Uncertainty Quantification for External Events Analysis of LWRS/RISMC Project

Carlo Parisi, Andrea Alfonsi, Cristian Rabiti, Ronaldo H. Szilard

Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID, 83415-3860
Carlo.Parisi@inl.gov; Andrea.Alfonsi@inl.gov; Cristian.Rabiti@inl.gov; Ronaldo.Szilard@inl.gov

INTRODUCTION

In the framework of the US-DOE Light Water Reactor Sustainability/ Risk-Informed Safety Margin Characterization (LWRS/RISMC) project [1], methods, data and tools are being developed with the ultimate scope of improving the safety and operation of the current US nuclear fleet. A set of Industrial Applications (IA) concerning the most relevant safety issues is defined for applying and testing the developed toolkits. The ultimate scope of IA #2 is a realistic simulation of natural external hazards that impose threat to a Nuclear Power Plant (NPP) [2]. A methodology, which combines a qualified set of tools able to perform advanced risk-informed safety analysis, has been described in a previous paper [3]. In this paper we present the details of the uncertainty quantification (UQ) for the system thermal-hydraulic code and how the UQ is integrated in the global external-events analysis.

DESCRIPTION OF THE ACTUAL WORK

External Events analysis Methodology

IA #2 of LWRS/RISMC is developing a set of tools and a methodology for performing advanced safety analysis of external events. In particular, earthquake-initiated events, causing internal/external flooding and systems, structures and components (SSC) damages are being studied by the External-EVEnts-Baseline (EEVE-B) toolkit [3]. The workflow of the methodology and the tools used are presented in Table 1 and Figure 1.

An advanced toolkit (EEVE-A), based on the INL’s MOOSE platform codes [4], is also under development and validation. Results presented hereafter are obtained using the EEVE-B toolkit.

Table 1. Selected Tools for EEVE-B

<table>
<thead>
<tr>
<th>Tools</th>
<th>Task</th>
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<tbody>
<tr>
<td>LS-DYNA</td>
<td>EQ Analysis</td>
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<tr>
<td>OPENSEES</td>
<td>Piping Analysis</td>
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<tr>
<td>NEUTRINO</td>
<td>Flooding Analysis</td>
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<td>RELAP5-3D</td>
<td>System TH</td>
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<td>RAVEN</td>
<td>Sensitivity/Uncertainty</td>
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<td>EMRALD</td>
<td>Dynamic PRA</td>
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Uncertainty Tool

The RAVEN code [5], developed at INL, is the tool used for the Uncertainty Quantification (UQ) step. RAVEN is a generic software framework designed to perform parametric and probabilistic analysis based on the response of system codes. It can investigate system codes responses as well as input space using various sampling schemes. It can also allow the use to perform system feature discovery using state-of-the-art methods (e.g., using dynamic supervised learning techniques, limit surfaces, etc.). In the framework of LWRS/RISMC IA #2, RAVEN is applied only to the UQ and uncertainty propagation of the RELAP5-3D system thermal-hydraulic code [6] calculations.

Reference system: the INL Generic PWR

The developed external-events methodology is being applied to the so-called INL Generic PWR (IGPWR). IGPWR is based on a 2546 MWth 3-loop Westinghouse NPP. The primary and part of the secondary sides plus some of auxiliary systems are considered in the analyses while containment and balance-of-plant (BOP) are instead neglected. The typical events that are being analyzed are the Loss-Of-Offsite Power (LOOSP) and the Station Blackout (SBO) events.
RELAP5-3D modeling

A RELAP5-3D code thermal-hydraulic model of the primary and of part of secondary side of the IGPWR was developed. Boundary conditions for simulating LOOP/SBO events were included. Long-term and short term scenarios with and without recovery actions were simulated. Nodalization validation was performed using NPP publicly available data and previous works [7]. The RELAP5-3D calculations were run for the mission time (24 hrs.) or till the onset of the fuel failure (peak clad temperature (PCT) of 2200 F).

![Fig. 2. RELAP5-3D model of the IGPWR.](image)

RAVEN/RELAP5-3D Sensitivity & Uncertainty Calculations

RAVEN code is coupled via a dedicated application program interface (API) to the RELAP5-3D system code. The API allows, with a set of dedicated RAVEN input commands, to:

- automatically perturb the RELAP5-3D input decks, changing the selected uncertainty parameters. Different sampling strategies can be chosen (e.g., Monte Carlo, Grid, etc.);
- run on HPC machines (e.g., INL’s FALCON cluster) multiple RELAP5-3D input decks at the same time;
- post-process all the RELAP5-3D outputs, performing statistic calculations;
- visualize results of multiple runs.

The applied UQ methodology is based on the Code Scaling, Applicability, and Uncertainty evaluation (CSAU) method [8], with Monte Carlo perturbations of the input space. The investigated transient is an EQ-induced SBO, with internal flooding causing battery failures. Operator and emergency crew actions are simulated, including secondary side depressurization and primary side injection by mobile, high-pressure, diesel-driven (Kerr) pumps (see Figure 3).

![Fig. 3. SBO transient - RELAP5-3D pressure trends.](image)

According to [9], deployment of mobile pumps requires at least 150 minutes from the initiating event. In Figure 4, it is reported the PCT. The fuel experience an overheating caused by the core uncovers. The fuel is quenched by the effects of the auxiliary turbine-drive feedwater pump recovery (blackrun) and by the accumulator injections. The primary water injection by mobile pumps guarantees a long-term cooling.

![Fig. 4. SBO transient - RELAP5-3D PCT calculation.](image)

A simplified Phenomena Identification and Ranking Table (PIRT) table has been developed for identifying the main TH phenomena involved during the analyzed transient. They are:

- natural circulation in the primary loop;
- secondary side mass inventory loss through the Steam Generator Steam Relief Valve and Pilot-Operated Relief Valve (SG SRV and PORV);
- primary mass inventory loss through the Main Coolant Pump (MCP) seal and the pressurizer PORV.
The selected Figure-of-Merit (FOM) is the PCT. Relevant input parameters (e.g., MCP seal LOCA area, core pressure losses, valves critical flow, core decay power, etc.) have been identified and a ranking has been automatically performed, exploiting the “ImportanceRank” function of RAVEN. Different probabilities distributions has been assigned to the input uncertainties parameters, using selected references.

Wilks’ formula \([10]\) is used for achieving a 95% fractile/95% confidence limit on the resulting FOM, running 59 RELAP5-3D calculations. An example of the RAVEN/RELAP5-3D UQ for a SBO transient is given in Figure 5.

![Figure 5](image)

The information obtained by the “fine-mesh” limit surface is then used for informing the EMRALD dynamic PRA calculations. When the sampled EMRALD parameters identify a point that is in the safe or failed zones, the results are automatically stored in its database for calculating the core damage frequency. If the sampled point falls within a user-defined distance from the limit surface, then RELAP5-3D (including the UQ calculations) are run for exactly determines the fuel status. In this way, the final coupled calculations EMRALD/NEUTRINO/RELAP5-3D are informed with the UQ.

CONCLUSIONS

A methodology for performing risk-informed earthquake/flooding/system analysis of the IGPWR has been developed. The methodology is based on the use of state-of-the-art deterministic and probabilistic tools. In this framework, UQ has a relevant role. In this paper we described the activities related to the UQ of the RELAP5-3D code through the RAVEN code. RAVEN demonstrated to be a versatile tool, allowing the easy management of the large number of calculations and data required for the UQ. The uncertainty boundary has then been used for determining a limit surface and for informing the coupled EMRALD/NEUTRINO/RELAP5-3D calculations, resulting in a reduction of the computational costs and in a better characterization of the calculated safety margin.

REFERENCES