PBMR Response to Events

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Presentation Objectives

- **Describe possible scenarios in response to selected initiating events**
  - PCU transient with no reactivity addition and intact HPB
  - Group rod withdrawal reactivity excursion
  - PCU heat exchanger leak
  - Medium (230mm) unisolable break in HPB
- **Describe plant response in terms of**
  - Event sequence diagrams
  - Simplified event trees
  - Plant transient response
  - Source terms and radiological consequences, if any

PCU Transients with No Reactivity Addition

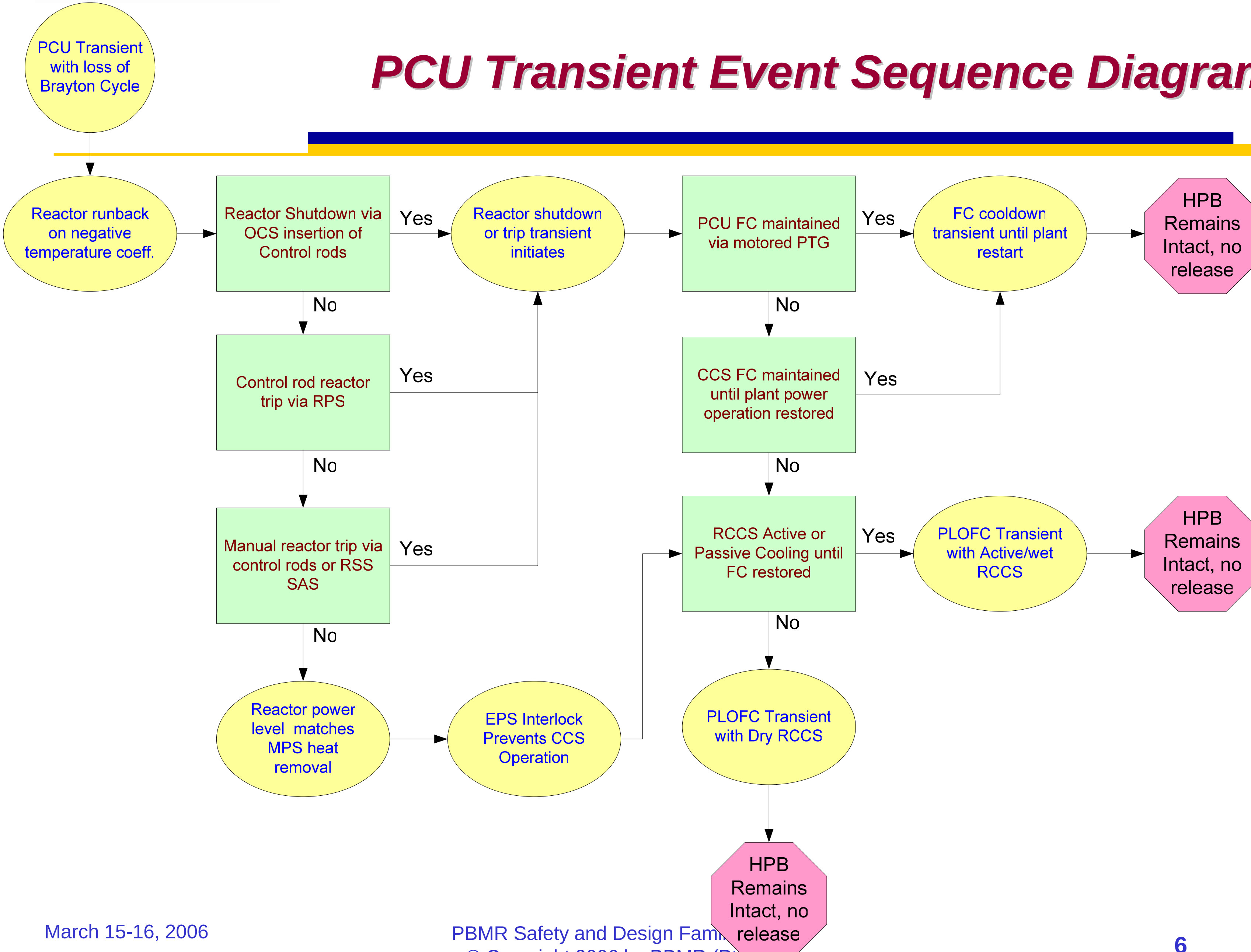
Example Initiating Events for PCU Transients

Initiating Event	Plant Impact
PTG Trip	Challenge to EPS and RPS reactor trip functions
Reactor Trip	Challenge to EPS PTG trip function; reactor trips by definition
Loss of ACS cooling to PCU heat exchangers	Challenge to trip functions; PCU unavailable as heat removal path
Loss of offsite power	Challenge to trip functions; PCU unavailable for heat removal, reactor trips on loss of power to RPS scram breakers
Station Blackout	Challenge to trip functions; PCU, CCS, and RCCS active cooling initially unavailable

Nominal Operating Temperatures

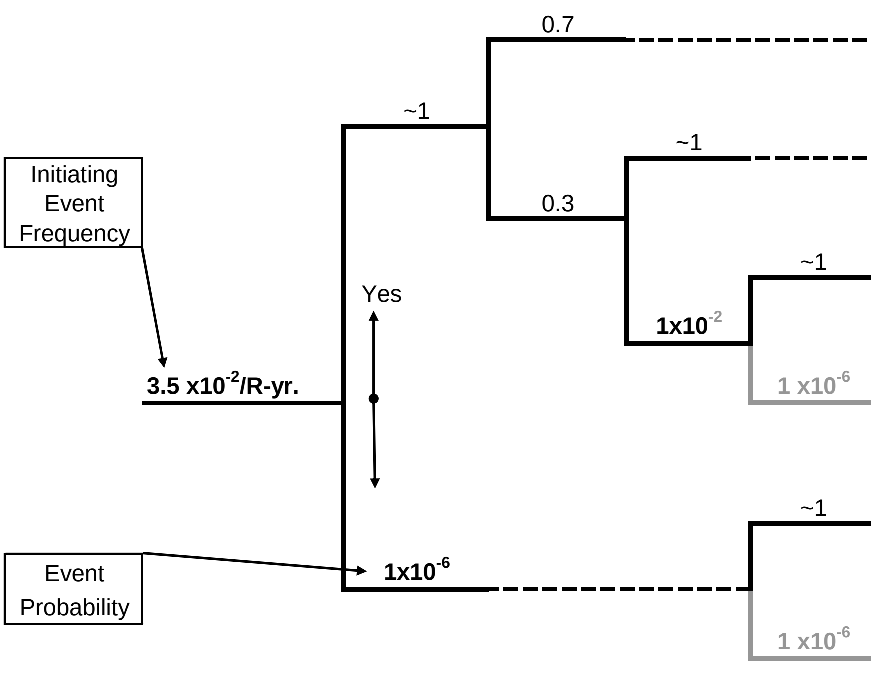
SSC	Material	Max Nominal Temperature [°C]
Pebble Fuel	Ceramic	1082
Core Barrel	SS 316	394
RPV	Carbon steel 508/533	268

PCU Transient Event Sequence Diagram



PCU Transient Event Tree

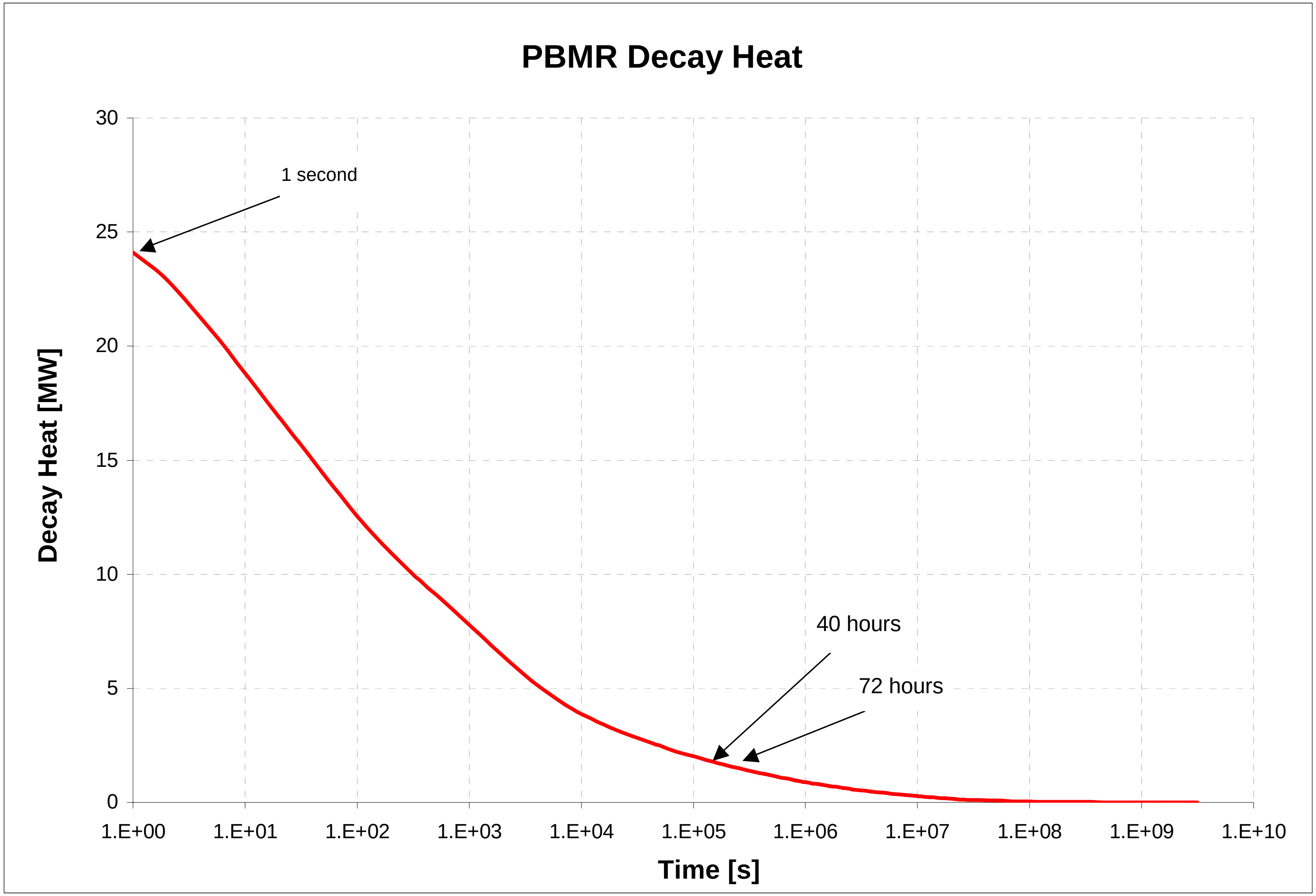
Initiating Event	Response to Initiating Event				Sequence No.	Event Sequence Frequency (/ Reactor-yr.)	End State		
Loss of Brayton Cycle	Reactor Trip via RCS/RSS	Core Heat Removal via PCU	Core Heat Removal via CCS	Core Heat Removal via RCCS			Delayed Release from Fuel?	Release from MPS?	Number of Reactor Modules Impacted



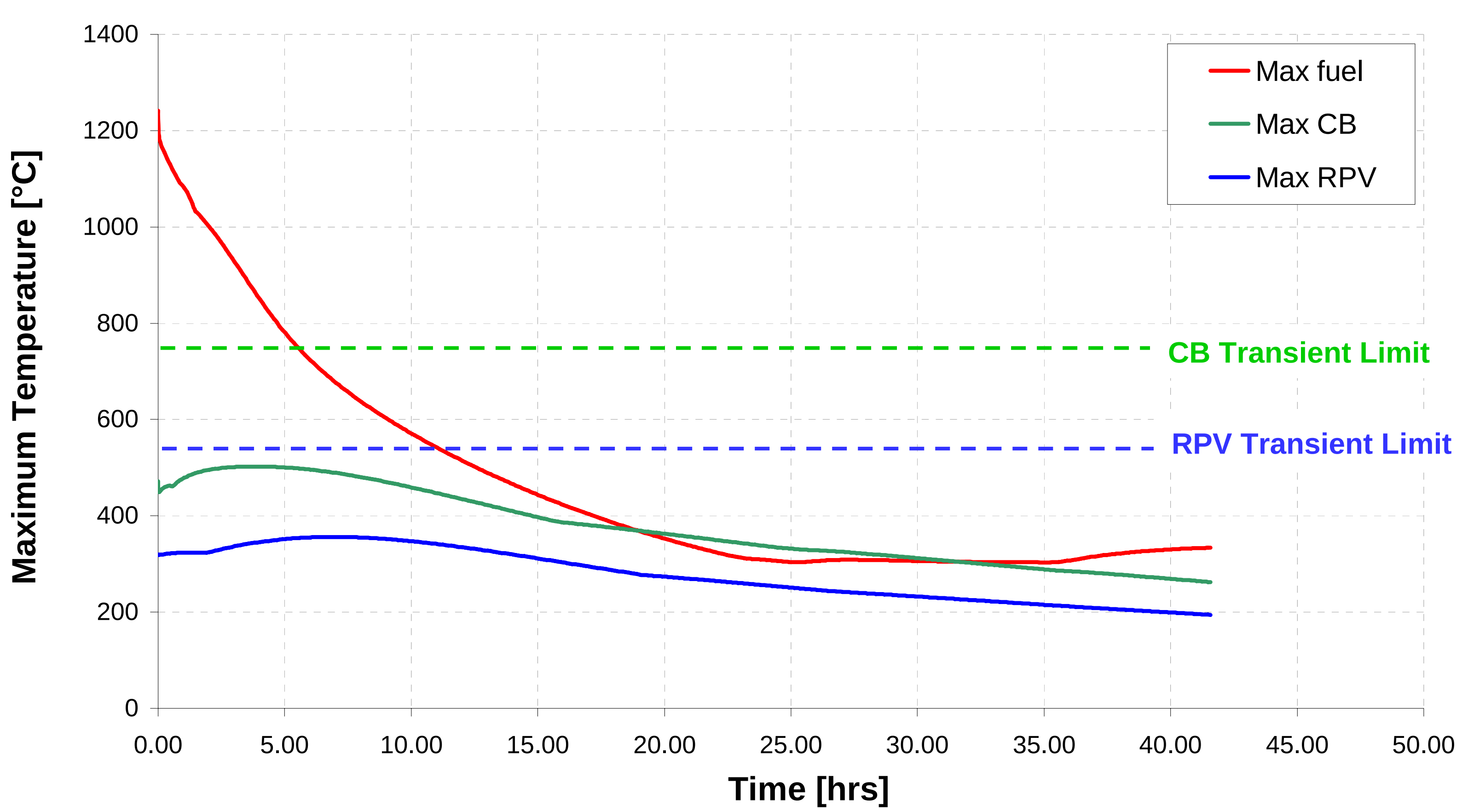
Sequence No.	Event Sequence Frequency (/ Reactor-yr.)	Delayed Release from Fuel?	Release from MPS?	Number of Reactor Modules Impacted
1	2.5×10^{-2}	No	No	1
2	1.1×10^{-2}	No	No	1
3	1.1×10^{-4}	Yes	No	1
4	$<10^{-8}$	Yes	No	1
5	3.5×10^{-8}	Yes	No	1
6	$<10^{-8}$	Yes	No	1

(Yellow) Cases selected for plant response information

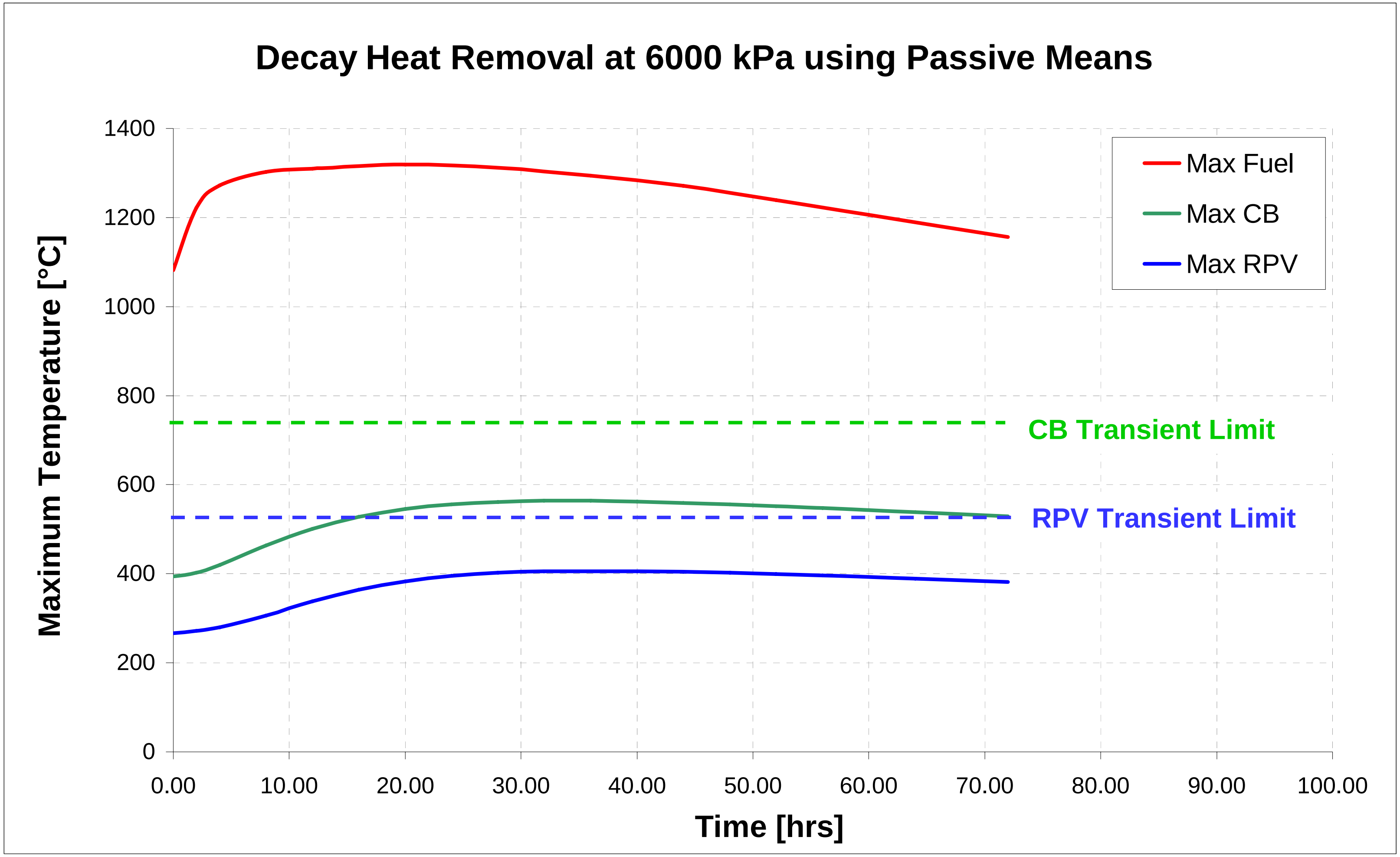
400MWt Decay Heat Curve



Pressurized Forced Cooling Via CCS
Event Tree Sequence 2



Pressurized Loss of Forced Cooling (PLOFC) to RCCS (Sequence 3)



PCU Transients Event Summary

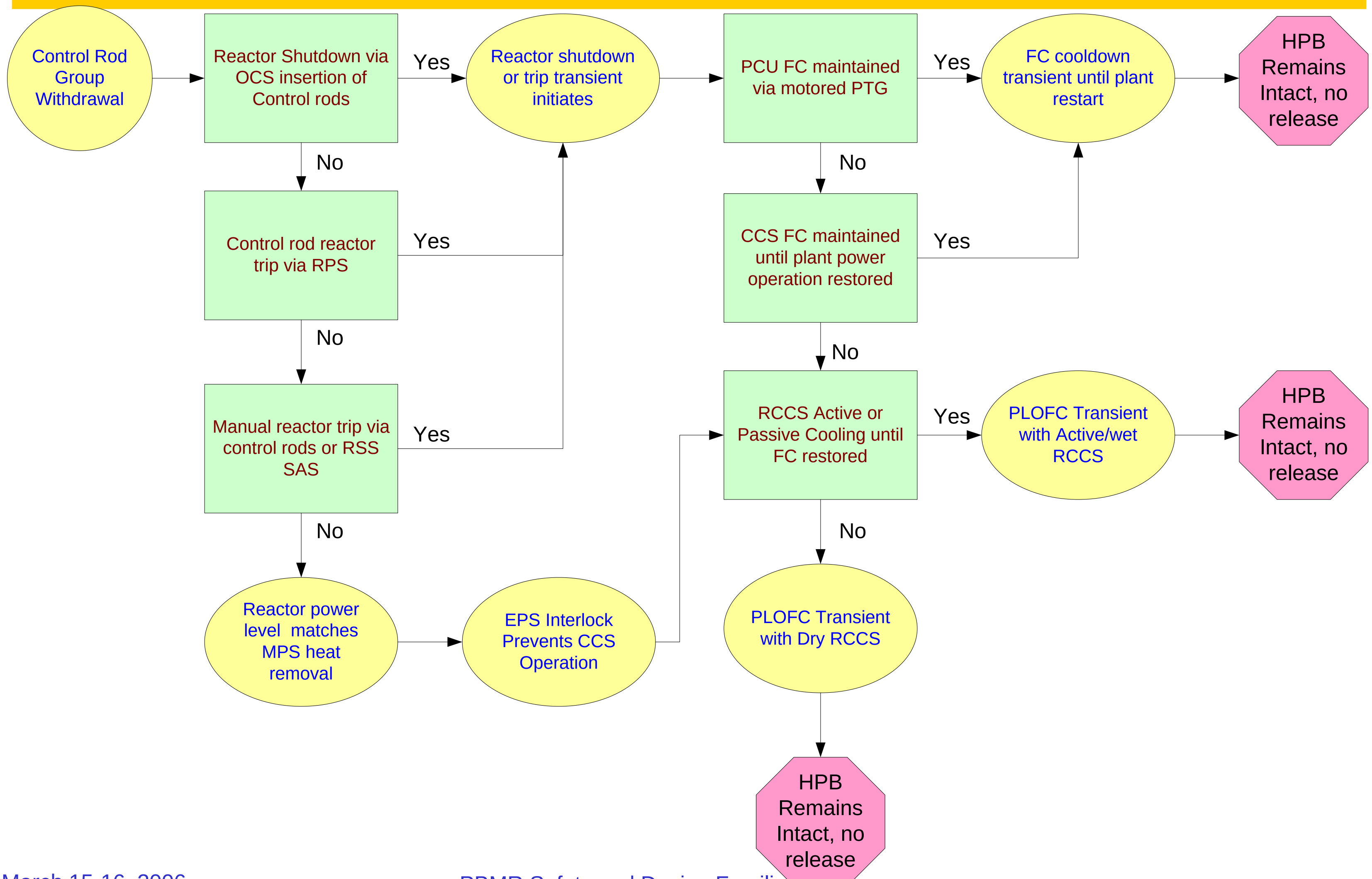
- **Event sequences with continued forced cooling via PCU or CCS involve:**
  - Decreasing peak and average core temperatures
  - SSC temperatures within code limits for transients
  - No delayed fuel release
  - No release from HPB or reactor building
- **Event sequences with loss of forced cooling via successful or unsuccessful RCCS involve**
  - Maximum core temperature transient with peak at around 1300°C at 20 hours
  - Maximum SSC temperatures within code limits for transients
  - Delayed fuel release contained within HPB
  - No release from HPB
- **Event sequences with failure of reactivity control systems are controlled via passive negative temperature feedback and no adverse impact on SSC temperatures and releases**

Control Rod Group Withdrawal

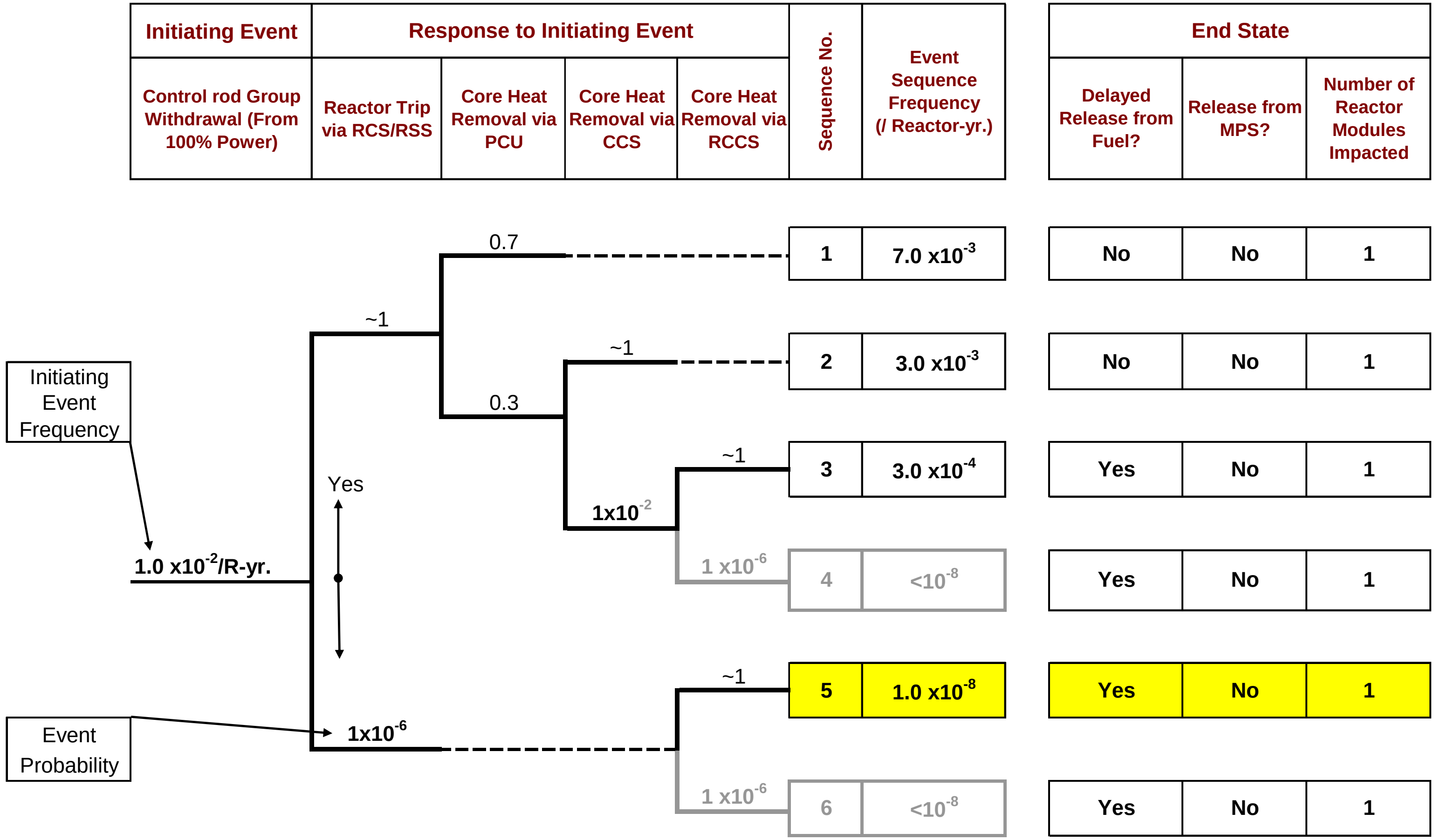
Reactivity Insertion Mechanisms Considered in PBMR Design

- Range of initial conditions of core temperature, core reactivity, control rod insertion, Xenon decay times
- Overcooling of the core, e.g. spurious opening of recuperator bypass valves
- Core compaction from seismic events
- Increased moderation from water ingress
- Control rod and control rod group withdrawal
- Removal of RSS small absorber spheres

Group Control Rod Withdrawal Event Sequence Diagram



At Power Control Rod Group Withdrawal Event Tree

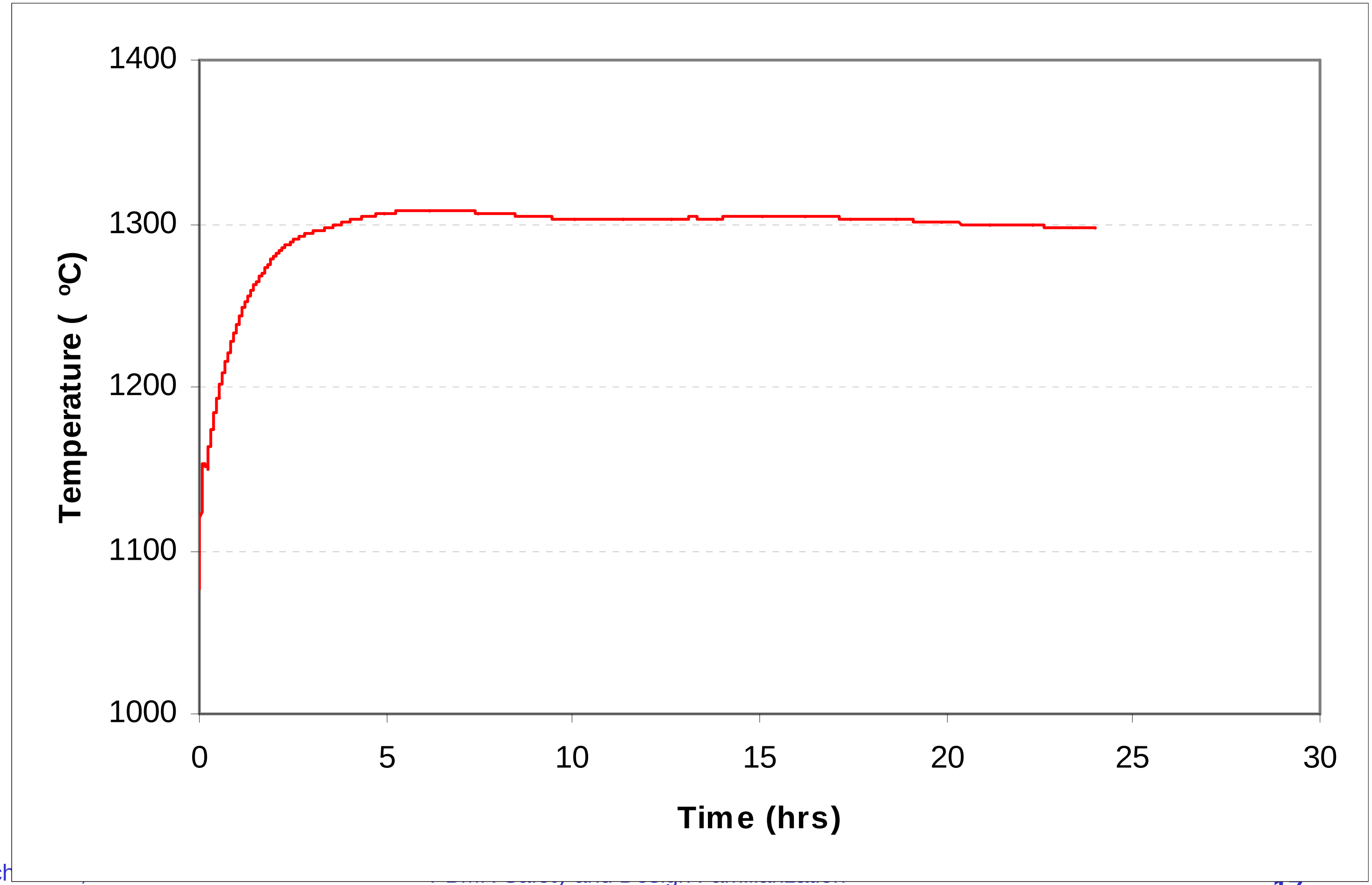


Cases selected for plant response information

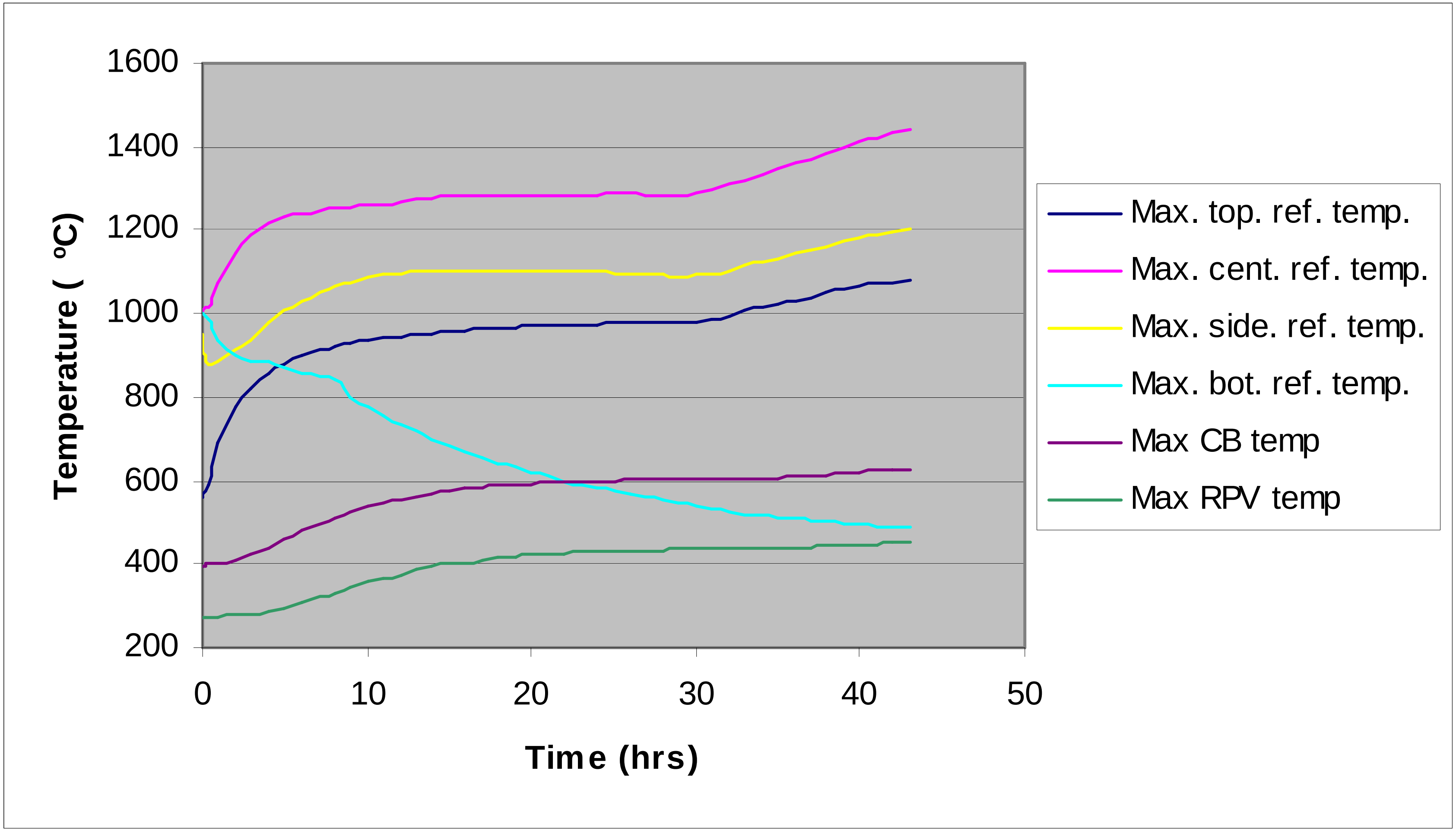
Control Rod Withdrawal Transients with No RCS or RSS Mitigative Response

- **Initial Conditions**
  - Initial reactor inlet and outlet temperatures same as normal full power operating conditions (900°C Reactor outlet temp.)
  - Reactor critical with rods at normal power position
  - PCU tripped
- **Control rod group (12 control rods) withdrawal at 1 cm/sec until all rods fully withdrawn**
- **Transients calculated for 24 hours**

Maximum Fuel Temperature for Control Rod Group Withdrawal from Hot Standby Sequence 5



Other SSC Maximum Temperatures for Control Rod Group Withdrawal from Hot Standby Sequence 5

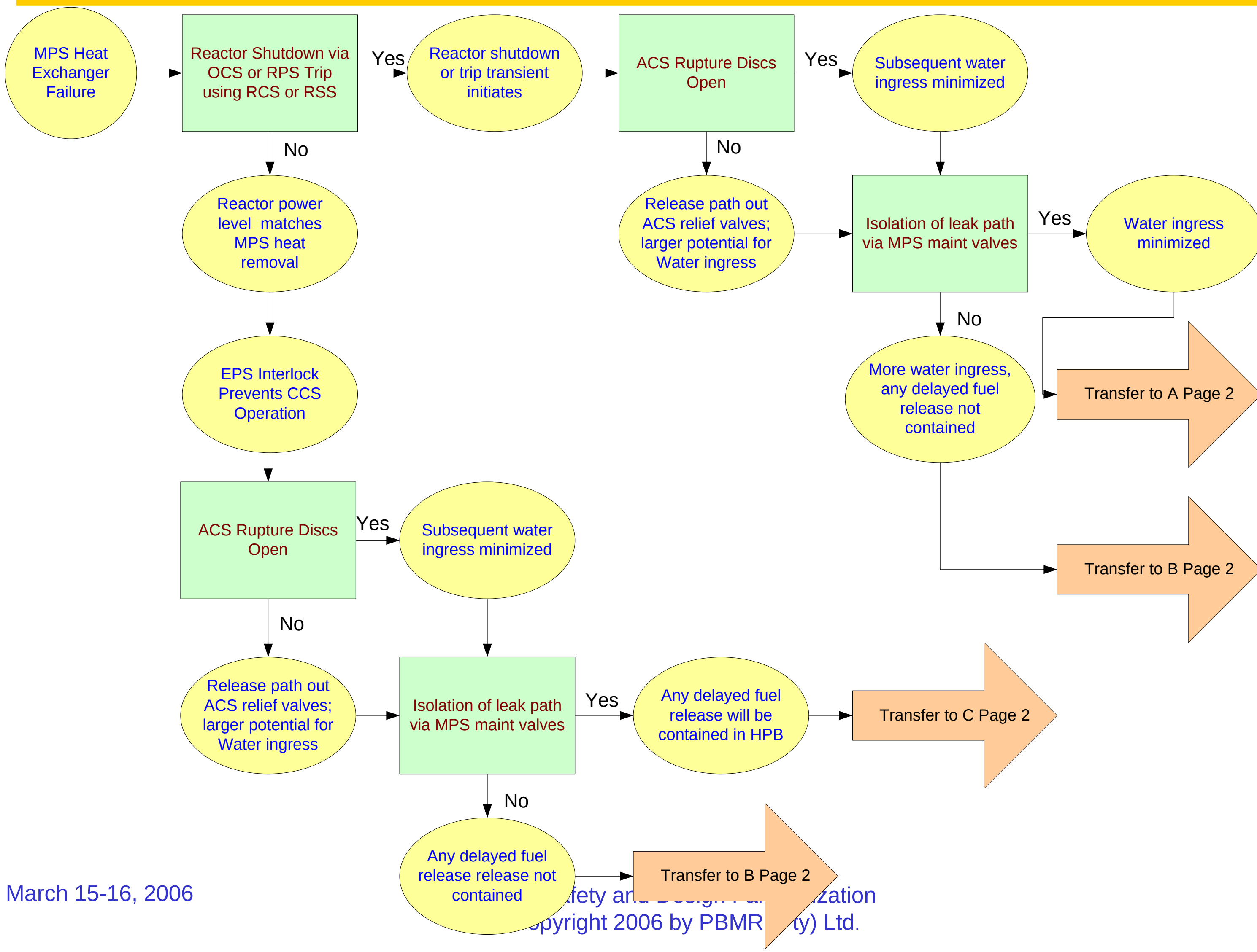


Control Rod Group Withdrawal Event Summary

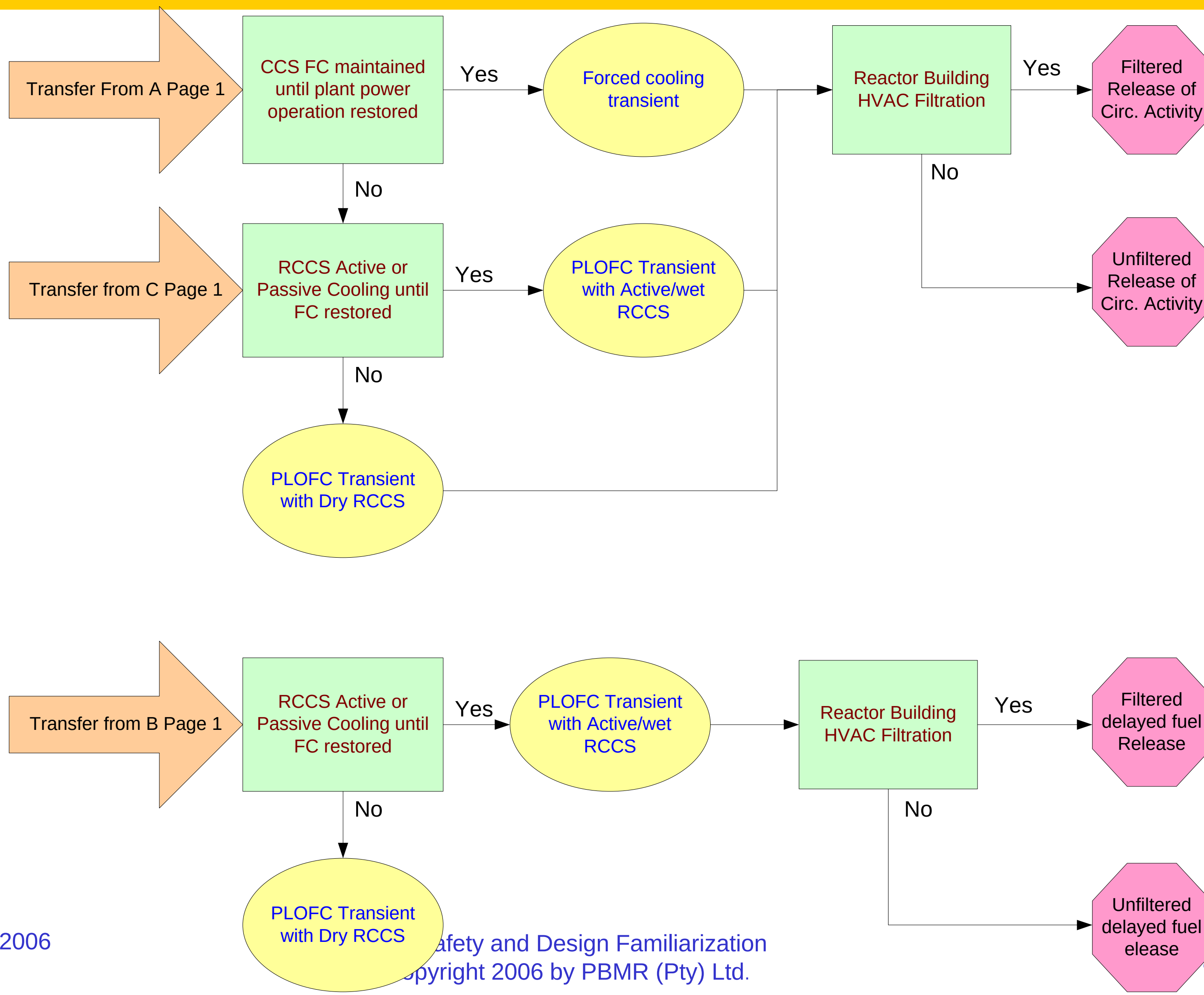
- **Initial response governed by large negative temperature coefficient**
- **No adverse impact on SSC temperatures with sequences with failure to trip**
- **HPB remains intact**
- **End states similar to PCU transients**

MPS Heat Exchanger Failure

PCU Heat Exchanger Failure Event Sequence Diagram 1 of 2

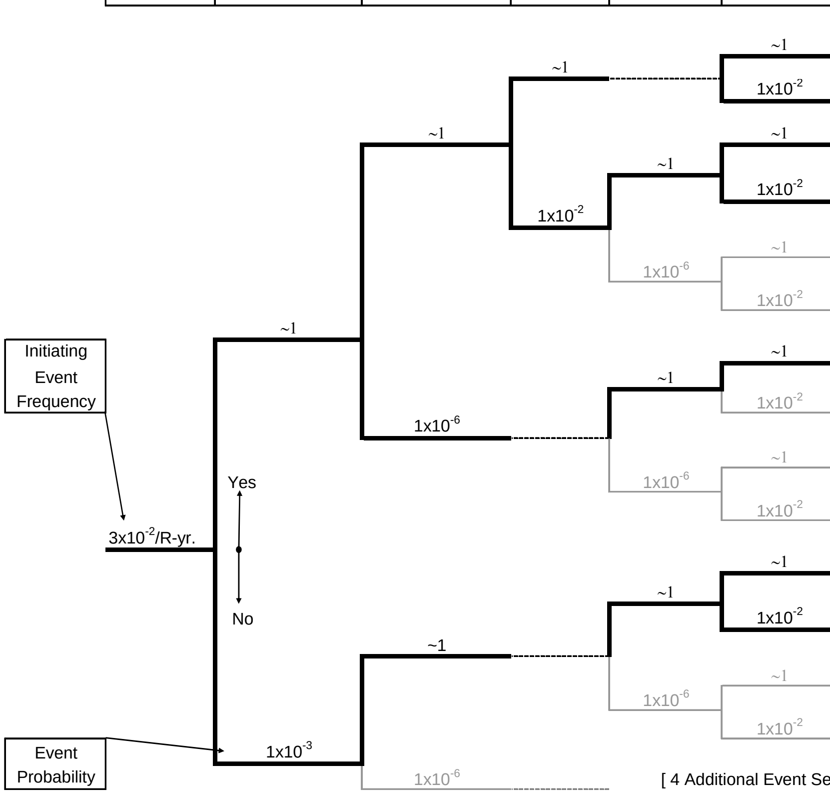


PCU Heat Exchanger Failure Event Sequence Diagram 2 of 2



MPS Heat Exchanger Break Event Tree

Initiating Event	Response to Initiating Event				
MPS HX Tube Break	Break Isolation via Maint. Valve	Reactor Trip via RCS/RSS	Core Heat Removal via CCS	Core Heat Removal via RCCS	Release Filtration via HVAC

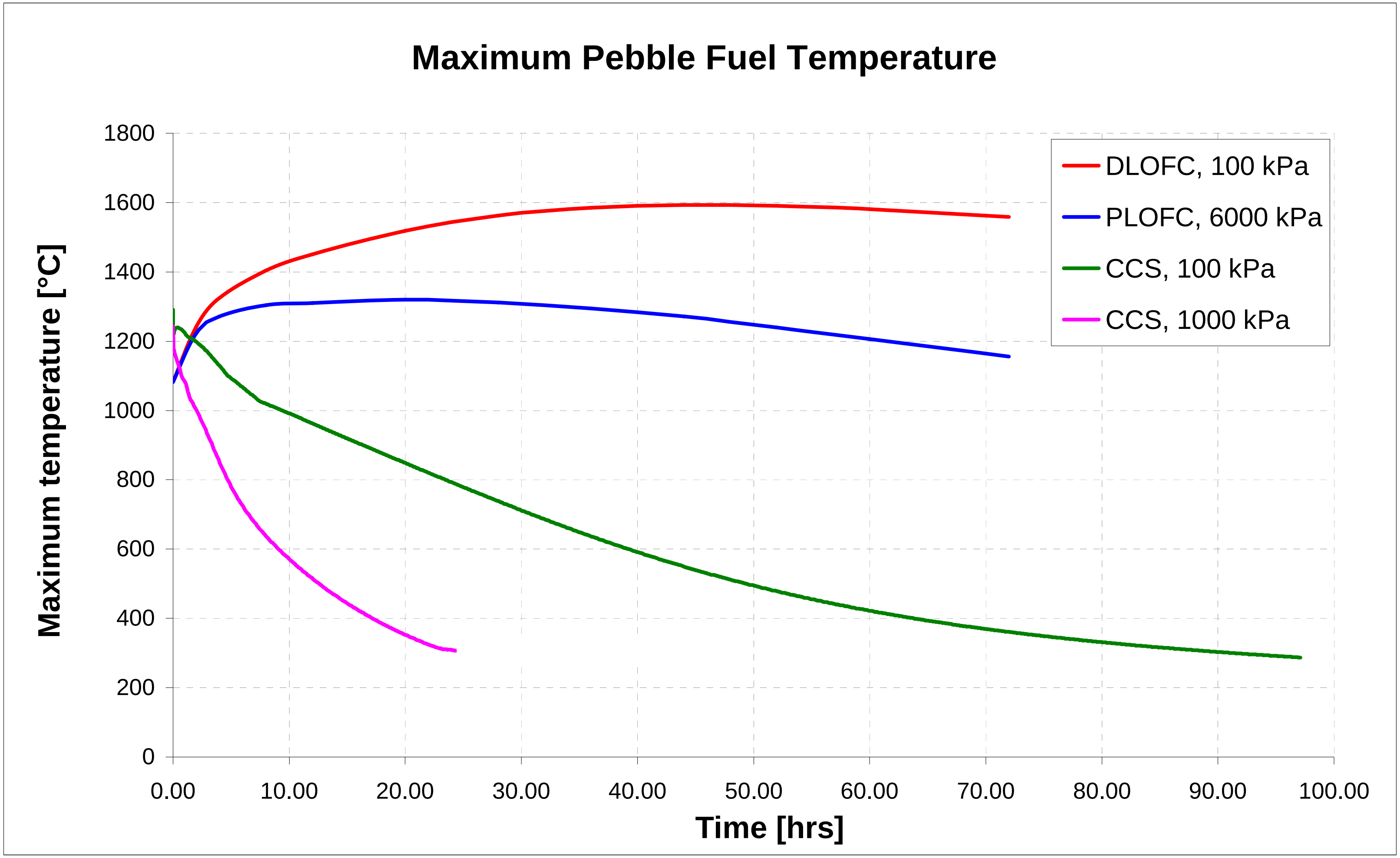


Sequence No.	Event Sequence Frequency per R-yr.	Release of Circulating Activity	Delayed Release from Fuel?	Delayed Fuel Release from MPS?	Release is filtered?	Number of Reactor Modules Impacted
1	$3x10^{-2}$	Yes	No	No	Yes	1
2	$3x10^{-4}$	Yes	No	No	No	1
3	$3x10^{-4}$	Yes	Yes	No	Yes	1
4	$3x10^{-6}$	Yes	Yes	No	No	1
5	$<10^{-8}$					
6	$<10^{-8}$					
7	$3x10^{-8}$	Yes	Yes	No	Yes	1
8	$<10^{-8}$					
9	$<10^{-8}$					
10	$<10^{-8}$					
11	$3x10^{-5}$	Yes	Yes	Yes	Yes	1
12	$3x10^{-7}$	Yes	Yes	Yes	No	1
12	$<10^{-8}$					
13	$<10^{-8}$					

[4 Additional Event Sequences with Frequencies < 10^{-8} per reactor year]

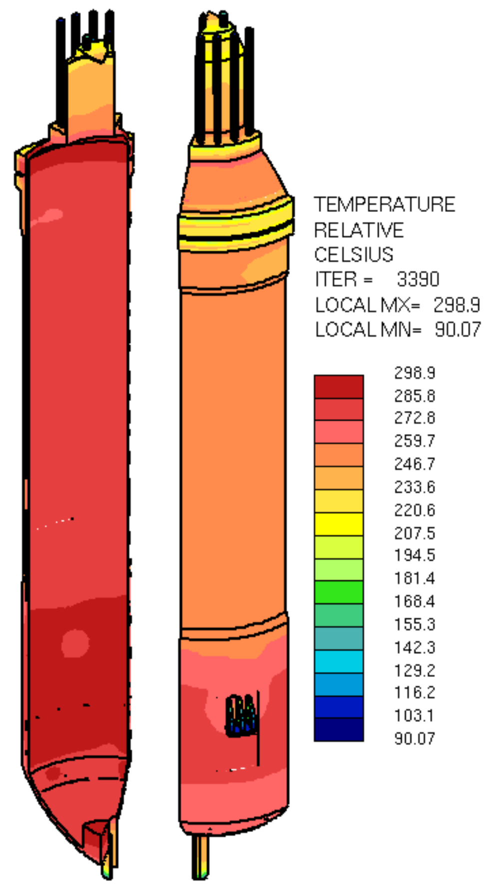
Cases selected for plant response information (highlighted in yellow: sequences 11 and 12)

Comparison of Fuel Temperatures for Forced Cooling (CCS) & Passive Core Cooldown

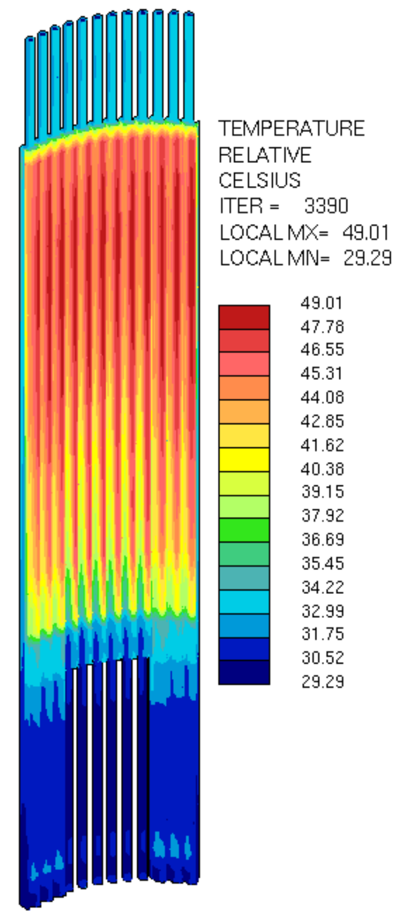


Peak Component Temperatures During DLOFC (Event Tree Sequences 11 and 12)

- **Detail 60° model**
  - Detail of hot spots
  - Thermal Gradients
  - Component temperatures
  - Leakage flows



RPV (inner and outer surface)

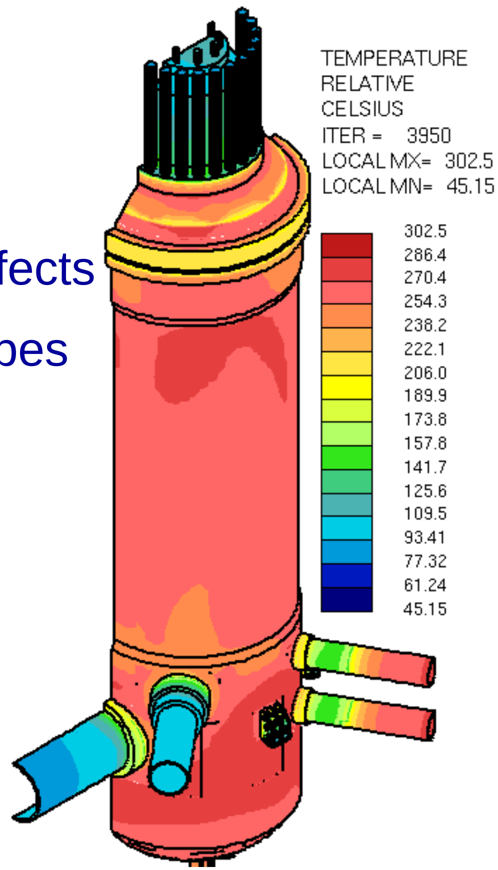


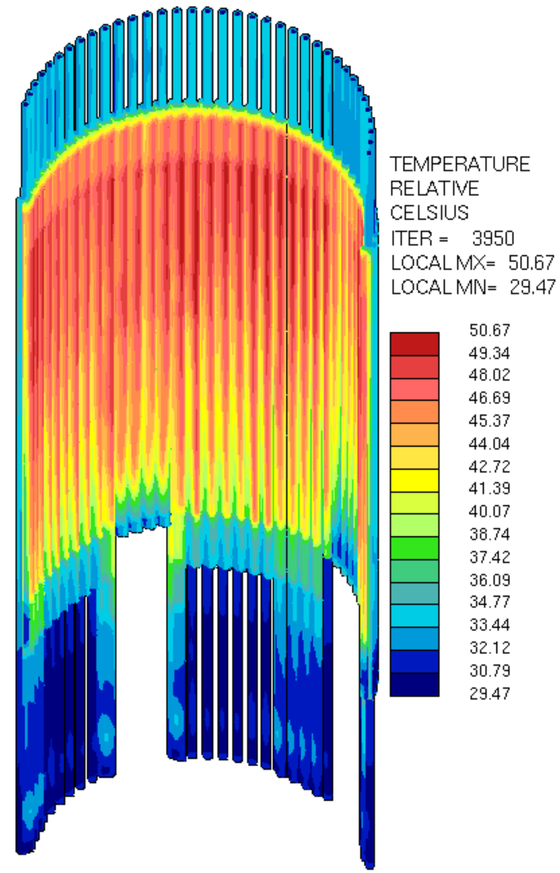
RCCS pipes

Peak Component Temperatures During DLOFC (Event Tree Sequences 11 and 12)

- **180° Reactor cavity**

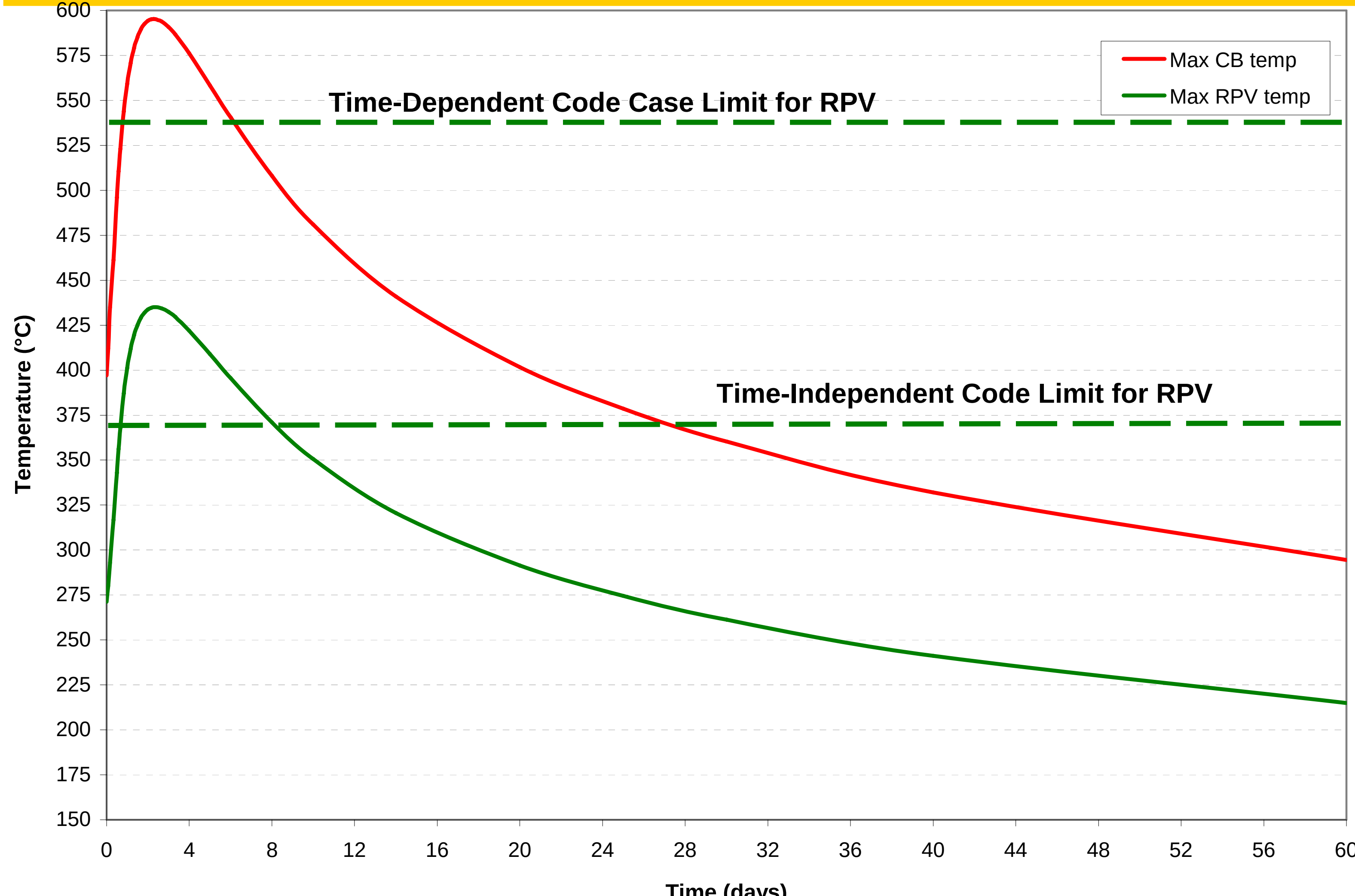
  model:
  - 3-D effects
  - Unsymmetrical effects
  - Detail natural convection effects
  - Effects of inlet and outlet pipes



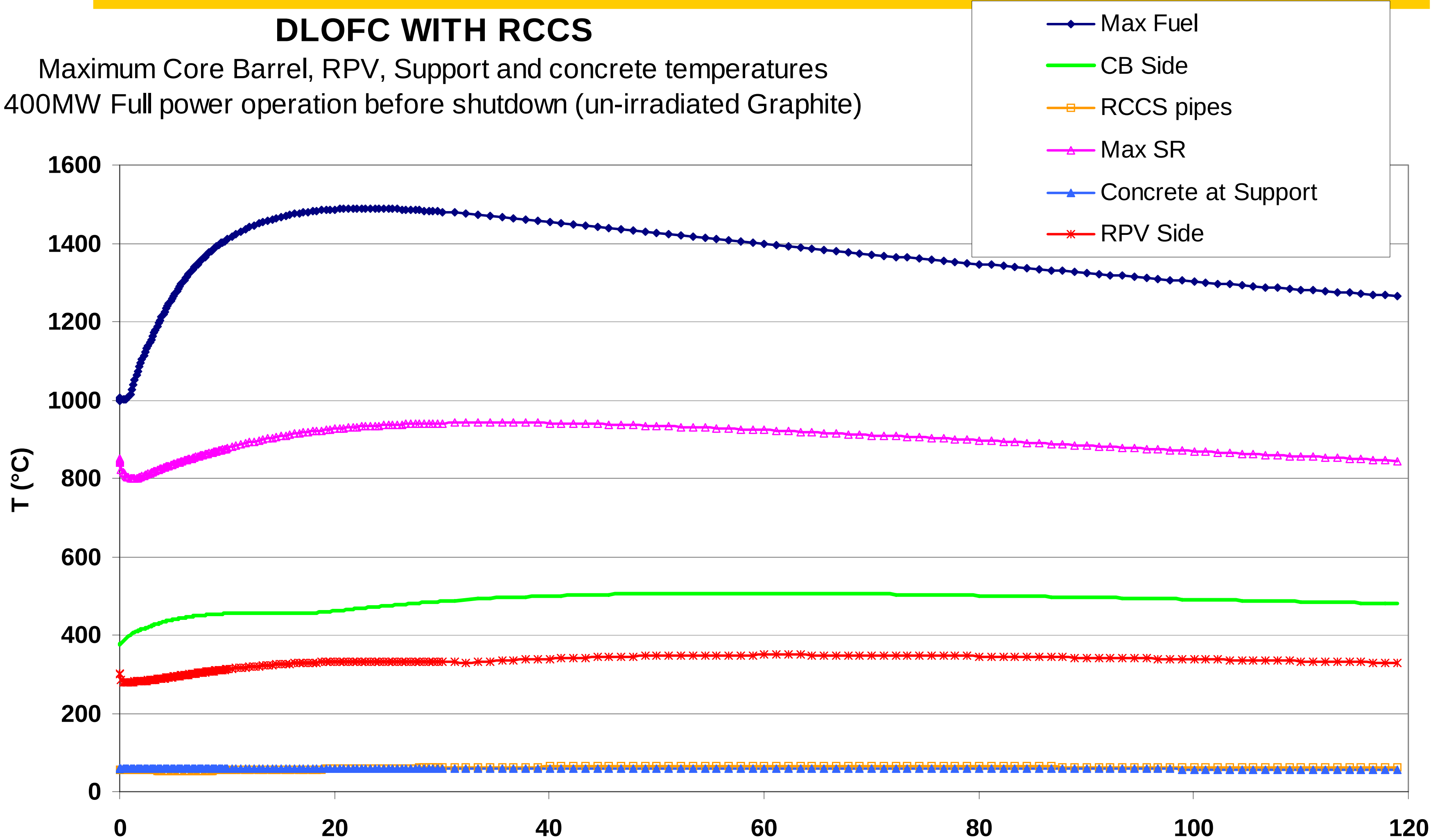


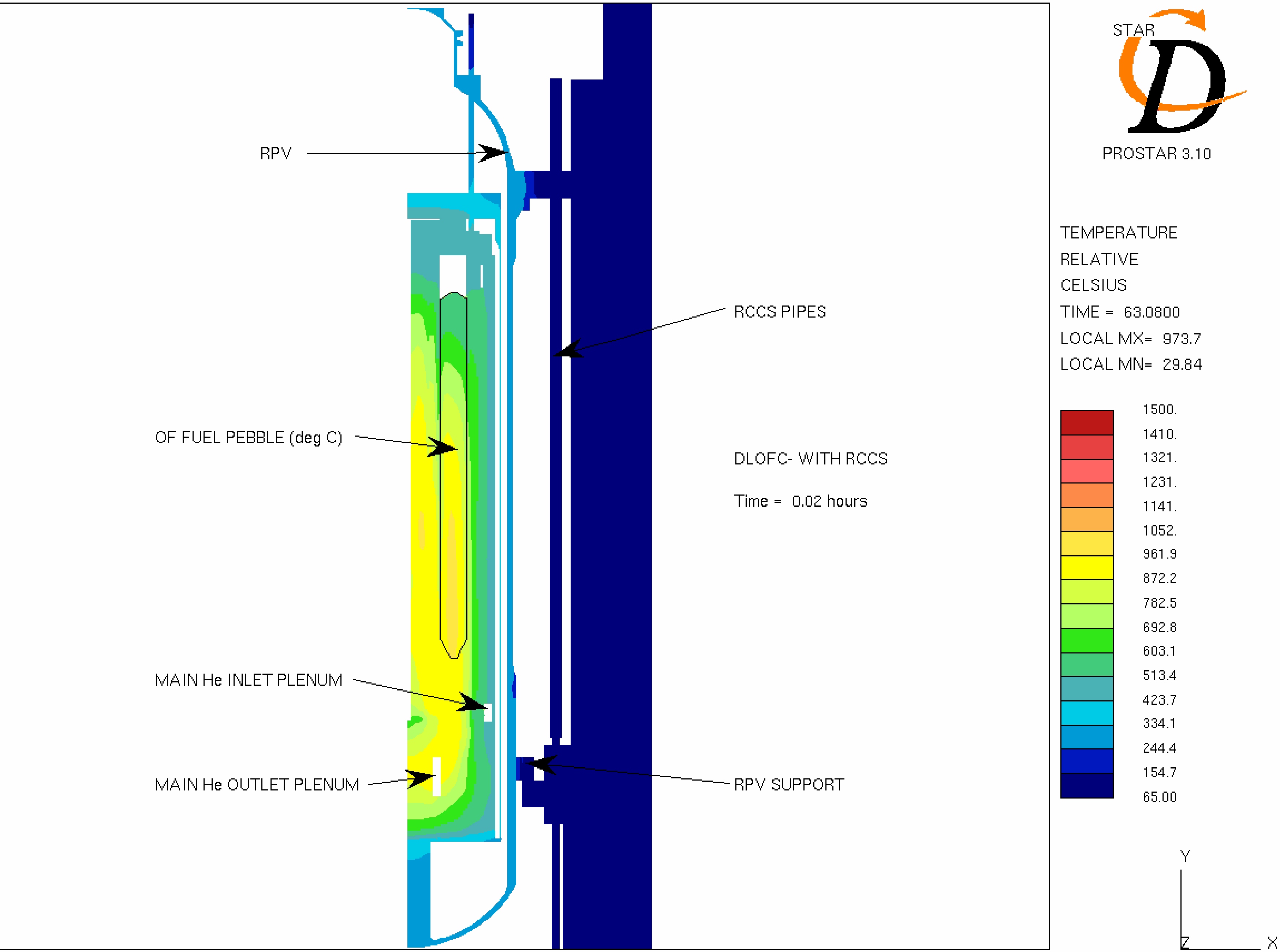
RCCS standpipe temperature

Maximum Core Barrel and RPV Temperatures During DLOFC (Event Tree Sequences 11 and 12)



Peak Temperature Transients During DLOFC (Event Tree Sequences 11 and 12)




STAR
PROSTAR 3.10
RPV
RCCS PIPES
OF FUEL PEBBLE (deg C)
DLOFC- WITH RCCS
Time = 0.02 hours
MAIN He INLET PLENUM
MAIN He OUTLET PLENUM
RPV SUPPORT
TEMPERATURE
RELATIVE
CELSIUS
TIME = 63.0800
LOCAL MX= 973.7
LOCAL MN= 29.84
1500.
1410.
1321.
1231.
1141.
1052.
961.9
872.2
782.5
692.8
603.1
513.4
423.7
334.1
244.4
154.7
65.00
Y
Z
X

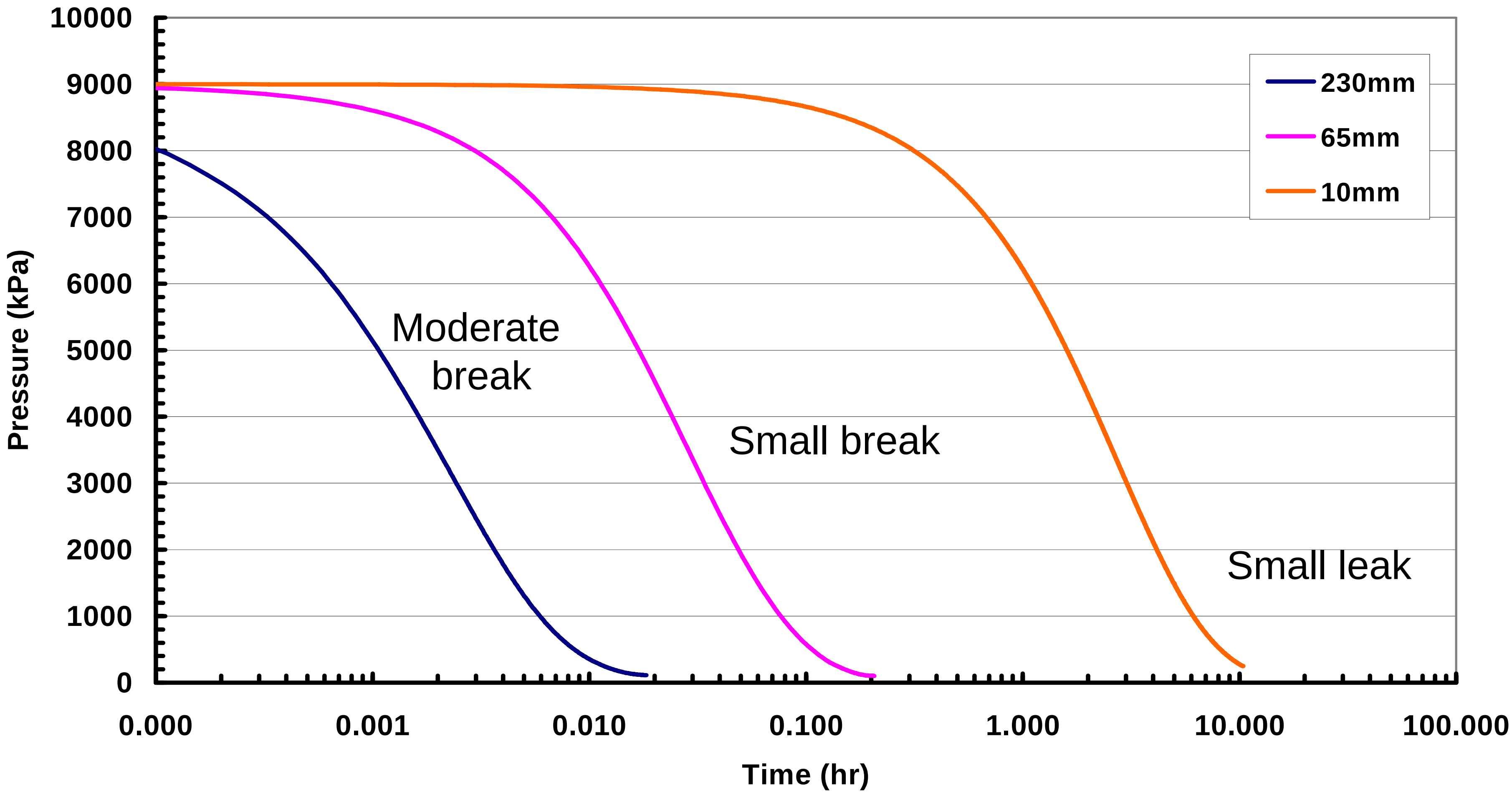
Representative Radionuclide Inventories

Volatility Group	Key Nuclide	Inventory in Contamination (Ci)	Inventory in Defective Particles (Ci)
Noble Gases	Kr-88	~120	~600
Halogen	I-131	~20	~580
Cesium	Cs-137	~10	~40
Strontium	Sr-90	~10	~40

Relative I-131 Inventories

Source	I-131 Inventory (Ci)
Circulating activity	<<1
Plate out on internal HPB surfaces	<1
Uranium contaminated fuel particles	~20
Failed and defective coated particles	~580
Intact coated particles	$\sim 1 \times 10^{7}$

MPS Pressure Following HPB Leaks and Breaks

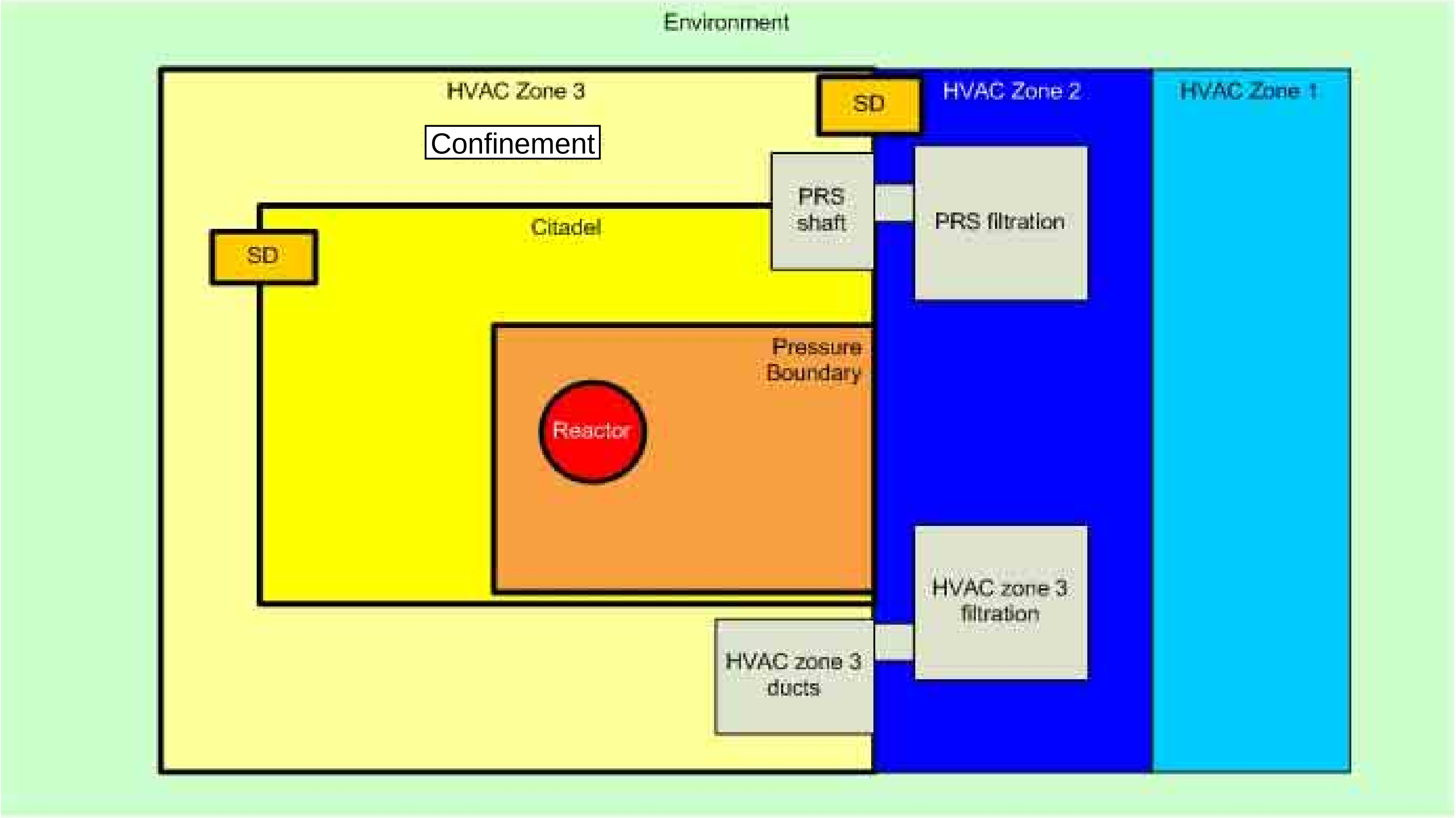


PBMR Containment System

The Containment System is comprised of:

- Citadel
  - *Reactor Cavity*
  - *PCU Citadel*
- Vented Confinement Building
- Pressure Relief System
- Specialized Doorways Subsystem
- HVAC System Filtration

Confinement Philosophy

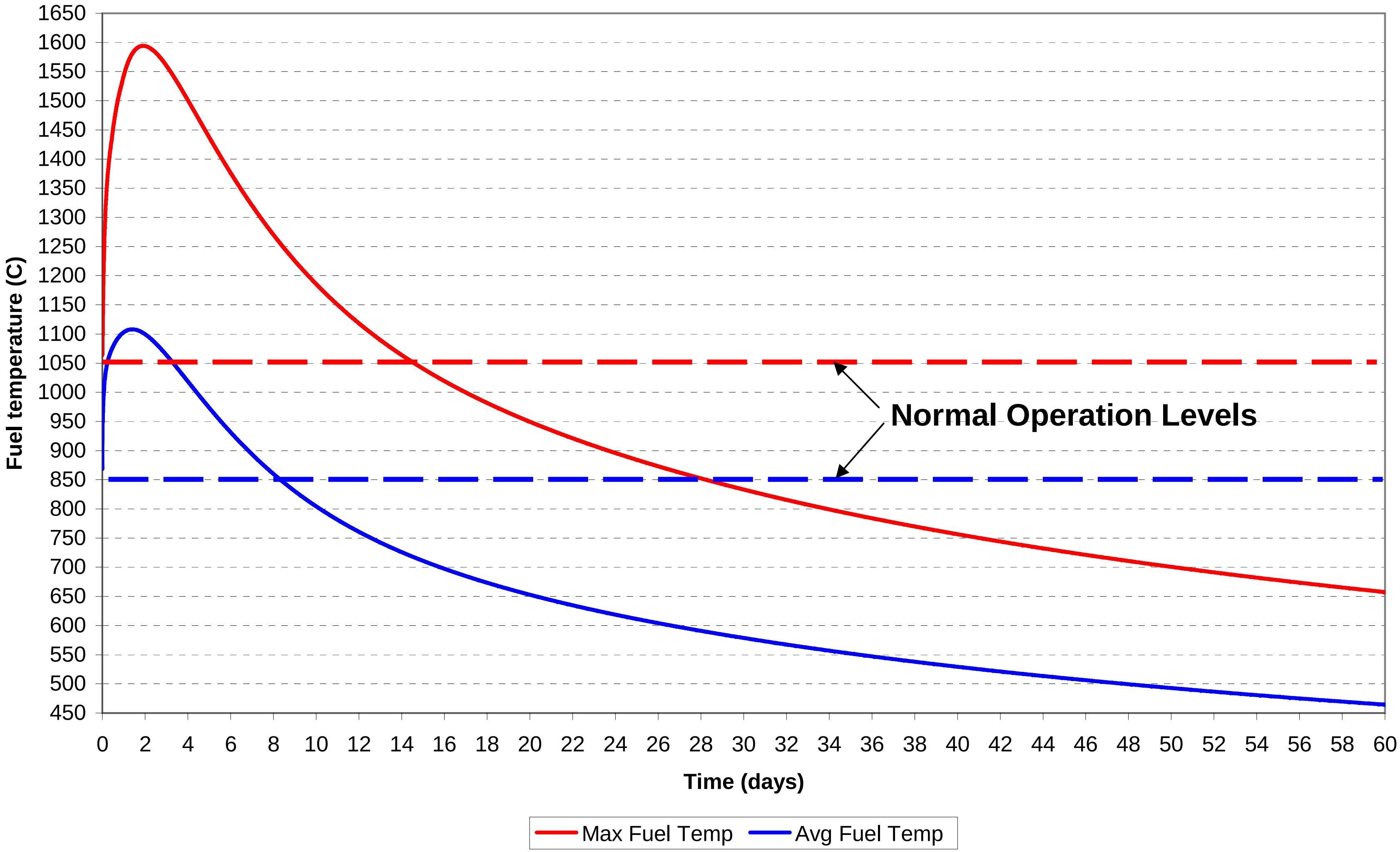


SD Specialized doorways

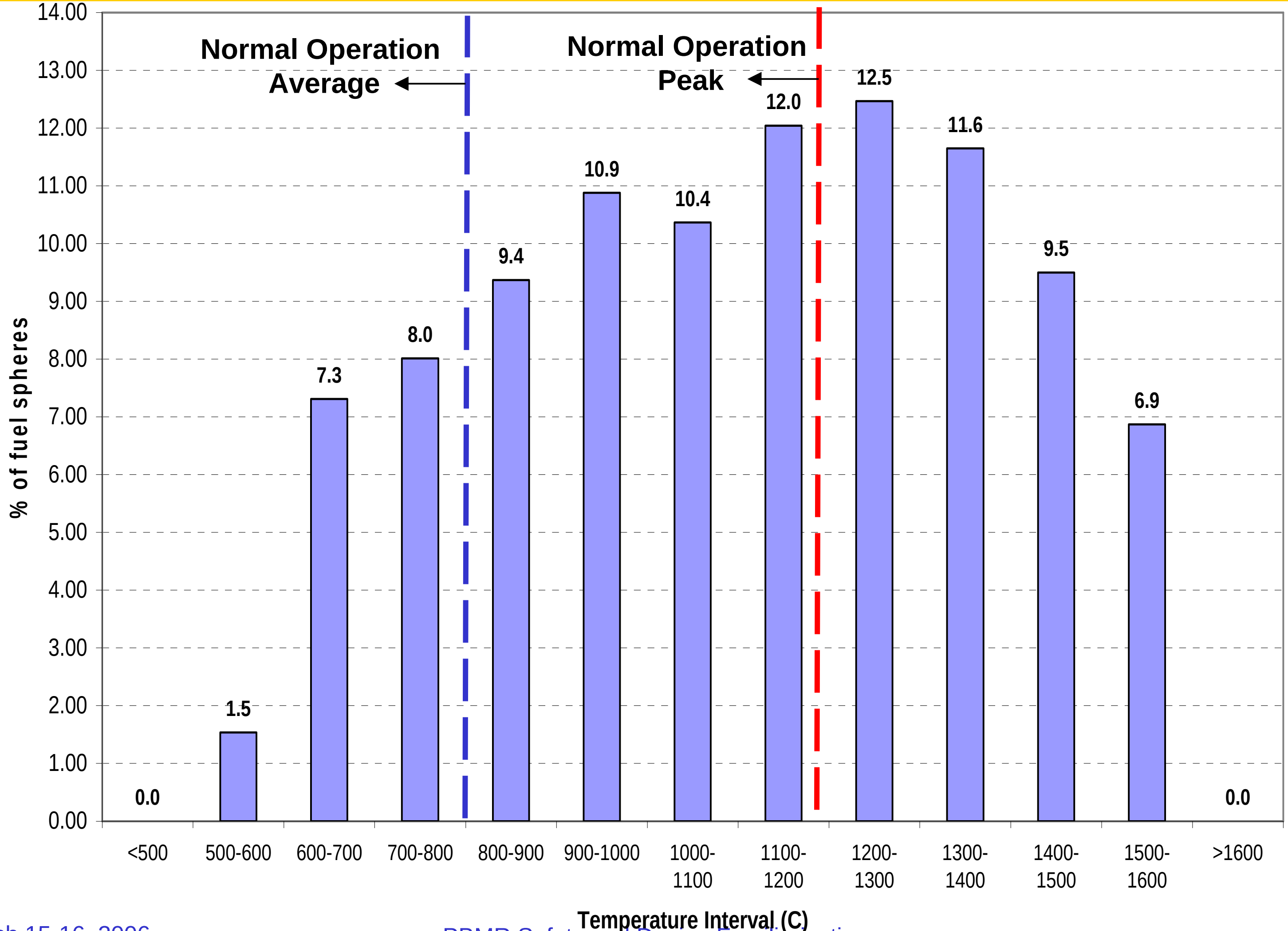
Delayed Fuel Release Mechanisms

- **Partial released from contamination, initially failed, or defective particles when temperatures exceed normal operation levels and from particles that fail during the event**
- **Timing of release is tens of hours to days**
- **Inventory is much larger than circulating activity and liftoff**
- **Amount of release from fuel depends on fraction of core above normal operation temperatures for given times and on radionuclide volatility**
  - Governed by amount of forced cooling
  - No difference whether small leak or large break
- **Amount of release from HPB depends on location and size of leak/break and on timing relative to expansion/contraction of gas within the HPB**
  - Small leaks have greater releases from HPB
  - Releases cease when the HPB internal system temperature decreases due to core temperature cooldown

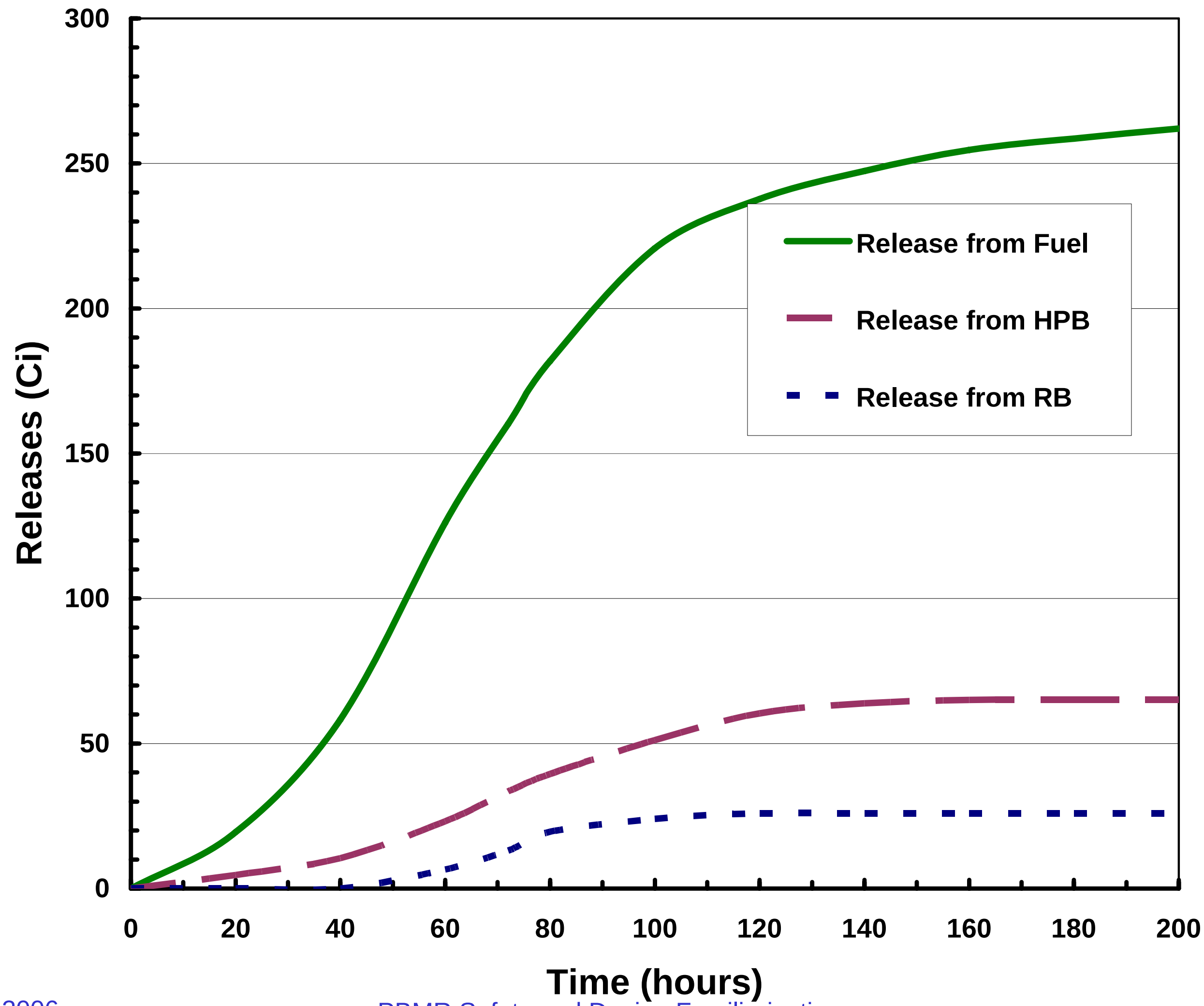
Fuel Temperatures During Depressurized Loss of Forced Cooling (DLOFC)



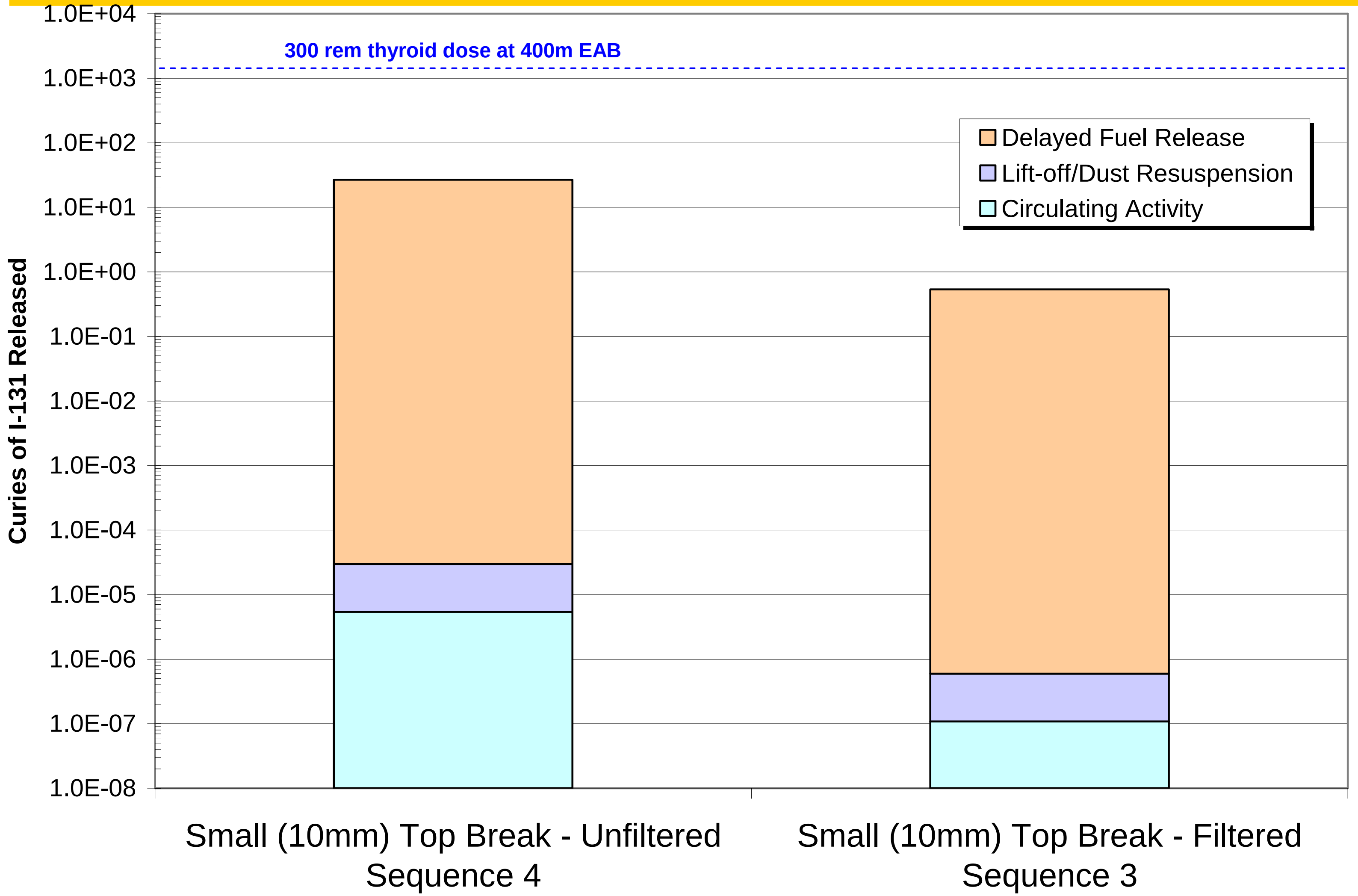
Number of Fuel Spheres In Temperature & Time Intervals during Passive Heat Removal



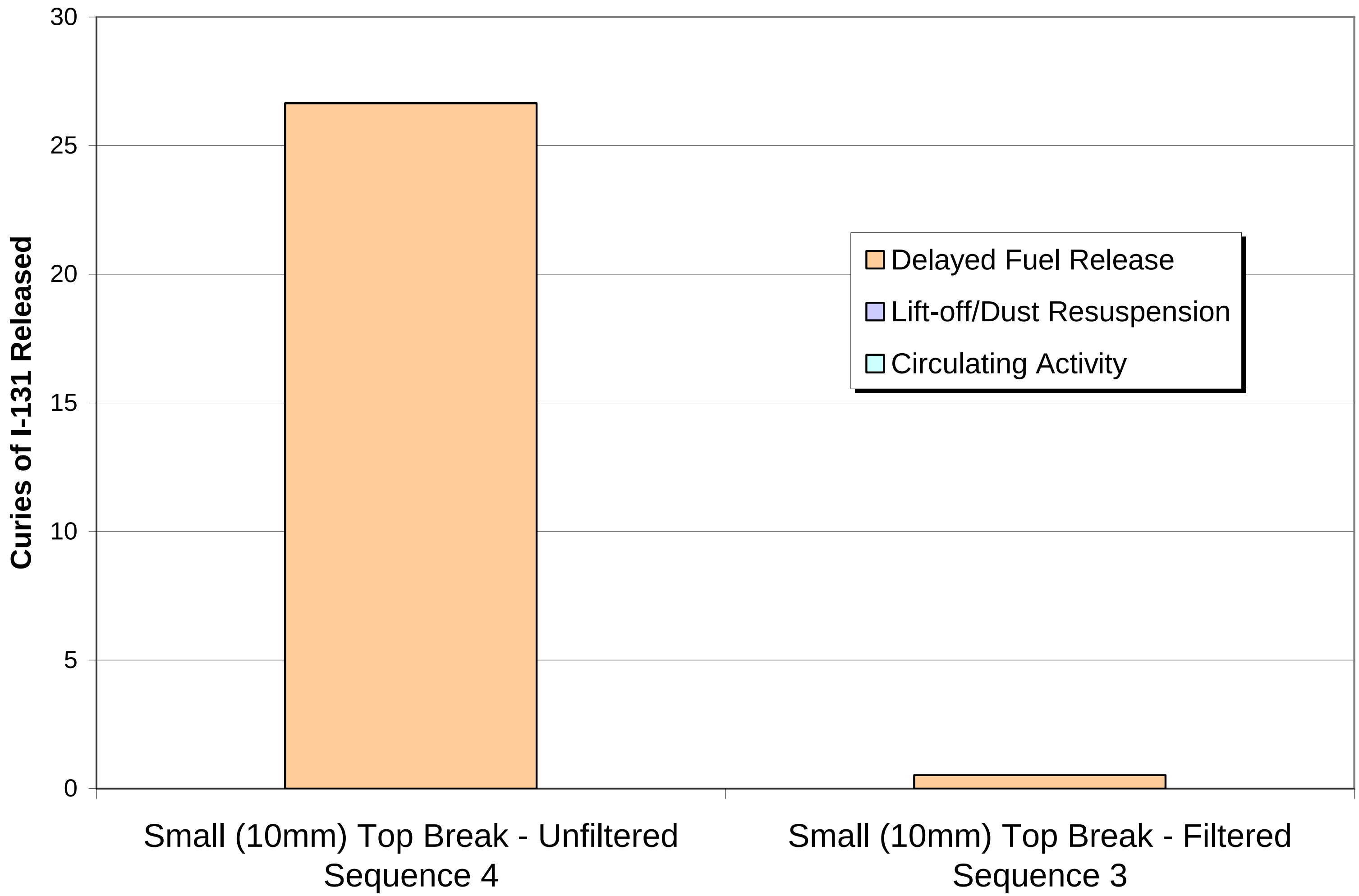
Representative Time Dependence of I-131 Release during Small HPB Leak DLOFC



I-131 Release from Reactor Building During HPB Small Leak DLOFC (log scale)



I-131 Release from Reactor Building During HPB Break DLOFC (linear scale)

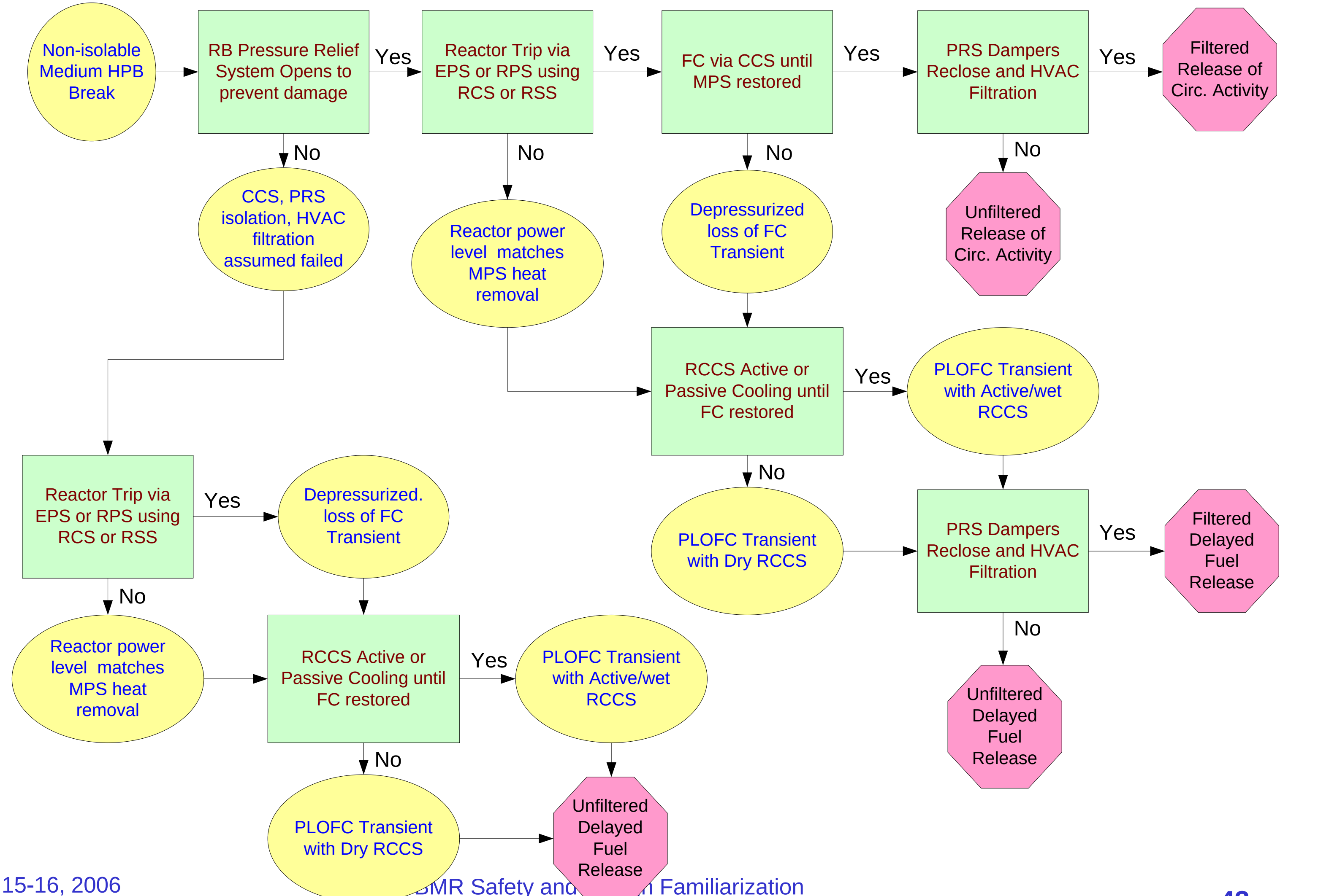


PCU HX Tube Break Event Summary

- **Event sequences with continued forced cooling via PCU or CCS involve:**
  - Decreasing peak and average core temperatures
  - SSC temperatures within code limits for transients
  - Immediate release of circulating activity only
- **Event sequences with passive core heat removal via RCCS and failure to isolate leak with maintenance valve involve:**
  - Immediate release of circulating activity
  - Delayed release from initially failed coated particles and contamination due to heatup
  - Water ingress negligible impact
- **Small leak provides mass transport of delayed release via helium depressurization**
- **Successful operation of HVAC provides consequence mitigation**

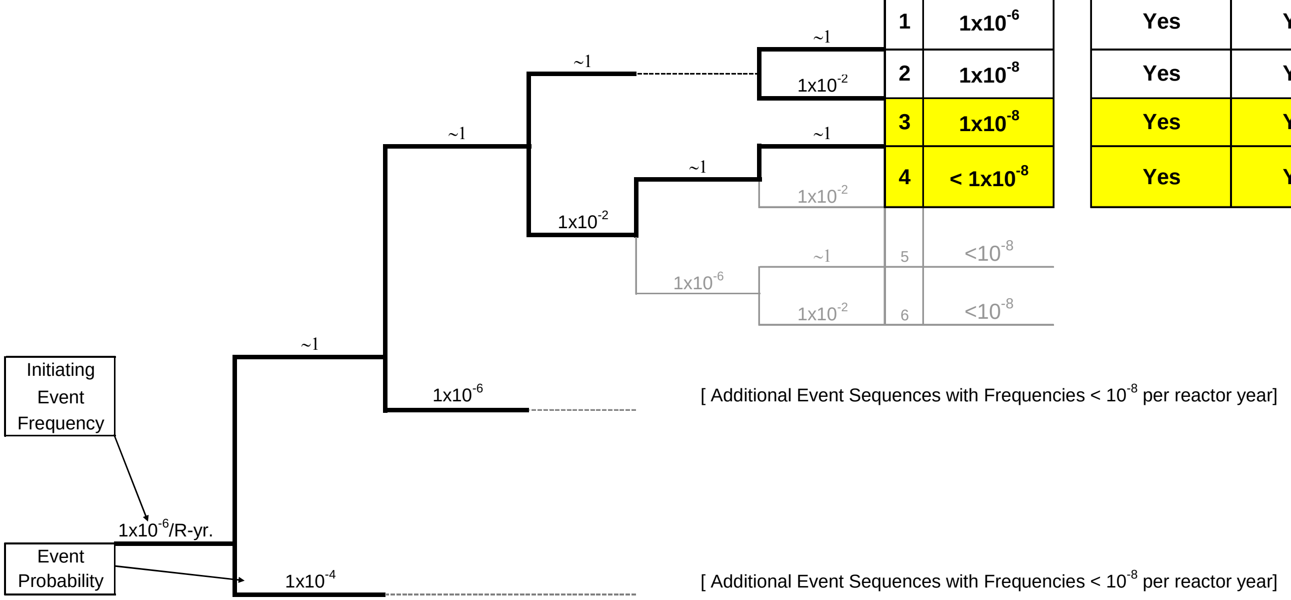
Medium Break in HPB Pressure Boundary

Medium HPB Break (230mm) Event Sequence Diagram



Non Isolable Medium HPB Break Event Tree

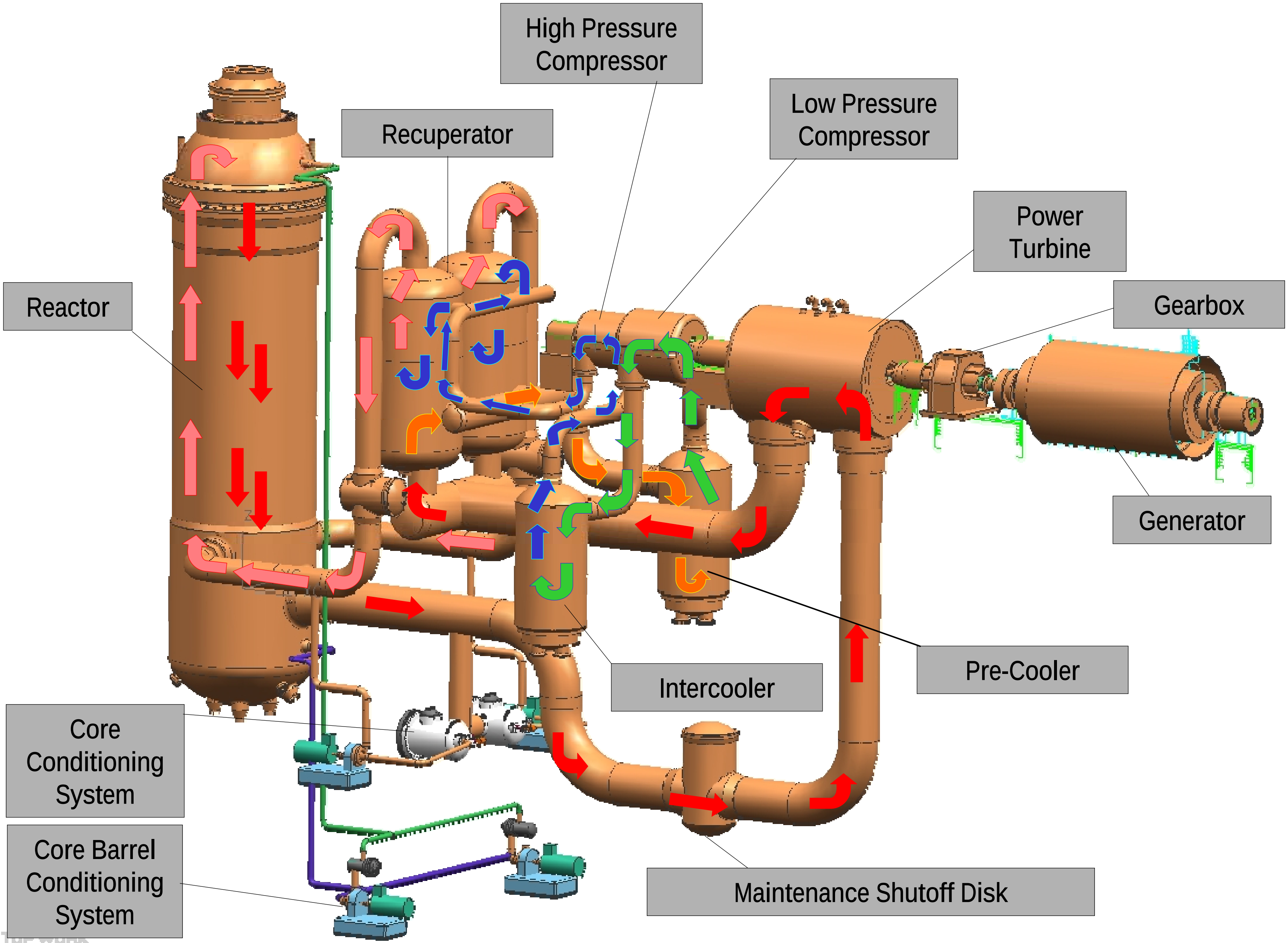
Initiating Event	Response to Initiating Event					Sequence No.	Event Sequence Frequency per R-yr.	End State				
230mm HPB Break	PRS Prevents Structural Damage	Reactor Trip via RCS/RSS	Core Heat Removal via CCS	Core Heat Removal via RCCS	Release Filtration via HVAC			Release of Circulating Activity	Lift-off of Plateout and Dust	Delayed Release from Fuel?	Release is filtered?	Number of Reactor Modules Impacted
						1	$1x10^{-6}$	Yes	Yes	No	Yes	1
						2	$1x10^{-8}$	Yes	Yes	No	No	1
						3	$1x10^{-8}$	Yes	Yes	Yes	Yes	1
						4	$< 1x10^{-8}$	Yes	Yes	Yes	No	1
						5	$<10^{-8}$					
						6	$<10^{-8}$					



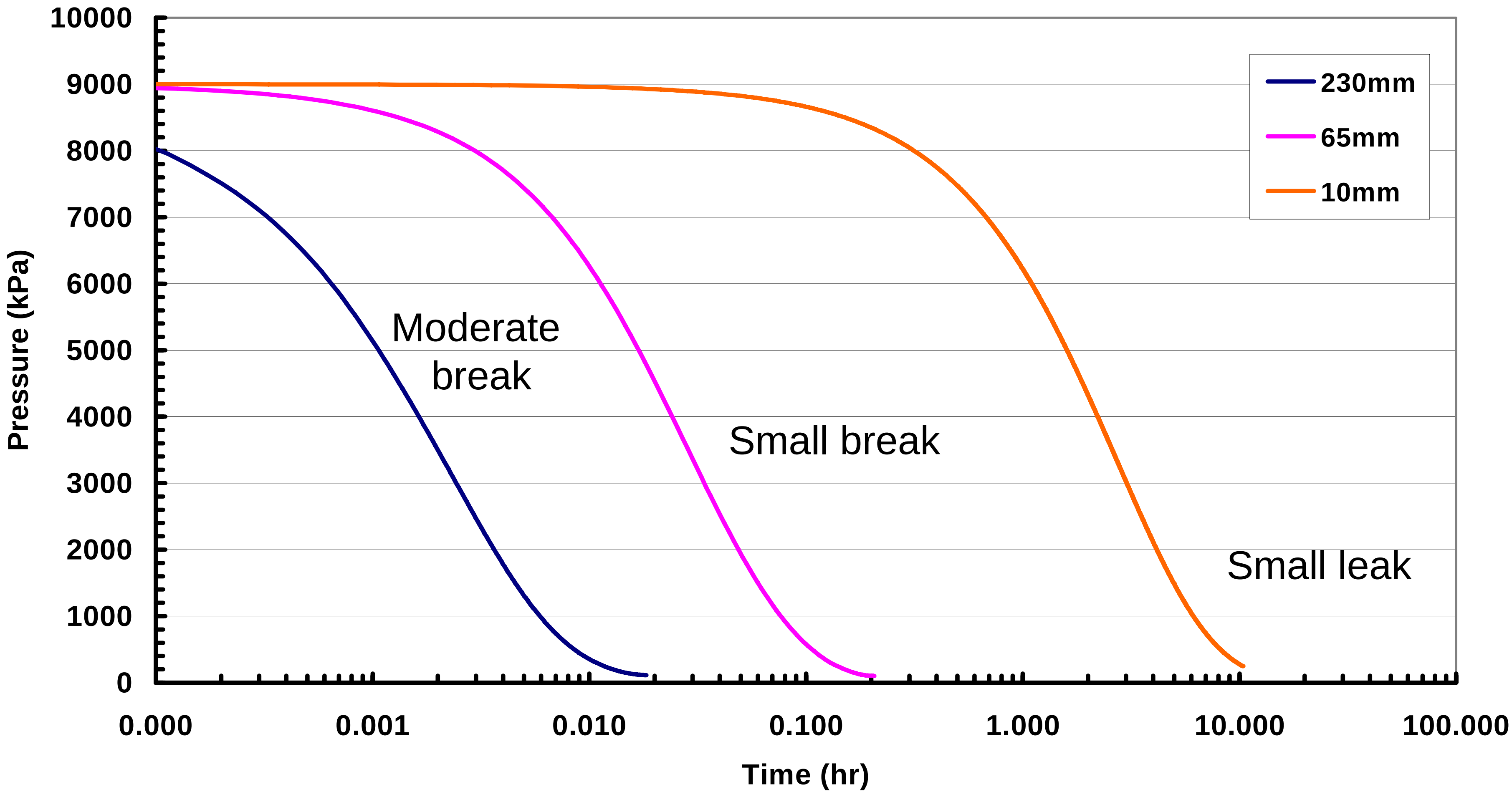
Cases selected for plant response information

Circulating Activity, Plateout, and Dust Release Mechanisms

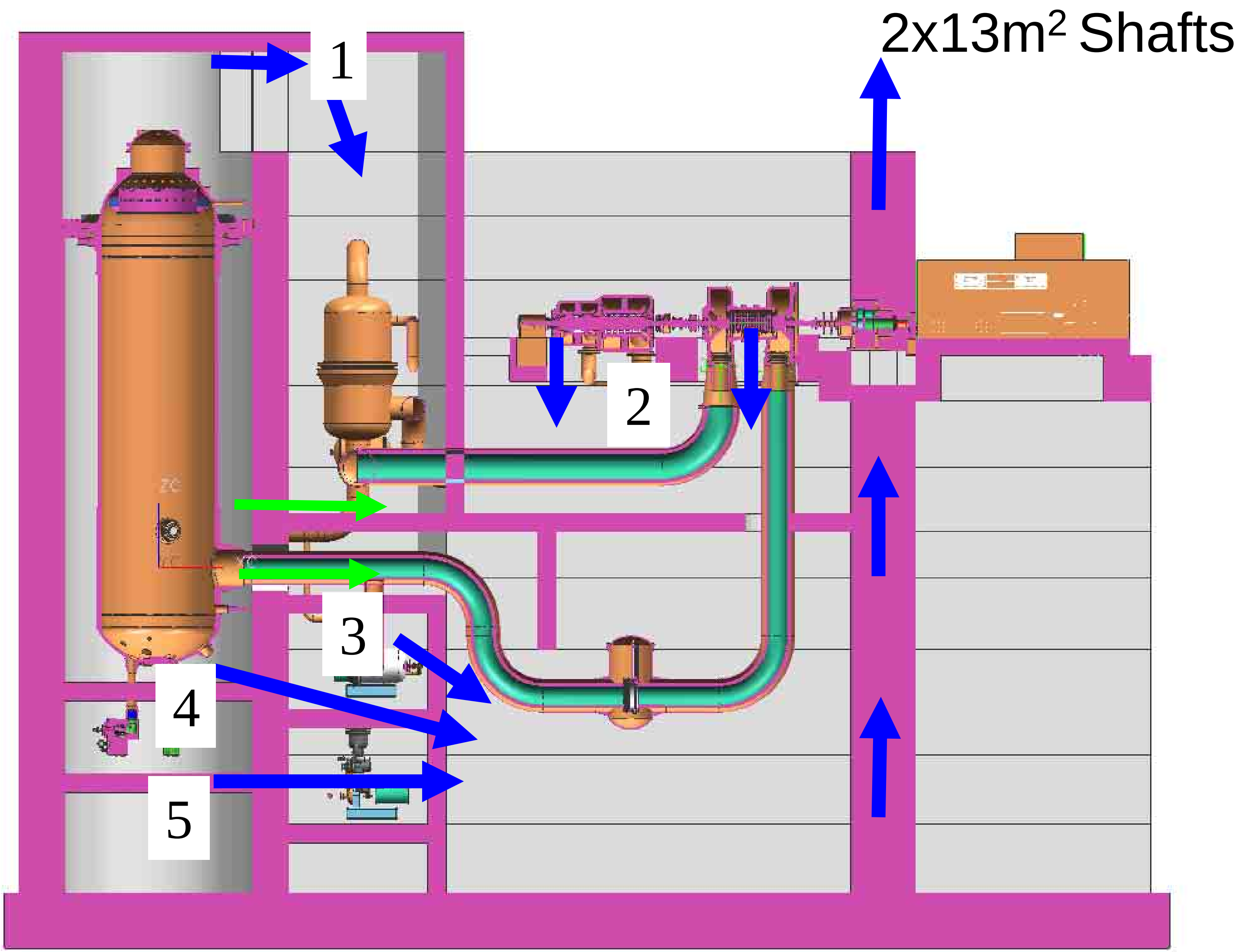
- **Circulating Activity**
  - Released from HPB with helium relatively quickly (minutes)
  - Amount of release depends on location and isolation and any operator actions to intentionally depressurize to HICS
- **Liftoff of Plateout and Dust**
  - Partial released from HPB with helium relatively quickly (minutes)
  - "Liftoff" physical and chemical phenomena include:
    - *Particulate entrainment: removal of dust, oxidic and metallic particles from surfaces*
    - *Desorption: removal of atoms or molecules sorbed from surfaces*
    - *Diffusion: transport of fission or activation products from surface inward or to and from particulates*
    - *Aerosol formation: mechanism by which the particulates are formed*
  - Amount of release depends on size of HPB leak or break that results in surface shear forces greater than normal operation flows


High Pressure Compressor
Low Pressure Compressor
Recuperator
Power Turbine
Gearbox
Reactor
Generator
Pre-Cooler
Intercooler
Core Conditioning System
Core Barrel Conditioning System
Maintenance Shutoff Disk

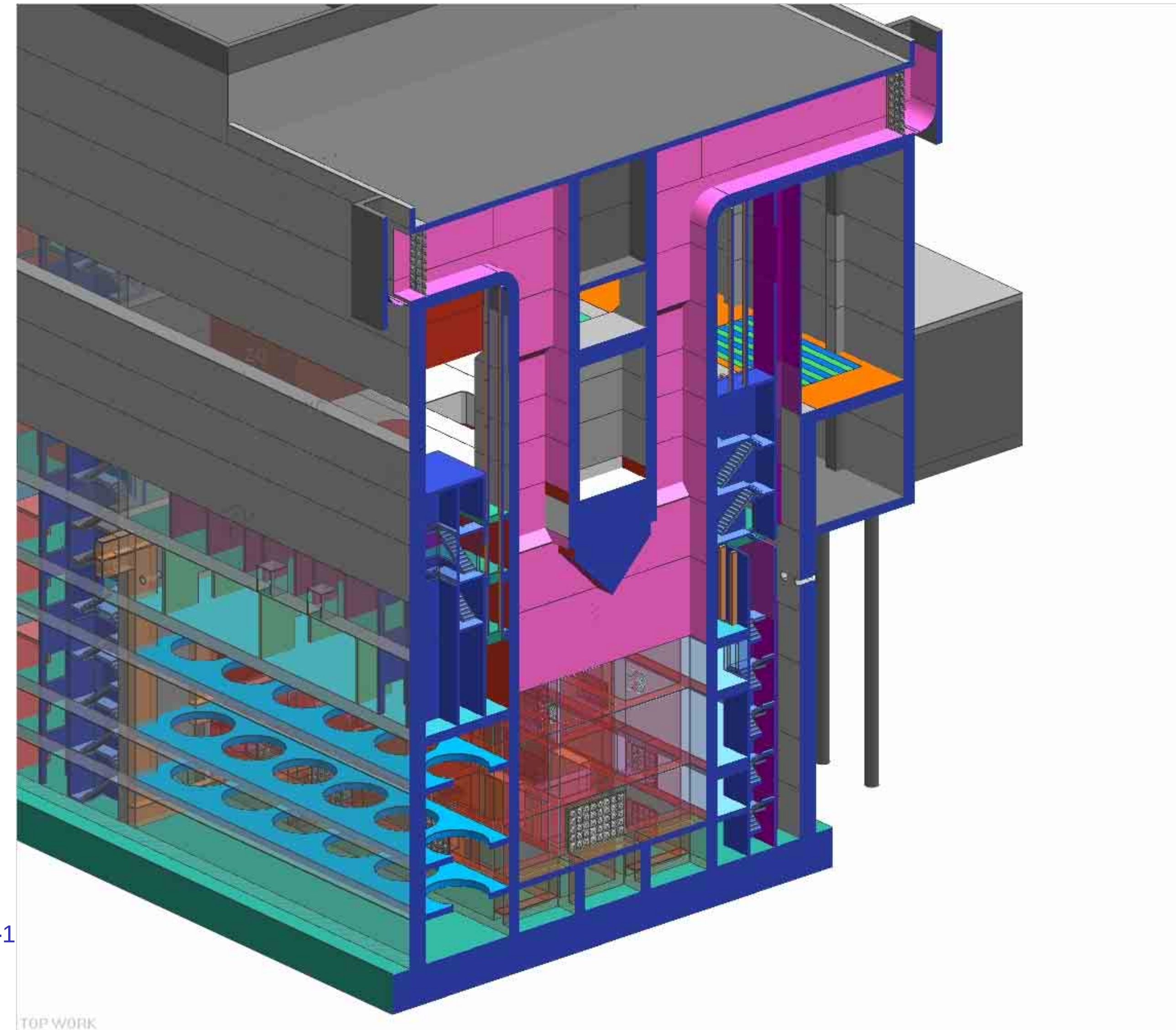
MPS Pressure Following HPB Leaks and Breaks



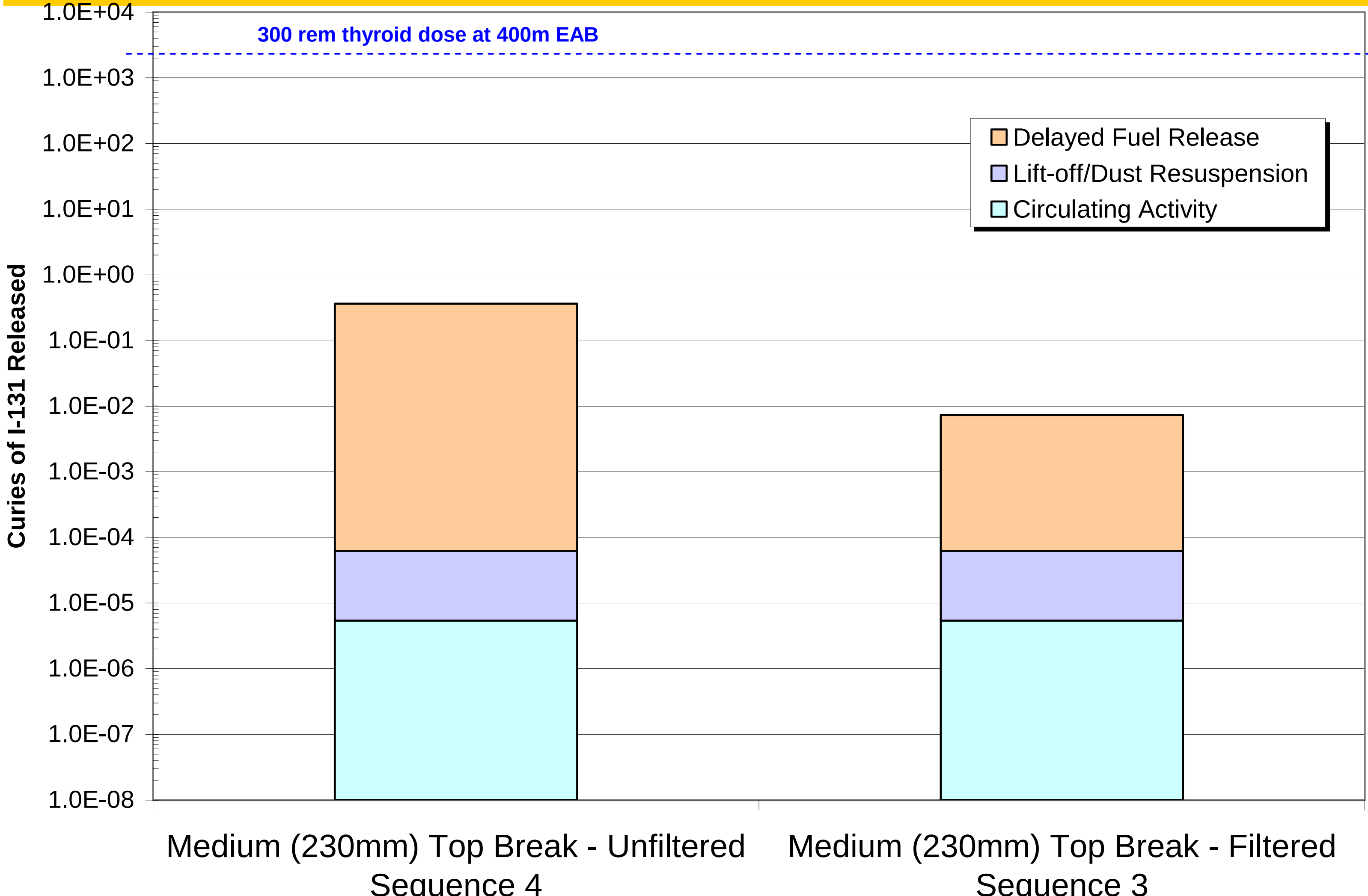
Depressurization Routes



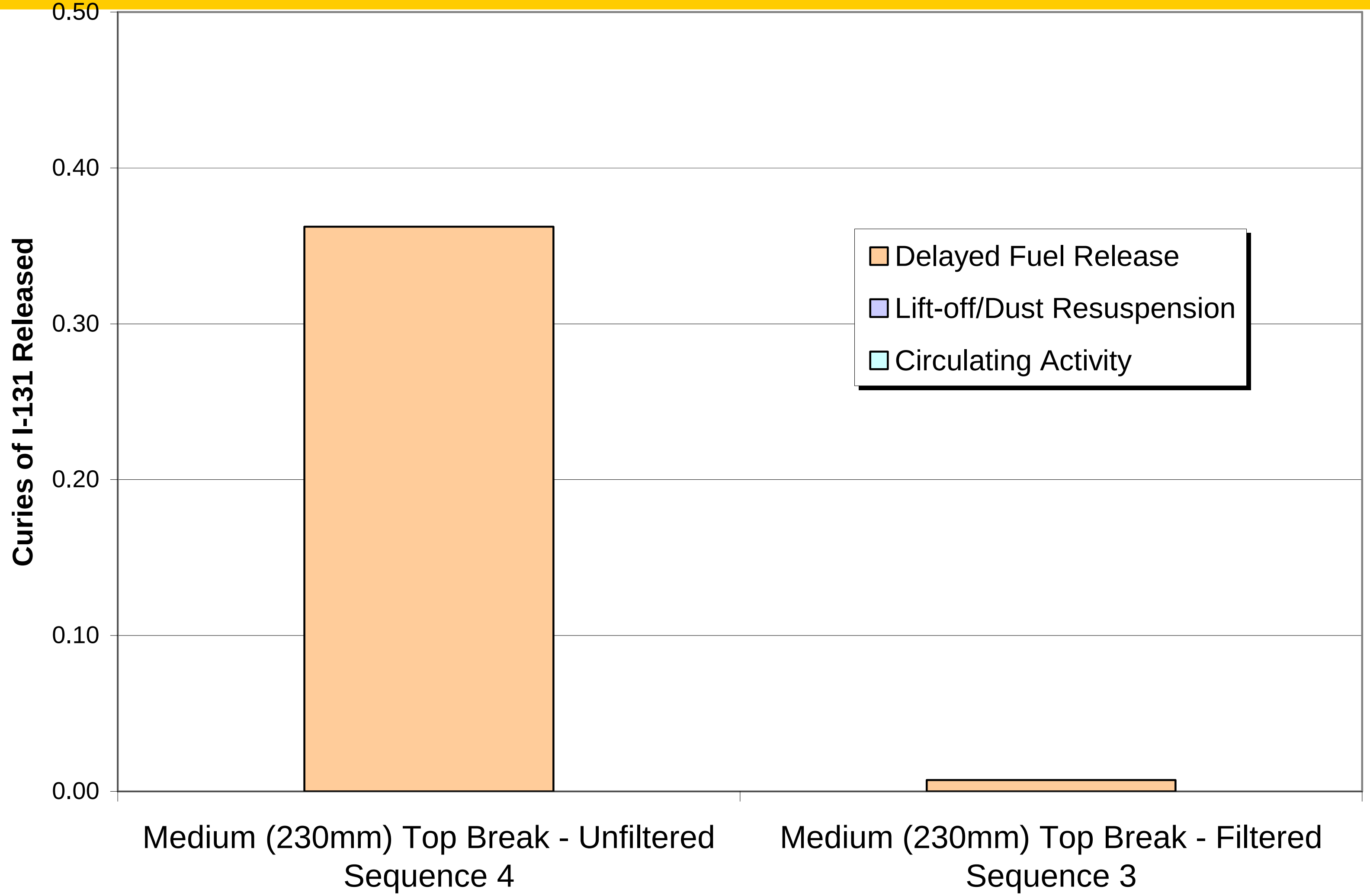
Vent Shaft Layout



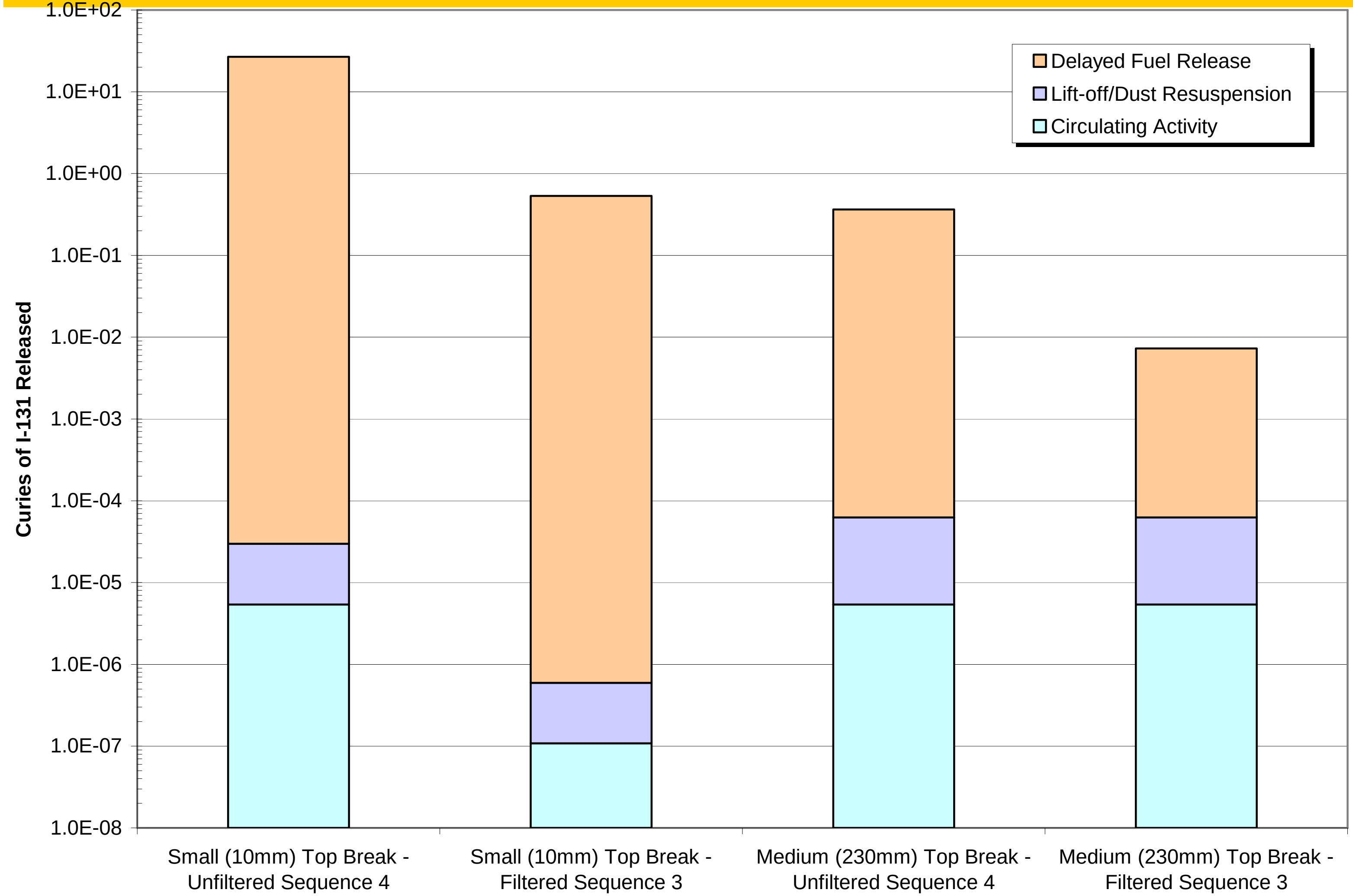
I-131 Release from Reactor Building During HPB Break DLOFC (log scale)



I-131 Release from Reactor Building During HPB Break DLOFC (linear scale)



Comparison of Medium and Small Break I-131 Reactor Building Release Source Terms



Medium HPB Break Event Summary

- **Event sequences with continued forced cooling via PCU or CCS involve:**
  - Decreasing peak and average core temperatures
  - SSC temperatures within code limits for transients
  - Immediate release of circulating activity and partial release of plateout via liftoff and resuspension of dust
  - Immediate release unfiltered
- **Event sequences with passive core heat removal via RCCS involve:**
  - Similar immediate release of circulating activity, liftoff, and dust
  - Delayed release from initially failed coated particles and contamination due to heatup
- **Medium leak reduces driving force for mass transport of delayed release**
- **Successful operation of PRS and HVAC provides consequence mitigation for delayed release only**
- **Moderate HPB break has lower consequences than small breaks**

Important PBMR Paradigm Shifts

- The fuel, helium coolant, and graphite moderator are chemically compatible under all conditions.
- The fuel has very large temperature margins in normal and accident conditions.
- The safety of the PBMR is not dependent on the presence of the helium coolant.
- The response times of the reactor are very long (days as opposed to seconds or minutes).
- There is no inherent mechanism for runaway reactivity excursions or power excursions.
- The PBMR has three concentric and independent radionuclide barriers.
- Accident phenomena can be modeled mechanistically.
- An LWR-type containment is neither advantageous nor necessarily conservative.

P B M R

Wrap-up