# Accident Tolerant Fuels: A PRA Comparison


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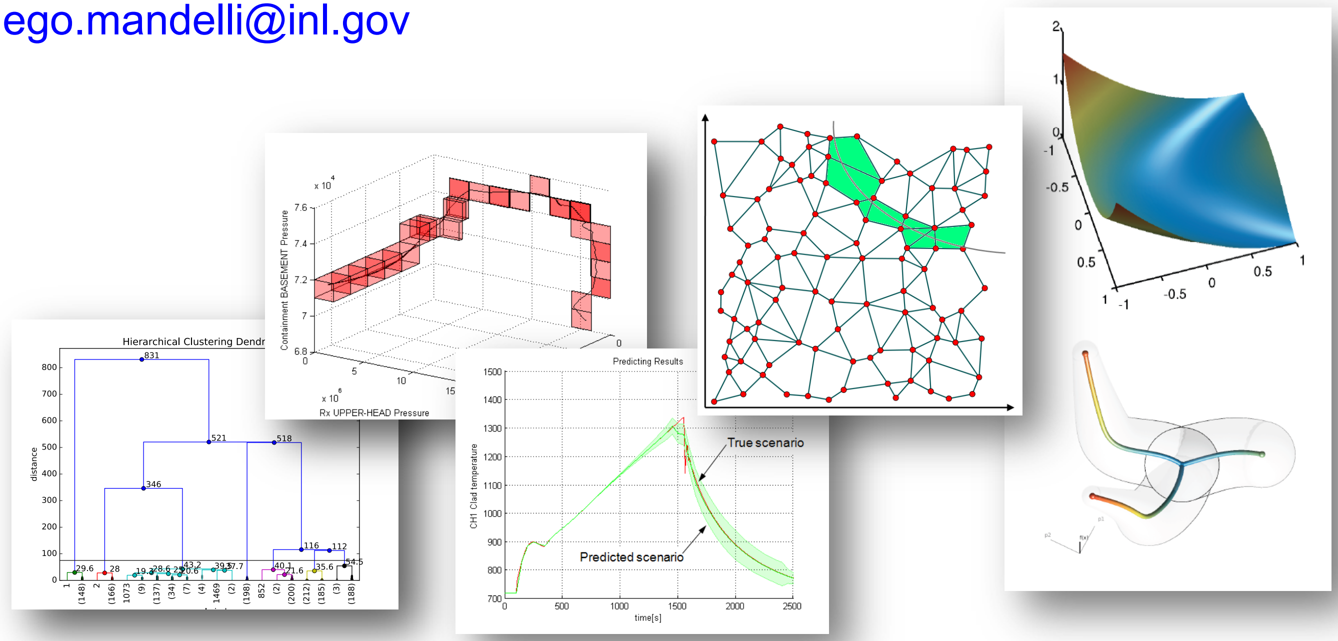


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# Introduction

- Accident Tolerant Fuel (ATF) goals: withstand accident scenarios with better performances than currently employed fuels
  - E.g., smaller hydrogen generation

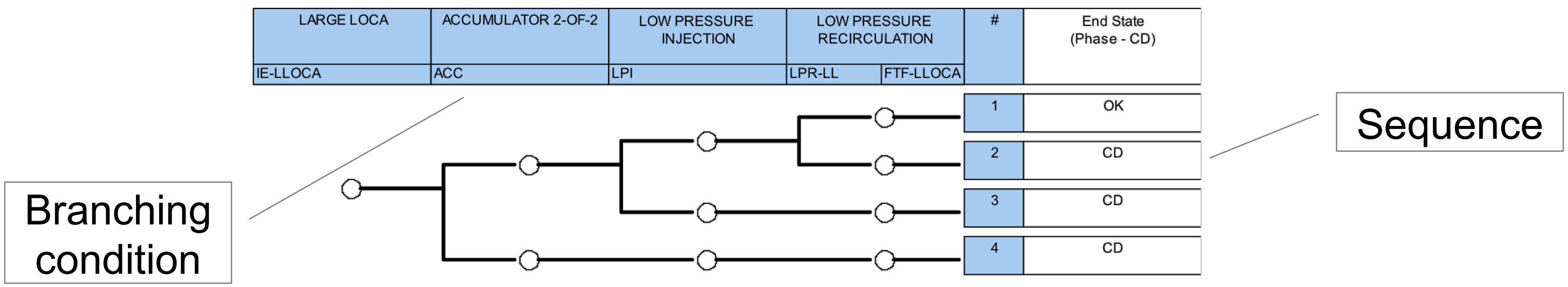
- LWRS - RISA research on ATF
  - "Plant-Level Scenario-Based Risk Analysis for Enhanced Resilient PWR – SBO and LBLOCA", INL Technical Report INL/EXT-18-51436 (2018)

- Objective: evaluate and compare ATF performances
  - Metric: Probabilistic Risk Assessment (PRA) centric

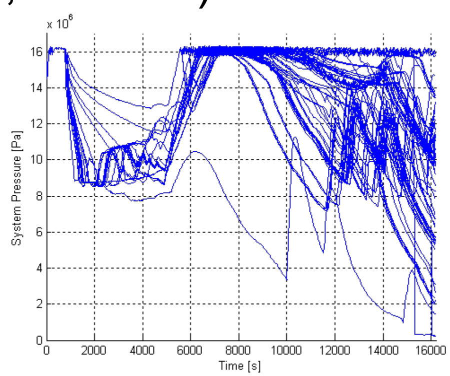
- Approach: blend of Classical and Dynamic PRA methods
  - Integrate Dynamic PRA results into existing Classical PRA

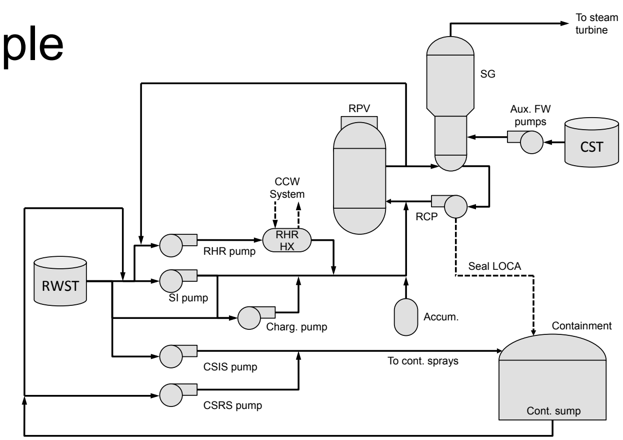
# Classical and Dynamic PRA

- Classical PRA: based on static Boolean structures
  - Event-Trees (ET): inductively model accident progression




- Dynamic PRA: simulation-based methods that couple
  - System simulator codes (e.g., RELAP5-3D)
  - Stochastic tools (e.g., RAVEN)



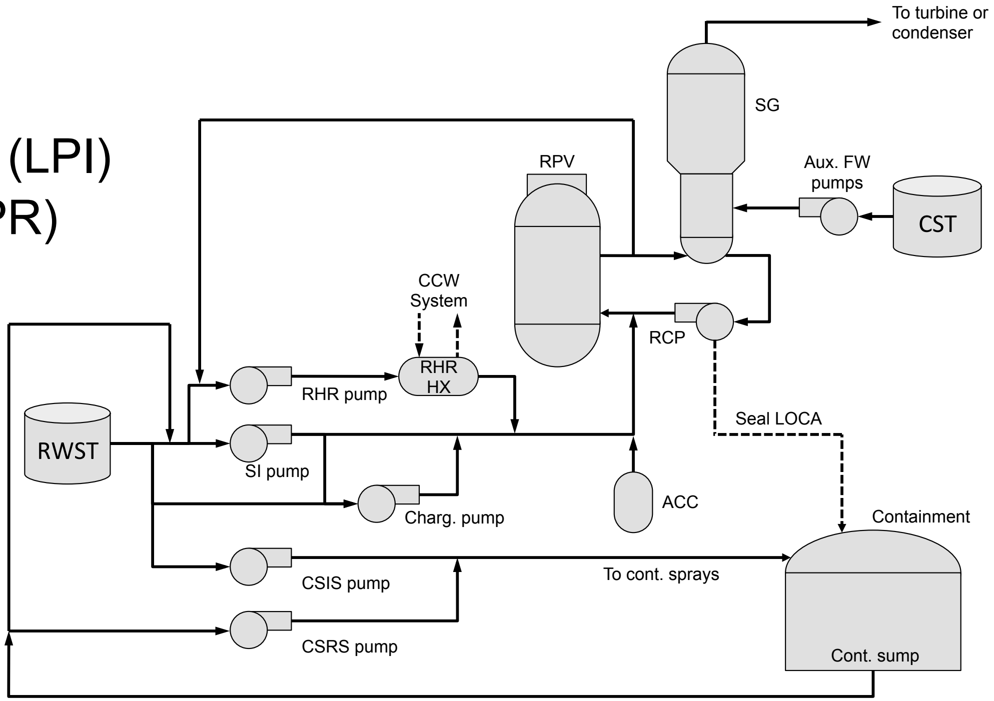



# Application

- Test case:
  - 3-loop PWR system
  - Large break LOCA (LB-LOCA)
    - Double-ended guillotine (2A)

- Systems considered:
  - Accumulators (ACCs)
  - Low Pressure Injection System (LPI)
  - Low Pressure Recirculation (LPR)

- Fuel types considered:
  - Zr
  - Cr-coated
  - FeCrAl



# Dynamic PRA: Fuel Models

- ATF fuel-clad oxidation mechanism recently added to RELAP5-3D
- Amount of clad being oxidized and the amount of $H_2$ produced is calculated at every time step
- Clad deformation and rupture modeled by using a simplified mechanistic model derived from the FRAP-T6 code
- FeCrAl and Cr-coated clad oxidation reactions*

$$2\,\mathrm{Al} + 3\,\mathrm{H_2O} \longrightarrow \mathrm{Al_2O_3} + 3\,\mathrm{H_2} + 67.3\,\mathrm{MJ/kg\ mole}$$

$$2\,\mathrm{Cr} + 3\,\mathrm{H_2O} \longrightarrow \mathrm{Cr_2O_3} + 3\,\mathrm{H_2} + 64.84\,\mathrm{MJ/kg\ mole}$$

* M. Kurata, "Research and Development Methodology for Practical Use of Accident Tolerant Fuel in LightWater Reactors," *Nuclear Engineering and Technology*, **48**, 1, 26 – 32 (2016).

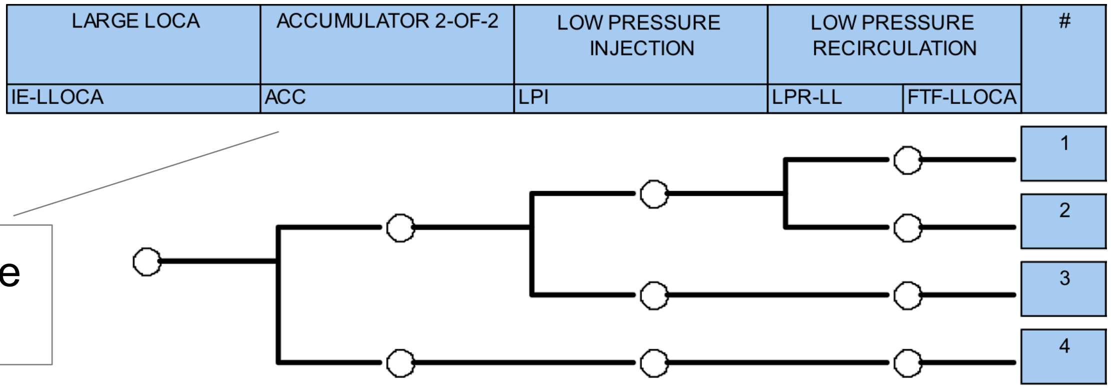
# Dynamic PRA: RAVEN

- Sampled parameters

# LPI trains available (out of 2)
Activation time of the LPI trains

# HPI trains available (out of 3)
Activation time of the HPI trains

# LPR trains available (out of 2)
Switch time of the LPR trains



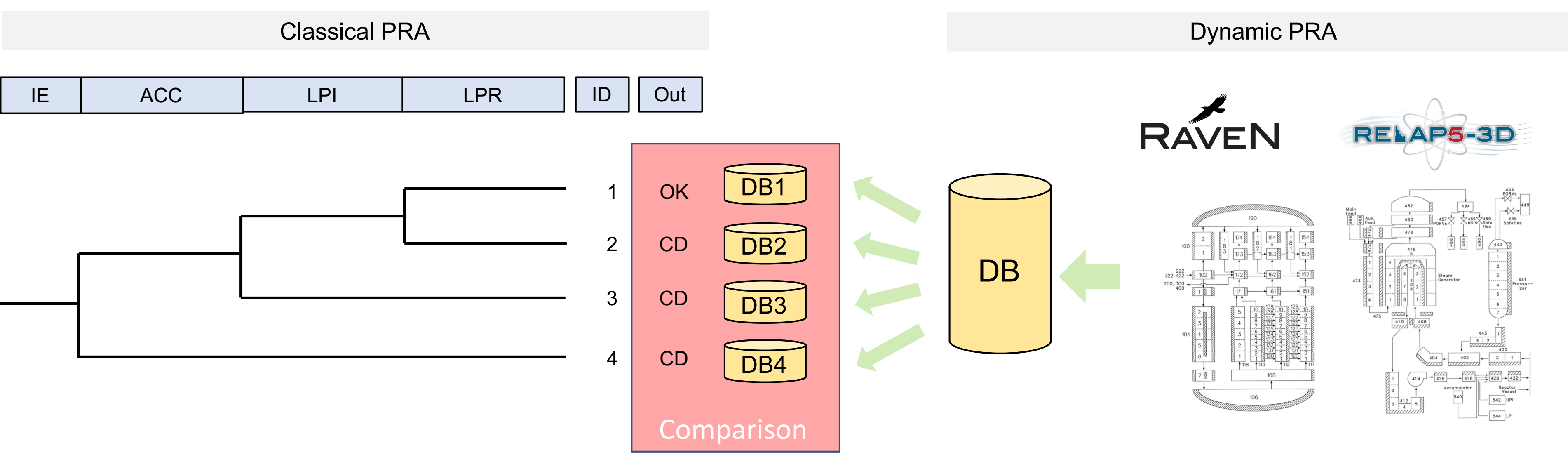

# ACCs available (out of 2)

- Output data:
  - Simulation end state (OK or CD)
  - Simulation end time
  - PCT
  - Amount of hydrogen generated

# PRA Comparison Methodology

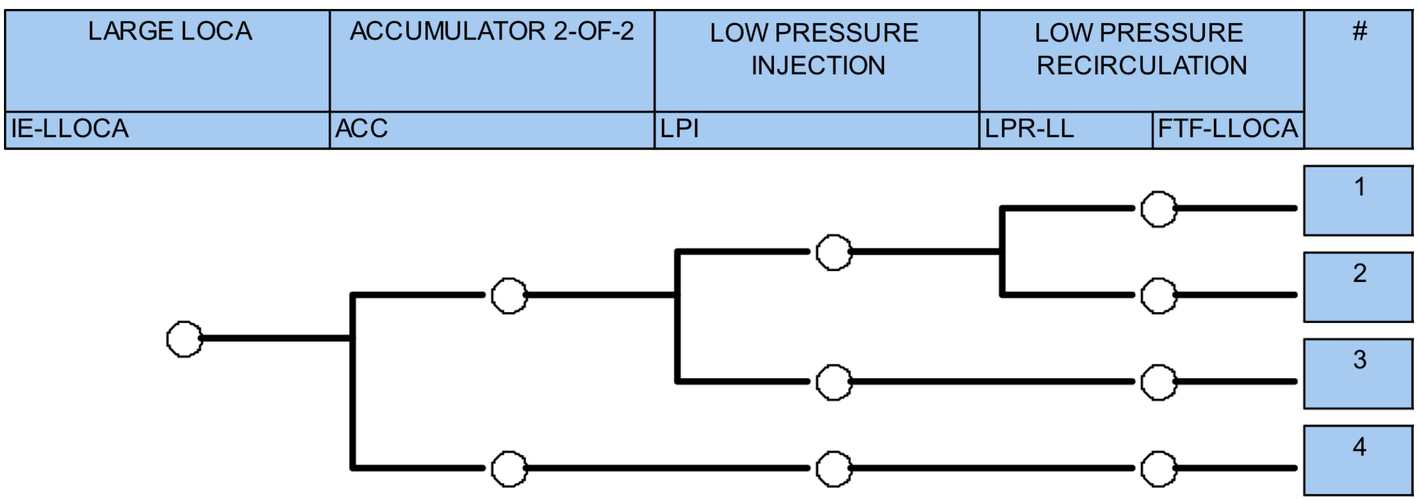
- Set of simulation runs is partitioned into groups
  - One group for each sequence of the Event-Tree

- Process:
  1. Identify the link between Event-Tree branching conditions and simulation parameters
  2. Associate each simulation to a unique Event-Tree sequence



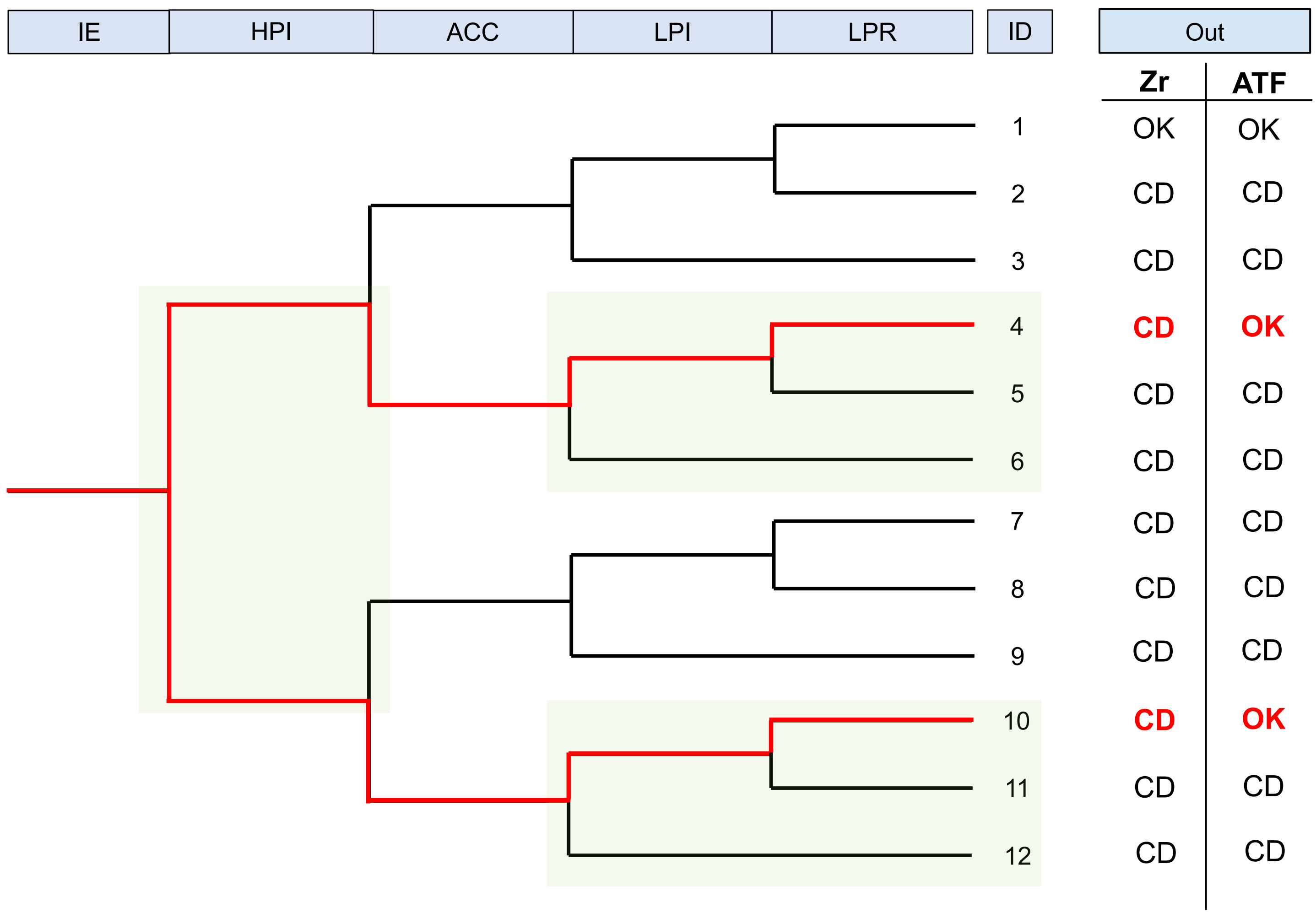
# Results

- Initial analysis shows different fuel performances in Branch 4
- Next step: re-structure the ET to better capture differences
  - Add HPI branching condition
  - Expand branches after ACC failure




| Out | |
|---|---|
| Zr | ATF |
| OK | OK |
| CD | CD |
| CD | CD |
| CD | OK/CD |

# Results for Re-Structured ET



# Results for Re-Structured ET

- Analysis of sequences leading to OK
  - PCT

| Branch | Zr | Cr | FeCrAl |
|---|---|---|---|
| 4 | CD | [1250,1450] | [1160,1350] |
| 7 | [827,1047] | [1030,1200] | [1040,1250] |
| 10 | CD | [1330,1530] | [1200,1400] |

  - Safety Margins

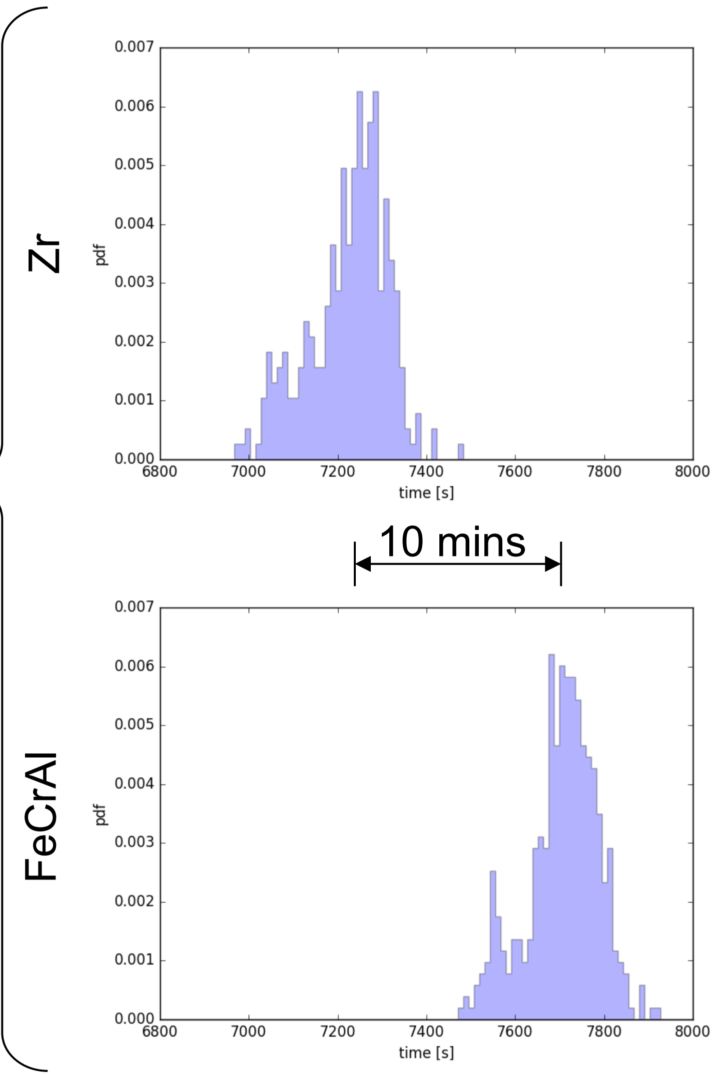
| Branch | Zr | Cr | FeCrAl |
|---|---|---|---|
| 4 | CD | [350,500] | [450,600] |
| 7 | [430,650] | [600,770] | [580,780] |
| 10 | CD | [270,430] | [400,550] |

# Results for Re-Structured ET

- Analysis of sequences leading to CD
  - Time reach CD

| Branch | Zr | Cr | FeCrAl |
|---|---|---|---|
| 2 | [6300,6750] | [6500,7000] | [6800,7200] |
| 3 | [200,700] | [400,1000] | [400,700] |
| 5 | [6250,6700] | [6600,7050] | [6750,7150] |
| 6 | [165,180] | [250,330] | [350,400] |
| 8 | [7000,7450] | [7200,7600] | [7500,7900] |
| 9 | [390,395] | [520,600] | [420,620] |
| 11 | [190,270] | [7300,7800] | [7500,7900] |
| 12 | [190,270] | 380 | 380 |

Sequence 11: \HPI \ACC LPI \LPR



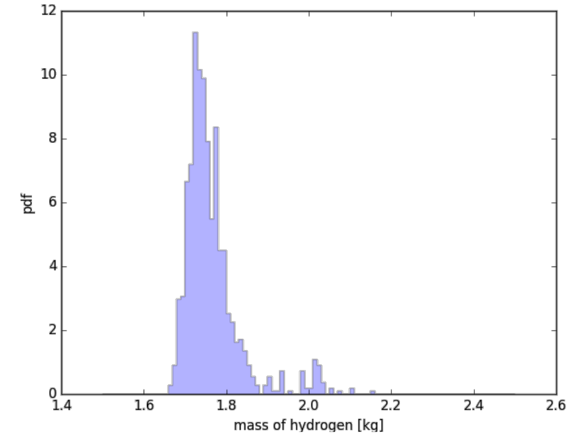
# Results for Re-Structured ET

- Analysis of sequences leading to CD
  - Hydrogen Generation

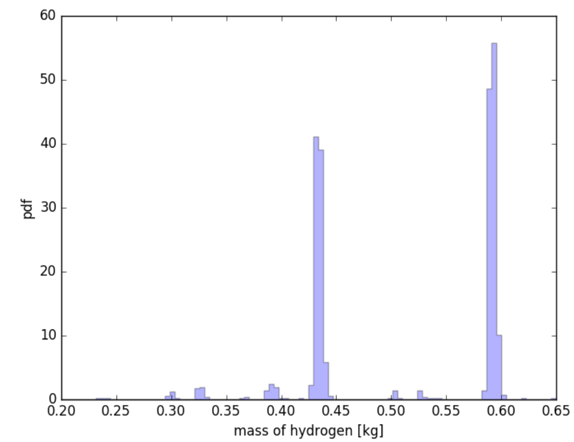
| Branch | Zr | Cr | FeCrAl |
|---|---|---|---|
| 2 | [3.7,7.5] | [1.,9.] | [0.4,1.2] |
| 3 | [0.6,4.] | [0.5,8.] | [0.1,0.9] |
| 5 | [1.7,10.] | [1.7,6.] | [0.45,1.] |
| 6 | [1.65,2.2] | [1.5,3.] | [0.2,0.65] |
| 8 | [1.7,2.2] | [1.7,6.] | [0.4,0.9] |
| 9 | [1.85,2.05] | 2 | 0.57 |
| 11 | [1.5,3.5] | [2.1,7.2] | [0.4,0.8] |
| 12 | 1.9 | 0.5 | 0.5 |

Sequence 6: HPI \ACC \LPI \LPR

Zr




FeCrAl




- Considerations
  - Simulation stops when PCT reach failure criterion
    - Zr: 1477 K (2200 F)
    - ATF: 1804 K
  - Fuel performance code coupled with RELAP5-3D should be employed

# Conclusions

- Objective: risk informed analysis of ATF
- Method
  - Classical PRA
    - Accident progression (ET level)
  - Dynamic PRA
    - Simulations generated by RAVEN and RELAP5-3D
    - Sampling parameters informed by ET
- Results
  - Few accident sequences can have in different outcomes
  - ET might required re-structuring (updated success criteria)
    - New sequences
    - New branching conditions