RAVEN/RELAP5-3D UQ analysis for a DOE LWRS/RISMC Multiple Hazards Demonstration

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Topics

- LWRS/RISMC Multiple (External) Hazards Demo Motivation
- Toolkits
- Main steps
- Testing RELAP5-3D/RAVEN capabilities
  - Limit Surface Search
  - UQ for External Events
Motivation

**Goals of the RISMC Pathway**
- Develop and demonstrate a risk-assessment method **coupled** to safety margin quantification
- Create an advanced “RISMC toolkit”

**Motivation:** to perform an advanced risk analysis of accidental events caused by a combination of natural external hazards i.e. earthquake and flooding
- Use of INL advanced simulation tools & methods
- Perform **realistic** risk analysis for a generic PWR/BWR
- Study NPP behavior under:
  - Internal/External flooding scenario caused by EQ (e.g., EQ-induced pipe rupture, levee break)
- Outcomes for FY16:
  - Risk analysis of scenarios caused by external events, **using realistic plant models, simulations and uncertainties** (for a generic PWR)
- **Two toolkits** (External EVEnts toolkits, **EEVE**) + pathways are defined
The Toolkits: EEVE-B & EEVE-A

**Baseline Demonstration [EEVE-B]**
- Use of existing, validated & state-of-the-art tools (e.g., RELAP5-3D)
- one-way coupling
- generic NPP

**Advanced Component [EEVE-A]**
- Use of advanced INL tools (e.g., RELAP-7),
- Direct coupling (e.g., flooding-RELAP7),
- Use of Reduced Order Model (ROM) & Surrogates
- Advanced Seismic probabilistic risk analysis (ASPRA)
Industry Application #2 - Methodology

5 Phases identified for the EEVE-Baseline

- Simulate effects of EQ on a NPP SSCs using advanced seismic analysis methodology
  - Use of Non-linear soil-structure interaction (NLSSI) methodology [**LS-DYNA & MASTODON**]
  - Piping fragilities evaluation [**OPENSEES**]
- Simulate NPP flooding scenarios caused by EQ-induced pipe rupture [**NEUTRINO**]
- Simulate NPP primary circuit + part of BOP dynamics [**RELAP5-3D**]
- Apply S/U analysis [**RAVEN**]
- Evaluate risk of scenarios (ranking) using dynamic PRA analysis [**EMRALD**]
**IGPWR Basic Information**

- INL-Generic PWR (IGPWR) defined for EE analysis
- Main Characteristics:
  - 3 Loop PWR / NSSS by Westinghouse
  - Core average power: 2546 MW\(_{th}\) [855 MW\(_{e}\)]
  - Core: 157 FA [15x15 Westinghouse FA]
  - Sub-atmospheric Containment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (SI units)</th>
<th>Value (British units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Power [MW(_e)]</td>
<td>2,546</td>
<td></td>
</tr>
<tr>
<td>Reactor Inlet / Outlet Temperature [°C / °F]</td>
<td>282 / 319</td>
<td>540 / 606</td>
</tr>
<tr>
<td>Number of Fuel Assemblies</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>Rod Array</td>
<td>15x15</td>
<td></td>
</tr>
<tr>
<td>RCS Coolant Flow [kg/s / lbw/hr]</td>
<td>12,738</td>
<td>101.6E+8</td>
</tr>
<tr>
<td>Nominal RCS Pressure [MPa / psig]</td>
<td>15.5</td>
<td>2,250</td>
</tr>
<tr>
<td>MCP seal water injection [m³/s / gpm]</td>
<td>3.78E-3</td>
<td>8</td>
</tr>
<tr>
<td>MCP seal water return [m³/s / gpm]</td>
<td>1.42E-3</td>
<td>3</td>
</tr>
<tr>
<td>MCP Power [MW / hp]</td>
<td>5.22</td>
<td>7,000</td>
</tr>
<tr>
<td>Number of SG</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>PRZ PORV set points op./clos. [MPa / psig]</td>
<td>16.2 / 15.7</td>
<td>2,350 / 2,280</td>
</tr>
<tr>
<td>PRZ PORV capacity [kg/s / lbm/hr]</td>
<td>2 x 22.5</td>
<td>2 x 179,000</td>
</tr>
<tr>
<td>PRZ SV set points op./clos. [MPa / psig]</td>
<td>16.4 / 17.7</td>
<td>2,375 / 2,575</td>
</tr>
<tr>
<td>PRZ SV capacity [kg/s / lbm/hr]</td>
<td>3 x 37.0</td>
<td>3 x 293,330</td>
</tr>
<tr>
<td>Relief Tank Rupture Disc capacity [kg/s / lbw/hr]</td>
<td>113.4</td>
<td>9.0E+5</td>
</tr>
<tr>
<td>Relief Tank Rupture Disc set point op. [MPa / psig]</td>
<td>6.89</td>
<td>1000</td>
</tr>
<tr>
<td>Relief Tank Total Volume [m³ / ft³]</td>
<td>36.8</td>
<td>1300</td>
</tr>
<tr>
<td>Relief Tank Water Volume [m³ / ft³]</td>
<td>25.5</td>
<td>900</td>
</tr>
<tr>
<td>SG PORV capacity [kg/s / lbw/hr]</td>
<td>1 x 3.73E+5</td>
<td></td>
</tr>
<tr>
<td>SG PORV set points op./clos. [MPa / psig]</td>
<td>7.24 / 6.89</td>
<td>1,050 / 1,000</td>
</tr>
<tr>
<td>SG SV capacity [kg/s / lbw/hr]</td>
<td>5 x 3.73E+5</td>
<td></td>
</tr>
<tr>
<td>SG SV set points op./clos. [MPa / psig]</td>
<td>8.16 / 7.53</td>
<td>1,184 / 1,092</td>
</tr>
<tr>
<td>Secondary Pressure [MPa / psig]</td>
<td>5.49</td>
<td>796</td>
</tr>
<tr>
<td>Secondary Side Water Mass @ HFP [kg / lbw]</td>
<td>41,639</td>
<td>91,798</td>
</tr>
<tr>
<td>SG Volume [m³ / ft³]</td>
<td>166</td>
<td>5,868</td>
</tr>
</tbody>
</table>
Seismic Analysis

- Calculation of Non Linear Soil-Structure Interaction (NLSSI) by LS-DYNA/MASTODON code
  - Use of generic soil
  - Propagation of EQ ground motion
  - Acceleration Response Spectra
- Piping analysis by OPENSEES code
  - Determination of fragility curves (PGA vs Probability of Failure)
PRA Analysis – SAPHIRE/EMRALD codes

- **PRA model**
  - Updated **SAPHIRE** model for generic 4-loops PWR to **generic 3-loops PWR**
  - PWR Simplified **LOOP** and **SBO** PRA (event trees + fault trees) developed
  - Convert **SAPHIRE** PRA to **EMRALD** PRA models
  - **EMRALD** calculates PRA dynamically:
    - Run **RELAP5-3D/RAVEN** [when possible fuel damage could occur] & **NEUTRINO** [when flooding could occur] codes
    - Process **RELAP5-3D/RAVEN** & **NEUTRINO** results into the final result probabilities
**EMRALD logic**

Path Given for External Events simulation

1. IE EQ causing LOOP
2. Calculation of **Peak Ground Acceleration (PGA)** for given EQ
3. Evaluate DG availability given EQ (LOOP → SBO yes/no)
4. Determine Pipe Failures (Yes/No)
   - If Yes → Run 3D **NEUTRINO** flooding Simulation
5. Run multiple samples for **additional component failure rates** (e.g., electrical components), given EQ
6. Call **RAVEN/RELAP5-3D** given all component failures
7. Log Fuel Damage
NEUTRINO Internal Flooding Model

Switchgear Room 1 – NEUTRINO Flooding Simulation

to RAVEN/RELAP5-3D simulation

Components Affected by Flooding

<table>
<thead>
<tr>
<th>Equipment ID</th>
<th>Description</th>
<th>Height</th>
<th>Affected Comp./Systems</th>
</tr>
</thead>
</table>
| BAT-1-A      | control storage battery | 18 in. | • TD-AFW
• 5G & PRZ PORV
• Switchgear (close and tripping power for all 12.47/4.16 KV and some 480 V breakers)
• Annunciators
• EDG (air start solenoid, fuel pump power, control circuit)
• Control Panels
• Emergency Lighting
• Vital Bus Inverters |
| BAT-1-B      | control storage battery | 18 in. | • TD-AFW
• 5G & PRZ PORV
• Switchgear (close and tripping power for all 12.47/4.16 KV and some 480 V breakers)
• Annunciators
• EDG (air start solenoid, fuel pump power, control circuit)
• Control Panels
• Emergency Lighting
• Vital Bus Inverters |
| SWGR-4KV-1   | 4160V medium voltage switchgear (and components) | 4 in. | Out of mission time (8hr) |
| LC-480V-1    | 480V load center (and components) | 6 in. | Out of mission time (8hr) |
| BAT-CHGR-1-A | battery charger | 4 in. | Out of mission time (8hr) |
| BAT-CHGR-1-B | battery charger | 4 in. | Out of mission time (8hr) |
| 125VDC-PNL-1 | 125V DC distribution panel | 16 in. | • TD-AFW
• 5G & PRZ PORV
• Switchgear (close and tripping power for all 12.47/4.16 KV and some 480 V breakers)
• Annunciators
• EDG (air start solenoid, fuel pump power, control circuit)
• Control Panels
• Emergency Lighting
• Vital Bus Inverters |
| UPS-1-A      | vital bus UPS (and components) | 12 in. | • Vital Instrumentation (Reactor Protection System) |
| UPS-1-B      | vital bus UPS (and components) | 12 in. | • Vital Instrumentation (Reactor Protection System) |
**EQ-induced SBO**

- **RELAP5-3D** nodalization developed/validated for *Station Blackout (SBO)* transients
- Reference reports for **Boundary Conditions & Validation**:
  - Code-to-code comparison **RELAP5-3D/MELCOR**
  - “Analysis of core damage frequency: Surry, Unit 1 internal events”, NUREG-CR-4550, Vol.3, Rev.1, Pt.1.
- Different **SBO** scenarios analyzed:
  - **Un-mitigated**
    - Long-Term SBO (fuel failure in ~14 hrs)
    - Short-Term SBO (fuel failure in ~2.5 hrs)
  - **Mitigated**
    - *Long-Term SBO (no fuel failure)*
    - Short-Term SBO (fuel failure in ~2.5 hrs)
  - Early Failure of MCP considered for all the above cases
    - MCP leak 182 gpm @ t=+13 min
- Above scenarios bound all possible cases considered by **PRA (SAPHIRE) & EMRALD/NEUTRINO**
IGPWR – RELAP5-3D modeling

- INL RELAP5-3D model for the IGPWR
  - 208 volumes / 248 junctions
  - 240 HS / 1312 mesh points

- **Primary System**
  - RPV, 3 main circulation circuits (SGs, MCPs, HLs and CLs, PRZ)

- **Secondary side**: Steam Lines until MSIV, MFW/AFW inlet

- **Core configuration**:
  - 3 hydraulic channels connected with junctions (cross flow simulation) → representing 3 different core zones: central, middle and outer core zones [different power]

  - no BOP
  - no Containment
<table>
<thead>
<tr>
<th>EVENT DESCRIPTION</th>
<th>TIME [hh:mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP seal leakage (21 gpm)</td>
<td>00:00</td>
</tr>
<tr>
<td>Early MCP seal failure (182 gpm)</td>
<td>00:00</td>
</tr>
<tr>
<td>Initiating event Station blackout – loss of all onsite and offsite AC power</td>
<td>00:00</td>
</tr>
<tr>
<td>Reactor trip, MSIVs close</td>
<td>00:00</td>
</tr>
<tr>
<td>MCP seals initially leak at 21 gpm/pump (~1 Kg/s)</td>
<td>(00:00)</td>
</tr>
<tr>
<td>TD-AFW auto initiates at full flow</td>
<td>(00:01)</td>
</tr>
<tr>
<td>RCP seal fail, leaking 182 gpm/pump</td>
<td>N/A</td>
</tr>
<tr>
<td>First SG SRV opening</td>
<td>00:15</td>
</tr>
<tr>
<td>(00:03)</td>
<td>(00:03)</td>
</tr>
<tr>
<td>Operators control TD-AFW to maintain level</td>
<td>00:15</td>
</tr>
<tr>
<td>(00:15)</td>
<td>(00:15)</td>
</tr>
<tr>
<td>Void Formation in the UH</td>
<td>01:41</td>
</tr>
<tr>
<td>(00:27)</td>
<td></td>
</tr>
<tr>
<td>Operators initiate controlled cooldown of secondary at ~100 F/hr (~55.5 K/hr)</td>
<td>01:30</td>
</tr>
<tr>
<td>(01:30)</td>
<td>(01:30)</td>
</tr>
<tr>
<td>UP water level starts to decrease</td>
<td>02:02</td>
</tr>
<tr>
<td>(01:57)</td>
<td>(01:13)</td>
</tr>
<tr>
<td>Accumulators begin injecting</td>
<td>02:34</td>
</tr>
<tr>
<td>(02:25)</td>
<td>(02:15)</td>
</tr>
<tr>
<td>Vessel water level begins to increase</td>
<td>02:36</td>
</tr>
<tr>
<td>(02:30)</td>
<td>N/A</td>
</tr>
<tr>
<td>Start emergency diesel pump for injection into RCS</td>
<td>03:30</td>
</tr>
<tr>
<td>(03:30)</td>
<td>(03:30)</td>
</tr>
</tbody>
</table>
### EQ-induced SBO – Bounding Scenarios – Mitigated LTSBO

<table>
<thead>
<tr>
<th>EVENT DESCRIPTION</th>
<th>TIME [hh:mm]</th>
<th>INL / RELAP5-3D (SOARCA report / MELCOR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP seal leakage (21 gpm)</td>
<td>03:43</td>
<td>03:43</td>
</tr>
<tr>
<td>Early MCP seal failure (182 gpm)</td>
<td>(03:35)</td>
<td>(03:35)</td>
</tr>
<tr>
<td>SG cool-down stopped at 120 psig (9.29 MPa) to maintain TD-AFW flow</td>
<td>~07:35</td>
<td>~08:44</td>
</tr>
<tr>
<td>ECST empty. Operator activate a portable, diesel-driven pump (Godwin pump) for supply water to the TD-AFW</td>
<td>08:00</td>
<td>08:00</td>
</tr>
<tr>
<td>DC Batteries Exhausted. Operator actions control the secondary pressure at 120 psi and maintain TD-AFW flow</td>
<td>N/A</td>
<td>12:38</td>
</tr>
</tbody>
</table>

- **Primary/Secondary Pressures**
- **ECST / AFW Capacity**
- **Core PCT**
Bounding Scenarios

- **Mitigated STSBO**
  - Immediate permanent loss of TD-AFW
  - Recovery actions (e.g., primary side depressurization, Kerr pump injection) not available before \( t \approx 2\) hr
  - Scenario always ended up in fuel damage \( \rightarrow \) no EMRALD/RELAP5-3D calculations

- **Mitigated LTSBO & Battery Failure for internal flooding**
  - Failure of Batteries (\( \rightarrow \) temporary loss of TD-AFW) assumed to happen during first 1 hr from the EQ
  - Fuel Failure depending by the recovery time and the MCP leakage rate
  - Fuel failures maps help to reduce number of RELAP5-3D calculations
    - RELAP5-3D runs executed by EMRALD when we are uncertain about fuel damage status
      - e.g., MCP seal leakage 21 gpm, battery failure \( t=1000\) s, \( 3\) hr < recovery time < \( 3.5\) hr

### Mitigated STSBO

<table>
<thead>
<tr>
<th>TD-AFW Failure Time (hr)</th>
<th>Recovery Time (hr)</th>
<th>0.5</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

### Mitigated LTSBO + Battery Failure for Internal Flooding

<table>
<thead>
<tr>
<th>Batteries Failure Time (s)</th>
<th>Recovery Time (hr)</th>
<th>1.5</th>
<th>2</th>
<th>3</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>S</td>
<td>S</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>1000.</td>
<td>S</td>
<td>S</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>2500.</td>
<td>S</td>
<td>S</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>3600.</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>F</td>
<td>F</td>
</tr>
</tbody>
</table>

### Mitigated LTSBO + Battery Failure for Internal Flooding + Early MCP Seal Failure

- Primary/Secondary Pressures
- RPV Level
- Core PCT
**Automatic Limit Surface Search**

- Can we do better than this, i.e., automatically refine the Limit Surface?
  - identify with more accuracy the boundary between green (safe) and red (failed) state
  - a detailed Limit Surface can avoid the EMRALD/RELAP5-3D on-line calculations
  - Manual computer codes runs can be impractical and computationally expensive

- Use of RAVEN code for Automatic Limit Surface Search
  - Use of Reduced Order Models (ROM)
    - Reduce the complexity of the problem
    - Based on regression/interpolation techniques
    - Set of equations are trained to approximate the original model

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**Flowchart**

1. Generate a set of training simulations to sample plant response
2. Build/update a ROM model
3. Use ROM to determine an approximated limit surface
4. Choose next sample close to the limit surface
5. Run simulation for the sampled point
6. Reach convergence
   - No
   - Yes
     - Stop
Automatic Limit Surface Search

• Several ROM available in RAVEN
  – Use of external library Scikit-learn
    • Open source machine learning library for Python
  – **Support Vector Machine (SVM) /Classifier** ROM used: identify to which category a calculation result belong (safe/failed fuel)
    • Train using a set of starting points (RELAP5-3D calculations)
    • RBF (exponential) kernel
    • Good and fast convergence of the surface
• Automatic Limit Surface calculations for different plant scenario (early/not early MCP seal failure, HPI loss, etc.)
• Information contained in the picture is passed via a binary file to EMRALD
Automatic Limit Surface Search

LIMIT SURFACE SEARCH: Mitigated LTSBO + Battery Failure for Internal Flooding + Early MCP Seal Failure

Testing different SVM parameters for convergence studies
RELAP5-3D/RAVEN Uncertainty Analysis

- Quantification of uncertainties on the RELAP5-3D deterministic calculations results needed (BEPU calculation)
- RAVEN code applied to RELAP5-3D also for performing UQ
- UQ → PIRT for Mitigated-LTSBO
  - Important TH phenomena influencing the PCT
    - NC in primary loop
    - Secondary Side Mass Inventory loss through SG SRV/ PORV
    - Primary Side Mass Inventory loss through MCP seal PRZ SRV/PORV
    - Heat Transfer between primary/secondary system
- Preparing a (partial) list of RELAP5-3D input parameters perturbed by RAVEN code:
  - Decay power
  - MCP Seal LOCA break area
  - Core Pressure losses
  - Valves flow areas
  - Heat Exchange multiplier
  - …
**RELAP5-3D/RAVEN Uncertainty Analysis**

- Selected Input parameters to be perturbed using Monte Carlo sampler + assigned PDF
- Test the **RAVEN** code “BasicStatistics” function
  - Automatically calculate the basic statistics and matrices (sensitivity, pearson, covariance, etc.)
  - Identify the **most relevant parameters** for the selected transient
- Final PCT UQ calculation
  - Different approaches possible:
    - MC (500-1000 calculations) → brute force
    - Tolerance Limits (Wilks` formula)
      - 59 / 93 / 124 / 153 calculations (first, second, … order statistics)
    - Train a meta-model, then perform MC on meta-model
- **RAVEN** code allows to pursue each of the above approaches
  - Exploit INL “FALCON” HPC resources
  - Optimized “fast running” **RELAP5-3D** model: 24hr mission time runs in 1 hr

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### Initial List of Uncertain Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity</th>
<th>Covariance</th>
<th>Pearson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay Power</td>
<td>-1.82E-04</td>
<td>-2.07E+00</td>
<td>-2.94E-01</td>
</tr>
<tr>
<td>Core Pressure Losses</td>
<td>1.25E-02</td>
<td>1.43E+02</td>
<td>4.63E-01</td>
</tr>
<tr>
<td>SG / PRZ PORV/SRV valve flow areas</td>
<td>4.83E-04</td>
<td>5.49E+00</td>
<td>2.95E-01</td>
</tr>
<tr>
<td>MCP seal break area</td>
<td>9.52E-05</td>
<td>1.08E+00</td>
<td>5.80E-02</td>
</tr>
<tr>
<td>SG HX Multiplier</td>
<td>1.36E-04</td>
<td>1.55E+00</td>
<td>1.66E-01</td>
</tr>
</tbody>
</table>

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### Basic Statistics
RELAP5-3D/RAVEN Uncertainty Analysis

- 4 parameters selected for final perturbation
- MC (1000 runs):
  - 1122 K (95%)
  - E(PCT): 903 K +/- 101
- …. or Wilks’ formula applied with LHS:
  - First/fourth order statistics (59 / 153 runs)
  - 59 runs → “conservative” value for PCT

Calculation Results (5/Expected/95 Percentile)

LHS sampling PCT results
RELAP5-3D/RAVEN Uncertainty Analysis

- Last Step → inform the Limit Surface Search with the UQ results
  - Performing the LSS including epistemic uncertainty
  - 6 dimension LSS (4 epistemic, 2 stochastic)
- N-dimensional surface obtained (6-dim)
- Projection of 3 dimensions (Battery Time/Operator action/Core Power)
RELAP5-3D/RAVEN Uncertainty Analysis

- Effects of the epistemic uncertainties $\rightarrow$ restriction of the "safe" area
- More calculations ongoing for achieving better surface resolution $\rightarrow$ fuel failure points imported in EMRLAD
Summary

- Methodology & Tools for LWRS/RISMC External Events analysis defined

- Combined calculations of Structural Mechanics/PRA/Flooding/System Thermal-hydraulic/UQ performed

- Combination of BE advanced tools for the analysis of PWR SBO: MASTODON/EMRALD/NEUTRINO/RAVEN/RELAP5-3D codes

- RAVEN code coupled to RELAP5-3D allowed to inform EMRALD dynamic PRA with BEPU calculations
  - Automatic Limit Surface Search
  - Computation of Calculation Statistics
  - Monte Carlo/Tolerance Limits for Uncertainty propagation