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ANALYSIS OF SAFETY IMPACTS FROM EXTERNAL FLOODING USING THE RISK-INFORMED SAFETY MARGIN CHARACTERIZATION (RISMC) TOOLKIT

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ABSTRACT

The existing fleet of U.S. nuclear power plants is in the process of extending its lifetime and increasing the power generated from these plants via power uprates. In order to evaluate the impact of these factors on the safety of the plant, the Risk-Informed Safety Margin Characterization (RISMC) project aims to provide insight to decision makers through a series of simulations of the plant dynamics for different initial conditions (e.g., probabilistic analysis and uncertainty quantification). This paper demonstrates how Idaho National Laboratory (INL) researchers use the RISMC Toolkit to investigate complex nuclear plant phenomena using RAVEN and RELAP-7. The analysis focused on a highly relevant topic currently facing some nuclear power plants – specifically flooding issues. This research and development looked at challenges to a hypothetical pressurized water reactor, including: (1) a potential loss of off-site power followed by the possible loss of all diesel generators (i.e., a station black-out event), (2) earthquake induced station-blackout, and (3) a potential earthquake induced tsunami flood. The analysis is performed by using a set of codes: a thermal-hydraulic code (RELAP-7), a flooding simulation tool (NEUTRINO) and a stochastic analysis tool (RAVEN) – these are currently under development at INL. Using RAVEN, we were able to perform multiple RELAP-7 simulation runs by changing specific parts of the model in order to reflect specific aspects of different scenarios, including both the failure and recovery of critical components. The simulation employed traditional statistical tools (such as Monte-Carlo sampling) and more advanced machine-learning based algorithms to perform uncertainty quantification in order to understand changes in system performance and limitations as a consequence of power uprate. Qualitative and quantitative results obtained gave a detailed picture of the issues associated with potential accident scenarios. These types of insights can provide useful material for decision makers to perform risk-informed margins management.

1. INTRODUCTION

The Risk-Informed Safety Margin Characterization (RISMC) Pathway develops and delivers approaches to manage safety margins. This important information supports nuclear power plant owner/operator decision-making associated with near and long-term operation. The RISMC approach can optimize plant safety and performance by incorporating a novel interaction between probabilistic risk simulation and mechanistic codes for plant-level physics. The new functionality allows the risk simulation module to serve as a “scenario generator” that feeds information to the mechanistic codes. The effort fits with the goals of the RISMC Pathway, which are twofold.

1. To develop and demonstrate a risk-assessment method coupled to safety margin quantification. The method can be used by decision-makers as part of their margin management strategies.
2. To create an advanced RISMC Toolkit. This RISMC Toolkit would enable a more accurate representation of a nuclear power plant safety margin and its associated influence on operations and economics.

When evaluating the safety margin, what we want to understand is not just the frequency of an event like core damage, but how close we are (or not) to key safety-related events and how might we increase our safety margin through proper application of Risk Informed Margin Management (RIMM). In general terms, a “margin” is usually characterized in one of two ways:

- A deterministic margin, typically defined by the ratio (or, alternatively, the difference) of a capacity (i.e., strength) over the load
- 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., for an important process observable such as clad temperature) will be exceeded under accident scenario conditions.

The RISMC Pathway uses the probabilistic margin approach to quantify impacts to reliability and safety. As part of the quantification, we use both probabilistic (via risk simulation) and mechanistic (via physics models) approaches.

In order to perform advanced safety analysis, the RISMC project has a toolkit that was developed at INL using MOOSE [1] as the underlying numerical solver framework. This toolkit consists of the following software tools:

RELAP-7: the code responsible for simulating the thermal-hydraulic dynamics of the plant.

RAVEN: it has two main functions: 1) act as a controller of the RELAP-7 simulation and 2) generate multiple scenarios (i.e., a sampler) by stochastically changing the order and/or timing of events.

PEACOCK: the Graphical User Interface (GUI) that allows the user to create/modify input files of both RAVEN and RELAP-7 and it monitors the simulation in real time while it is running.

GRIZZLY: the code that simulates the thermal-mechanical behavior of components in order to model component aging and degradation. Note for the analysis described in this paper, aging was not considered.

2. EXAMPLE OF THE FLOODING ANALYSIS

The Figure 2 summarizes all the steps followed in this paper using the RISMC approach:

Initiating event modeling: modeling characteristic parameters and associated probabilistic distributions of the event considered

Plant response modeling: modeling of the plant system dynamics

Components failure modeling: modeling of specific components/systems that may stochastically change status (e.g., fail to performs specific actions) due to the initiating event or other external/internal causes

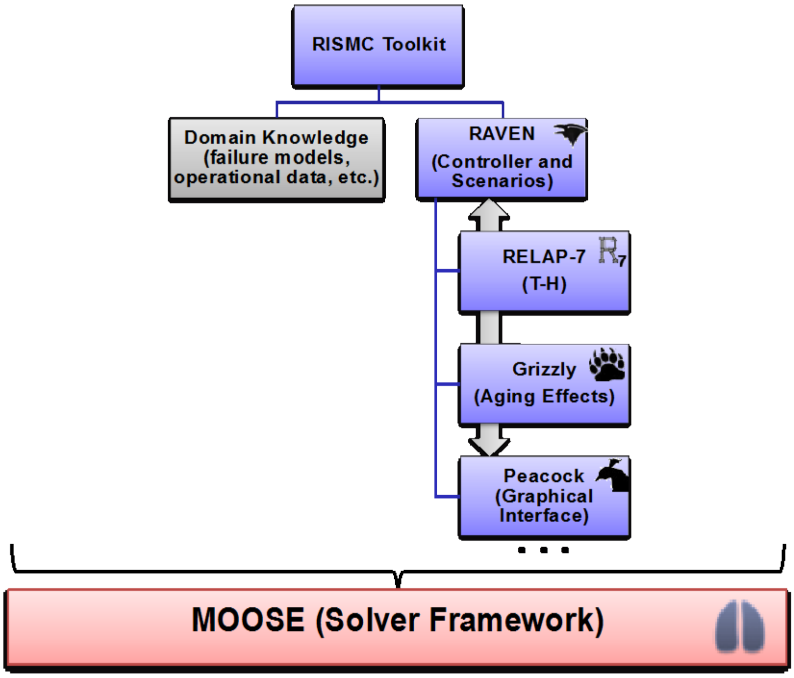

Figure 2: Overview of the RISMC toolkit

Scenario simulation: when all modeling aspects are complete, (see previous steps) a set of simulations can be run by stochastically sampling the set of uncertain parameters.

Given the simulation runs generated in Step 4, a set of statistical information [e.g., core damage (CD) probability] is generated. We are also interested in determining the limit surface: the boundaries in the input space between failure and success.

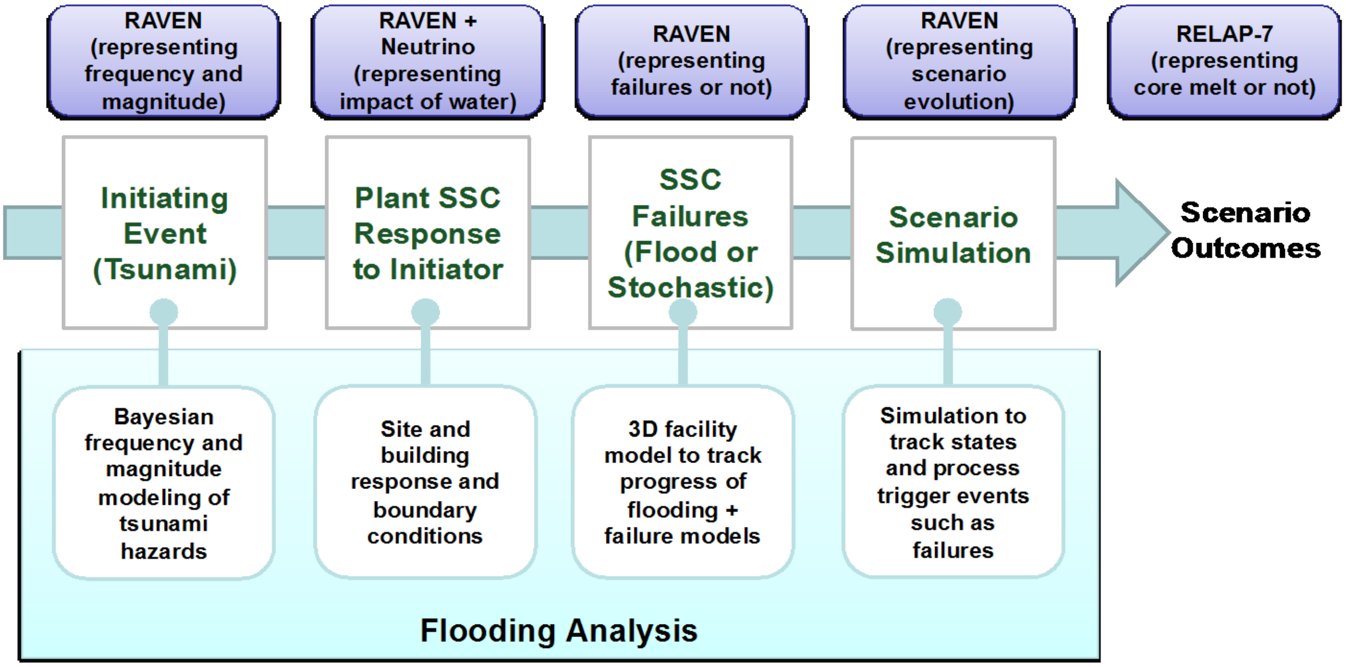

Figure 1: Overview of the RISMC scheme to simulate initiating event and plant

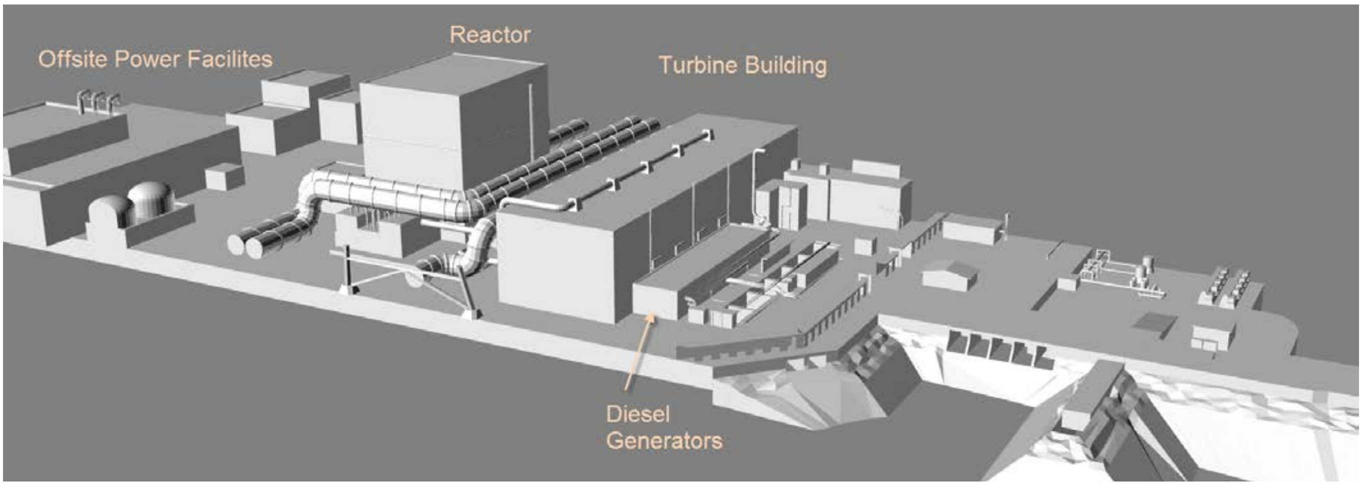

Figure 3: 3D plant model developed to simulate flooding

A generic 3D facility model (see Figure 3) was created and used to simulate various tsunami flooding examples. For initial testing only a slice of the entire facility (containing just a single unit) was used, this includes:

- Turbine building
- Reactor building
- Offsite power facilities and switchyard
- Diesel Generator (DG) building

The 3D model is used as the collision geometry for any simulations. For this demonstration all objects are fixed rigid bodies – future analysis will explore the possibility of moving debris (caused by the flood) and possible secondary impacts due to this debris.

To mimic a tsunami entering the facility, a bounding container was added around the perimeter of the model and for the ocean floor. Then, over 12 million simulated fluid particles were added for the ocean volume. A wave simulator mechanism was constructed by having a flat planar surface that moves forward and rotates, pushing the water and creating a wave in the fluid particles. Once the wave is "started," the fluid solver handles all of the remaining calculations in order to simulate the moving wave through the facility.

Various wave heights can be generated by minor parameter adjustments to the movement of the wave generator. As the fluid particles are initially forced forward their movement energy is transferred and affects the particles around them using the mathematical equations for fluid physics built into the fluid solver.

There are many different approaches for simulating and optimizing fluid movement, each having different advantages and purposes. To achieve the most realistic and accurate results, a smooth particle hydrodynamics (SPH) based solver called NEUTRINO was used [2]. NEUTRINO also factors in advanced boundary handling and adaptive time stepping to help to increase accuracy and calculation speed. Most simulations were done using 14 treads on a PC with seven cores (operating at 2.4Ghz), and took approximately 3 minutes per frame with a total run time ranging from 75-90 hours depending on how many frames were needed for the simulation.

As the particles of a simulation move, they interact with the rigid bodies of the 3D model. The simulated fluid flows around buildings, splashes, and interacts in a similar manner to real water. Measuring tools can also be added to the simulation to determine fluid contact information, water height, and even flow rates into openings at any given time in the simulation. This dynamic information can be used in two ways, a static success or failure of components or structures depending on wave height, or a dynamic result based on time for use in more detailed analysis.

Several simulations were run at different wave heights. The fluid penetration into the site is measured for each of the simulations to determine at what height the different systems fail. For our specific case, we are monitoring the venting for the diesel generators and the offsite power structures.

As shown in Figure 4, the fluid particles are penetrating both air intake vents for an 18 m wave. Evaluating this scenario in more detail, we can determine that at simulation time (or frame) 1,275 DG1 fails from splash particles and DG2 fails at 1,375.

We performed a series of simulations using the NEUTRINO code on the 3D plant model in order to measure plant response for several wave heights in the [0, 30] meters range. The basic idea is to build a response function that can be implemented in the RAVEN control logic that, depending on the sampled parameter *h* (wave height), it determines the status of both DGs and power grid switchyard.

We found that the DGs tended to fail with smaller waves than the power grid structures, because the DG building is closer to the ocean shore and air intake vents face the wave directly (see Figure 5). In fact, if the wave is greater than 18 m, water enters in both DGs air intake while power grid switchyard is flooded only for wave height greater than 30 m (see Table 1).

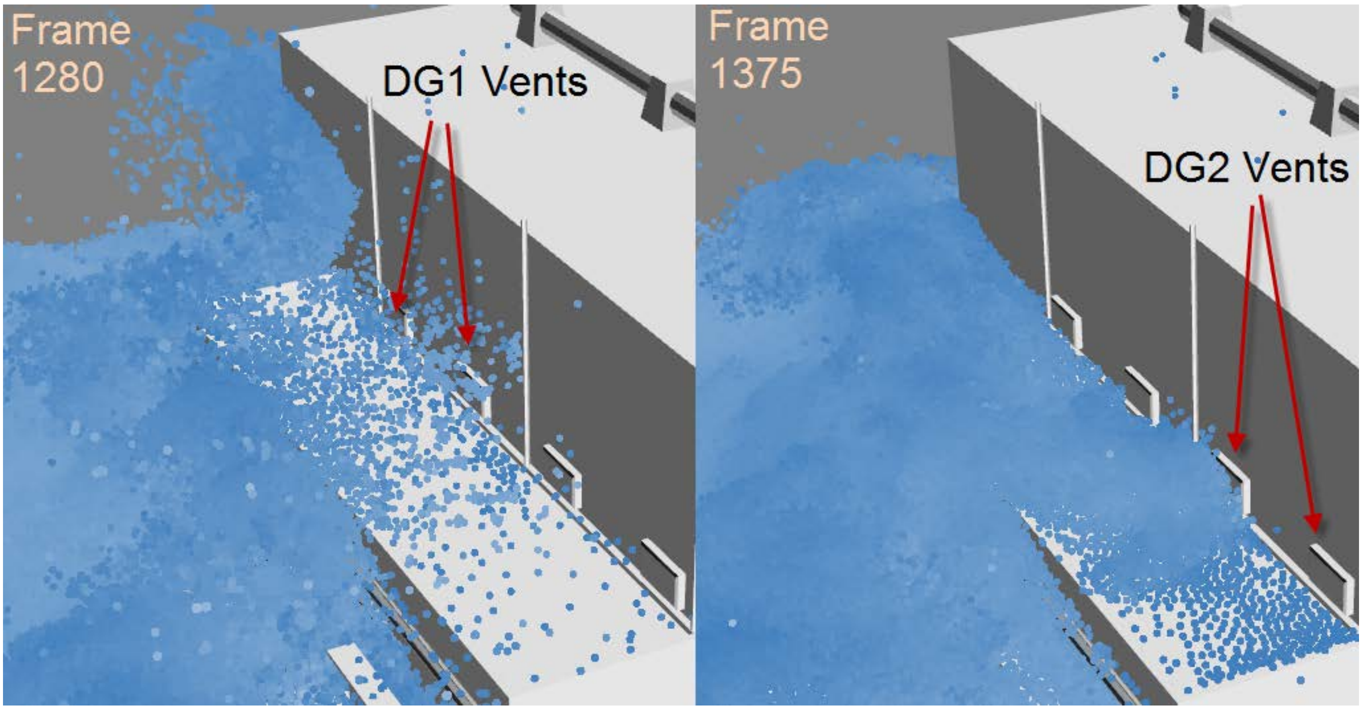

Figure 4: Time spacing between failures of generators due to fluid in the air intake vents of the generator room.

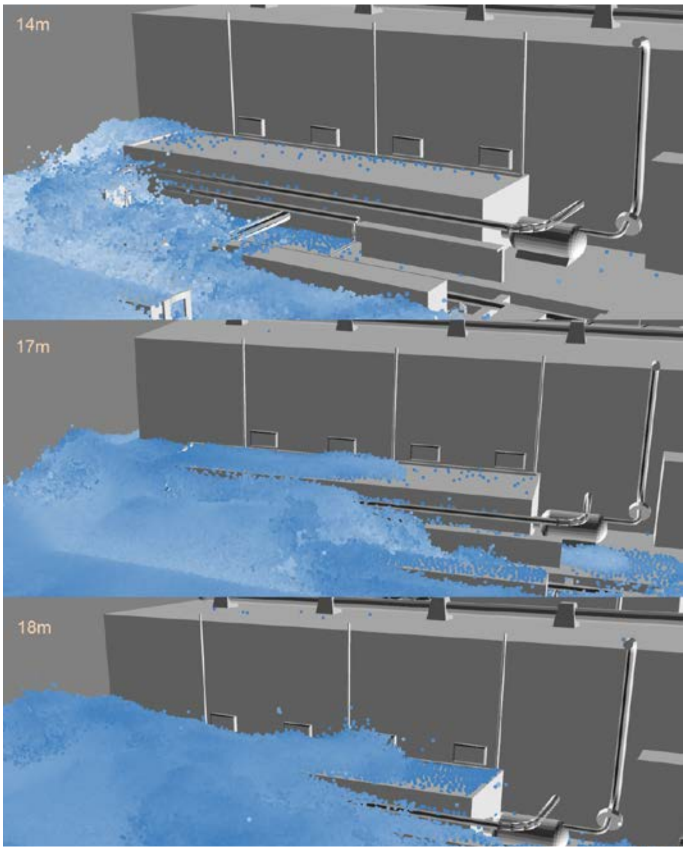

Figure 5: Max flooding levels for several wave heights.

Note that, given the fact that the 3D plant model represents only a slice of the site and there is only a small opening to the backside of the facility that allows water to reach the power grid switchyard, the power grid switchyard may fail with smaller waves if a more complete model would be used.

Table 1: Status of the two DGs (DG1 and DG2) and the power grid switchyard as function of the wave height using the NEUTRINO simulation code

Wave height (m)	DG1 status	DG2 status	Off-site power switchyard status
< 17	Ok	Ok	Ok
17-18	Failed	Ok	Ok
18-30	Failed	Failed	Ok
>30	Failed	Failed	Failed

As a second step, we started to evaluate how power uprates change the time to reach CD for different values of DG failure time. Two facts need to be considered:

1. A power uprate implies that a higher energy is generated within the core and, hence, clad failure temperature is reached sooner
2. A late DG failure time allows the ECCS to successfully remove more heat from the RPV. Since decay heat curve is exponential we expect that such dependency is not linear

Such reduction in time to reach CD ranges from 3,200 s to 4,000 s (see Figure 6); hence, on average the core reaches CD about an hour quicker if power level increases from 100% to 120%.

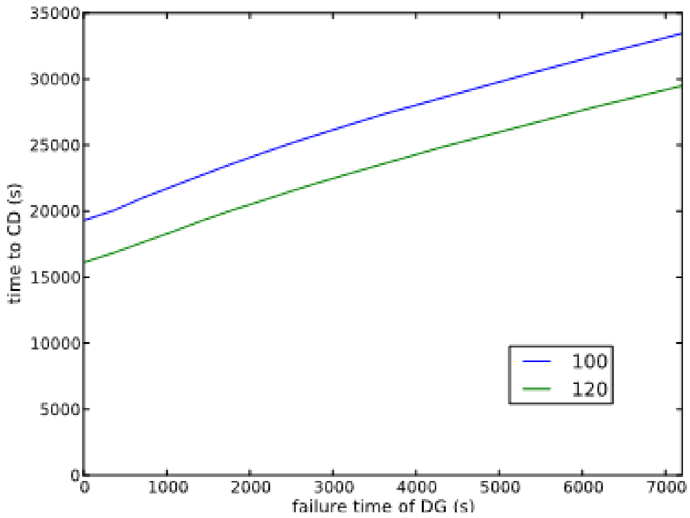

Figure 7: Time needed to reach CD as function of DG failure time

While our analysis deterministically measures timing reduction due to power uprate, it does not show how such uprate probabilistically change the probability to reach CD. In other words, how does an average time reduction of one hour to reach CD modify the actual probability of CD event itself? We answer this question by using Latin hypercube sampling (LHS) available within the RAVEN statistical framework, specifically we:

1. Sampled *N* times the distribution of the uncertain parameters found in our model [see Reference (3) for additional details)]
2. Run *N* times RAVEN/RELAP-7 simulations with simulation parameter values changed accordingly to the sample values (generated in Step 1)
3. Evaluated overall CD probability by looking at the outcome of each RAVEN/RELAP-7 simulation

An example of transient leading to CD using the RAVEN statistical framework is shown in Figure 7 for the following sampled scenario:

- Wave height h = 22.4 m
- Wave hits the plant at t_{wave} = 29 min
- DG recovery time t_{DGrec} is about 32 10^3 s
- power grid recovery time t_{DGrec} is about 39 10^3 s

As expected since *h* > 18m, the wave hits the DG building and disables them: AC is completely lost at this time (SBO condition). Since recovery time of both DG and power grid are above the time needed to reach CD, the final outcome of the simulation is CD which is reached at 23.6 103 s (6.5 h).

Using the RAVEN statistical framework, we performed Latin Hypercube Sampling of the distributions associated with the uncertain parameters. We performed such sampling for both power levels: 100% and 120%. We then divided all the simulated scenarios (10,000 simulations for each power level) into two groups, CD or OK.

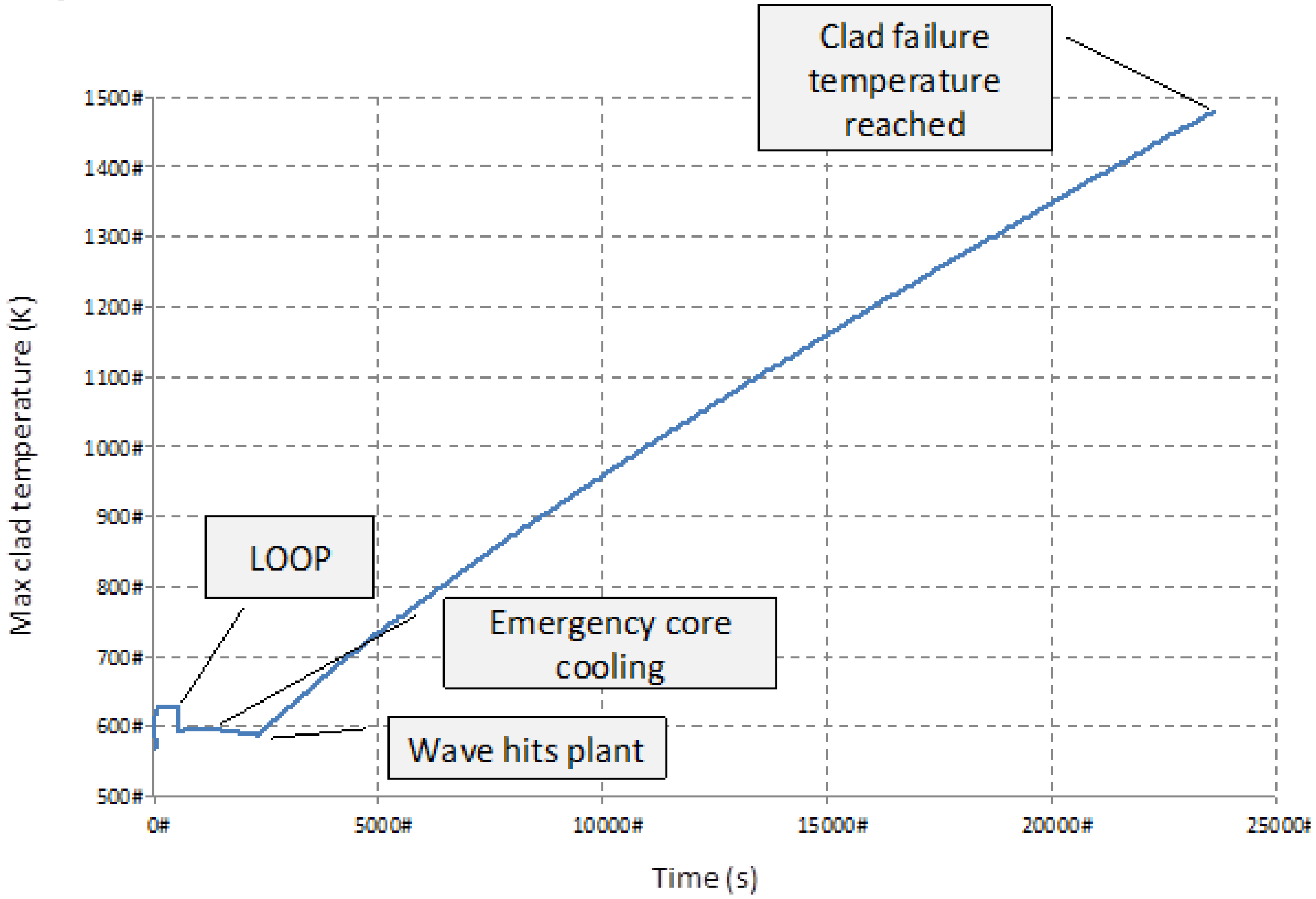

Figure 6: Example of sampled scenario leading to CD due to a 22.4 m height wave hitting the plant at about 30 min after LOOP. When the wave hit the plant, since its height is above 18 m, the DG are disabled and the recovery times are past CD condition.

For our analysis, we found that the probability of core damage was 2.2 10^{-3} (at 100% nominal power) and 5.2 10^{-3} (when at a 120% power uprate).

6. CONCLUSIONS AND DISCUSSION

In this paper we have summarized the series of steps that are needed to evaluate a RISMC detailed demonstration case study for an emergent issue using RAVEN and RELAP-7. We studied the impacts of power uprates on a flooding induced SBO event using the RISMC toolkit. We started by modeling both the PWR system dynamics using the RELAP-7 code and the flooding scenario using the NEUTRINO code.

Even though the RELAP-7 and NEUTRINO codes were not tightly coupled to each other (i.e. the flooding analysis causes triggers such as a DG failure that is captured in the RELAP-7 calculation), it was possible to evaluate the overall system response on a much greater level of detail than compared to classical event tree and fault tree based methodologies.

Our statistical analysis was performed using the RAVEN code which allowed us to evaluate the impacts of power uprates on the overall probability of core damage. We also determined how plant recovery procedures get reduced in time due to the power uprate itself.

In this report we particularly focused on steps that are necessary to complete such statistical analysis and the information that can be generated from it. Such information can be used to perform decision making for the three possible scenarios:

1. Power uprate is feasible since core damage probability increase is below the acceptable limits
2. Power uprate is not feasible since core damage probability increase is above the acceptable limits
3. Even though is above the acceptable limits, power uprate is feasible if recovery procedures are enhanced

For the third scenario, recovery procedure enhancement may include the following:

- Increase a wave protection wall in order to reduce flooding level in the plant. This will act on the fraction of the wave height distribution that causes DG failure.
- Improve AC emergency recovery procedures (e.g., FLEX system). This action acts directly on either the DG or power grid recovery distribution, i.e., a lower DG or power grid average recovery time.
- Move the DGs to a non-flood prone area of the plant site.
- Improve the bunkering of the DG building in order to reduce the likelihood of flood-caused failures.

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