Application of RELAP5-3D for the Risk-Informed External Events Analysis

C. Parisi, S. Prescott, Z. Ma, R. Spears, J. Coleman, R. Szilard

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www.inl.gov

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Outline

- LWRS/RISMC Project Overview
- External Hazards analysis methodology
- Application
- Results

RISMC Overview

- US DOE Light Water Reactor Sustainability Program (LWRS) – Risk-Informed Margin Characterization (RISMC) is a multi-years effort led by INL for better **characterize the safety margins** of the existing US LWR fleet
  - Ultimate goal: <u>**increase LWR economics and reliability, sustain safety**</u>
- INL working on developing new:
  - Tools (e.g.: RAVEN, MOOSE tools)
  - Data
  - Methods

RISMC Overview

- What does it means Risk-Informed Margin Characterization?
  - Develop **Risk-Assessment method** coupled **to safety margins quantification**
    - Integration of PRA and deterministic methods
    - Highest level of knowledge for a safety analyst / NPP operator

[from IAEA SSG No. 2]

Option	Computer Code	Availability of Systems	Initial and Boundary Conditions
1) CONSERVATIVE	Conservative	Conservative Assumptions	Conservative Input Data
2) COMBINED	Best Estimate	Conservative Assumptions	Conservative Input Data
3) BEST ESTIMATE	Best Estimate	Conservative Assumptions	Realistic + Uncertainty
4) RISK INFORMED	Best Estimate	Derived from PRA	Realistic + Uncertainty

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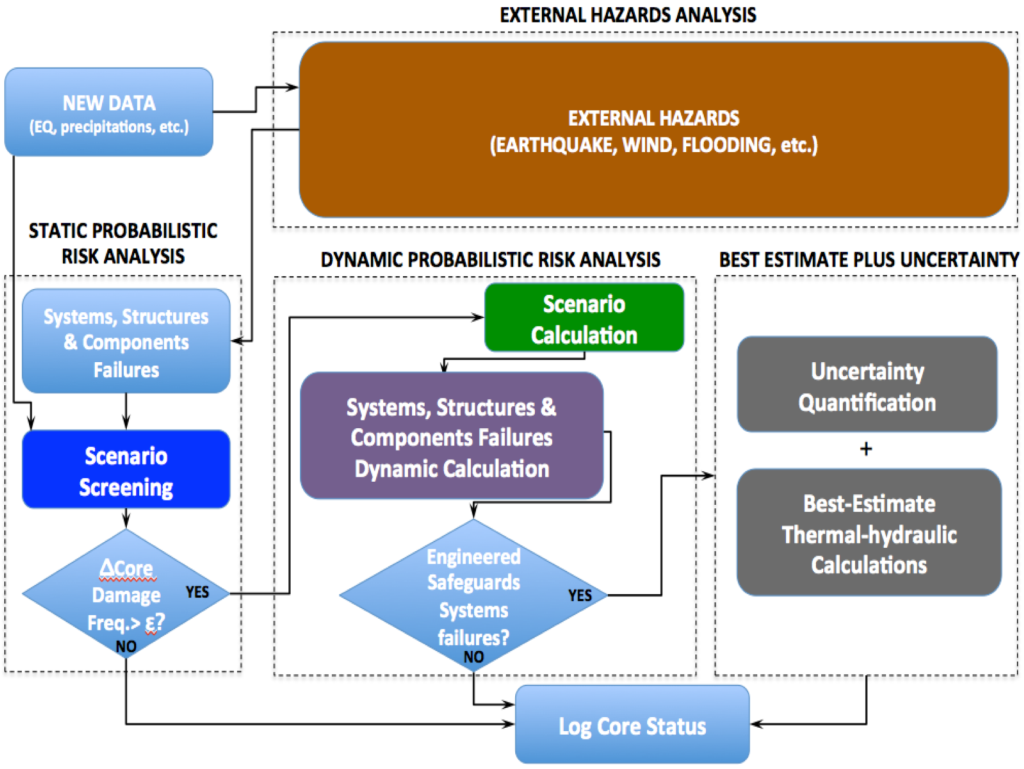
- Can we today pursue a RISMC approach?
  - **INL Tools**, e.g.:
    - RELAP5-3D → Best-Estimate System TH analysis + 3D NK
    - PHISICS → 3D NK + Burnup analysis
    - SAPHIRE → Static PRA
    - RAVEN & EMRALD → Dynamic PRA
    - RAVEN → UQ
    - NEUTRINO → 3D Flooding
    - MASTODON → Seismic analysis
  - **Data**: INL RELAP5-3D and PRA database for US LWRs
  - **Computational power**: INL Falcon Supercomputer (34,992 cores/121 TB memory / 1.087 Pflops (10^{15}) LINPACK rating
  - **Methodologies**: coupling of different tools tested for different industrial problems (LOCA, External events, etc.)

Risk-Informed External Events Analysis

- Scope of **External Events** Risk-informed Analysis key-points:
  - Perform an integrated analysis of the whole NPP
  - Include different combination of natural external hazards (e.g., earthquake and flooding)
  - Develop new tools/improve existing ones
  - Develop a consistent methodology
  - Apply analysis to a generic NPP representative of the US LWRs fleet

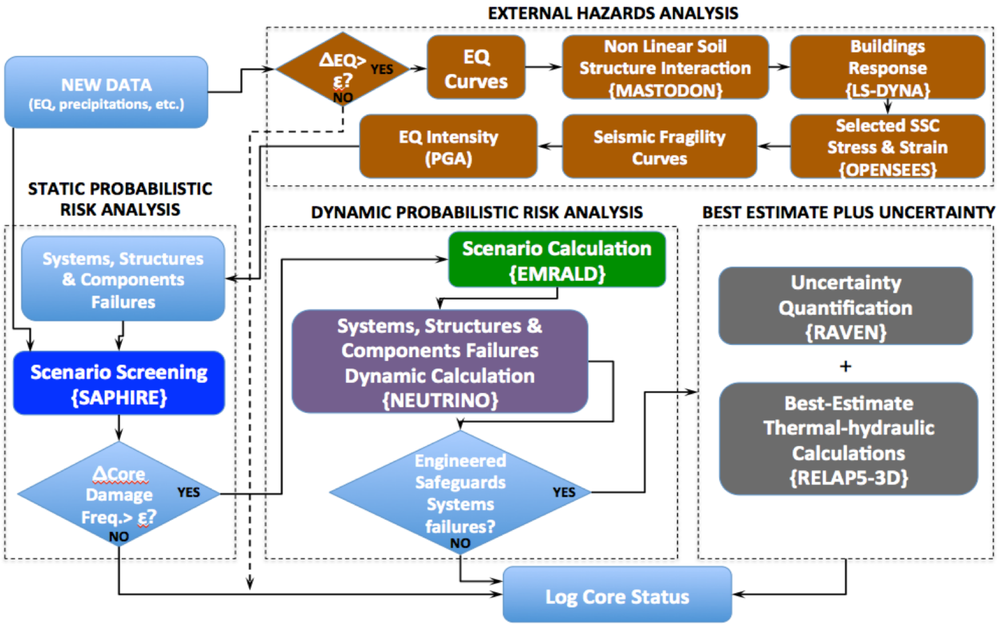
Risk-Informed External Events Analysis

- **Methodology workflow**
  - External Hazards block can be configured to perform different types of analysis (e.g., EQ, wind, flooding, etc.)
- **Main Steps**
  1. Identify new hazards
  2. Perform EE advanced analyses
  3. Check with classical PRA if ΔCDF is relevant (analyst threshold)
  4. If yes, send the significant failure sequences to the dynamic PRA tool simulation
  5. If safety-significant components are affected, run BEPU calculation
  6. Log core status → determine failed/safe core conditions



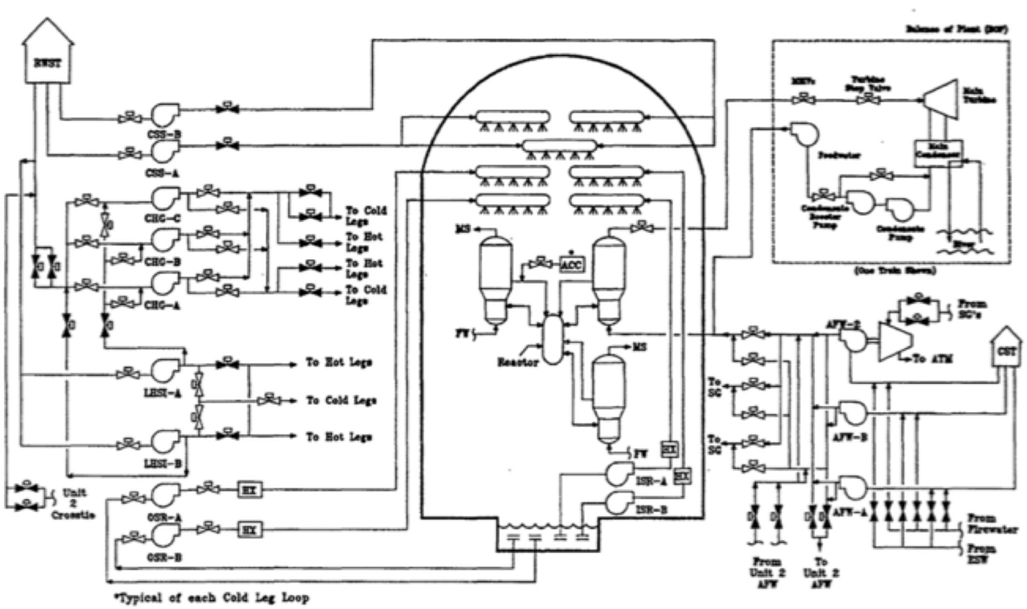
Risk-Informed External Events Analysis

- Application to **Earthquake-induced internal flooding event**
- Main Steps
  1. Identify new hazards (new EQ spectrum)
  2. Perform EE advanced analyses
     - *Use of Non-linear soil-structure interaction (NLSSI) methodology [**LS-DYNA** & **MASTODON codes**]*
     - *Piping fragilities evaluation [**OPENSEES]***
  3. Check with classical PRA if ΔCDF is relevant → **SAPHIRE** code
  4. If yes, send the significant failure sequences to the dynamic PRA tool simulation (**EMRALD** code)
     - **NEUTRINO** 3D flooding analysis
  5. If Safety-significant components are affected, run BEPU calculation by **RELAP53D+RAVEN** codes
  6. Log core status → determine failed/safe core conditions



System Analysis: INL Generic PWR

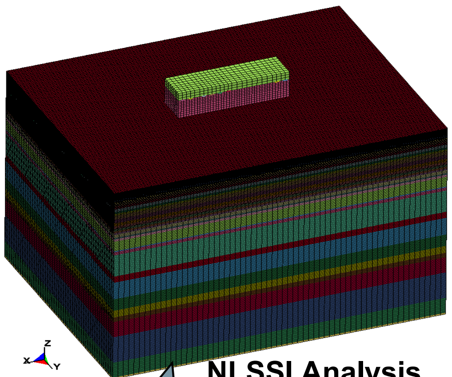
- INL-Generic PWR (IGPWR) defined for EE analysis
- Main Characteristics:
  - 3 Loop PWR / NSSS by Westinghouse
  - Core average power: 2546 MW_{th} [855 MW_e]
  - Core: 157 FA [15x15 Westinghouse FA]
  - Sub-atmospheric Containment



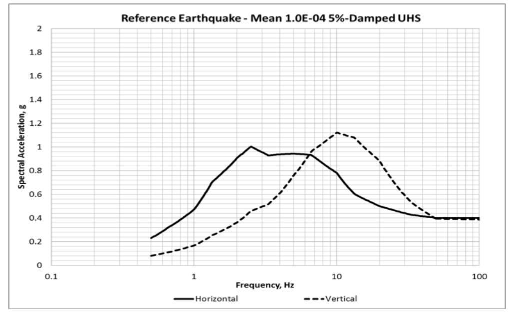
IGPWR ESF

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

Steps 1&2 - New Hazards & EQ + Structural analysis

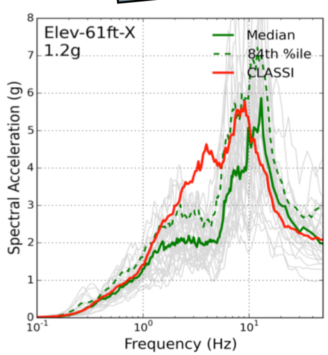


NLSSI Analysis

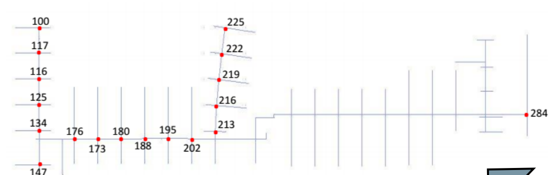


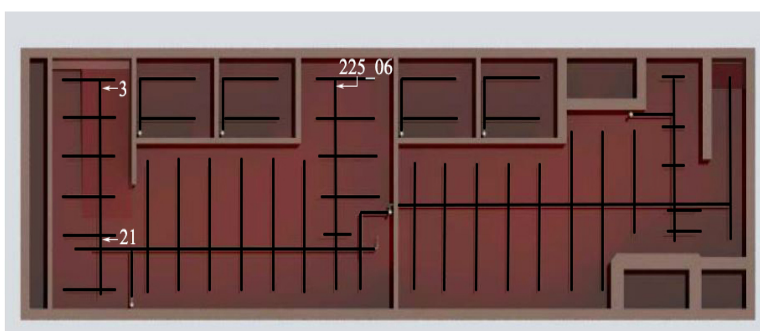
Seismic Hazard Cure

- Calculate 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**)

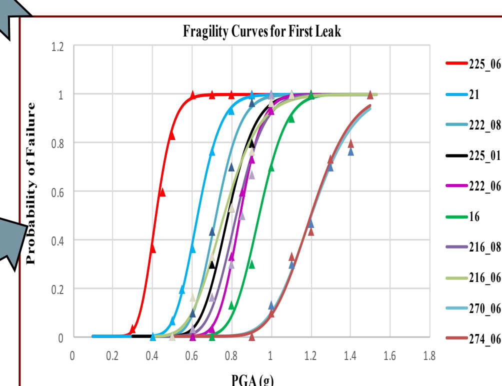


Acceleration Response Spectra for Aux Building





Structural Analysis of Fire Suppression System



Seismic Fragility Curves

Step 3 – Identify new risks w/ classical PRA

- **Use of Classical PRA model**
  - **INL *SAPHIRE*** code model for generic generic 3-loops PWR
  - Added External events/EQ→ ref. “NRC Risk Assessment of Operational Events Handbook Volume 2 – External Events”
  - Introduced *New Seismic Hazards Vector*
    - Grouped in 3 seismic bins (low/medium/high magnitudes EQ)
  - Focus on seismic-induced Loss-of-Offsite Power (LOOP) sequences
  - Select **4 main LOOP sequences** based on:
    - Relatively higher frequencies
    - Inclusion of important mitigating systems (AFW, ECCS)
    - Inclusion of internal flooding scenarios (proof of risk-informed approach)
  - 2 LOOPs sequences degenerate in Station Black-out (SBO)

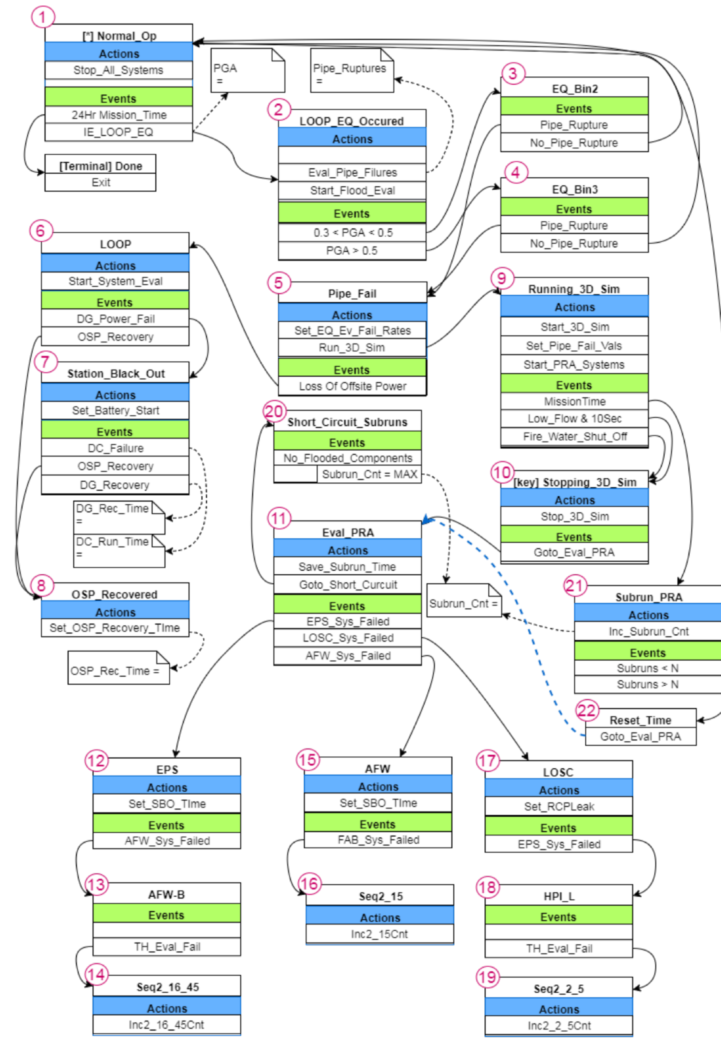
Step 3 – Identify new risks w/ classical PRA

– SAPHIRE calculations shows that new EQ spectrum is causing
  - new failure modes (fire suppression system rupture in the Switchgear/Battery room)
  - general increase of failure frequencies for other components → increase of LOOP & SBO sequence frequencies for Bin 2 & 3 (Medium and High magnitudes EQs)

Seismic Bin	EQK Sequence	Sequence Frequency with New Seismic Hazard	Sequence Frequency New Seismic Hazard + New Failure Modes	% difference
BIN-1	2-02-05	9.89E-09	9.89E-09	~0. %
	2-15	4.07E-10	4.07E-10	~0. %
	2-16-03-10	1.89E-07	1.89E-07	~0. %
	2-16-45	1.67E-08	1.67E-08	~0. %
BIN-2	2-02-05	9.26E-08	1.38E-07	49 %
	2-15	2.30E-07	1.76E-06	665%
	2-16-03-10	8.32E-07	1.86E-06	123%
	2-16-45	2.49E-06	6.85E-06	175%
BIN-3	2-02-05	4.72E-07	5.26E-07	11%
	2-15	1.71E-06	8.53E-06	398%
	2-16-03-10	1.26E-06	1.99E-06	57 %
	2-16-45	7.19E-06	1.56E-05	116%

Step 4 – Calculate new risk w/ dynamic PRA

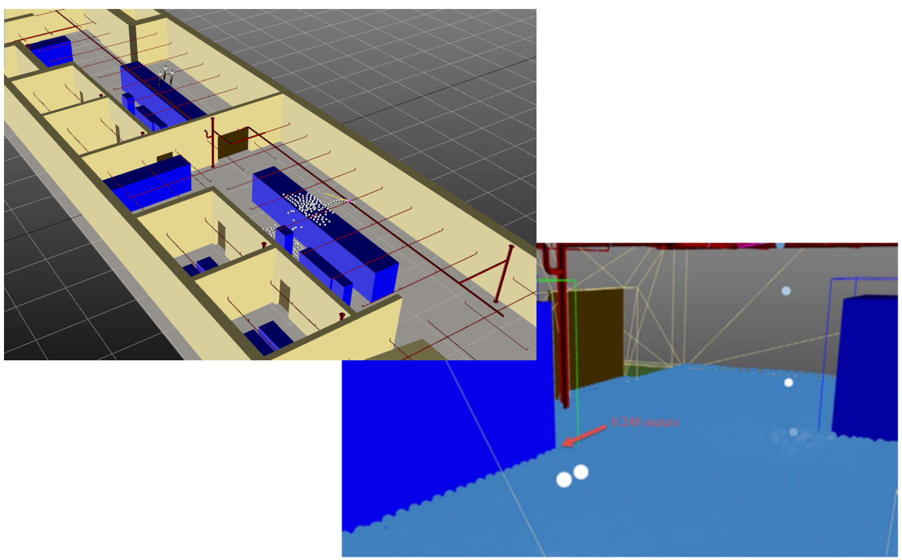
- Inform EMRALD dynamic PRA tool with:
  - new SAPHIRE PRA sequences
  - fragility curves from the structural analysis
  - results from flooding and system analysis
- EMRALD steps:
  1. IE EQ causing LOOP
  2. Calculation of Peak Ground Acceleration (PGA) for given EQ
  3. Evaluate DG availability given 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



EMRALD Workflow

Step 4 – Calculate 3D flooding scenarios

- If EMRALD detects possibility of pipe break in the switchgear room → calls NEUTRINO flooding tool for 3D flooding analysis
  - **Major difference compared w/ classical PRA approach →** in that case, switchgear room flooding = all components in the room fail!



Switchgear Room 1 – NEUTRINO Flooding Simulation

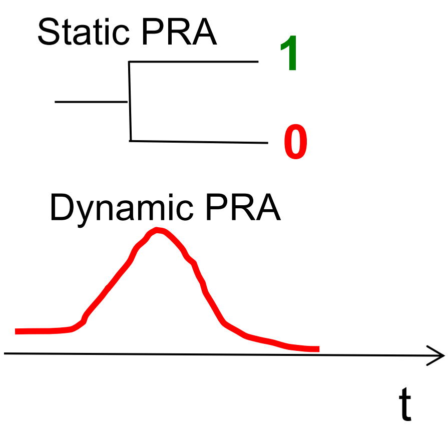
SWITCHGEAR ROOM 1

Equipment ID	Description	Height*	Affected Comp./Systems
BAT-1-A	control storage battery	18 in.	• **TD-AFW** • **SG & 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** • **SG & 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** • **SG & 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	12 in.	• **Vital Instrumentation (Reactor**

Components Affected by Flooding

Step 5 – Calculate System TH performance

- If **Safety-significant components** are affected, run BEPU calculation by **RELAP5-3D+RAVEN** codes
  - E.g., flooding in the switchgear room could cause DC battery loss
  - E.g., high magnitude EQ could damage ESFs
- RELAP5-3D simulate the LOOP and SBO sequences, including recovery actions
  - In dynamic PRA, recovery actions **have not** a boolean value (success/fail at assigned time)
  - Recovery actions success have a PDF (sampled by EMRALD)



- RELAP5-3D simulates
  - LOOP 2-02-05: loss of offsite, no offsite recovery at +2hr
  - SBO 2-16-45: SBO & loss of DC battery for flooding

Step 5 – Calculate System TH performance

- For just those two sequences, hundreds of RELAP5-3D calculations would be needed
- E.g., SBO 2-16-45
  - Failure of Batteries (→ temporary loss of TD-AFW) during first 1 hr from the EQ
  - Fuel Failure depending by the battery failure time and recovery time
  - Needs lots of fuel failure maps → tedious and impractical process →introduce user errors
- Coupling of RAVEN/RELAP5-3D, using the **Automatic Limit Surface** search algorithm allows
  - identify with more accuracy the boundary between green (**safe**) and red (**failed**) state
  - detailed Limit Surfaces avoid the **EMRALD/RELAP5-3D** on-line calculations

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

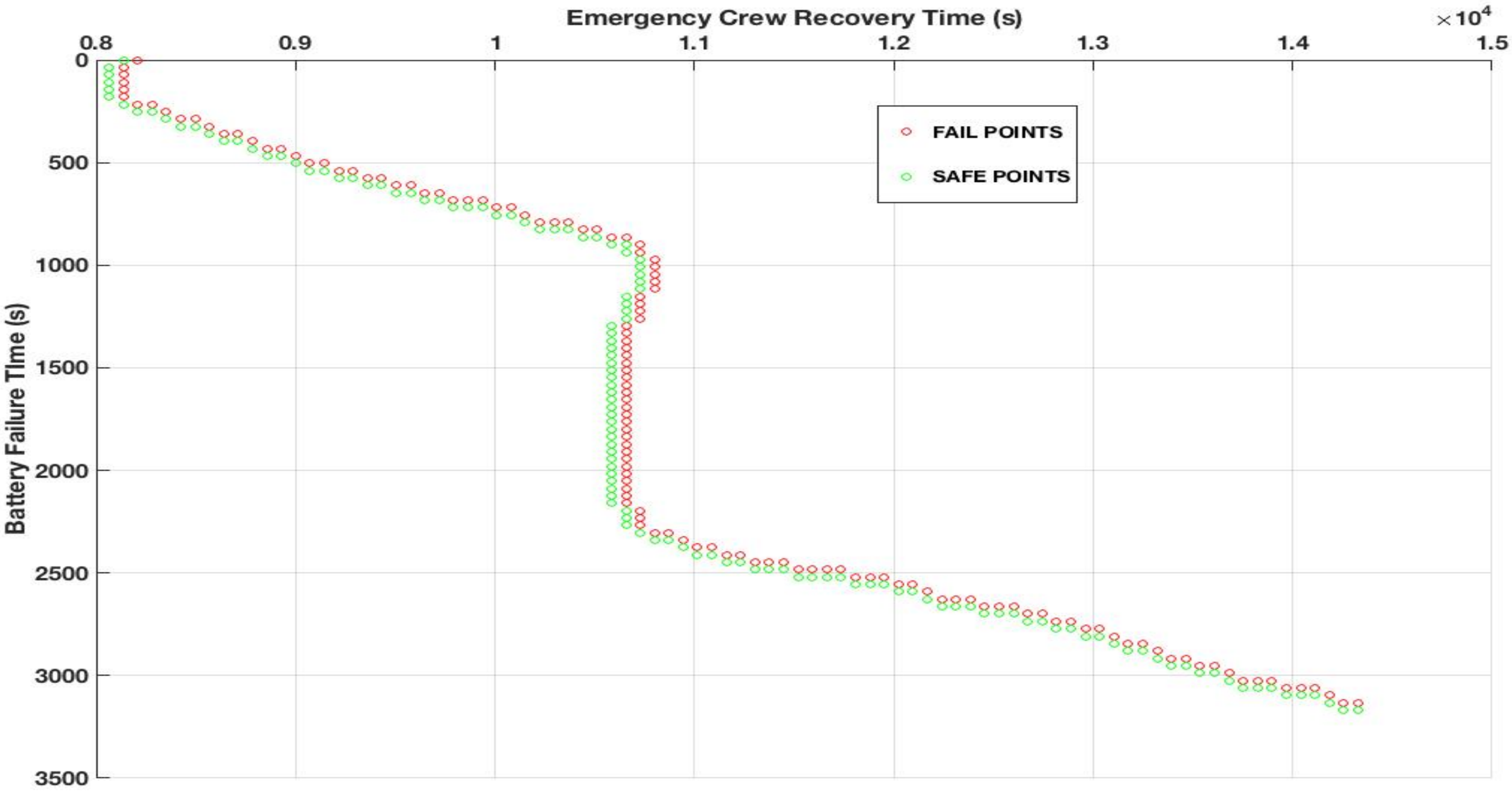
Mitigated LTSBO + Battery Failure for Internal Flooding + Early MCP Seal Failure

Step 5 – Calculate System TH performance

- **RELAP5-3D/RAVEN** code for Automatic Limit Surface Search
  - Use of Reduced Order Models (ROM)
    - Reduce the complexity of the problem
    - Set of equations are trained to approximate the original model
  - Several ROM available in **RAVEN**
    - Train using a set of starting points (**RELAP5-3D** calculations)
- Automatic Limit Surface calculations possible for different NPP scenarios (early/not early MCP seal failure, HPI loss, etc.)
- Information contained in the following pictures (LOOP 2-02-05 and SBO 2-16-45 are passed via a binary file to **EMRALD**)

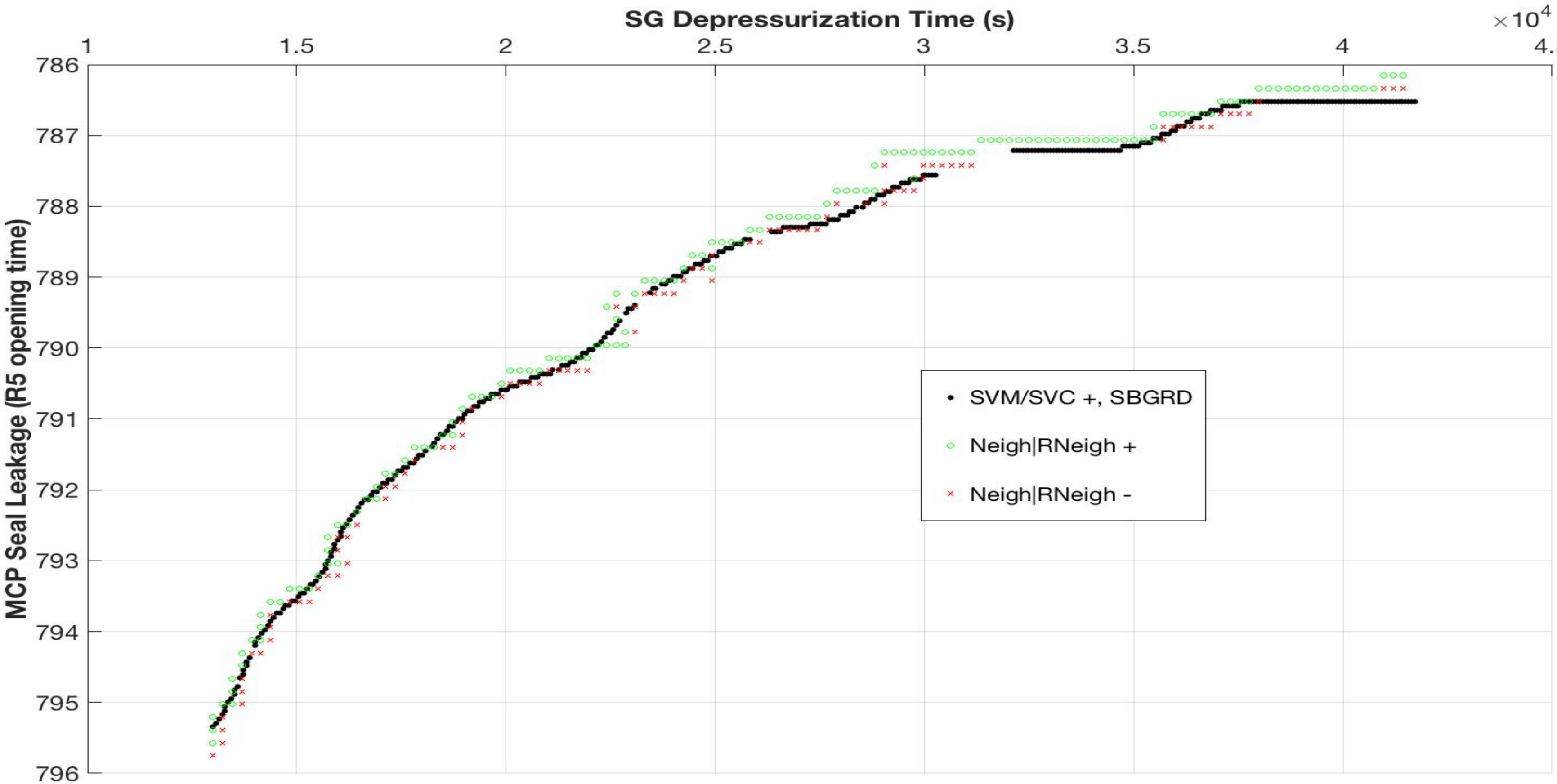
Step 5 – Calculate System TH performance

- SBO 2-16-45 (Battery failure time vs. Emergency Crew Recovery Time)



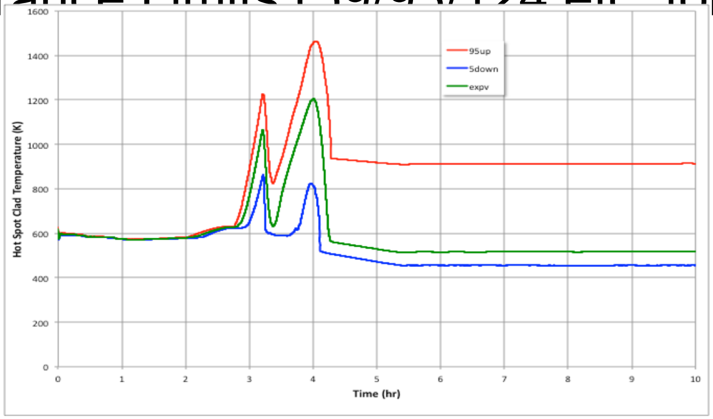
Step 5 – Calculate System TH performance

- LOOP 2-02-05 (Main Coolant pump seal leak rate vs. SG depressurization time)



Step 5 – Calculate System TH performance

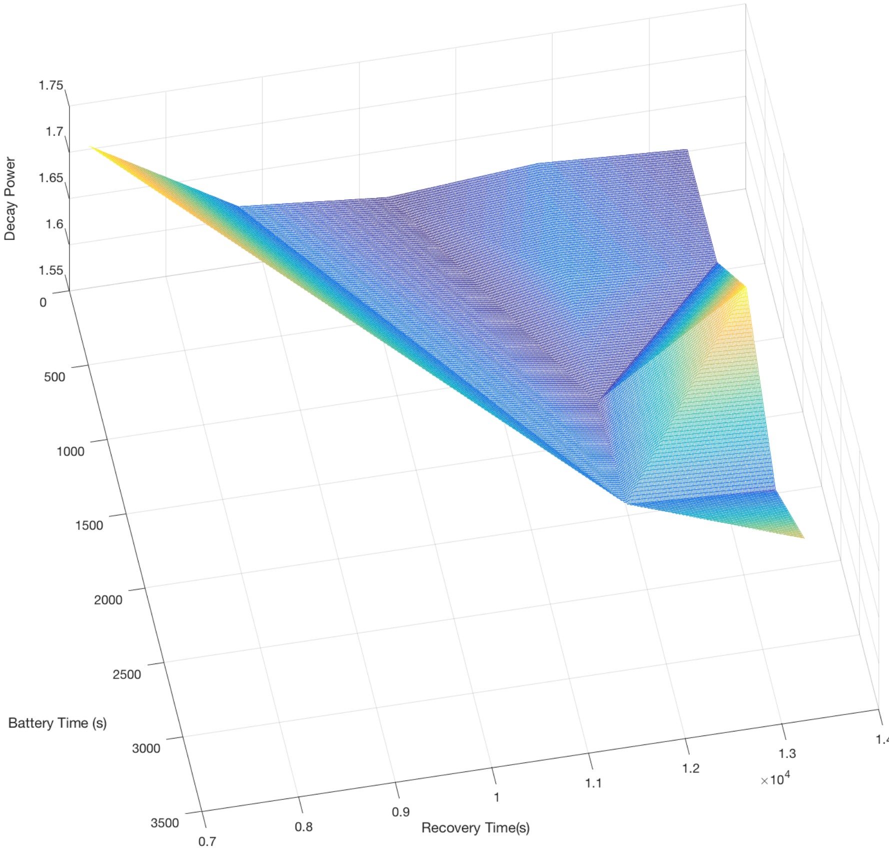
- Limit Surfaces can be informed with uncertainties (full BEPU calculation)
- RAVEN can perform Monte Carlo perturbation of the RELAP5-3D input parameters (see Friday afternoon workshop)
  - Relevant uncertainty parameters identified by a PIRT
  - Perform basic statistics calculations for obtaining sensitivity/Pearson/covariance etc → ranking of uncertainty parameters
  - Application of Tolerance Limits (59/93/124 etc. for first, second, …order statistics)



RELAP5-3D/RAVEN for mitigated LTSBO

Step 5 – Calculate System TH performance

- Informing the Limit Surface Search with the UQ results
  - Performing the LSS including epistemic uncertainty
  - 6 dimension LS (4 epistemic, 2 stochastic)
- n-dimensional surfaces can be obtained (6-dim, in this example)
- Projection of 3 dimensions (Battery Time/Operator action/Core Power)



RELAP5-3D/RAVEN Limit Surface including uncertainty parameters

Step 6 – Log Core Status

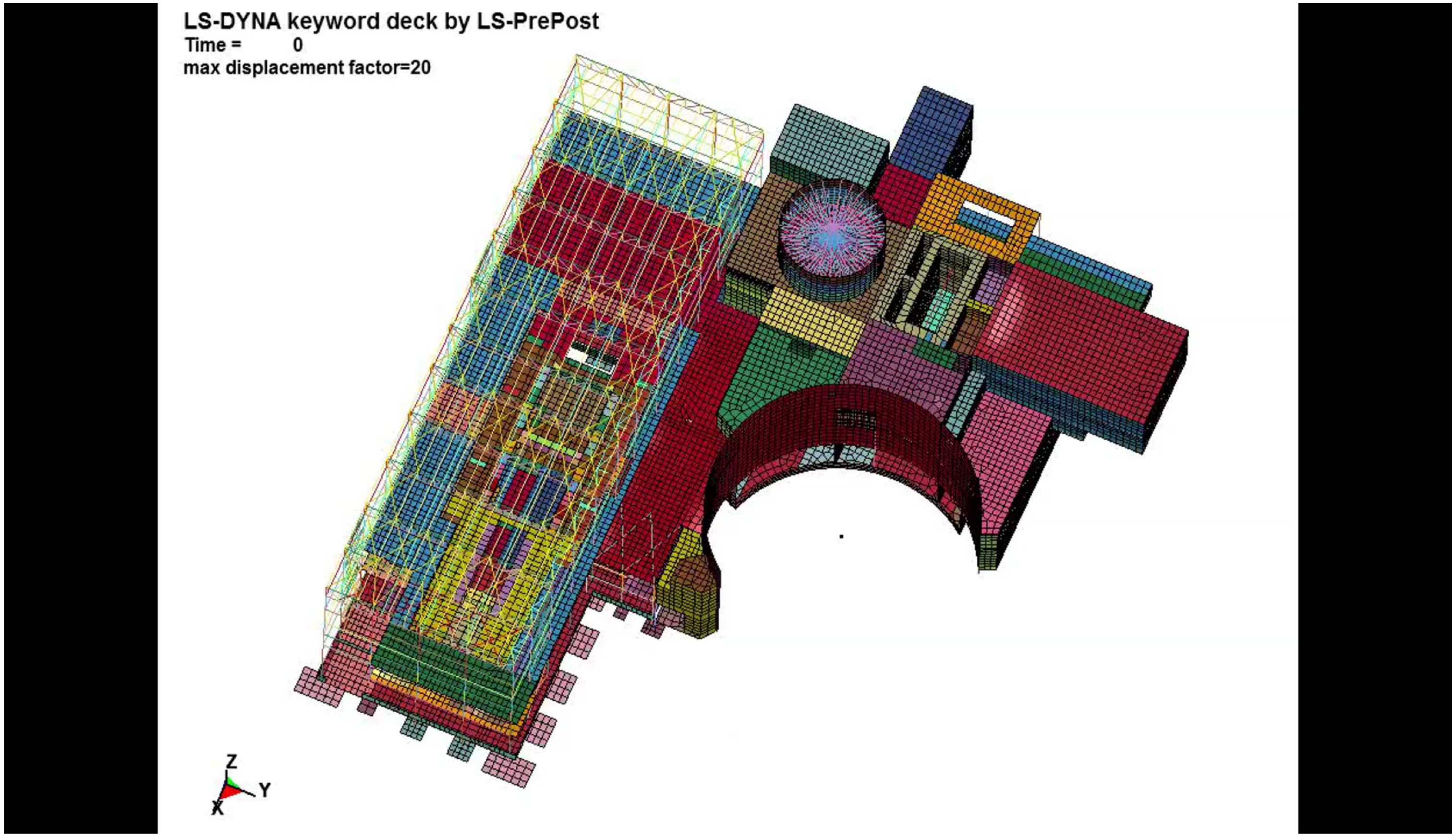
- EMRALD calculations informed by Seismic / NEUTRINO / RELAP5-3D / RAVEN results
- Comparison with static PRA analysis demonstrates the sensible reduction in CDF for the different sequences
- Use of advanced simulation tools helps to identify the failure probabilities of different components

Sequence Case (Bin2+ Bin3)	CDF No SWGR Pipe Failure [SAPHIRE]	CDF SWGR Pipe Failure [SAPHIRE] (S1)	CDF SWGR Pipe Failure [EMRALD+NEUTRINO+ RELAP5-3D/RAVEN] (E1)	CDF Reduction EMRALD vs. SAPHIRE (1-E1/S1)*100
LOOP 2-02-05	5.65E-07	6.64E-07	5.74E-07	-14%
LOOP 2-15	1.94E-06	1.03E-05	1.94E-06	-81%
SBO 2-16-03-10	2.09E-06	3.85E-06	2.09E-06	-46%
SBO 2-16-45	9.68E-06	2.25E-05	5.74E-07	-97%

3D Component	Counts	Failure %
480V bus #1	30320	97.0768%
UPS 1 B	209	0.6692%
125VDC Panel 1	515	1.6489%
4KV bus #1	160	0.5123%
480V bus #2	27	0.0864%
UPS 1 A	2	0.0064%

Conclusion

- Risk-Informed External Hazards methodology has been developed
- Testing application for a spectrum of Earthquakes, including internal flooding events
- Developed methodology is based on INL state-of-the-art codes
  - RELAP5-3D provides Best-Estimate analyses for relevant PRA sequences
  - Coupled with RAVEN, can inform dynamic PRA calculations using Limit-Surface concept (+Uncertainty)
- Results from test application showed that Risk-Informed analyses can sensibly decrease the level of conservatism



Multi-scale & Multi-physics + Risk-Informed Analysis decrease conservatism, identify new risks