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ML/AI Applied to Severe Accident Uncertainty Analysis

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ML/AI in Severe Accident Analysis

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Model Training

- Severe accident simulations can be expensive
- Can more efficient reduced order models be developed from mechanistic codes?

Insights from Severe Accident Uncertainty Analysis

- Severe accident uncertainty analyses are unique
- Vast amounts of data generated
- Can we develop insights about emergent states to enable more robust safety decision-making?

Prioritization of Safety-significant Parameters

- Severe accidents are unique in the manner in which many conditions interact to lead to a potential for consequences
- Extracting what is important requires extensive interrogation of data
- Insights are often associated with "attractor" states that emerge

Model-informed Safety R&D

- Accelerated pace of innovation in nuclear energy requiring robust safety decisions in light of uncertainty
- How do we define robustness of a safety decision?
- Where do we need to prioritize R&D to better resolve uncertainties?

How Should We Define ML/AI in Severe Accident Uncertainty Analysis?

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- Potentially vast array of research applications

- Safety-focused R&D seeks to leverage ML/AI to more effectively manage uncertainty and inform decision-making
  - How do we more effectively generate insights from results of very complex models?
  - What do we learn that is elevating application of methods beyond data mining?
- Characterizing risk about understanding uncertainties associated with how a technology performs when subject to a vast array of perturbations
  - Some perturbations may be well understood and defended against (e.g., design basis)

What Severe Accident Uncertainty Analysis is NOT

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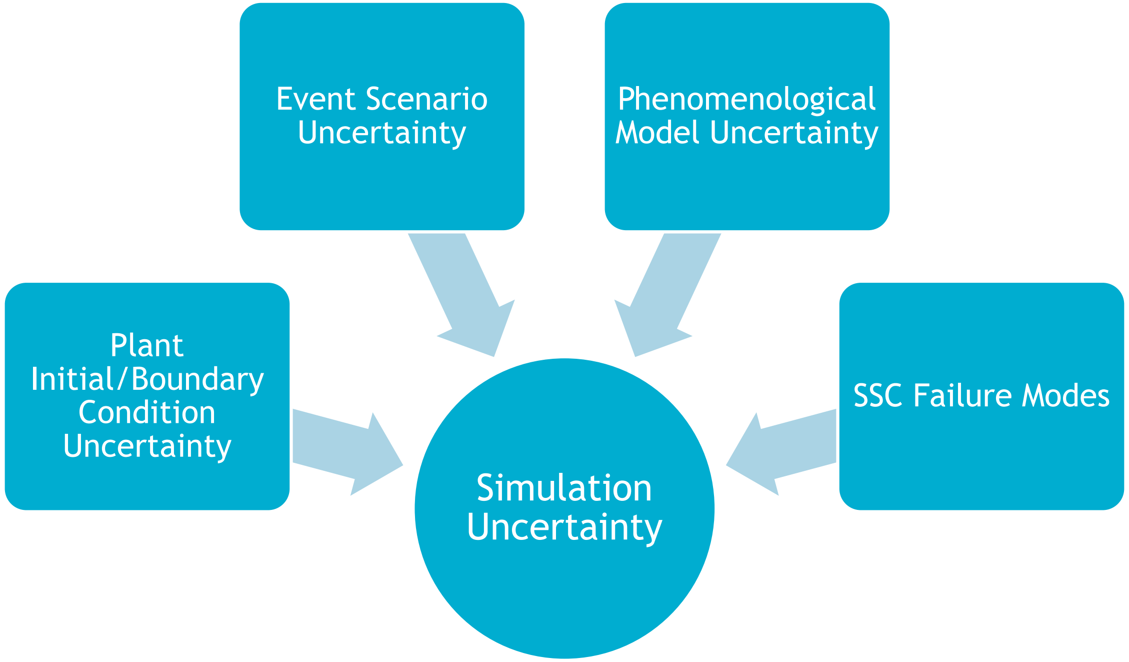
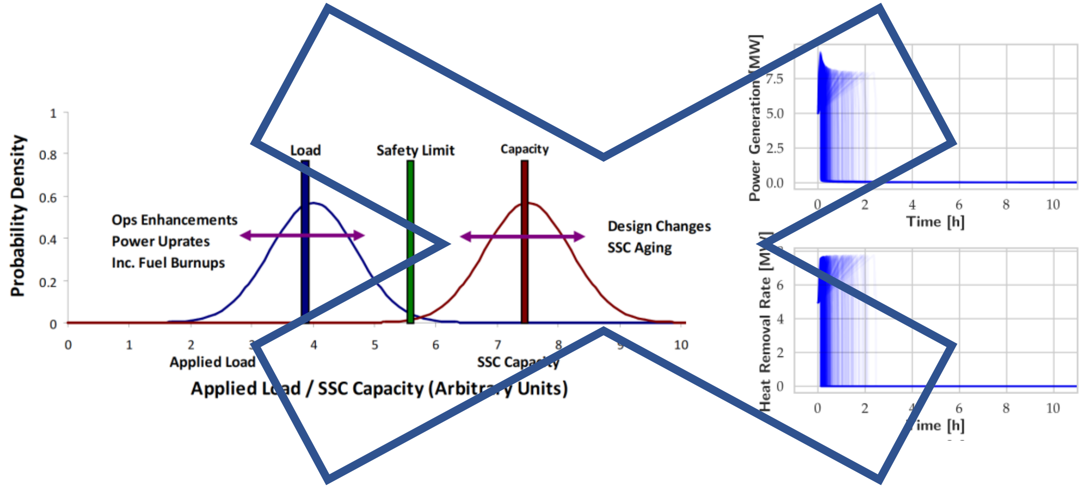
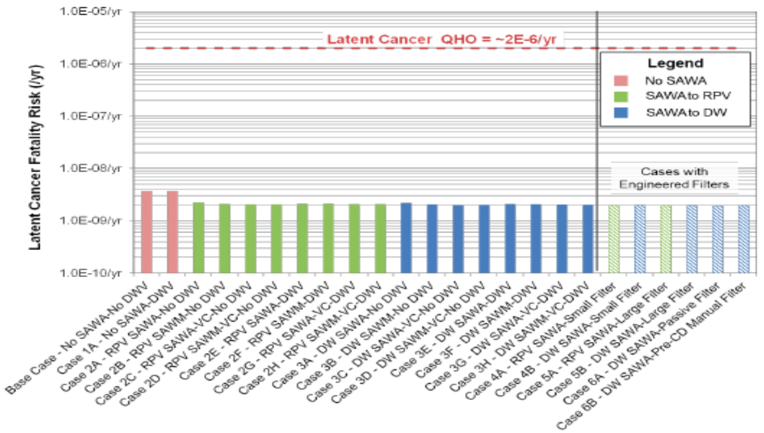
Uncertainty



Engineering Performance



Risk-Informed Assessment

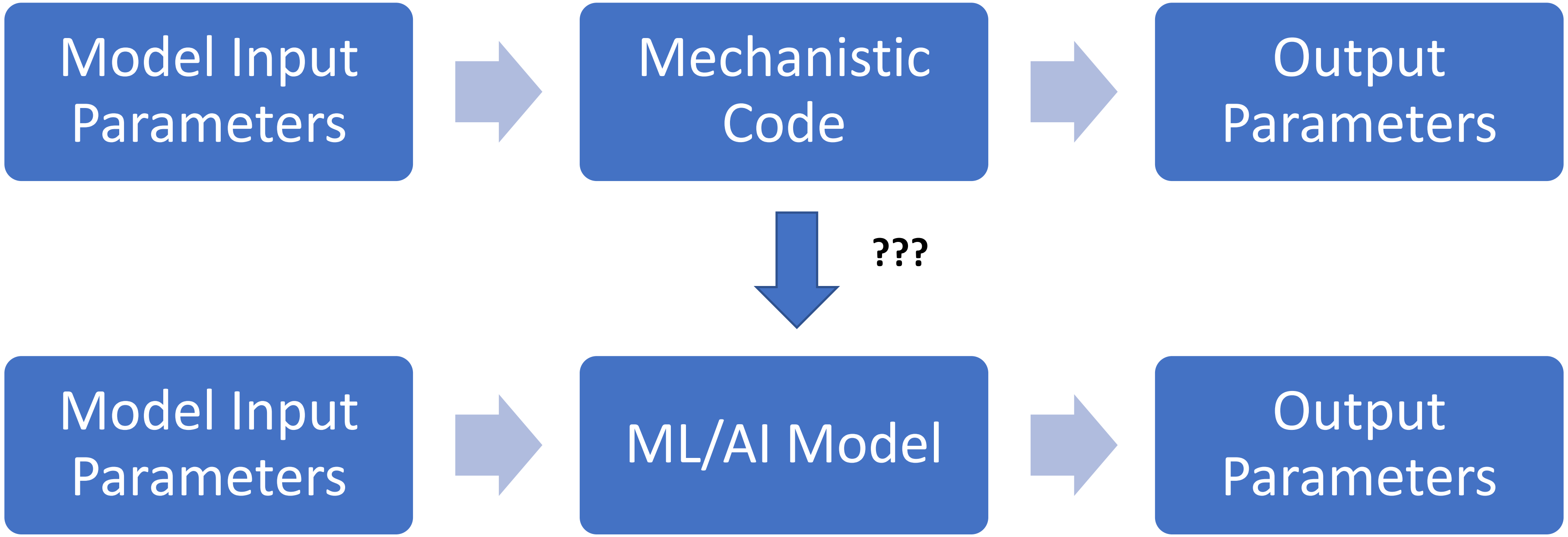


What is Unique about Severe Accident Analysis?

- Modeling safety significant accidents requires consideration of progression/propagation of failures in engineered system
  - Characterized by compounding increase in number of degrees of freedom

$$\frac{d\mathbf{s}}{dt} = \hat{\mathcal{M}}(\mathbf{s}, \dot{\mathbf{s}}, t)$$

$$\frac{d\hat{\mathcal{M}}}{dt} = \hat{\mathcal{H}}\left(\hat{\mathcal{M}}, \mathbf{s}, \dot{\mathbf{s}}, t\right)$$



What should we be trying to learn?

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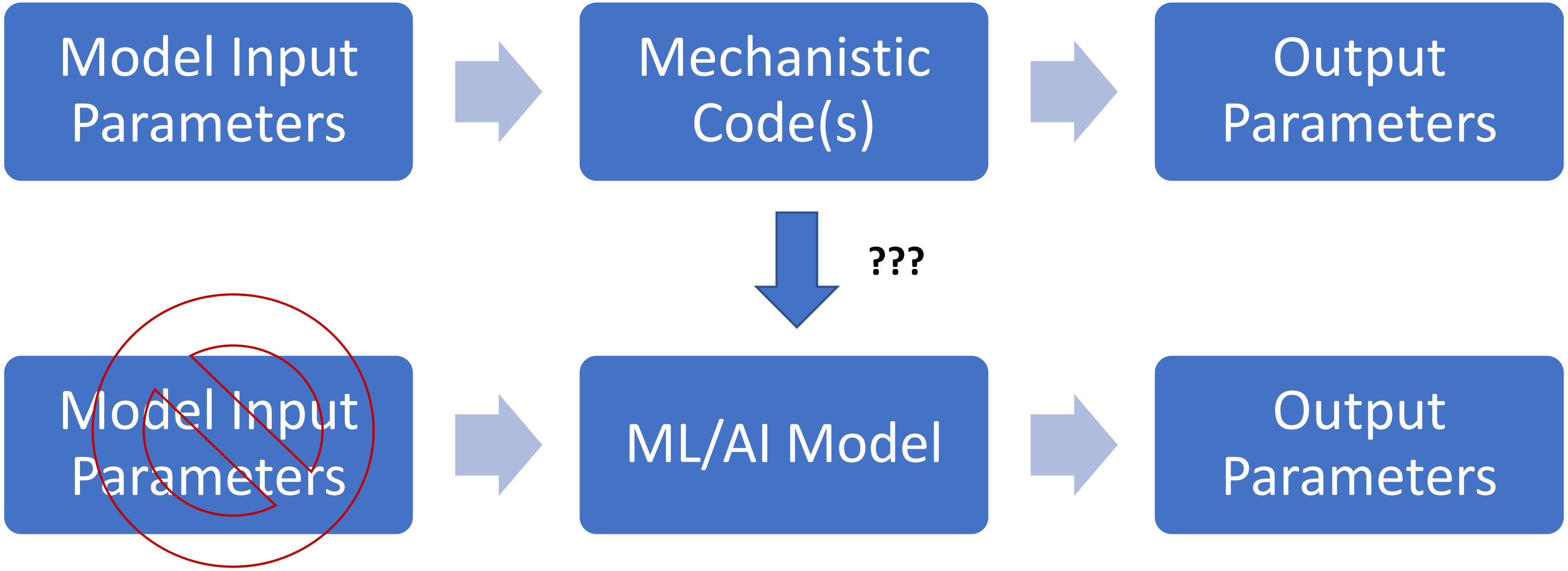
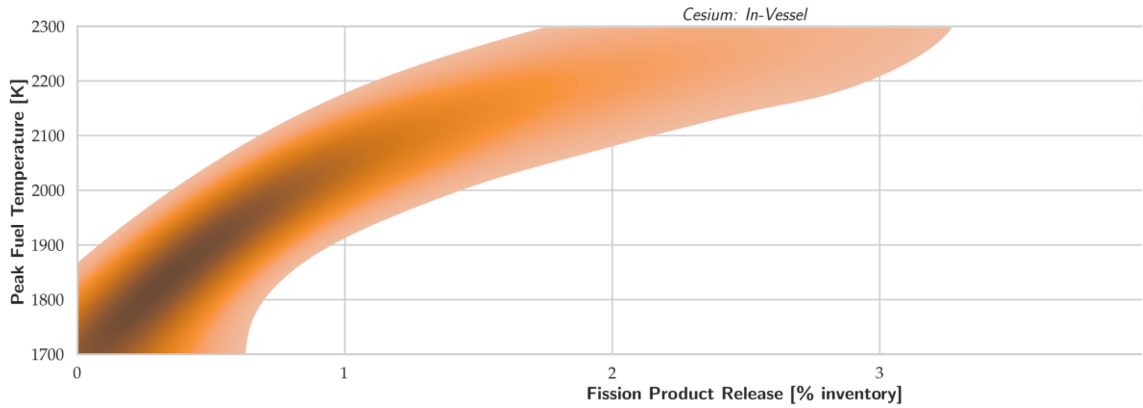
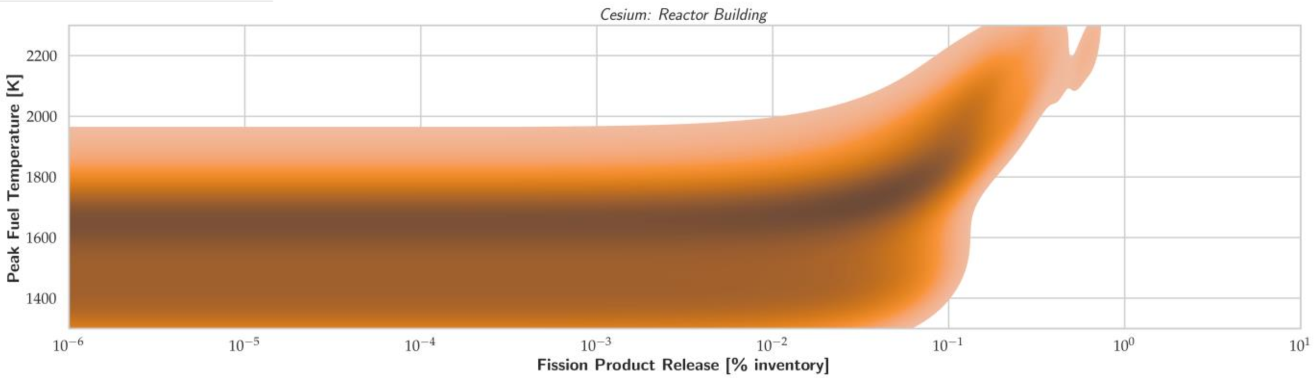


A surrogate model to rule all models?

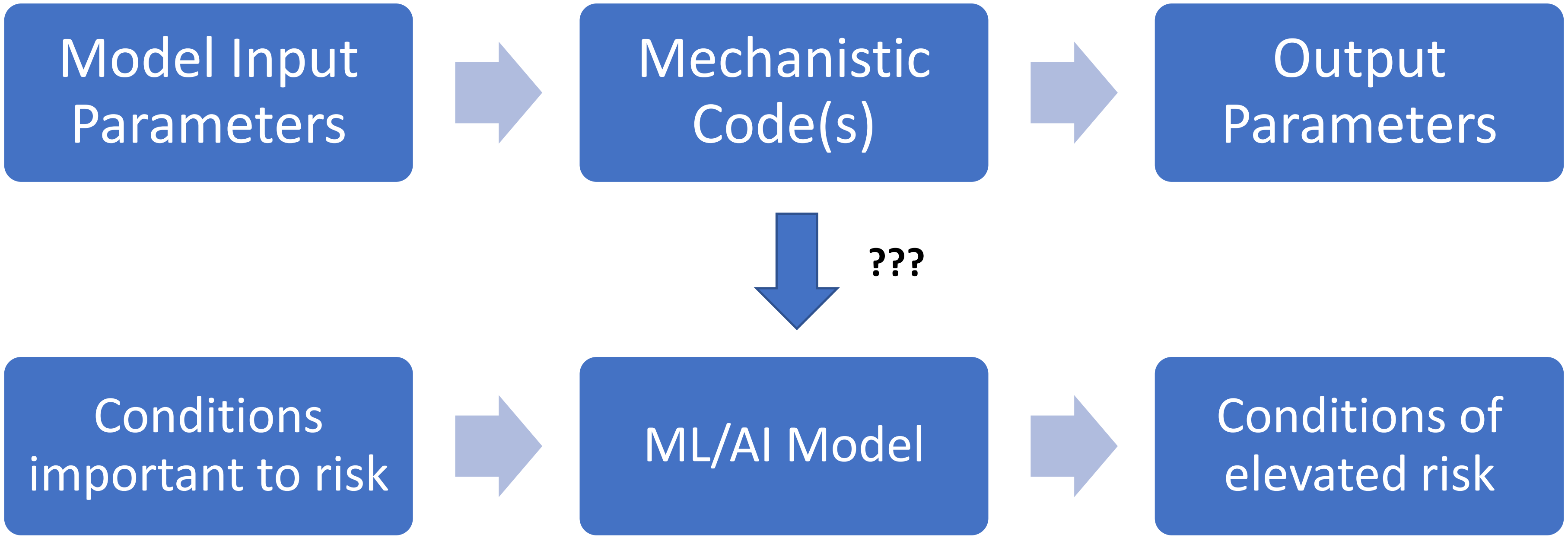




The further away in accident progression from the model, the greater the degree of decoherence

What should we be trying to learn?

Conditions that promote transitions that elevate risk or safety-significance



Emergent Insights

- Many legacy Level 2 assumptions in PRAs have evolved from internal events PRAs
  - These assumptions have typically not driven internal event PRA results (e.g., LERF)
  - Often made for expediency or to bound prevailing knowledge gaps in past
- Consider Ice Condenser plant
  - Conditional containment failure probability aided by availability of hydrogen igniters
    - Core damage does not imply containment failure (large early release)
  - DC power is typically available across many dominant cutsets in internal events PRA
    - Hydrogen igniters are available
  - For DC power loss cutsets, expedient to assume containment failure due to hydrogen combustion
    - Generally not dominant in internal event PRAs
  - A range of external events could consequentially fail DC power
    - Hydrogen igniters unavailable
    - LERF becomes similar to CDF without credit for DC power

State-of-the-Art Reactor Consequence Analysis (SOARCA) Project

Sequoyah Integrated Deterministic and Uncertainty Analyses

Draft Report

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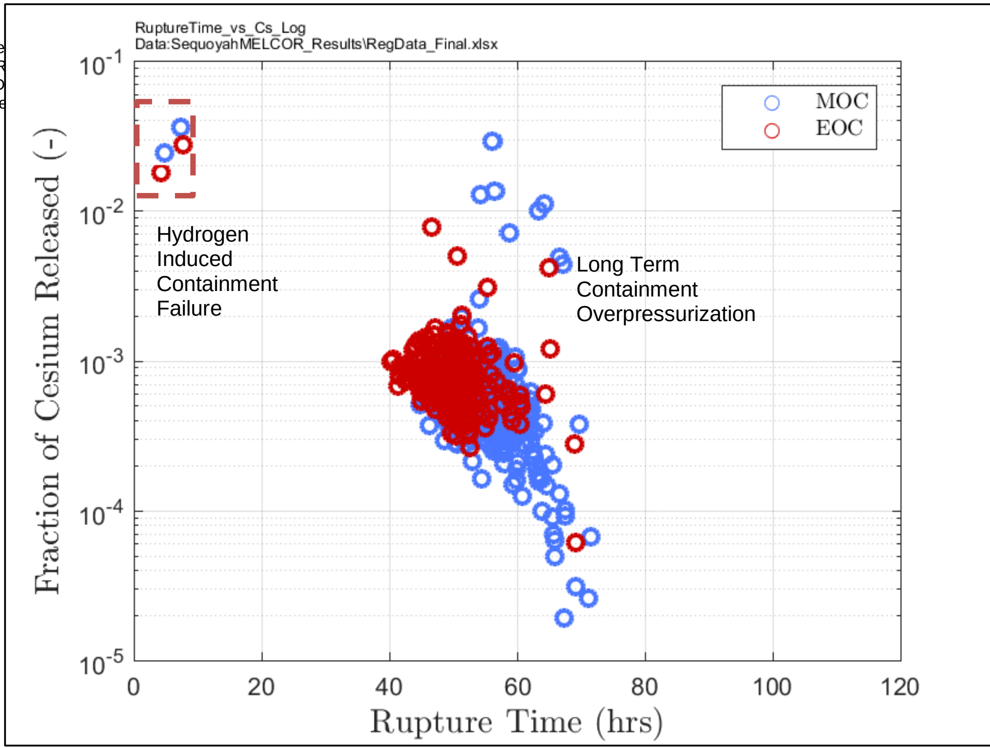
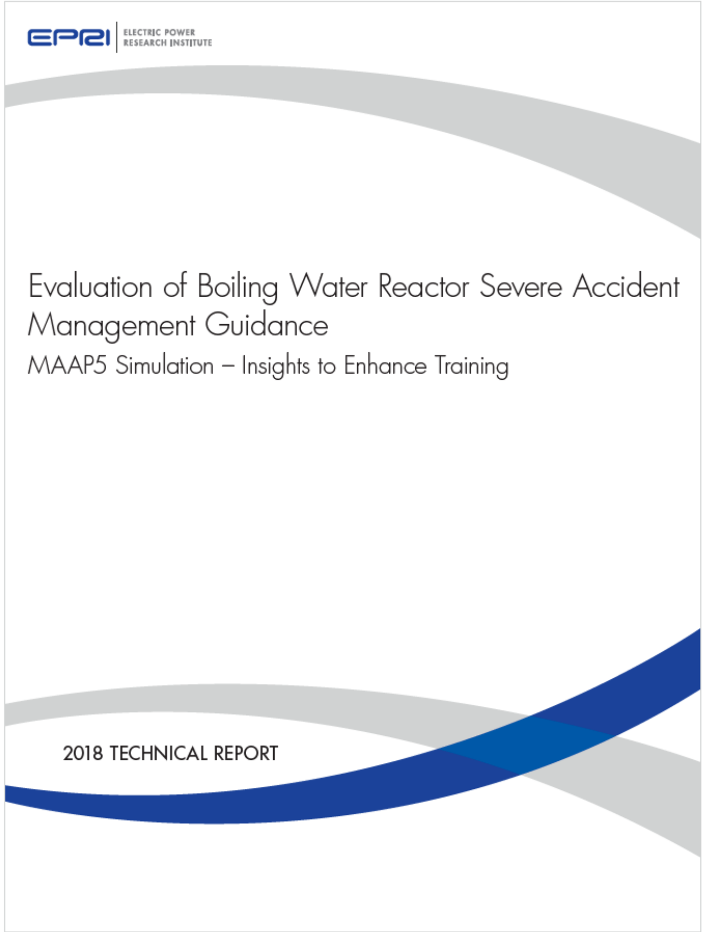
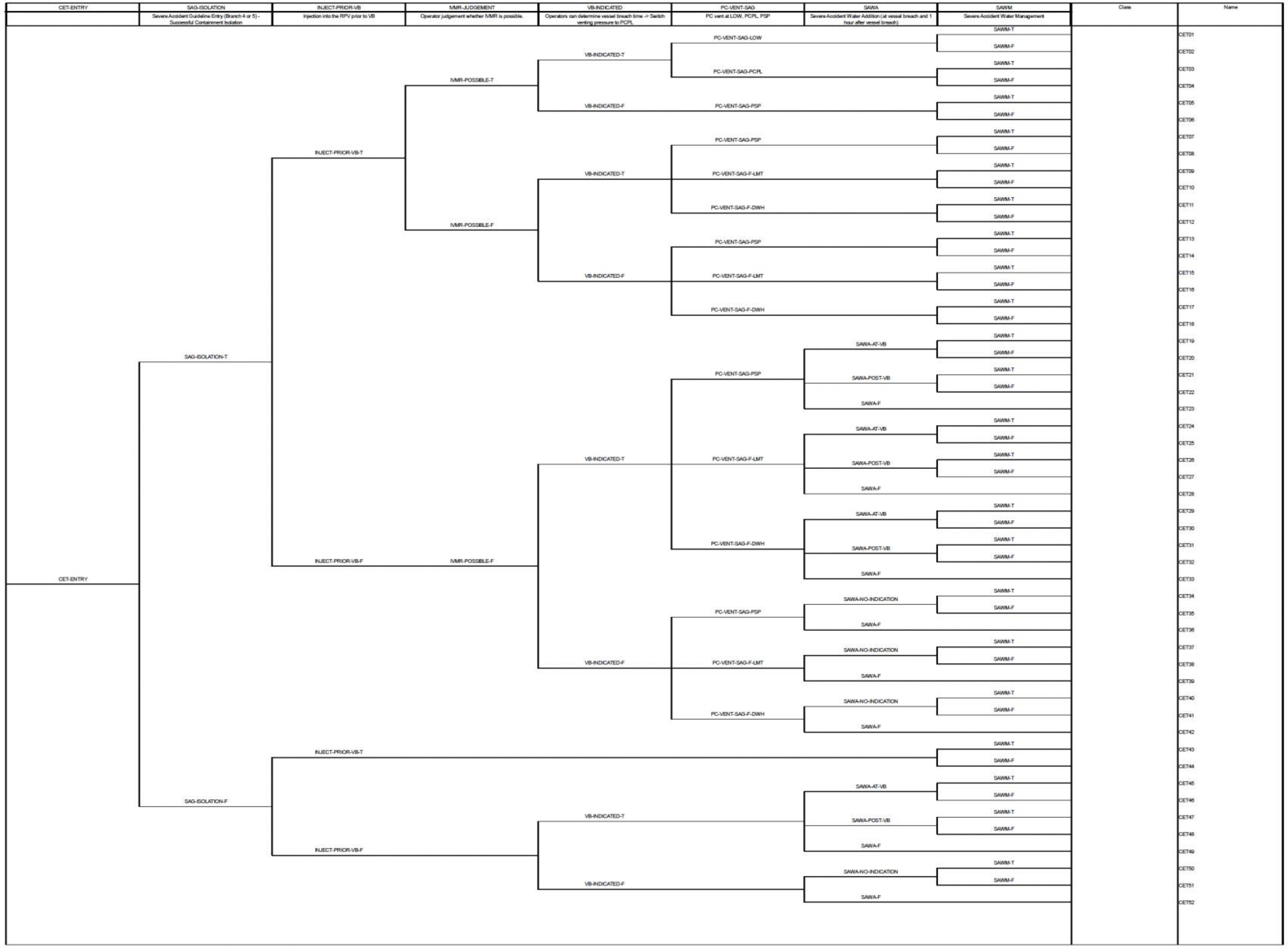


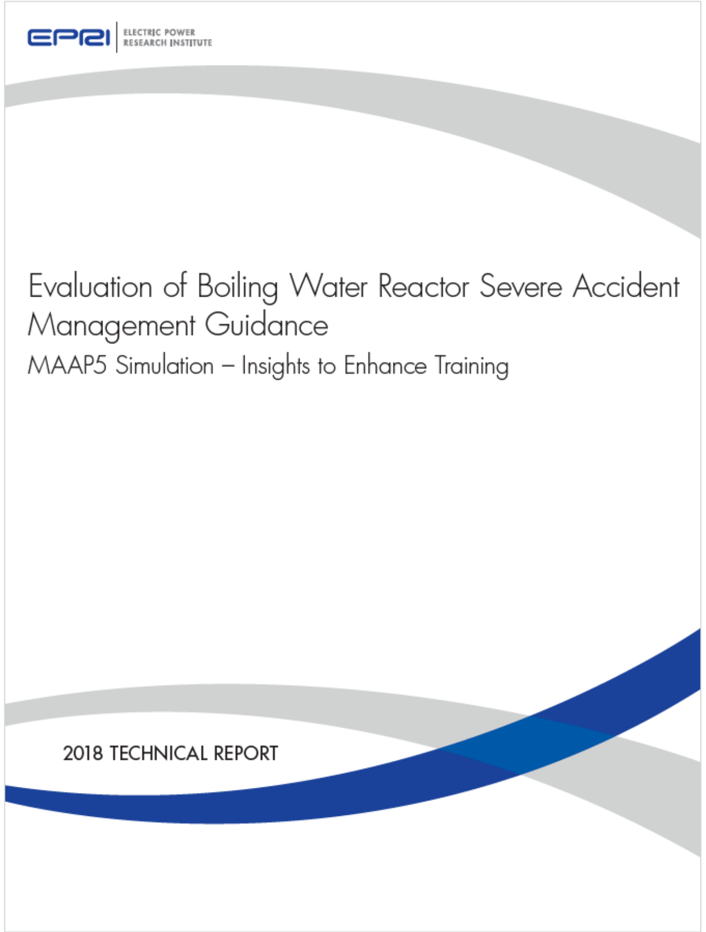
Developing Risk Importance Insights from Mod/Sim-PRA – Past EPRI SAMG Work

Event	Abbreviation	Description
RCIC Injection - T	rcic_inj	RCIC successfully initiated
RCIC Trip Time – 4hr		RCIC operates for a period of 4 hr.
RPV Pressure Control - T	rpv_prss_cntl	Operators control RPV pressure to maintain RCIC operation
PC Vent -T	pc_vent	Initial opening of containment vent to facilitate long term RCIC operation
Blowdown HCTL - T	rpv_hctl	Upon loss of RCIC, operator successfully depressurizes the RPV as defined by the heat capacity temperature limit
Blowdown MSCWL – T (F)	rpv_mscwl	Upon loss of RCIC, operator depressurizes the RPV when level drops below minimum steam cooling water level limit – true (T) or false (F)
PC Isolation – T (F)	pc_isolation	Upon loss of RCIC or when transition from EOP to SAG, operator isolates the previously opened containment vent – true (T) or false (F)

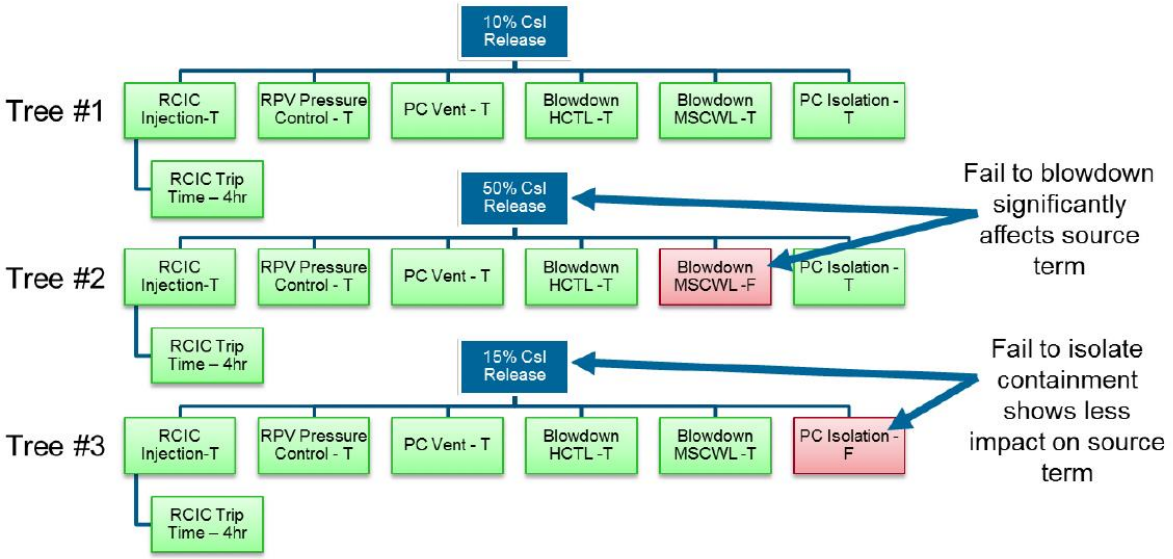


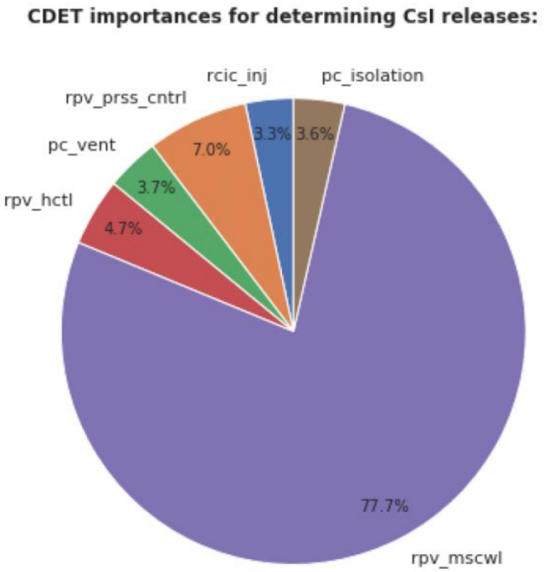
Insights from Mod/Sim-PRA – Past EPRI SAMG Work

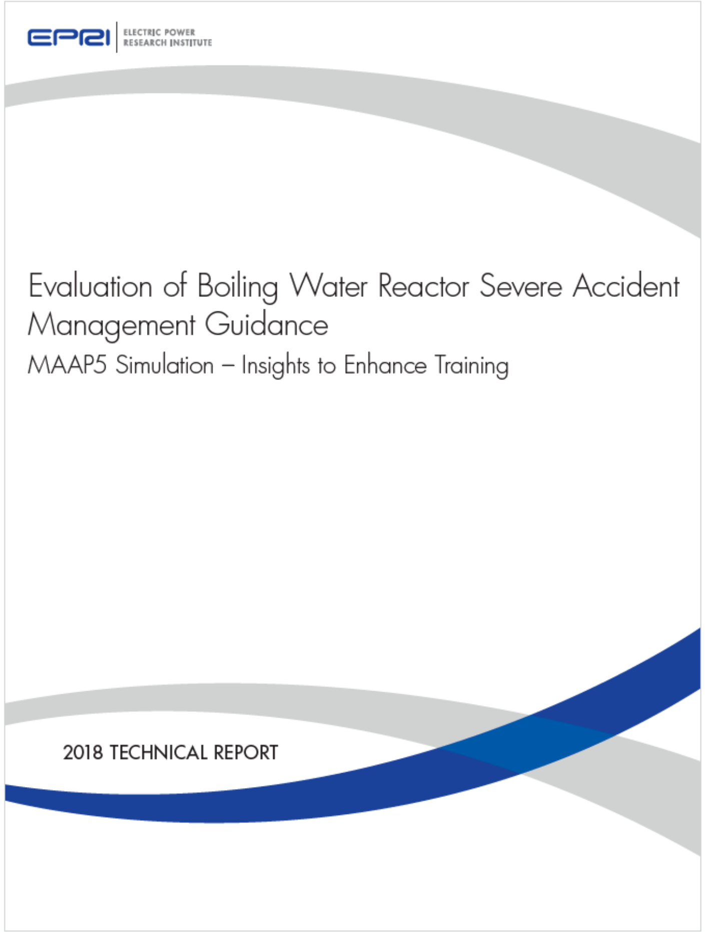




Application of Random Forest – Past EPRI SAMG Work







Correlating Events – Identifying Precursors

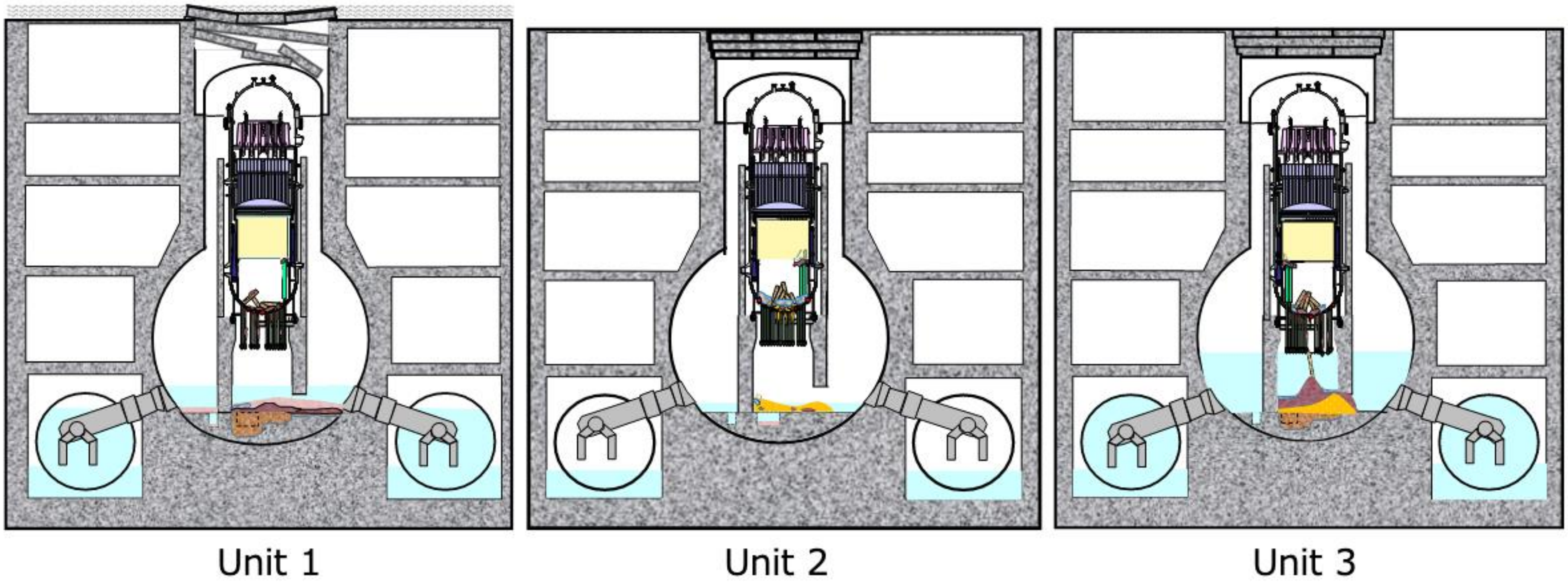
- Evolution of accident reflects transitions between range of potential degraded states
  - Occurrence of specific events in time during accident scenario can be essential to establish conditions necessary for emergence of subsequent accident conditions

<u>Illustrative example</u>

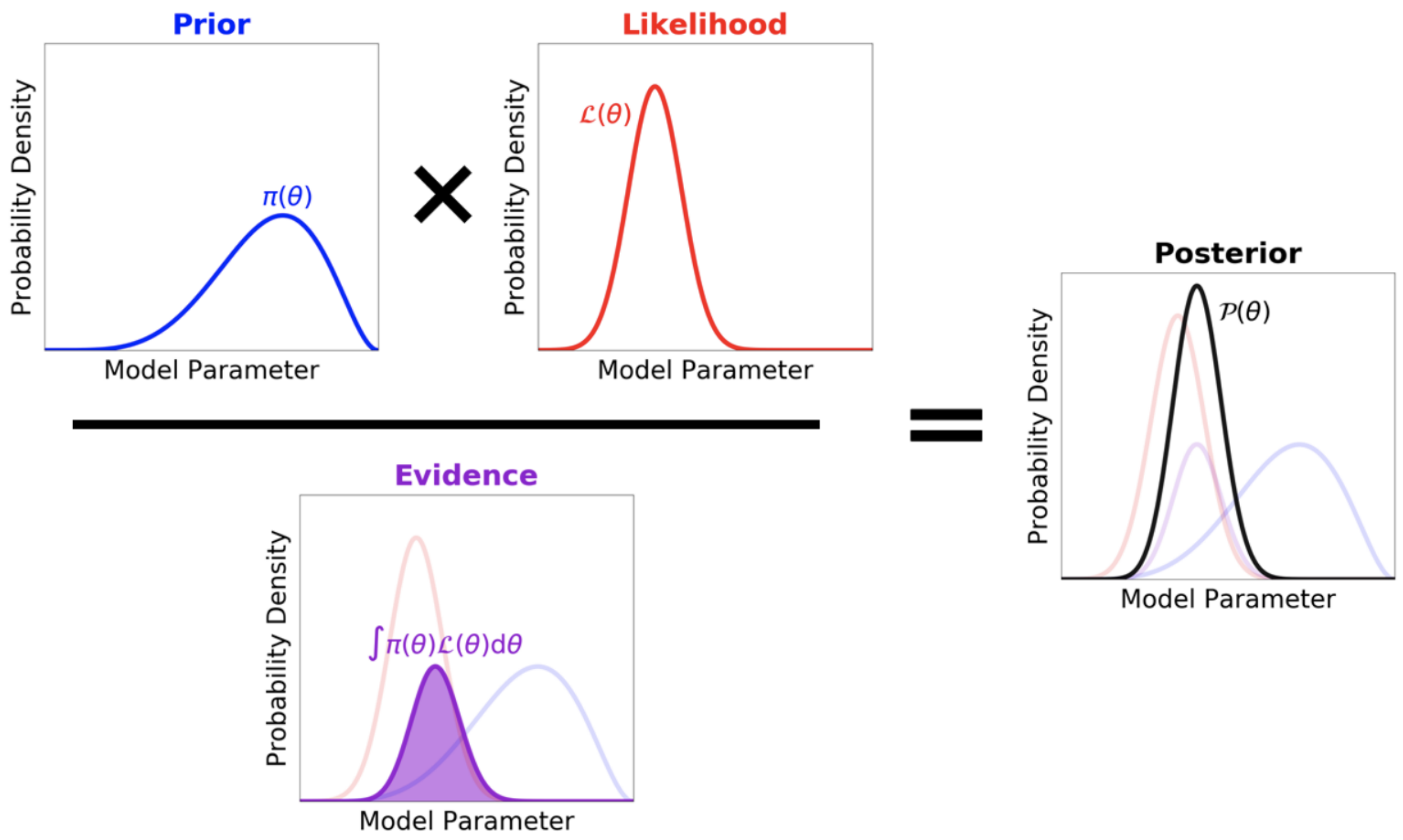
- Depressurization of the BWR RPV prior to lower head breach critical occurrence in a severe accident
- Can occur by seizure of a cycling SRV due to
  - Excessive number of cycles
  - Thermally-induced seizure
- Thermal seizure of a cycling SRV requires sufficiently high temperatures of gases exiting RPV
  - Sensitive to how energy is transported from degrading core to upper internal region and steam lines
- Peach Bottom SOARCA also investigated the potential for main steam line creep rupture as a competing mechanism
- MSL rupture significant impact on magnitude of fission product releases
  - Greater fraction of fission products discharged from RPV bypass the suppression pool

Model Learning for Inference Generation from Fukushima Daiichi

- A range of accident scenarios occurred at Fukushima Daiichi
  - Represents a broad range of conditions that have not previously occurred at reactor scale
- It is tempting to directly utilize insights from three core melt events

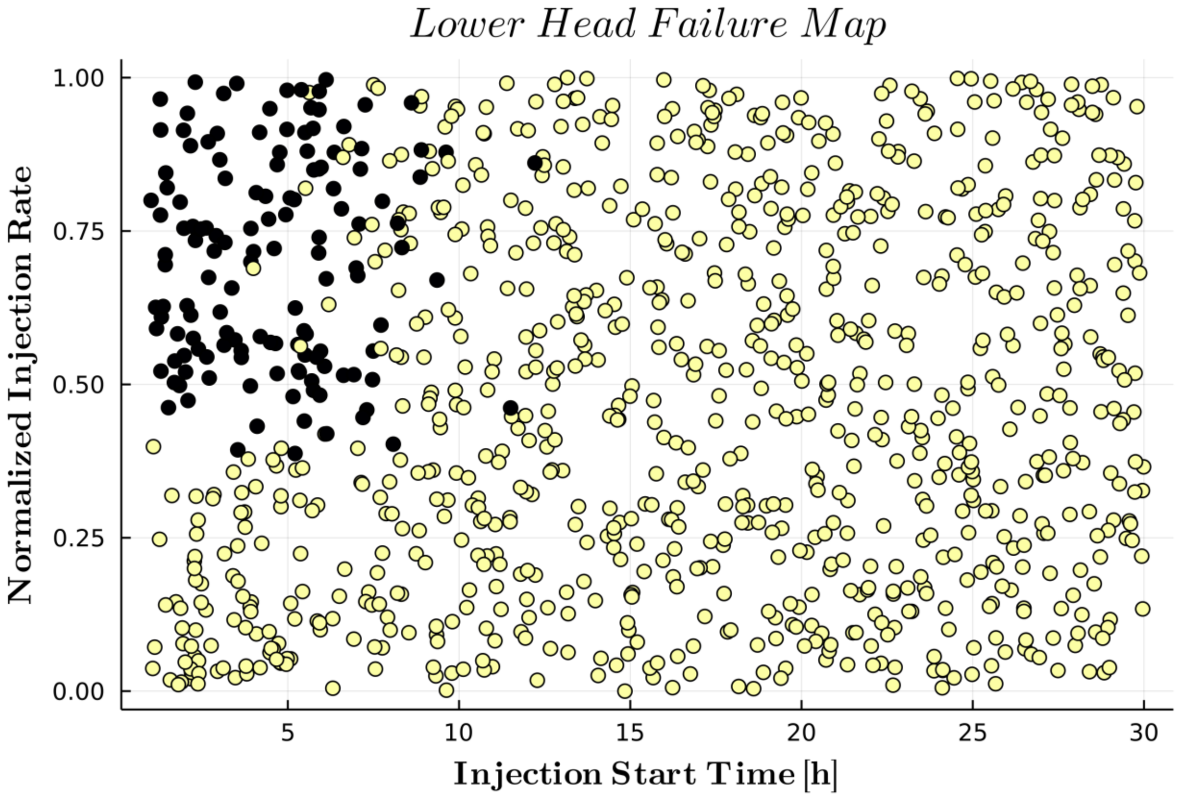


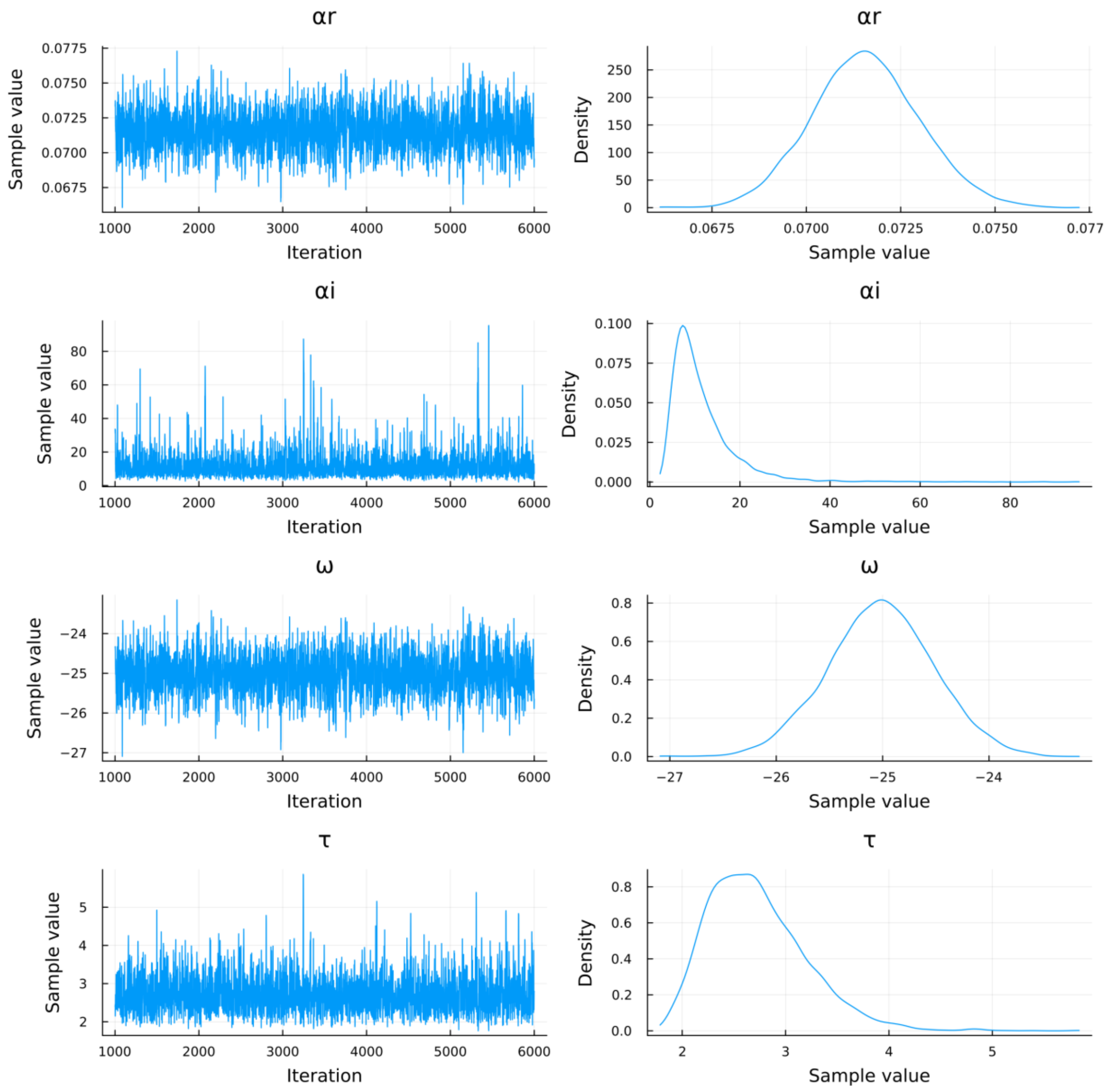
Probabilistic Machine Learning and Markov Chain Monte Carlo



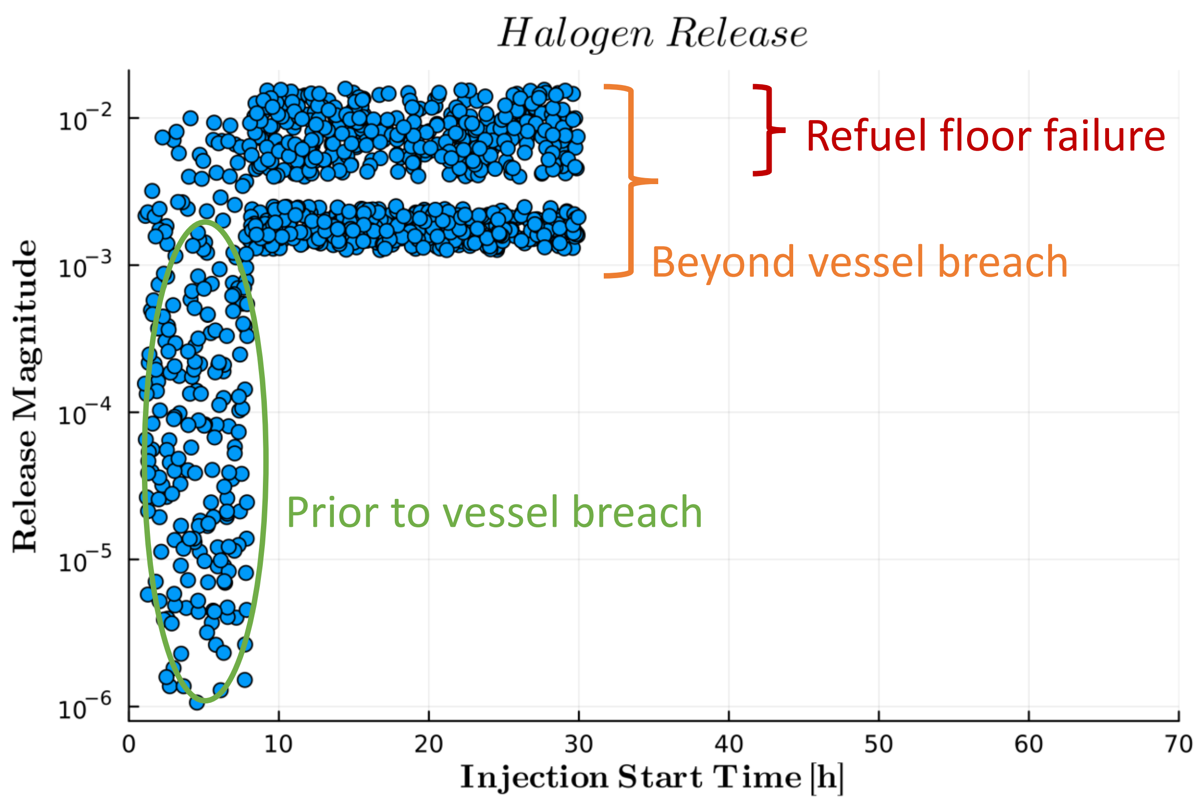
Characterization of Lower Head Failure – Water Injection Realization Variability

- Model formed using Bayesian logistic regression

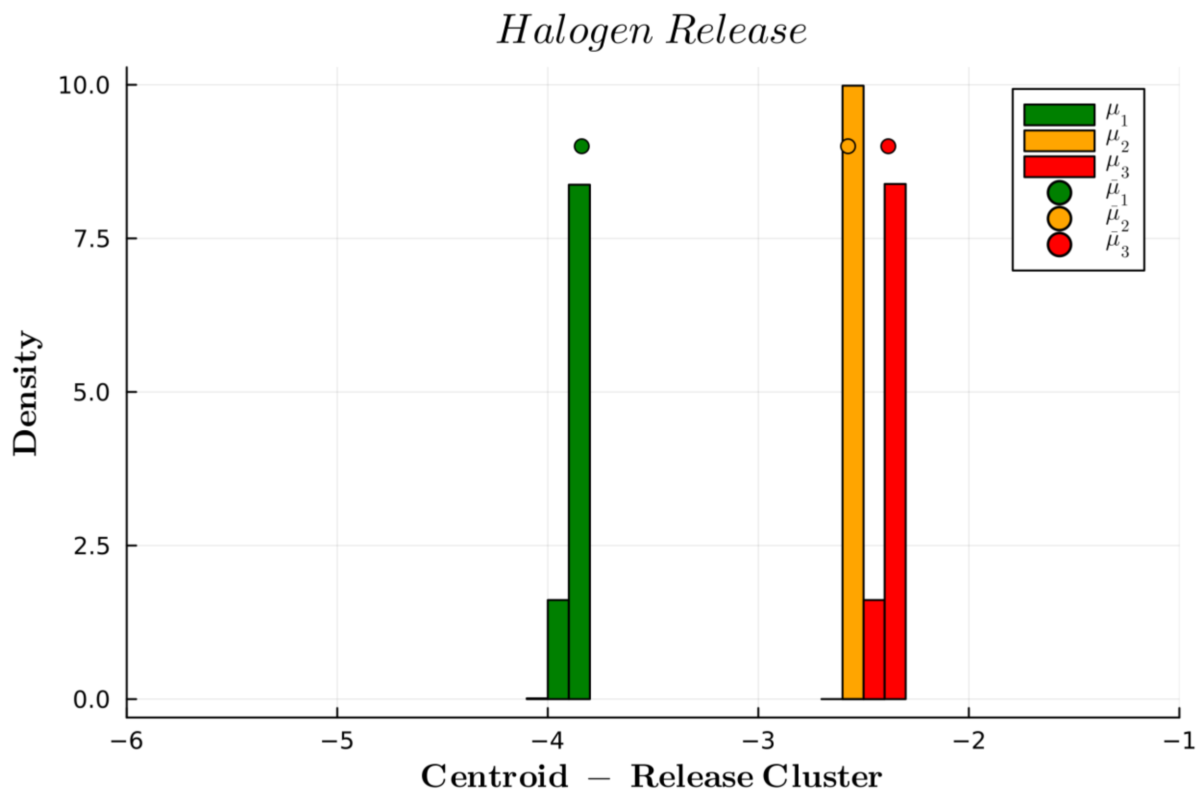




Clustered Releases – Water Injection Realization Variability



- Bayesian hierarchical model
  - Based on mixture of Gaussians
  - Categorical distributions applied for representing discrete events



How can Learned Models influence Decision-Making?

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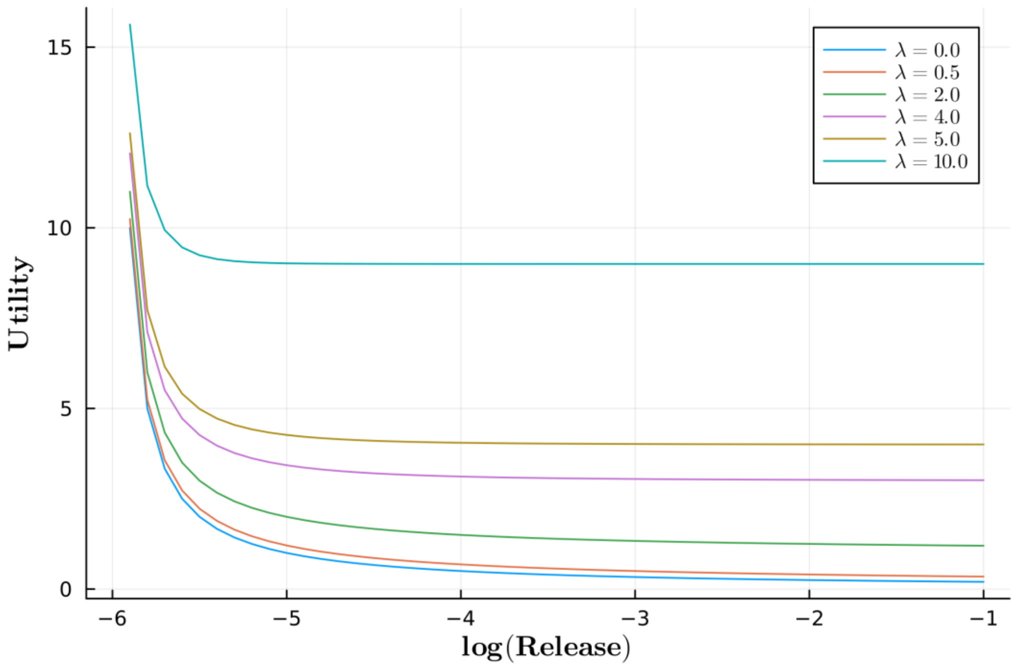
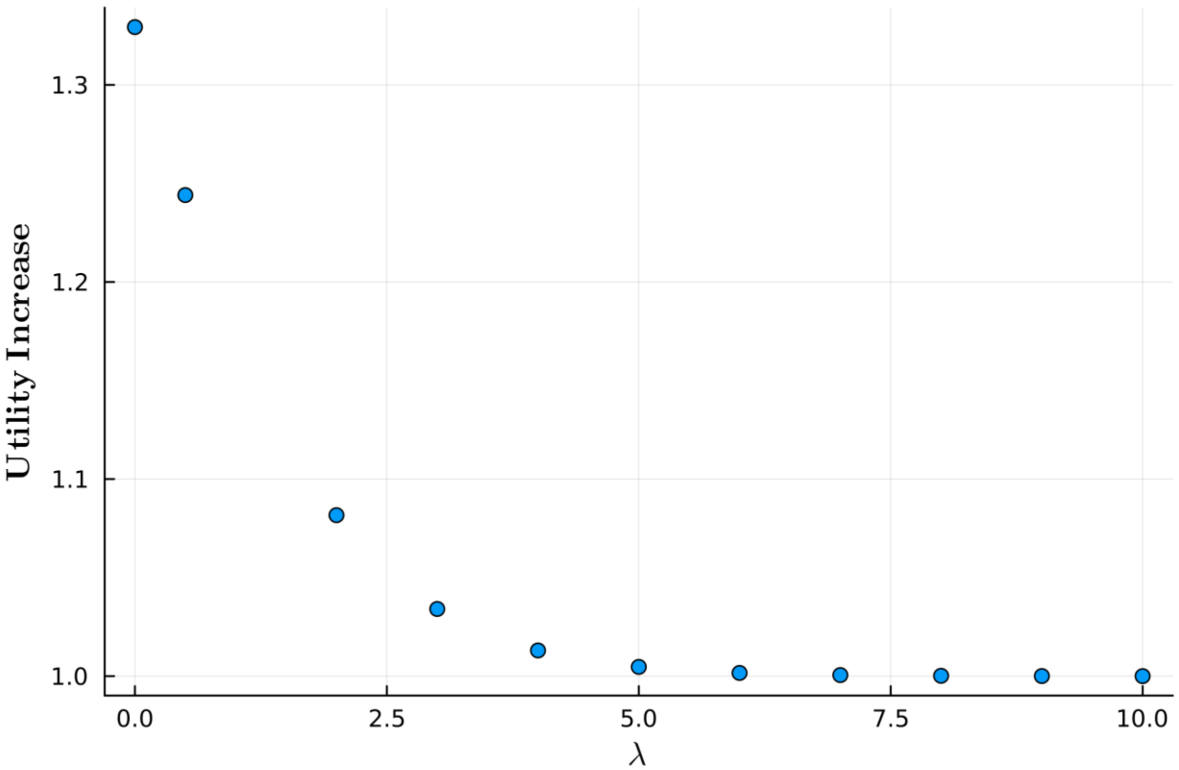
- Decision-making often involves selection between options that have overall safety benefit
- It is tempting to inform decision-making in the context of a single realization
  - Design bases are often developed around stylized design basis accident scenarios
  - How does risk profile expressed in severe accident realization uncertainty influence insights?
- Imagine situation where enhanced releases seen due to lower head failure are prevented
  - Consider different functions to characterize simple comparisons of *utility* under uncertainty

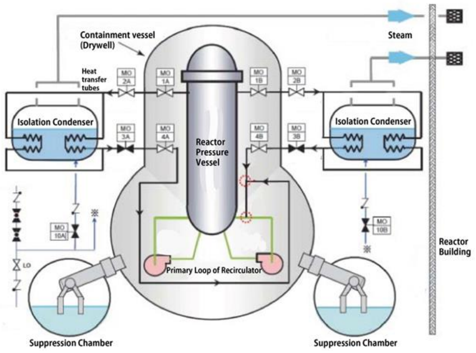




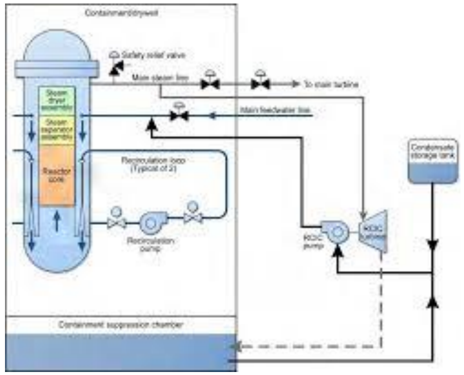
Characterizing Safety System "Dynamic Range" – Perspectives on Resiliency

- Nuclear energy does not exist without safety design philosophy with safety philosophy developed for LWRs under significant evolution
- Establishing the safety basis for advanced nuclear is fundamental to enabling
  - Innovation in reactor design to drive novel applications in evolving energy systems
- Traditional PRA methods not well-suited to establish safety *profile* for
  - Passive safety systems
  - Autonomous safety systems
  - Applications of nuclear energy systems beyond firm electricity generation assets

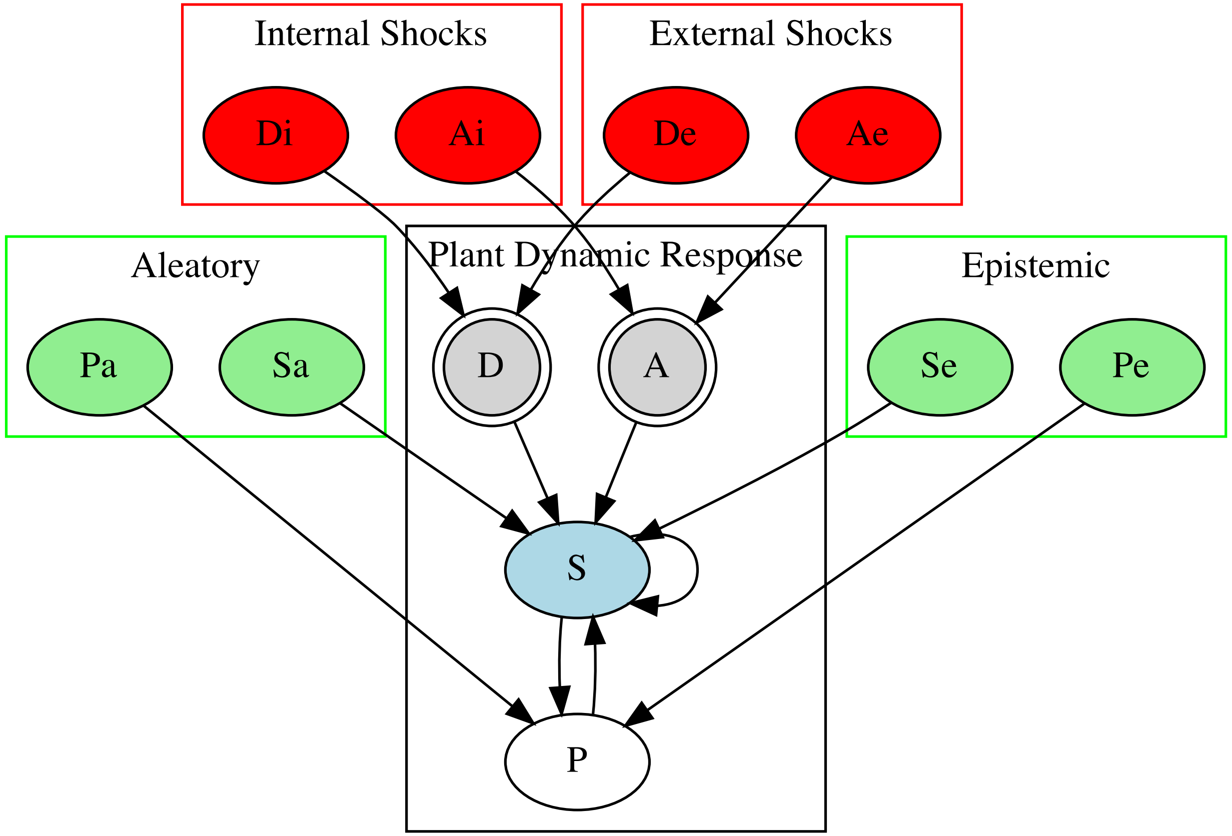
Fukushima range of behavior



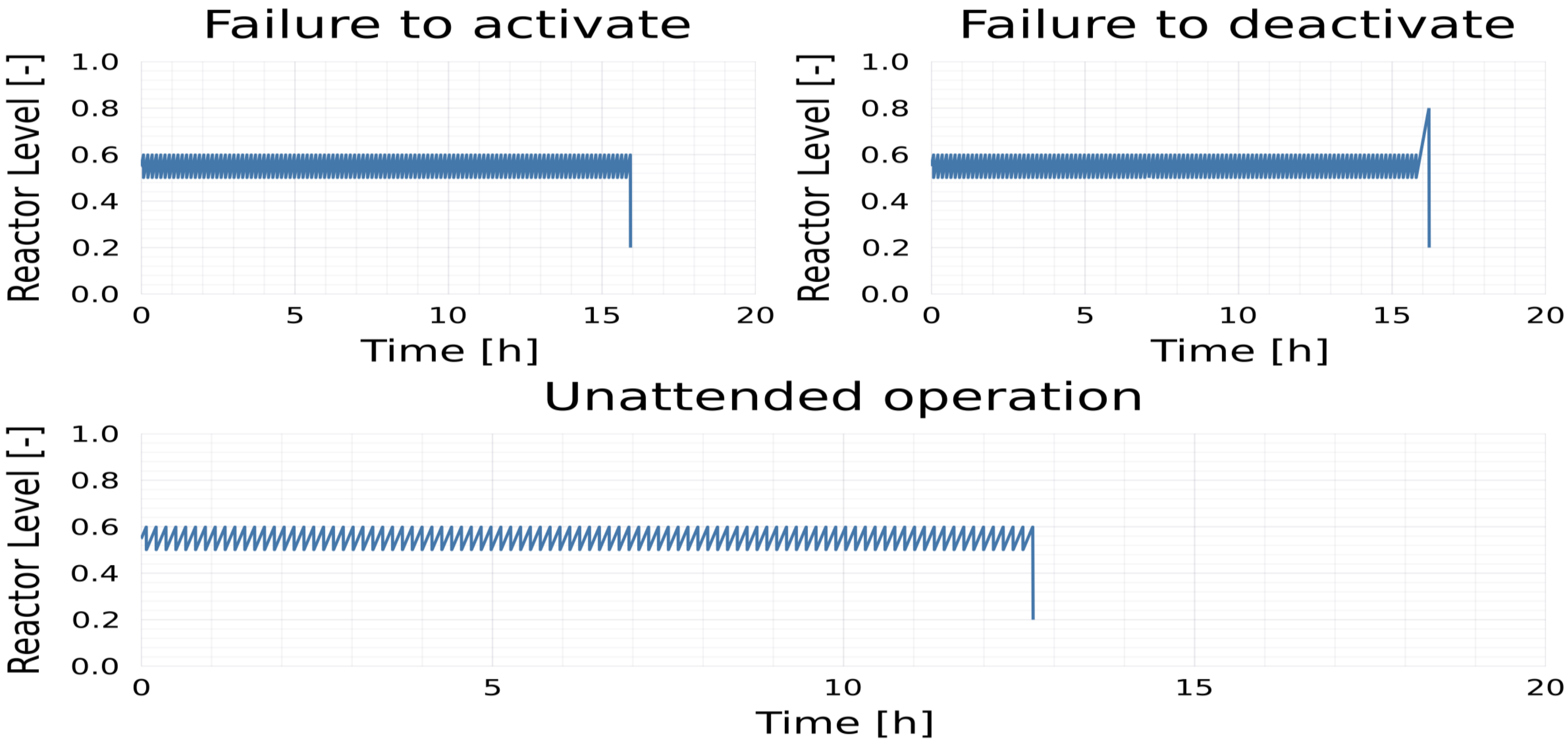
Isolation Condenser



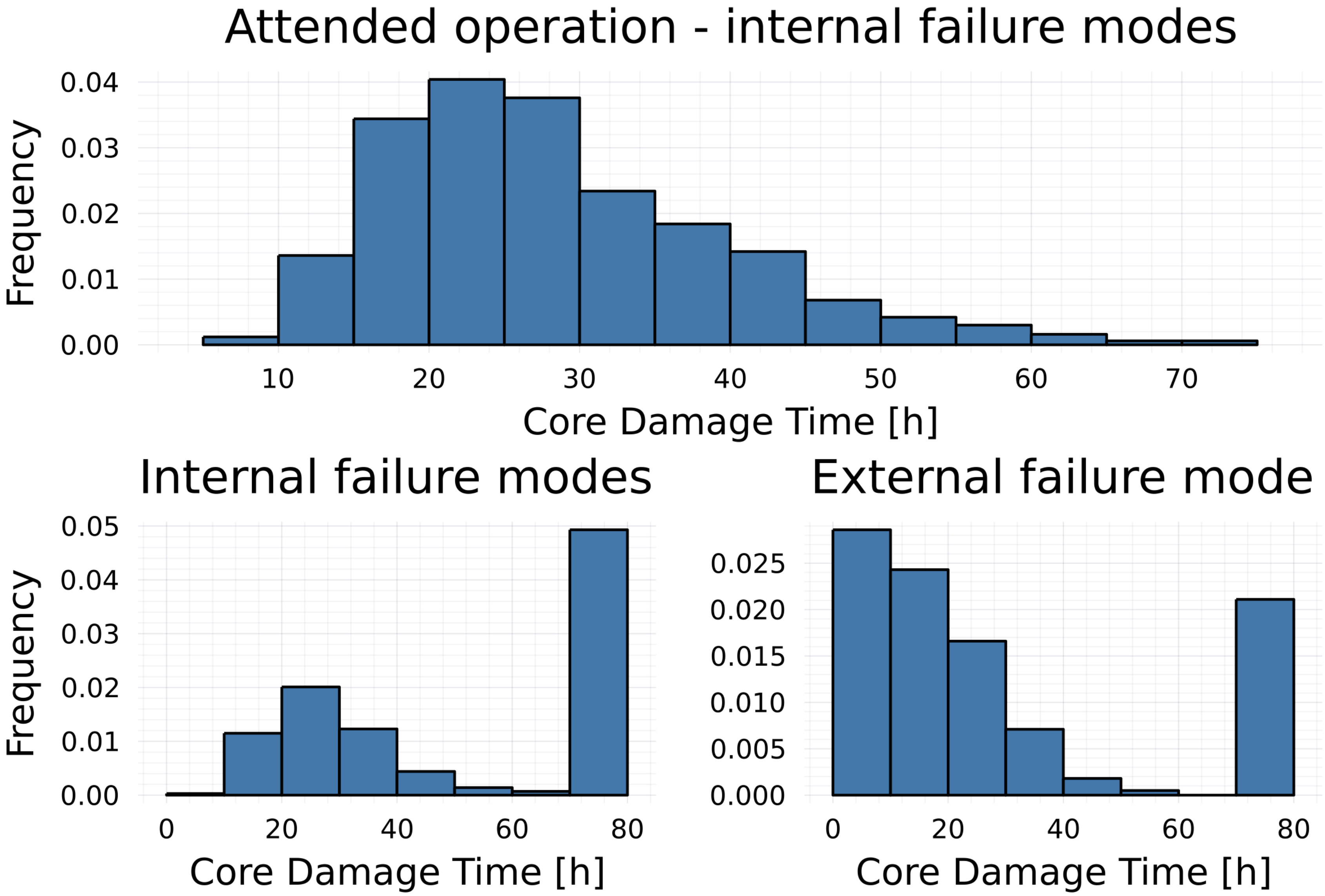
RCIC



Safety System Response – RCIC Modes of Operation



Emergent Characterization of Performance and Risk



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