DYNAMIC PRA OF A MULTI-UNIT PLANT

D. Mandelli[†], C. Parisi, A. Alfonsi, D. Maljovec, S. St Germain,
R. Boring, S. Ewing, C. Smith, C. Rabiti

Idaho National Laboratory (INL), 2525 Fremont Ave, 83402 Idaho Falls (ID), USA

[†] Reference Author: diego.mandelli@inl.gov

Dynamic Probabilistic Risk Analysis (PRA) methods couple stochastic methods (e.g., RAVEN, ADAPT, ADS, MCDET) with safety analysis codes (RELAP5-3D, MELCOR, MAAP) to determine risk associated to complex systems such as nuclear plants. Compared to classical PRA methods, which are based on static logic structures (e.g., Event-Trees, Fault-Trees), they can evaluate with higher resolution the safety impact of timing and sequencing of events on the accident progression. Recently, special attention has been given to nuclear plants which consist of multiple units and, in particular, on the safety impact of system dependencies, shared systems and common resources on core damage frequencies. In the literature, while classical PRA methods have been employed to model multi-unit plants, Dynamic PRA methods have never been applied to analyze a full multi-unit model. This paper presents a PRA analysis of a multi-unit plant using Dynamic PRA methods. We employ RAVEN as stochastic method coupled with RELAP5-3D. The plant under consideration consists of the three units and their associated spent fuel pools (SFPs). The studied initiating event is a seismic induced station blackout event. We will describe in detail how the multi-unit plant has been constructed and, in particular, how unit dependencies and shared resources are modeled.

I. INTRODUCTION

Multi-unit plants are defined as plants which include more than one reactor. In the U.S. the situation is the following[1]:

- 25 power plants have 1 reactor
- 33 power plants have 2 rectors
- 3 power plants have 3 reactors
- 1 power plant has 4 reactors

[1] Note that in this list we have not considered adjacent power plants, i.e., plants that are located in proximity to each other

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.

Following the accident event occurred in 2011 at the Fukushima Daiichi special attention has been given to multi-unit plants. This attention has focused on the safety aspects of plants that cannot be considered as entities isolated from each other.

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 ET/FT tools. In addition, more advanced research studies have been developed in [1,2,3].

The objective of this paper is to propose an analysis of a multi-unit power plant without using classical ET/FT tools [4] but employing a fully coupled simulation-based (i.e., Dynamic PRA [5]) approach: the RISMC approach [6,7]. The rationale behind this choice is that great modeling improvements can be achieved by employing system simulators instead of static Boolean structures like ETs/FTs.

Accident dynamics is in fact not set a-priori by the analyst (i.e., in an ET/FT structure) but it is entirely simulated given a set of initial and boundary conditions. Note that timing and sequencing of events are implicitly modeled in the analysis along with interactions between accident evolution and system dynamics.

II. RISMC APPROACH

The RISMC approach [6,7] employs both deterministic and stochastic methods in a single analysis framework (see Figure 1). In the deterministic method set we include:

- Modeling of the thermal-hydraulic behavior of the plant [8]
- Modeling of external events such as flooding [9]
- Modeling of the operators' responses to the accident scenario [10]

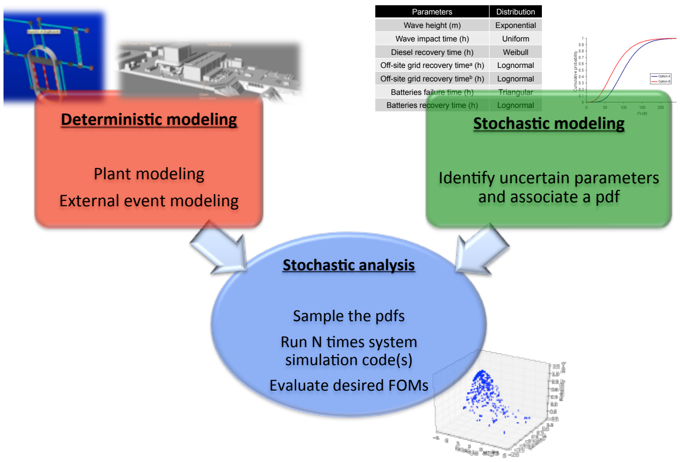

Figure 1 – Overview of the RISMC approach

Note that deterministic modeling of plant or external events can be performed by employing specific simulator codes but also surrogate models, known as reduced order models (ROM) [11]. ROMs would be employed in order to decrease the high computational costs of employed codes.

In addition, multi-fidelity codes can be employed to model the same system; the idea is to switch from low-fidelity to high-fidelity code when higher accuracy is needed (e.g., use low-fidelity codes for steady-state conditions and high-fidelity code for transient conditions).

In stochastic modeling we include all stochastic parameters that are of interest in the PRA analysis such as:

- Uncertain parameters
- Stochastic failure of system/components

As mentioned earlier, the RISMC approach heavily relies on multi-physics system simulator codes (e.g., RELAP5-3D [12]) coupled with stochastic analysis tools (e.g., RAVEN [13]).

From a mathematical point of view, a single simulator run can be represented as a single trajectory in the phase space. The evolution of such a trajectory in the phase space as function of time t can be described as follows:

$$\frac{\partial \boldsymbol{\theta}(t)}{\partial t} = \boldsymbol{\mathcal{H}}(\boldsymbol{\theta}, \boldsymbol{p}, \boldsymbol{s}, t) \quad (1)$$

where:

- $\boldsymbol{\theta} = \boldsymbol{\theta}(t)$ represents the temporal evolution of a simulated accident scenario, i.e., $\boldsymbol{\theta}(t)$ can represent temperature inside the core of a PWR, the pressure level inside a containment building, the radionuclide concentration at a specific point outside the plant, etc.
- $\boldsymbol{\mathcal{H}}$ is the actual simulator code that describes how $\boldsymbol{\theta}$ evolves in time
- $\boldsymbol{p}$ is the set of uncertain parameters
- $\boldsymbol{s} = \boldsymbol{s}(t, \boldsymbol{p})$ represents the status of components

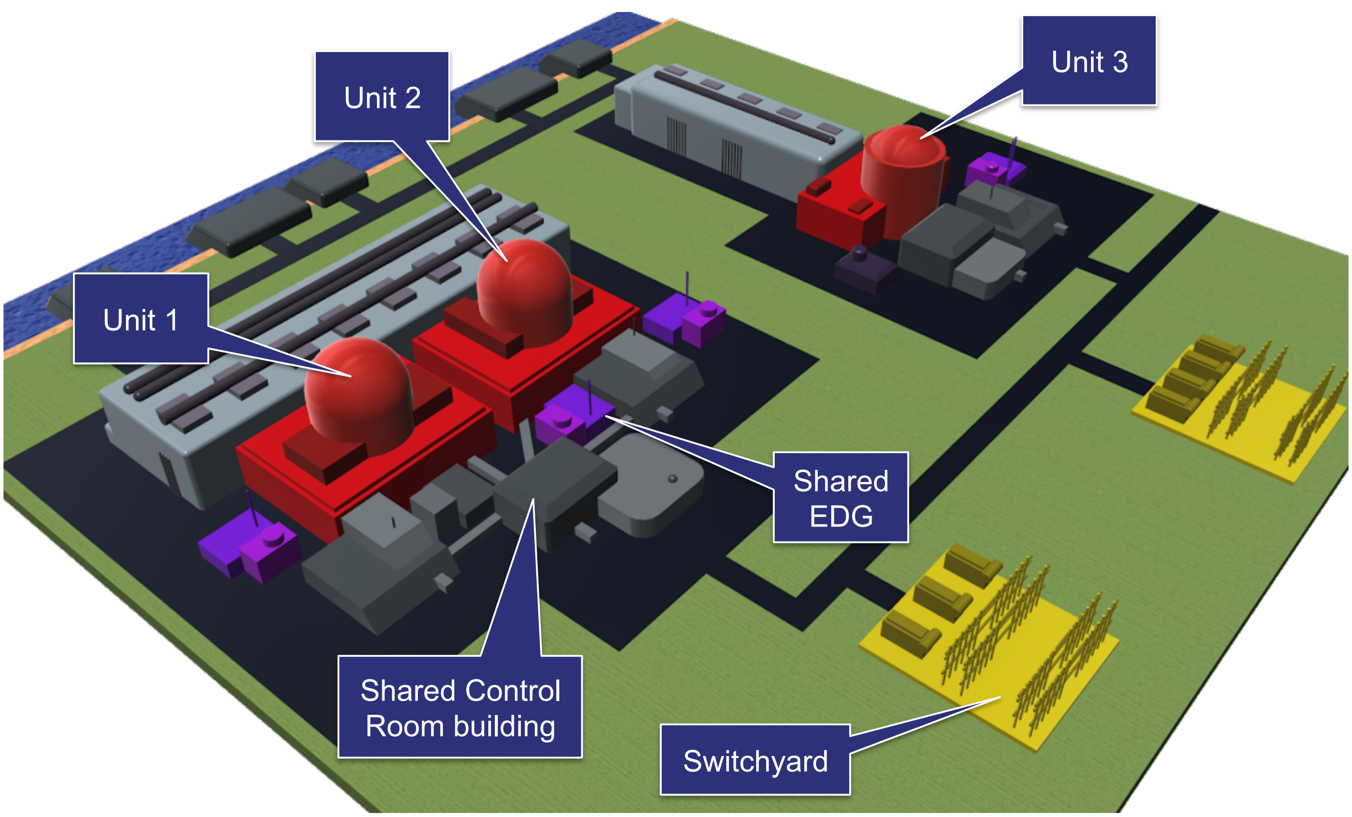

Figure 2 – Overview of the multi-unit plant

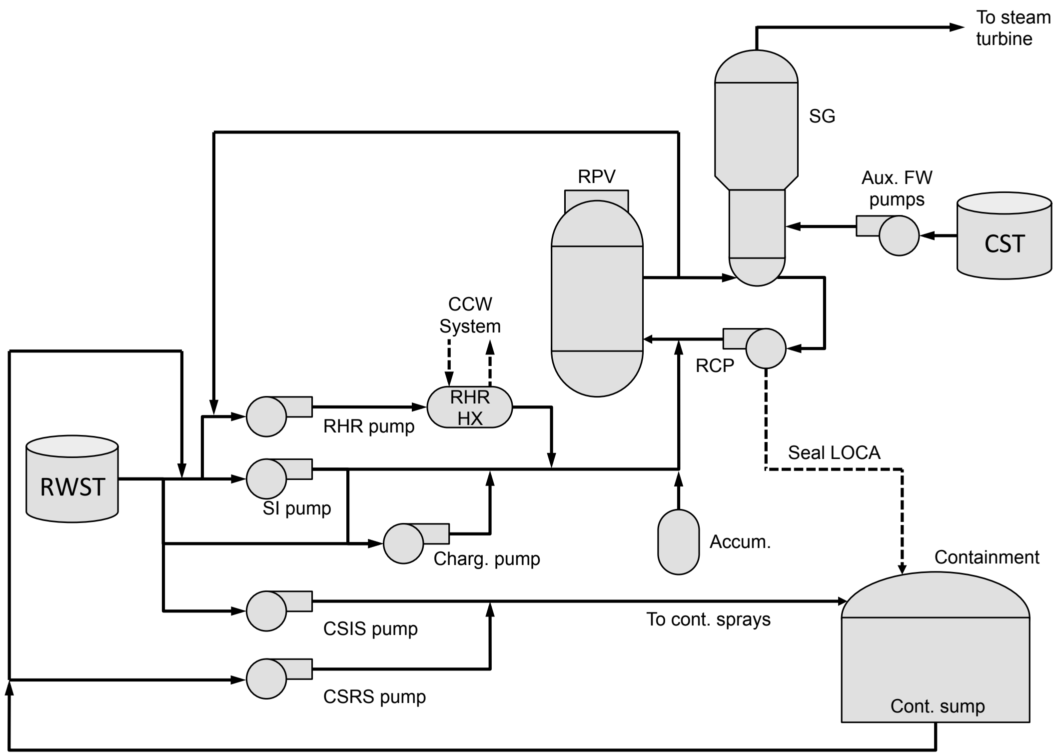

Figure 3 – Generic scheme of a PWR system

and systems of the model (e.g., status of emergency core cooling system, AC system)

By using the RISMC approach, if Monte-Carlo sampling is chosen, the PRA analysis is performed by [8]:

1. Associating a probabilistic distribution function (pdf) to the set of uncertain parameters $\boldsymbol{p}$ (e.g., timing of events)
2. Performing stochastic sampling of the pdfs defined in Step 1
3. Performing a simulation run given $\boldsymbol{p}$ sampled in Step 2, i.e., solve Eq. (1)
4. Repeating Steps 2 and 3 M times and evaluating user defined stochastic parameters such as Core Damage (CD) probability P_{CD} as
$$P_{CD} = \frac{M_{CD}}{M}$$
where M_{CD} is the number of simulation that lead to CD.

In a multi-unit type of scenario, the dynamic of each unit is not independent but it can actually interact with the other units. Example of interactions are:

- electrical cross-ties
- shared plant resources such as portable AC generators

Since Equation 1 refers to a single unit, when multiple units are considered then it is needed to track the temporal evolution of each unit: multiple $\boldsymbol{\theta}$ needs to be evaluated (one for each unit). Assuming that a three-unit plant is considered, Equation 1 now becomes as follows:

$$\begin{cases} \frac{\partial \boldsymbol{\theta_1}(t)}{\partial t} = \boldsymbol{\mathcal{H}_1}(\boldsymbol{\theta_1}, \boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, t) \\ \frac{\partial \boldsymbol{\theta_2}(t)}{\partial t} = \boldsymbol{\mathcal{H}_2}(\boldsymbol{\theta_2}, \boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, t) \\ \frac{\partial \boldsymbol{\theta_3}(t)}{\partial t} = \boldsymbol{\mathcal{H}_3}(\boldsymbol{\theta_3}, \boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, t) \end{cases} \tag{2}$$

Note that now the vector $\boldsymbol{s_i}$ $(i = 1, \ldots, 3)$ of each unit is shared among other units. This feature captures shared resources and possible system cross-ties among units.

In addition, intra-unit interactions such as a sub-set of human actions in a unit may be driven by the actual status of other unit (e.g., thermo-hydraulic limit and operational boundaries). Again, these actions may have cascade effects on the other units. This is particularly relevant for severe accident scenarios. Thus, now Eq. 2 becomes as follows:

$$\begin{cases} \frac{\partial \boldsymbol{\theta_1}(t)}{\partial t} = \boldsymbol{\mathcal{H}_1}(\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}, \boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, t) \\ \frac{\partial \boldsymbol{\theta_2}(t)}{\partial t} = \boldsymbol{\mathcal{H}_2}(\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}, \boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, t) \\ \frac{\partial \boldsymbol{\theta_3}(t)}{\partial t} = \boldsymbol{\mathcal{H}_3}(\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}, \boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}, t) \end{cases} \tag{3}$$

From a modeling point of view, solving Eq. 2 or Eq. 3 poses different challenges. Equation 2 can in fact be solved by:

1. Sampling the set of uncertain parameters $\boldsymbol{p}$
2. Determining the temporal profile of $\boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}$

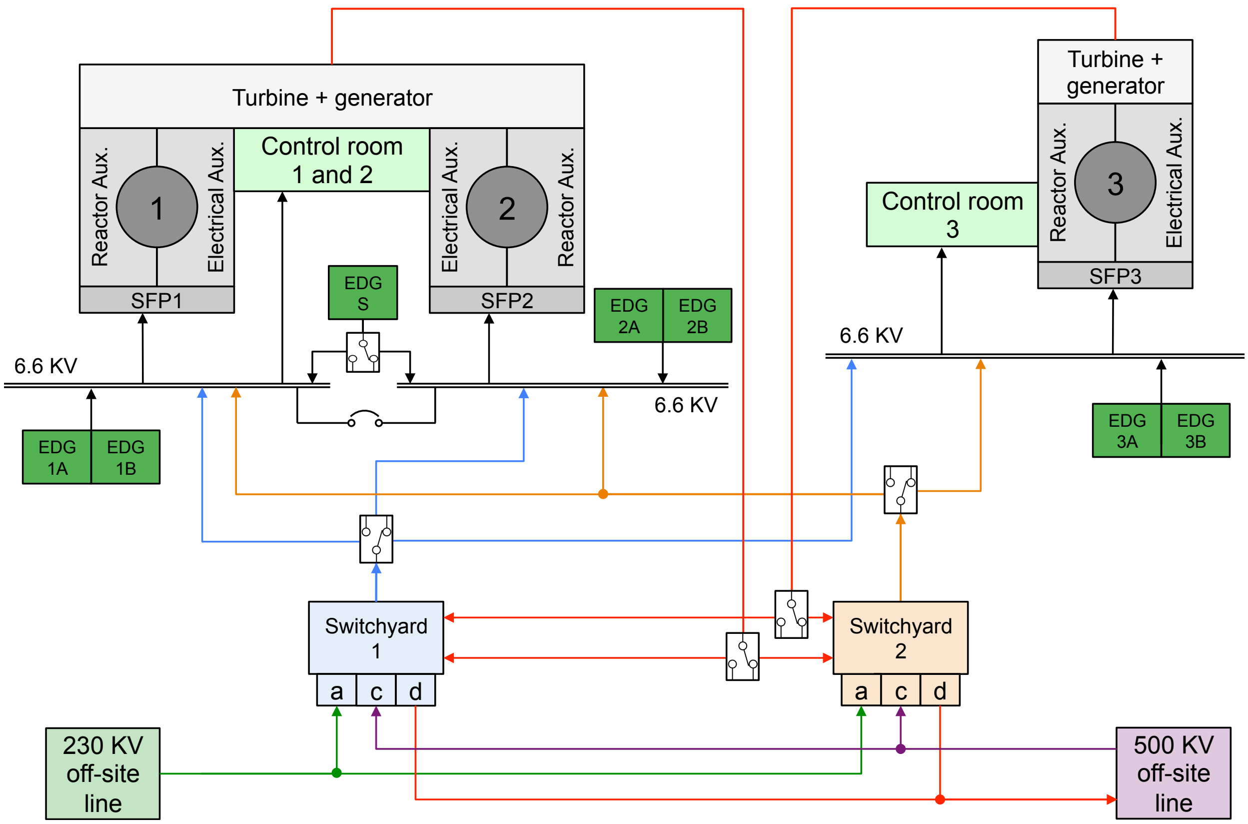

Figure 4 – Electrical scheme of the multi-unit plant

3. Run the simulator for each unit independently given $\boldsymbol{p}, \boldsymbol{s_1}, \boldsymbol{s_2}, \boldsymbol{s_3}$

On the other side, solving Eq. 3 requires a system simulator that allows running the simulation of each unit simultaneously and sharing the variables $\boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}$ among them.

Even though we are investigating cases that can be described by both Eq. 2 and Eq. 3, this paper will focus on multi-unit case that can be described by Eq. 2.

III. MULTI-UNIT TEST CASE

For the scope of this paper we have chosen a 3-unit plant as shown in Figure 2. In more detail, the system we have considered is the following (see Table 1):

- Unit 1: 1 PWR (see Figure 3) at full power (100 %) and it own Spent Fuel Pool (SFP)
- Unit 2: 1 PWR in mid-loop operation (i.e., shut-down mode) and it own SFP. The mid-loop status is characterized by a primary coolant system drained to the hot leg centerline and the existence of openings which a further reduction of the mass inventory poses a serious risk, due to boil off and possible entrainment or spill over of liquid
- Unit 3: 1 PWR at full power (108 %) that restarted a few weeks earlier and its own SFP with a higher heat load since it contains used fuel recently moved from the reactor.

In addition, special attention has been given to the design of the electrical and hydraulic systems (see Figure 5):

- The plant electrical system is shown in Figure 4. Two electrical switch-yards can provide electrical power to all units. 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. Note also that the 6.6 KV emergency buses of Unit 1 and Unit 2 can be cross-tied.
- The auxiliary feedwater (AF) system of Unit 1 and Unit 3 can be cross-tied. Thus cooling to the secondary side can be provided from one unit to the other one.
- The Condensate Storage Tanks (CSTs) of Units 2 and Unit 3 can be cross-tied. Thus the water source for the secondary side of either unit can be used as water source for the other one.
- 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.

IV. INITIATING EVENT

The considered accident scenario is a seismic event which causes the following events:

- Both switch-yards are disabled
- All EDGs are disabled except EDGS which is initially aligned to Unit 2
- CST of Unit 2 has lost 80% of its capacity
- 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

The proposed accident scenario resembles a Station Black Out (SBO) event at the plant level except for the fact that the EDGS is the only source of AC power available and it can be directed toward either Unit 1 or Unit 2.

Table 1. Initial status of the six models.

System	Status
Unit 1	Operating at 100%
Unit 2	Mid-loop operation
Unit 3	Operating at 108% with fresh fuel (recently out for refueling), high heat load in SFP3
SFP1	Operating with its own power load
SFP2	Operating with its own power load
SFP3	Operating with its own power load

V. HUMAN INTERACTIONS

From a human modeling point of view, several interactions have been considered in the analysis. Example of considered human interactions are:

- Action time to start recovery procedure at the plant level
- Type of recovery strategy to perform
- Involuntary alignment of EDGS from Unit 2 to Unit 1
- Time to perform CST or AF system cross-ties
- Time to perform emergency water injection and AC restoration using portable systems

Note that:

1. Some actions can have a negative influence on a unit but have a positive influence on a different unit.
2. Erroneous actions affect evolution of the already planned recovery strategy

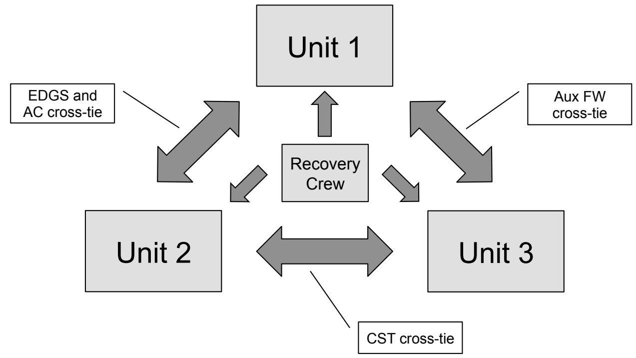

Figure 5. Summary of the shared resources in the considered multi-unit test case.

These observations can be considered as additional motivation to employ simulation-based (i.e., Dynamic) PRA methods to perform this type of analysis. Coupling between models requires an implicit timing consideration coupled with system dynamics.

For few of the human interactions we employed the HUNTER [10] approach in order to quantify the statistical properties (e.g., a probability to perform a certain erroneous action or pdf of time to perform a certain action).

VI. MULTI-UNIT MODELING

The thermo-hydraulic behavior of all PWRs and all SFPs has been modeled using the RELAP5-3D code. Each PWR and SFP is modeled separately, i.e., the nodalization and the initial conditions are set on separate input files.

Each RELAP5 model is coded such that the stopping conditions are the following:

1. Emergency water injection and AC restoration using portable systems has been completed
2. Max clad temperature reaches 2200 F

Note that a mission time has not specified; each simulation in fact ends when a safe (see condition 1) or fail condition (see condition 2) has been reached.

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. This feature allows the user to link several models together in order to perform multi-model types of analyses.

From a multi-unit point of view, 7 RAVEN models are linked: a PWR and a SFP for each unit and a global multi-unit model. The global multi-unit model includes the control logic of the overall plant and implements the plant recovery sequencing and timing of events.

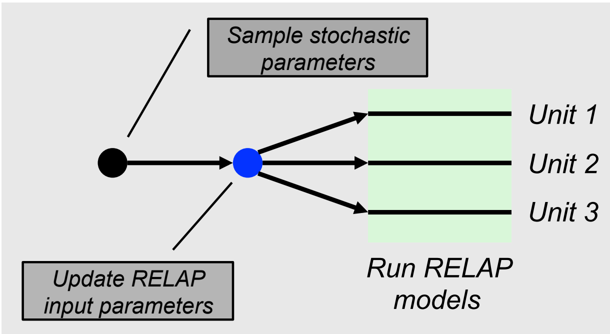

Figure 6 – Calculation flow of the multi-unit test case.

VII. STOCHASTIC ANALYSIS

For the scope of this paper we have identified the following as stochastic parameters to sample in the analysis:

1. CST x-tie time between units 2 and 3
2. FW x-tie time between units 1 and 3
3. Recovery strategy
4. Seal LOCA size PWR unit 1
5. LOCA time PWR 1
6. DC lifetime unit 1
7. Involuntary alignment of EDGS to unit 1 bus
8. AC x-tie of units 1 and 2
9. Auxiliary portable system recovery time unit 1
10. DC lifetime unit 2
11. Auxiliary portable system recovery time unit 2
12. Seal LOCA size PWR 3
13. LOCA time PWR 3
14. DC lifetime unit 3
15. Auxiliary portable system recovery time unit 3
16. LOCA size SFP 1
17. LOCA time SFP 1
18. LOCA size SFP 2
19. LOCA time SFP 2
20. LOCA size SFP 3
21. LOCA time SFP 3

An example of simulated scenario is shown in Figure 7. 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.

1. At time $t = 0$, SBO condition is reached, Unit 2 is the only unit with available AC power through the EDGS.
2. The chosen recovery strategy prioritizes Unit 3

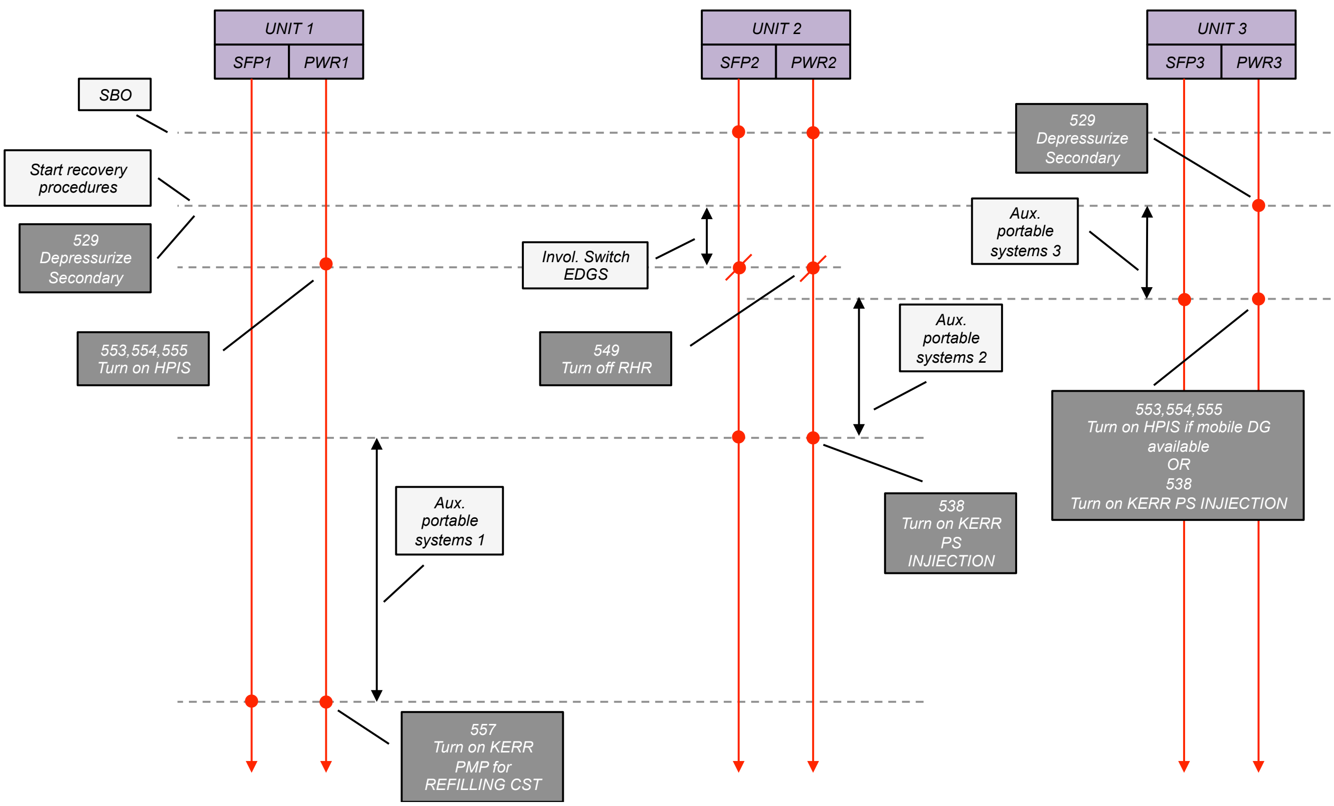

Figure 7. Example of multi-unit scenario

and therefore, efforts to connect auxiliary portable systems are initially directed towards Unit 3. The objective is moved afterwards to Unit 1.

3. 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.
4. Efforts to connect auxiliary portable systems are directed to Unit 2 once completed on Unit 3.
5. Once completed, efforts to connect auxiliary portable systems are directed to Unit 1.

VIII. SYSTEM ANALYSIS

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 define 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. Hence $2^6 = 64$ possible combinations are allowed.

The objective of this analysis is to rank PDSs based on their probability values.

Using a Monte-Carlo [14] sampling strategy we have simulated about 2000 accident scenarios. For each simulation run we have performed the following steps:

1. Sample a value for each stochastic parameter that is part of the set of parameters $\boldsymbol{p}$ (e.g., timing of events)
2. Performing the actual simulation run given $\boldsymbol{p}$ sampled in Step 1 for each model of the multi-unit plant
3. Collect the output (OK or CD) from each model and construct the PDS associated to the run
4. Associate a unique probability value to the PDS accordingly to the chosen sampling
5. Repeat Steps 1 trough 4, *N* times
6. Group simulation runs based on their own PDS and evaluate probability associated to each of the 64 allowed PDSs

IX. 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 six more relevant (from a probabilistic point of view) PDSs are shown in Table 2. Given the initiating event, there is a probability equal to 21.6 E-3 that the plant at least one model will reach a CD situation. In particular, the PWRs of units 2 and 3 are the more sensitive to reach a damaged condition. For the PWR of unit 2, the involuntary alignment of the EDGS is the most important factor for reaching CD condition.

Note that a PDS that includes more than one model in a CD condition is the PDS number 5 where both the PWRs of units 2 and 3 are damaged.

The SFPs can tolerate lasge time in a SBO condition, however a break in the SFP quickly accelerates the heatup process. In this case the first PDS that includes a CD condition in a SFP is the 6th PDS.

Table 2. Summary of the obtained results.

Rank	PDS						Probability
	P1	S1	P2	S2	P3	S3	
1	OK	OK	OK	OK	OK	OK	0.979
2	OK	OK	OK	OK	**CD**	OK	3.4 E-3
3	OK	OK	**CD**	OK	OK	OK	4.2 E-3
4	**CD**	OK	OK	OK	OK	OK	4.6 E-4
5	OK	OK	**CD**	OK	**CD**	OK	7.6 E-5
6	OK	OK	OK	OK	**CD**	**CD**	9.5 E-6

X. CONCLUSIONS

In this paper we have presented a first step toward a simulation-based approach to analyze multi-unit plants. We have described the basic method to perform both deterministic and stochastic modeling of a generic multi-unit plant by employing RAVEN and RELAP5-3D codes. We have presented a preliminary set of results that have been generated by employing high performance computing systems due to high computational time of each simulation run and due to the high number of simulation runs requested. We have shown that more quantitative analysis details can be obtained from this kind of approach.

We want to highlight again how this paper represents a first phase toward the modeling of very complex systems such as multi-unit plants. Research directions we are now following include the use of surrogate models in order to decrease the computational costs of the analysis and interface Dynamic PRA results with classical PRA methods.

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