, or detailed 3D energy transfer modeling) in order to interpret the calculation into a state such as “no damage,” “cracked,” or “disabled.”

The simulation then continues by translating the physics-based mechanistic calculation into an impact in the accident scenario. For example, if the structure is cracked, this state would be applied to the component in the model (perhaps it is a wall or a pipe) using another stochastic model (in this case, a cracking model). Once the component state is specified, then the scenario would continue since the cracked component may experience a dislocation (the crack grows) or further damage. If the component were a pipe containing water, then we might experience a flow out of the pipe at the point of the crack, which could be in a critical location in the SMR. The water outflow from the pipe would immediate result in two impacts:

- Reduced flow past the crack (possibly reducing heat transfer at the point where the water was originally needed)
- Possible spatially-related damage, depending on the location of the leaking water.

How we simulate these spatial types of interactions is through physics-based 3D environments that have been developed for industries such as visualization (e.g., movie special effects) and environment depictions (e.g., virtual reality). These 3D environments are capable of mimicking realistic physics such as flowing water and objects impacting other objects. For example, in the case of a pipe containing water, the environment model will know what the pipe material is, how fast it is going to impact items around it (if it cracks and breaks loose), its impact orientation, etc.

While the special interactions are being represented in the 3D environment, the accident scenario generator continues since water flowing from the leak may (later in time) fail collateral components (say a pump in the same room as the leaking pipe). At this point in the scenario, we are representing a flooding scenario (that was initiated by a seismic event). Further, there may be other components in that room that are sensitive to the leaking water, for example the pump motor controller which is an electronic component.

Note that this example scenario described above is just one possible outcome of the seismic event. However, it is the coupling of probabilistic and mechanistic calculations together that will, in the advanced SMR PRA, be able to search (automatically) for vulnerabilities. Further note that a variety of special-type scenarios may be modeled and represented in these advanced models, including fire propagation, physical damage, flooding, and seismic impacts. A variety of 3D physics toolkits are available, both commercially and through open source, and typically have features including:

- Discrete and continuous collision detection (to know when something hits something else)
- Solvers for rigid body dynamics (to mimic realistic movements)
- Fluid, particle, and character controllers (to represent fluids, movement of objects, and representation of people)
- Articulated mechanical dynamics (to represent complex components and systems)
- Fluids allow the simulation of liquids and gases using a particle system and emitters.
- Particle behavior permitting the simulation of explosions and debris effects

These types of environment modules will be able to be run as part of the cloud-based analysis server.

2.4 Modeling with Emulators

The SMR PRA framework discussion has identified attributes of the safety case that need to be considered in planning for development of SMR analysis capabilities. One overarching point is that a large volume of analysis is required; therefore, either an unprecedentedly fast and powerful analysis code will need to be developed, or a less fast but still powerful tool will be needed to underpin the development of one or more emulators for purposes discussed below. And, the development of the regulatory safety case is not the only driver of analysis – analyzing the performance case will also be important for SMRs.

When simulating accident scenarios as part of a safety analysis, we may have the need of several physics-based simulations that must be run for one or more scenarios. A subset of these simulation modules might be run “offline” and their results stored in whatever format is native to that particular application. Alternatively, we may be able to translate these complicated mechanistic calculations into what are called “emulators” wherein the emulator mimics the more complicated analysis but is able to run orders of magnitude faster. Note that a variety of emulators are available (from simple to complex).

By “emulator,” we mean a tool that mimics an analysis code by providing at least some of its key outputs, much more quickly than a code run, given a subset of the inputs to the full analysis code. Emulators have been used for generations, and better ones are still being developed. So-called “response surfaces” were being used in nuclear safety in the 70’s; since then, such things as neural nets and, more recently, Gaussian Process Models have been explored for application. The general idea is that one invests up front in doing enough code runs to characterize system response within an issue space, and “trains” the emulator with these results. Thereafter, one can get an estimate of system performance from the emulator without running the code itself, at a time savings that is enormous compared to the execution times of legacy codes. Emulators enable kinds of uncertainty quantification and vulnerability search that are essentially impractical with slow (traditional) codes.

2.5 How the Framework will Assist the Licensing Process

Details of future licensing processes are evolving, but it is clear that SMR licensing will require:

1. A scenario-based approach to demonstrate plant capabilities, including a considered selection of events to be analyzed and a graded approach to analyze those events;
2. Significant attention to uncertainty;
3. A PRA;
4. Resolution of SMR-specific technical issues;
5. Resolution of technology-specific issues;
6. Careful definition of system configurations and performance levels that need to be maintained during operation.

The **first** item above corresponds somewhat to the traditional safety analysis, but is formulated to allow for different technologies, and for certain lessons that have been learned in traditional licensing practice. In traditional licensing, selection of events to be analyzed has been partly prescribed. It is not generally clear what the limiting case is within a given issue space; many analyses need to be conducted in order to identify that limiting case. Results are not based on a single code run per design-basis event, but rather the whole suite of runs that were needed in order to establish which case was limiting.

The **second** item marks a departure from the past conservative, margin-based approach to finding “adequate protection” in design-basis events. In past licensing practice, uncertainty was dealt with by requiring a set of analysis assumptions and analysis conservatisms that are believed to compensate sufficiently for analysis uncertainties to allow a finding of satisfaction of regulatory acceptance criteria, if analysis results so indicate. A particular interest of SMRs is that for fundamental reasons, they are expected to have greater effective margin than traditional designs.

The **third** item, PRA for SMRs, reflects relatively new regulatory requirements on new reactors,[3] and from a purely technical point of view, would include items 1 and 2. If NRC endorses consensus standards that apply to a given SMR design, the norms implied by that standard will need to be addressed.

The **fourth** item corresponds to SMR-specific issues, especially issues that pertain to most, if not all, SMR designs. Certain issues have already been identified for SMRs generally, including multi-unit-site considerations: how siting will work, what the required staffing levels will be at multi-unit sites, and so on.

The **fifth** item corresponds to questions and issues relating to technologies that are qualitatively different from operating plants. This includes non-LWR SMR technologies, and could even include LWR SMRs sufficiently different from existing LWRs to call into question the applicability of existing rules. Passive system reliability falls into this category. SMRs will need to make exceptionally strong cases for passive system reliability, because SMRs achieve economy partly by not having certain active backup systems that the Westinghouse AP-1000 and ESBWR have.

The **sixth** item relates to the implementation of the safety case during operation. This point should apply generically to all plant types, but is remarked here because the SMR-specific and technology-specific considerations driving the fifth and sixth points will play out in operation through this sixth item.

2.5.1 Evolution of Licensing Practice

Reactor regulation has evolved significantly since most currently-operating plants were licensed. This has resulted partly from identification of weaknesses in traditional licensing and partly from improvements in modeling and analysis. As summarized below, further improvements are contemplated, even for the already-licensed technologies.

Since future licensing practice has not been determined yet, there are limits to what can be said about it. However, based on experience in many technologies including nuclear, there are reasons to expect certain basic features in any reasonable future process. It will be necessary to show that hazards have been considered systematically, and appropriate controls have been developed. This will be done through a scenario-based analysis, with careful attention to uncertainty.

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[3] 10 CFR Part 52 requires PRA in design certification, and already-operating plants were required to perform IPEs; in addition, there is in 10 CFR 50.71 a requirement on new plants to perform PRAs:

(h)(1) No later than the scheduled date for initial loading of fuel, each holder of a combined license under subpart C of 10 CFR part 52 shall develop a level 1 and a level 2 probabilistic risk assessment (PRA). The PRA must cover those initiating events and modes for which NRC-endorsed consensus standards on PRA exist one year prior to the scheduled date for initial loading of fuel. 50.71 h [continued]

(2) Each holder of a combined license shall maintain and upgrade the PRA required by paragraph (h)(1) of this section. The upgraded PRA must cover initiating events and modes of operation contained in NRC-endorsed consensus standards on PRA in effect one year prior to each required upgrade. The PRA must be upgraded every four years until the permanent cessation of operations under § 52.110(a) of this chapter.

(3) Each holder of a combined license shall, no later than the date on which the licensee submits an application for a renewed license, upgrade the PRA required by paragraph (h)(1) of this section to cover all modes and all initiating events.

NUREG-1860 presents a case for selecting the hazards based (at least in part) on risk analysis.[4] More recently (post-Fukushima), the NRC has issued a “Risk Management Task Force” report (NUREG-2150) containing the following:

The inclusion of a design-enhancement category in the United States would result in the following framework for design-basis and beyond-design-basis events:

- Design-basis Events
    - Normal operation
    - Anticipated operational occurrences
    - Design-basis accidents
    - Design-basis external hazards
- Beyond-design-basis Events
    - Design-enhancement events
        - Internal events
        - External hazards
    - Residual risk scenarios
        - Internal events
        - External hazards

Two key concepts related to the identification of relevant scenarios, categorization, and subsequent design features and operating limits are:

- The threshold to define when a scenario needs to be considered within a category.
- The acceptance criteria to define when a design feature or operating limit provides the desired protection from the defined scenario(s).

For present purposes, it is neither necessary nor appropriate to assume that all details of the above excerpt will govern SMR licensing. **But it is clear that while terminology and details may vary, explicit, scenario-based analysis of plant safety will play a key role, and significant emphasis will be placed on selection of events to be analyzed.** Consequently, the need for extensive analysis, and emulators, supporting the safety case will be paramount.

2.5.2 Analysis is a Key to Licensing

The technical case to be made for SMRs – licensing as well as economic – requires a great deal of analysis. The economic case may not immediately require a significant investment in emulation, but the novelty of SMR technology and the rigors of licensing will call for analysis that could benefit significantly from a carefully-formulated emulation capability.

- Even for existing plants, a lot of analysis is required (more than usually realized). For example, “safety analysis” may seem to be predicated on one code run per design basis event, but a lot of analysis went into identification of that limiting case. Even now, errors or omissions are occasionally found in the identification of limiting cases for operating plants.

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[4] Quote from NUREG-1860: “In the current regulatory approach, risk information and insights are used to supplement the deterministic-based structure. In the [NUREG-1860] Framework, the regulatory structure is established from the start integrating both deterministic and probabilistic information and insights.”

- Certain technology attributes of SMRs are potentially difficult to analyze. This is particularly true of “passive system” reliability.
- Certain SMR issues are new and call for new analysis. For example, multi-unit issues will need to be thought about carefully, and (according to some), the matter of sharing operators between SMR units needs careful thought as well. This will need sophisticated analysis of the scenario set.
- Finally, licensing is more demanding than it was when the old paradigm was established; even without Fukushima, the bar would arguably be higher, and with Fukushima, doubt on this point is removed.
- Deployment of SMRs in multiple-use contexts (e.g., making electricity and process heat, or making electricity in a situation that calls for load following) creates a class of analysis needs that current plants have not had to face.
- Moreover, given the inherent margin advantages that SMRs are believed to have, they arguably have an incentive to show that they can meet more stringent criteria.

In addition, the ability to call on analysis results in search algorithms will be hugely beneficial. This will help in:

- Deciding which events to analyze;
- Choosing the limiting case within a given issue space;
- Safety analysis;
- Analysis of plant performance.

2.6 Examples of the Proposed Software Architecture

In this section, we describe some of the tools and approaches that may be used as the backbone of an SMR PRA approach.

Software Module	Description	Maturity Level	Open Source?
SAPHIRE	Software to solve static cut set based logic models	**High**	No, the source is available for use at the INL
RELAP	Software to solve T-H conditions	**High**	No, the source is available for use at the INL
MySQL	Software to manage data storage in a full relational database	**High**	Yes
EMRALD	Software to solve reliability-based simulation models	**Low**	Yes
Jini	Software to develop distributed systems consisting of network services and clients.	**High**	Yes
WebGL	Software to display advanced a graphical 3D environment in an Internet browser	**High**	Yes
id Tech 4 Engine	Software to create and use a graphical 3D environment and physics engine	**High**	Yes
OpenBUGS	Software to perform Monte Carlo-based Bayesian updating	**Medium**	Yes

The cloud-based architecture of the advanced PRA allows for multiple, heterogeneous servers running custom tools developed in multiple languages and on various platforms. Figure 9 shows that each integrated server typically runs a single analysis tool. As shown in the figure, these tools do not talk directly to one another (unless needed), rather they communicate with a central hub. This hub is responsible for receiving and storing input data (in a modern relational database) and analysis requests from the client. It also transforms data from its stored format into a format required by an analysis. The analysis provides an output that the hub will then receive and store or possibly transform and pass to another analysis.

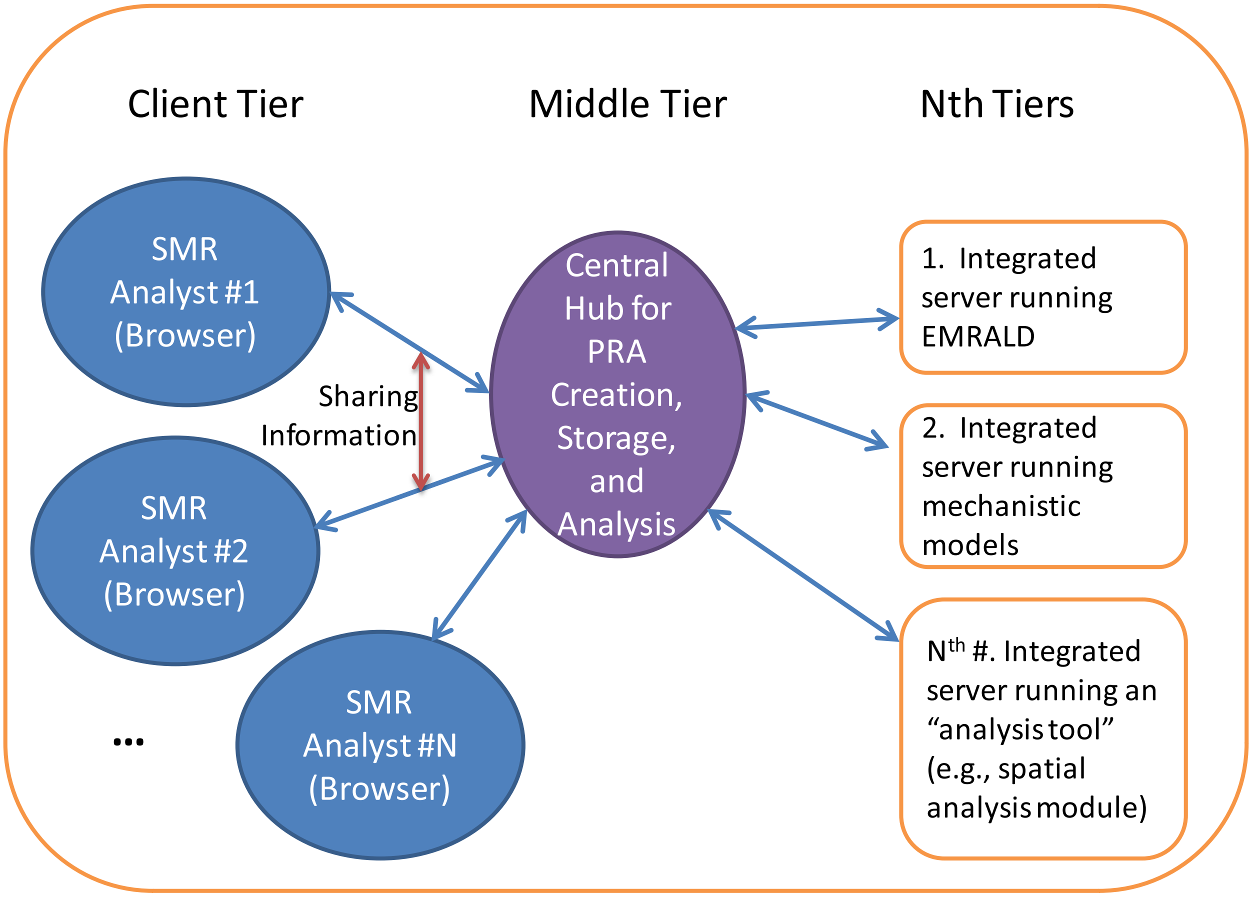


Figure 9. Schematic of the tiers of the cloud-based SMR PRA tool.

In order for these tools to communicate, each tool must define its required inputs and its possible outputs. For example, a seismic modeling tool may require an abstract equation representing the breaking point of a pipe and the magnitude of a given earthquake. The model then outputs at what point the pipe broke or perhaps that the pipe withstood the accident.

The output of the seismic model is passed to the central hub and stored as the result to be either returned to the user as the result or passed as input to another mechanistic or probabilistic module. Figure 10 provides an example of the transformations that might be performed for a segment of piping in a NPP in order to store the component in a relational database and display it in a 3D rendering environment (for example, using WebGL and the id Tech 4 engine). Then, in Figure 11, we show how that same component might also be associated with a mechanistic module to perform fluid flow calculations.

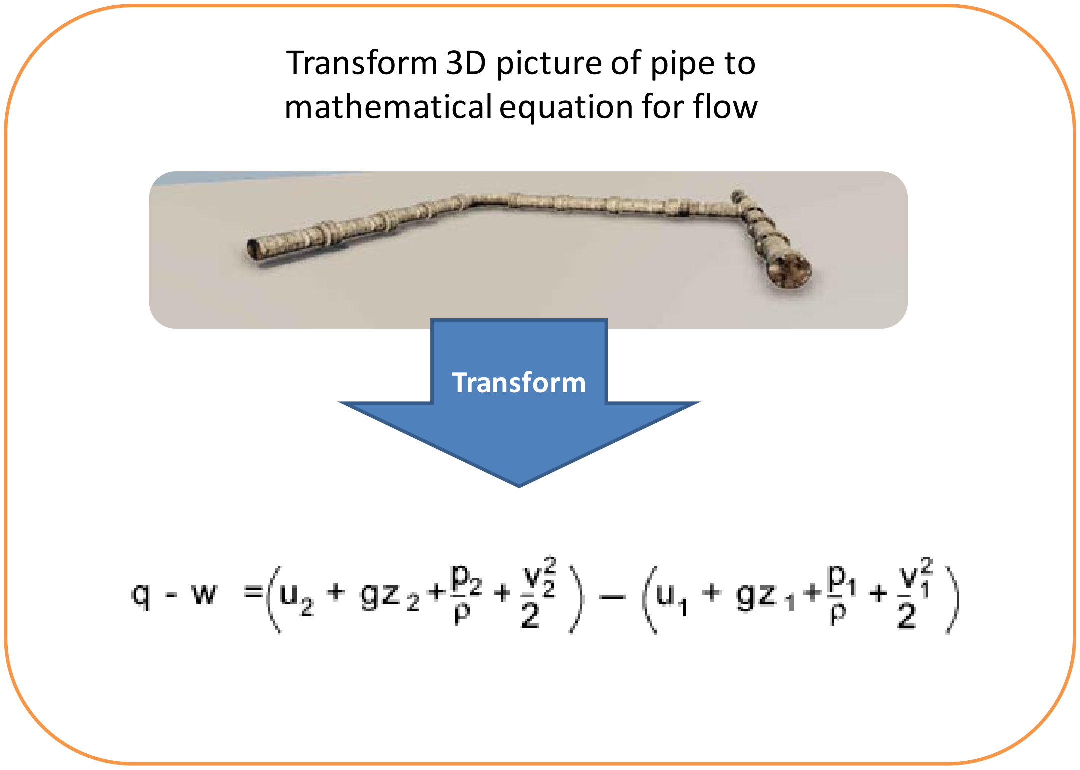
Transform 3D picture of pipe to XML representation.

Transform

Simplified XML representation:

```
<pipe>
  <material>
    <properties length = ‘22’ metal=‘iron’>
    </properties>
  </material>
</pipe>
```

Figure 10. Example of an abstraction and storage of a physical component (piping).



$$q - w = \left(u_2 + gz_2 + \frac{p_2}{\rho} + \frac{v_2^2}{2}\right) - \left(u_1 + gz_1 + \frac{p_1}{\rho} + \frac{v_1^2}{2}\right)$$

Figure 11. Example of the physical component (piping) coupled to an engineering flow model

The central hub of the cloud-based PRA approach must be developed with the ability to transform the results of one analysis into the required input format of another analysis. This transformation will require knowledge from the developers and/or subject matter experts of each of the individual tools to describe what the required inputs are, what format the inputs need to be in, what the output will be, and what format the output will be provided in for each module. However, once these are defined, they will be the same for all users of the tool.

Each analysis tool that participates in the system will have to provide this information about the input and output. Once the input and output of any system is known, a transformation can then be built to take the data as it exists and manipulate it into the form required by the receiving system. The output that the system provides can also be received and stored as it is provided or transformed to a format to be stored by the hub until it is needed to be provided to another system or as an output to the client.

One of the key items related to the advanced PRA will be in implementing the cloud-based framework. Fortunately, many application platforms are moving toward this approach and the quality and quantity of available software tools for development are rapidly increasing.

A cloud-based PRA software tool can be tied to the central hub shown in Figure 9. Since this software is linked to the central hub, the SSCs are directly tied together. To expand on the piping example above, one would take this pipe segment along with its hardware components (e.g., motor-operated valves, motor-driven pumps) and built-in physics models (e.g., aging or degradation models, physics-of-failure models) and link their failure modes and probabilities to a cloud-based logic model. This logic model will be linked to both the mechanistic models used for deterministic evaluations and probabilistic models used for risk assessment simulation. Once the model is developed using these cloud-based tools, it can be reviewed, updated, shared, extended, and analyzed in an efficient manner.

The cloud-based software tools will always contain the latest versions of the analysis methods along with the latest versions of the models. Since the latest version of the software and models will always be in place, the analysts will never be using outdated information nor be using analysis modules that have been updated. This cloud-based process will allow multiple users to access the models to review, make changes, or perform analyses. Revision tracking on the latest versions of the models will also provide information about the changes performed. Another important aspect of cloud-based software tools is the ability to collaborate between different operating system platforms (potentially any platform that can run an Internet browser).

Chapter 3

Implementation Plan

To implement the SMR PRA framework, the INL will focus on the development of computational approaches and tools that will be used to conduct analysis of safety performance of SMRs. As a part of this approach, the use of PRA will be explored, wherein safety-related scenarios will be described via different probabilistic models (e.g., fault trees, event trees, influence diagrams, simulation) with the intent to support risk-informed decision making.

Development and implementation of SMR PRA methods will require new analytic methods and adaptation of traditional methods to the new design and operational features of SMRs. As an example, PRA has been used to evaluate the safety of nuclear plants with respect to severe accident consequences, such as core damage. However, these current methods have seen little application related to modeling the margin of safety. As such, there is a need to move beyond the current limitations of static, logic-based models in order to provide more integrated, intelligent, scenario-based models based upon predictive modeling which are tied to causal factors. Understanding the causes that reduce safety margins will be the key to:

1. Developing engineering controls to effectively manage risks and
2. Demonstrating the technical basis of safety margins as part of the licensing phase.

An initial thrust of this program element will be for the construction of an overall analysis and modeling cloud-based framework that will be open for National Laboratories, DOE, NRC, and industry use in order to successfully demonstrate the technical basis related to safety margins. We will build this capability by focusing on available open-source tools coupled with existing PRA capabilities available at the INL.

The overall proposed approach is broken down into three phases.

- Phase 1 (Framework)
    - Addresses the development of the general technological framework for the SMR PRA concept (i.e., the "vision" document). This report completes Phase 1. Explanatory (for example, by describing analysis case studies) information that provides details of the Framework is presented in this chapter. Then, the specific features and requirements to implement the Framework are listed in Chapter 4.
- Phase 2 (Development)
    - Addresses the research and development required prior to trial implementation of the key modules that fit into the SRM PRA framework. Completion of this phase will result in
        - The technology evaluation and preliminary development of needed modules
        - The determination of the overall open framework supporting the operation of the concept
- Phase 3 (Demonstration)
    - Addresses the trial implementation of the SMR PRA concept demonstrating its usefulness as a design, decision, and optimization tool. Completion of this

phase will result in the implementation, testing, and trial application of the concept. Specific SMR case studies will be performed.

Phase 1 of the project provides the genesis of the detailed SMR PRA concept. Since this project is an evolution of current PRA practices, the formulation and understanding of the technological framework is vital to success of the overall project. Included in the formulation of the framework is consideration of supporting technologies that are currently available (e.g., 3D environments, multi-processor computers, open source software) and technologies that may mature within a short time period (e.g., voice-controlled software interfaces) that could be of use to the U.S. nuclear community.

Phase 2 of the project provides the beginnings of the implementation for the SMR PRA concept. Of particular concern during this phase of the project is in the behavior of the key modules with respect to global interactions with the advanced PRA environment. One of the drivers of the SMR PRA framework will be in the modularization of important parts of the supporting and analysis environment using the cloud-based approach. The work for Phase 2 is subdivided into two general tasks.

- Task 2.1, the selection of supporting SMR PRA modules, focuses on defining the framework and relevant technologies needed for integration into advanced PRA.

- Task 2.2, the prototype development of the SMR PRA modules, focuses on determining specific attributes operational characteristics for the key SMR PRA modules.

Phase 3 addresses the implementation and testing of the key supporting and analysis modules for the SMR PRA framework.

Details of implementation are described in the following sections.

3.1 Use of 3-D Physics Toolkits for PRA

In Section 2.3 we described how physics may be used to represent accident scenarios in a PRA framework. In this section we provide additional detail of this approach by way of a hypothetical example and discussion of the associated tools and methods.

First, assume a particular facility has seen an earthquake. We could simulate the occurrence of a specific size earthquake (e.g., as measured by peak acceleration) by stochastically sampling the frequency based upon seismic hazard curves. As an example, we show a typical hazard curve as produced by the US Geological Survey in Figure 12. (Frankel & al, 1996) Depending on the location of my hypothetical facility, the frequency of a 0.1 g earthquake ranges from 0.1/yr to less than 0.0001/yr.

For this example, we will assume that the facility is located in Memphis. A stochastic sample is produced that indicates that a 0.2 g earthquake will occur after 22.3 years of operation at the facility (note that this is a hypothetical example). At this point in the scenario simulation, we can tell (a) the size of the earthquake, and (b) when it will occur.

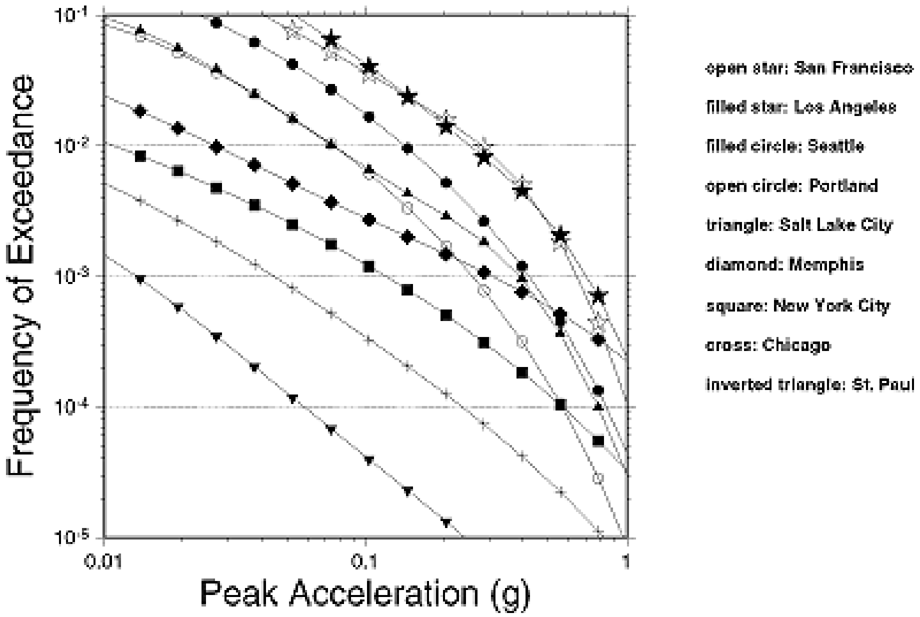
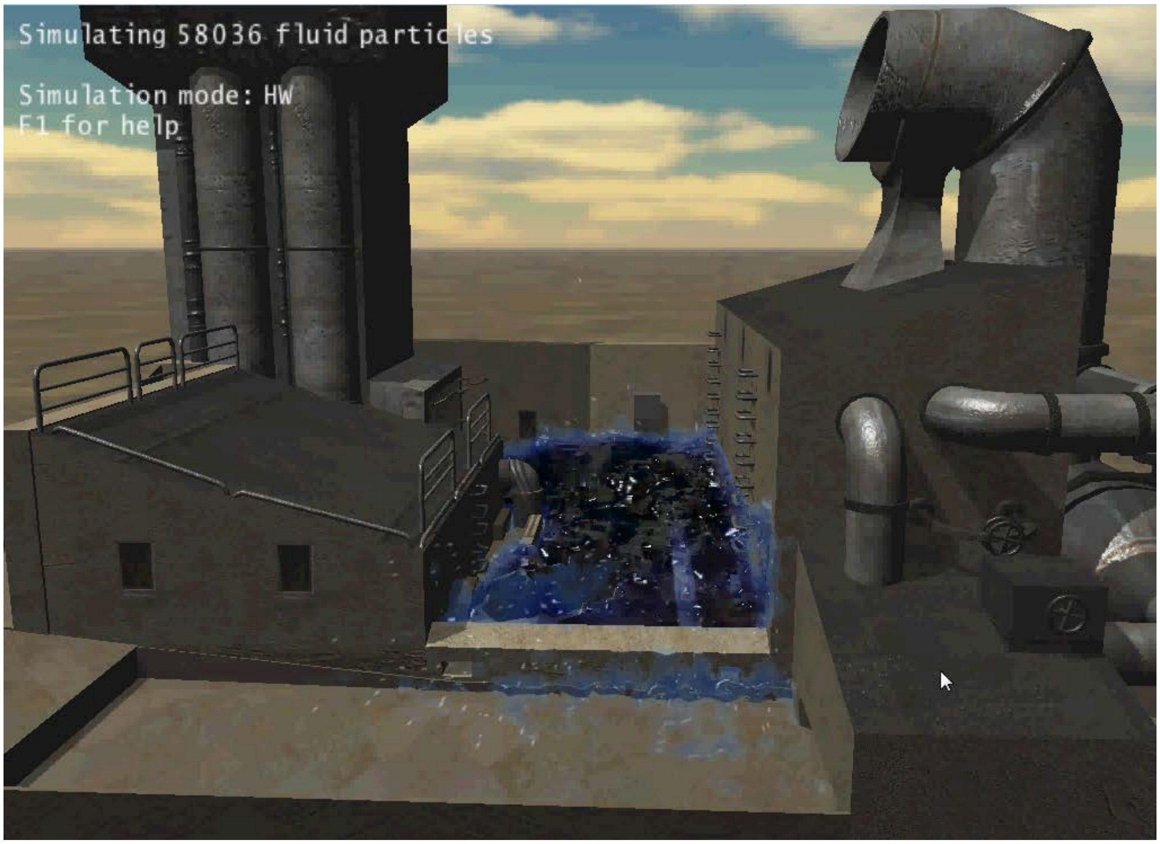


Figure 12. Seismic hazard curve produced by the USGS.

Following the arrival of the earthquake (at year 22.3 in the virtual facility), the power may be failed at the external pumping station for the facility. In this example, we assume that a portable diesel generator has been brought to the site and setup for the pumping station. As water fills the pool and the station operates (see Figure 13), a pipe facture caused by the earthquake causes water to spray out and hit the generator (see Figure 14). This water damage is detected by the simulation and reported to the PRA model. Note that this **entire scenario is produced and managed "on the fly" by the simulation 3D environment** – the scenario is not scripted a priori (unlike an event tree model where the scenario is described, generally at a higher level, by the analyst). Also note that the next simulation case for a similar type of earthquake will (most likely) produce a different set of outcomes. By running a large number of simulations, we can understand the behavior of the SMR facility and look for potential vulnerabilities.



```
Simulating 58036 fluid particles

Simulation mode: HW
F1 for help
```

Figure 13. Pumping station pool simulation showing the water physics.

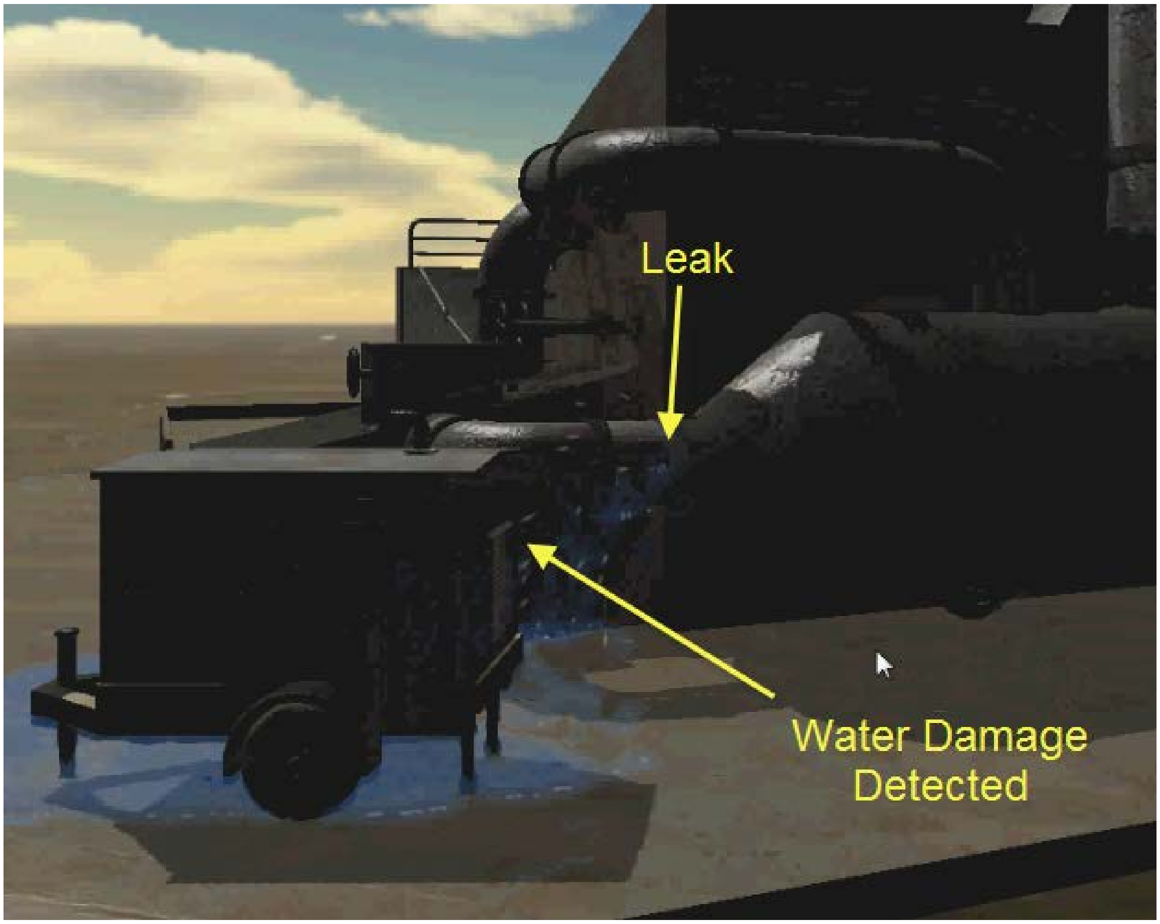


Figure 14. Leak and water damage detection by the simulation physics.

Through the advancement of 3D modeling and simulation, complex interactions between objects in advanced models can automatically be determined through calculated physics in real-time. These advancements give us the opportunity to rethink how we approach PRA. Instead of analysts having to think of both accident scenarios and the possible outcomes; they would only have to come up with the scenarios and then "see" the outcomes.

3.1.1 Simulation Progress

The advancement in 3D simulations to mimic the real world has mainly come about because of the computer software industry. Highly successful software started to incorporate small 3D aspects in the early 1990's. The success of these programs led to computer hardware assistance in 3D acceleration and became widely available in the mid-1990's. Graphics cards started incorporating better and more GPUs (Graphics Processing Unit) in order to deliver more realistic looking 3D images and physics. GPUs advanced into highly parallel processors customized to perform 3D rendering and lighting using pixel and vertex shading. (Wikipedia, 2013a) (Wikipedia, 2013b)

As the visual affects increased from fairly crude, blocky non-physics graphics, a desire for more realistic environmental behavior emerged. Companies developed software and hardware to do advanced-physics calculations in a highly-parallel fashion. Because these calculations greatly benefit from parallelization, separate hardware is generally needed to perform these simulations in real-time. Graphics cards became a natural fit and started incorporating the physics capabilities directly into their GPU processors. For example, PhysX was bought by the Nvidia corporation and runs on most currently-produced video cards. (Nvidia, 2013)

The advancement of real world physics in simulation engines has made it possible to mimic the physical interactive behavior of most things we see in everyday life. This includes things like gravity, collision reaction, light reflection, fluid movement, vapor behavior, and even pressure (for examples, see Figure 15 and Figure 16). These simulations engines that were originally designed for entertainment have and continue to open up many opportunities in various scientific fields of study, including safety analysis.

3.1.2 Project or System Modeling

The first step of SMR safety simulation would be to make, in the virtual environment, the system or item that is to be tested. This is a 3D model of the system or structure to be used in the simulation. This model would consist of many 3D components. Each component would have physical properties assigned to it or be made up of smaller components with properties assigned to them. These properties determine how it will interact with its environment. For example, its material density would determine if the item floated in water, or it could contain a fracturing structure to indicate if and how it may break upon collision of other items. The more detailed the model, the more accurate the simulation.

Ideally each component of an existing PRA would be modeled with the desired properties, such as the generator in the example in Section 3.1 above. This initial modeling can be an intensive process, however as the process continues, item or component libraries are developed. This would reduce most of the modeling to just combining many items from the library into a larger model with only hand constructing unique items. The final result could be all the components of a PRA model inside the infrastructure of a full SMR or just a section of the plant needed for a specific scenario.

There are many different modeling tools with a wide range of capabilities. For example, some have tools more tailored for nature modeling with many polygons and angles; another may focus on more simple manmade items like cars, buildings, or tools; others may focus on item properties and complex interactions. A few modeling environments include Unreal Development Kit, Blender, Maya, and 3D Studio Max.

Figure 15. Unreal Engine 4 elemental demo image.

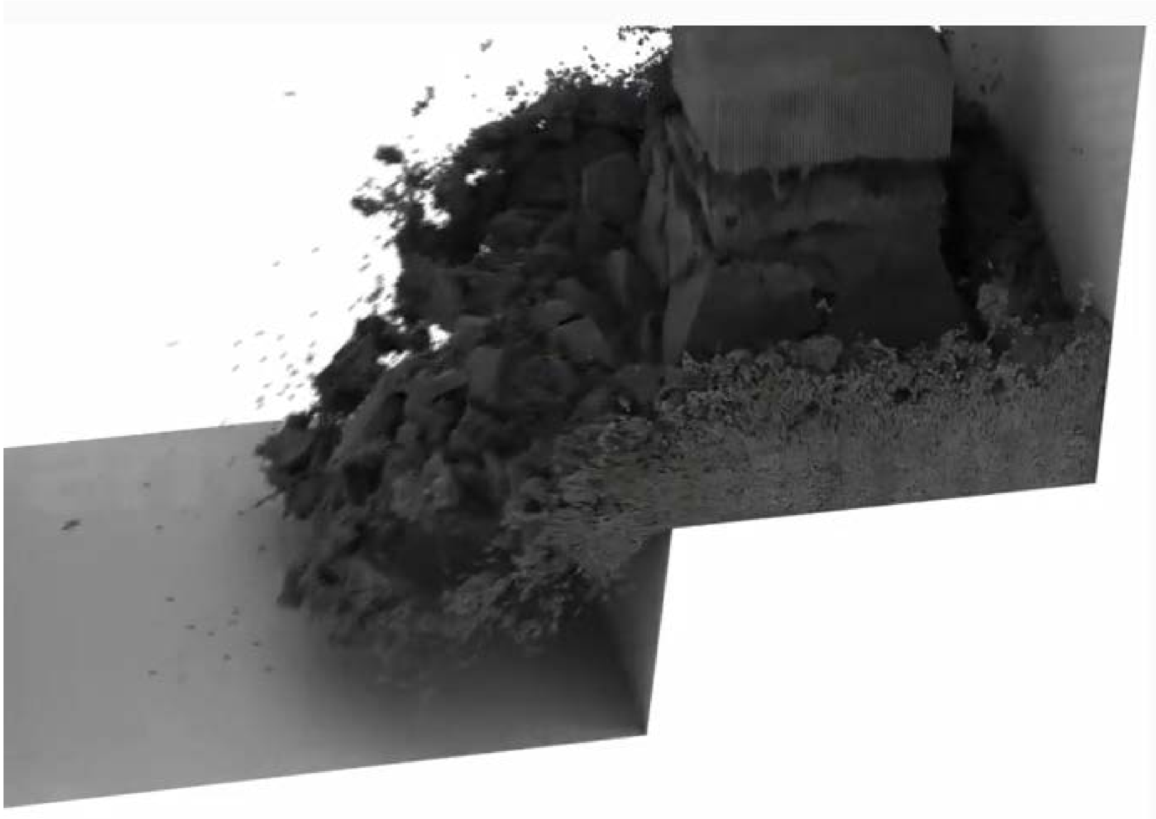


Figure 16. Sand block in Lagoa Multiphysics demo.

3.1.3 Scenario Models

A scenario is just a low-level model (e.g., a component) with active properties engaged with a larger model (e.g., the plant). Usually this model would be more simplistic and used in combination with a more complex model for running a simulation. For example, modeling a river with its flow set to increase 50% over a given period of time (say to represent a flood over the course of 36 hours) could represent the water rise – this result would then be coupled with an existing SMR structural model by placing it next to the river.

After a complex model with assigned physics is created, many scenario models can easily be created to test different analyst ideas. Flooding scenarios from failed dams, rising rivers, or tsunamis could be readily modeled. These scenarios would demonstrate how the water would flow against barriers and what compartments or equipment might be flooded. Models with high wind and debris could be made to test against other forces of nature.

Previous incidences could also be modeled to test the accuracy of modeling and give starting points for building variations on an existing knowledge base.

3.1.4 Simulation

A simulation is just the execution of a scenario and model combination in a physics engine. The simulation engine takes the entire model (simulation and model) and starts a time flow with all the simulated physical reactions that should take place (see Figure 17). For example, if there is nothing that interacts, then nothing will happen in the simulation. However, if an object is initially modeled at the top of a hill then it will start to move down the slope as soon as it is perturbed in the simulation.

Simulation capabilities are dependent on hardware. The better the hardware the more complex of a model it can simulate without external optimization. Dependent hardware is either the CPU or the GPU on the video card, depending on the physics engine and processor availability.

As with the modeling software, there are many simulation engines. Many are designed to work directly with or are part of the 3D modeling package. This makes it possible to keep modeling properties and engine capabilities up to date and compatible with each other. Different engines are also coding language dependent, if you want to interact with the model through code, you have to use the language that is compatible with that engine. For example, Blender’s engine requires Python for any code-based interaction while Unreal’s engine uses C++.

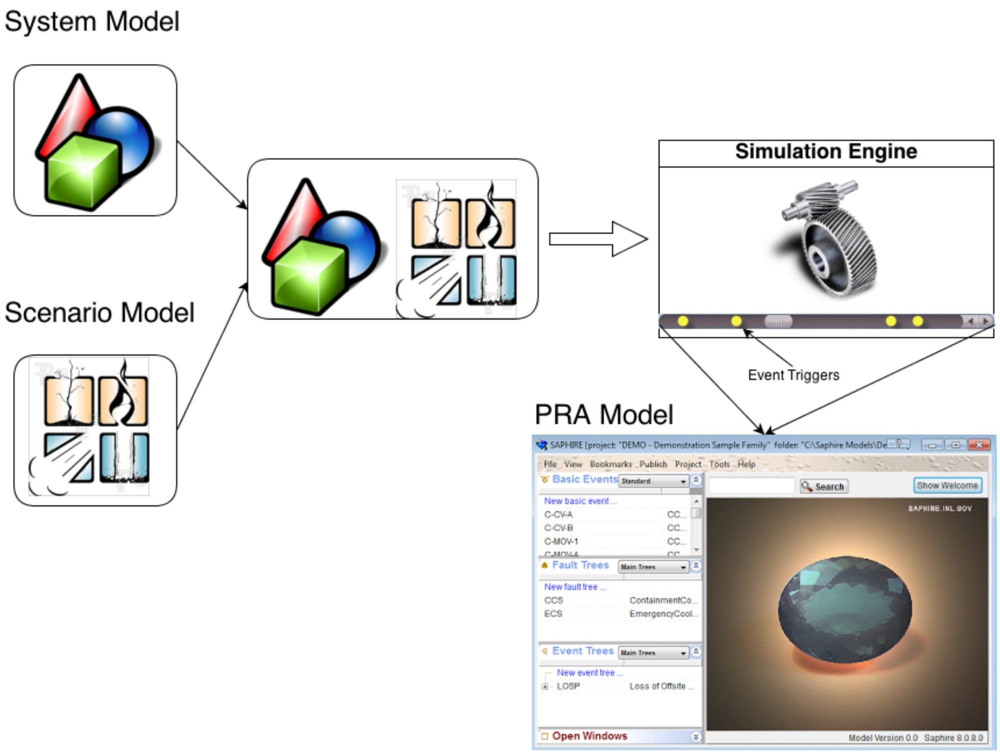


Figure 17. Flow of models for a simulation

The various 3D modeling engines also have varied physics capabilities. For example, some do not have particle emitters or some do not allow for reflective lighting. This also means that care must be taken to determine a physics engine that meets the needs for desired simulations – and perhaps an ensemble of models and physics engines may be needed to represent different kinds of scenarios.

We are fortunate that advanced physics engines are now able to model rain, fluid, and vapor movement. Wind for use in storms is simulated in a model using “forces” physics. Basic earthquake modeling can also be done through standard physics; however these would need to be coupled with more detailed energy-propagation models and physics-of-failure representation. Fire is usually simulated visually and not with true fire physics (e.g., no heat transfer), however improved physics is currently being tested and done in custom simulators. Incorporation of fire into standard engines should be soon coming. (Balci & Foroosh, 2006)

3.1.5 PRA Interaction

Software or code can interact or receive information from a physics engine simulation. Through this capability, PRA could know the occurrence of various events in the simulation. This is done through sensors or triggers placed in the model. For example, a trigger can be placed on an item for a collision, so if an item collides with it that trigger is activated (see Figure 18). The trigger activation sends a notification to the PRA software so that it can take appropriate action (e.g., fail a component that may impact other systems or trigger an alarm in a control room).

An item in the 3D model may represent a component of the PRA model, but a sensor or trigger may be attached to one or more basic events of the model. Also those sensors may trigger different basic events depending on the time of event. For example, sensing water on an electric valve may trigger (logically set the event to “true”) the valve’s basic event of ‘fails to open’ if the valve is currently closed, or it may trigger the ‘fails to close’ basic event if it is open at the time of the trigger.

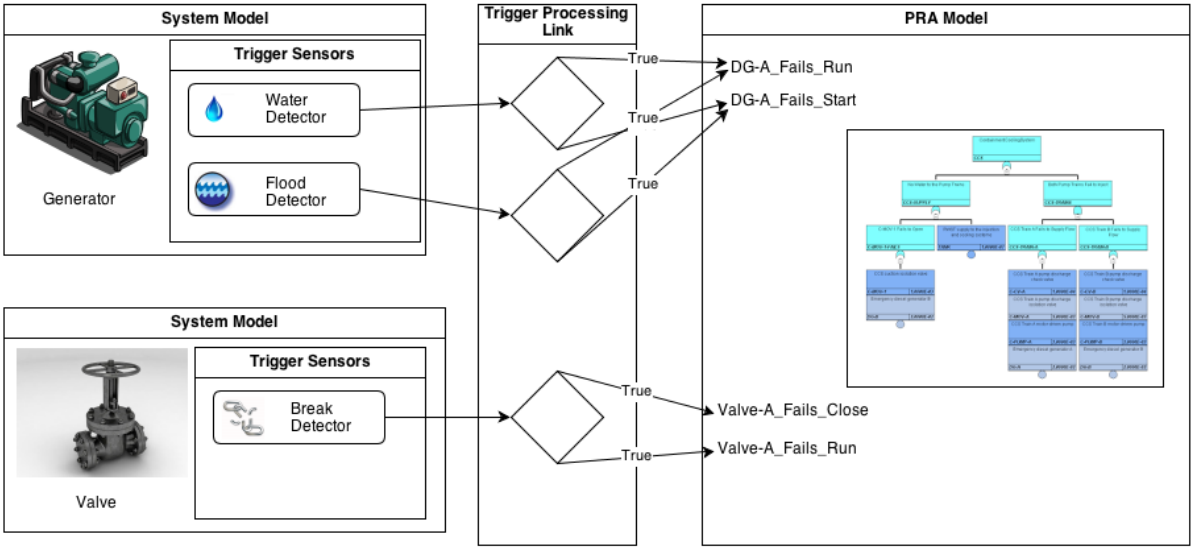


Figure 18. Correlation between assigned model trigger sensors and PRA Basic Events

By running the simulation with these time dependent interactions, an analyst could see not only what affects a scenario has on the plant, but the relative time relationship between the events.

3.1.6 Extended Possibilities of Physics Simulation

With advanced models and simulations, analysts would also have the ability to test better “What If” ideas. Take the portable generator example. If a mitigation action was needed, the analyst could test possible solutions. “What if we were to place a deflective cover over the electronics and air intake” versus “What if we require it to be no closer than ten feet to a water source?” This type of testing can help determine practical and effective designs or procedures.

Often in software development, a set of standard tests are performed before a version is released. This same principle could be applied to SMR design modifications. A set of standard scenarios (both design-basis and beyond design-basis types) could be established so that **any planned changes** could be modeled and ran against this set to see if they cause negative or positive safety repercussions.

Once the SMR PRA framework is completed, 3D models and the linking to a PRA model would exist – consequently we would have an interactive risk monitor and advanced training device. Physics engines provide a simple way for a user to interact with the environment by walking through it as a character (where this “character” could take on many different roles, an operator, maintenance person, an inspector). This interaction could be extended to affect the PRA model. A user could “enter” the 3D model and select components to modify – then they could see the safety changes. This would enable anyone familiar with the physical version of the SMR to easily see the ramifications of their modifications. Further, with the 3D model, simulated walkthroughs would be available. This feature could provide uses for training or disaster response needs.

3.2 Use of the Safety Margin Approach

Figure 19 shows the major elements of a probabilistic safety margin analysis. In general, when a facility experiences an initiating event, the scenario occurs based on the hazard and the corresponding safety systems that attempt to mitigate this hazard. The “load” will be mostly the same for many different scenarios – for example the decay heat load will be similar in all scenarios where the initial power level is at 100%. The “capacity” depends on the ability of the fuel and clad to withstand accident conditions and, consequently, will be mostly the same from one scenario to the next. Cases where we consider changes in fuel or clad would impact the capacity part of the plant’s safety margin.

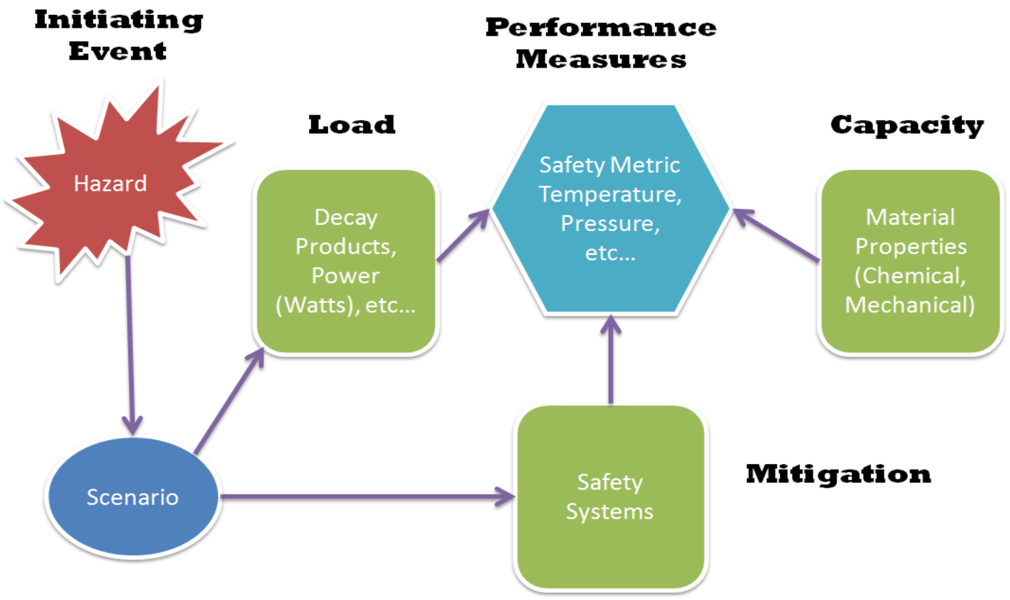


Figure 19. Elements of a safety margin analysis.

For example, consider that the capacity of an SMR may change due to increased durability of the fuel (perhaps an improved clad is being proposed). The 2200°F limit that exists for current light water reactor fuels may, in this case, increase to 2400°F. Figure 20 illustrates a hypothetical alternate fuel (Alternative #2) with a different cladding material. This cladding material creates more heat on its surface, perhaps through chemical reactions; however it has a higher capacity before failure (2400°F). The increase in load and capacity has an end result similar to the illustration in Figure 4 even though the peak cladding temperatures are generally higher in this example.

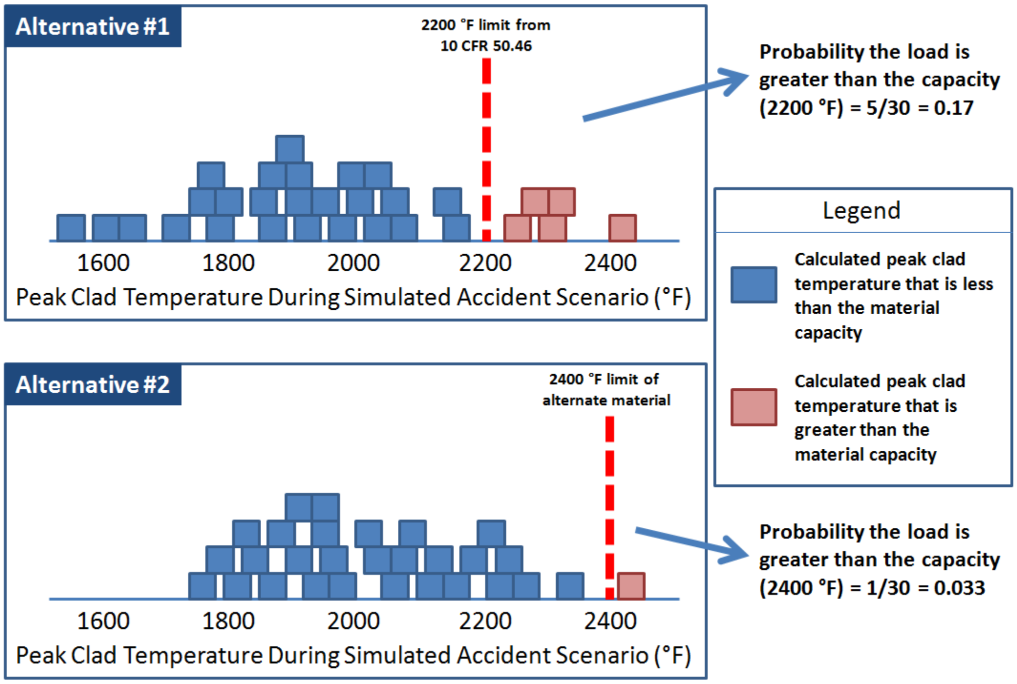


Figure 20. Safety margin example when evaluating changes to an SMR using materials with different capacities and performance.

Other loads may need to be considered as well, such as pressure, vibration, thermal shock on a blow-down, etc., all of which challenge the capacity of the component in consideration for each load. The physics of these would be accounted for via different physics models.

In order to quantify the initial condition of the component prior to subjecting it to an accident scenario simulation, it requires simulations run using normal operational parameters to estimate the wear on the component. From these thermo-hydraulic analyses, we can determine the percentage of cracks in a coating or the amount of material worn due to fretting from vibrating at normal operational flows. For instance, simulations for fuels can hold the burn-up constant, quantifying what state the proposed component will be in at the end of the fuel burn-up life. Alternately, a maximum usage time to maintain safety margins can be characterized based on the condition of the materials through simulation.

3.3 Bayesian Modeling for Extreme Events

One unique aspect proposed in the design of the advance PRA approach for SMRs is the ability to directly represent external event scenarios. A key part of these types of scenarios is represented by the ability to model and quantify the initiating event portion of the off-normal event. In this section, we describe details of the proposed approach to represent the initiating event frequency and magnitude by way of Bayesian modeling. The hypothetical example in this section focuses on rainfall events, but is applicable to other types of situations.

The analysis in this example provides an inference process related to severe rainfall events around a specific location (e.g., a plant site near a major river). The probable maximum precipitation (PMP) for many facilities is defined as a specified duration storm (say, for example, 4 days) that drops a large quantity of rain (say, for example, 7 inches). In addition, some of these PMP events are represented as this first storm followed by a later storm, thereby acerbating the scenario due to the ground saturation from the first storm. For example, a PMP representative event may be the first 4-day storm, and then a 2-day break and then another 3-day storm that drops a large quantity of rain.

The preferred approach to modeling these types of initiating events assumed that the two storms are not independent (e.g., a hurricane or a large storm system sits on top of the plant site for a period of time). For this rainfall, we will assess the frequency of 7” + 16” or 23” of rain falling in the 9 day window.

Information on rain storms is available from organizations such as the National Oceanic and Atmospheric Administration (NOAA). For example, we collected information for a particular area of the U.S from the publically-available Precipitation Frequency Data Server. (NOAA, 2013) This information is reproduced below in Table 2. For the analysis, we were assuming a maximum of a 9-day window. Consequently, we produced values for a 9-day window based upon interpolation between 7- and 10-day windows for each average recurrence interval.

Table 2. NOAA precipitation frequencies (example).

Window	**Average Recurrence interval (years)**									
(days)	**1**	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
1	**2.96**	**3.53**	**4.31**	**4.91**	**5.74**	**6.4**	**7.07**	**7.75**	**8.68**	**9.39**
2	**3.57**	**4.27**	**5.2**	**5.93**	**6.93**	**7.71**	**8.51**	**9.32**	**10.4**	**11.3**
3	**3.83**	**4.58**	**5.56**	**6.31**	**7.32**	**8.11**	**8.89**	**9.68**	**10.7**	**11.5**
4	**4.09**	**4.89**	**5.92**	**6.69**	**7.72**	**8.5**	**9.28**	**10.0**	**11.1**	**11.8**
7	**4.98**	**5.94**	**7.12**	**8.00**	**9.14**	**10.0**	**10.8**	**11.6**	**12.7**	**13.5**
9	5.45	6.48	7.72	8.66	9.85	10.8	11.7	12.6	13.7	14.6
10	**5.69**	**6.75**	**8.02**	**8.99**	**10.2**	**11.2**	**12.1**	**13.1**	**14.2**	**15.1**
20	**7.82**	**9.24**	**10.7**	**11.8**	**13.1**	**14.1**	**15**	**15.8**	**16.9**	**17.6**

Note: Bold values are taken from the NOAA Atlas 14 point precipitation frequency estimates. Non-bolded **values are interpolated from the NOAA values.**

Using the values in Table 2, we need to estimate the recurrence interval for the 23” rain fall event within a 9-day window. As part of the advanced PRA framework, we proposed to integrate an open-source Bayesian analysis tool called OpenBUGS. We will not describe the characteristics of this tool here, but additional information and source code may be found on the OpenBUGS web site. (OpenBUGS, 2013)

For this hypothetical example, we created an OpenBUGS script to perform the Bayesian inference, building upon the Generalize Extreme Value (GEV) modeling as described in (Kelly & Smith, 2011). Additional details on the GEV model and assumptions may be found in Chapter 13 of Kelly & Smith (2011). The script that was produced is shown below.

Modeling extreme rainfall condition using Generalize Extreme Value (GEV)

```
model
{ for(i in 1:N) {
z.p[i] ~ dnorm(mean[i],prec)
z.p.pred[i]~dnorm(mean[i],prec)
y.p[i] <- -log(1 - p[i])
mean[i]<- mu - sigma/xi*(1 -pow(y.p[i],-xi))
}
mu~dnorm(0,0.0001)
xi~dunif(-1,1)
prec<-pow(sd,-2)
sd~dunif(0,10)
sigma~dunif(0,10)
}
data
list(p=c(1,0.5,0.2,0.1,0.04,0.02,0.01,0.005,0.002,0.001,0.0002,1.E-4,2.E-5,1.E-5),
z.p=c(5.453, 6.480, 7.720, 8.660, 9.847, 10.800,11.667,
12.600,13.700,14.567,NA,NA,NA,NA), N=14)
```

Running the script produces two types of information:

- Uncertainty distributions for NOAA-provided precipitation levels (in inches) during a 9-day window. These distributions can be compared to the confidence intervals estimated by NOAA as a sanity check.
- Uncertainty distributions for predicted precipitation levels (outside the range of NOAA-provided values).

These resulting sets of information would be integrated directly into the simulation engine found in the 3D plant representation. The rainfall event (that is produced stochastically by the simulation) would impact the SMR buildings and SSC, wherein the physics from the 3D model would determine what, if anything, happens as a result of the initiator.

The results of the analysis produced the uncertainty results shown in Figure 21. From this figure, it appears that the recurrence frequency for 23" rain events (in a 9-day window) is between 5,000 years and 50,000 years, and is near 10,000 years.

Additional analyses were performed in order to determine the recurrence frequency that would provide an average rainfall precipitation level of 23 inches within a 9-day window. It was found that a frequency of 1-in-12,500 years (or 8E-5 frequency) would result in a 23-inch rainfall event (on average). The resulting distribution for this case is shown in Figure 22.

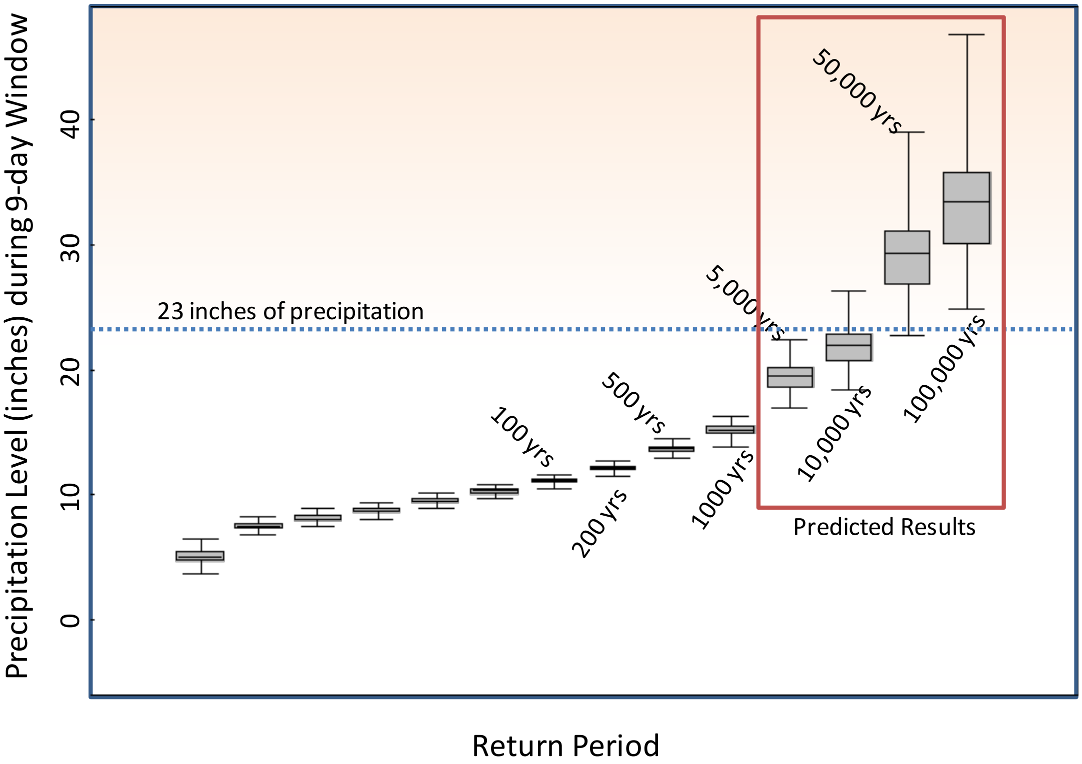


Figure 21. Bayesian analysis result for precipitation levels for selected recurrence frequencies.

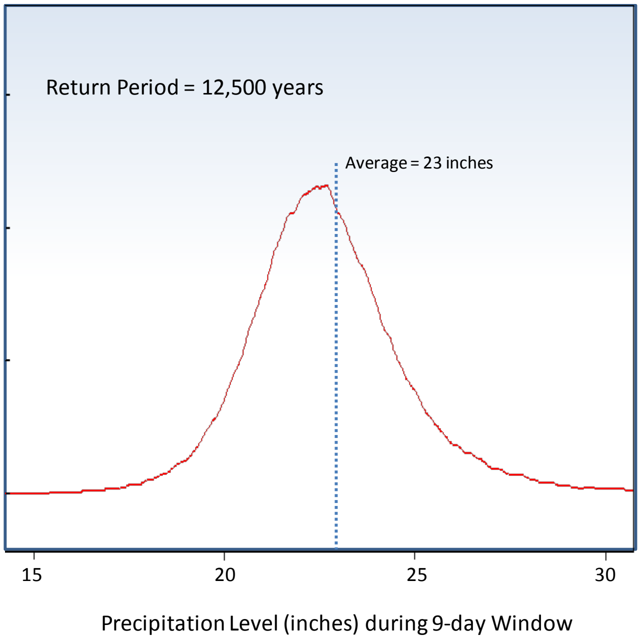


Figure 22. Rain precipitation-level distribution (9-day window) with a recurrence of 12,500 years.

3.4 Examples of Modeling with Emulators

3.4.1 Adaptive Sampling and Reduced Order Models

Propagation of uncertainties in complex systems such as nuclear power plants is usually performed by sampling algorithms that perform a series of simulation runs given a set uncertainty parameters.

Typically two problems arise: the set of uncertain parameters is very large and the computational costs are very high. Therefore, the space of the possible solutions, i.e., the issue space (each dimension corresponds to an uncertainty parameter), can be sampled only very sparsely (e.g., through Monte-Carlo or Latin Hypercube Sampling) and this precludes the ability to fully analyze impact of uncertainties on the system.

The scope of adaptive sampling is to iteratively guide the choice of the next sample by analyzing the previous sampling history. Typically this is performed by building a surrogate (i.e., Reduced Order) model from the set of previous simulation runs and predicting the system behavior (see Figure 23). In more detail three steps are needed:

1. Perform a set of initial simulation runs
2. Build a surrogate model using the sampling results given in Step 1 (State Estimation)
3. Using the model built in Step 2, chose a set of candidate sample points, assign an importance parameter to each point and pick the point(s) with highest importance (best candidate(s)) as next sample(s) (Action Selection).

After the best candidate point has been chosen, a new simulation run is performed and the surrogate model is updated given the outcome of the new simulation. This process typically ends when convergence is reached (i.e., the learning of the model is completed).

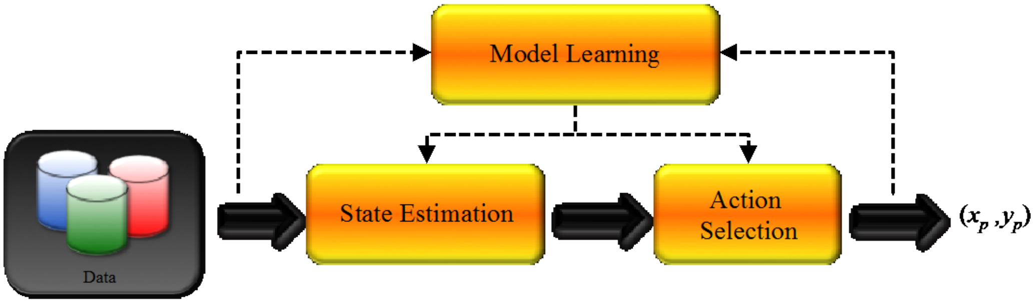


Figure 23: Generic scheme of adaptive sampling algorithms

The generic scheme shown above can be typically implemented using two classes of algorithms (see Figure 24 for a simplified 2-dimensional case):

1. Classification based (e.g., by using Support Vector Machine)
2. Regression based (e.g., by using Kriging or topologically based algorithms)

Both classes aim to predict the simulation outcome given a set of initial points. The prediction for the first class is performed in a binary fashion, i.e., system success or system failure, while the second class performs the prediction in a continuous manner (e.g., predict maximum core temperature T_{max}). This prediction is performed almost instantaneously (ranging from seconds to minutes) compared to the time required by a system simulator codes (usually hours/days depending on the transient).

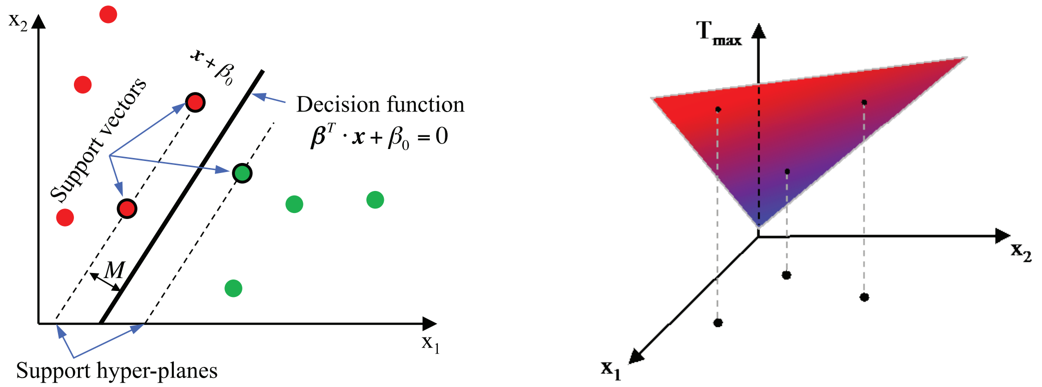


Figure 24: Classification (left) and regression (right) based learning models

3.4.2 Predictive Emulators

The ability to generate faster-than-real-time system emulators (i.e., Reduced Order Models) allows the construction of predictive models that can be used to assist the decision makers (e.g., reactor operators) during plant off-normal conditions. These predictive models can offer the following two capabilities:

1. *Diagnosis*: identification of plant status. Such tools might prove useful when sensor data coming from the plant is either missing, incomplete (e.g., communication issues) or subject to error (damaged sensor or due to wrong interpretation of system status).
2. *Prognosis*: prediction of plant dynamics. During accident scenarios that have not been covered by the set of operating emergency procedures, a model that can predict system dynamics may aid the operators in the process of deciding what is the best system recovery strategy.

3.5 Passive Component Modeling

An example of passive component modeling is a piping reliability model. This model can be applied to other passive components (tanks, vessels, barrier walls, cable, etc.) as well. Markov chain Monte Carlo (MCMC) methods are a valuable simulation tool. Piping can be modeled with a Markov model as shown in Figure 25.

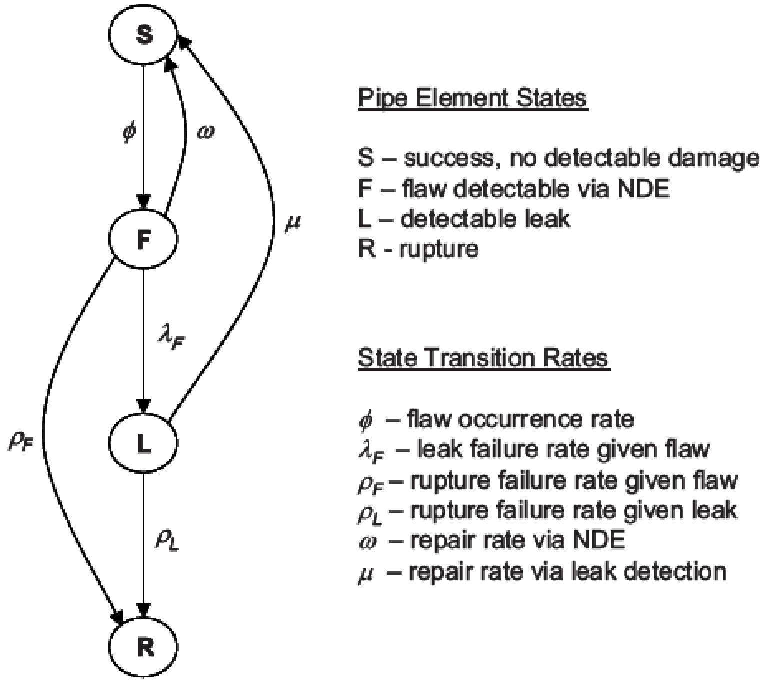


Figure 25. A pipe component Markov Model (Fleming et al, 2010).

The Markov model is expressed as a set of ordinary differential equations in time that describe the probability transitions between the pipe states. In general, a Markov Model consists of three things:

1. A set of states (e.g., component A is failed, component A is working)
2. Transitions between states (e.g., how do we get from one state to another state)
3. The rate of transition between the states

Examples of the state for any one component could include failed, operating, in repair, in maintenance, and so on. However, one of the complications that occur for these types of models is that for a system, combinations of specific component states need to be considered, which for many systems results in a (potentially) large number of states.

The Bayesian inference for the Markov model can be solved using the software package OpenBUGS, which is the open source version of Bayesian inference Using Gibbs Sampling (BUGS). Other software packages are available, including WinBUGS, the windows source version of BUGS, and JAGS, which stands for Just Another Gibbs Sampler. The analyst selects input information, including the time interval (such as an operating year), the failure rate distributions and their shapes, and the repair rate distributions and their shapes. These selections are guided from the analysis of the body of power plant operating experiences. For SMR applications, data from the most similar power plants, such as light water, sodium-cooled, or helium-cooled high temperature reactors, can be used. Then OpenBUGS or another software package is used to run Monte Carlo cases. These runs may be accomplished on the analysis server that is part of the cloud-based analysis tool. The results of these cases will fill in a distribution to determine the failure rate and repair rate values of the pipe which may feed into a “larger” PRA model.

Chapter

4

Features and Requirements

This section provides a breakdown of the proposed features and requirements for the SMR PRA Framework.

As described in Chapter 1, the overall proposed framework has defining analysis attributes that can be separated into three general areas of interest, Models, Phenomena, and Integration. In addition to these three analysis area, a fourth area exists, that of a cloud-based computer architecture, that will facilitate the creation, storage, collaboration, and analysis of the SMR PRA models and results. We describe the SMR PRA features and requirements grouped into these four areas. Note that features are **shown in bold**, while the requirements to implement the associated feature are *shown in italics*.

Requirements that are necessary are described using the word "shall," while less-important requirements are described using the word "should." Optional requirements are described using the word "may."

1. Models
    a. **A 3D representation of the SMR facility**
        i. *A 3D modeling engine capable of representing the physical dimensions of key SSCs shall be used.*
        ii. *A 3D modeling engine capable of representing physical properties such as mass, inertia, momentum, and frictional interfaces for key SSCs shall be used.*
        iii. *A 3D modeling engine capable of representing individual SSC objects (as opposed to a group of objects that appear to be discrete entities) shall be used.*
        iv. *A 3D modeling engine capable of representing SSCs using switchable degrees of meshing fidelity (from few mesh points to many in a high-resolution object) shall be used.*
        v. *A 3D modeling engine capable of representing the spatial interaction of objects due to failures of SSCs shall be used. For example, if the physics-of-failure engine determines that a wall will collapse due to energy imparted to it, the failure of the wall should be simulated.*
        vi. *A 3D modeling engine capable of large scale particle tracking shall be used.*
        vii. *A 3D modeling engine capable of texturing and rendering a semi-realistic version (either via pictures or video) of the SMR facility may be used.*
    b. **Representation of all applicable SMR hazards**
        i. *An enhanced PRA controller capable of storing and invoking all applicable plant hazards shall be used. For example, for any SMR facility, an understanding of possible initiating events (seismic, transients, loss-of-offsite power, floods, …) shall be stored in the SMR model.*
        ii. *An enhanced PRA controller capable of creating an ensemble for any applicable plant hazards should be used via a Bayesian approach.*

For example, three different versions of a site seismic hazard curve (representing the frequency of different magnitude earthquakes) may exist from different experts – the enhanced PRA controller should be able to use the information from all three site hazard curves in a probabilistic fashion.

   c. **Importing and conversion of 3D models.**
      i. *An enhanced PRA controller may provide a mechanism to import and convert typical 3D model formats in order to facilitate the efficient creation of SMR models.*
   d. **Bayesian inference models to provide uncertainty information.**
      i. *A Bayesian engine shall provide a mechanism to determine parameter uncertainty distributions.*
      ii. *A Bayesian engine shall provide a mechanism to propagate uncertainty distributions though the probabilistic and mechanistic models.*
      iii. *A Bayesian engine may provide a mechanism to quantify the validity of models using Bayesian model checking.*
   e. **Emulators to provide analysis speed increases.**
      i. *An enhanced PRA controller should provide a mechanism to use emulators (or reduced-order-models) as a surrogate for other models when possible.*
      ii. *An enhanced PRA controller should provide a mechanism to use adaptive sampling during simulation when possible.*

2. Phenomena
   a. **A representation of realistic motion of objects**
      i. *A 3D physics engine capable of representing the motion of objects shall be used.*
      ii. *A 3D physics engine capable of representing and managing collisions of objects shall be used.*
   b. **A representation of external hazards to the facility.**
      i. *A 3D physics engine capable of representing fluid flow (typically by performing particle tracking) entering the facility site shall be used.*
      ii. *A 3D physics engine capable of representing fluid flow through the facility infrastructure (e.g., entering penetrations or doors in buildings, moving to lower levels through stairwells) shall be used.*
      iii. *A 3D physics engine capable of representing fluid flow around the facility SSCs shall be used.*
      iv. *A Bayesian engine shall provide a mechanism to predict the occurrence rate of any applicable hazard.*
      v. *A simulation engine capable of representing the occurrence of any applicable hazard shall be used.*
   c. **A representation of physics-of-failures for SSCs.**
      i. *For different hazard-induced loading conditions (e.g., a wall of water from a tsunami, energy imparted from an earthquake), physics-of-failure model(s) that will estimate a failure probability for a SSC shall be associated with the respective SSC.*
      ii. *A physics-of-failure model(s) shall be able to loosely-couple to the 3D physics engine in order to both provide information (e.g., a door has failed due to a blast overpressure) about SSCs and to receive*

    information from the 3D environment (e.g., a pump is submerged in six feet of river water).
    iii. *A physics-of-failure model(s) should be able to tightly-couple to the 3D physics engine when possible in order to increase analysis realism.*
    iv. *A physics-of-failure model(s) shall be able to represent active-SSC failures.*
    v. *A physics-of-failure model(s) shall be able to represent passive-SSC failures.*
    vi. *A physics-of-failure model(s) should be able to represent applicable aging mechanisms when considering SMR operation over extended periods of time.*
  d. **An analysis of physics-of-failures for SSCs.**
    i. *A physics-of-failure engine that will simulate failure for a SSC shall be used.*
    ii. *A physics-of-failure engine shall be coupled to a 3D modeling engine in order to represent time- and spatial-dependent failures. For example, if a fire causes a pipe rupture, the flow of water will be tracked to determine other possible failures in the simulated scenario.*
  e. **A representation of mechanistic calculations for SMR thermal-hydraulics.**
    i. *A mechanism for loosely-coupling thermal-hydraulic conditions during scenario simulation shall be used.*
    ii. *A mechanism for tightly-coupling thermal-hydraulic conditions during scenario simulation should be used when possible in order to increase analysis realism.*
  f. **A representation of system-level failure behavior.**
    i. *A mechanism for determining system failure conditions during scenario simulation shall be used. For example, dependency state tables could provide information to the simulation engine in order to effectively manage dependencies (e.g., a pump may require ac power).*
    ii. *A mechanism for triggering changes in SSC conditions (e.g., failures, operational changes due to scenario responses) during scenario simulation shall be used.*
  g. **A representation of mechanistic calculations for SMR thermal-hydraulics.**
    i. *A mechanism for loosely-coupling thermal-hydraulic conditions during scenario simulation shall be used.*
    ii. *A mechanism for tightly-coupling thermal-hydraulic conditions during scenario simulation may be used.*

3. Integration
  a. **An intelligent scenario generator that can determine applicable physics as needed as part of the simulation**
    i. *A simulation engine capable of enabling specific physics-of-failure models for SSC as needed as part of a scenario shall be used. For example, during an earthquake, fragility-types of failure models may need to be invoked in order to determine the failure probability of the SSC.*

    ii. *A simulation engine capable of ignoring specific physics-of-failure models for SSC as needed as part of a scenario should be used. For example, during an earthquake, failure models related to flooding should not need to be invoked.*

b. **An intelligent scenario generator that can manage the communication and interaction between different physics as part of the simulation**
    i. *A simulation engine capable of storing and passing information between other engines (e.g., between the physics-of-failure engine and the 3D physics engine) shall be used.*
    ii. *A simulation engine capable of providing scenario-based results to analysts shall be used. For example, the simulation engine should be able to describe a scenario that leads to elevated fuel temperatures by presenting the temporal string of events leading to the undesired outcome.*
c. **Analysis capabilities such as a vulnerability search, safety importance level for a SSC, and safety-margin determination.**
    i. *The simulation engine shall provide the ability to find vulnerabilities (i.e., potential weaknesses related to hazards and associated scenarios) as part of the integrated simulation approach.*
    ii. *The simulation engine should provide the ability to determine safety importance for specific SSCs as part of the integrated simulation approach.*
    iii. *The simulation engine shall provide the ability to determine a user-definable safety margin as part of the integrated simulation approach.*
d. **Inclusion of economic impacts.**
    i. *The simulation engine may provide a mechanism to include possible economic impacts due to scenario outcomes. For example, the shutdown costs related to a seismic event that causes plant damage may be tracked as part of seismic hazard simulation.*
e. **Ensemble representation.**
    i. *The simulation engine should provide a mechanism to effectively use multiple (possible disagreeing) physics models in a coherent fashion.*
f. **Safety outcome classification.**
    i. *The simulation engine shall provide a mechanism to allow users to specify safety outcomes of interest. For example, if the clad peak temperature is of interest, this physical parameter should be identified and tagged to outcomes (e.g., exceeding a clad capacity temperature results in melting of fuel).*
    ii. *The simulation engine shall provide a mechanism to allow users to track specified safety outcomes of interest as the focus of the analysis. For example, if clad peak temperature is identified, the safety case and associated simulation would use that as a safety metric. Note that multiple safety metrics shall be tracked.*

4. Cloud-based Architecture
    a. **Library to create, store, and manage physics-of-failures models for SSCs.**
        i. *For different loading conditions that may impact a SSC (e.g., a wall of water from a tsunami, energy imparted from an earthquake), the physics-based model that will estimate a failure probability for a SSC shall be stored in a central repository for each SSC.*

b. **Library to create, store, and manage operational data for SSCs.**
    i. *SSC operational data (e.g., failure rates, CCF factors, maintenance unavailabilities) shall be stored in a central repository.*
    ii. *SSC operational data shall be able to be set as read-only in order to provide for a high-level of quality assurance.*
    iii. *SSC operational data shall be able to be modified by the owners of any stored data.*

c. **Library of plant operating rule information.**
    i. *Plant operating rules (e.g., operational procedures, technical specifications, maintenance schedules) should be stored in a central repository.*
    ii. *Plant operating rules (e.g., operational procedures, technical specifications, maintenance schedules) should be integrated into the simulation engine. For example, if a maintenance schedule will result in a SSC being unavailable for a period of time, the simulation engine should account for this impact to system performance.*

d. **Search facility to find information.**
    i. *The enhanced PRA controller shall provide a search capability in order to find information such as that stored for models, phenomena, or analysis results.*

e. **Importing of PRA information.**
    i. *The enhanced PRA controller should provide a mechanism to import typical failure or phenomena models and operational data.*

f. **Security of stored information.**
    i. *The enhanced PRA controller shall provide a secure mechanism of storing SMR PRA data.*
    ii. *The enhanced PRA controller shall provide an ID/password approach to control accessing SMR PRA data.*

g. **Collaboration for both model creation and analysis.**
    i. *The enhanced PRA controller should provide a mechanism to share, in a user-definable fashion, the SMR PRA model. For example, a team of PRA analysts should be able to work concurrently on the same PRA model.*
    ii. *The enhanced PRA controller should provide a mechanism to share, in a user-definable fashion, results of specific SMR PRA analysis. For example, the safety case results for a SMR PRA should be able to be shared with NRC staff.*

h. **Design support functionality.**
    i. *The enhanced PRA controller should provide a mechanism to allow analysts the ability to proposed plant changes that are evaluated to determine their safety effectiveness.*

i. **Determination of the safety case.**
    i. *The enhanced PRA controller shall provide the safety case documentation based upon the PRA and associated results. Recall that the safety case is the structured argument (as supported by the PRA) that a SMR is adequately safe.*

j. **Analysis engine computation infrastructure.**
    i. *The enhanced PRA controller shall provide a mechanism to share multiple computer resources (e.g., DOE high-performance computers, workstation clusters) as part of a shared analysis capability.*

   ii. *The enhanced PRA controller may provide a mechanism to distribute different "engines" (e.g., simulation, 3D modeling, 3D physics, and physics-of-failure) across different tiers of servers dedicated to running these engines.*

k. Modeling and analysis via an Internet browser.

   i. *The enhanced PRA controller shall provide a mechanism to allow users to access the modeling and analysis capabilities using any modern browser via a client-server approach.*

l. Backup of information.

   i. *The enhanced PRA controller should provide a mechanism to allow users to download their SMR PRA model and results for local storage.*

   ii. *The enhanced PRA controller should provide a mechanism to allow users to back up their SMR PRA model and results to redundant cloud-based storage.*

m. Facility training.

   i. *The enhanced PRA controller may provide a mechanism to allow users to train on the SMR facility by interacting with off-normal scenarios as part of the simulation.*

Chapter

5

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