# RELAP5-3D Analyses for the US-DOE LWRS/RISMC Program, Industry Application #2

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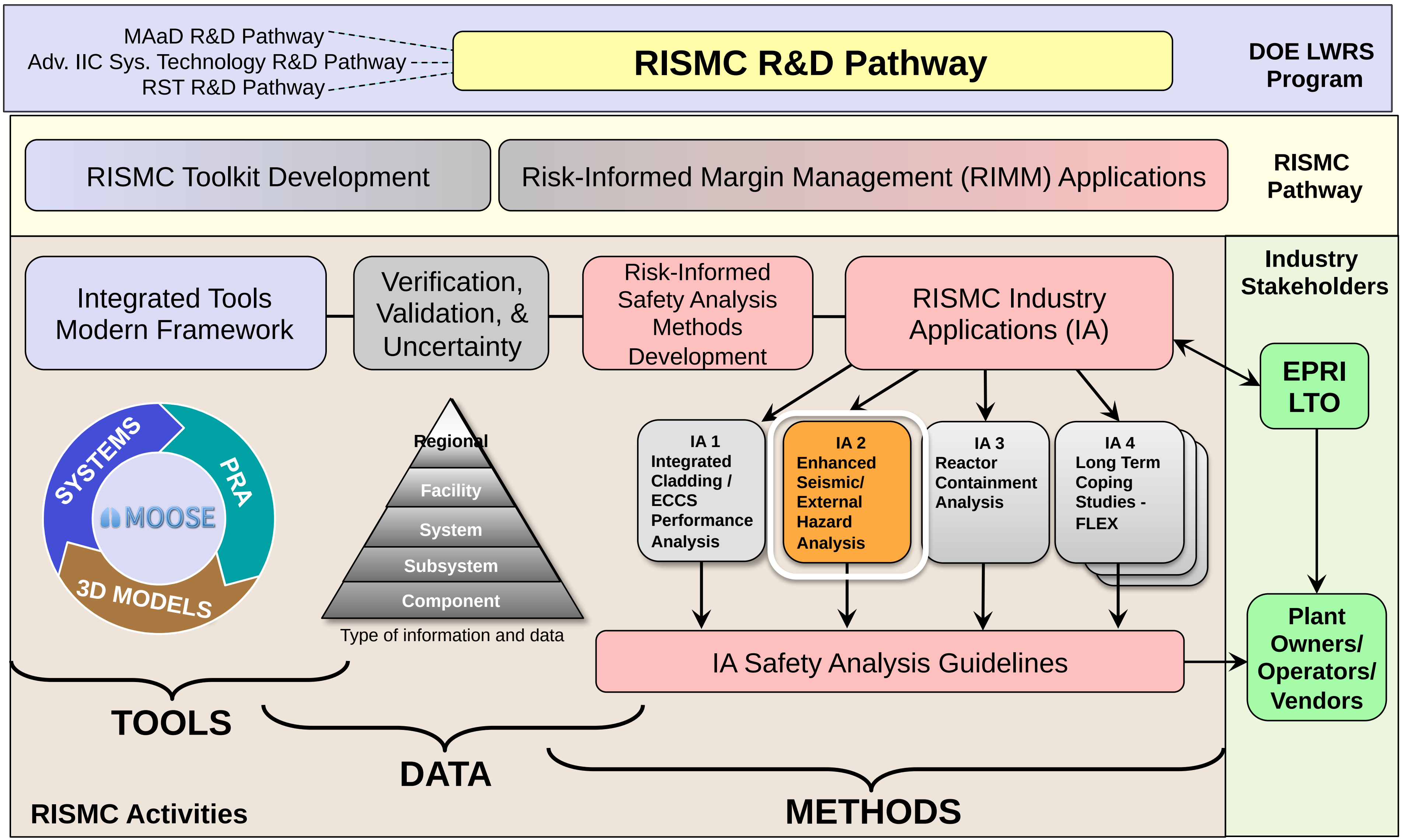
# *Topics*

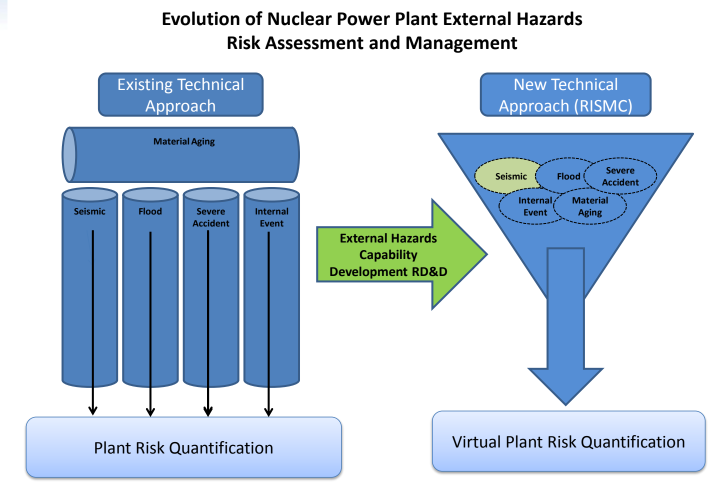
- LWRS/RISMC Overview
- Industry Application #2 (IA #2) Motivation
- IA #2 Toolkits for External Events Analysis (EEVE-A & EEVE-B)
- IA #2 INL Generic-PWR application
  - RELAP5-3D Model
  - SBO Results
  - UQ
- Coupled analysis

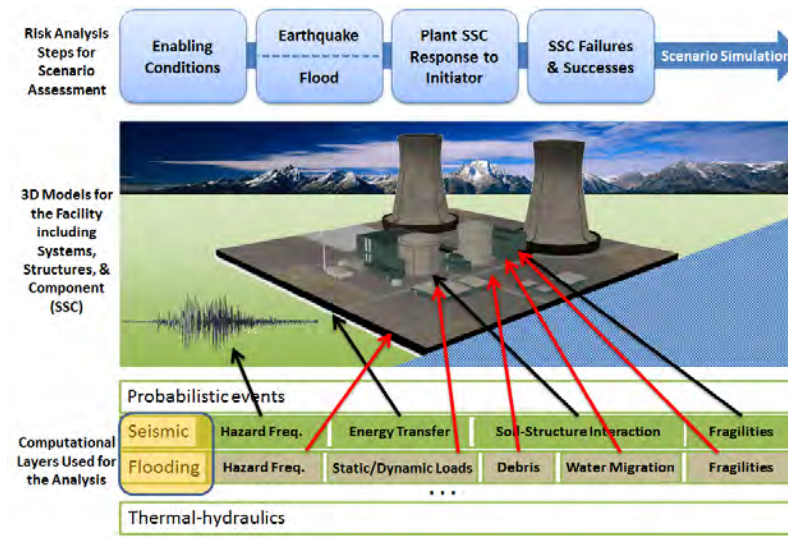
# LWRS/RISMC – Focus on Tools / Data / Methods



# IA #2 – Motivation

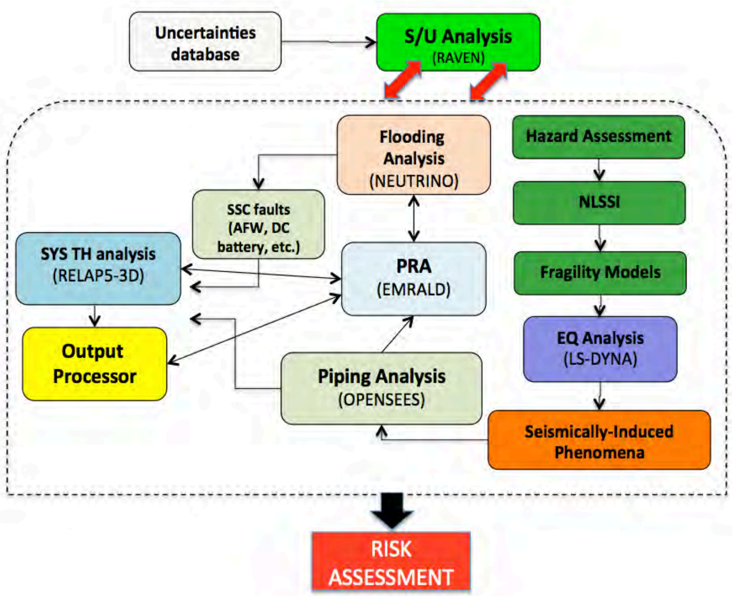
- **Goals of the RISMC Pathway**
  - Develop and demonstrate a <u>risk-assessment method</u> ***coupled*** to <u>safety margin quantification</u>
  - Create an advanced "RISMC toolkit"
- **IA#2 Motivation:** to perform an advanced risk analysis of accidental events caused ***by a combination of natural external hazards***, i.e. <u>earthquake and flooding</u>
  - Use of INL advanced simulation tools & methods
  - Perform <u>realistic</u> 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, <u>**using realistic plant models, simulations and uncertainties**</u> (for a generic **PWR**)
- **Two toolkits** (External EVEnts toolkits, **EEVE**) + pathways are defined



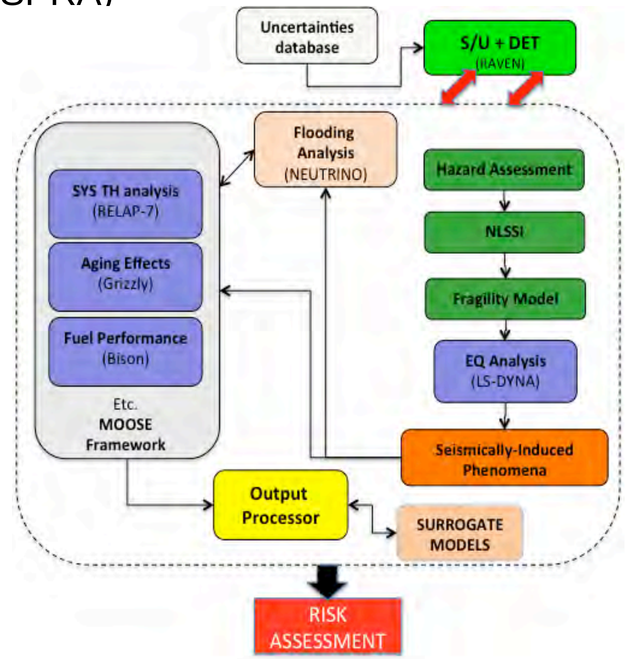



# The Toolkits: EEVE-B & EEVE-A

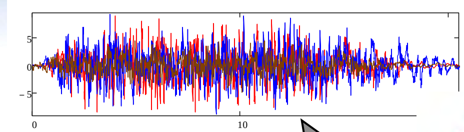
- **Baseline Demonstration [EEVE-B]**
  - Use of existing, validated & state-of-the-art tools (e.g., RELAP5-3D)
  - one-way coupling
  - generic NPP
  - No EQ uncertainty analysis

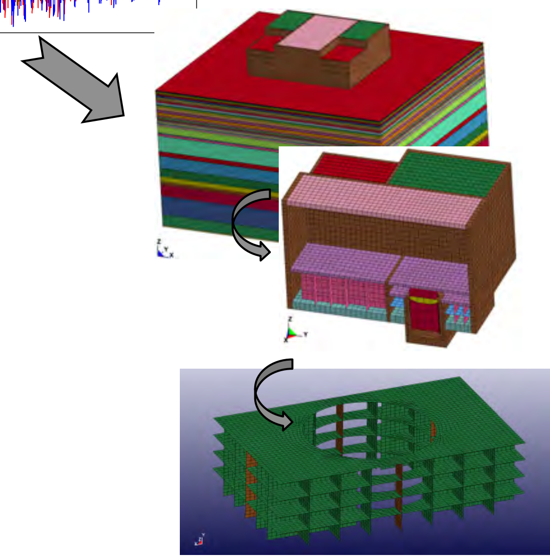



- **Advanced Component [EEVE-A]**
  - Use of advanced INL tools (e.g., RELAP-7),
  - Direct coupling (e.g., flooding-RELAP7),
  - Detailed NPP (industry feedback needed),
  - Use of Reduced Order Model (ROM) & Surrogates
  - Advanced Seismic probabilistic risk analysis (ASPRA)

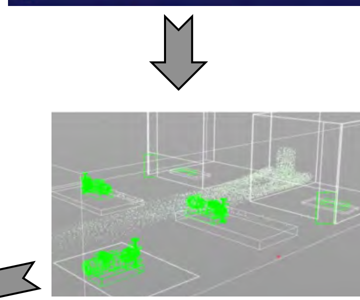


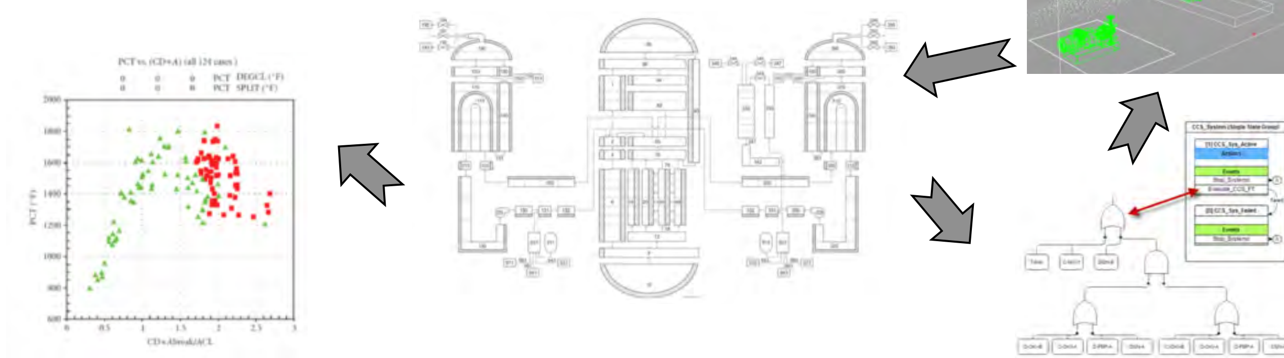
# *Baseline Demonstration (FY2016)*





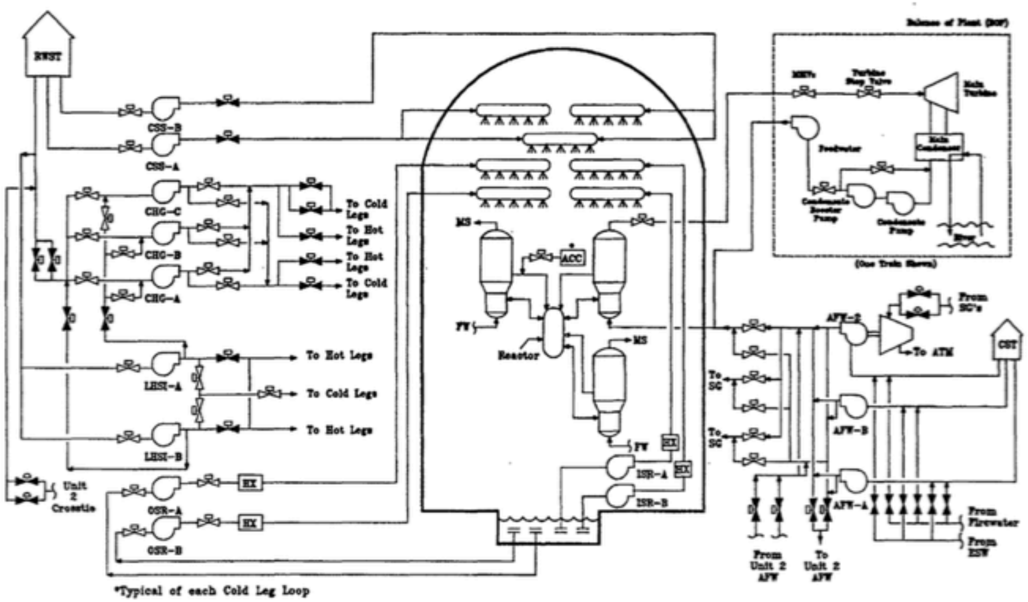
- **<u>5 Phases</u>** identified for the *Baseline Demo*
  1) Simulate effects of EQ on a NPP SSCs using advanced seismic analysis methodology
     - Use of Non-linear soil-structure interaction (NLSSI) methodology **[LS-DYNA]**
     - Piping fragilities evaluation **[OPENSEES]**
  2) Simulate NPP flooding scenarios caused by EQ-induced pipe rupture **[NEUTRINO]**
  3) Simulate NPP primary circuit + part of BOP dynamics **[RELAP5-3D]**
  4) Apply S/U analysis **[RAVEN]**
  5) Evaluate risk of different scenarios (ranking) using simplified 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

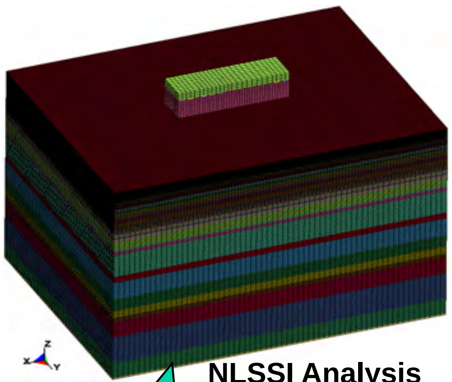


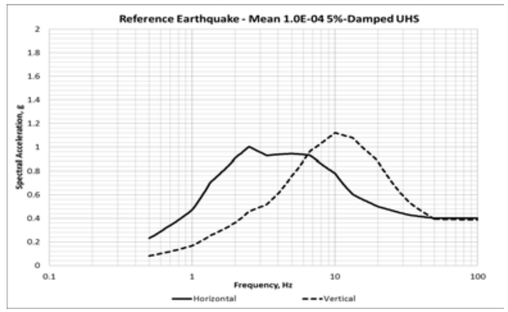
IGPWR ESF

| Parameter | Value (SI units) | Value (British units) |
|---|---|---|
| Core Power [$MW_{th}$] | 2,546 | |
| Reactor Inlet / Outlet Temperature [°C / °F ] | 282 / 319 | 540/ 606 |
| Number of Fuel Assemblies | 157 | |
| Rod Array | 15x15 | |
| RCS Coolant Flow [kg/s / $lb_m$/hr] | 12,738 | 101.6E+8 |
| Nominal RCS Pressure [MPa /psia] | 15.5 | 2,250 |
| MCP seal water injection [$m^3$/s / gpm] | 3.78E-3 | 8 |
| MCP seal water return [$m^3$/s / gpm] | 1.42E-3 | 3 |
| MCP Power [MW / hp] | 5.22 | 7,000 |
| Number of SG | 3 | |
| PRZ PORV set points op./clos. [MPa / psig] | 16.2 / 15.7 | 2,350 / 2,280 |
| PRZ PORV capacity [kg/s / $lb_m$/hr] | 2 x 22.5 | 2 x 179,000 |
| PRZ SV set points op./clos. [MPa / psig] | 16.4 / 17.7 | 2,375 / 2,575 |
| PRZ SV capacity [kg/s / $lb_m$/hr] | 3 x 37.0 | 3 x 293,330 |
| Relief Tank Rupture Disc capacity [kg/s / $lb_m$/hr] | 113.4 | 9.0E+5 |
| Relief Tank Rupture Disc set point op. [MPa / psid] | 6.89 | 1000 |
| Relief Tank Total Volume [$m^3$ / $ft^3$] | 36.8 | 1300 |
| Relief Tank Water Volume [$m^3$ / $ft^3$] | 25.5 | 900 |
| SG PORV capacity [kg/s / $lb_m$/hr] | 1 x 47.0 | 1 x 3.73E+5 |
| SG PORV set points op./clos. [MPa / psig] | 7.24 / 6.89 | 1,050 / 1,000 |
| SG SV capacity [kg/s / $lb_m$/hr] | 5 x 94.0 | 5 x 7.46E+5 |
| SG SV set points op./clos. [MPa / psig] | 8.16 / 7.53 | 1,184 / 1,092 |
| Secondary Pressure [MPa / psia] | 5.49 | 796 |
| Secondary Side Water Mass @ HFP [kg / $lb_m$] | 41,639 | 91,798 |
| SG Volume [$m^3$ / $ft^3$] | 166 | 5,868 |

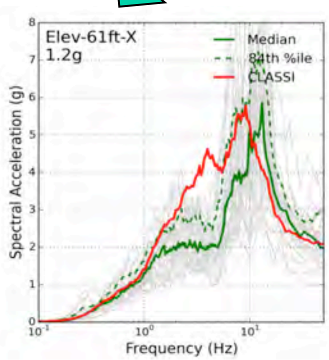
# Seismic Analysis

- Calculation of Non Linear Soil-Structure Interaction (NLSSI) by LS-DYNA 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)

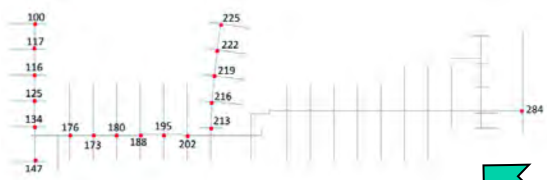

NLSSI Analysis

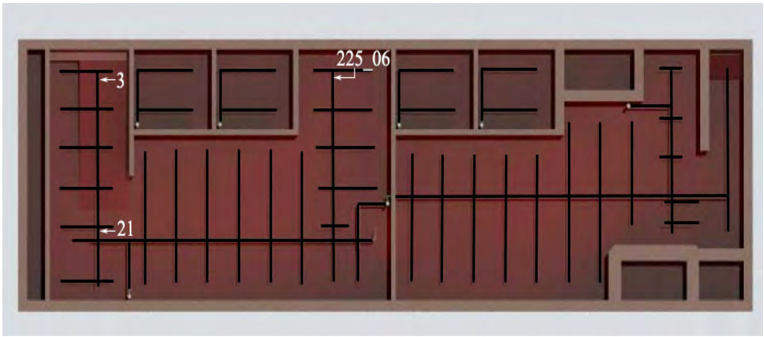


Seismic Hazard Cure

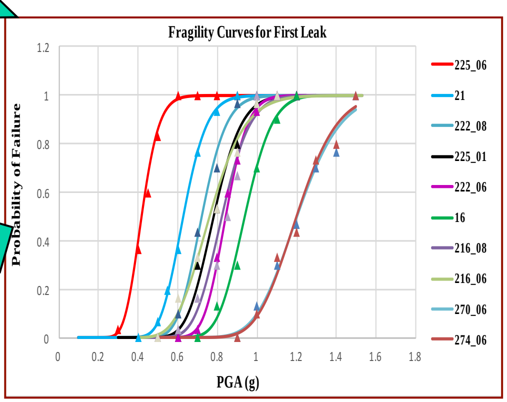


Acceleration Response Spectra for Aux Builiding



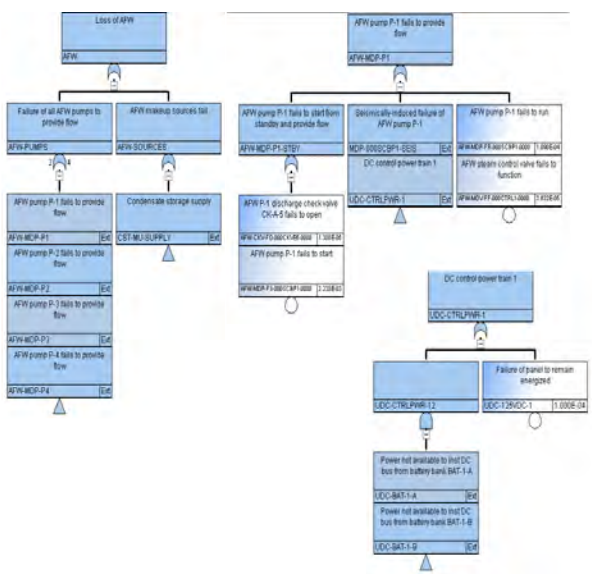
Strcutural Analysis of Fire Suppression System



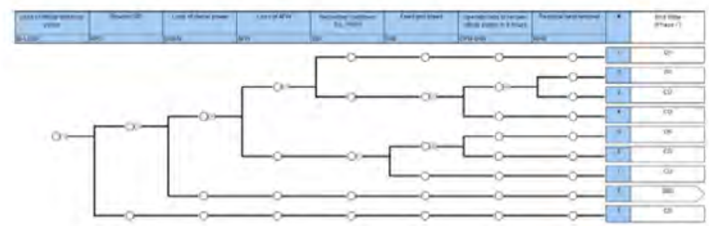
Seismic Fragility Curves

# PRA Analysis – EMRALD code

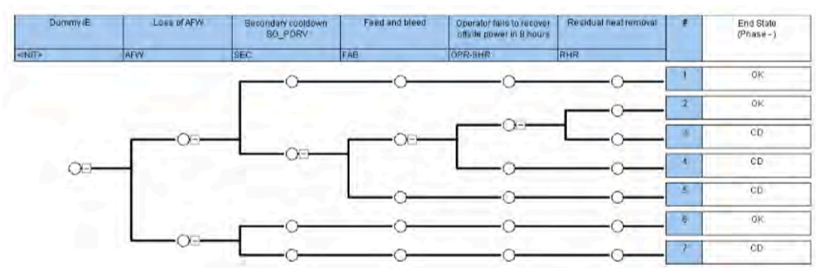
- **EMRALD** code simulates an equivalent model to the **SAPHIRE** PRA Model in a time driven manner
- PWR Simplified LOSP and SBO event trees implemented
- Run **RELAP5-3D** [when possible fuel damage could occur] & ***NEUTRINO*** [when flooding could occur] codes
- Process **RELAP5-3D** & ***NEUTRINO*** results into the final result probabilities



**Main Fault Tree**



**Loss-of-Offsite Power Event Tree**

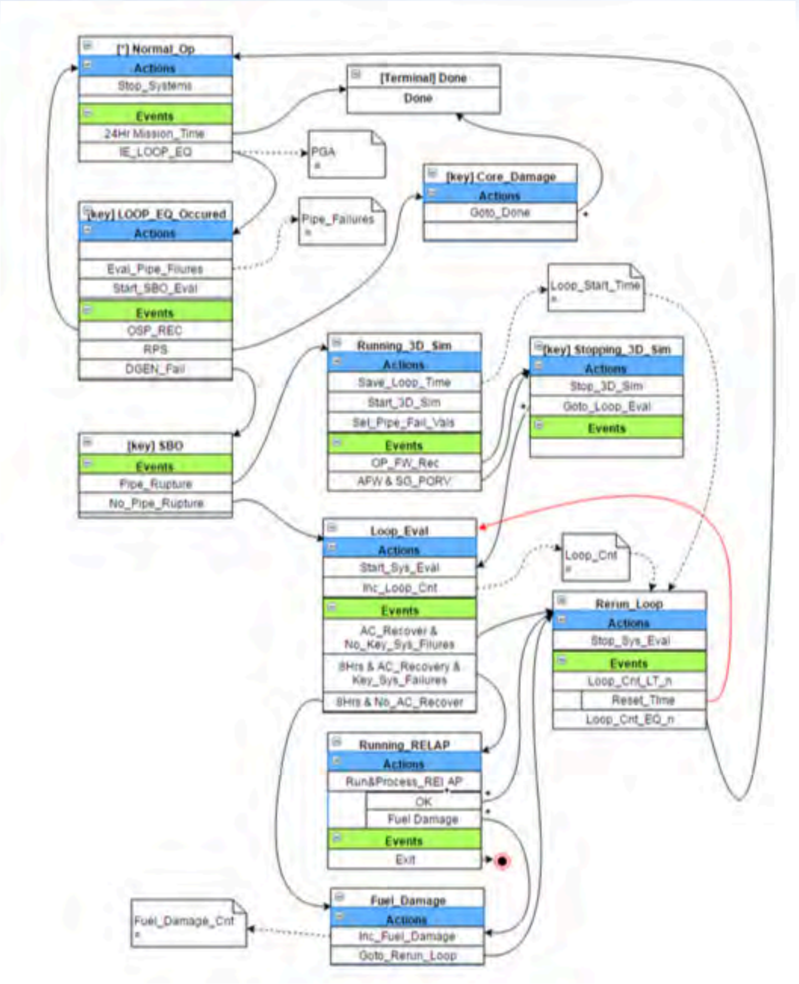



**Station Blackout Event Tree**

# EMRALD logic

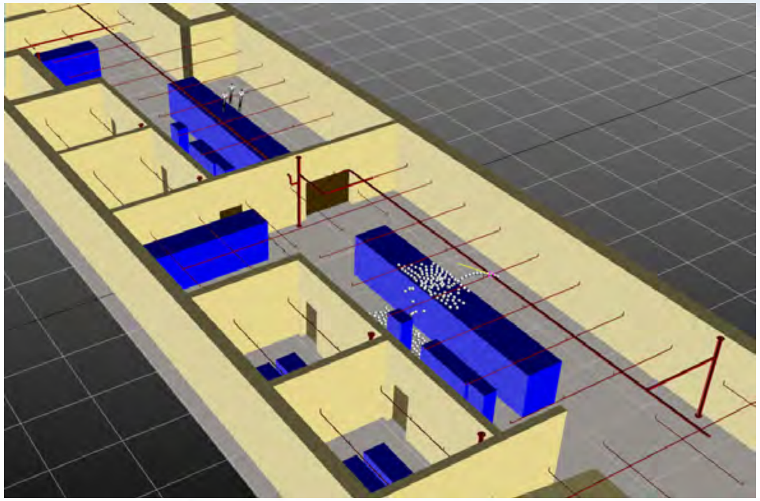
Path Given for External Events simulation

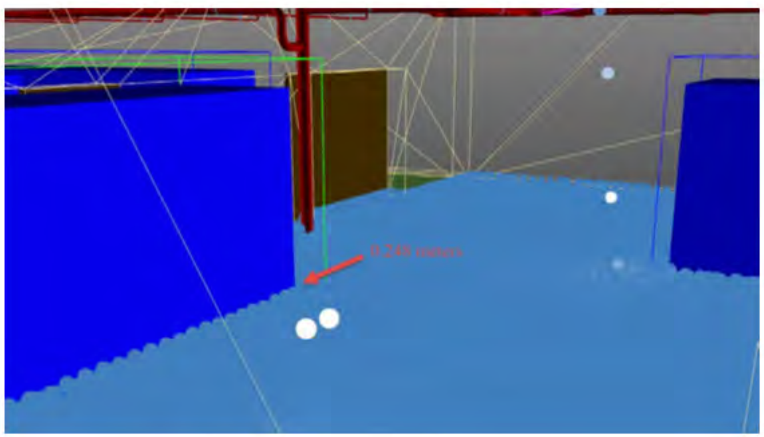
1. IE EQ causing LOOSP
2. Calculation of **Peak Ground Acceleration (PGA)** for given EQ
3. Evaluate DG availability given EQ (LOOSP → SBO yes/no)
4. Determine Pipe Failures (yes/no)
5. Run 3D ***NEUTRINO*** flooding Simulation
6. Run multiple samples for additional component failure rates, given EQ
7. Run **RELAP5-3D** given all component failures
8. Log Fuel Damage




**EMRALD Workflow**

# NEUTRINO Internal Flooding Model





***Switchgear Room 1 – NEUTRINO Flooding Simulation***

SWITCHGEAR ROOM 1

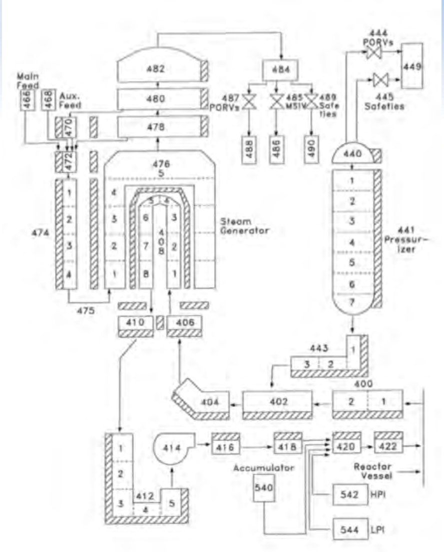
| Equipment ID | Description | Height* | Affected Comp./Systems |
|---|---|---|---|
| BAT-1-A | control storage battery | 18 in. | • TD-AFW<br>• SG & PRZ PORV<br>• Switchgear (close and tripping power for all 12.47/4.16 KV and some 480 V breakers)<br>• Annunciators<br>• EDG (air start solenoid, fuel pump power, control circuit)<br>• Control Panels<br>• Emergency Lighting<br>• Vital Bus Inverters |
| BAT-1-B | control storage battery | 18 in. | • TD-AFW<br>• SG & PRZ PORV<br>• Switchgear (close and tripping power for all 12.47/4.16 KV and some 480 V breakers)<br>• Annunciators<br>• EDG (air start solenoid, fuel pump power, control circuit)<br>• Control Panels<br>• Emergency Lighting<br>• 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<br>• SG & PRZ PORV<br>• Switchgear (close and tripping power for all 12.47/4.16 KV and some 480 V breakers)<br>• Annunciators<br>• EDG (air start solenoid, fuel pump power, control circuit)<br>• Control Panels<br>• Emergency Lighting<br>• 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 | 12 in. | • Vital Instrumentation (Reactor |

**Components Affected by Flooding**

**to RELAP5-3D simulation**

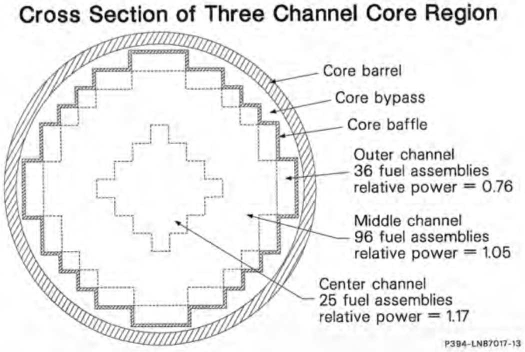
# IGPWR – RELAP5-3D modeling

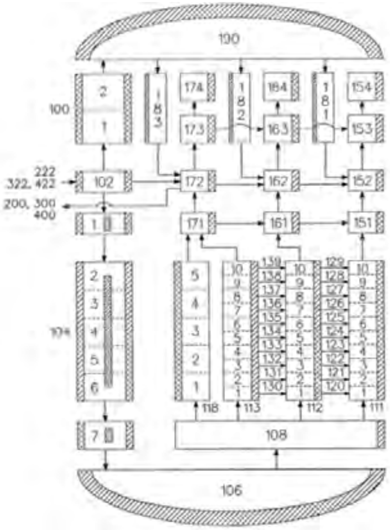
- INL **RELAP5-3D** model for the IGPWR based on the INL **RELAP/SCDAP** model by *P. Bayless* (NC studies for SBO Analysis)
  - 208 volumes / 248 junctions
  - 240 HS / 1312 mesh points
- **Primary System**
  - RPV, 3 main circulation circuits (SGs, MCPs, HLs and CLs, PRZ)
- **Secondary side**: Steam 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




SG, PRZ, MCP, HL/CL

Cross Section of Three Channel Core Region



RPV

# IGPWR – RELAP5-3D modeling

- Nodalization review:
  - ✓ Updated the input deck to **RELAP5-3D** syntax
  - ✓ Developed a new core model
  - ✓ Updated the RCS to upgraded power conditions (from 2411 to 2546 MWth)
- Nodalization provisions for modeling possible EQ-induced accidents → SBO event simulation capabilities
  - **Mitigation actions** included, e.g.:
    - SG depressurization by operator at 100 F/hr
    - mobile pump injection
    - TD-AFW blackrun
  - Boundary Conditions (timing of events) to be provided by **EMRALD**/**NEUTRINO** flooding analysis
    - EQ-induced Internal flooding → k.o. of some ESF (e.g., battery rooms, HPIS switchgear, etc.)
  - Simulations run up to the onset of fuel damage (**RELAP5-3D** applicability range)

# IGPWR– RELAP5-3D modeling

- Steady State Results

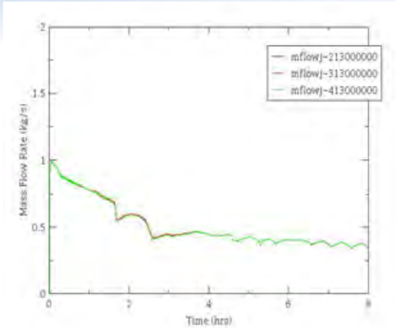
| Parameter | Reference Value | RELAP5-3D value | Deviation (%) |
|---|---|---|---|
| Reactor Power (W) | 2,546 | 2,546 | imposed |
| PRZ pressure (MPa) | 15.5 | 15.5 | imposed |
| Total RCS coolant loop flow rate (Kg/s) | 12,738 | 12,738 | 0.0 |
| CL Temperature (K) | 555.6 | 557.3 | 0.3 |
| | | 557.3 | 0.3 |
| | | 557.3 | 0.3 |
| HL Temperature (K) | 591.8 | 593.1 | 0.2 |
| | | 593.1 | 0.2 |
| | | 593.1 | 0.2 |
| Feedwater Temperature (K) | 501.5 | 501.5 | imposed |
| | | 501.5 | imposed |
| | | 501.5 | imposed |
| Steam flow rate per SG (Kg/s) | 473 | 470.1 | -0.6 |
| | | 470.7 | -0.5 |
| | | 471.0 | -0.4 |
| Steam Pressure at the Outlet Nozzle (MPa) | 5.405 | 5.405 | imposed |
| | | 5.405 | imposed |
| | | 5.405 | imposed |
| Liquid mass per SG (Kg) | 41,639 | 41,640 | 0.0 |
| | | 41,638 | 0.0 |
| | | 41,638 | 0.0 |
| Steam Temperature (K) | 542 | 542 | 0.0 |
| | | 542 | 0.0 |
| | | 542 | 0.0 |

# *EQ-induced SBO – Bounding Scenarios*

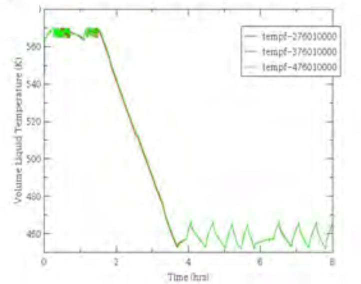
- Reference reports for Boundary Conditions & Validation:
  - US NRC **SOARCA** Report, NUREG/CR-7110, Vol. 2
  - *"Analysis of core damage frequency: Surry, Unit 1 internal events",* NUREG-CR-4550, Vol.3, Rev.1, Pt.1.
- Different SBO scenarios analyzed:
  - Un-mitigated
    - Long-Term SBO (fuel failure 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 & **EMRALD**/**NEUTRINO**

# Bounding Scenarios – Unmitigated LTSBO

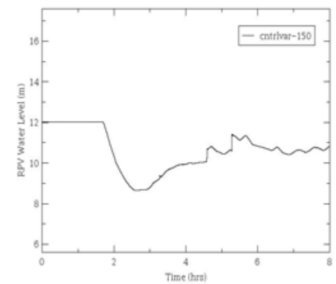
| EVENT DESCRIPTION | TIME [hh:mm] INL / RELAP5-3D (SOARCA report / MELCOR) |
|---|---|
| Initiating event<br>Station blackout – loss of all onsite and offsite AC power | 00:00 |
| Reactor trip, MSIVs close<br>RCP seals initially leak at 21 gpm/pump (~1 Kg/s) | 00:00<br>(00:00) |
| TD-AFW auto initiates at full flow | 00:01<br>(00:01) |
| First SG SRV opening | 00:15<br>(00:03) |
| Operators control TD-AFW to maintain level | 00:15<br>(00:15) |
| Operators initiate controlled cooldown of secondary at ~100 F/hr (~55.5 C/hr) | 01:30<br>(01:30) |
| Upper plenum water level starts to decrease | 01:40<br>(01:57) |
| Accumulators begin injecting | 02:34<br>(02:25) |
| Vessel water level begins to increase | 02:35<br>(02:30) |
| SG cool-down stopped at 120 psig (9.29 MPa) to maintain TD-AFW flow | 03:41<br>(03:35) |
| Emergency CST empty | ~06:20<br>(05:00) |
| DC Batteries Exhausted / SG PORVs reclose | 08:00 |



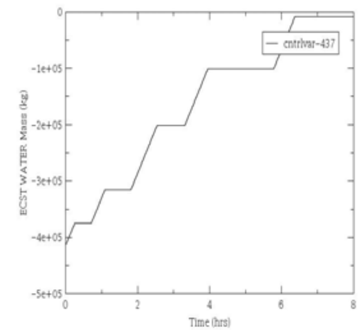

MCP Seal Leakage




SG Temperature



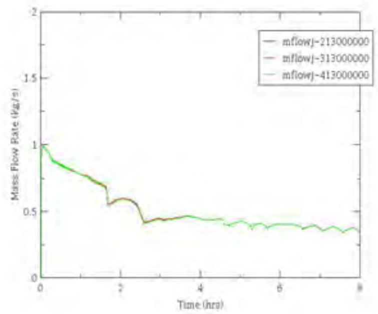

RPV Level



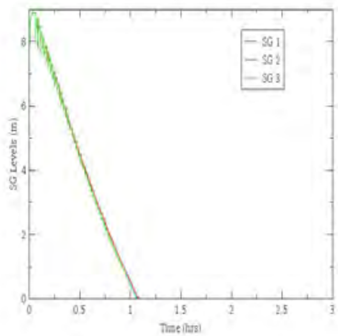

ECST Capacity

# Bounding Scenarios – Unmitigated STSBO

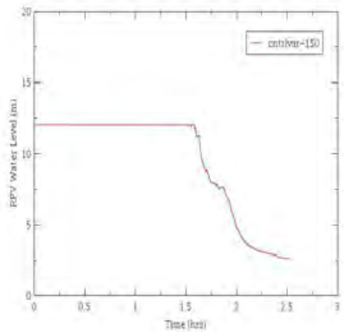
| EVENT DESCRIPTION | TIME [hh:mm] INL / RELAP5-3D (SOARCA report / MELCOR) |
|---|---|
| Initiating event<br>Station blackout – loss of all onsite and offsite AC power | 00:00 |
| Reactor trip, MSIVs close<br>RCP seals initially leak at 21 gpm/pump (~1 Kg/s) | 00:00<br>(00:00) |
| TD-AFW auto initiates at full flow | 00:01<br>(00:01) |
| EQ damage of ECST and of Auxiliary Buildings<br>Loss of TD-AFW & Loss of DC power | 00:01.6<br>(N/A) |
| First SG SRV opening | 00:04<br>(00:03) |
| Operators control TD-AFW to maintain level | N/A |
| SG Dryout | 01:06<br>(01:16) |
| Pressurizer SRV open | 01:12<br>(01:30) |
| Start of fuel heatup | 01:58<br>(01:57) |



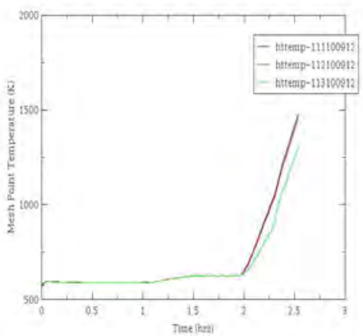
MCP Seal Leakage



SG Level



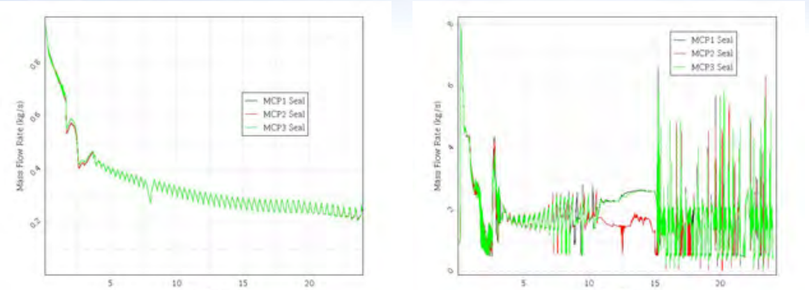
RPV Level



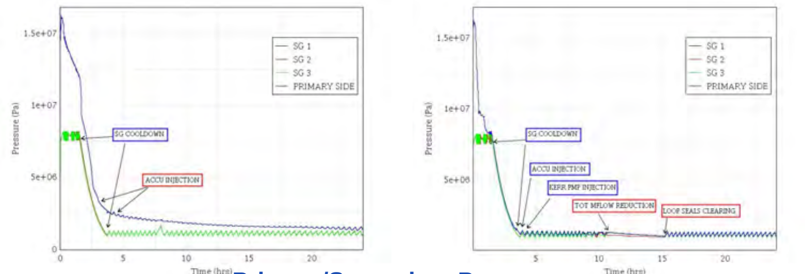
Fuel Clad Temperature

# Bounding Scenarios – Mitigated LTSBO

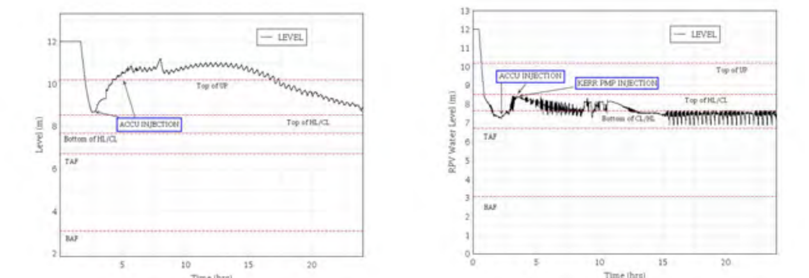
| EVENT DESCRIPTION | TIME [hh:mm] INL / RELAP5-3D (SOARCA report / MELCOR) | |
|---|---|---|
| | MCP seal leakage (21 gpm) | Early MCP seal failure (182 gpm) |
| Initiating event<br>Station blackout – loss of all onsite and offsite AC power | 00:00 | 00:00 |
| Reactor trip, MSIVs close<br>MCP seals initially leak at 21 gpm/pump (~1 Kg/s) | 00:00<br>(00:00) | 00:00<br>(00:00) |
| TD-AFW auto initiates at full flow | 00:01<br>(00:01) | 00:01<br>(00:01) |
| RCP seal fail, leaking 182 gpm/pump | N/A | 00:13<br>(00:13) |
| First SG SRV opening | 00:15<br>(00:03) | 00:15<br>(00:03) |
| Operators control TD-AFW to maintain level | 00:15<br>(00:15) | 00:15<br>(00:15) |
| Void Formation in the UH | 01:41 | 00:27 |
| Operators initiate controlled cooldown of secondary at ~100 F/hr (~55.5 K/hr) | 01:30<br>(01:30) | 01:30<br>(01:30) |
| UP water level starts to decrease | 02:02<br>(01:57) | 00:38<br>(01:13) |
| Accumulators begin injecting | 02:34<br>(02:25) | 02:15<br>(02:15) |
| Vessel water level begins to increase | 02:36<br>(02:30) | N/A |
| Start emergency diesel pump for injection into RCS | 03:30<br>(03:30) | 03:30<br>(03:30) |



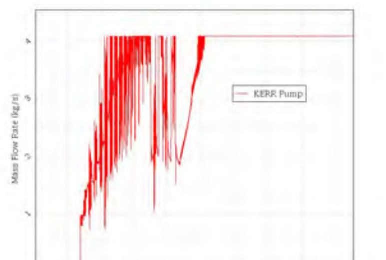
MCP Seal Leakage



Primary/Secondary Pressures



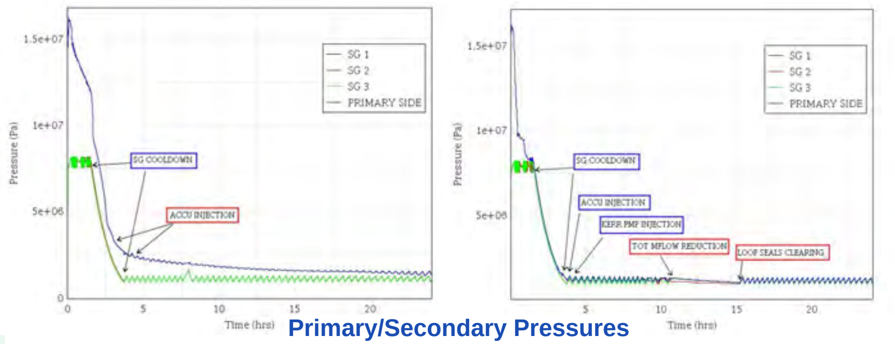
RPV Level



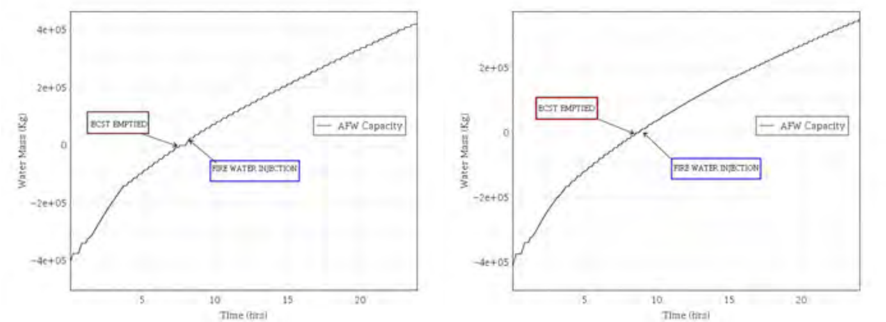
Kerr Pump Mass Flow

# EQ-induced SBO – Bounding Scenarios – Mitigated LTSBO

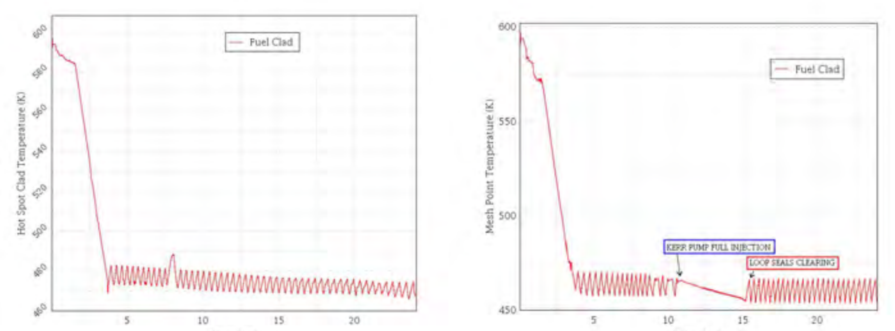
| EVENT DESCRIPTION | TIME [hh:mm] INL / RELAP5-3D (SOARCA report / MELCOR) | |
|---|---|---|
| | MCP seal leakage (21 gpm) | Early MCP seal failure (182 gpm) |
| SG cool-down stopped at 120 psig (9.29 MPa) to maintain TD-AFW flow | 03:43 (03:35) | 03:43 (03:35) |
| ECST empty. Operator activate a portable,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




Primary/Secondary Pressures




ECST / AFW Capacity




Core PCT

# Bounding Scenarios

- **Mitigated STSBO**
  - Immediate loss of TD-AFW
  - Recovery actions (e.g., primary side depressurization, Kerr pump injection) not available before t~2hr
  - Scenario always ended up in fuel damage → no EMRALD? RELAP calculations
- **Mitigated LTSBO & Battery Failure for internal flooding**
  - Failure of Batteries (→ TD-AFW) supposed 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 BC are in fuel status uncertain zone
      - e.g., MCP seal leakage 21 gpm, battery failure t=1000 s, 3 hr < recovery time < 3.5 hr

| TD-AFW Failure Time (hr) | Recovery Time (hr) | | |
|---|---|---|---|
| | 0.5 | 1 | 2 |
| 0.0 | F | F | F |
| 1 | F | F | F |
| 2 | S | F | F |

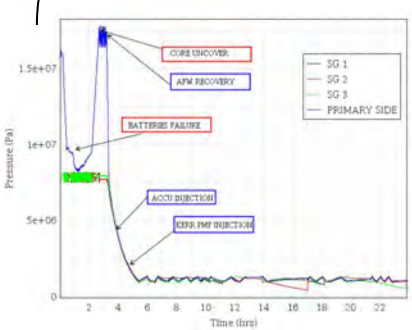
Mitigated STSBO

| Batteries Failure Time (s) | Recovery Time (hr) | | | |
|---|---|---|---|---|
| | 1.5 | 2 | 3 | 3.5 |
| 0.0 | S | S | F | F |
| 1000. | S | S | S | F |
| 2500. | S | S | F | F |
| 3600. | S | S | S | F |

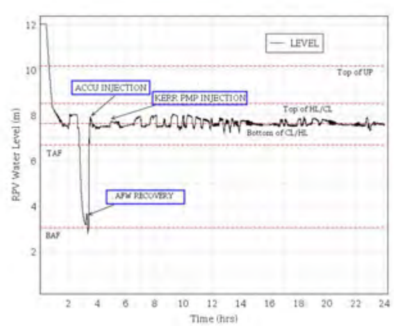
Mitigated LTSBO + Battery Failure for Internal Flooding

| Batteries Failure Time (s) | Recovery Time (hr) | | | |
|---|---|---|---|---|
| | 1.5 | 2 | 3 | 3.5 |
| 0.0 | S | S | F | F |
| 1000. | S | S | F | F |
| 2500. | S | S | F | F |
| 3600. | S | S | F | F |

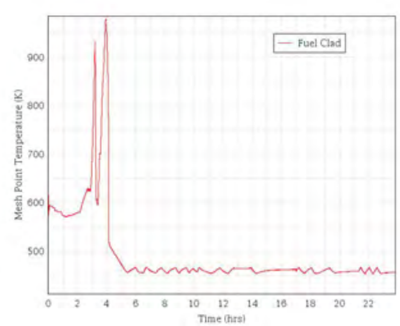
Mitigated LTSBO + Battery Failure for Internal Flooding + Early MCP Seal Failure




Primary/Secondary Pressures




RPV Level




Core PCT

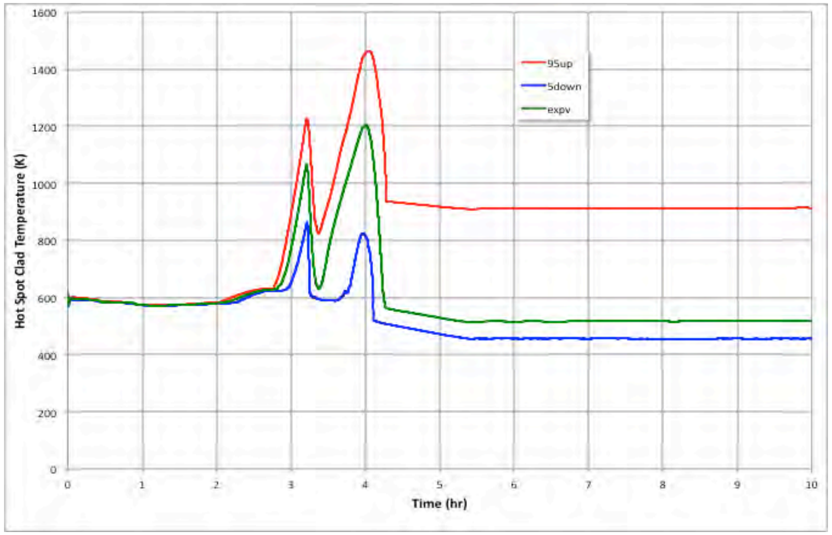
# RELAP5-3D/RAVEN Uncertainty Analysis

- Quantification of **uncertainties** on the RELAP5-3D deterministic calculations results needed
- **RAVEN** code applied to RELAP5-3D for performing uncertainty quantification (→ *tomorrow afternoon workshop for details*)
- Simplified UQ performed for testing chain of codes capabilities
  - Simplified 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
- Selected **RELAP5-3D** input parameters to be perturbed by **RAVEN** code:
  - Decay power
  - MCP Seal LOCA break area
  - Core Pressure losses
  - Valves flow areas
  - Heat Exchange multiplier

# Coupled EMRALD/NEUTRINO/RELAP5-3D

- Sensitivity Analysis showed that MCP seal mass flow has negligible effect on PCT
- Remaining four parameters perturbed using Monte Carlo sampler and assigned PDF
- Wilks`s formula applied:
  - 59 calculations for 95% fractile/ 95% confidence limit on PCT

| Run # | Sensitivity Parameter |
|---|---|
| Reference Case | Nominal values |
| 1A | Core Decay Heat +7 % |
| 1B | Core Decay Heat -7 % |
| 2A | Reduction of RPV internal circulation mass flow |
| 2B | Increase of RPV internal circulation mass flow |
| 3A | SG/PRZ PORV and SRV valve flow areas increased by 30% |
| 3B | SG/PRZ PORV and SRV valve flow areas decreased by 30% |
| 4A | MCP seal LOCA +20 gpm |
| 4B | MCP seal LOCA -20 gpm |
| 5A | SG HX Multiplier +20% |
| 5B | SG HX Multiplier -20% |




RAVEN/RELAP5-3D UQ for PCT

# Coupled EMRALD/NEUTRINO/RELAP5-3D

- Coupled calculations **EMRALD**/**NEUTRINO**/**RELAP5-3D** run
- **NEUTRINO** calculation (flooding) computational expensive → minimization of **RELAP5-3D** calculations using pre-calculated failure maps
- CDF for EQ-induced SBO obtained

| Parameter | Value |
|---|---|
| Total EMRALD runs | 67,877,823 |
| Total Running Time | ~263 hours |
| Significant EQ Events | 4311 |
| SBO Events | 258 |
| NEUTRINO simulations | 261 |
| RELAP5-3D indirect calculations | 245 |
| RELAP5-3D direct calculations | 3 |

| Event | Probability (events/year) |
|---|---|
| EQ induced SBO | 3.80E-6 |
| CDF | 2.84E-8 |
| CDF w/o RELAP5-3D feedback | 1.47E-8 |

# Summary

- Methodology & Tools for LWRS/RISMC IA#2 defined
- Two toolkits and pathways defined (EEVE-A and EEVE-B)
- Combined calculations of **Structural Mechanics/PRA/Flooding/ System Thermal-hydraulic/UQ** performed
- **RELAP5-3D** provided reliable BE TH analysis for PWR SBO event
  - Coupled to **EMRALD**/**NEUTRINO** and **RAVEN** codes
- Activities continuing during FY2017
  - External flooding and detailed NPP model (NPP licensee feedback)

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