INL/MIS-23-74662-Revision-0

Sodium Fast Reactor Probabilistic Risk Assessment Activities

September 2023

Robby Christian

Changing the World's Energy Future

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Sodium Fast Reactor

Probabilistic Risk Assessment Activities

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Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

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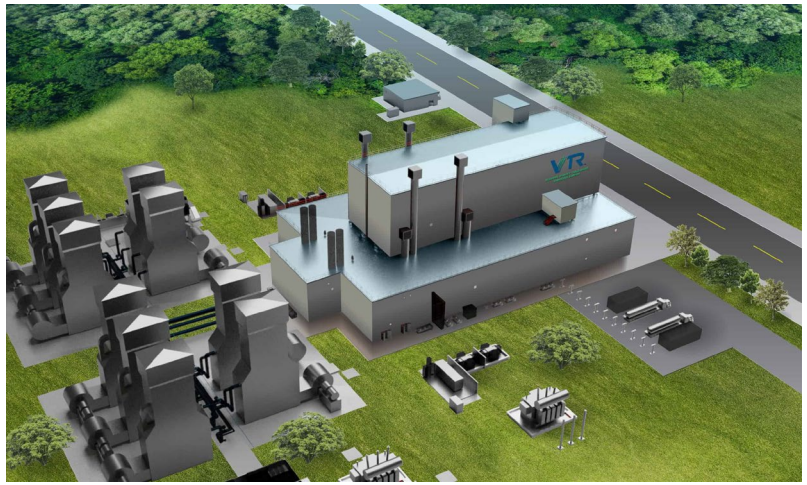
Introduction

- Current PRA work on a power-generating SFR design
- References previous publications:
  - Experimental Breeder Reactor II (EBR-II) Level 1 PRA, https://www.osti.gov/biblio/1483951
  - Versatile Test Reactor (VTR) safety analysis, https://www.osti.gov/biblio/1874798
  - VTR PRA report, not publicly available
- PRA
  - Scenarios initiating and leading to the undesired outcome
  - Likelihood of said scenarios
  - Magnitude of the consequences

EBR-II, https://factsheets.inl.gov/FactSheets/EBRII_TestBed.pdf



VTR, https://inl.gov/vtr/imagesvideos/

Generic Initiating Events for SFRs

- **Loss of flow**: Loss of primary pump power, blockage of core inlet, inlet pipe breaks, etc.
- **Reactivity insertion**: control rod ejection, core support failure, core radial movement, gas bubble in core, etc.
- Loss of primary heat sink
- **Overcooling**: pump faults, BoP transients, etc.
- Loss of decay heat removal systems
- **Transients** (including shutdown)
  - Spurious reactor trips
  - Anticipatory shutdown
  - Normal shutdown
  - Core characterization transients

- Loss of coolant (sodium)
- Core support or other structural failure
- Blockage
- **Support system failures**: Loss of power, loss of instrument air, loss of water systems
- External events
- Leak between primary/secondary system.

Reference: EBR-II Level 1 PRA, https://www.osti.gov/biblio/1483951

Likelihood and Consequence

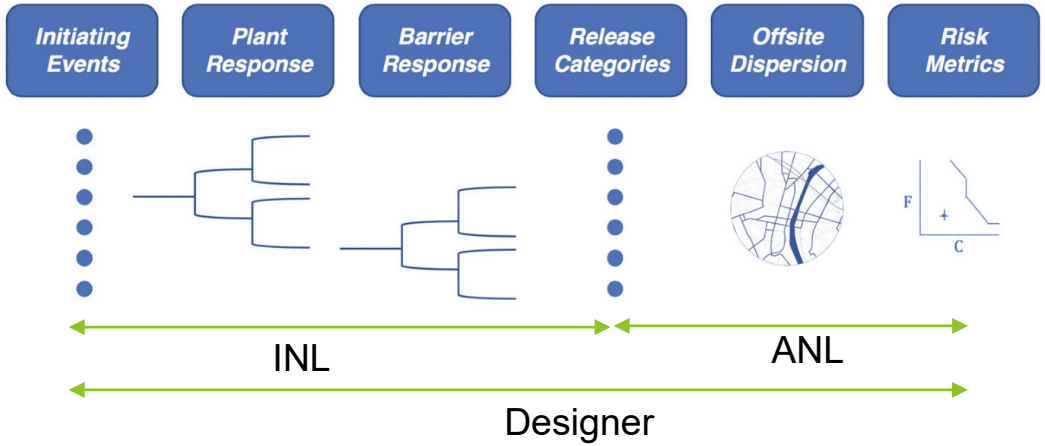
- Probability data:
  - US-NRC component reliability data, https://nrcoe.inl.gov/AvgPerf/
  - US-NRC CCF parameter estimates, https://nrcoe.inl.gov/ccf_pe/
  - Generic component failure data base for LWRs and liquid sodium reactors, https://www.osti.gov/biblio/975488
  - IAEA TecDoc 930: generic component reliability data for research reactor PSA, https://www-pub.iaea.org/MTCD/Publications/PDF/te_0930_scr.pdf
- Consequence assessment is done by Argonne National Laboratory (ANL)

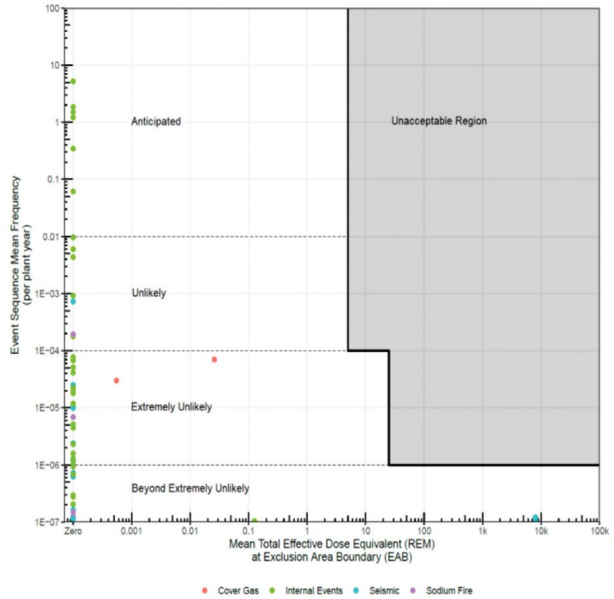
PRA Standard

- ASME/ANS RA-S-1.4-2021 Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants, https://www.asme.org/codes-standards/find-codes-standards/ra-s-1-4-probabilistic-risk-assessment-standard-advanced-non-light-water-reactor-nuclear-power-plants/2021/drm-enabled-pdf
- Integrated risk analysis. No PRA Level 1, 2, 3

ASME/ANS Non-LWR PRA Standard Elements

PRA Elements	Scope of Groups		
	Internal Events	Internal Hazards	External Hazards
Plant Operating State Analysis (POS)	✖	✖	✖
Initiating Events Analysis (IE)	✖	✖	✖
Event Sequence Analysis (ES)	✖	✖	✖
Success Criteria (SC)	✖	✖	✖
Systems Analysis (SY)	✖	✖	✖
Human Reliability Analysis (HR)	✖	✖	✖
Data Analysis (DA)	✖	✖	✖
Internal Flood PRA (FL)		✖	
Internal Fire PRA (FI)		✖	
Seismic PRA (S)			✖
Other Hazards Screening Analysis (EXT)			✖
High Winds PRA (W)			✖
External Flooding PRA (XF)			✖
Other Hazards PRA (X)			✖
Event Sequence Quantification (ESQ)	✖	✖	✖
Mechanistic Source Term Analysis (MS)	✖	✖	✖
Radiological Consequence Analysis (RC)	✖	✖	✖
Risk Integration (RI)	✖	✖	✖



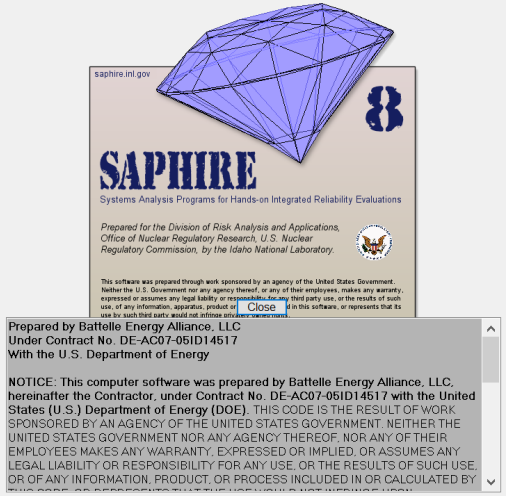


F/C Plot

Figures from: David Grabaskas, Jason Andrus, Dennis Henneke, Jonathan Li, Matthew Bucknor & Matthew Warner (2022) Development of the Versatile Test Reactor Probabilistic Risk Assessment, Nuclear Science and Engineering, 196:sup1, 278-288, DOI: 10.1080/00295639.2021.2014741

Tools

- **Static PRA**: Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE) Version 8, https://saphire.inl.gov/
- Event trees, Fault trees, cutset solvers (MCUB, rare event, Min/Max, BDD)

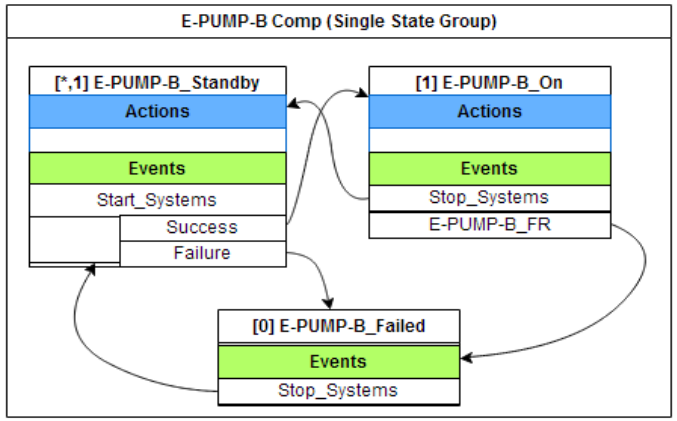


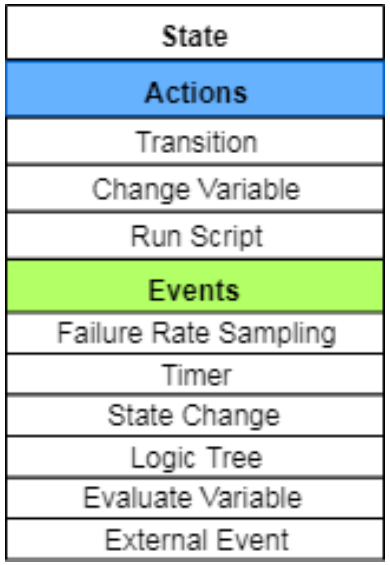
- **Dynamic PRA**: Event Modeling Risk Assessment using Linked Diagrams (EMRALD), https://emrald.inl.gov/
- Dynamic PRA model based on a three-phased discrete event simulation
  - No time steps
  - Jumps to next thing that happens in time.
  - Monte Carlo sampling.
  - Good for long and/or short time jumps.

EMRALD Modeling

States

- Actions (transition, change variables, run script)
- Events -> Action (sampling, conditions, time, etc.)

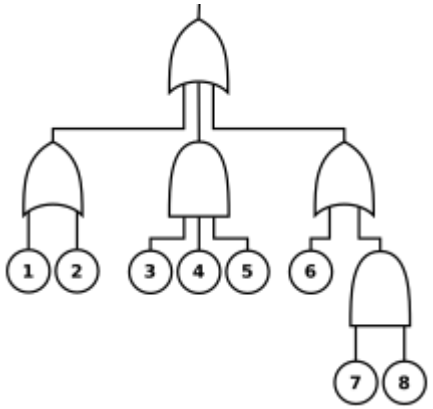




Diagrams

- Components
- Systems
- Plant response

Logic Trees



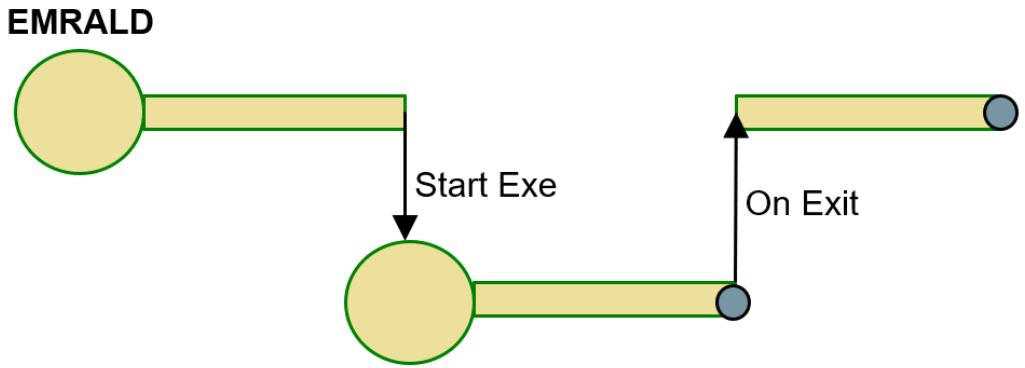
Variables

External Links

EMRALD Coupling Capabilities

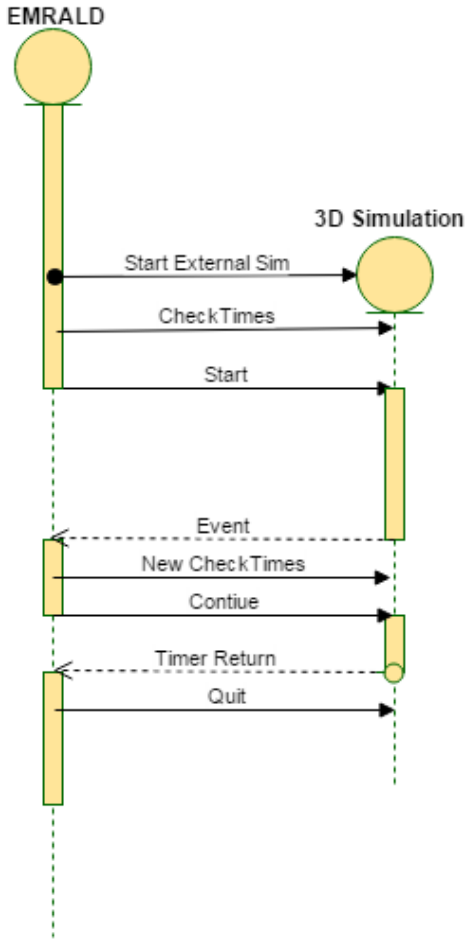
One Way Coupling

- Manual C# scripting in an EMRALD action window, or
- Customized form



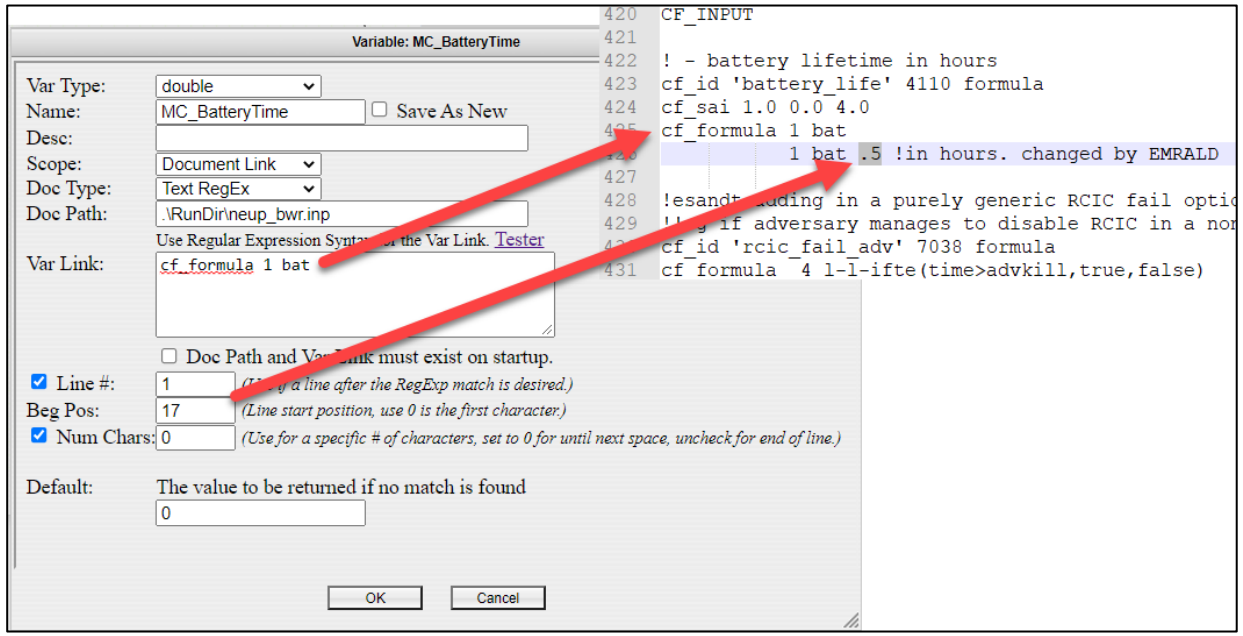
Two Way Coupling (XMPP)

- Message passing
- Requires open code or API
- Event times
- Feedback loops

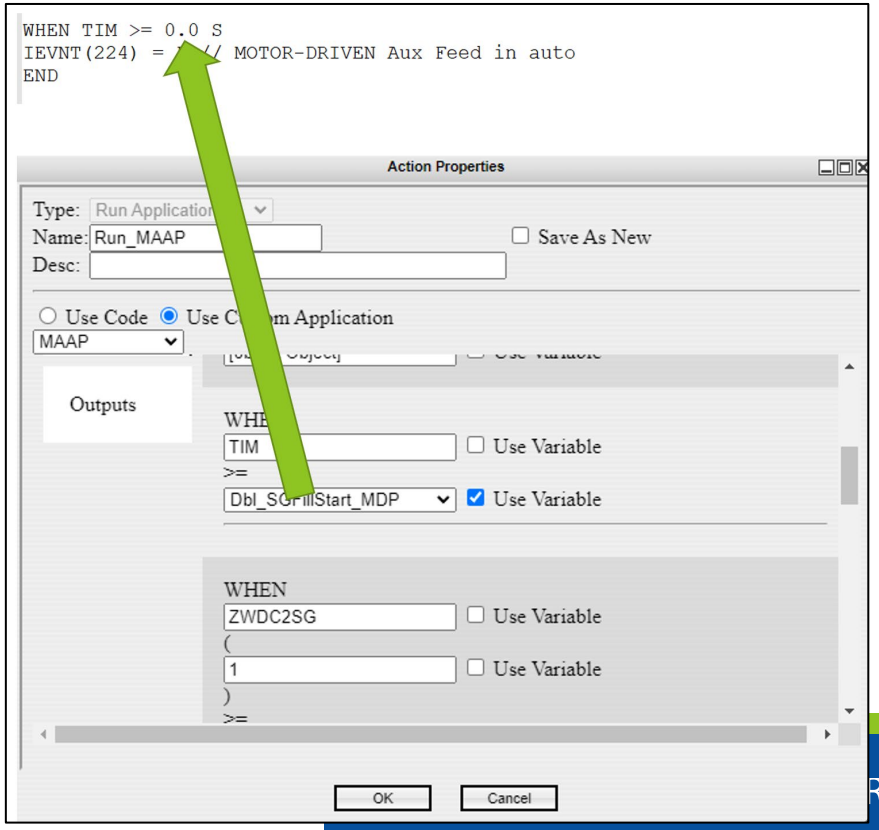


EMRALD Coupling Capabilities (2)

- **EMRALD-MELCOR**
- Modify MELCOR input file using EMRALD variable
- Run MELCOR in EMRALD action



- **EMRALD-MAAP**
- Modify input file, run MAAP, and fetch specific output data in a single form



EMRALD Coupling Capabilities (3)

- EMRALD-RELAP5
- Running_RELAP – There is **possible fuel damage** but **further calculations are needed using RELAP**.
  - Set_LGLeakRate – Sample and set if the RELAP simulation is to have a large leak rate.
  - Set_RecTime – Sample and set the recovery time for RELAP where an operator is able to manually adjust the PORV.
  - Inc_Loop_Cnt – Increment the counter indicating how many times RELAP was run for the current SBO event.
  - Run and Process_RELAP – **Modify the RELAP input deck with the failure time of any components or systems and run RELAP**. If RELAP indicates damage add to Fuel Damage to the current state list. After running RELAP move to Rerun_RELAP_Loop.
- References:
  - INL/EXT-16-40055: Multi-Hazard Advanced Seismic Probabilistic Risk Assessment Tools and Applications, https://www.osti.gov/biblio/1369534
  - INL/EXT-17-42666: Risk-Informed External Hazards Analysis for Seismic and Flooding Phenomena for a Generic PWR, https://www.osti.gov/biblio/1376899

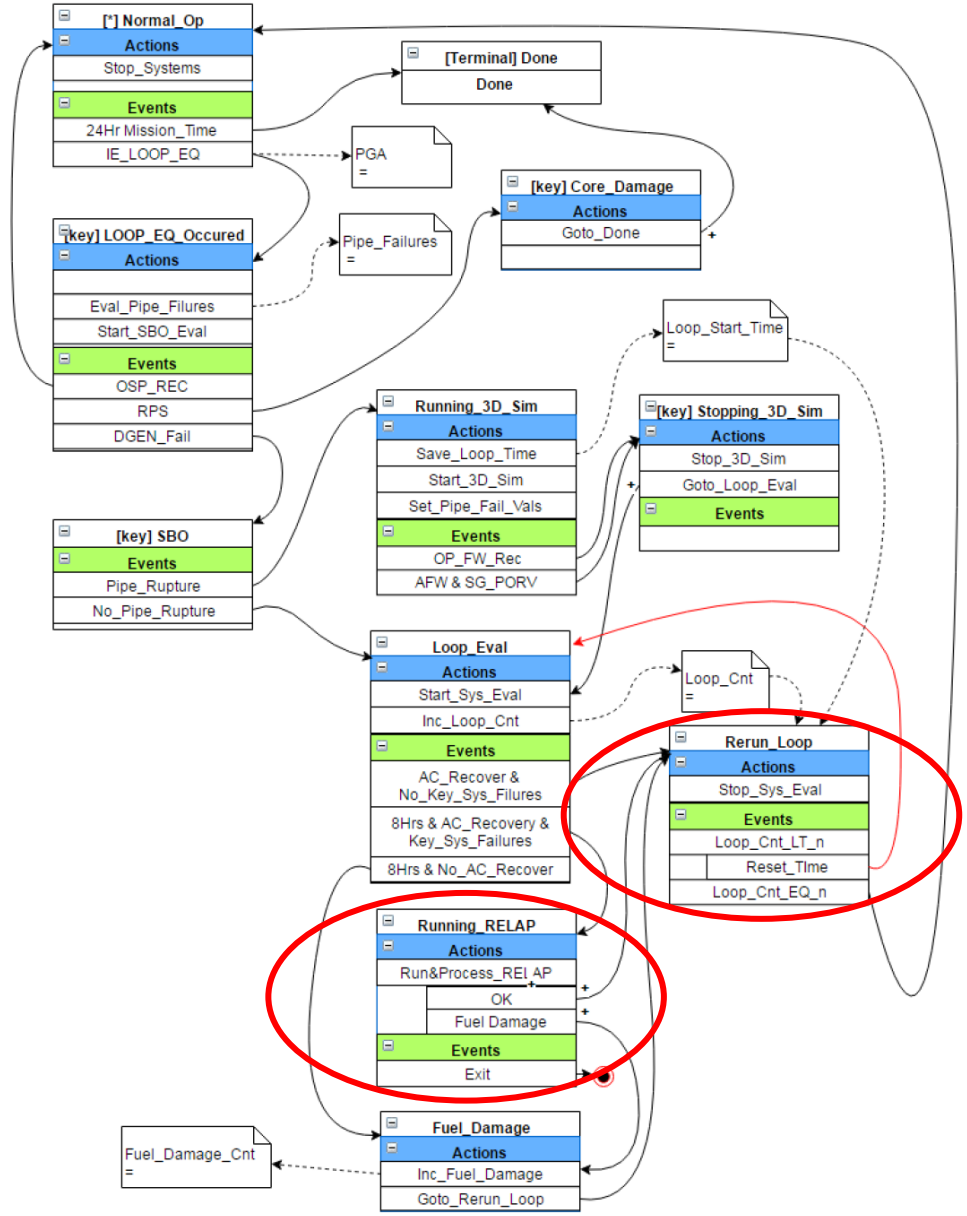


Figure: EMRALD diagram coupling seismic analysis, 3D simulations, and RELAP

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