RELAP5-3D role in the Risk-Informed External Events Safety Analysis

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RELAP5-3D is applied for the risk-informed external events safety analyses performed under the US-DOE LWRS Project, RISMC pathway. RELAP5-3D is part of the external events analysis toolkit.

Introduction

Risk-informed safety analyses for external events can bring sensible benefits to the nuclear power industry, easing the regulatory burden introduced in the aftermath of the Fukushima accident. In the framework of the US-DOE Light-Water Reactor Sustainability (LWRS) program, research into Risk-Informed Margin Characterization (RISMC) is conducted at INL to develop a toolkit for performing external hazards analysis. This toolkit, EEVE (External EVEnts) is comprised of INL and commercial state-of-the-art codes.

EEVE was originally set-up and applied for simulating earthquake-induced transients with internal flooding in a PWR [1]. However, it can be used to simulate other external events. RELAP5-3D constitutes the system code simulator for the EEVE toolkit.

Toolkit and Methodology

Risk-Informed safety analysis is the most realistic and least conservative safety analysis [2]. It involves the use of Best-Estimate Plus Uncertainty (BEPU) for deterministic calculations and the use of Probabilistic Risk-Analysis (PRA) for determining the availability of systems, structure and components (SSC) of a nuclear power plant (NPP). The final result is a better assessment of the NPP safety margins, with a reduction of undue conservatisms and a better understanding of the phenomena involved in the considered scenario. In the LWRS/RISMC approach [3], the toolkit has to have the capability of not only performing a classical "risk-informed" analysis, but it has to allow the simulation of a "virtual NPP." This is achieved by integrating the Best-Estimate (BE) codes available at INL in the EEVE toolkit.

The selected codes for the toolkit and the coupling scheme are shown in Fig. 1. Originally, EEVE was set-up and applied to simulate a PWR undergoing a transient induced by an earthquake (EQ) with internal flooding in a PWR. However, EEVE can be easily applied to other external hazards than just seismic events with flooding (e.g., high winds, intense precipitation, etc.). EEVE can be also used just for evaluating new data and determining critical areas that would benefit most from advanced analysis methods.

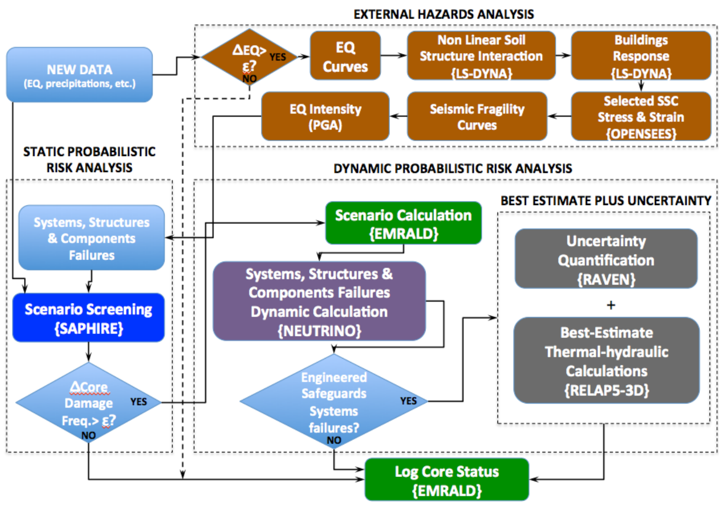

Figure 1. External Events Workflow and EEVE Toolkit.

Role of RELAP5-3D

1. EEVE Workflow

RELAP5-3D is selected as the BE code for the system analysis. According to the developed methodology described in Fig. 1, the first step is the deterministic calculations for evaluating the propagation of a set of earthquakes and for ascertaining the effects on a fire suppression system in an auxiliary building. These deterministic calculations are performed using the LS-DYNA and the OPENSEES structural mechanics codes. Their combined use allows the safety analyst to calculate the earthquake propagation in the soil, the building and the systems response to the earthquake shaking (LS-DYNA and OPENSEES), see Fig. 2.

Fig. 2. LS-DYNA seismic analysis of nuclear power plant buildings

The second step is to evaluate the probability failures and event trees of a generic 3-loop Westinghouse PWR, derived from a generic SAPHIRE Probabilistic Risk Assessment (PRA) code model. Events considered are seismically induced Loss of Offsite Power (LOOP), Station Blackout (SBO), and fire suppression piping failure. The SAPHIRE code allows pre-screening of all possible branches of the event trees and selection of those with the largest Core Damage Frequency increase for further analysis using dynamic PRA methods.

If the change in the core damage frequency is sufficiently high, the third step is taken. INL`s EMRALD code [4] performs dynamic PRA calculations of the identified sequences. It integrates risk analysis with on-line deterministic safety analysis results from seismically-induced internal flooding calculations from the NEUTRINO code, combined with Best-Estimate Plus Uncertainty (BEPU) analyses by RELAP5-3D-RAVEN coupled codes. NEUTRINO is a three-dimensional code which can simulate flooding scenarios of compartments, rooms, open fields, etc. (see Fig. 3).

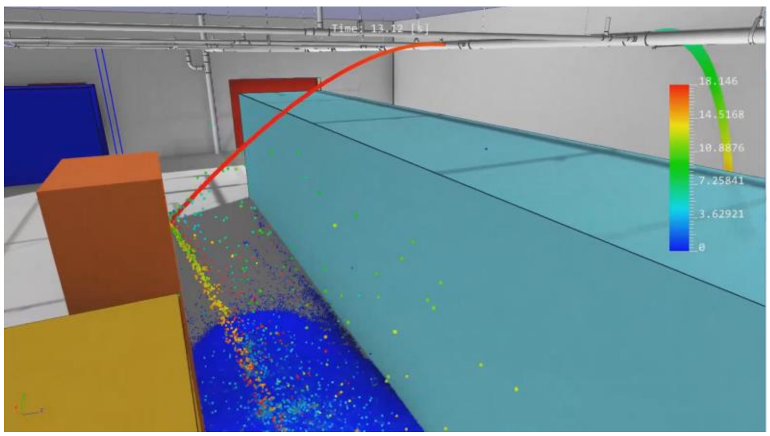

Fig. 3. NEUTRINO Flooding Simulation

If NEUTRINO finds that the flooding affects some of the Engineered Safeguard Systems (ESF), EMRLAD invokes RELAP5-3D/RAVEN system calculation for further analysis of the scenario (step 4). Otherwise, EMRALD log the outcome of NEUTRINO calculations as a “safe” status for the reactor core.

2. RELAP5-3D/RAVEN for BEPU

Risk-informed safety analysis involves the use of BEPU technology. Therefore, RELAP5-3D is coupled with RAVEN uncertainty code [5] to provide BEPU calculations to EMRALD.

RELAP5-3D/RAVEN coupled codes are invoked by EMRALD if ESFs fail because of damaging flooding conditions calculated by NEUTRINO. RELAP5-3D is run using a 3-loop Westinghouse PWR nodalization for the different LOOP and SBO scenarios.

For demonstration purposes, a simplified Phenomena Identification and Ranking Table (PIRT) has been developed and relevant input parameters and uncertainty distributions have been selected. Monte Carlo based perturbations are run by RAVEN, and first and fourth order statistics has been applied for both selected scenarios (LOOP and SBO), demonstrating the coupled codes capabilities. This meant running 59 and 153 Monte Carlo simulations for every RELAP5-3D case, perturbing input uncertainty parameters.

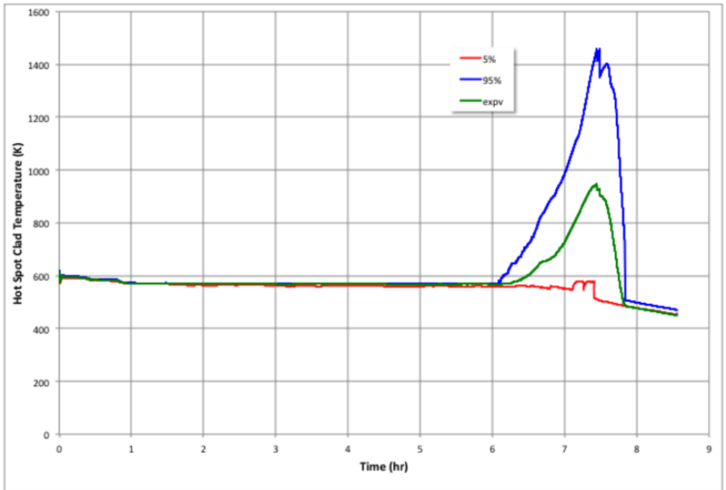

Fig. 4. Uncertainty bands for BEPU RELAP5-3D/RAVEN calculation for a LOOP scenario.

RAVEN has also been used for performing an automatic limit surface search for LOOP and SBO scenarios. A limit surface is an n-dimensional surface describing the plant status, e.g. identifying, as a function of selected plant parameters, the boundaries between failed and safe conditions for the core fuel. Using RELAP5-3D/RAVEN, the RAVEN machine-learning algorithms (near-neighbor, support-vector machine, etc.) have been used for determining relevant limit surfaces.

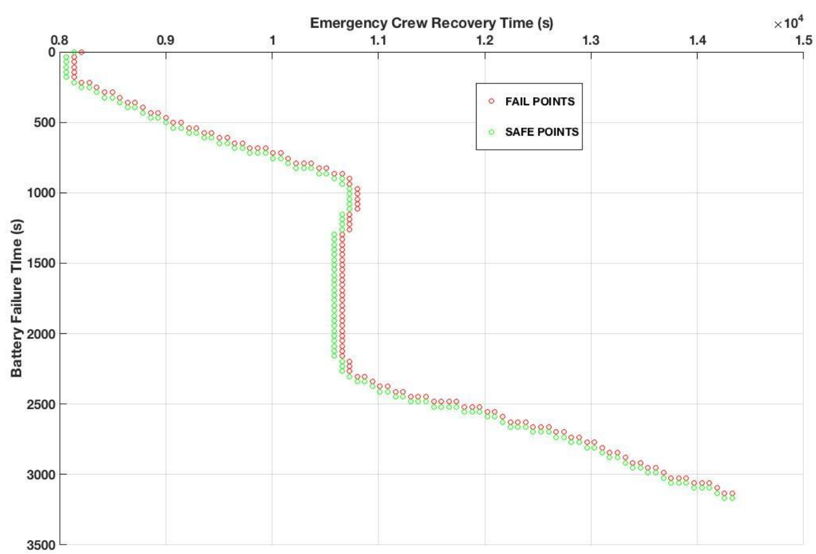

Fig. 5. RELAP5-3D/RAVEN limit surface for SBO scenario.

3. Interfacing RELAP5-3D/RAVEN with EMRALD

The results of RELAP5-3D/RAVEN calculations (BEPU and limit surfaces) are processed by EMRALD, the INL dynamic-PRA code. EMRALD records the core status for each RELAP5-3D/RAVEN run, depending on the success/failure criteria set-up by the safety analyst. For our cases, we assumed core failure if PCT>2,200 F. In this way, EMRALD is able to provide the estimation of the final Core Damage Frequency for the investigated scenarios.

Summary

RELAP5-3D represents the workhorse for the EEVE risk-informed external events analysis toolkit. Coupled with RAVEN, RELAP5-3D can provide BEPU calculations and automatic limit surface search for the studied scenarios. Future works should include the development of RELAP5-3D capabilities in performing a full BEPU analysis (i.e., by perturbing selected closure laws), integration of all EEVE codes on a common HPC platform, direct coupling between EMRALD and RELAP5-3D/RAVEN.

Bibliography

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