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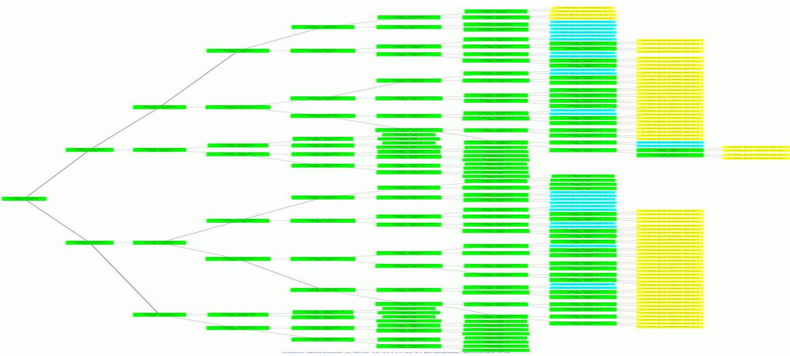

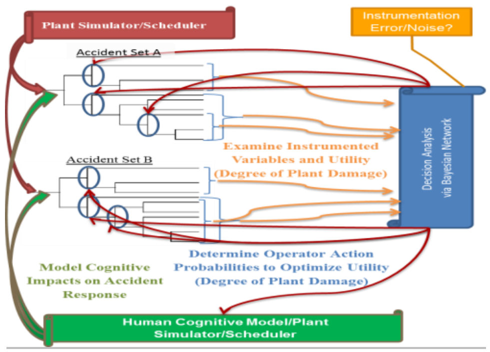

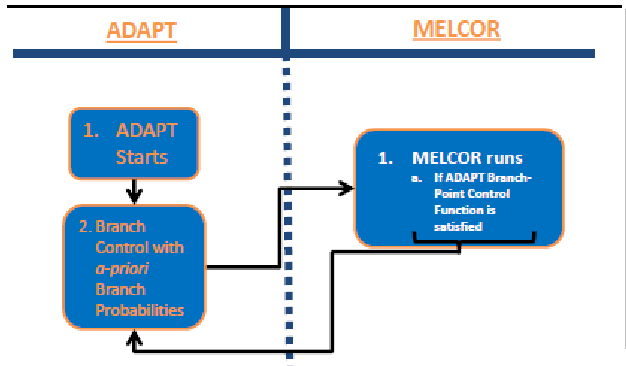

Intelligent Branching

The Pros and Cons of Discrete Dynamic Event Trees in PRA

Matthew Denman

Risk and Reliability

UQ and SS Course, April 23rd 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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John Reynolds - Computer Support

ACKNOWLEDGEMENTS

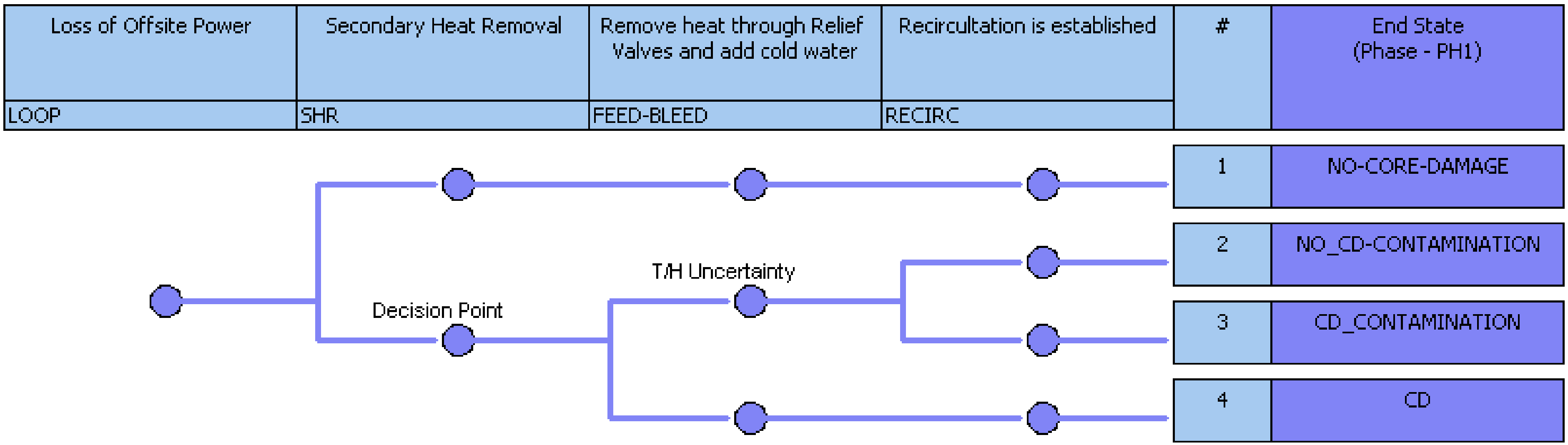
Outline

- Event Tree Method
  - Example – Loss of Off-Site Power
  - Discussion of PRA levels (1,2,3)
- Discrete Dynamic Event Trees
  - Overview
  - The Dynamic Driver (MELCOR)
  - Approach
  - Human Cognitive Modeling
  - Example SMR Problem
  - Future of Risk Management
- Conclusions

Event Tree Modeling

Loss-of-offsite-power event tree

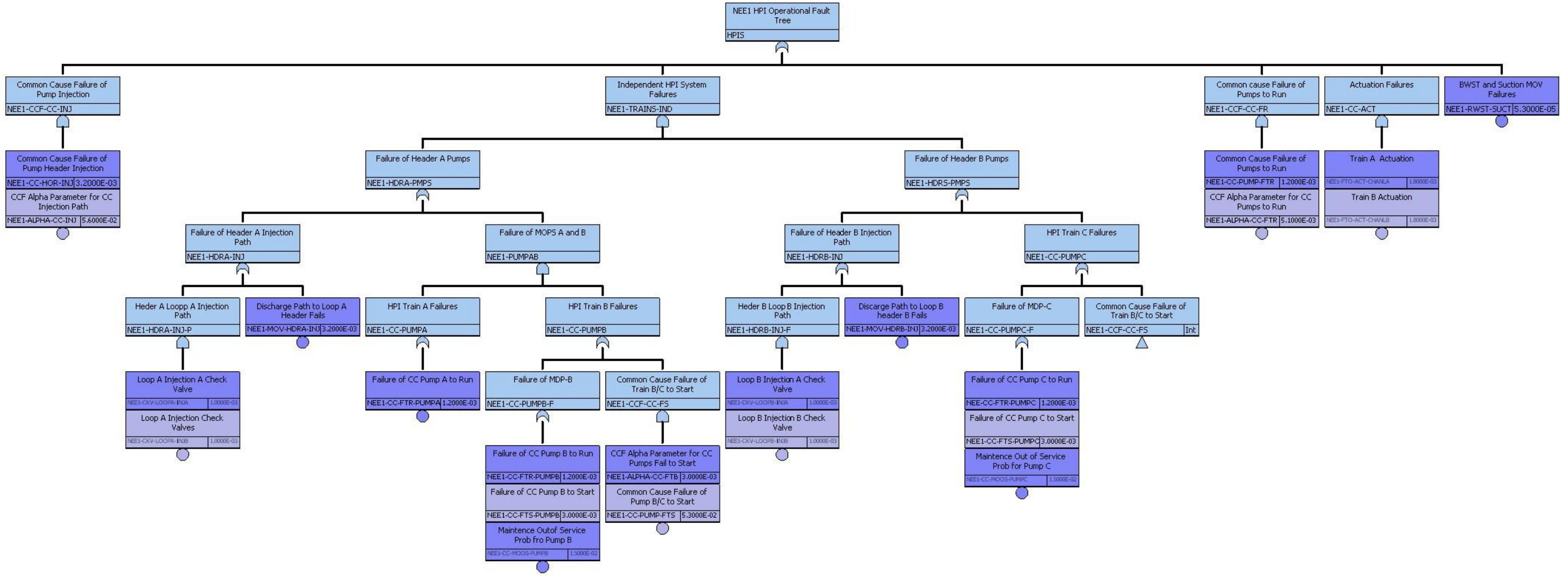
- Static event trees provide a computationally efficient way of exploring uncertainties in a complex state space
  - High level descriptions of actions or uncertainties on top
  - Moving through the tree from left to right
    - Up is action taken or success
    - Down is action not taken or failure



Adapted from Apostolakis 22.39 Lecture 9 Course Slides

Fault Trees

- Not the focus of this talk
- Uses logical arguments to calculate the failure of high level systems in the event tree
  - Difficult to capture dynamic and evolving conditions
  - Difficult to capture human actions



Human Performance

- The operators must decide to perform feed & bleed.
- Water is "fed" into the reactor vessel by the high-pressure system and is "bled" out through relief valves into the containment. Very costly to clean up.
- Must be initiated within about 30 minutes of losing secondary cooling (a thermal-hydraulic calculation).

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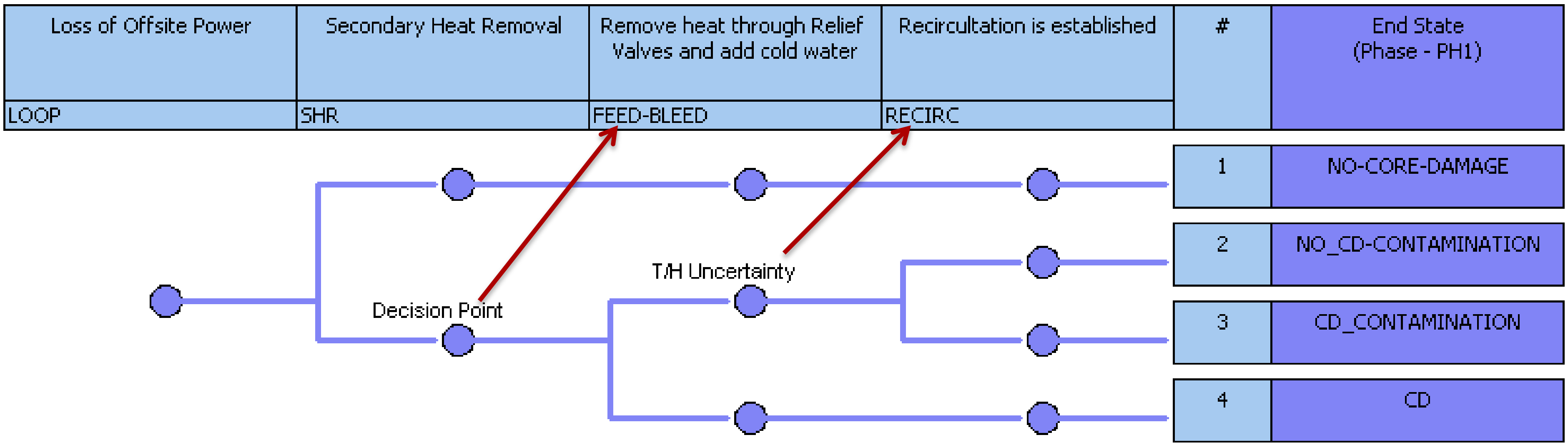
Loss-of-offsite-power event tree

- Static event trees provide a computationally efficient way of exploring uncertainties in a complex state space
  - High level descriptions of actions or uncertainties on top
  - Moving through the tree from left to right
    - Up is action taken or success
    - Down is action not taken or failure



Variations in plant states may be determined through meta-models

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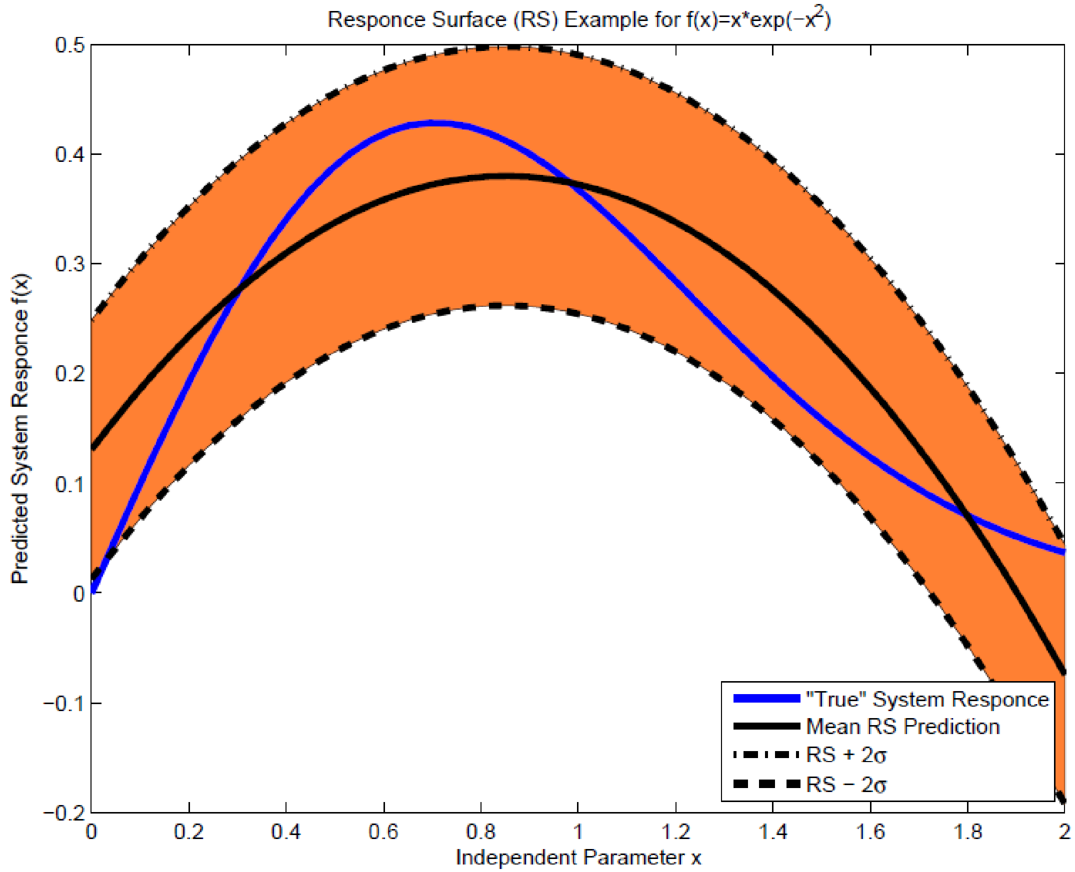
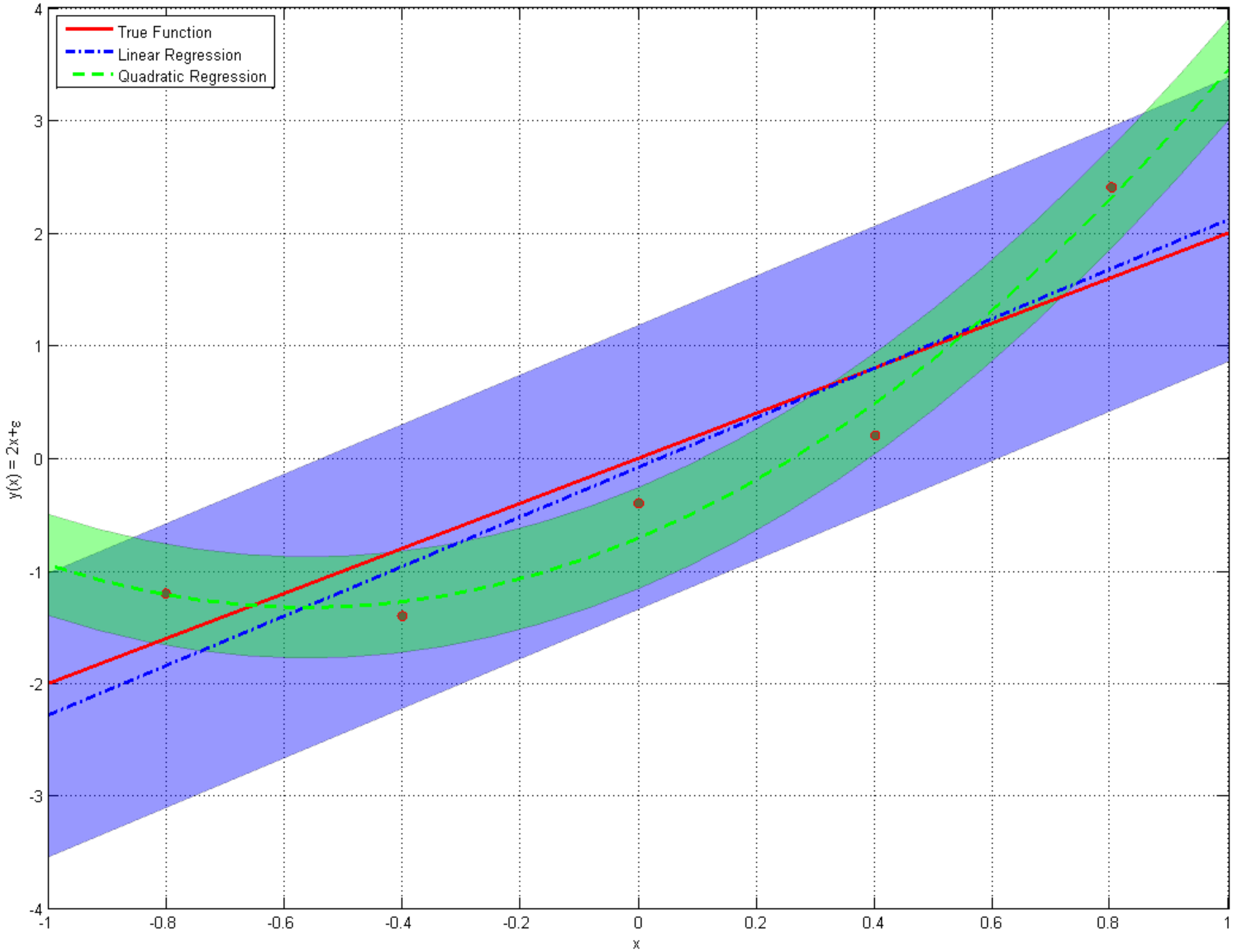
- Responses surface
  - Taylor (often quadratic) fit of the output of long running codes
  - Interaction terms often captured (but not shown to the left)
  - Used when:
    - hundreds, thousands, or millions of outputs are needed
    - Only 10s of simulations from the code are practical



$$\mathbf{y}_D = \mathbf{F}_D \boldsymbol{\beta} + \boldsymbol{\varepsilon}$$

$$\mathbf{F}_D = \begin{Bmatrix} \mathbf{f}^{\mathrm{T}}(\mathbf{x}_D^{(1)}) \\ \vdots \\ \mathbf{f}^{\mathrm{T}}(\mathbf{x}_D^{(N_D)}) \end{Bmatrix} = \begin{bmatrix} 1 & x_{D,1}^{(1)} & x_{D,2}^{(1)} & \cdots & x_{D,k}^{(1)} x_{D,l}^{(1)} & \cdots & (x_{D,m}^{(1)})^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ 1 & x_{D,1}^{(N_D)} & x_{D,2}^{(N_D)} & \cdots & x_{D,k}^{(N_D)} x_{D,l}^{(N_D)} & \cdots & (x_{D,m}^{(N_D)})^2 \end{bmatrix}$$

Caution should be employed when fitting meta models to noisy systems



From Langewisch Master’s Thesis, MIT, 2007

PRA Model Overview and Subsidiary Objectives

Level I

PLANT MODEL →

Results

Accident sequences leading to plant damage states

Level II

CONTAINMENT MODEL →

Results

Containment failure/release sequences

Level III

SITE/CONSEQUENCE MODEL

Results

Public health effects

PLANT MODE
At-power Operation
Shutdown / Transition Evolutions

SCOPE
Internal Events
External Events

Uncertainties →

Dynamic Event Tree Modeling

(Dynamic Programing)

Analysis Method

(Discrete-Dynamic-Event-Trees [DDET] via ADAPT)

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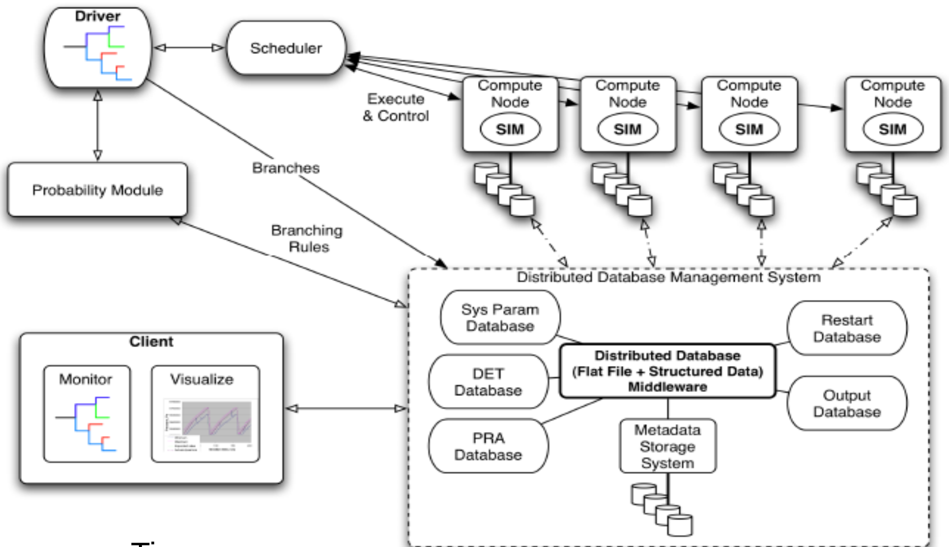
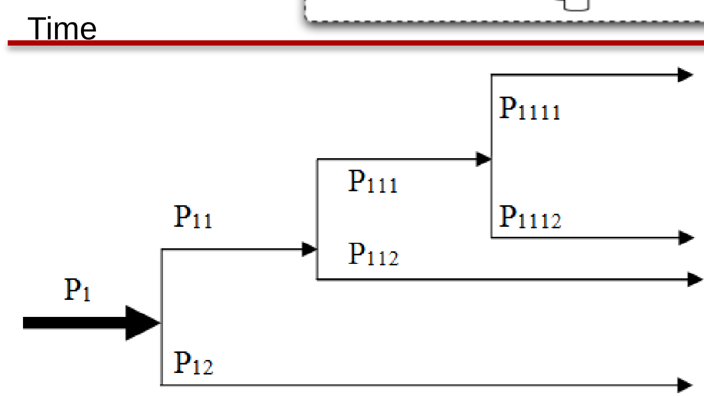
- DDET is an accelerated uncertainty propagation methodology
  - Predetermined set-points cause the dynamic code (e.g., MELCOR) to stop and restart multiple runs to characterize uncertainties.





New MELCOR simulations are branched mid-transient

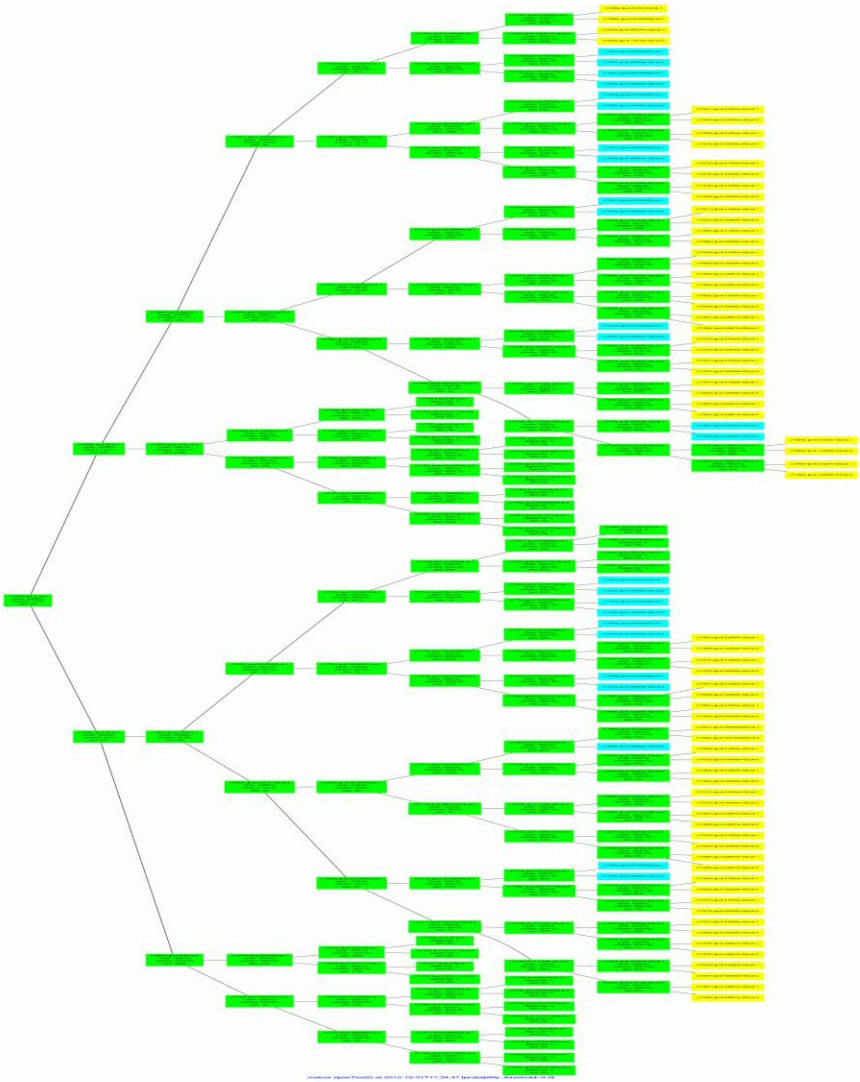
Key Point:
Speedup is derived because uncertainties in phenomena experienced late in an accident **need not** be simulated from t=0

DDET High Level Procedure

1. Create stable dynamic simulation
   - The model needs to be robust enough not crash the simulation when variables are changed mid-simulation
2. Decide key uncertain parameters of interest
   - Off-site power restoration
   - Decay Heat Levels
   - SRV Failure Timings
   - Core Oxidation Rates
   - …
3. Create and discretize cumulative distribution functions for key parameters
   - Similar to stratified sampling but simulations are not all started from t=0.
4. Program binary branch points into scheduler code (e.g. ADAPT)
   - ADAPT starts, stops, and branches MELCOR simulations as necessary

Example DDET Branching

- **Branching Visualization**
- **ADAPT uses control functions within MELCOR to determine when branching criteria are satisfied**
- **Branching criteria could be**
  - **Time**
  - **SCRAM Ignition**
  - **# of SRV Cycles**
  - **Initiation of Cladding Oxidation**
- **Branching must be binary, but staged binary branches can create for non-binary branching**



Dynamic Accident Progression Modeling – MELCOR

- NRC sponsored simulation code for analysis of accidents in nuclear power plants
  - Also applied to containment DBA simulation
  - PWR, BWR, HTGR, PWR-SFP, BWR-SFP, HTGR, SFR
- Fully Integrated, engineering-level code
  - Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings;
  - Core heat-up, degradation, and relocation;
  - Core-concrete attack;
  - Hydrogen production, transport, and combustion;
  - Fission product release and transport behavior
- Desktop application
  - Windows/Linux versions
  - Relatively fast-running
    - One or two days common
    - One or two weeks possible
    - Project to improve code performance
  - SNAP for post-processing, visualization, and GUI

Timeline of Nuclear Safety Technology Evolution

simplified parametric → *detailed best estimate*

Tier 1: Integrated Codes: MELCOR, MAAP, ASTEC

Tier 2: Mechanistic Codes
SCDAP, CONTAIN, VICTORIA

US Research → *International Research*

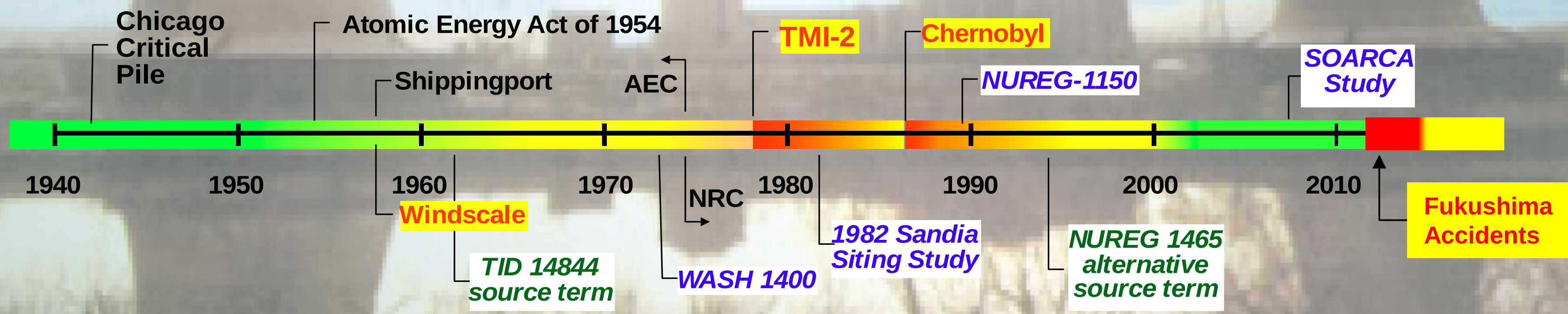
Phenomenological Experiments (PBF, ACRR, ACE, HI/VI, HEVA)

QUENCH, Phebus FP, VERCORS, MASCA

Deterministic Bounding Analysis

Risk Informed Regulation

Probabilistic Risk Informed Analysis



Nuclear Power Outlook

- **Optimistic**
- **Guarded**
- **Pessimistic**

Emerging Issues.....

Risk Informing Regulation
- ***Modernization, NUREG-1465***

License Amendments and Extension
- ***MOX, High Burnup***
- ***Plant aging***

Emergency Response Planning

Advanced Reactors
- ***AP1000, ESBWR, US-EPR***

NGNP - HTGR, VHTGR, H2 Economy

GNEP - Fast Burner Reactor, Reprocessing

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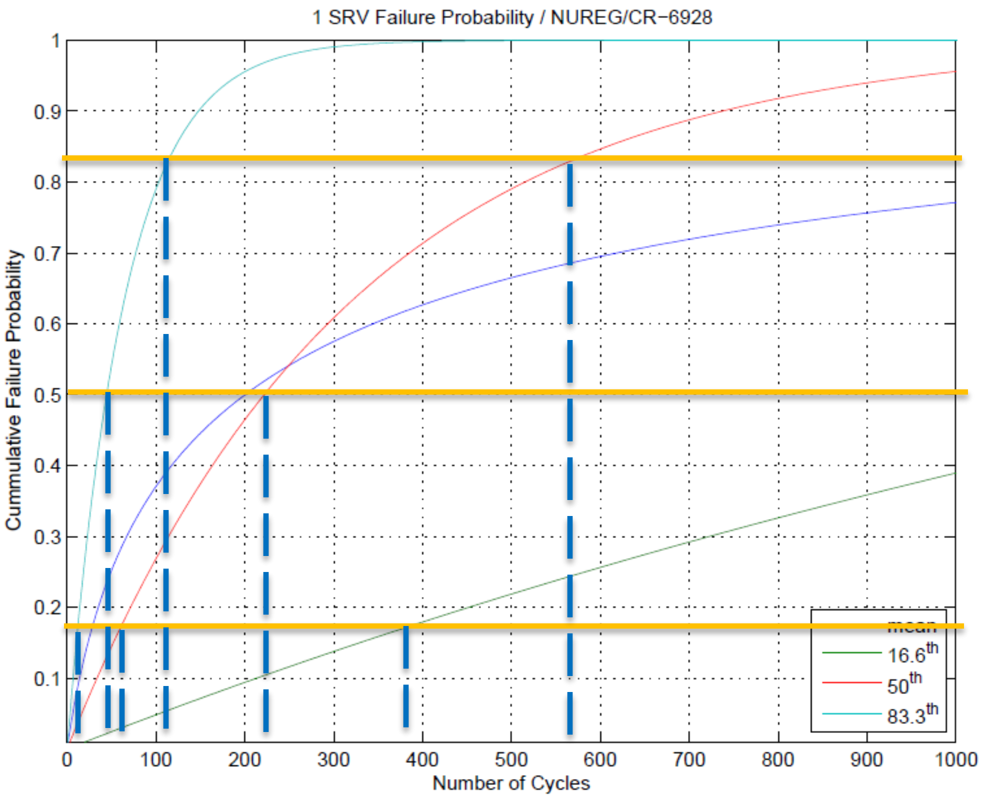
Branch Point Selection

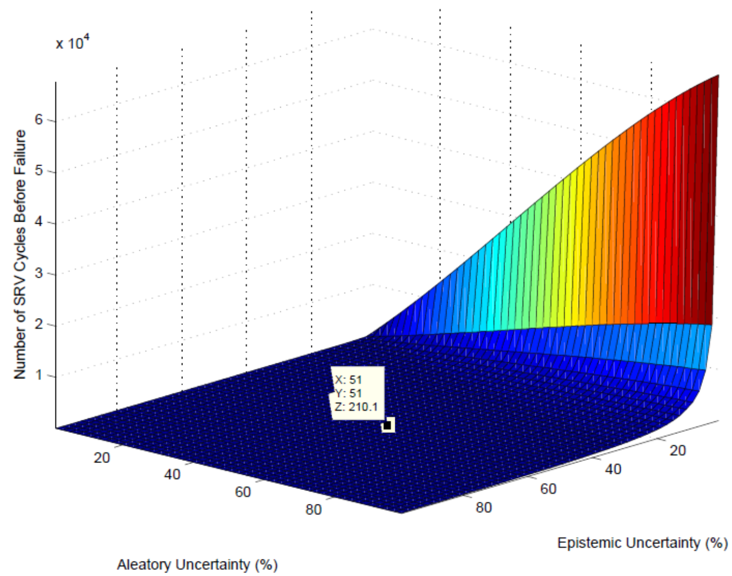
1. Determine what type of uncertainties exist in the parameter of interest
2. Discretize epistemic, aleatory, or epistemic and aleatory uncertainties into discrete bins
   - A robust analysis would increase the number of bins until the results converge (think meshing)
3. Branch the dynamic code once the discrete bin value have been reached



Example: SRV Stochastic Failure

Operation	Failure Mode	Source	5%	Median	Mean	95%	Distribution Type	Distribution α	Distribution β
All	FTO	EB/PL/KS	8.33E-07	1.89E-03	7.71E-03	3.50E-02	Beta	0.300	3.891E+01
	FTC	SCNID/IL	3.13E-06	3.62E-04	7.95E-04	3.05E-03	Beta	0.500	6.282E+02
	SO	EB/PL/KS	5.44E-11	1.24E-07	5.08E-07	2.33E-06	Gamma	0.300	5.900E+05
	FTCL	WSRC	4.62E-04	5.20E-02	1.00E-01	3.62E-01	Beta	0.500	4.500E+00

- From the SORCA analysis for the Surry PWR, SRV failure timing was shown to be an important variable for accident progression.
  - Very little data exists regarding SRV failure timing
- DDET allows for the analyst to examine SRV failure across both state of knowledge uncertainty and inherent randomness



$$W(n|x_i,y_i) = 1 - \left(1 - (x_i + y_i)\right)^n$$

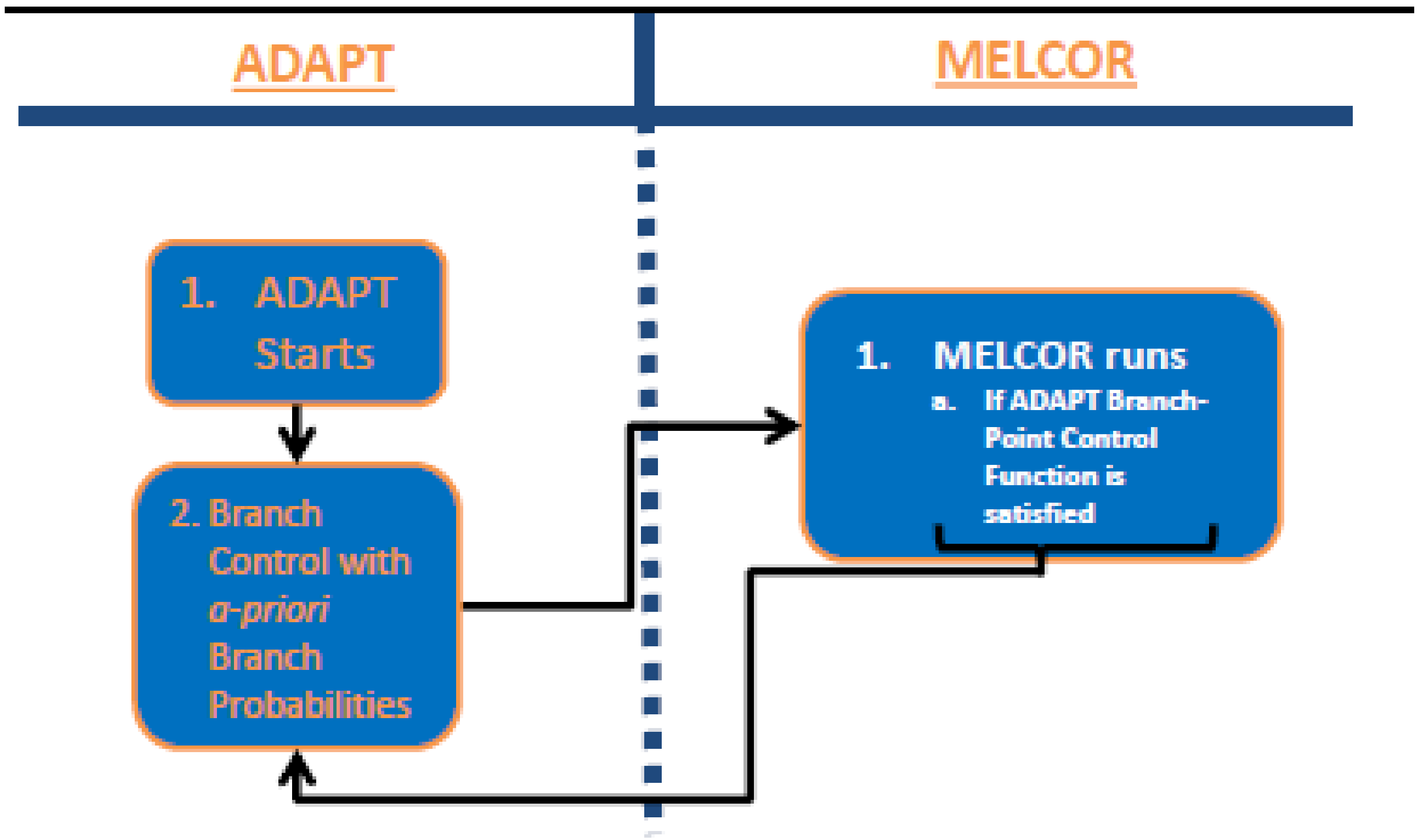
SRV Cycles Until Failure	Epistemic Variation			
Aleatory Variation		83th %	50th %	17rd %
	17th %	12	58	366
	50th %	44	213	1200
	83rd %	114	380	1986

DDETs and Cognitive Modeling

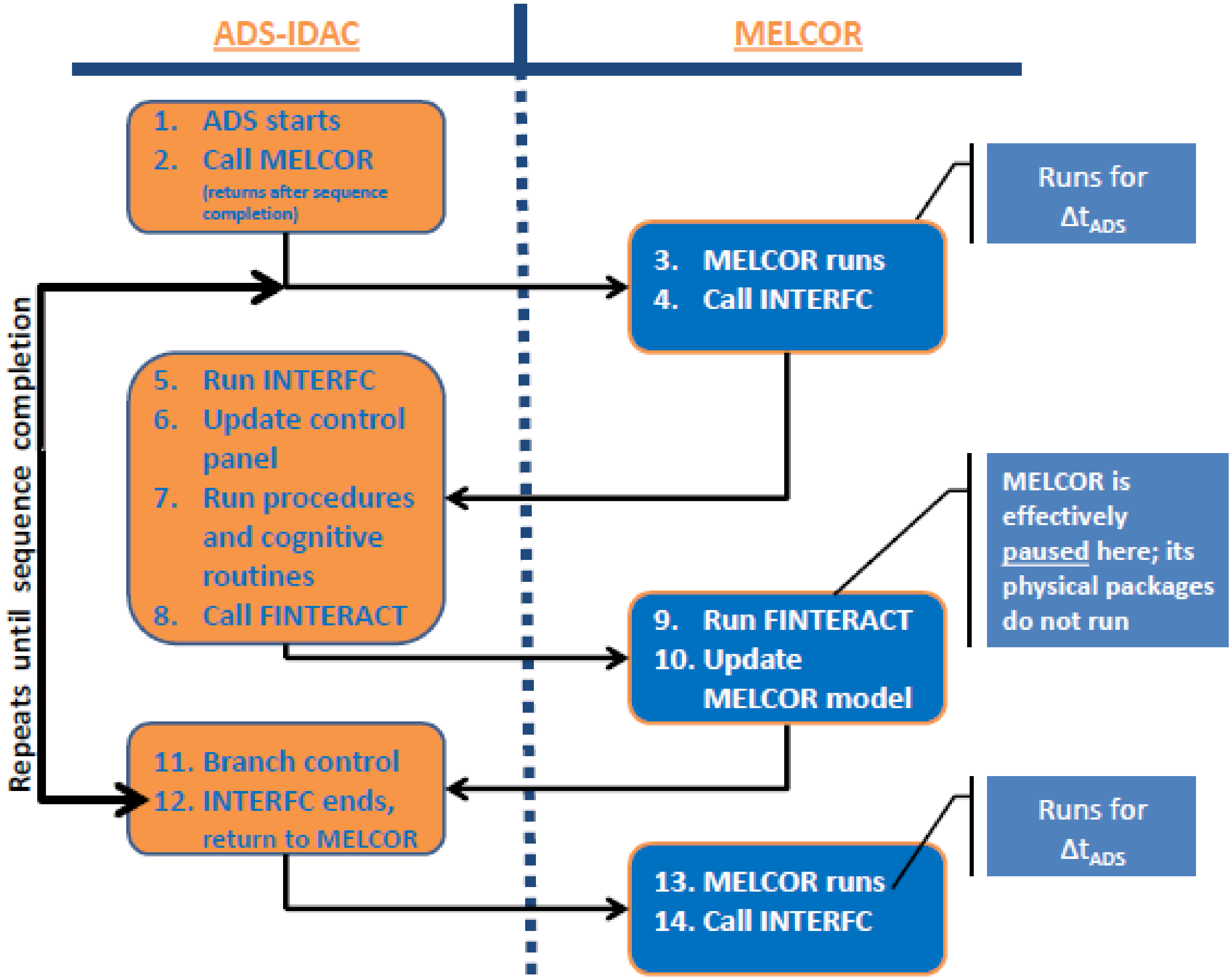
- ADAPT/MELCOR – Simple Cognitive Modeling Only
- ADS/IDAC/MELCOR – Most direct approach to cognitive modeling but difficulties arise when MELCOR crashes
- ADAPT/ADS/IDAC/MELCOR – More stable than ADS/IDAC/MELCOR but computer science challenges remain

Simplest Approach – ADAPT/MELCOR

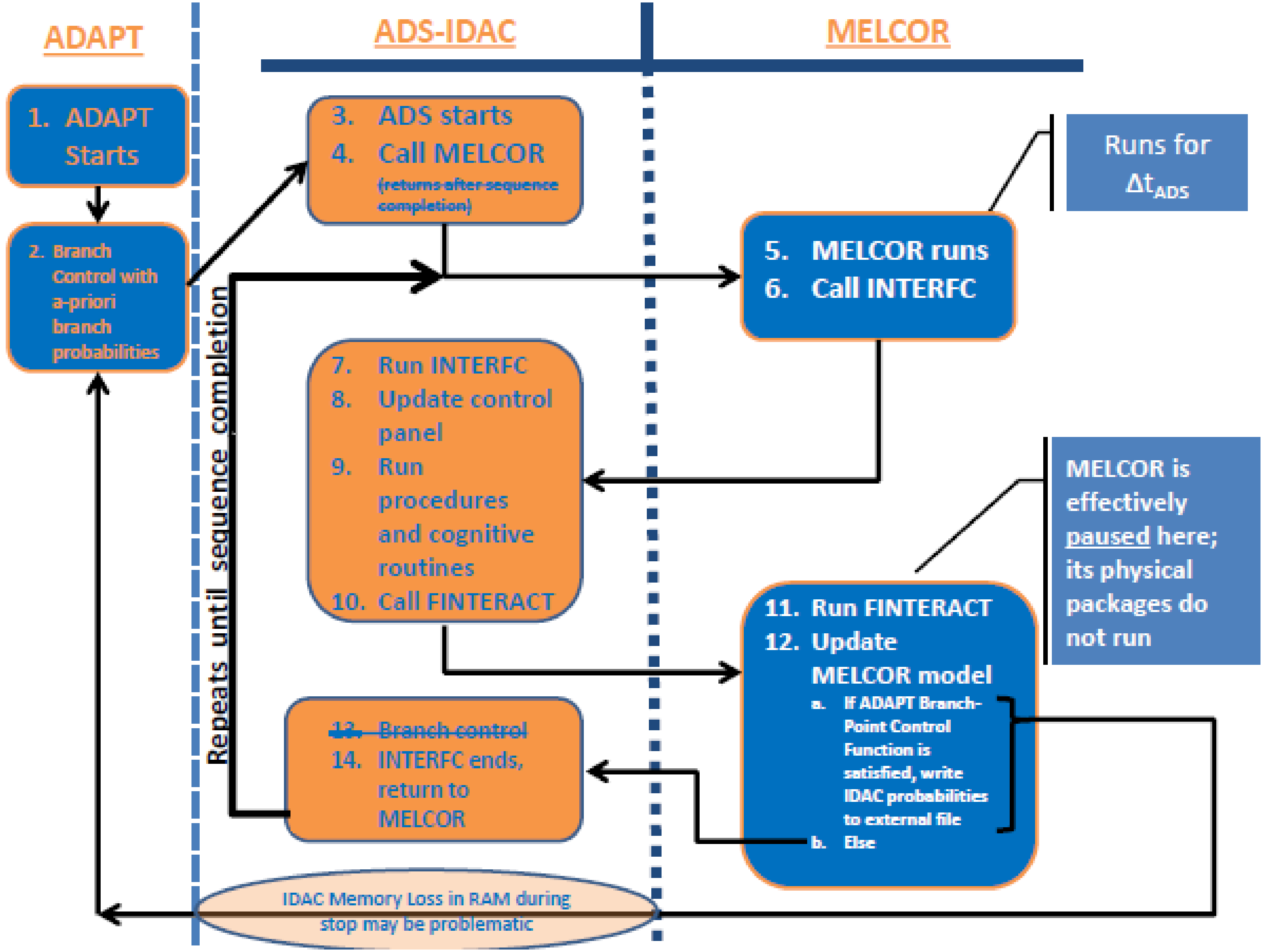
- Simple cognitive modeling can occur through use of MELCOR control functions.



ADS/IDAC/MELCOR



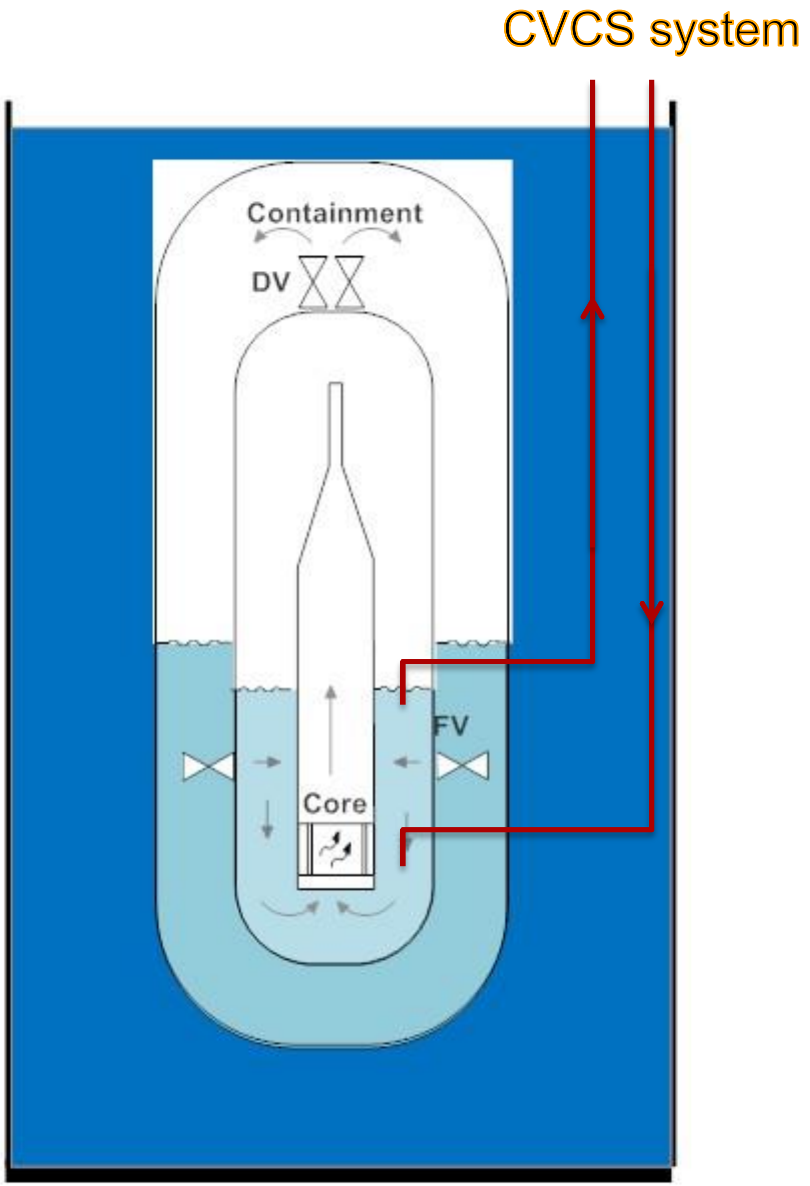
ADAPT/ADS/IDAC/MELCOR



Example Small Modular Reactor System

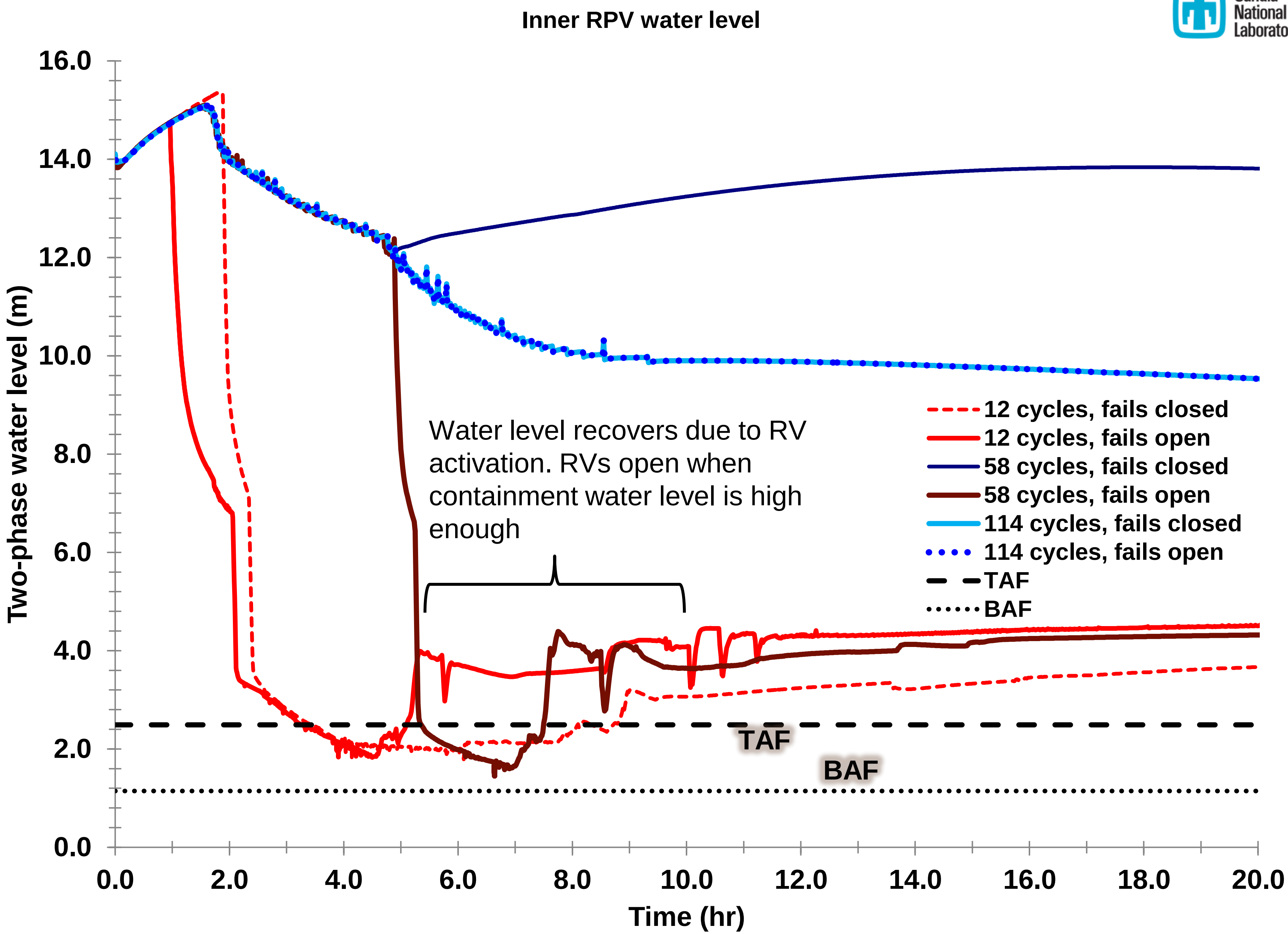
Generic Submerged Reactor

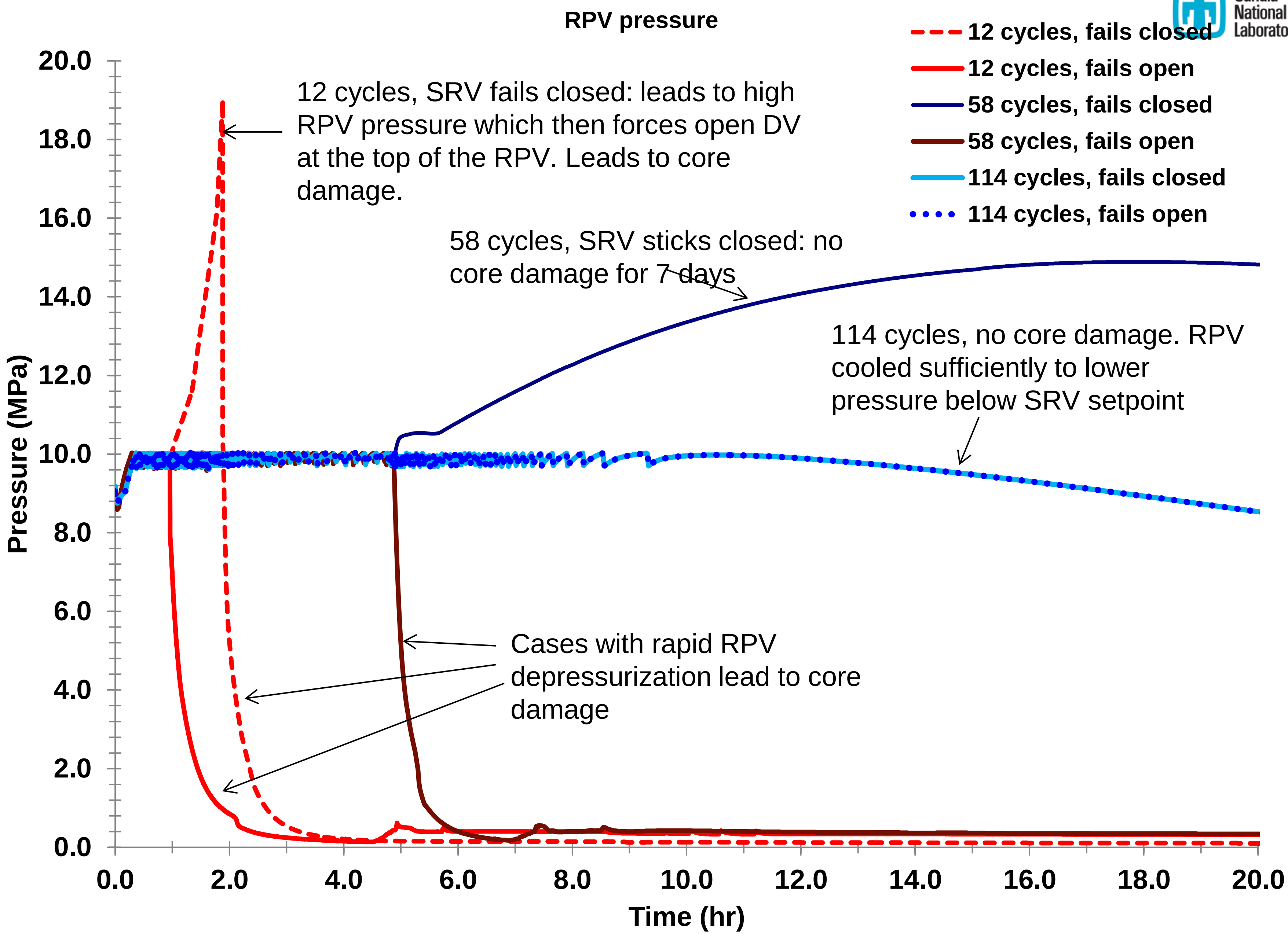
- Emergency Core Cooling System is composed of:
  - Depressurization Valves (DVs)
  - Feed Valves (FVs)
- Operator can use Chemical Volume and Control System (CVCS) system to add water to the system
  - A small LOCA probability is assumed which can allow for containment bypass (unintended consequence).



DV failure plots RVs are available

- Core damage bifurcations:
  1. # of SRV cycles, more cycles precludes core damage. Over 80 always prevents core damage
  2. If # SRVs is only 44-58 cycles, the failure position becomes important. If SRV fails closed (failure to open), then core damage is prevented
  3. Decay power. For low decay power, core damage can always be prevented *if the SRV always fails closed*, no matter the number of cycles if >=12 SRV cycles


Inner RPV water level
Two-phase water level (m)
Time (hr)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Water level recovers due to RV activation. RVs open when containment water level is high enough
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails closed
58 cycles, fails open
114 cycles, fails closed
114 cycles, fails open
TAF
BAF
TAF
BAF



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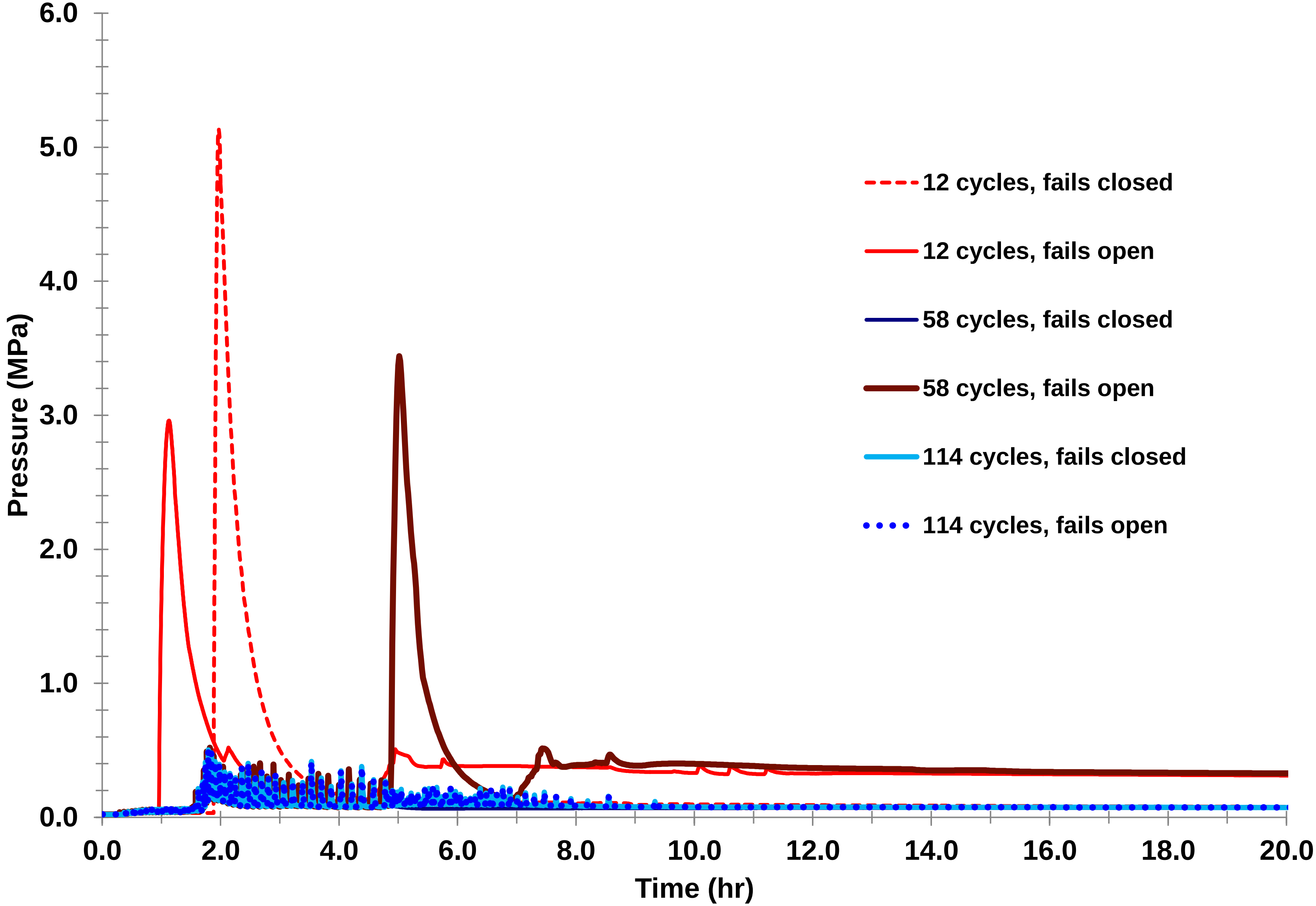
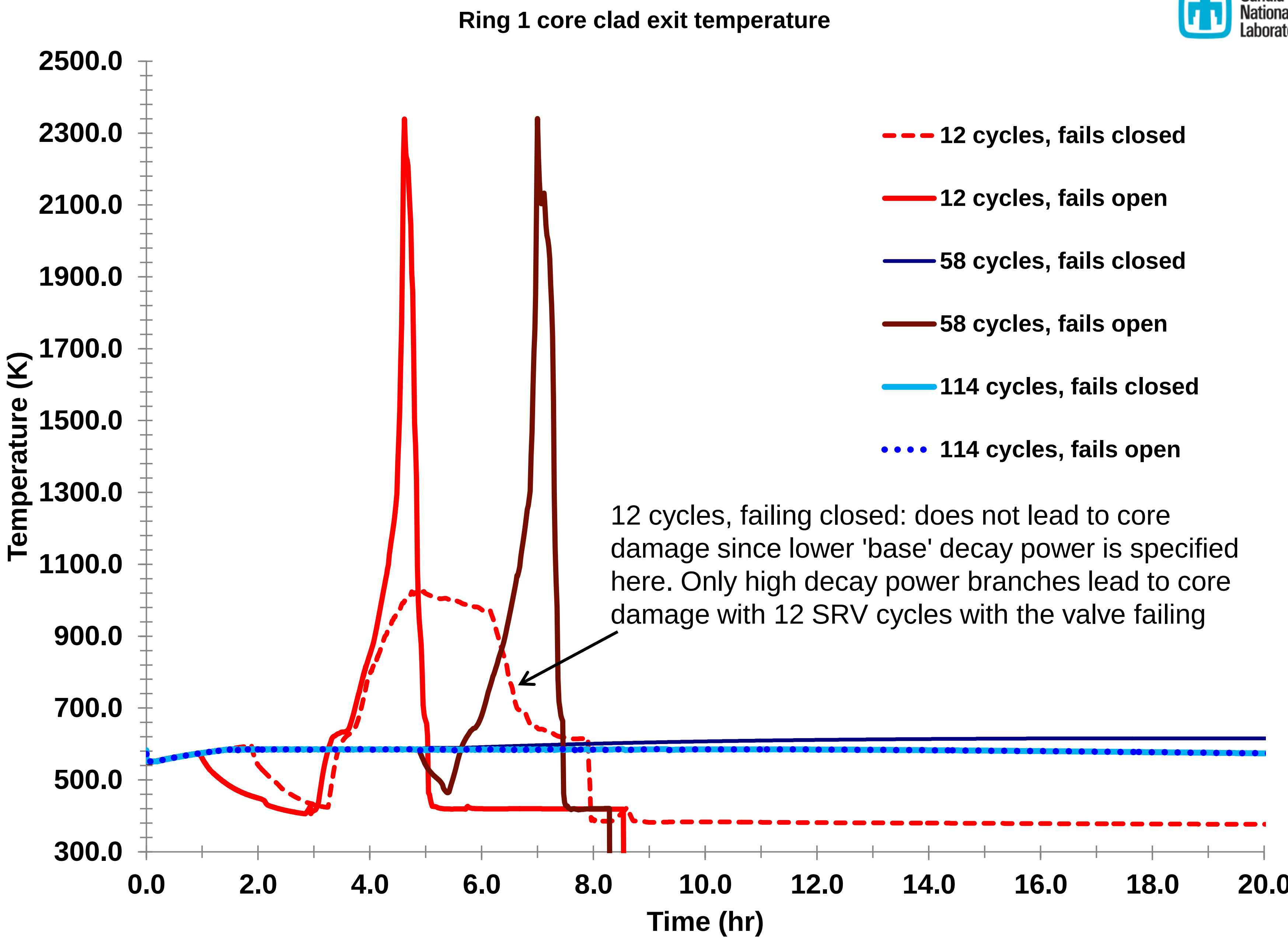
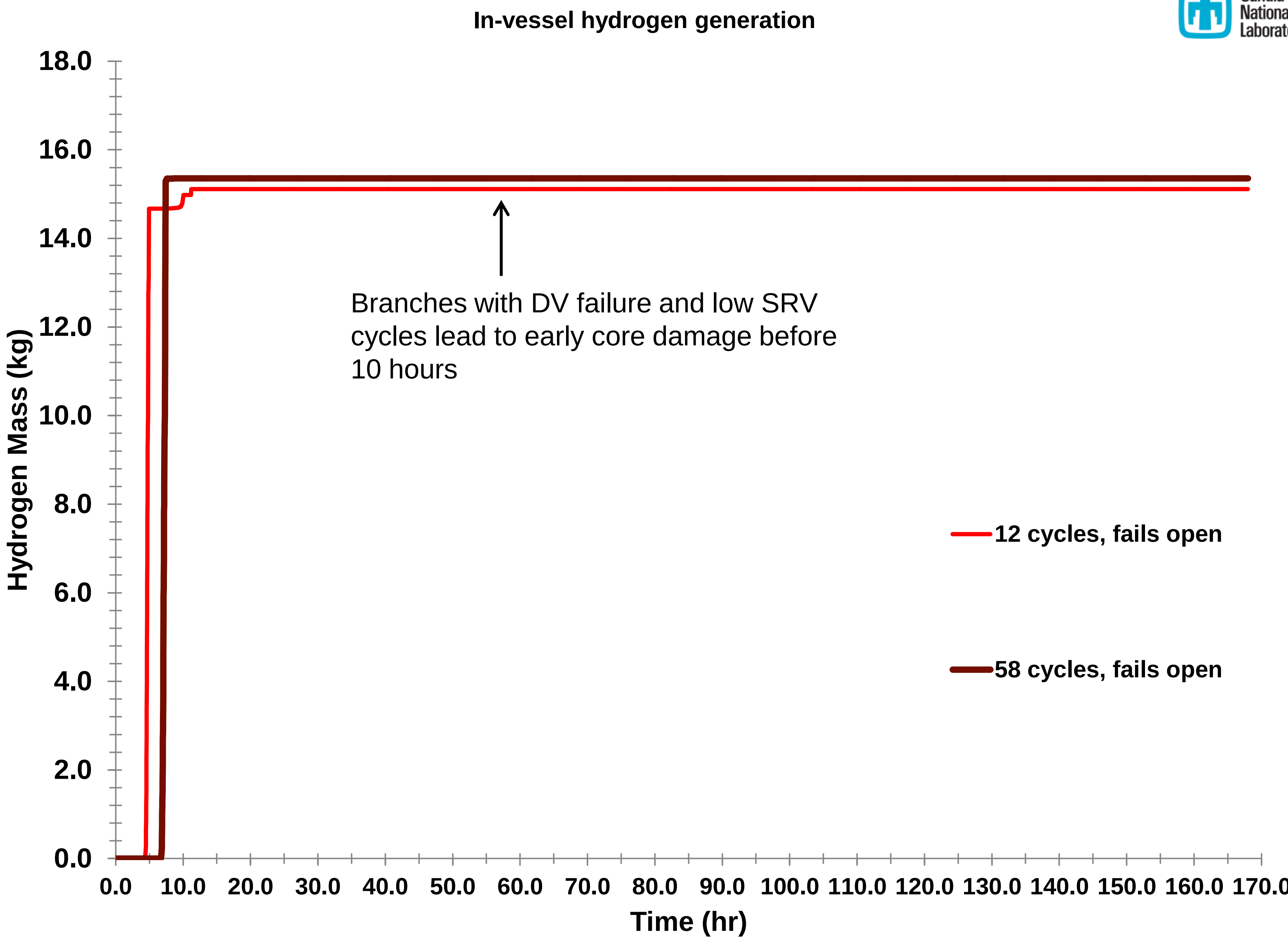
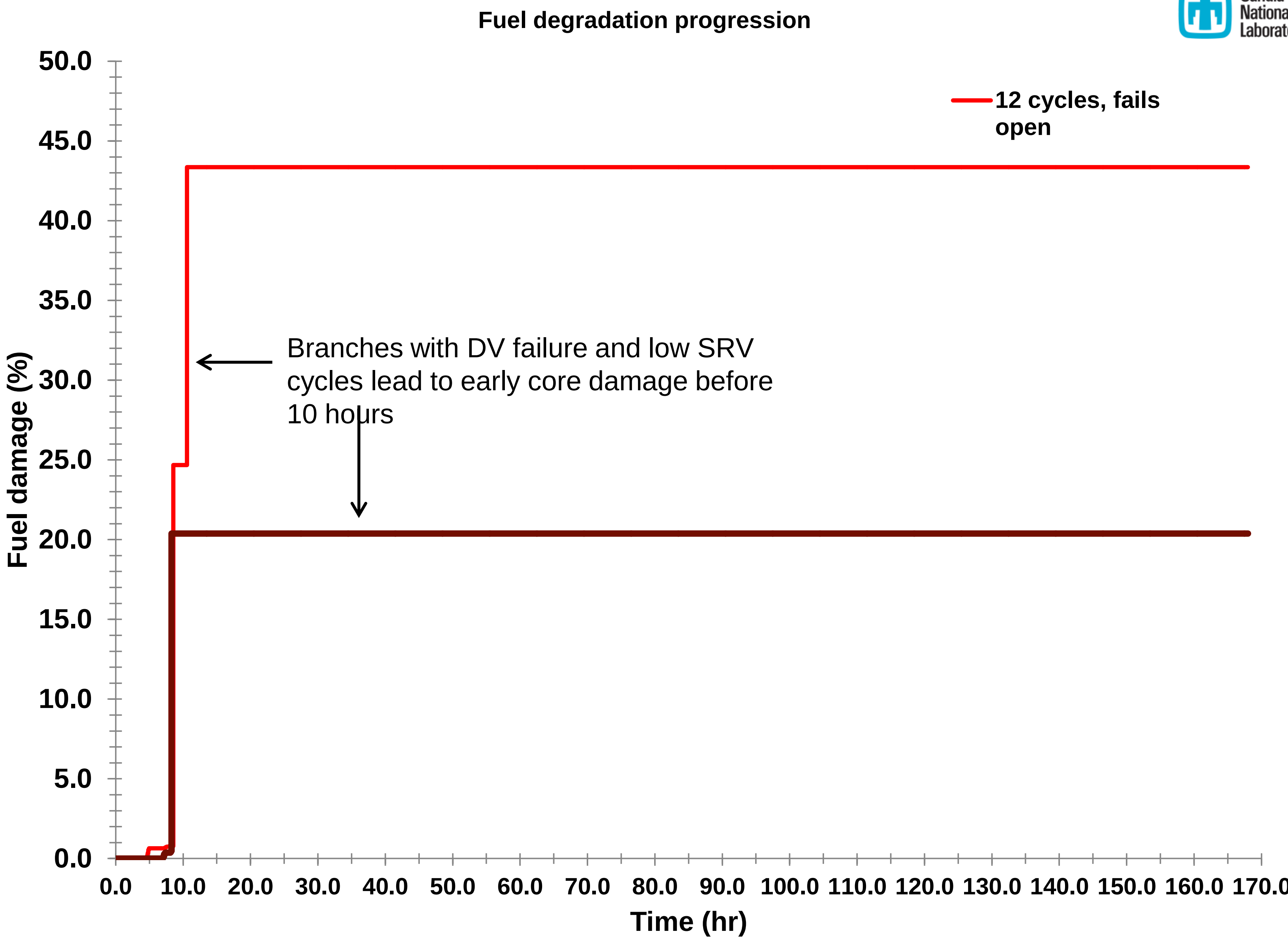
Containment pressure



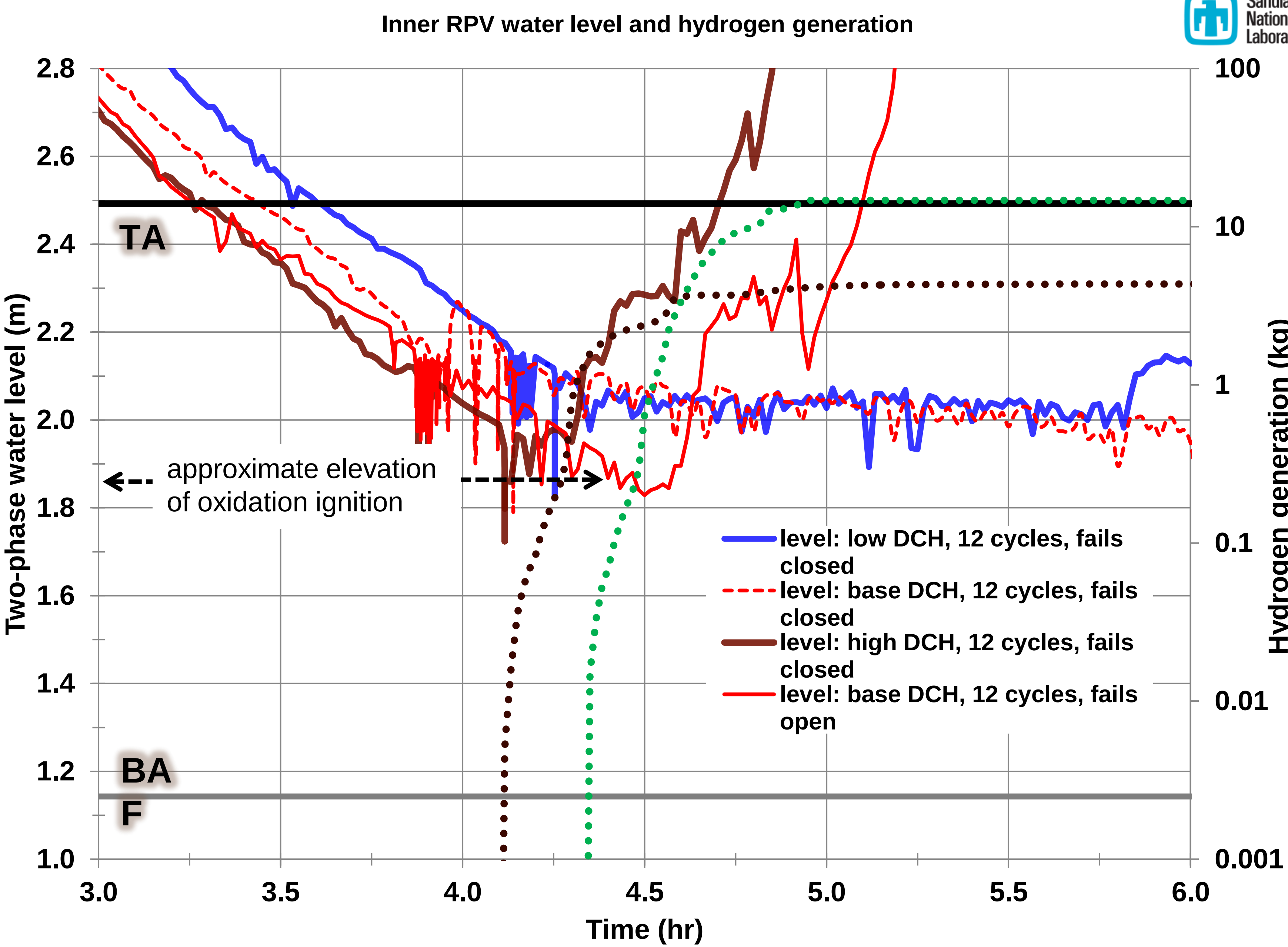

Ring 1 core clad exit temperature
2500.0
2300.0
2100.0
1900.0
1700.0
1500.0
1300.0
1100.0
900.0
700.0
500.0
300.0
Temperature (K)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Time (hr)
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails closed
58 cycles, fails open
114 cycles, fails closed
114 cycles, fails open
12 cycles, failing closed: does not lead to core damage since lower 'base' decay power is specified here. Only high decay power branches lead to core damage with 12 SRV cycles with the valve failing



In-vessel hydrogen generation
Hydrogen Mass (kg)
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
Time (hr)
Branches with DV failure and low SRV cycles lead to early core damage before 10 hours
12 cycles, fails open
58 cycles, fails open

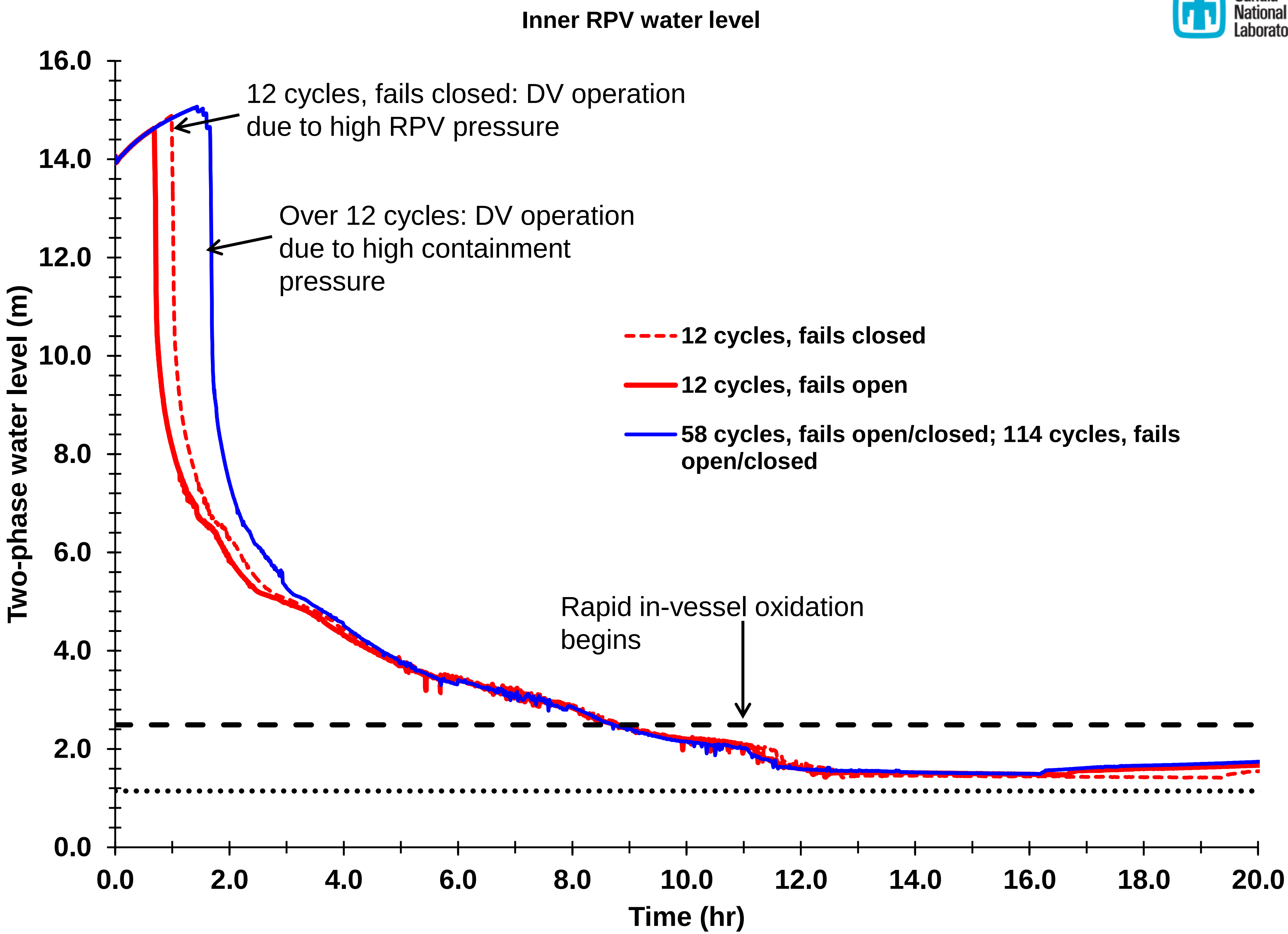


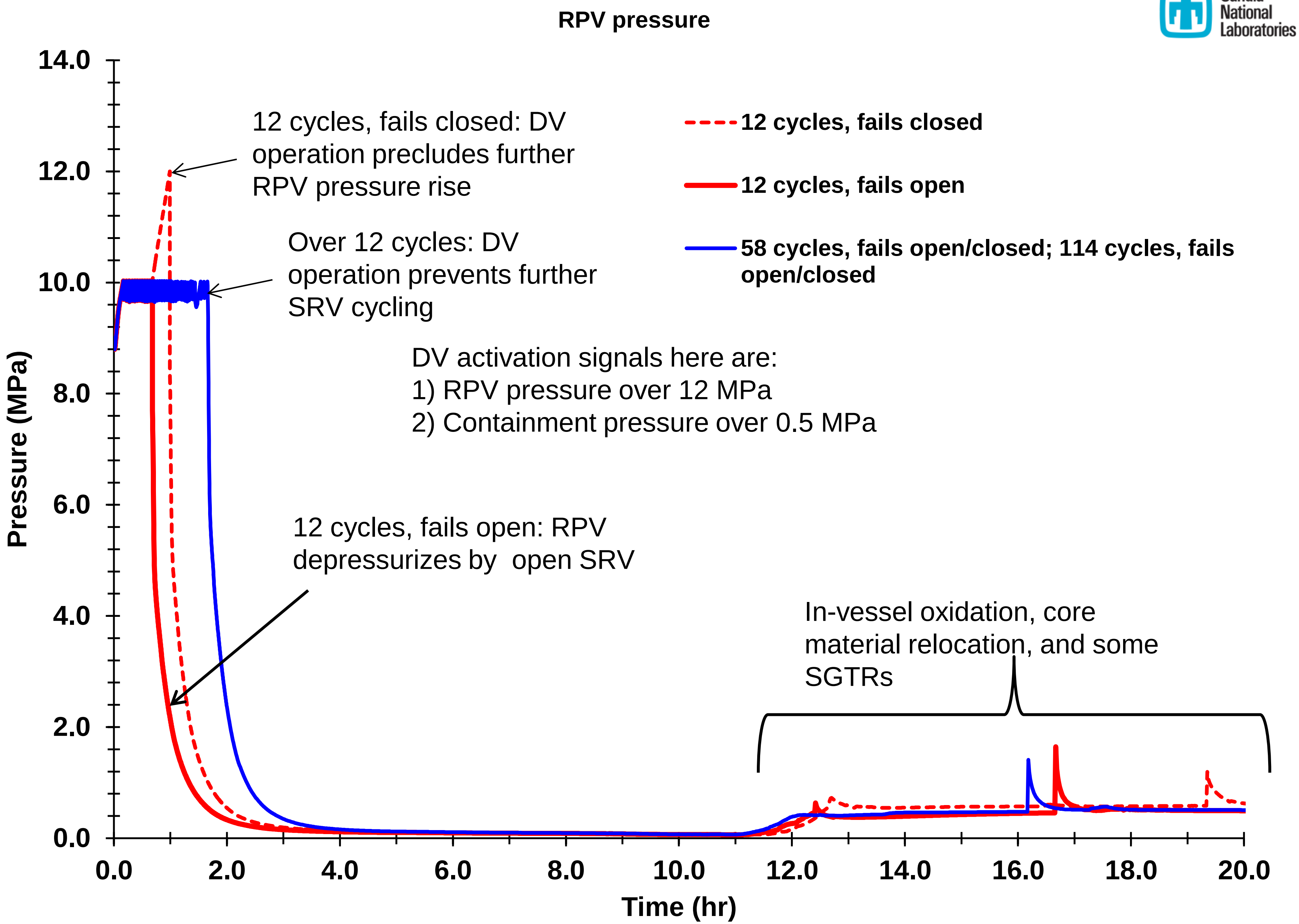
Fuel degradation progression
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Fuel damage (%)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
Time (hr)
12 cycles, fails open
Branches with DV failure and low SRV cycles lead to early core damage before 10 hours

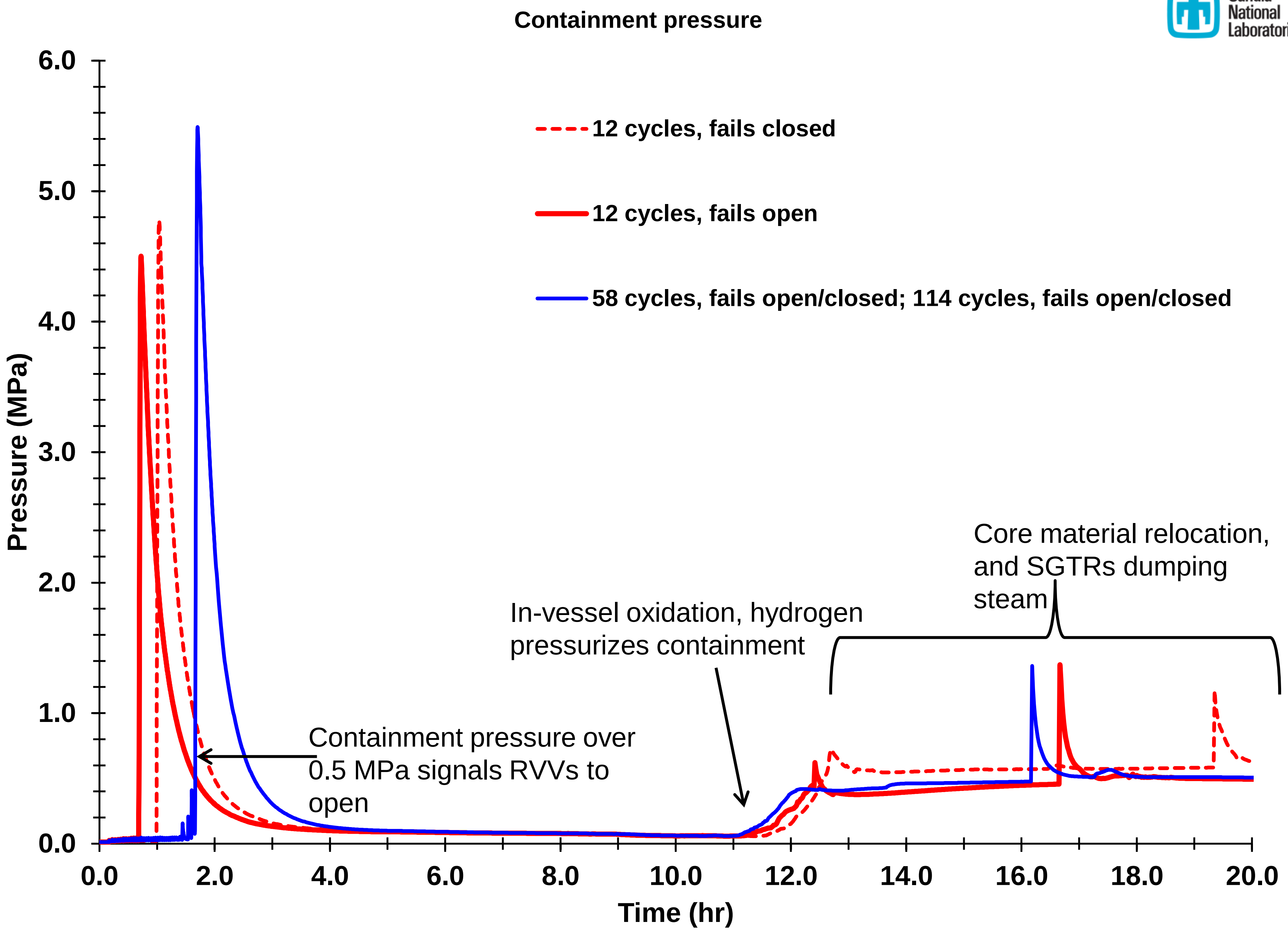

Inner RPV water level and hydrogen generation
Two-phase water level (m)
Hydrogen generation (kg)
Time (hr)
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
100
10
1
0.1
0.01
0.001
3.0
3.5
4.0
4.5
5.0
5.5
6.0
TA
BA
F
approximate elevation of oxidation ignition
level: low DCH, 12 cycles, fails closed
level: base DCH, 12 cycles, fails closed
level: high DCH, 12 cycles, fails closed
level: base DCH, 12 cycles, fails open

RV failure plots
DVs are available

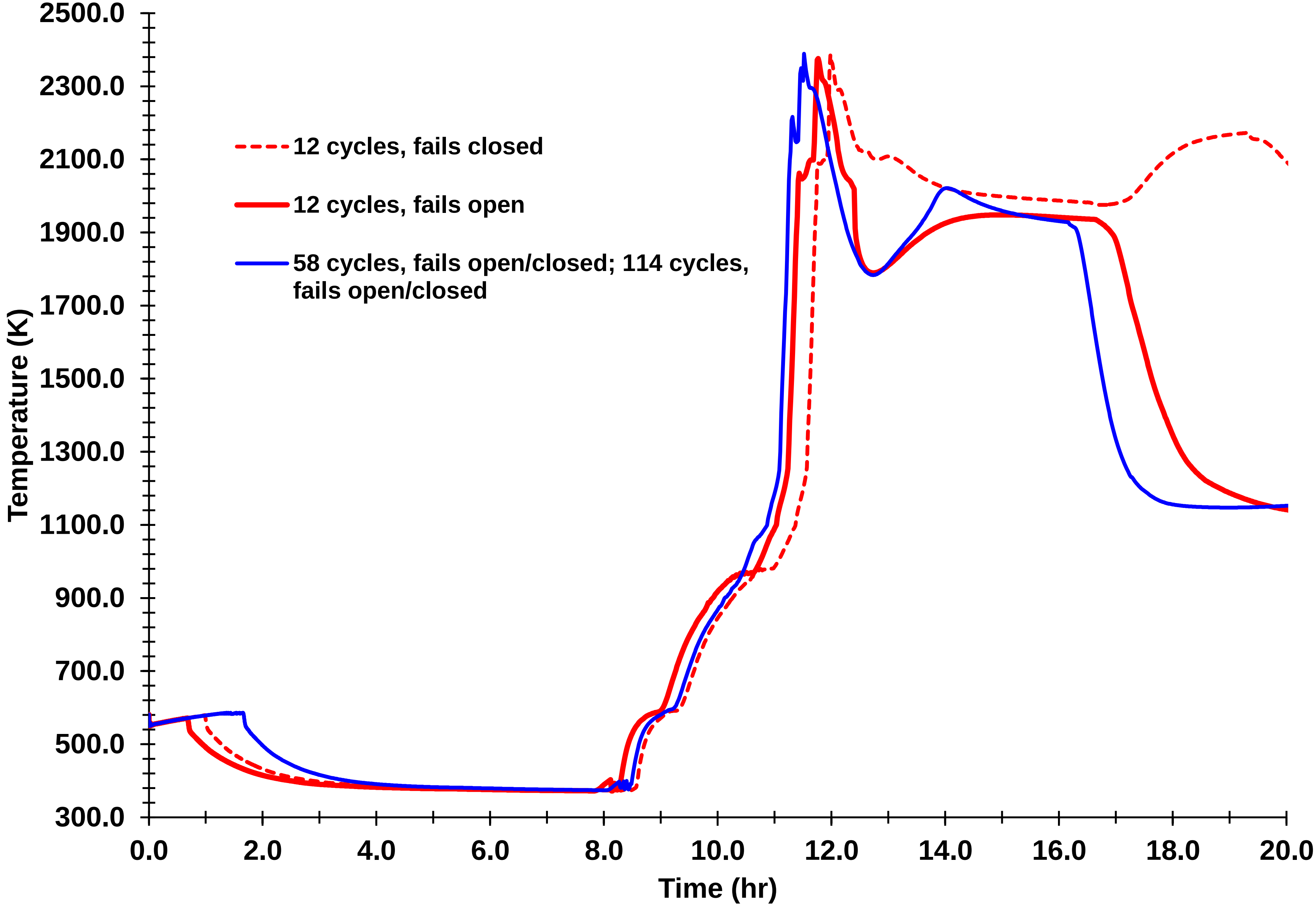
- Core damage bifurcations:
  - Spread, but no significant bifurcations

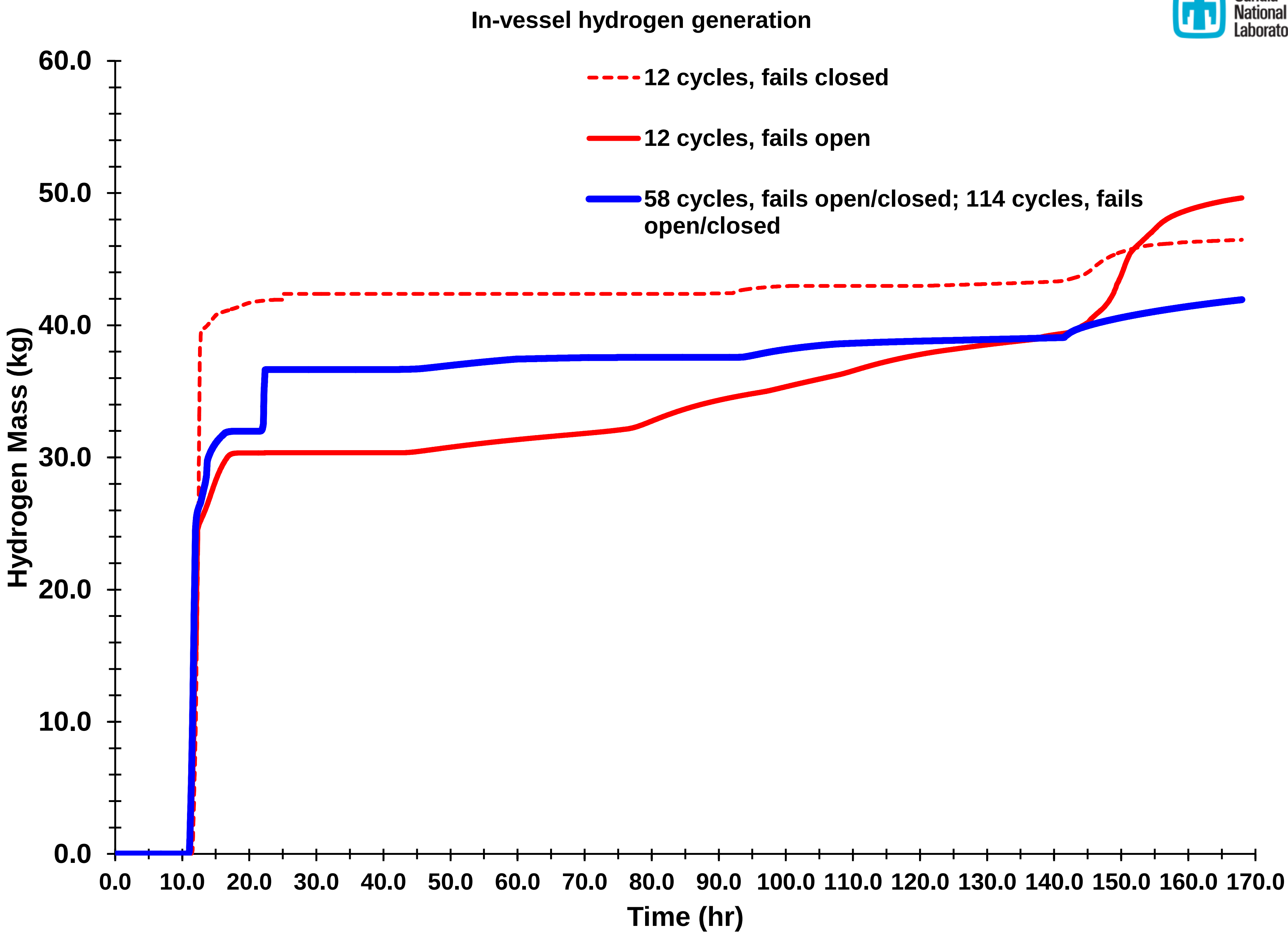

Inner RPV water level
12 cycles, fails closed: DV operation due to high RPV pressure
Over 12 cycles: DV operation due to high containment pressure
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails open/closed; 114 cycles, fails open/closed
Rapid in-vessel oxidation begins
Two-phase water level (m)
Time (hr)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0

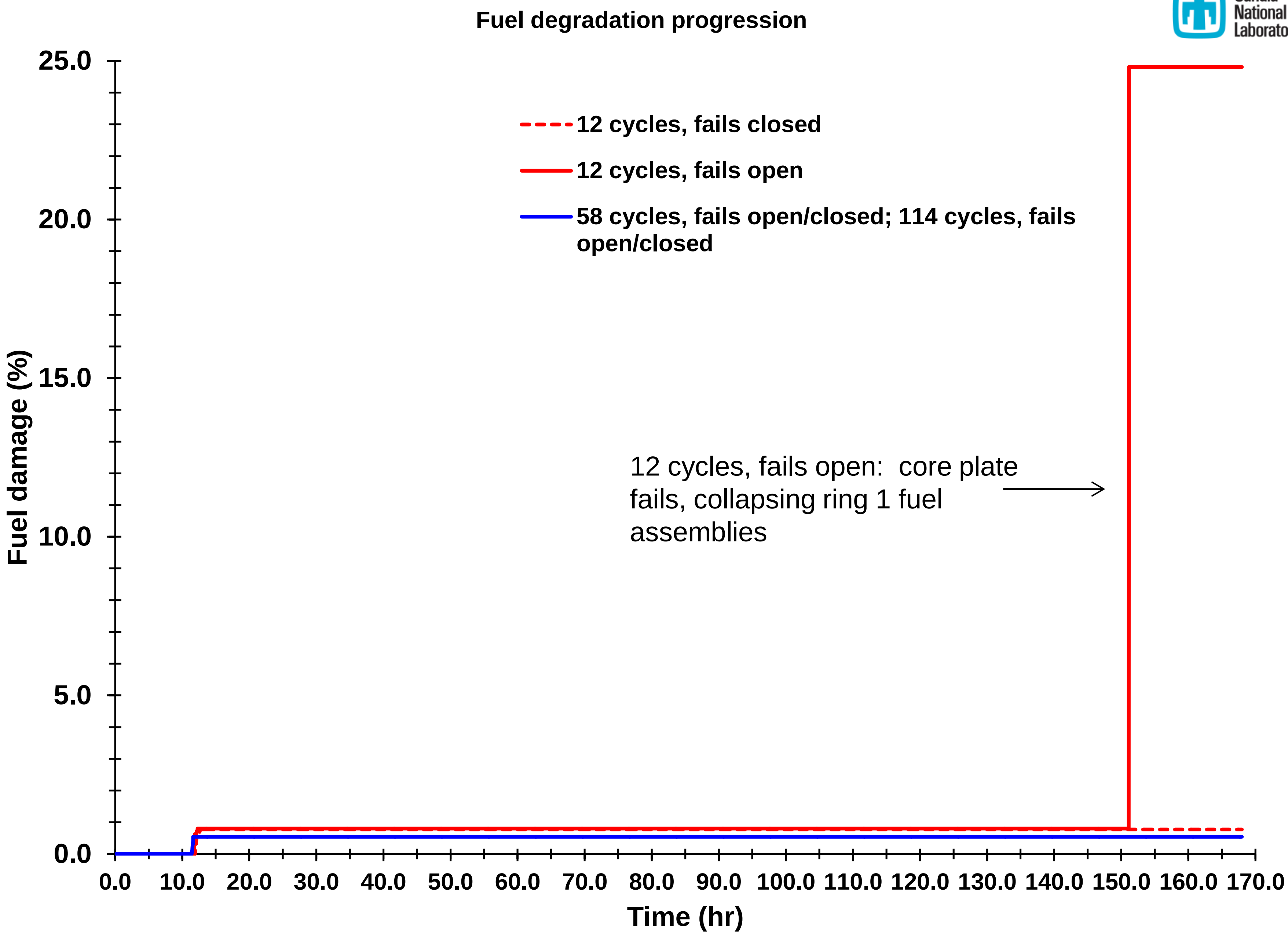

RPV pressure
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Pressure (MPa)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
Time (hr)
12 cycles, fails closed: DV operation precludes further RPV pressure rise
Over 12 cycles: DV operation prevents further SRV cycling
DV activation signals here are:
1) RPV pressure over 12 MPa
2) Containment pressure over 0.5 MPa
12 cycles, fails open: RPV depressurizes by open SRV
In-vessel oxidation, core material relocation, and some SGTRs
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails open/closed; 114 cycles, fails open/closed


Containment pressure
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails open/closed; 114 cycles, fails open/closed
Core material relocation, and SGTRs dumping steam
In-vessel oxidation, hydrogen pressurizes containment
Containment pressure over 0.5 MPa signals RVVs to open
Pressure (MPa)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Time (hr)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0

Ring 1 core clad exit temperature




In-vessel hydrogen generation
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails open/closed; 114 cycles, fails open/closed
Hydrogen Mass (kg)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
Time (hr)

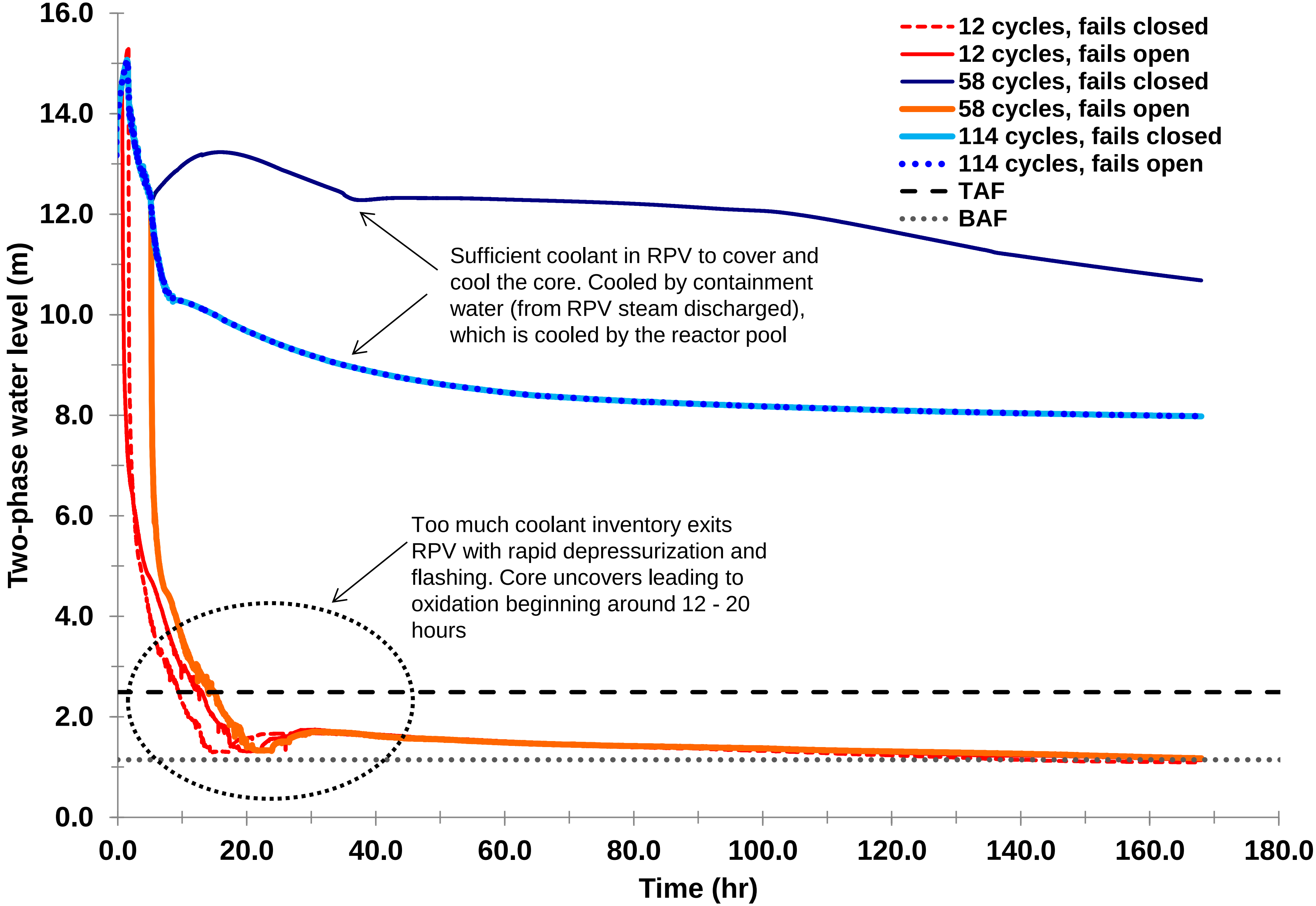


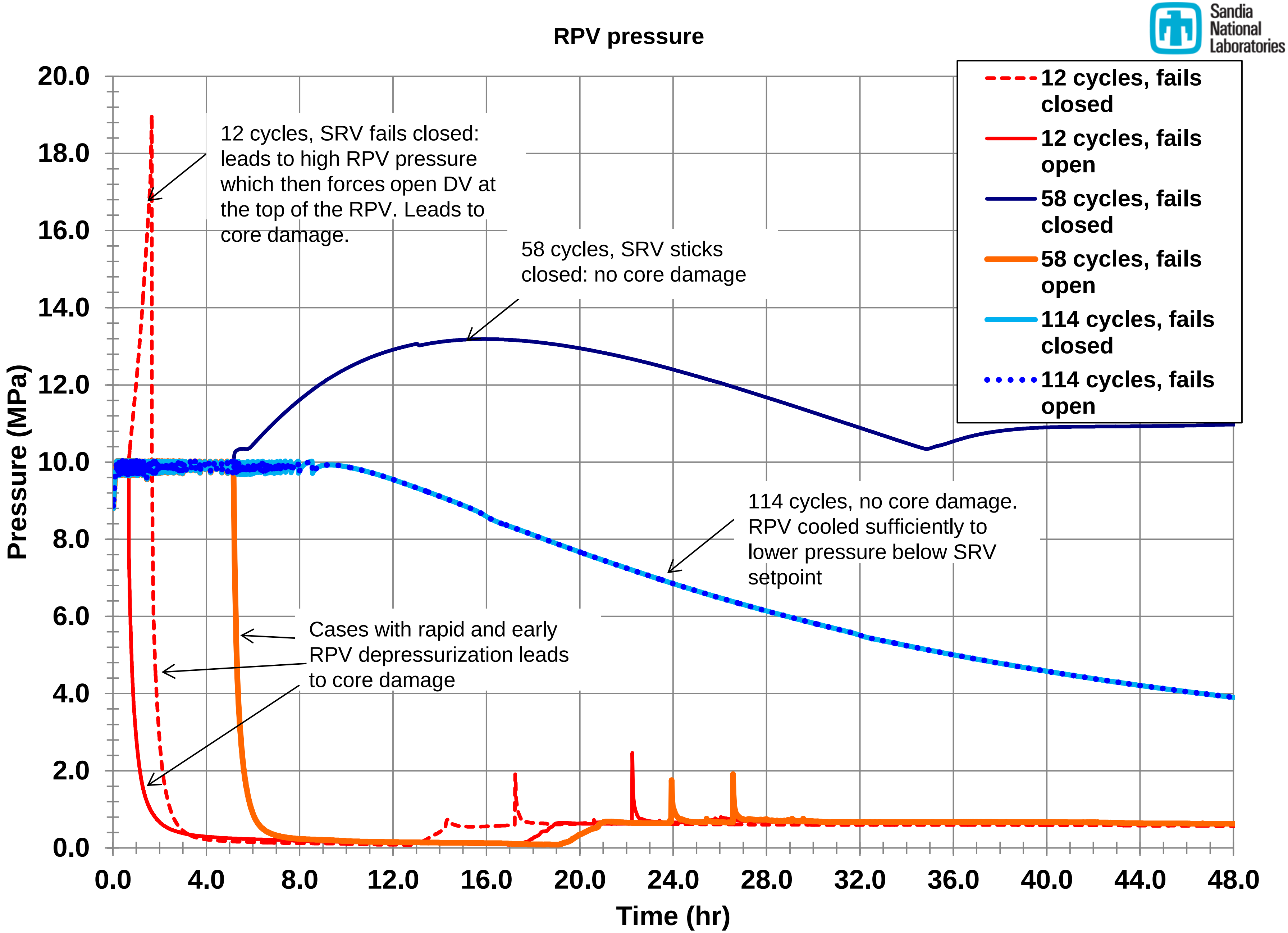
Fuel degradation progression
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails open/closed; 114 cycles, fails open/closed
12 cycles, fails open: core plate fails, collapsing ring 1 fuel assemblies
Fuel damage (%)
25.0
20.0
15.0
10.0
5.0
0.0
0.0 10.0 20.0 30.0 40.0 50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0
Time (hr)

ECCS failure plots

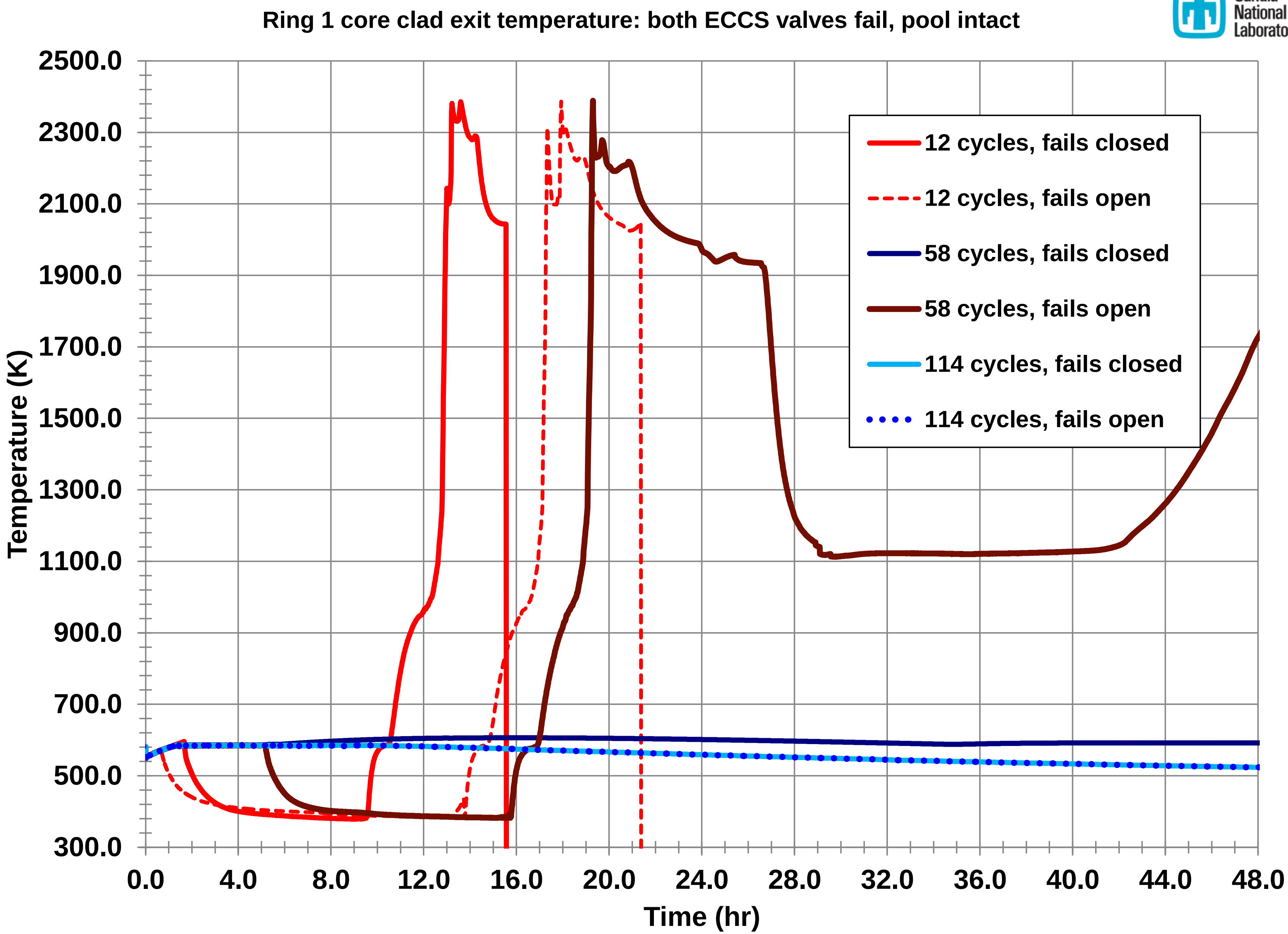
- Core damage bifurcations: very similar to DV failure case

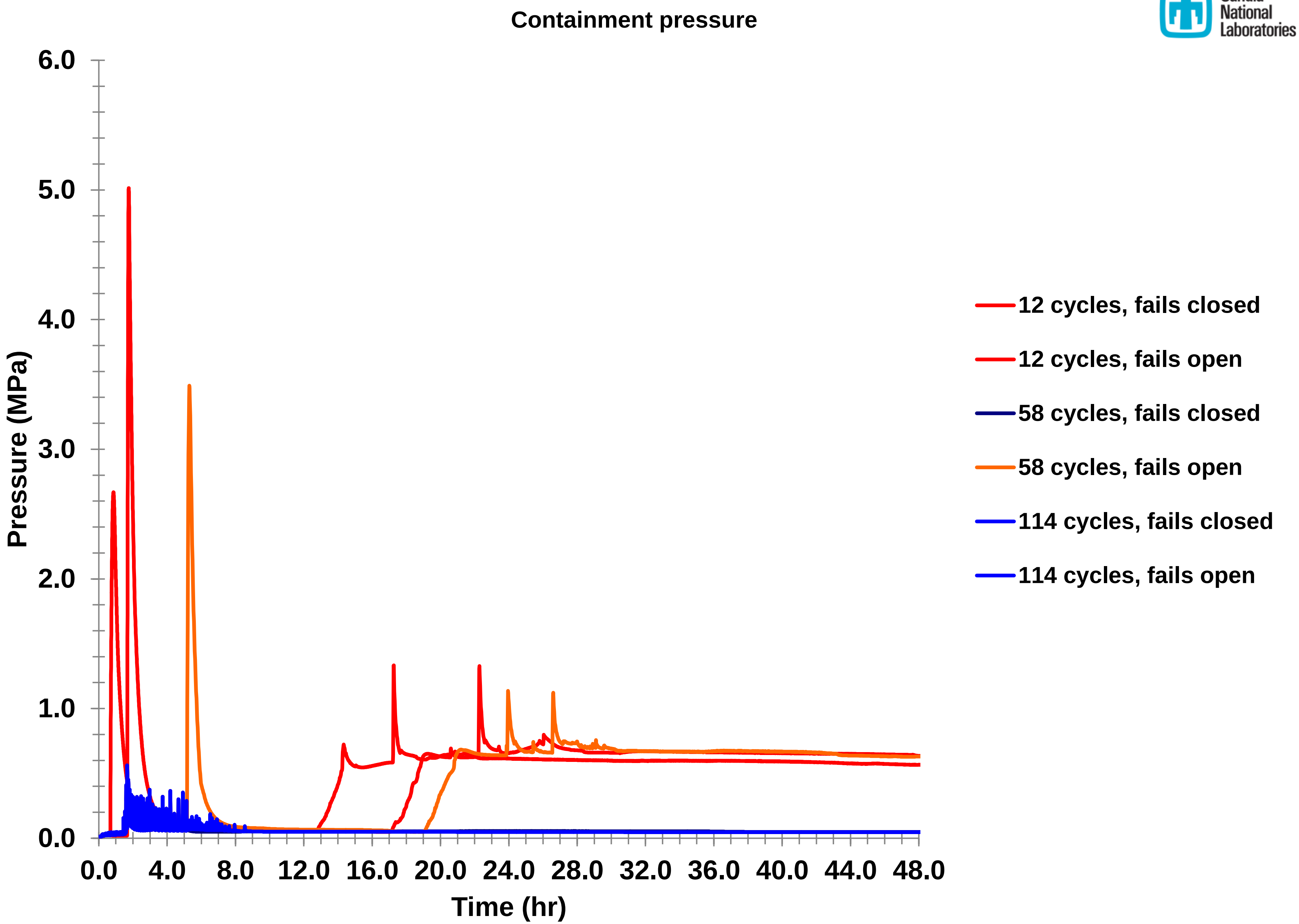
Inner RPV water level: ECCS fails (both valves), reactor pool intact. Effect of RPV SRV cycling



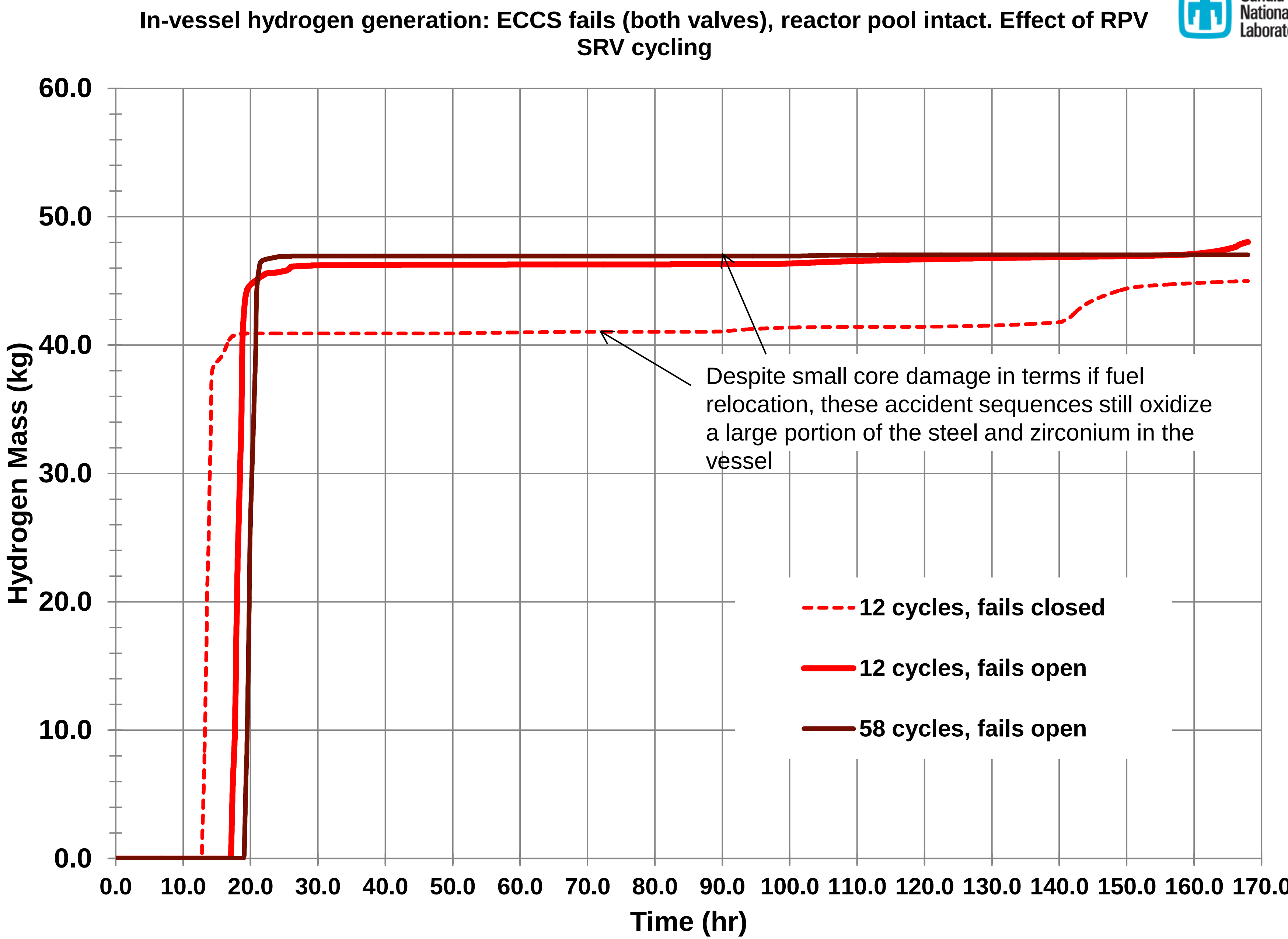


RPV pressure
Sandia National Laboratories
Pressure (MPa)
Time (hr)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
44.0
48.0
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails closed
58 cycles, fails open
114 cycles, fails closed
114 cycles, fails open
12 cycles, SRV fails closed: leads to high RPV pressure which then forces open DV at the top of the RPV. Leads to core damage.
58 cycles, SRV sticks closed: no core damage
114 cycles, no core damage. RPV cooled sufficiently to lower pressure below SRV setpoint
Cases with rapid and early RPV depressurization leads to core damage


Ring 1 core clad exit temperature: both ECCS valves fail, pool intact
2500.0
2300.0
2100.0
1900.0
1700.0
1500.0
1300.0
1100.0
900.0
700.0
500.0
300.0
Temperature (K)
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
44.0
48.0
Time (hr)
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails closed
58 cycles, fails open
114 cycles, fails closed
114 cycles, fails open

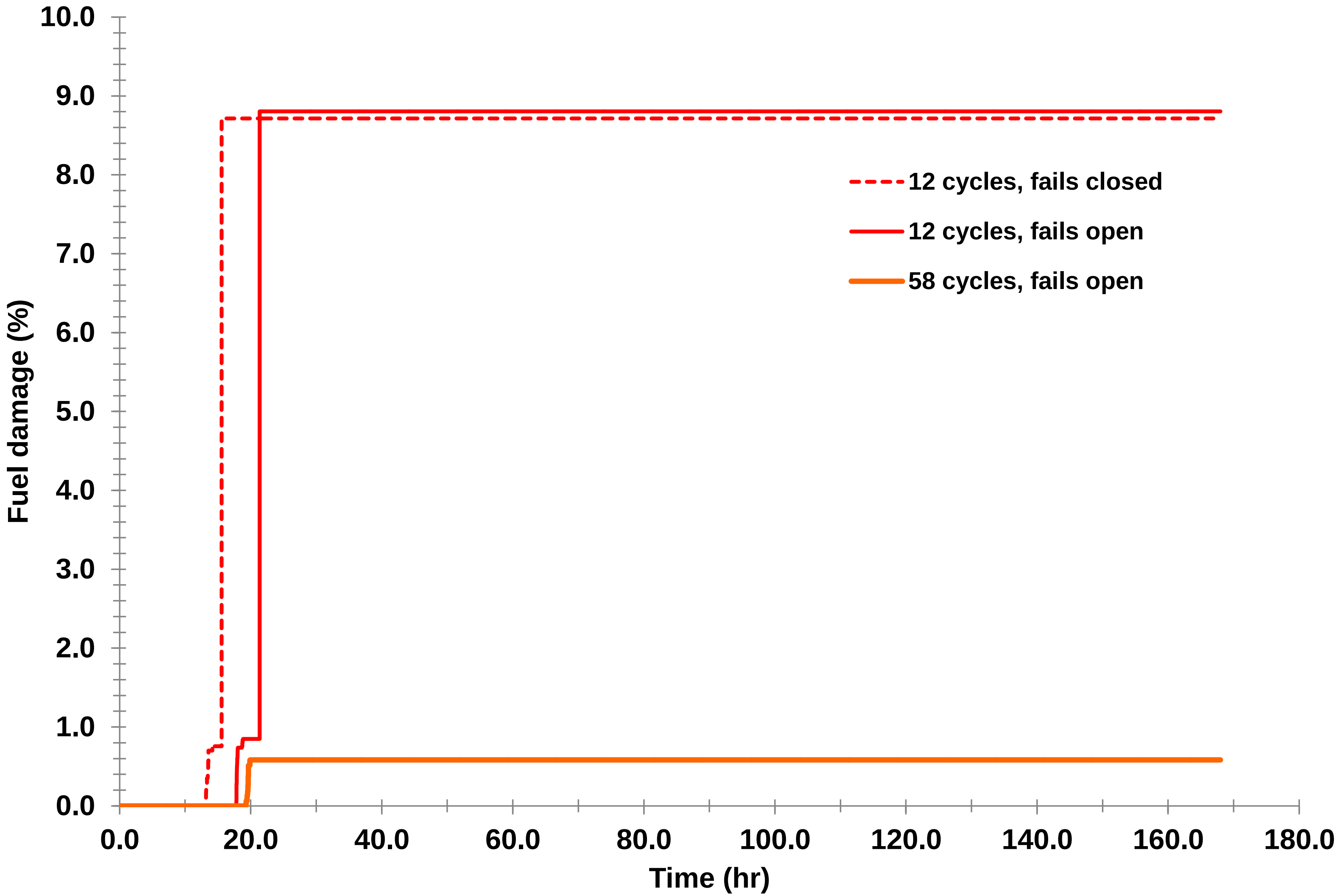


Containment pressure
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Pressure (MPa)
0.0
4.0
8.0
12.0
16.0
20.0
24.0
28.0
32.0
36.0
40.0
44.0
48.0
Time (hr)
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails closed
58 cycles, fails open
114 cycles, fails closed
114 cycles, fails open

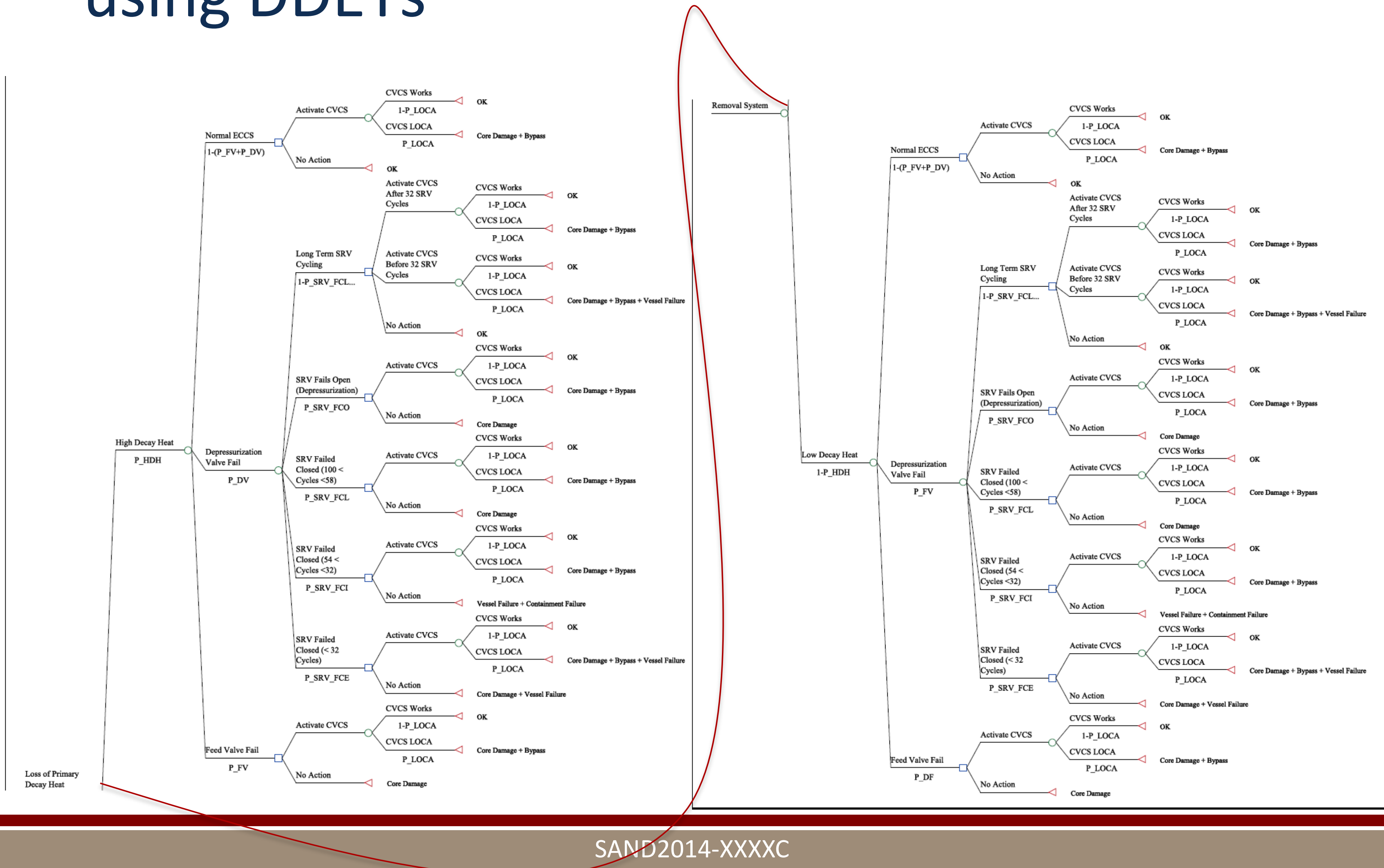


In-vessel hydrogen generation: ECCS fails (both valves), reactor pool intact. Effect of RPV SRV cycling
Hydrogen Mass (kg)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
Time (hr)
Despite small core damage in terms if fuel relocation, these accident sequences still oxidize a large portion of the steel and zirconium in the vessel
12 cycles, fails closed
12 cycles, fails open
58 cycles, fails open

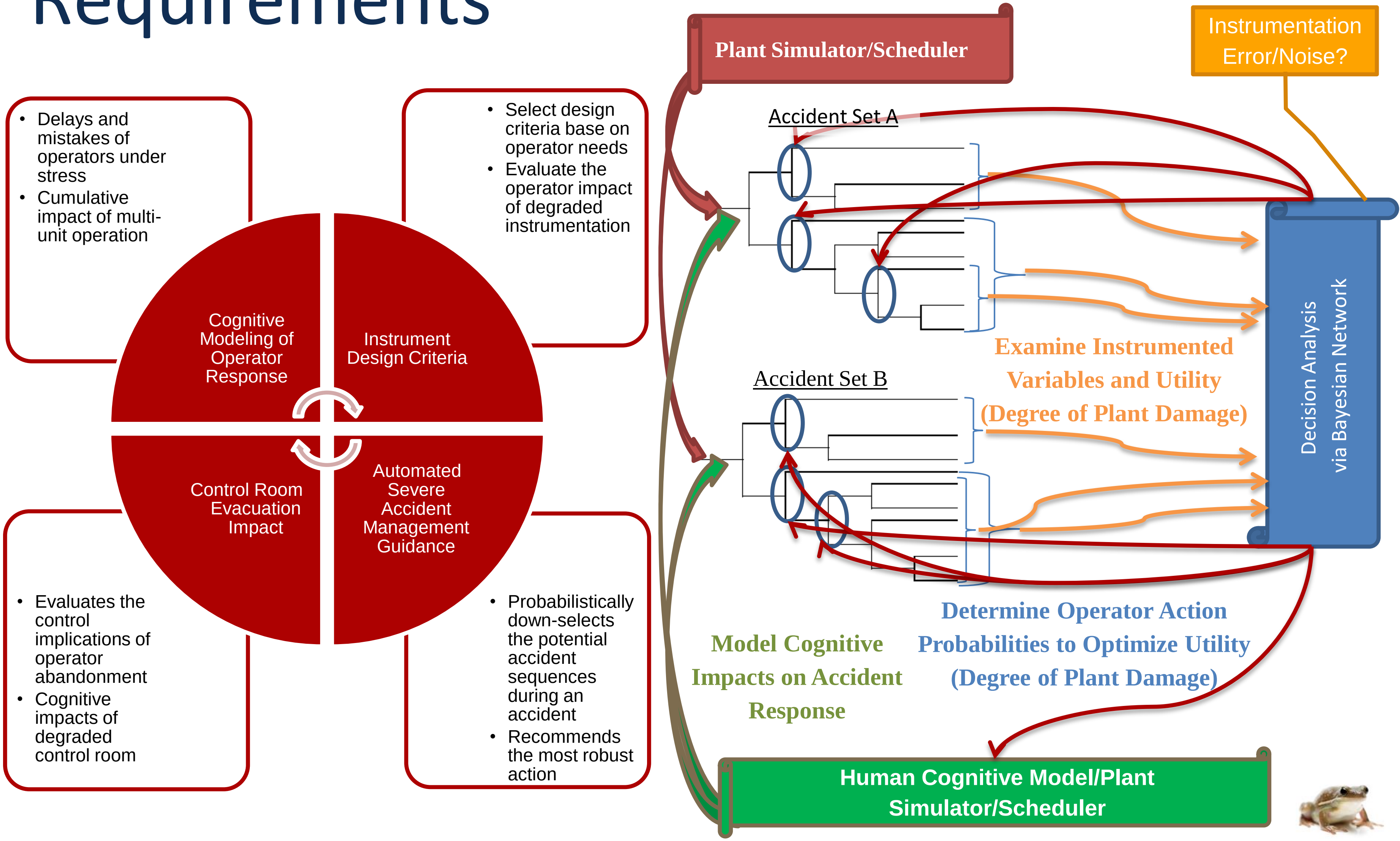
Fuel degradation progression: ECCS fails (both valves), reactor pool intact. Effect of RPV SRV cycling



Simplified Results of a Decision Problem using DDETs



The Future - Evaluating Staffing Requirements



Conclusions

- DDETs show great promise when solving risk problem with dynamic uncertainties
  - Relatively easy to treat the results in either uncertainty or sensitivity space
  - Allows for a structured approach to accident management
  - Explores late stage uncertainties better than traditional techniques
- Not all problems need DDETs
  - Short running problems
  - Intervention is not required
  - Only bounding answers are needed
- DDETs still have many challenges:
  - Post-processing the results
  - Large computational resources