RISMC Approach to Risk Analysis Using RELAP5 and RAVEN

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The Risk-Informed Safety Margin Characterization (RISMC) with RELAP5-3D and RAVEN seeks to understand events and means to increase safety margin.

Introduction

In the Risk-Informed Safety Margin Characterization (RISMC) approach [1], we want to understand not just the frequency of an event like core damage (CD), but also how close we are (or not) to key safety-related events and how we might increase our safety margin. In general terms, “margin” is usually characterized in one of two ways:

1. A deterministic margin, typically defined by the ratio of a capacity (i.e., strength) over the load
2. A probabilistic margin, defined by the probability that the load exceeds the capacity.

A probabilistic safety margin is a numerical value quantifying the probability that a safety metric, e.g. an important observable process such as clad temperature, is exceeded under accident conditions. The RISMC Pathway uses the probabilistic margin approach to quantify impacts to reliability and safety. We use this probabilistic margin idea to support decision making for plant power applications such as power uprates (e.g., from 100% to 120%) and plant life extension. The question we aim to answer is: how do these issues affect plant reliability?

Methodology

As part of the safety quantification (see Figure 1), we use both probabilistic (via risk simulation) and mechanistic (via physics models) approaches. Probabilistic analysis is represented by the stochastic risk analysis while mechanistic analysis is represented by the plant physics calculations. In other words, safety margin and uncertainty quantification rely on plant physics (e.g., thermal-hydraulics and reactor kinetics) coupled with probabilistic risk simulation. The coupling, which we call Computational Probabilistic Risk Assessment (CPRA), takes place through the interchange of physical parameters (e.g., pressures and temperatures) and operational or accident scenarios (e.g., the series of successes and/or failures representing a sequence of events).

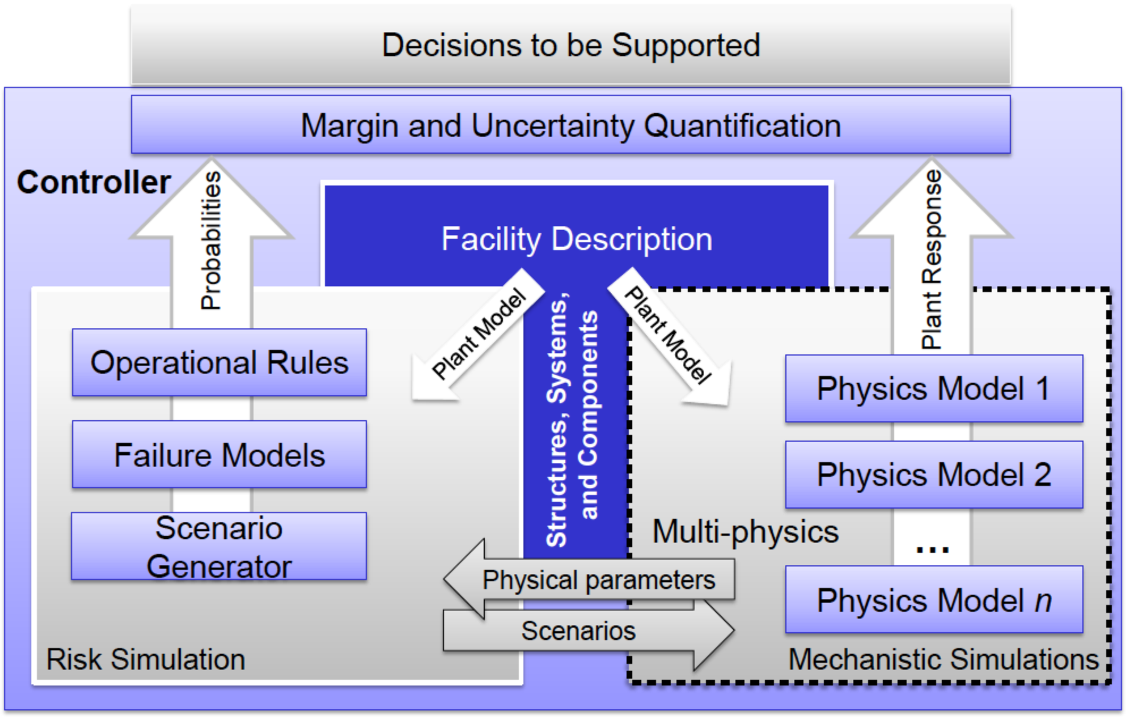

Figure 1: Overview of the RISMC approach

In order to perform advanced safety analysis, the RISMC Pathway has a toolkit that was developed internally at INL, which consists of several software tools such as RAVEN [2] coupled with RELAP5-3D. RAVEN generates multiple scenarios by stochastically changing the order and/or timing of events. In summary, the RAVEN statistical framework (see Figure 2) allows the user to perform generic statistical analysis such as:

- Sampling of codes: either stochastic (e.g., Monte-Carlo and Latin Hypercube Sampling [3]) or deterministic (e.g., Dynamic Event Tree [4])
- Generation of Reduced Order Models (ROMs) also known as surrogate models or emulators. These models aims to reduce the computational complexity of complicated models by reducing the original model state space or the degree of freedom. ROMs can be evaluated with lower accuracy but in significantly less time.

Post-processing of the sampled data and generation of statistical parameters (e.g., mean, variance, covariance matrix)

RAVEN is interfaced with several codes and, actually, the user can build its own interface for the code he is interested for.

The interface for RELAP5-3D allows RAVEN to change specific values of any card contained in the RELAP5-3D input files accordingly to the chosen sampling strategy.

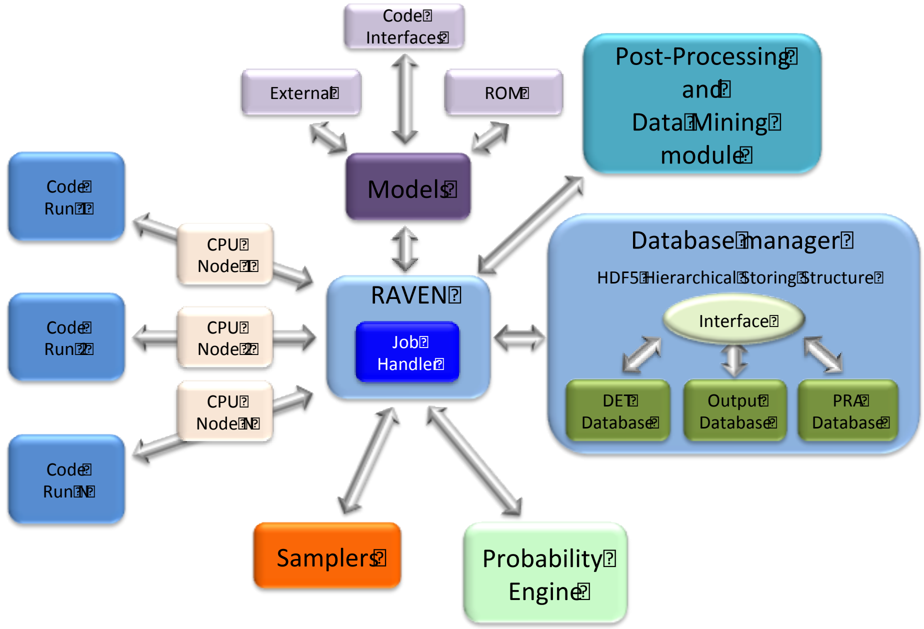

Figure 2: Overview of the RAVEN framework

In addition, at the end of each RELAP5-3D simulation run, RAVEN collects and store all information generated from the output files (in the Database manager), it generates CSV files of the output data, and it processes such data through its internal Post-Processing and Data Mining module.

If multiple simulations need to be run, RAVEN has the capability to run simulations in parallel on multiple nodes and/or multiple CPUs. RAVEN applicability ranges from Linux based desktop/laptop to high performance computing machines.

As mentioned earlier, RAVEN has also the capability to "train" ROMs from any data set generated by any codes. These ROMs are usually a blend of interpolation and regression algorithms and such "training process" basically consists of setting the optimal parameters of the interpolation and regression algorithms that best fits the input data set. Once the ROMs are generated, they can be used instead of the actual codes to perform any type of analysis since the generation of data from ROM is much faster the original code.

In a typical RISMC type analysis, the user specifies in the RAVEN input file not only where the RELAP5-3D executable files and the input files are located but it also lists, for each uncertain, its own probabilistic distribution and the where such parameter needs to be changed in the RELAP5-3D input file.

Then, the user specifies which sampling strategy has been chosen, what are the output variables that need to be retrieved (and subsequently stored in the RAVEN database) from the RELAP5-3D output files and which post-processing functions of the output data are required.

EXAMPLE

In one of the RISMC applications, a station blackout study (SBO) of a BWR power plant with a Mark I containment was considered. The three main structures of the BWR were: the Reactor Pressure Vessel (RPV) and the primary containment (this includes: Drywell, Pressure Suppression Pool and the reactor circulation pumps). While the original BWR Mark I includes a large number of systems, we consider a subset of it (see Figure 3):

- Reactor Core Isolation Cooling System (RCIC) and High Pressure Coolant Injection (HPCI): they provide high-pressure injection of water to the RPV.
- Water flow is provided by a turbine driven pump that takes steam from the main steam line and discharges it to the suppression pool.
- Safety Relief Valves (SRVs): DC powered valves that control and limit the RPV pressure.
- Automatic Depressurization System (ADS): separate set of relief valves that can be employed to depressurize the RPV.
- Firewater system (FW): water contained in the firewater system can be injected into the RPV when other water injection systems are disabled and the RPV is depressurized.

Set of power systems: two independent power grids that are connected to the plant station thorough two independent switchyards, diesel generators (DGs) which provide emergency AC power, and battery systems: instrumentation and control systems need DC power. The nodding diagram is given in Figure 3.

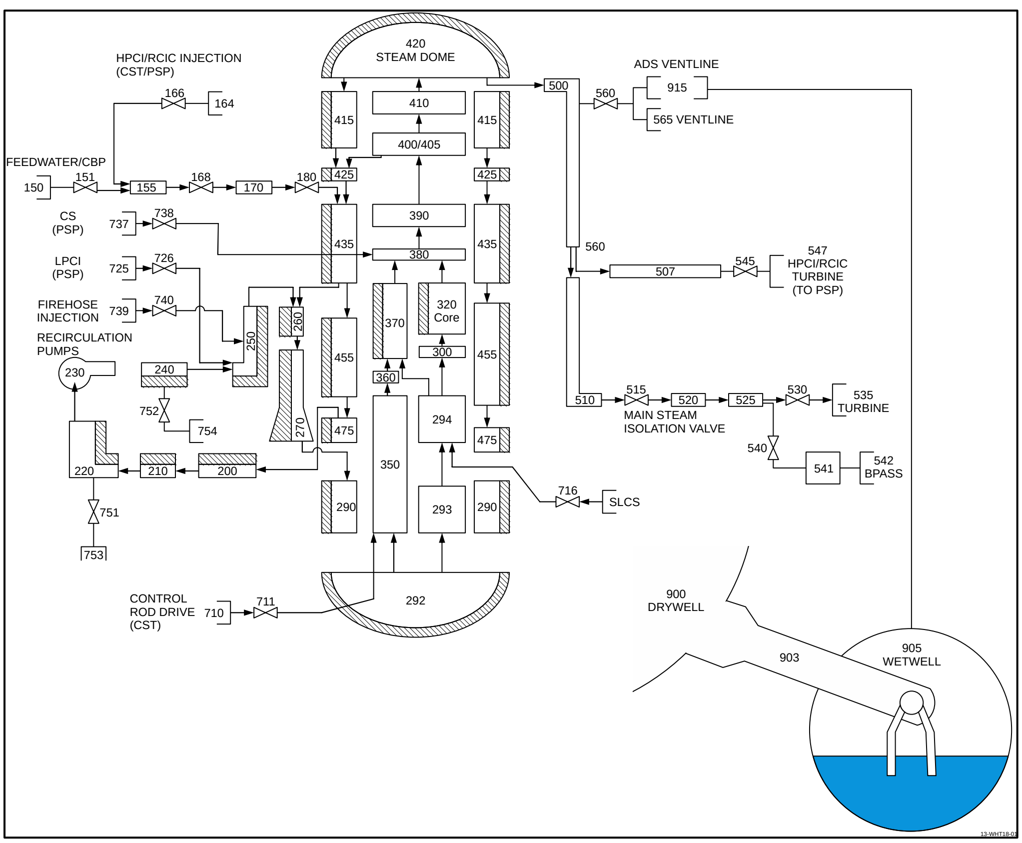

Figure 3: RELAP5 nodalization scheme for the BWR system

The accident scenario under consideration is a loss of off-site power (LOOP) followed by loss of the DGs, i.e., a SBO scenario. In more details, at the beginning of the scenario, LOOP condition occurs due to external events (i.e., power grid related). The operators successfully scram the reactor and put it in sub-critical conditions by fully inserting the control rods in the core; the emergency DGs successfully start, i.e., AC power is available, and the core decay heat is successfully removed from the RPV.

At a certain time, SBO condition occurs: due to internal failure, the set of DGs fails, thus removal of decay heat is impeded. Reactor operators start the SBO emergency operating procedures and perform: RPV level control using RCIC or HPCI, RPV pressure control using SRVs, and containment monitoring (both drywell and suppression pool). Plant operators start recovery operations to bring back on-line the DGs and the power grid. When AC power is recovered, through successful re-start/repair of DGs or off-site power, RHR can be now employed to keep the reactor core cool. Alternatively, as an emergency action, when RPV is depressurized, the plant staff can connect the FW system to the RPV in order to cool the core and maintain an adequate water level. Due to the limited life of the battery system and depending on the use of DC power, battery power can be depleted. When this happens, all remaining control systems are offline causing the reactor core to heat until clad failure temperature is reached, i.e., CD.

Once the input files of RELAP5 are set for the BWR SBO scenario, the RISMC approach consists of the following steps:

1. Identify a set of uncertain/stochastic variables: for our case we identified 12 stochastic variables as shown in Table 1 and we associated a probabilistic distribution to each of them.
2. Perform a set of Monte-Carlo or Latin Hypercube simulations where, in each simulation, the value of each stochastic variable is randomly sampled.

Table 1. Distributions for the Stochastic Variables

Stochastic variable	Distribution
DGs failure time (h)	Exponential
DGs recovery time (h)	Weibull
Battery life (h)	Triangular
SRV1 failure	Bernoulli
PG recovery (h)	Lognormal
Clad fail temperature (F)	Triangular
HPCI fails to run (h)	Exponential
RCIC fails to run (h)	Exponential
Battery failure time (h)	Exponential
Battery recovery time (min)	Lognormal
FW availability time (min)	Lognormal
FW flow rate (gpm)	Uniform

We performed two series of Latin Hypercube Sampling analysis for the two levels of reactor power (100% and 120%) using 20,000 samples for each case. The scope of this analysis is to evaluate how CD probability changes when reactor power is increased by 20%.

In addition, we evaluated the impact of auxiliary AC system generators as additional sources of AC power. The U.S. nuclear industry, as a measure after the Fukushima accident, developed a FLEX system to counterattack the risks associated with external events (e.g., earthquakes or flooding). Such a system employs portable AC and DC emergency generators located not only within the plant perimeter but also at strategic locations within the US borders in order to quickly supply affected NPPs with both AC and DC power. For our case, we assumed a new distribution associated with the AC recovery time within the plant instead of the DG recovery time distribution. Note that this model may not be indicative of any actual NPP FLEX strategies – for an actual FLEX evaluation, plant specific information would need to be considered.

We then performed a new Latin Hypercube Sampling analysis in order to estimate the new core damage probability value when the FLEX system is available. A summary of the results is shown in Table 2 for the two different cases (with and without the FLEX system) and for two different power values (100% and 120%).

Table 2. Analysis Results

Outcome	Without FLEX		With FLEX
	100%	120%	120%
OK	0.99	0.981	0.995
CD	9.82 E-3	1.95 E-2	4.59 E-3

As expected, the CD probability raises for a power uprate scenario since less time is available to recover AC power or FW injection system. However, through the implementation of the FLEX system, CD probability drops substantially since external can be recovered much faster.

References

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