EMUG

Dynamic Event Tree analysis for accident sequences in fission and fusion reactors

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SAPIENZA UNIVERSITÀ DI ROMA

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Outline

- Framework
- RAVEN interface for MELCOR
- DET tool overview
- Test Case #1: LOCA analysis for ITER WCLL TBM
- Test Case #2: Cyberattack on a BWR/3
- Ongoing Activities & Future Developments

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RAVEN for DET analysis

TARGET

- Explore possible pathways through which the system can evolve
- Quantify the probability of these scenarios.

APPROACHES

- Branching/failures on demand (i.e., time and field triggers)
- Branching based on failure probability distributions
- Multi-branching scenarios.

BOUNDARIES

- Maximum mission time
- Rules based on the simulator physic model
- Probabilistic thresholds

RAVEN – MELCOR for DET analysis

MELCOR simulation begins

Branching condition is met

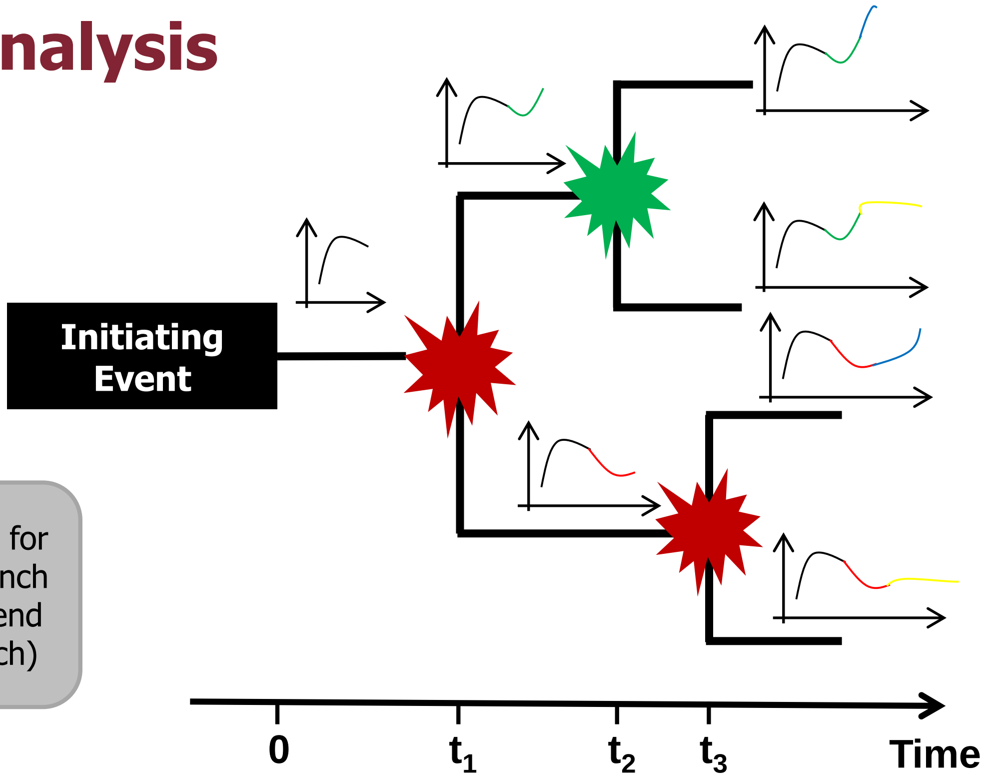
MELCOR run of the current branch stops

Has the stop condition (mission time of event) been reached?

Two (or more) branches are generated by RAVEN

MELCOR simulation for each generated branch restarts (from the end of the parent branch)

Completed history



Operational Tools:

- Parser Reader of .MES and EDF file
- MELCOR input deck modification
- File generation for external functions

RAVEN – MELCOR for DET analysis

Problem definition

MELCOR

EXEC_STOPCF – Special Stop Control Function

Optional

This record specifies the name of a LOGICAL valued control function that causes a graceful termination of the MELCOR calculation if its value is .TRUE. This function must have been defined as part of MELGEN input.

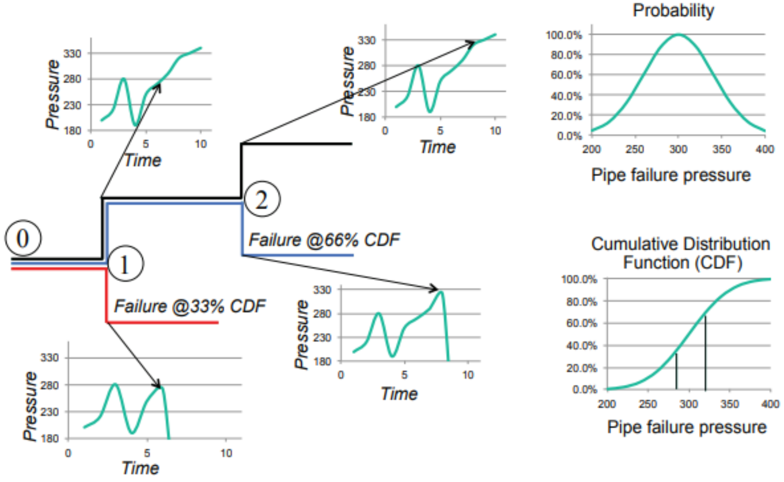
(1) ISCF

The name or number of a LOGICAL valued control function.

(type = integer/character*16, default = none, units = none)

Central L-OR included in STOPCF containing

RAVEN




```
CF_ID  'RECOVERY_TIME'  818  L-GT
CF_LIV FALSE
CF_ARG  2
          1  CF-VALU('TIME_FROM_PIE') 1.0   0.0
          2  CF-CONST  $RAVEN-RECOVERY_TIME:-1$
CF_MSG  FULL-OUTPUT  'RECOVERY'
```

```
CF_ID      'END_SIMULATION'      999           L-GT
CF_MSG  FULL-OUTPUT 'Run ended successfully!!!!!'
CF_ARG    2
            1     CF-VALU('MELTED_CLAD')      1.0        0.0
            2     CF-CONST                   1477.594
```

RAVEN – MELCOR for DET analysis

Tools overview

- **Different procedure** between MELCOR version **1.8.6** and version **2.2**
- DET for fusion application adopts **EDF for a bridge** between RAVEN and MELCOR

DET algorithm for Fission Applications

Input: X_i sampled variables & system model

START RUN
if *trip* == **TRUE**:
  tripVariable = self.messageReader
  for *each tripVariable*:
    self.writeBranchInfo (tripVariable) #creates two branches
    self.modifyInput (tripVariable)
  RESTART simulation for each branch

DET algorithm for Fusion Applications

Input: X_i sampled variables & system model

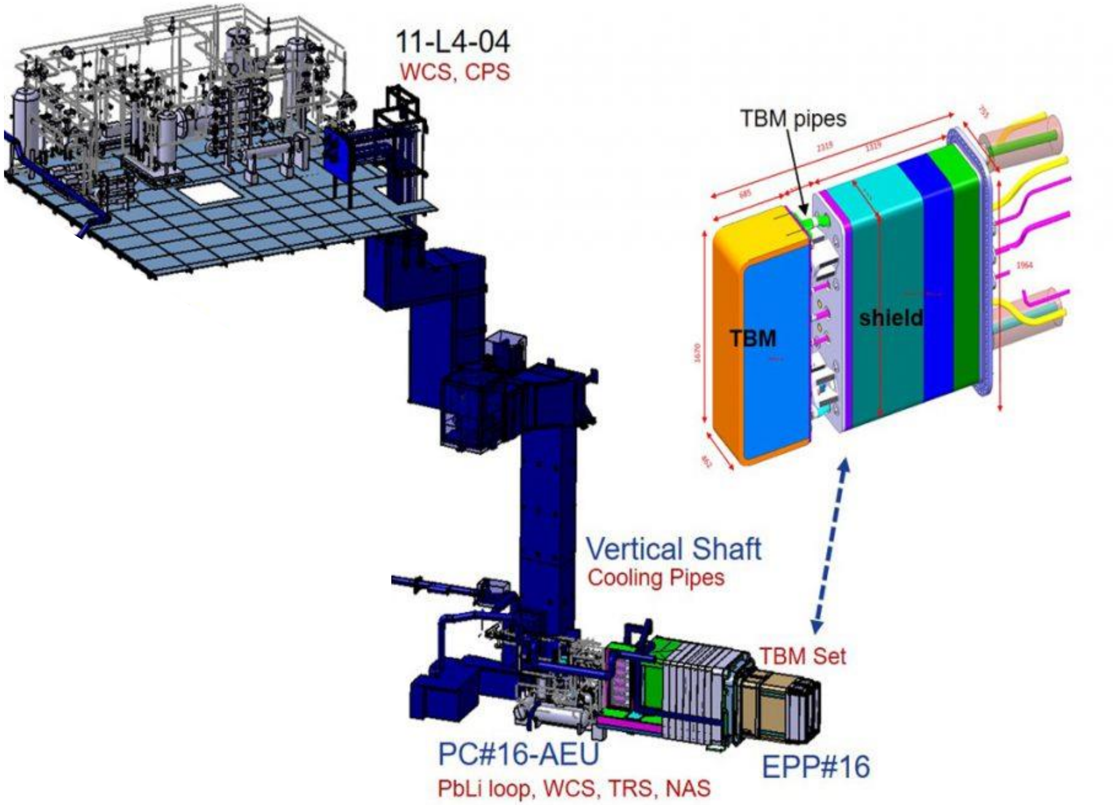
START RUN
for *each* X_i:
  sampledVar = self.ravensample
  self.writeEDF(sampledVar)
if *trip* == **TRUE**:
  tripVariable = self.messageReader
  for *each tripVariable*:
    self.writeBranchInfo (tripVariable) #create two branches
    self.writeEDF (tripVariable)
  RESTART simulation for each branch

Test Case: Loss of Coolant Accident analysis for ITER WCS

System Overview

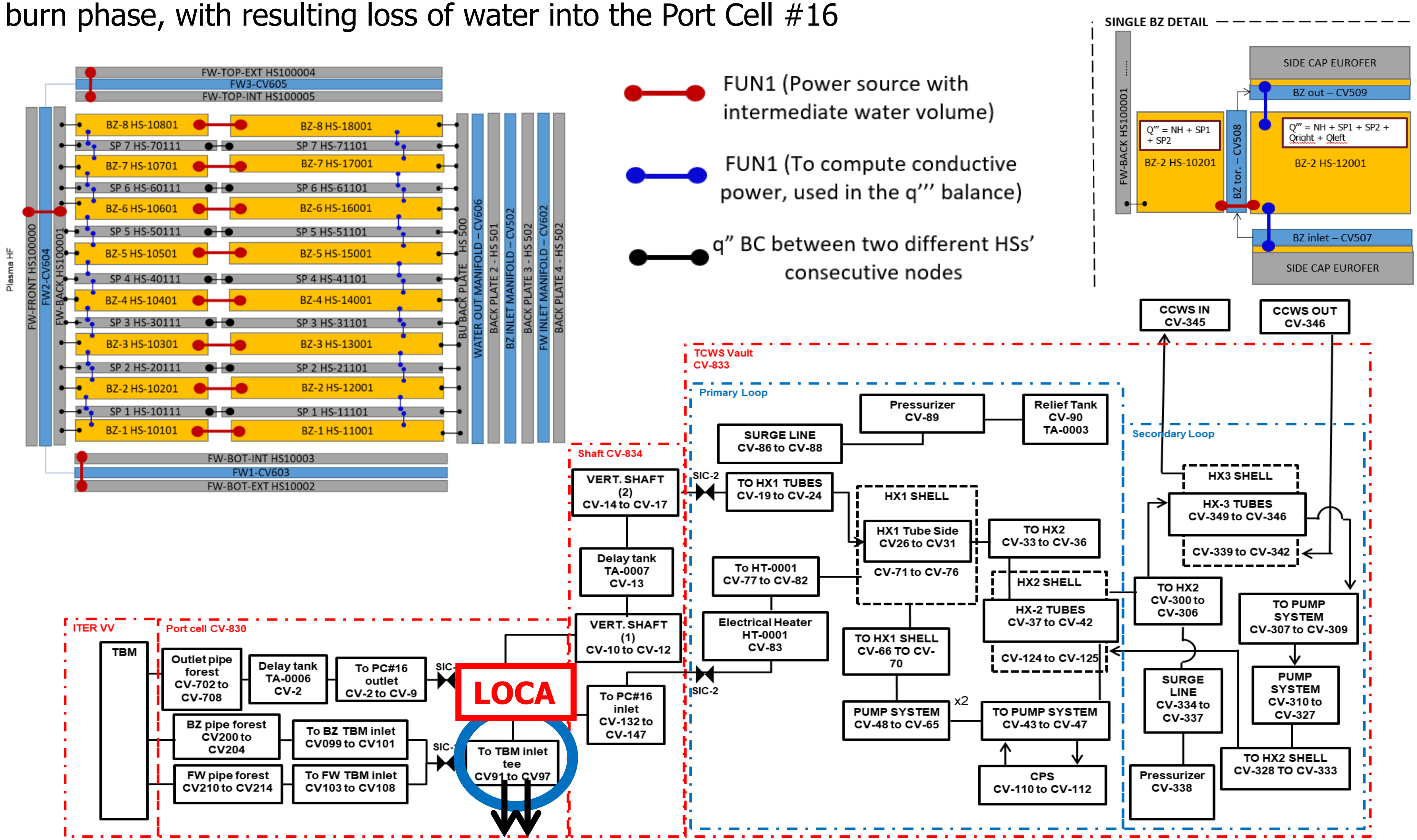
- TBS in ITER and a compulsory component for demonstrating the future power fusion reactor DEMO

- The main goal of the Test Blanket Modules (TBMs) is to **validate the tritium breeding technology**, necessarily vital for the self-sustaining fusion power plants where tritium is a fuel for the fusion reaction



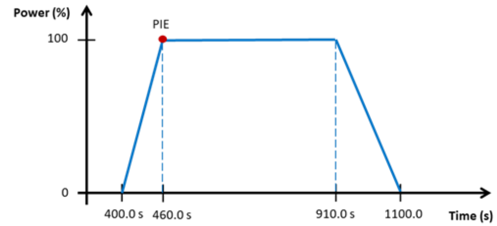
Test Case: Loss of Coolant Accident analysis for ITER WCS

Initiating Event: **double-ended guillottine break** of the TBM inlet WCS pipe during an ITER plasma burn phase, with resulting loss of water into the Port Cell #16



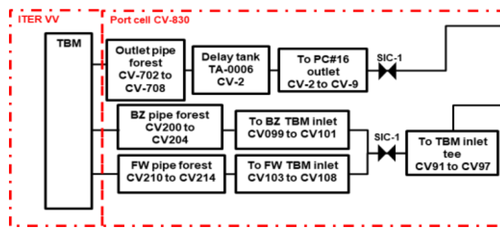
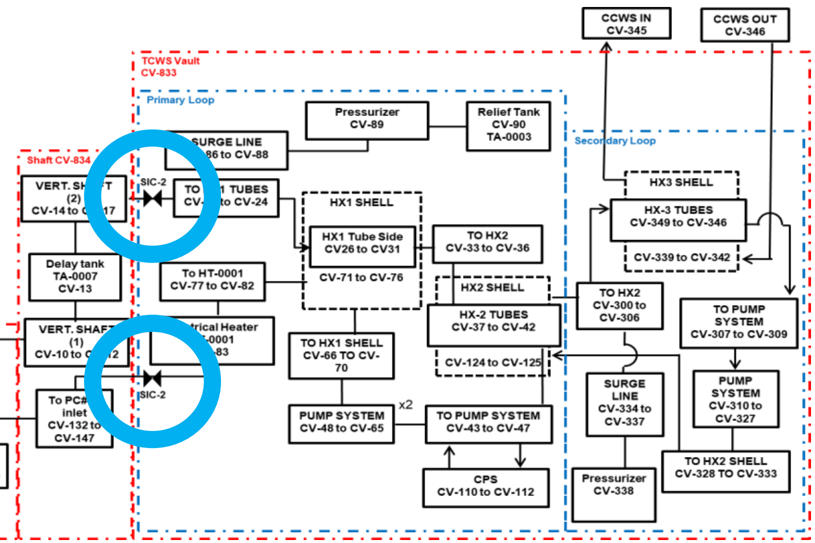
Test Case: Loss of Coolant Accident analysis for ITER WCS

Sampling Strategy



ITER plasma burn phase

1. Ramp up sequence from 0% power to flat-top 100%
2. Flat-top of 450.0 s
3. Ramp Down in 200.0 s

Event	Distribution	Lower Boundary [s]	Upper Boundary [s]	# of values sampled
Ramp Down Trigger	Uniform	3.0	51.0	17
Valve SIC-2 closure	Uniform	7.0	55.0	17

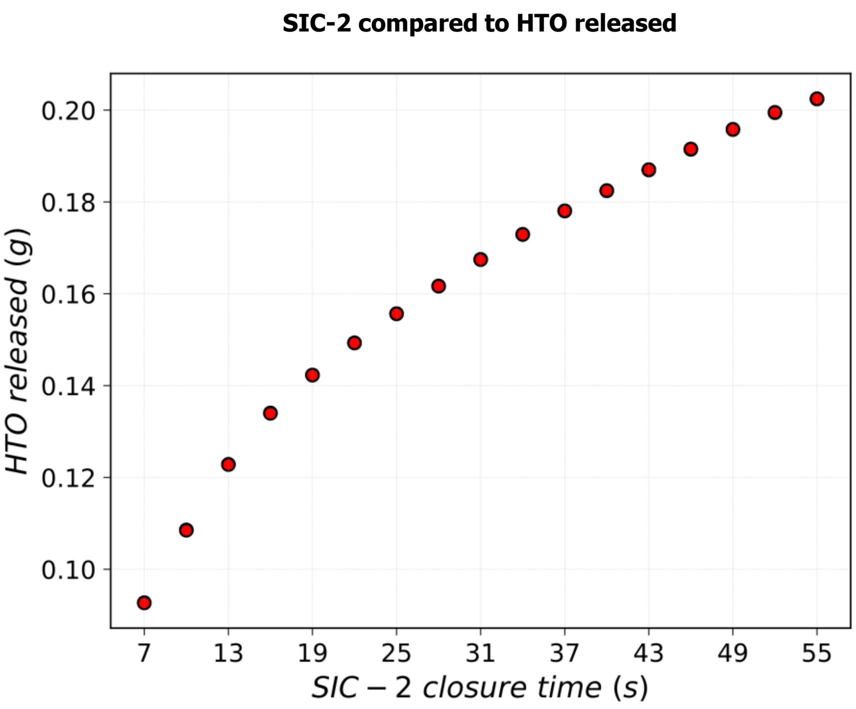
GOAL

Investigate the influence on **FW temperature transient** and tritiated water **HTO released** from the coolant system.

Test Case: Loss of Coolant Accident analysis for ITER WCS

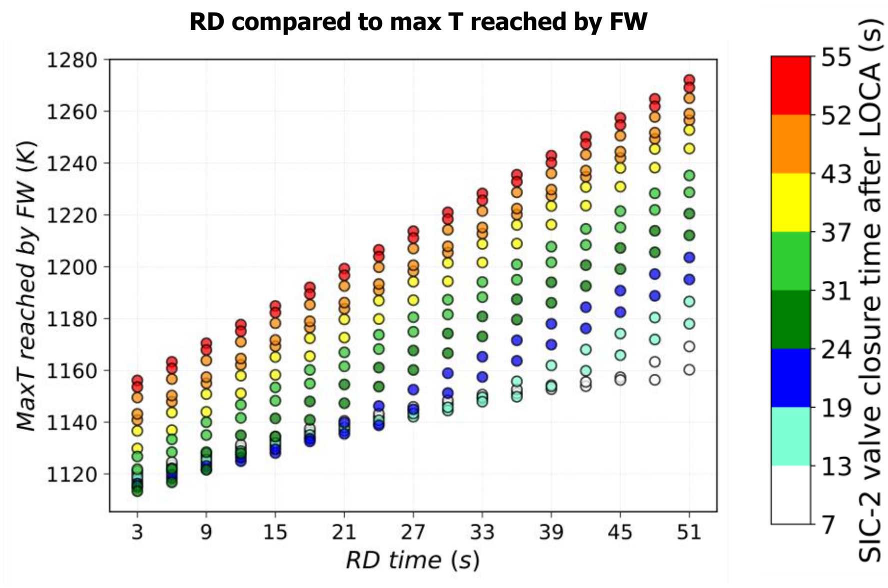
Main Results

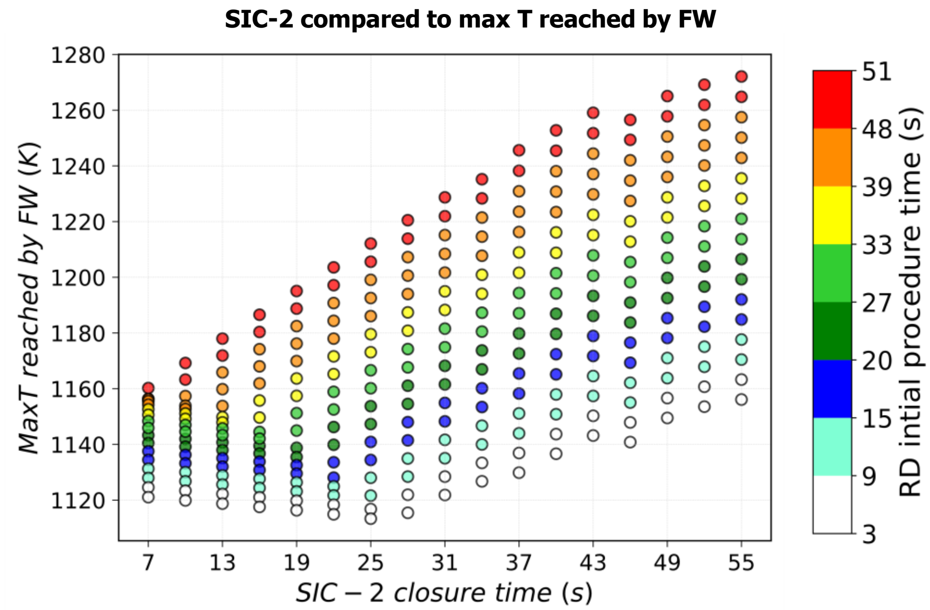
- Amount of HTO released isn't affected by RD procedure time but depends on the SIC-2 valve closure
- **Less HTO** is released when SIC-2 closure time is close to LOCA rupture
- **More effective** a SIC-2 closure close to LOCA rupture, and less effective for times > 50s.
- If SIC-2 > 60s **no effects** on HTO released



Test Case: Loss of Coolant Accident analysis for ITER WCS

Main Results





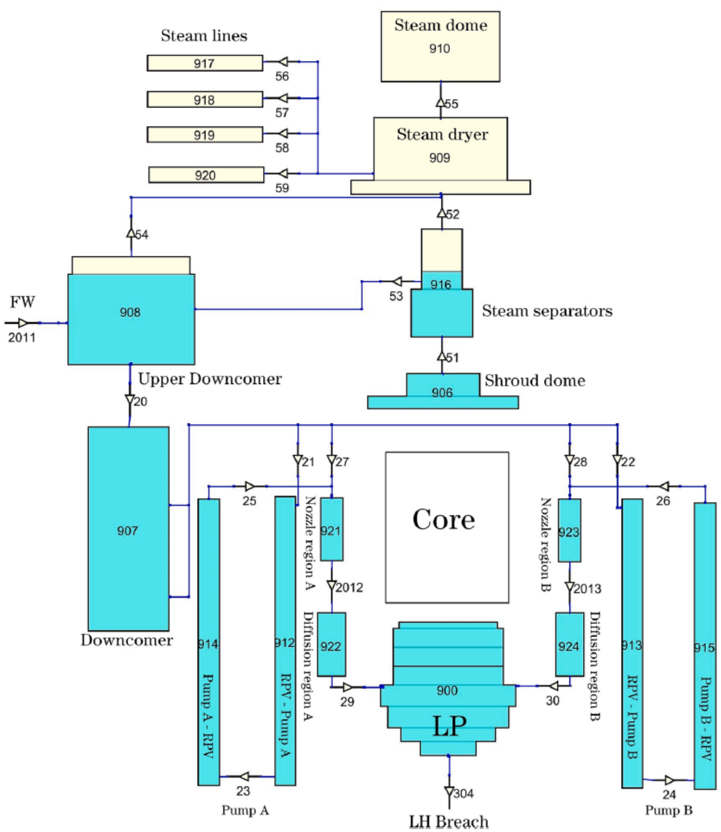
- Both RD and SIC-2 timings influence the max T reached by FW during the LOCA transient
- The max T increases with a delayed RD sequence from the LOCA event

- SIC-2 valve closure delay **permits a counterflow of coolant** from the WCS inventory to the FW
- Beneficial effects are seen **only** for RD times < 33s
- A **trend reversal** for the beneficial effect of coolant is seen at 25s to 10s (interval related to higher RD sequence)

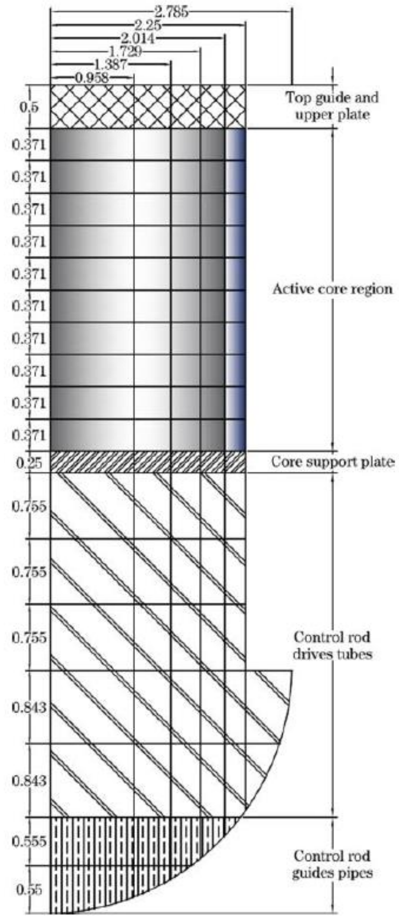
Test Case: Cyberattack on a BWR/3 during a hot-shutdown

Initiating Event: <u>Hot-shutdown from full power</u>

CVH nodalization



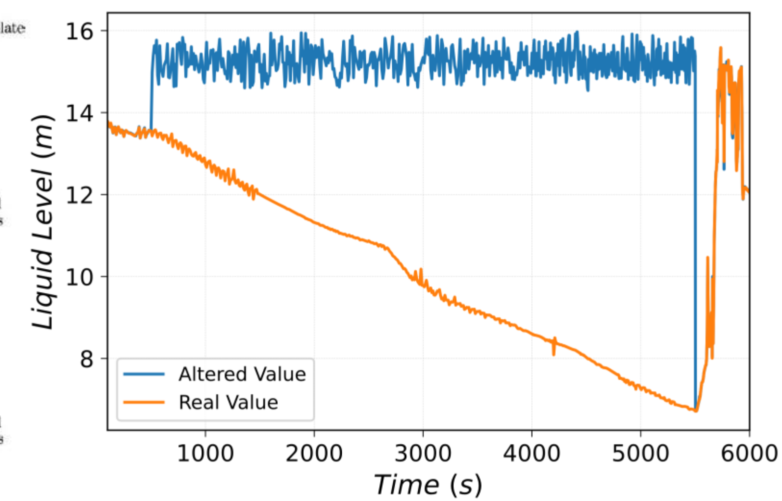
COR nodalization



Safety Systems Implemented

	Actuation	Parameter	Setpoint
RCIC	Initiation	Reactor water level low [m]	13.5
	Turbine trip and system isolation	Reactor water level high [m]	15.0
		Steam line pressure low [Pa]	3.447E+05
	Pump capacity	Volumetric flow rate [m^3/s]	0.037
HPCI	Initiation	Reactor water level low [m]	13.5
		High drywell pressure [Pa]	2.0E+05
	Turbine trip and system isolation	Reactor water level high [m]	15.0
		Steam line pressure low [Pa]	6.897E+05
	Pump capacity	Volumetric flow rate [m^3/s]	0.315
ADS	Initiation	Reactor water level low-low [m]	9.86
		Delay [s]	105.0
LPCI	Initiation	Reactor water level low-low [m]	9.86
		High drywell pressure [Pa]	2.0E+05
		Reactor pressure low [Pa]	3.206E+06
	Pump capacity	Volumetric flow rate [m^3/s]	2.523
	Pump trip	Reactor water level high [m]	15.0

Altered and actual liquid levels



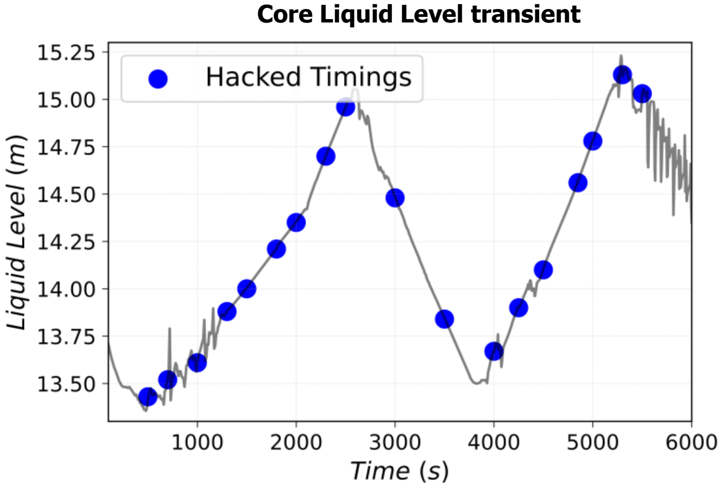
Test Case: Cyberattack on a BWR/3 during a hot-shutdown

Sampling Strategy

Event	Distribution	Lower Boundary [s]	Upper Boundary [s]	# of values sampled
Cyberattack	Uniform	500.0	6000.0	20
Recovery	Uniform	5500.0	150000.0	15

Discretization Strategy

- Guided exploration
- Restricted Sampling
- Truncation method based on PCT > 1477 K



GOAL

Investigate a **recovery time limit** for each of the sampled cyberattack times

LIMITING SURFACE

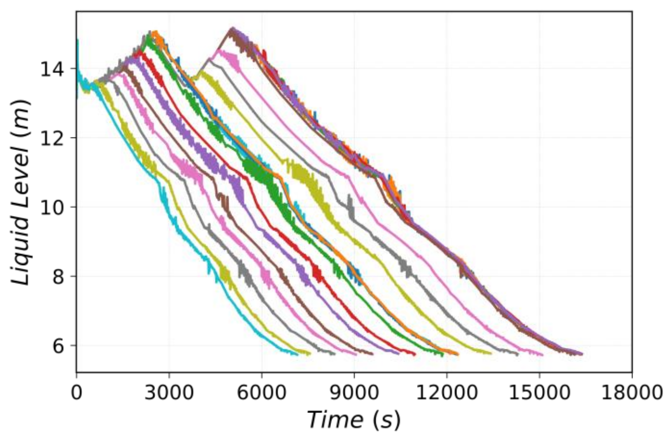
Test Case: Cyberattack on a BWR/3 during a hot-shutdown

Main Results

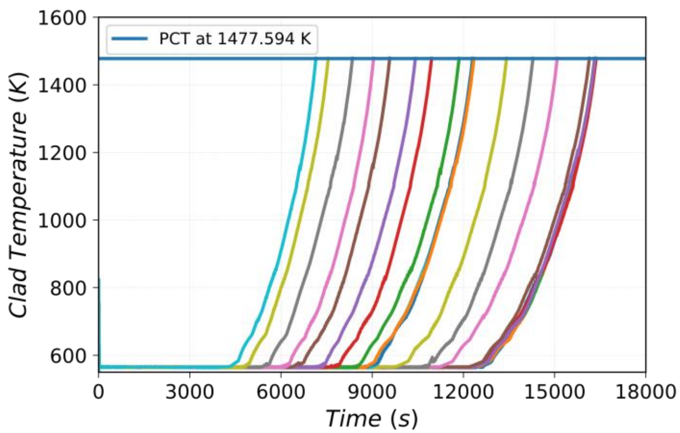
- Binary Classification between PCT scenarios and successfull recovery of the system

PCT

Liquid Level transient

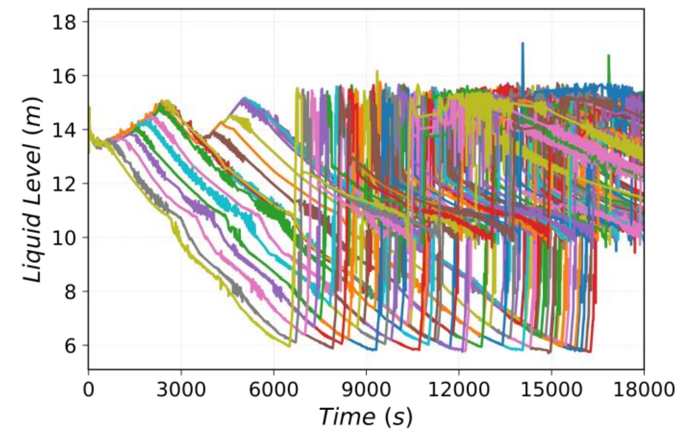


Temperature transient

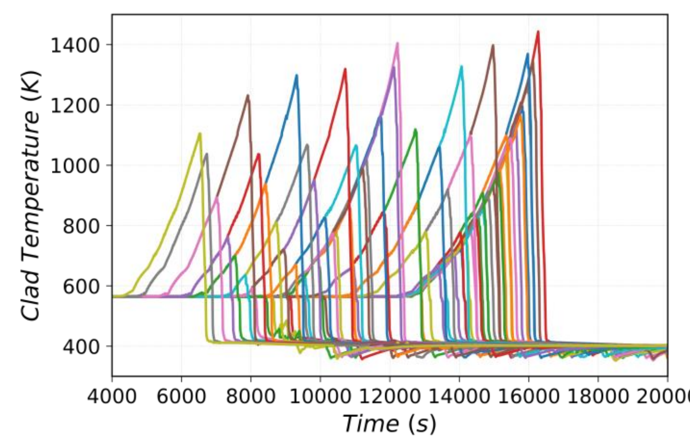


Successfull Recovery

Liquid Level transient



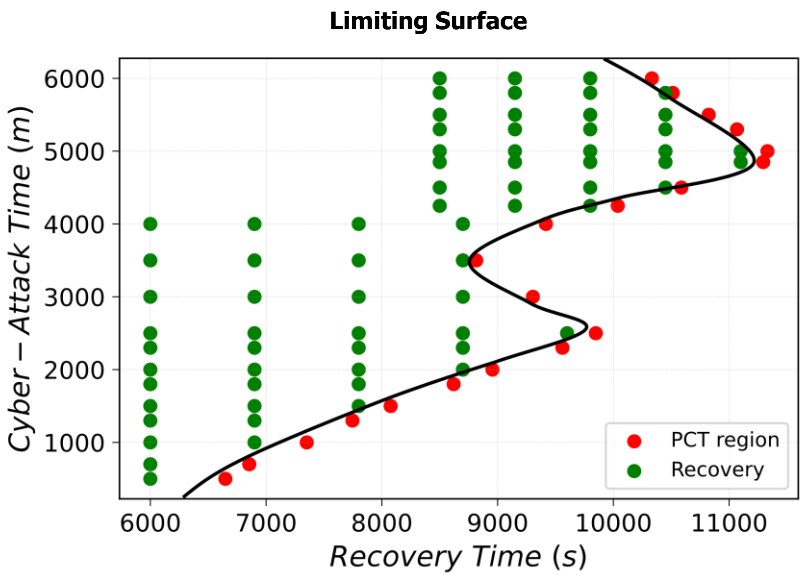
Temperature transient



Test Case: Cyberattack on a BWR/3 during a hot-shutdown

Main Results

- Two regions of the input space are identified, thus delineating the PCT region.
- The Limiting Surface is defined as the **boundary between system success and system failure**

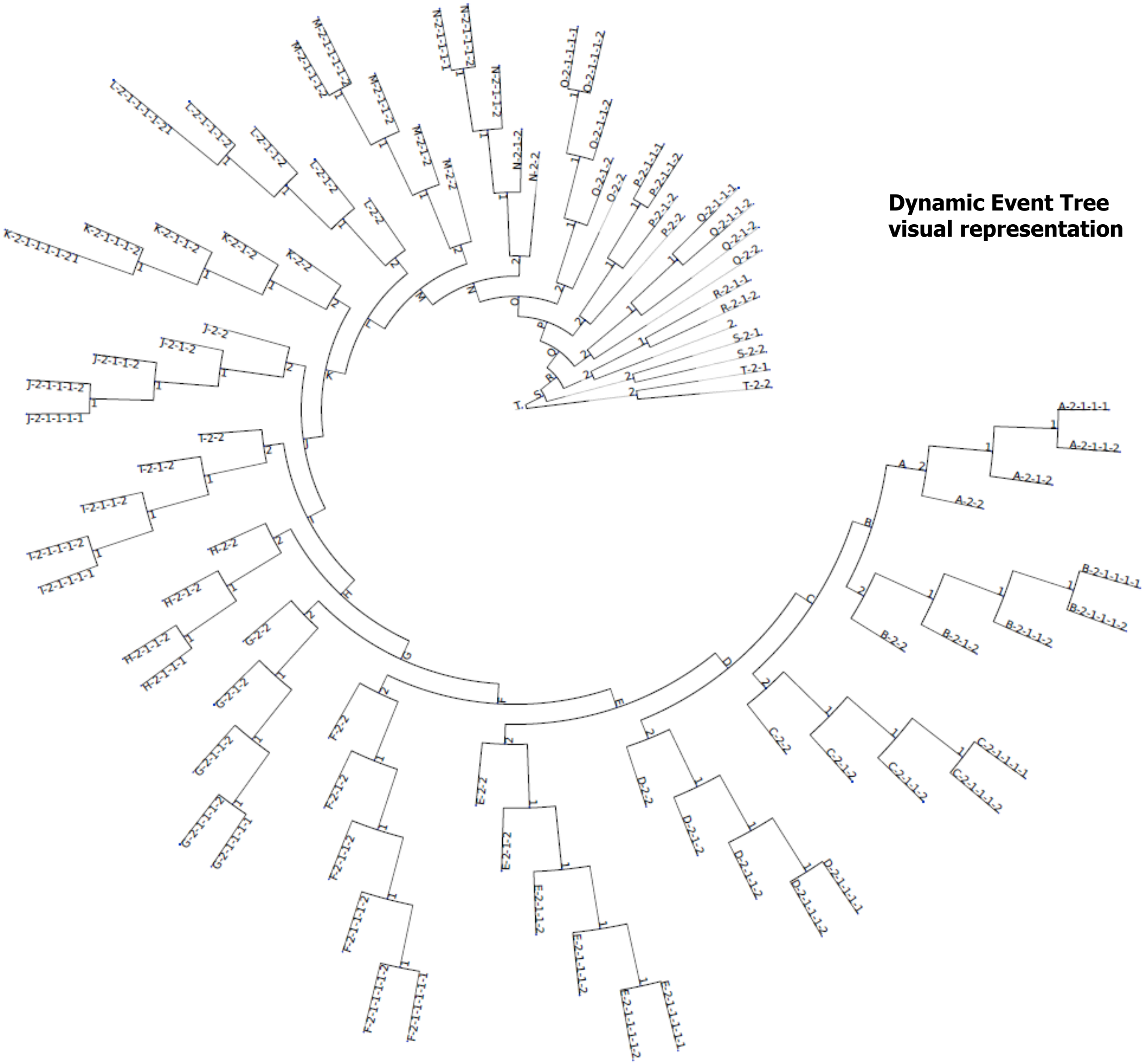


PCT scenarios

Branch ID	Cyberattack Time [s]	Liquid level [m]	PCT timing [s]
T-2-1	500.0	13.57	6648.16
S-2-1	700.0	13.52	6854.56
R-2-1-1	1000.0	13.64	7351.08
Q-2-1-1	1300.0	13.82	7745.96
P1-2-1-1-1	1500.0	13.95	8075.95
O-2-1-1-1	1800.0	14.21	8619.97
N-2-1-1-1-1	2000.0	14.44	8955.32
M-2-1-1-1-1	2300.0	14.96	9559.87
L-2-1-1-1-1-1	2500.0	15.0	9848.16
K-2-1-1-1-1	3000.0	14.39	9304.55
J-2-1-1-1-1	3500.0	13.83	8815.34
I-2-1-1-1-1	4000.0	13.85	9417.21
H-2-1-1-1	4250.0	14.22	10037.8
G-2-1-1-1-1	4500.0	14.41	10587.6
F-2-1-1-1-1-1	4850.0	14.92	11293.9
E-2-1-1-1-1-1	5000.0	15.08	11330.96
D-2-1-1-1-1	5300.0	14.86	11067.89
C-2-1-1-1-1	5500.0	14.75	10823.52
B-2-1-1-1-1	5800.0	14.66	10512.87
A-2-1-1-1	6000.0	14.21	10332.60

Test Case: Cyberattack on a BWR/3 during a hot-shutdown

Main Results



Dynamic Event Tree visual representation

Conclusions

- RAVEN and MELCOR for DET applications has been tested for both fission and fusion applications
- An external Python script has been developed to reproduce a Liming Surface
- ETEToolkit has been adopted to visually represent the Dynamic Event Tree

Next Steps

- Update the current interface to comply with Python code standards and share on open access the tool
- Adaptive DET concerning a SA on an BWR Spent Fuel Pool
- Support the development of Multibranch sampling

References

[1] Glingler T., et al., Dynamic Event Tree Analysis of a Severe Accident Sequence in a Boiling Water Reactor Experiencing a Cyberattack Scenario. Available at SSRN in preprint, (2023) http://dx.doi.org/10.2139/ssrn.4376822

[2] D'Onorio M. D., et al., Dynamic Event Tree Analysis as a Tool for Risk Assessment in Nuclear Fusion Plants Using RAVEN and MELCOR. IEEE T Plasma Sci., vol. 50 no. 11 (2022): pp. 4514–4520. https://doi.org/10.1109/tps.2022.3165170.

[3] Alfonsi, A., et al., Dynamic Event Tree Analysis Through RAVEN, INL/CON-13-29344, Idaho National Laboratory, (2013), https://inldigitallibrary.inl.gov/sites/sti/sti/5806439.pdf.

[4] Alfonsi A., et al., RAVEN and dynamic probabilistic risk assessment: Software overview, Safety and Reliability: Methodology and Applications, London: Taylor & Francis Group, (2015), https://doi.org/10.1201/b17399-109.

[5] Mandelli D., et al., Scenario clustering and dynamic probabilistic risk assessment, Reliability Engineering & System Safety, Vol. 115, (2013), https://doi.org/10.1016/j.ress.2013.02.013

[6] Idaho National Laboratory, RAVEN github repository, branch/mattdon/New_MELCOR_Interface https://github.com/idaholab/raven