Multi-Unit Dynamic Probabilistic Risk Assessment With RELAP5-3D

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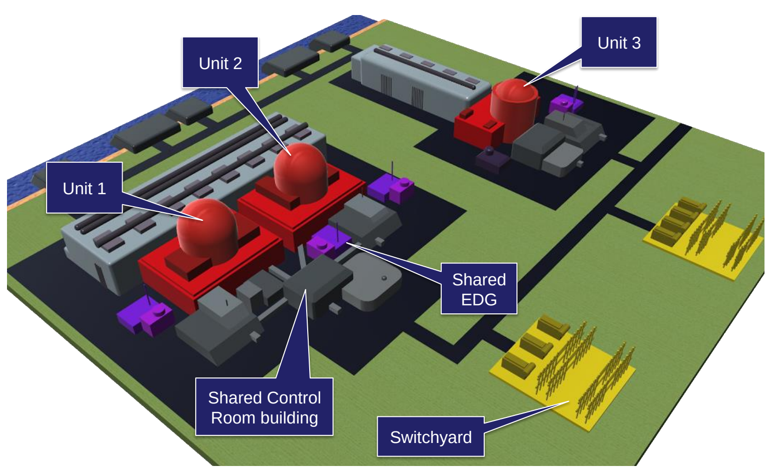
An analysis of a multi-unit power plant is performed without the classical Probabilistic Risk Assessment (PRA) tools, but rather, with a fully coupled simulation-based, the Risk Informed Safety Margin Characterization (RISMC) approach.

Introduction

Multi-unit plants are defined as plants which include more than one reactor. In the U.S. the situation is the following: 25 power plants have 1 reactor, 33 power plants have 2 reactors, 3 power plants have 3 reactors and 1 power plant has 4 reactors. The situation is similar for other countries such as Canada and Japan were several power plants include a large number of reactors (6, 7 or even 8 reactors). Worldwide about 80 plants have more than 2 reactors and 32 power plants have more than 3 reactors.

Historically, the analysis of the safety aspects of multi-unit plants has been performed in the past for a few selected cases (Seabrook, Byron/Braidwood) using classical Probabilistic Risk Assessment (PRA) tools.

Here we present an analysis of a multi-unit power plant without using classical PRA tools [1] but employing a fully coupled simulation-based (i.e., Dynamic) PRA [2] approach: the RISMC approach [3,4]. The rationale behind this choice is that great modeling improvements can be achieved by directly employing system simulators in the PRA.



The RISMC approach employs both deterministic and stochastic methods in a single analysis framework. In the deterministic method set we include modeling of: the thermal-hydraulic behavior of the plant, external events such as flooding and operators' responses to the accident scenario.

Test Case

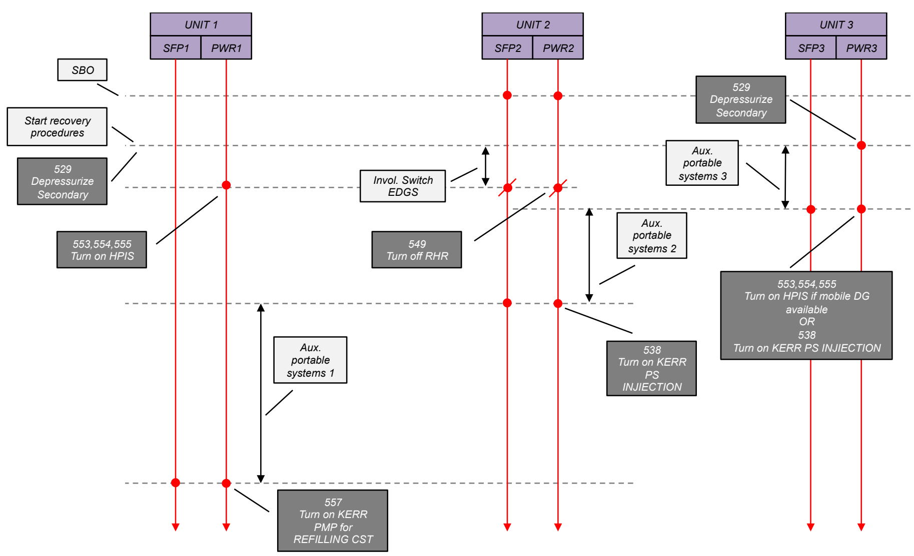
We have chosen a 3-unit where each unit includes both the PWR system and its own Spent Fuel Pool (SFP). While Units 1 and 3 are at full power, Unit 2 is in in mid-loop operation. In addition, special attention has been given to the design of the plant electrical and hydraulic systems:

- Two electrical switch-yards provide electrical power to the plant. All units have a set of Emergency Diesel Generators (EDGs) and, in addition, a swing EDG (i.e., EDGS) can be employed to provide an alternate AC power to either Unit 1 or Unit 2
- The auxiliary feed-water (AF) system of Unit 1 and Unit 3 can be cross-tied
- The Condensate Storage Tanks (CSTs) of Units 2 and Unit 3 can be cross-tied
- Plant recovery crew is a shared resource within the plant. As part of the accident scenario, the recovery crew can perform AC power and safety injection using mobile equipment located within each unit

The considered accident scenario is a seismic event which disables both switch-yards and all EDGs except for the EDGS. In addition, CST of Unit 2 has lost 80% of its capacity while CST of Unit 3 is completely lost. The seismic event might also rupture the SFPs. Thus, a leak might be present during the accident scenario. From a human modeling point of view, several interactions have been considered in the analysis. Example of considered human interactions are the CST or AF system cross-ties, the involuntary alignment of EDGS from Unit 2 to Unit 1 and the emergency water injection using portable systems. Note that some actions can have a negative influence on a unit but have a positive influence on a different unit and erroneous actions affect evolution of the already planned recovery strategy.

Analysis

The thermo-hydraulic behavior of all PWRs and all SFPs has been modeled using the RELAP5-3D code. Each RELAP5-3D model is coded such that the stopping conditions are the following: emergency water injection and AC restoration using portable systems has been completed or max clad temperature reaches 2200 F. The actual modeling of the plant, i.e., interactions among units and shared system modeling, has been performed using the ensemble models [13] available in the RAVEN code [6]. This feature allows the user to link several models together in order to perform multi-model types of analyses.



For this analysis we have identified 23 stochastic parameters to sample in the analysis which directly dictate timing and sequencing of event among all the three units

An example of simulated scenario is shown above. The figure shows the temporal evolution of the three units (both PWR and SFP). The red dots imply that the model has reached a safe condition (either AC power is available or auxiliary portable systems have been connected) while the signed red dots implies that the above mentioned safe condition has been lost.

- At time t=0, SBO condition is reached, Unit 2 is the only unit with available AC power through the EDGS
- The chosen recovery strategy prioritizes Unit 3 and therefore, efforts to connect auxiliary portable systems are initially directed towards Unit 3. The objective is moved afterwards to Unit 1
- An involuntary alignment of the EDGS causes the loss of AC power for Unit 2 but it provides AC power to Unit 1. At this point the recovery strategy prioritizes Unit 2 over Unit 1
- Efforts to connect auxiliary portable systems are directed to Unit 2 once completed on Unit 3
- Once completed, efforts to connect auxiliary portable systems are directed to Unit 1

One issue related to multi-unit PRA is that Historically the concept of core damage (CD) probability has been typically associated to a single unit. At a plant level, a separate value of CD probability can be associated to all PWRs and SFPs. However, note that there is a high correlation among the six models of the plant (PWRs and SFPs). Thus, it is also expected that a high correlation among CD probabilities among the six models. Thus, instead of defining a single CD probability value for each PWR and SFP we have defined a probability value to a Plant Damage State (PDS) variable. This variable is a 6-dimensional vector where each vector element describes the status of a plant model. For the scope of this paper we allowed two possible values for each element of the vector: OK or CD.

The objective of this analysis is to rank PDSs based on their probability values. Using a Monte-Carlo sampling strategy we have simulated a large amount of accident scenarios. For each simulation run we have performed the following steps:

1. Sample a value for each stochastic parameter (e.g., timing of events)
2. Perform a multi-unit simulation run given the parameters sampled in Step 1
3. Collect the output (OK or CD) from each RELAP5-3D model and associate the multi-unit simulation run to a specific PDS
4. Repeat Steps 1 trough 3, multiple times
5. Evaluate probability associated to all PDSs

Results

We performed a first preliminary analysis of this multi-unit model using a Monte-Carlo sampling. We have generated about 2000 simulation runs. This limited number of simulations cannot be considered a sufficient statistical population and, hence, the results obtained can only be considered as preliminary.

A summary of the five more relevant (from a probabilistic point of view) PDSs are shown below. Note that none of the recovery strategies were able to recover PWR of Unit 3: its condition at the beginning of the accident is the worst among the three units (lost of CST inventory on top of SBO condition). From separate calculations, PWR of Unit 3 could be saved only if emergency water injection were connected within the first 50 minutes after SBO condition. Such condition cannot be met given the boundary conditions of the accident progression. PWR of Unit 1, on the other side, never reaches CD condition: this is due to the fact that CST inventory is intact (compared to PWR of Unit 3) and, thus, the time required to reach CD condition is much longer. In addition, PWR of Unit 1 can be put in safe condition through several ways.

Rank	PDS						Prob.
	PWR1	PWR2	PWR3	SFP1	SFP2	SFP3	
1	OK	OK	**CD**	OK	OK	OK	0.890
2	OK	OK	**CD**	**CD**	OK	OK	5.9 E-2
3	OK	OK	**CD**	OK	**CD**	OK	3.4 E-2
4	OK	OK	**CD**	OK	OK	**CD**	1.2 E-2
5	OK	**CD**	**CD**	OK	OK	OK	2.1 E-3

References

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