HTGR Technology Course for the Nuclear Regulatory Commission

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Module 14

HTGR Accident Analyses

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Technology Insights

Idaho National Laboratory

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Outline

- **Licensing basis event selection**

- **Event types and accident analysis results**
  - Challenges to core heat removal
  - Challenges to control of heat generation
  - Challenges to control of chemical attack

Context of Licensing Basis Events within Elements of Industry-Proposed Licensing Approach

- **What must be met**
  - Top Level Regulatory Criteria (TLRC)

- **When TLRC must be met**
  - **Licensing Basis Events**

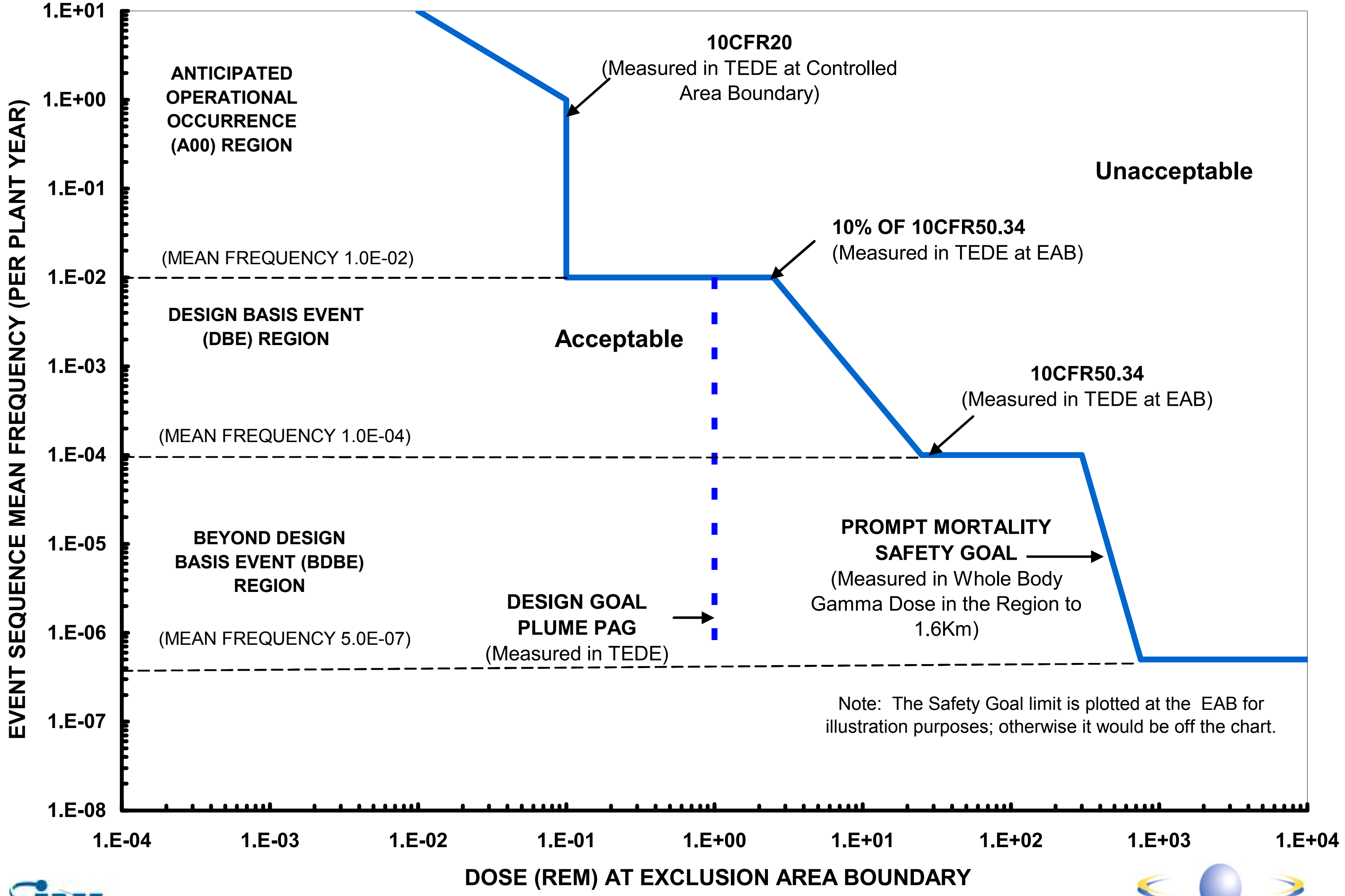
- **How TLRC must be met**
  - Safety Functions
  - SSC Safety Classification
  - Regulatory Design Criteria

- **How well TLRC must be met**
  - Deterministic DBAs
  - Defense-in-Depth
  - Regulatory Special Treatment

Industry Proposed Process for LBE Selection (1/3)

1. Define region boundaries
2. Compare risk assessment results to region dose limits
3. Identify as AOOs families of events in AOO region that could exceed 10CFR20 offsite doses if certain equipment or design features had not been selected
4. Evaluate AOO consequences including uncertainties and assure that mean consequences meet 10CFR20 offsite dose limits

Industry Proposed Licensing Basis Event Regions



Note: The Safety Goal limit is plotted at the EAB for illustration purposes; otherwise it would be off the chart.

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Industry Proposed Process for LBE Selection (2/3)

5. Identify as DBEs families of events in DBE region that could exceed 10CFR50.34 doses if certain equipment or design features had not been selected
6. Evaluate consequences of any DBEs with upper bound uncertainty in the AOO region and assure that the mean consequence meets 10CFR20 offsite dose limits
7. Evaluate DBE consequences including uncertainties and assure that the mean consequence of each meets the EPA Protective Action Guidelines at the EAB site boundary (design goal)
8. Select deterministic Design Basis Accidents (DBAs) from the DBEs by assuming that only SSCs relied on to meet 10CFR50.34 (those classified as Safety Related) are available
9. Evaluate DBEs and deterministic DBA consequences including uncertainties and assure that the upper bound consequences meet 10CFR50.34 offsite dose limits

Pebble Bed Example of Safety Classification for Core Heat Removal Function

Are SSCs Available and Sufficient to Remove Core Heat in the DBE?							**SSCs Classified as Safety Related?**
Alternative Sets of SSCs	**DBE 1c**	**DBE 2b**	**DBE 6c**	**DBE 7a**	**DBE 7b**	**DBE 11b**	
Reactor PCU ACS	***No***	***No***	***No***	***No***	***No***	***No***	
Reactor SBS ACS	***No***	***No***	***No***	***Yes***	***No***	***No***	
Reactor CCS ACS	***No***	***Yes***	***No***	Yes	***Yes***	***Yes***	
Reactor Reactor vessel Active RCCS ACS	***Yes***	Yes	***Yes***	Yes	Yes	Yes	
Reactor Reactor vessel Passive RCCS	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reactor Reactor vessel Building & ground	Yes	Yes	Yes	Yes	Yes	Yes	

Note: ***Italics*** indicates response during DBE

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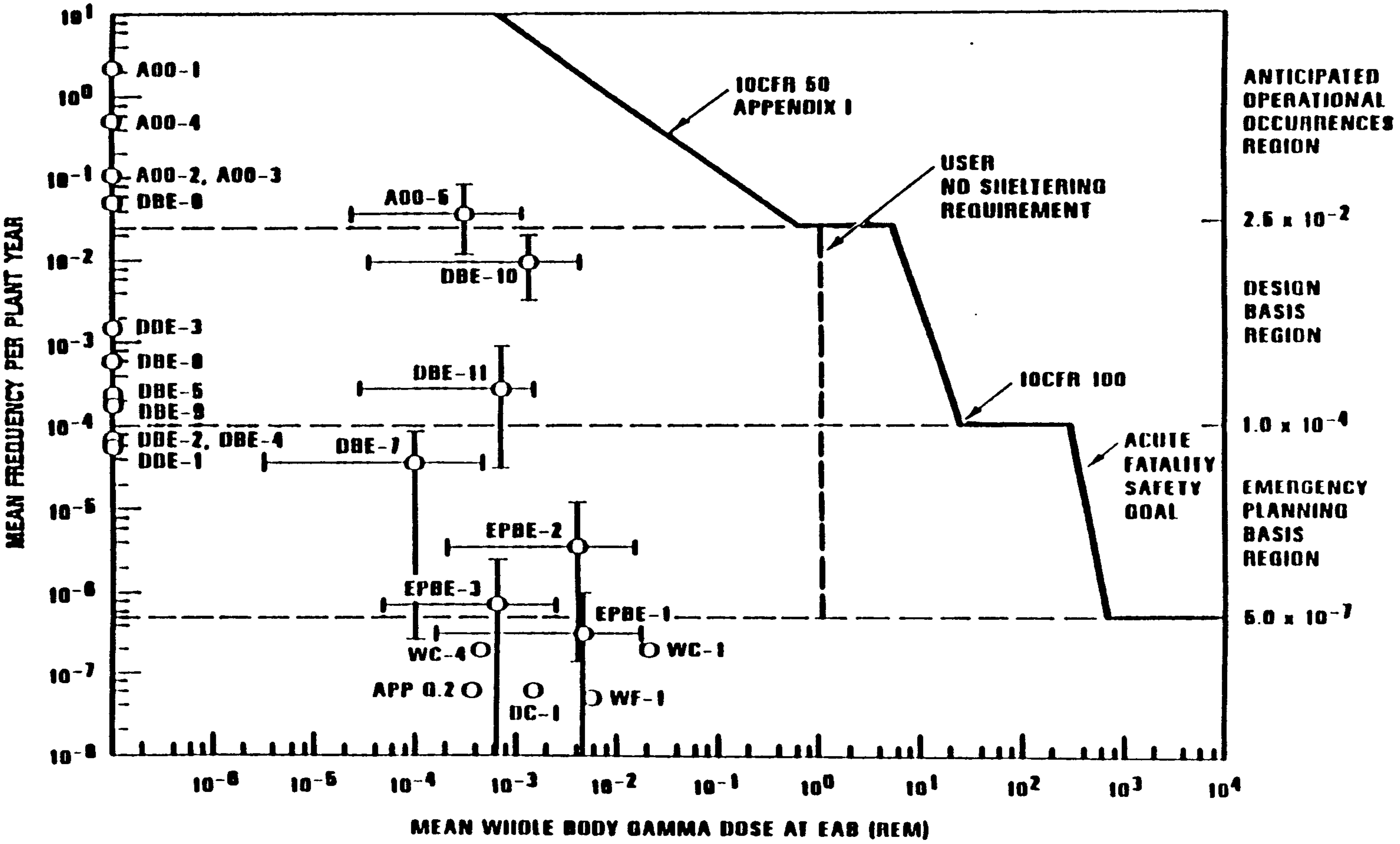
Industry Proposed Process for LBE Selection (3/3)

10. Identify as BDBEs the dose-dominant families of events in BDBE region
11. Evaluate consequences of any BDBEs with upper bound uncertainty in the DBE region and assure that the upper bound consequence of each meets 10CFR50.34 offsite dose limits
12. Evaluate BDBE consequences including uncertainties and assure that the mean consequence of each meets the EPA Protective Action Guidelines (design goal)
13. Evaluate overall cumulative risk including all LBEs and assure NRC safety goal quantitative health objectives (51FR130) are met
14. Assure that residual risk is negligible

Prismatic MHTGR Licensing Basis Events



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- **Licensing basis event selection**
- **Event types and accident analysis results**
  - Challenges to core heat removal
  - Challenges to control of heat generation
  - Challenges to control of chemical attack

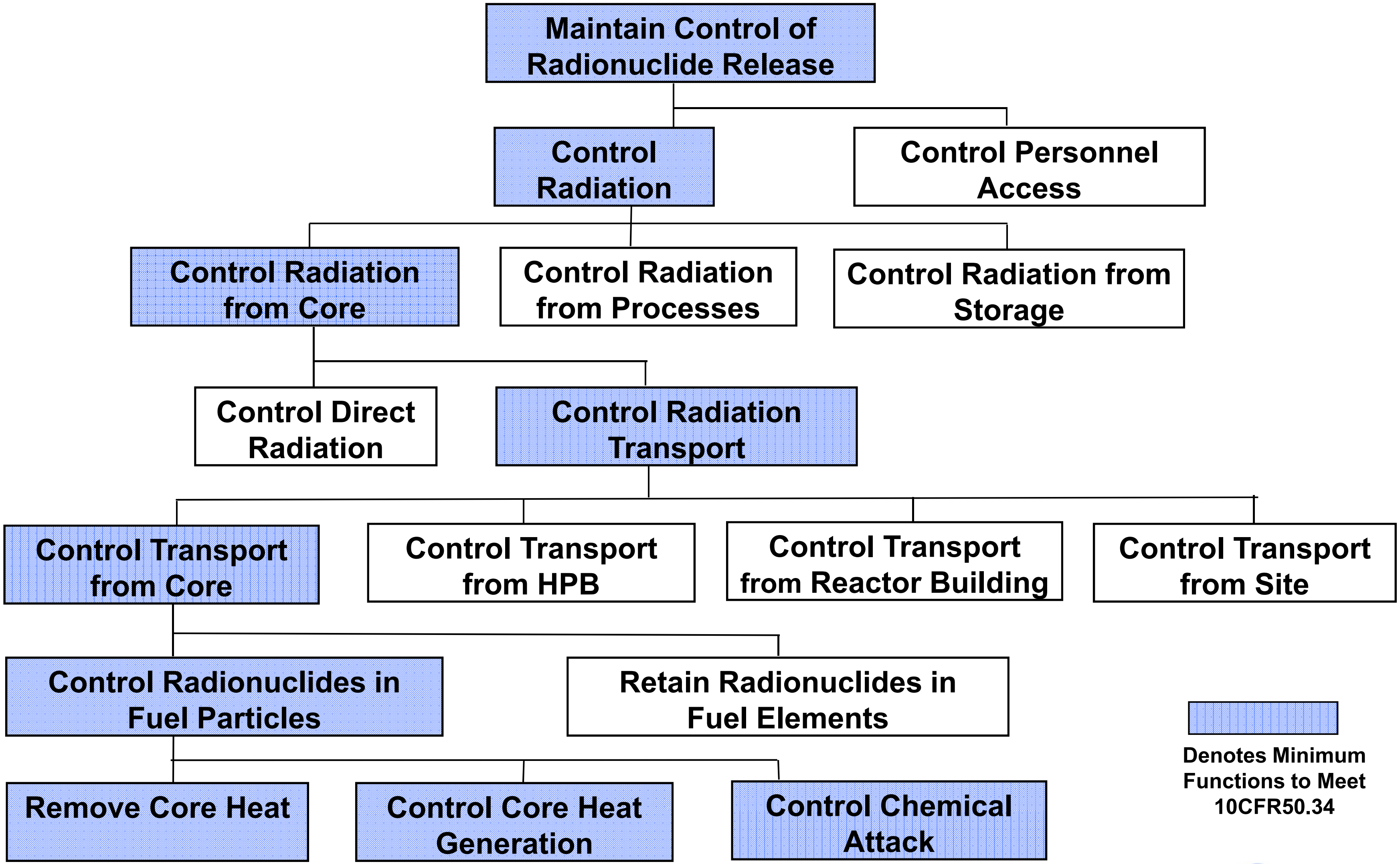
Modular HTGR Accident Safety Evaluations

- **Challenges to core heat removal**
  - Loss of heat transport (HTS) & shutdown forced cooling systems (SCS/CCS)
    (Pressurized conduction cooldown or PLOFC)
  - Depressurization and Loss of HTS & SCS/CCS
    (Depressurized conduction cooldown or DLOFC)

- **Challenges to control heat generation**
  - Accidental control rod withdrawal
  - Station blackout without trip

- **Challenges to control chemical attack**
  - Water/steam ingress from SG tube break
  - Air mixture ingress from RB following HPB leaks/breaks

Functions for Control of Radionuclide Release



- ▨ Maintain Control of Radionuclide Release
  - ▨ Control Radiation
    - ▨ Control Radiation from Core
      - Control Direct Radiation
      - ▨ Control Radiation Transport
        - ▨ Control Transport from Core
          - ▨ Control Radionuclides in Fuel Particles
            - ▨ Remove Core Heat
            - ▨ Control Core Heat Generation
            - ▨ Control Chemical Attack
          - Retain Radionuclides in Fuel Elements
        - Control Transport from HPB
        - Control Transport from Reactor Building
        - Control Transport from Site
    - Control Radiation from Processes
    - Control Radiation from Storage
  - Control Personnel Access

▨ Denotes Minimum Functions to Meet 10CFR50.34

Pebble Bed Relative I-131 Inventories within HPB

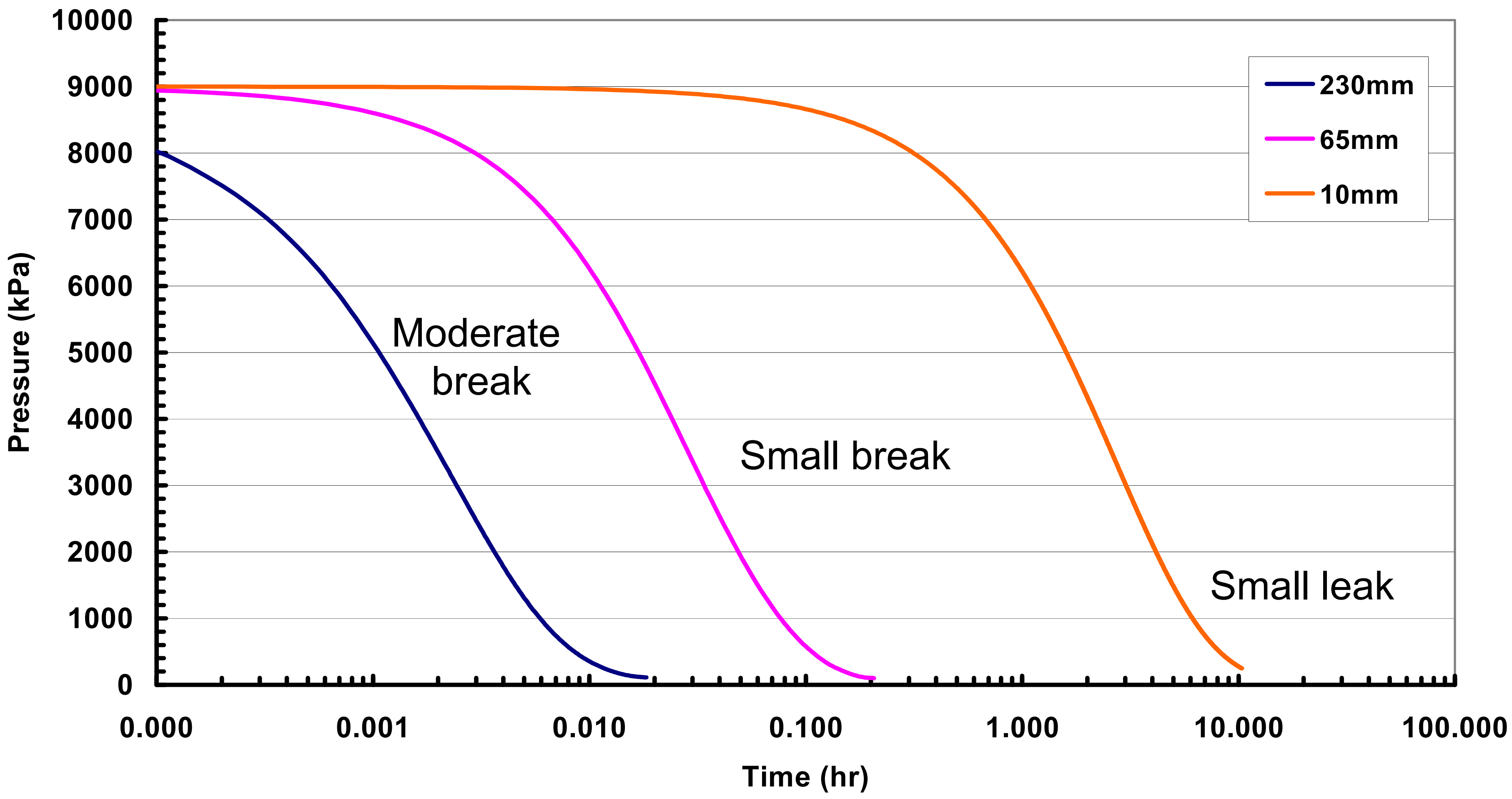
Source	I-131 400MWt Inventory (Ci)
Circulating activity	<<1
Plateout on internal Helium Pressure Boundary (HPB) surfaces	<1
Uranium contaminated fuel particles	~20
Failed and defective fuel particles	~580
Intact fuel particles	1×10^7

Circulating Activity, Plateout, and Dust Release

- Circulating activity
  - Released from HPB with helium in minutes to days as a result of HPB leak/break
  - Amount of release depends on location and any operator actions to isolate and/or intentionally depressurize

- Liftoff of plateout and resuspension of dust
  - 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
  - For large breaks partial release from HPB with helium relatively quickly (minutes)
  - Amount of release depends on HPB break size that results in surface shear forces greater than normal operation flows

Pebble Bed Main Power System (MPS) Pressure Following HPB Leaks and Breaks (400MWt)



Pebble Bed Shear Force Ratio (SFR) Results for Range of HPB Leak/Break Sizes at Core Inlet Plenum (CIP)

SFR vs. CIP Equivalent Break Size for 500MWt PBMR Design				
	10mm	**30mm**	**100mm**	**230mm**
Reactor Inlet	0.03	0.04	0.83	2.3
Reactor Outlet	0.02	0.02	0.99	1.0
Reactor Lower Volume	0.07	0.08	0.99	2.4
CCS Inlet Connection	0.02	0.02	0.95	1.0
IHX Inlet	0.01	0.01	0.23	1.0
Circulator Outlet	0.01	0.01	0.02	1.0

Breaks ≤100mm have SFR <1: insignificant dust resuspension and liftoff

Removal of Core Heat Accomplished by Passive Safety Features

- **Small thermal rating/low power density**
  - Limits amount of afterheat
  - Low linear heat rate

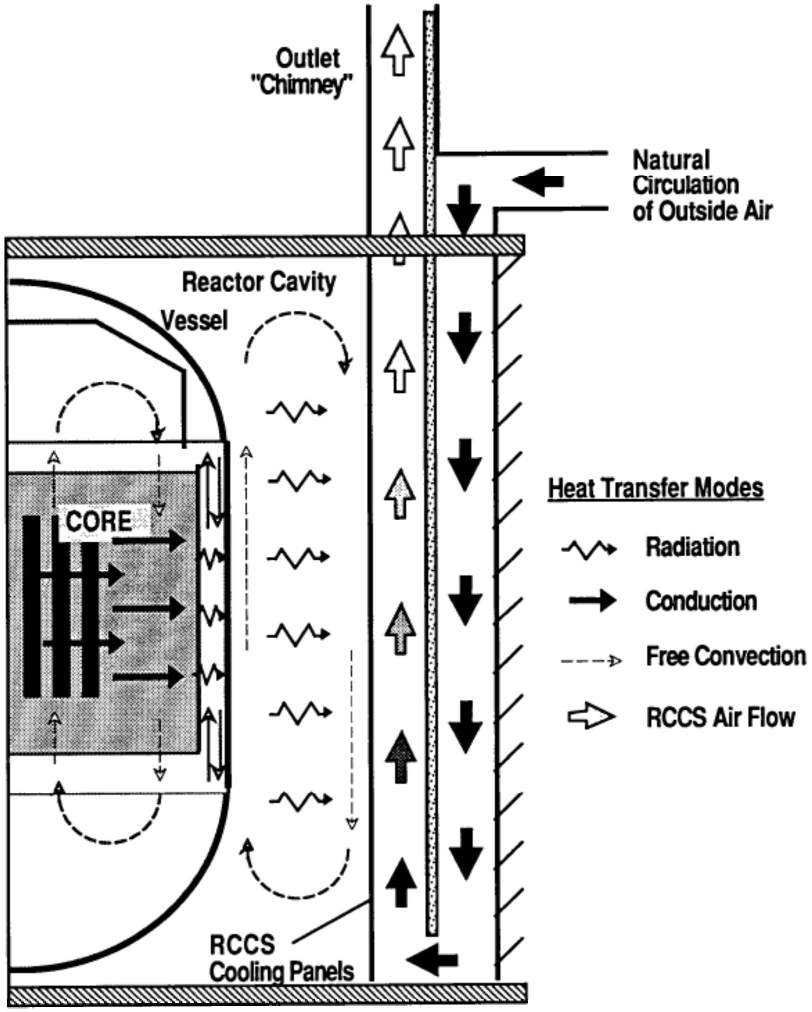
- **Core annular/cylindrical geometry**
  - Heat removal by passive conduction and radiation mechanisms
  - High heat capacity graphite
  - High temperature core materials

SSCs Supporting Core Heat Removal

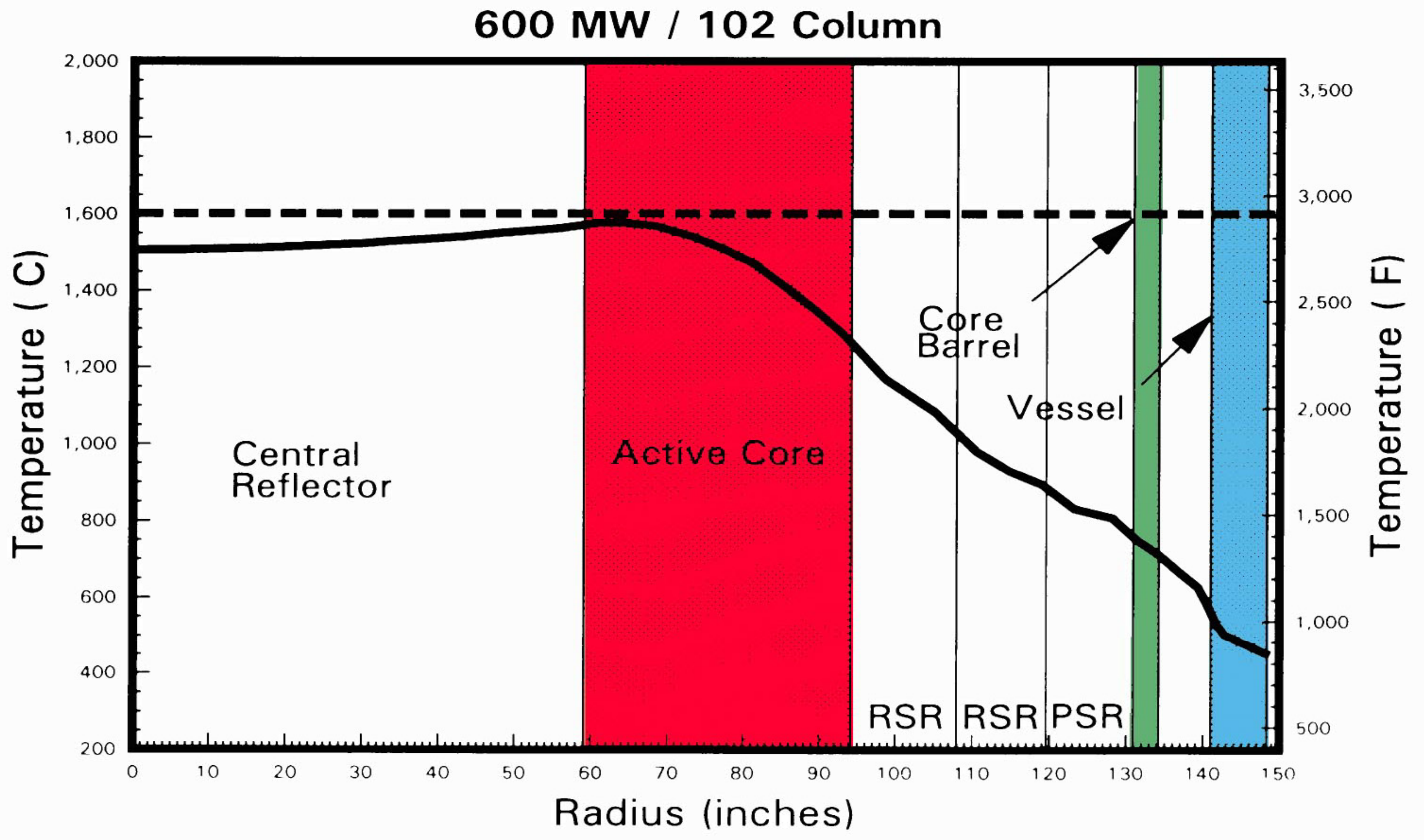
Active and **passive** engineered systems

- Heat Transport System (HTS)/ Main Power System (MPS)
- Shutdown Cooling System (SCS)/ Core Conditioning System (CCS)
- Helium Purification System Post Accident Train (Pebble Bed HPS PAT)
- **Reactor Cavity Cooling System (RCCS)**
  - Active mode
  - **Passive mode**

Passive Heat Transfer to Air-Cooled RCCS



Prismatic DCC Peak Fuel Temperatures



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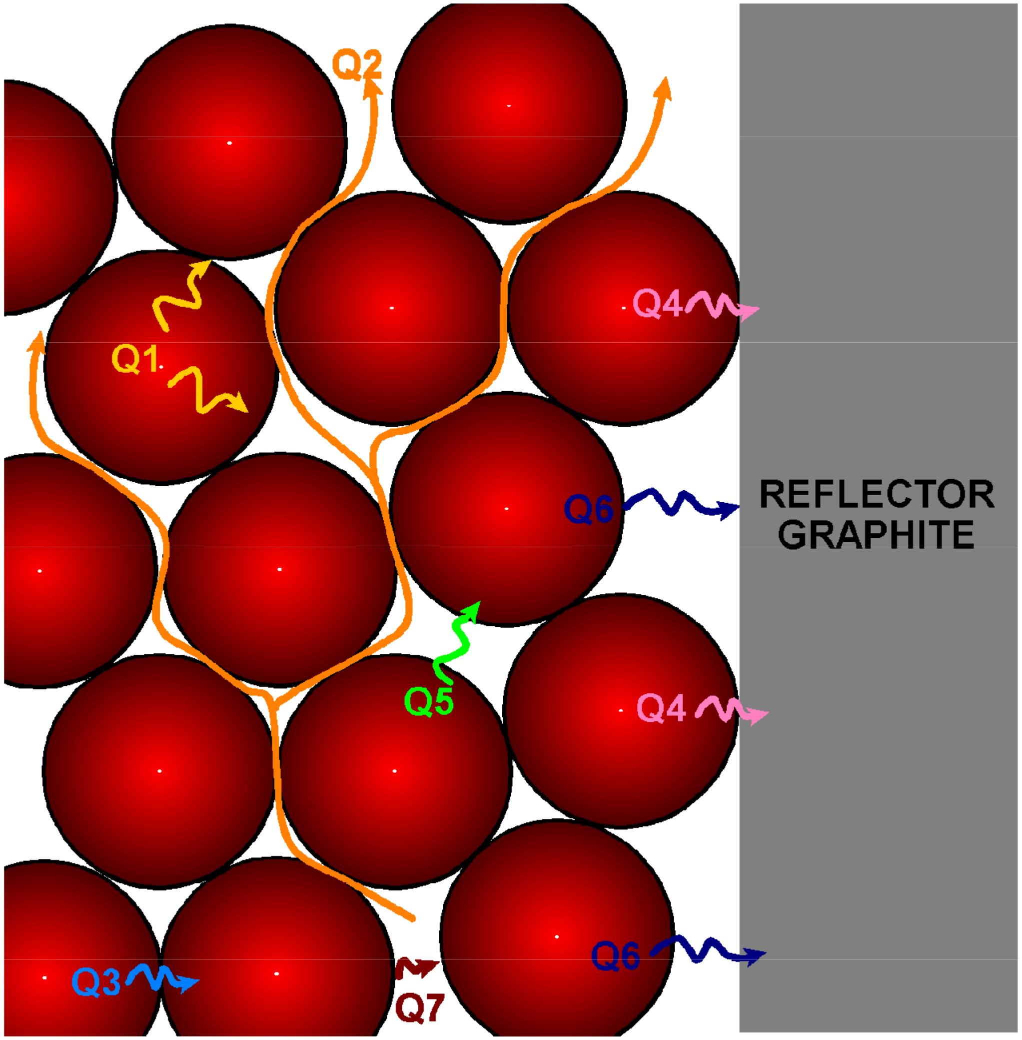
Heat Transfer in the Pebble Bed



Q1: Conduction from the centre of the pebble to the surface

Q2: Convection from the pebble surface to the gas

Q3: Point contact conduction between the pebble surfaces that are in contact with one another

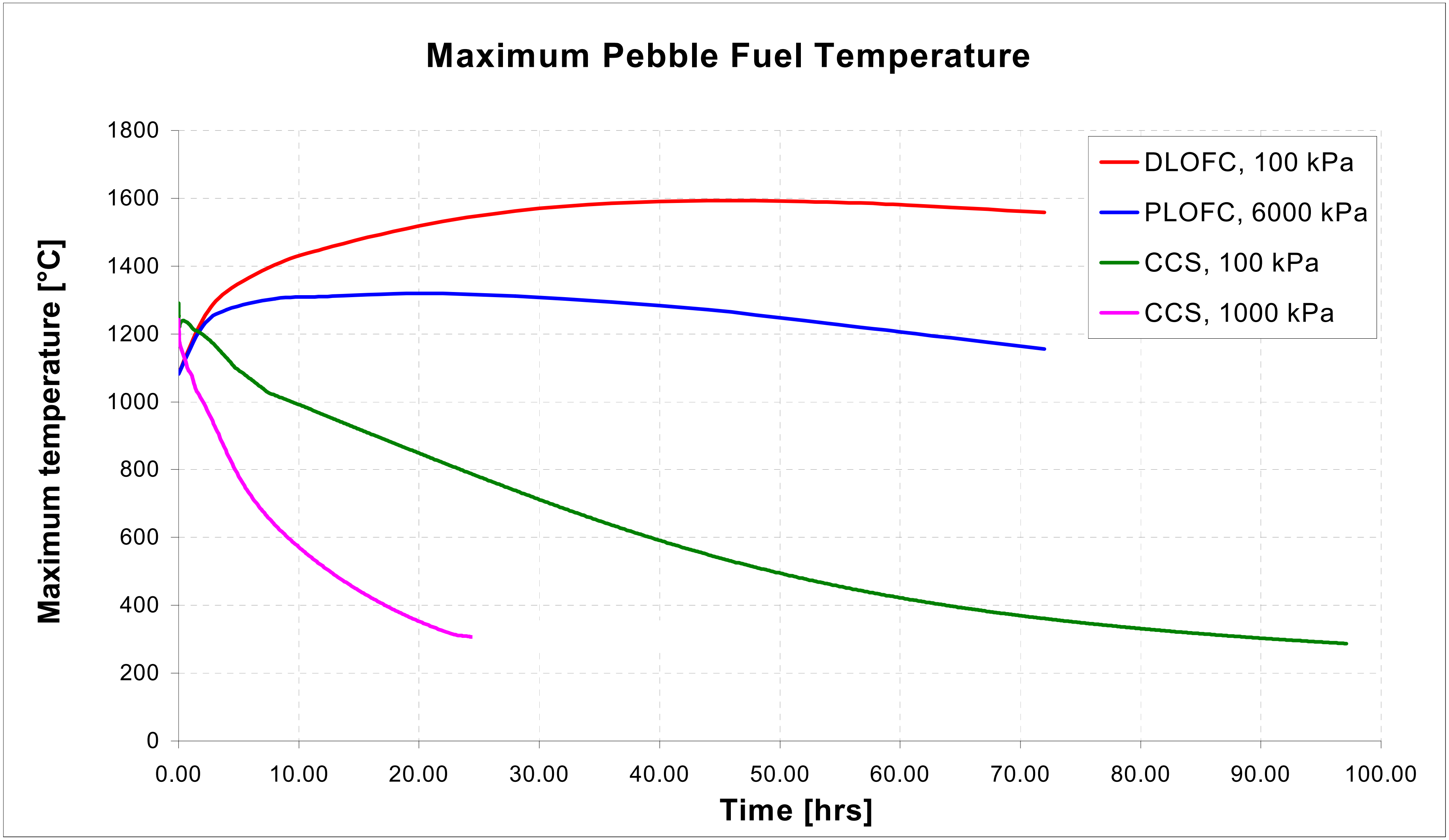
Q4: Point contact conduction between the pebble surfaces that are in contact with the reflector

Q5: Thermal radiation between the pebble surfaces

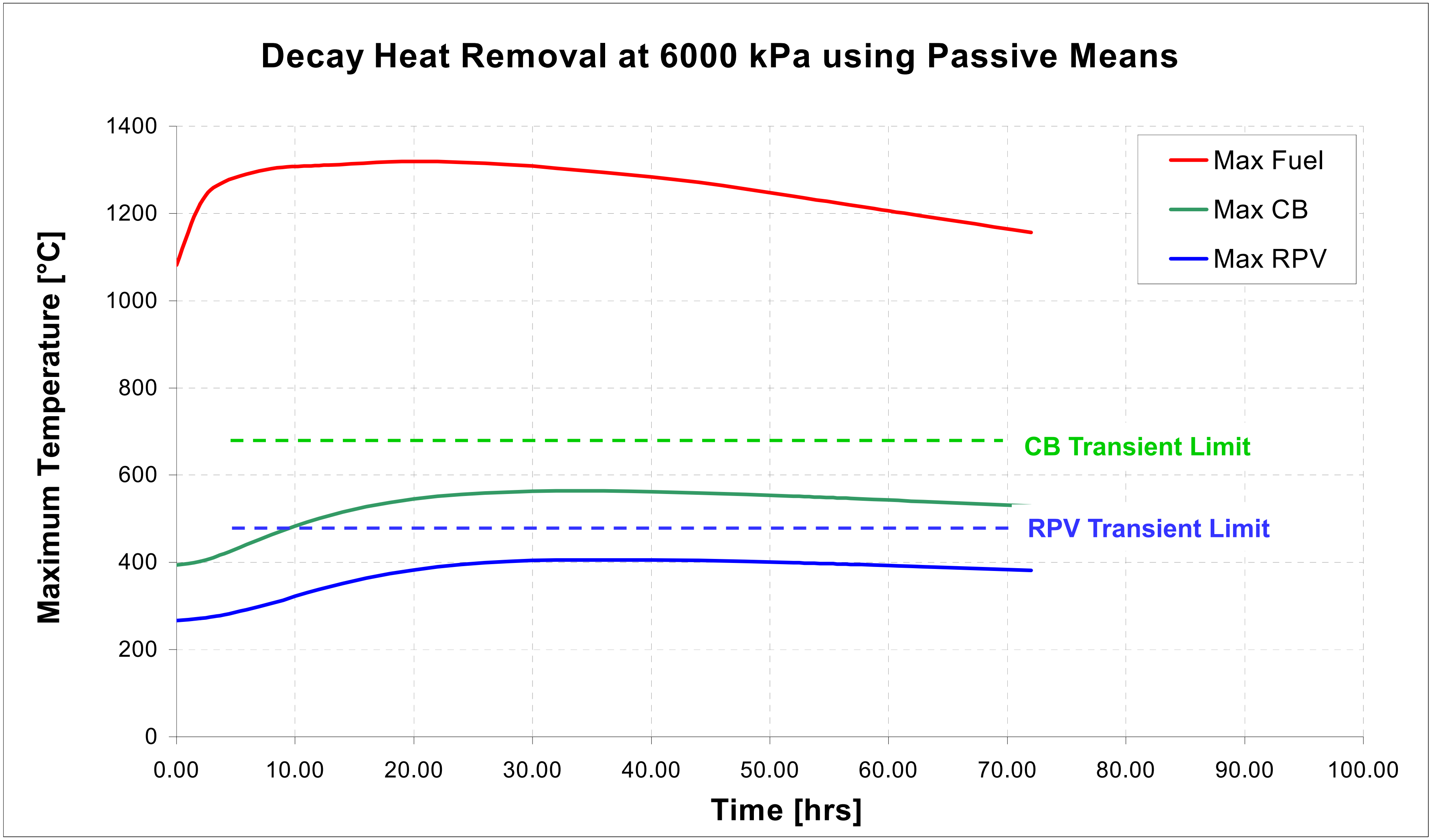
Q6: Thermal radiation between the pebble surfaces and the reflector

Q7: Conduction in the gas

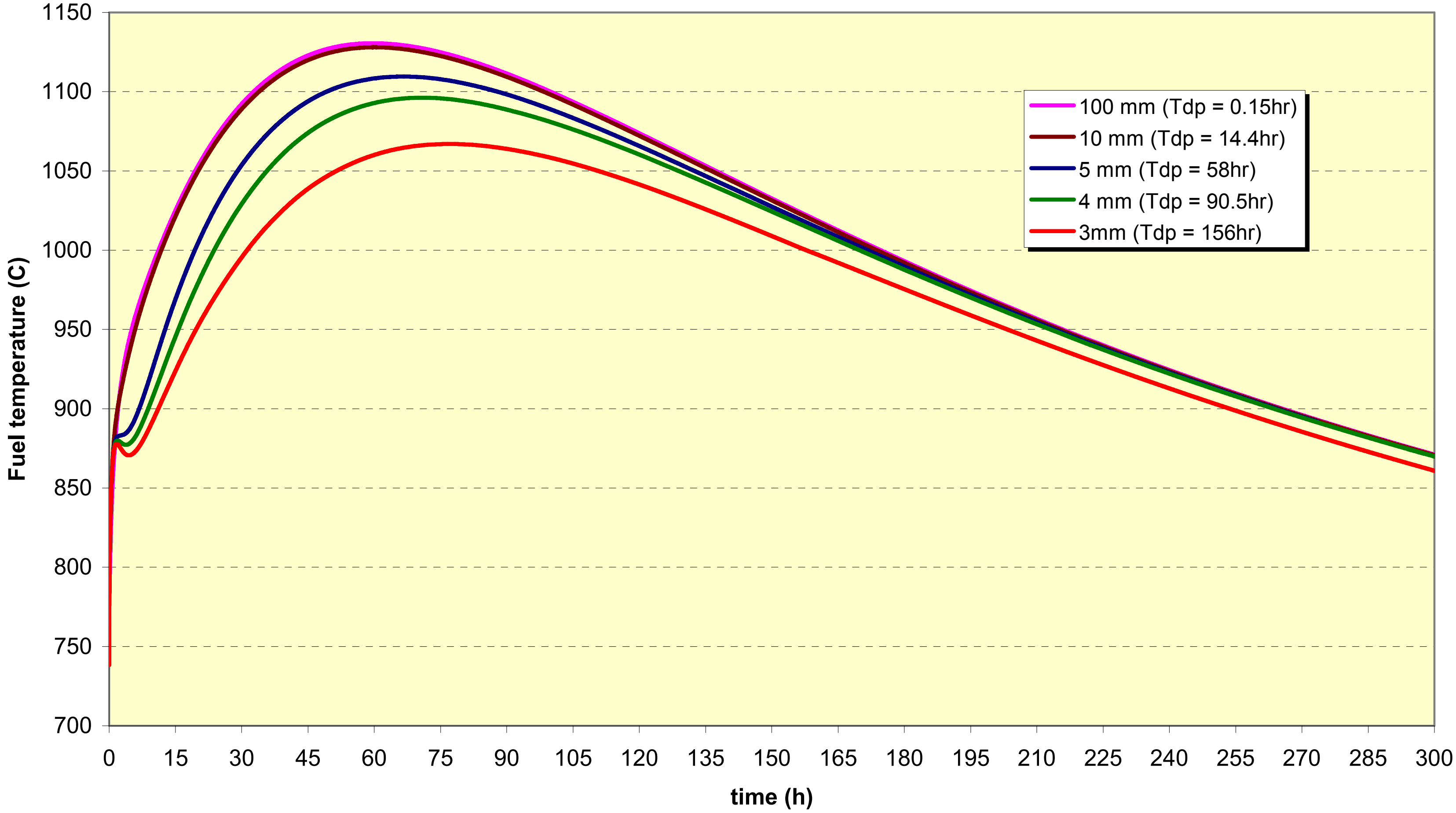
Pebble Bed Fuel Temperatures with Forced Core Cooling (CCS) & Passive Conduction Cooldown (400MWt)



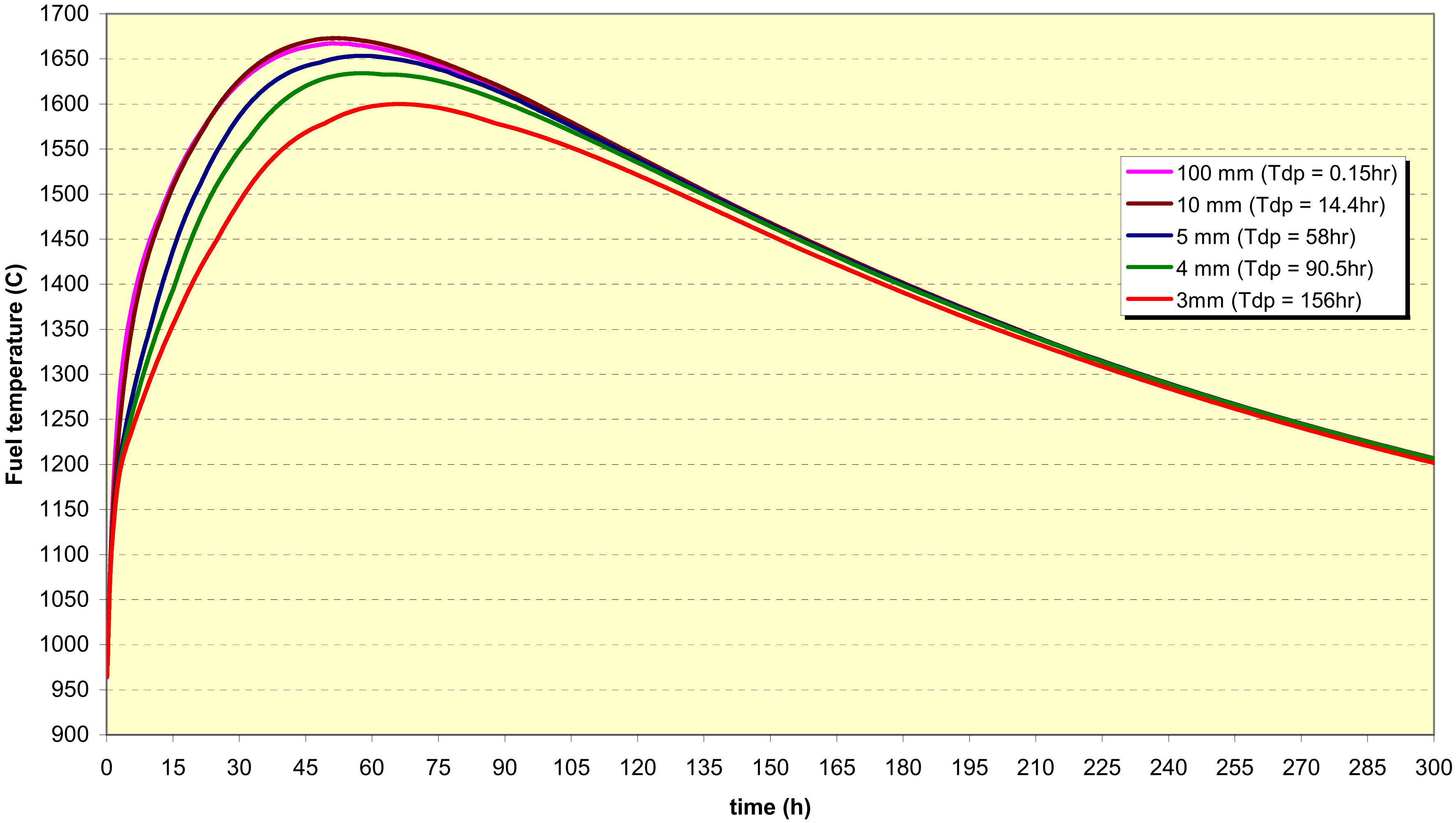
Pebble Bed Temperatures for PLOFC (400MWt)



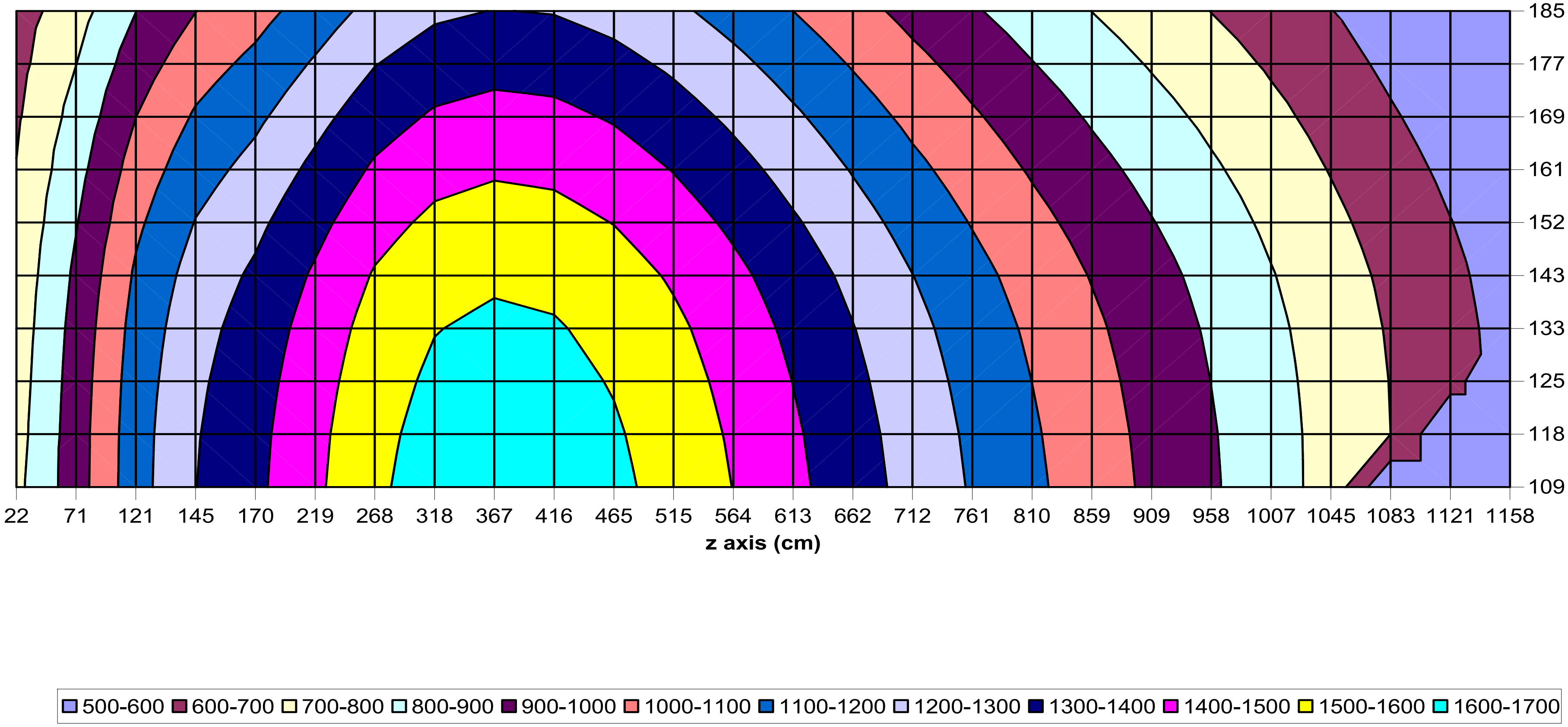
Pebble Bed DLOFC Core Average Fuel Temperature (500MWt)



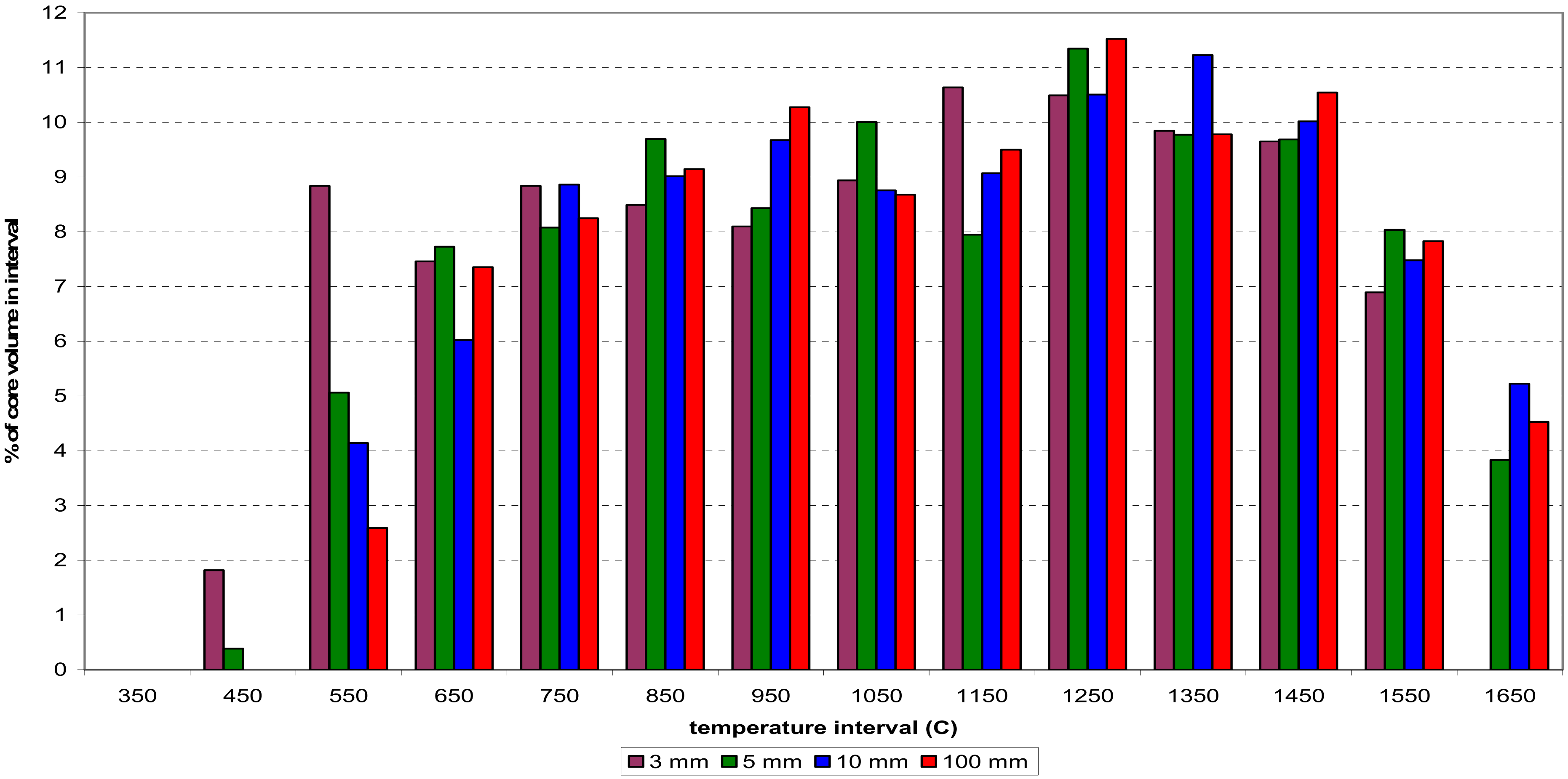
Pebble Bed DLOFC Maximum Fuel Temperature (500MWt)



Pebble Bed Spatial DLOFC Maximum Fuel Temperature (53hr) for 100mm Break (500MWt)



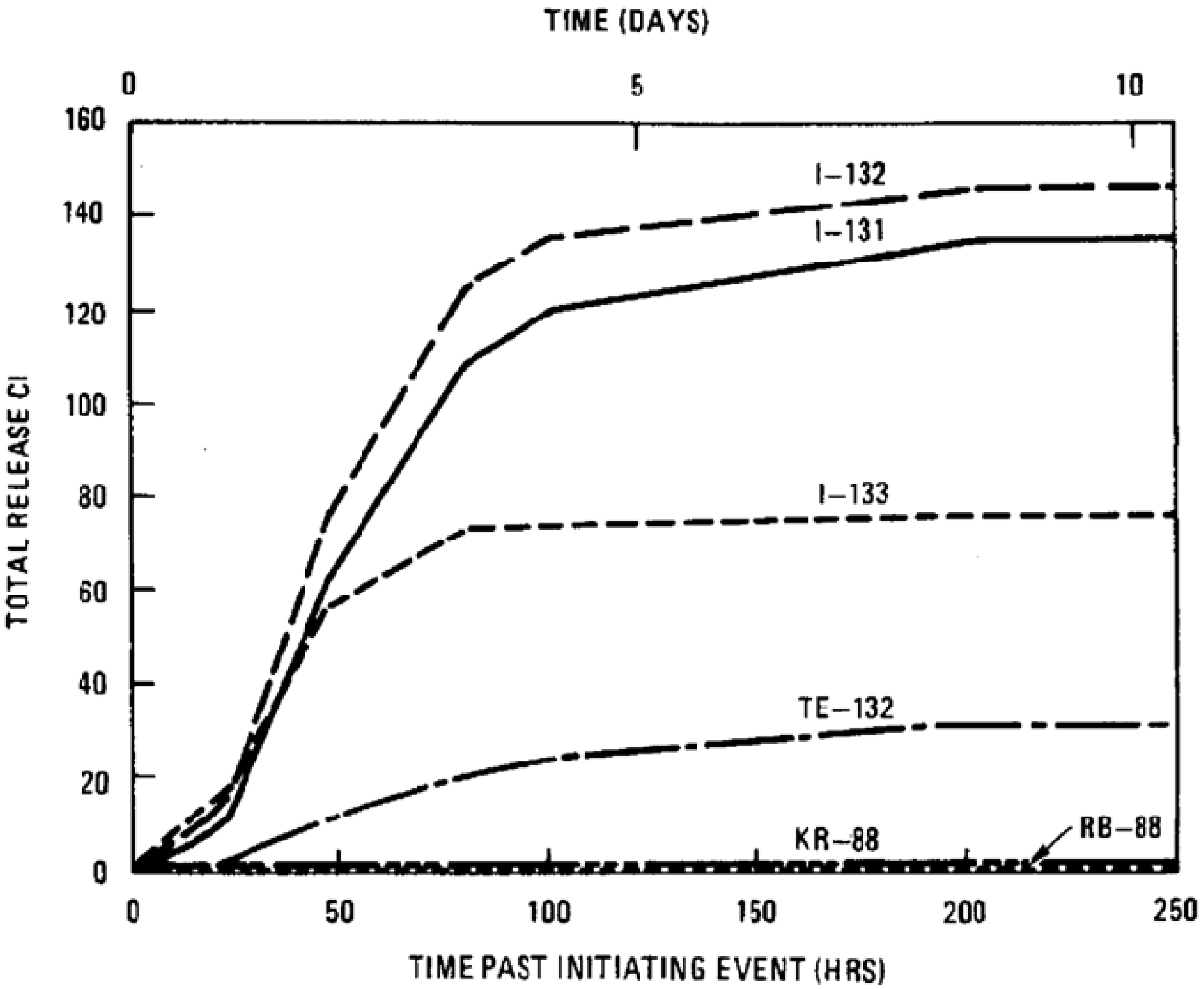
Pebble Bed DLOFC Temperatures Showing % of Fuel Volume at 50 Hr (500MWt)



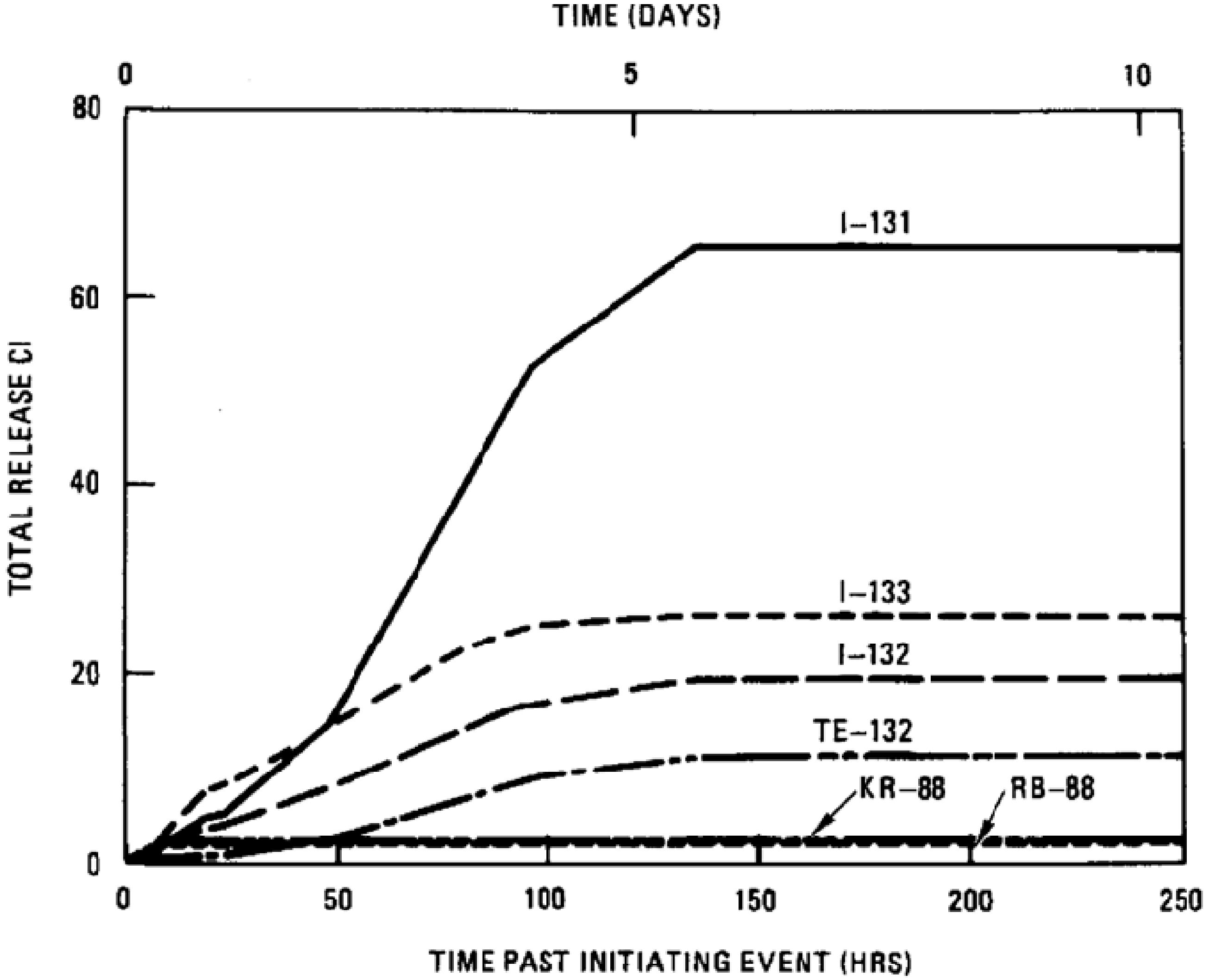
Delayed Fuel Release Mechanisms

- **Partial release 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
  - Dependent on 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 mixture within the HPB**
  - Small leaks have greater releases from HPB
  - Releases cease when the HPB internal system temperature decreases due to core temperature cooldown

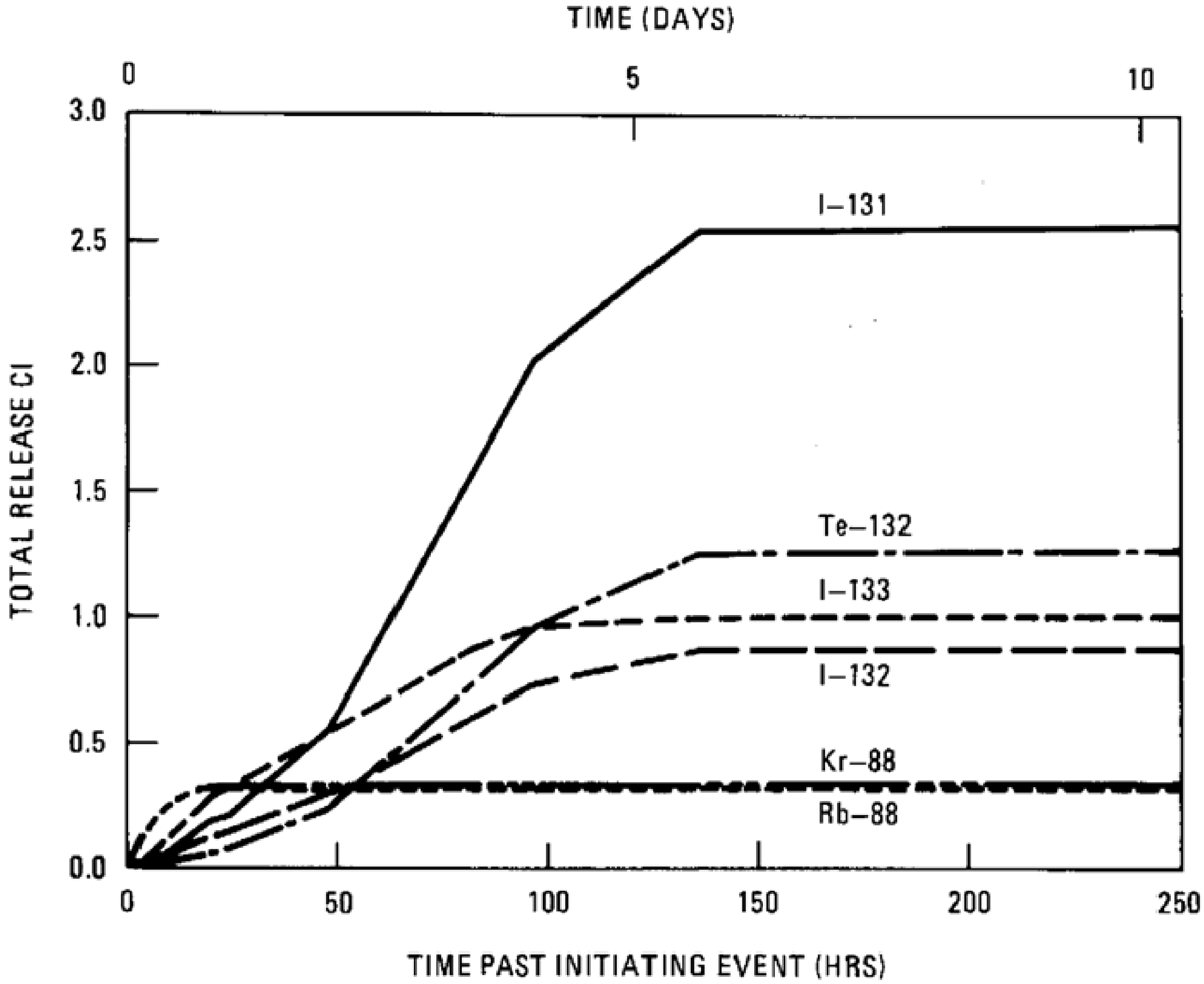
Prismatic Cumulative RN Releases from Fuel During DCC (350MWt)



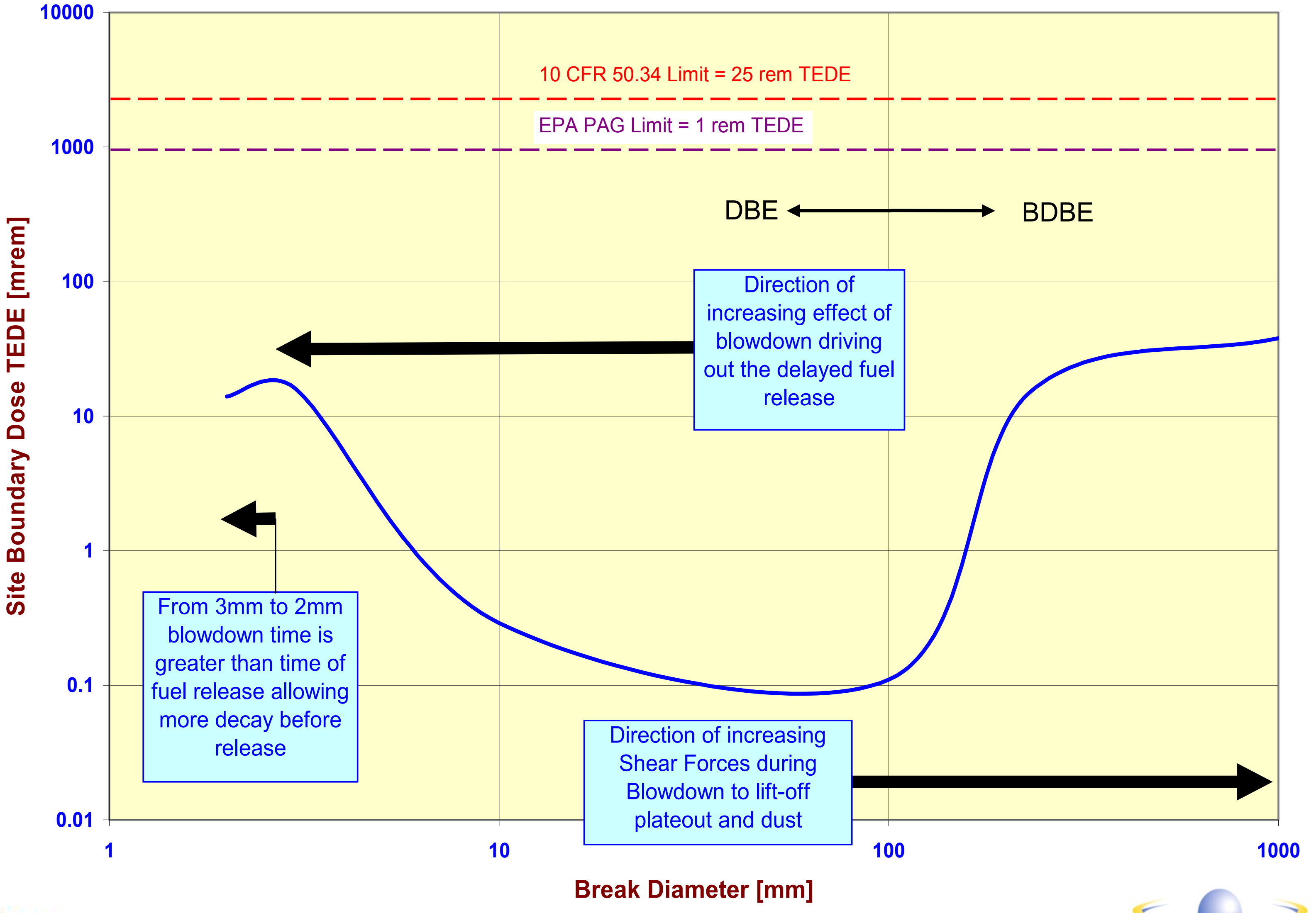
Prismatic Cumulative RN Releases from HPB During Small Leak DCC (350MWt)



Prismatic Cumulative RN Releases from RB During Small Leak DCC (350MWt)



Pebble Bed DLOFC Dose as a Function of HPB Leak/Break Size for Vented RB (500MWt)



Outline

- **Licensing basis event selection**

- **Event types and accident analysis results**
  - Challenges to core heat removal
  - ➡ Challenges to control of heat generation
  - Challenges to control of chemical attack

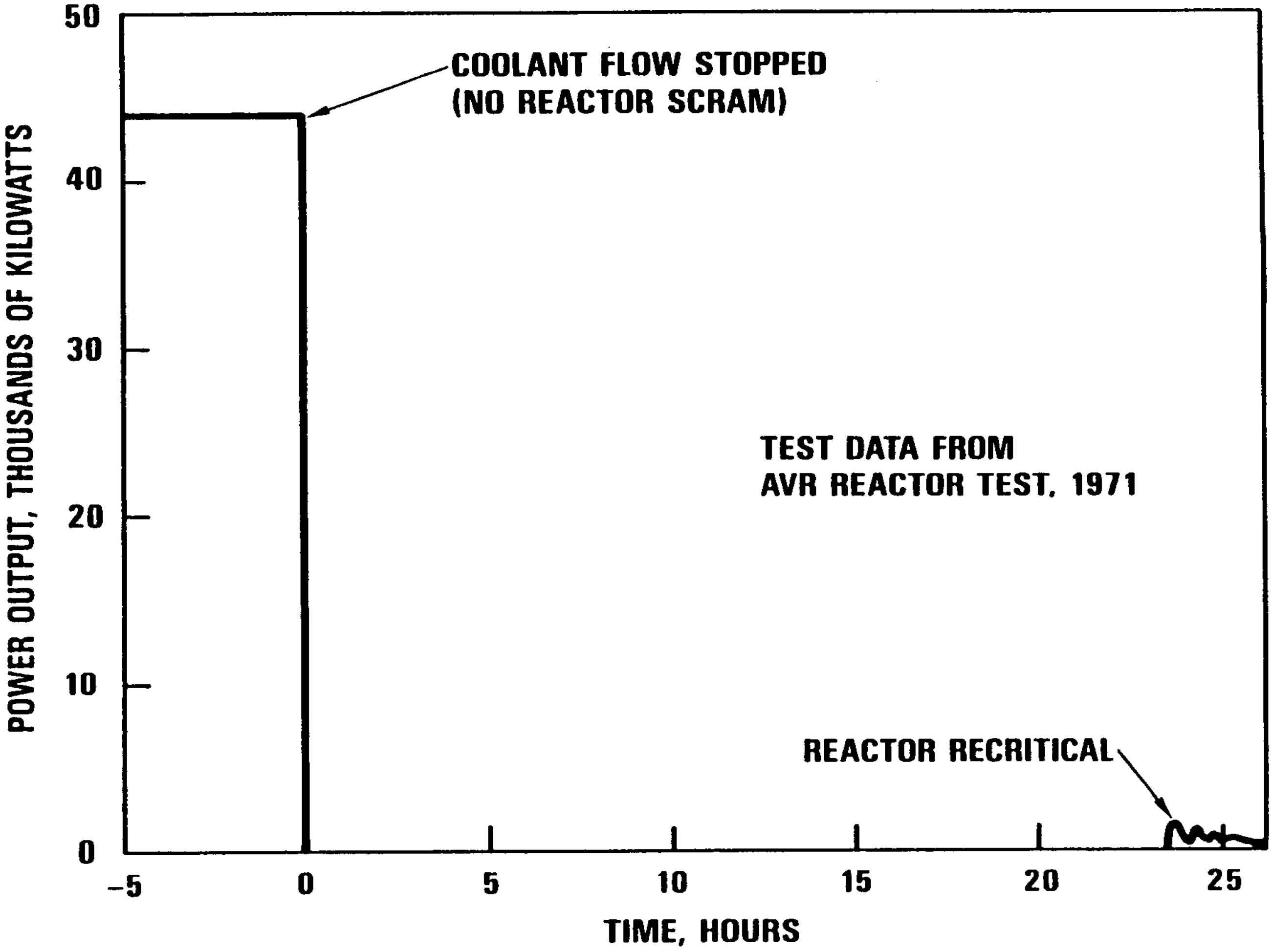
HTGR Control of Heat Generation

- Continued functioning of reactor shutdown system only necessary for long-term shutdown
  - Negative temperature coefficient for reactivity
    - Temperature differential of 750K maintained between operational and maximum allowable fuel temperature
    - Reactor shuts itself down before maximum fuel temperature reached
  - Limited excess reactivity
  - Integrity of core structures
    - Ceramic core structures and fuel elements
    - Simple and robust core structure design

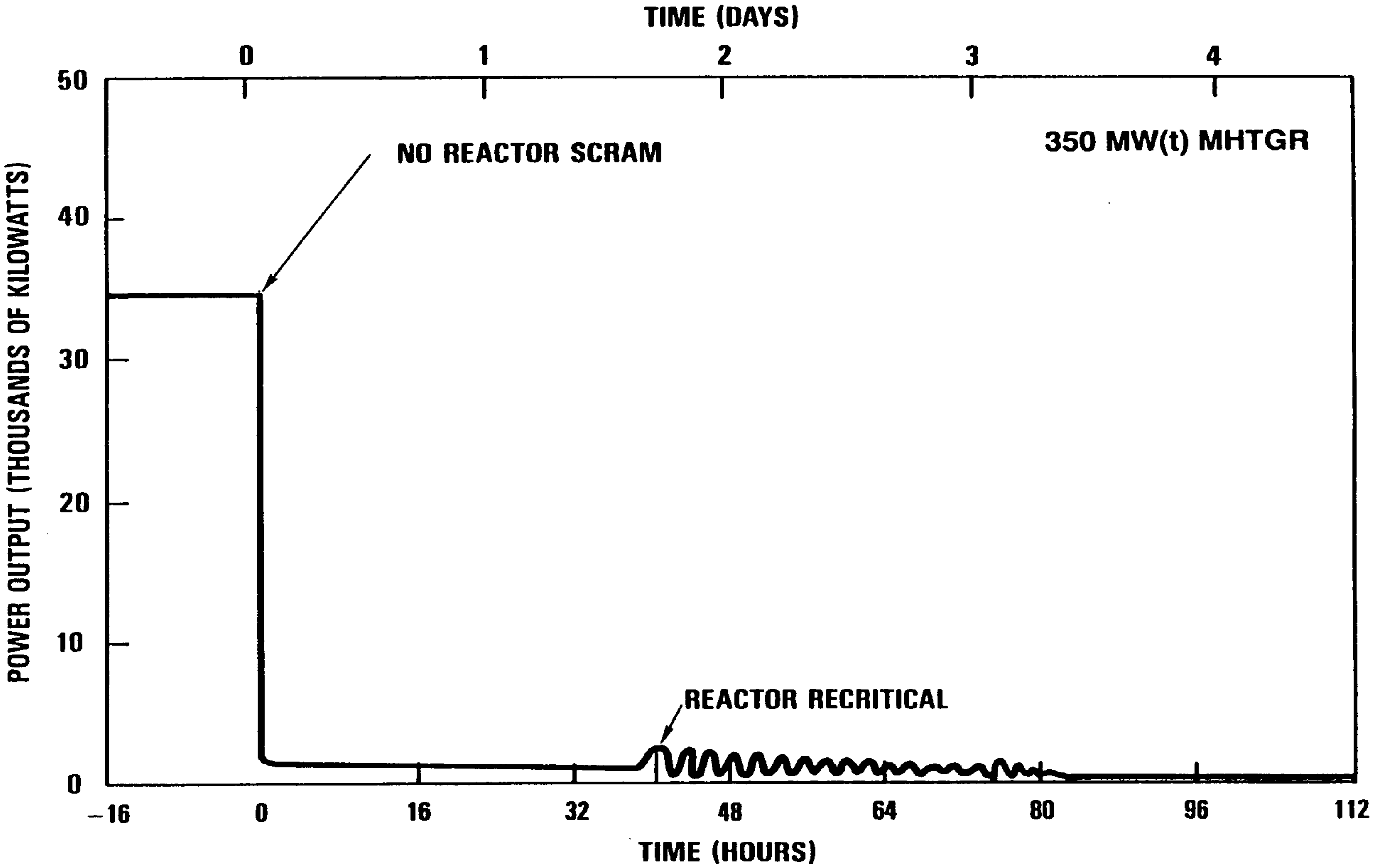
HTGR Reactivity Insertion Mechanisms

- Range of initial conditions of core temperature, core reactivity, control rod insertion, Xenon decay times
- Control rod and control rod group withdrawal
- Removal of RSS small absorber spheres
- Increased moderation from water ingress
- Core compaction from seismic events (pebble bed)

AVR Test Demonstrated that Nuclear Reaction Terminates with Loss of Forced Cooling



MHTGR Analysis Showed Similar Behavior to AVR Test



Prismatic Accidental Control Rod Withdrawal Analysis Demonstrates Mitigation of Reactivity Event

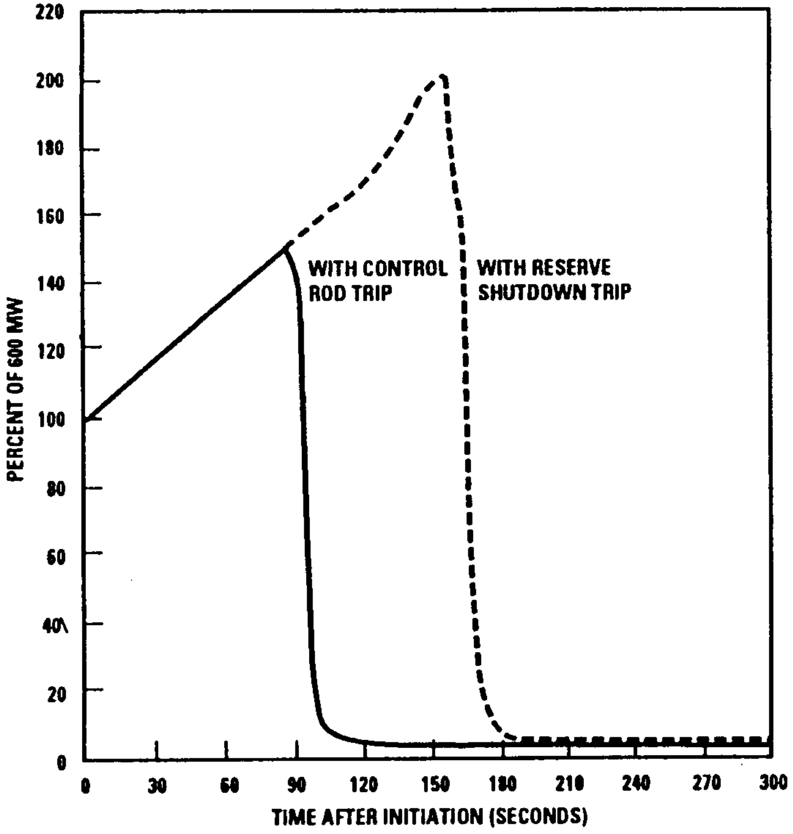
- **Spurious rod withdrawal initiated from 100% power**

- **Transient analyzed with two protection system responses**
  - Normal control rod trip
  - Backup reserve shutdown control material trip (rod trip suppressed)

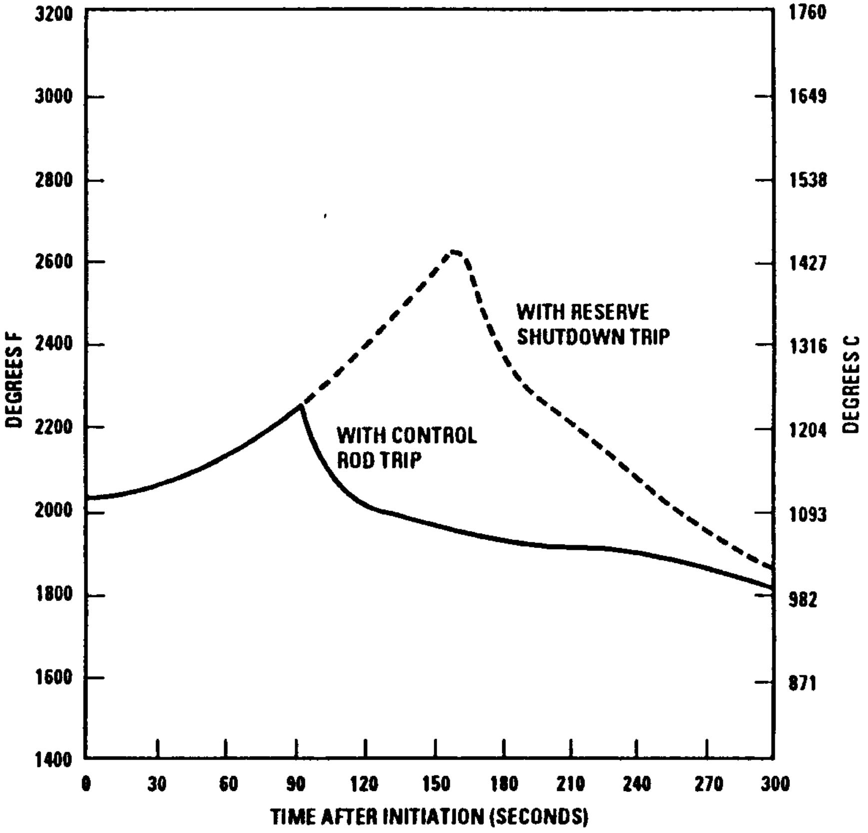
- **Reactor thermal and nuclear characteristics provide inherent limit on power increase rate and magnitude**

Prismatic Reactor Temperatures Well Below Limits during Accidental Control Rod Withdrawal

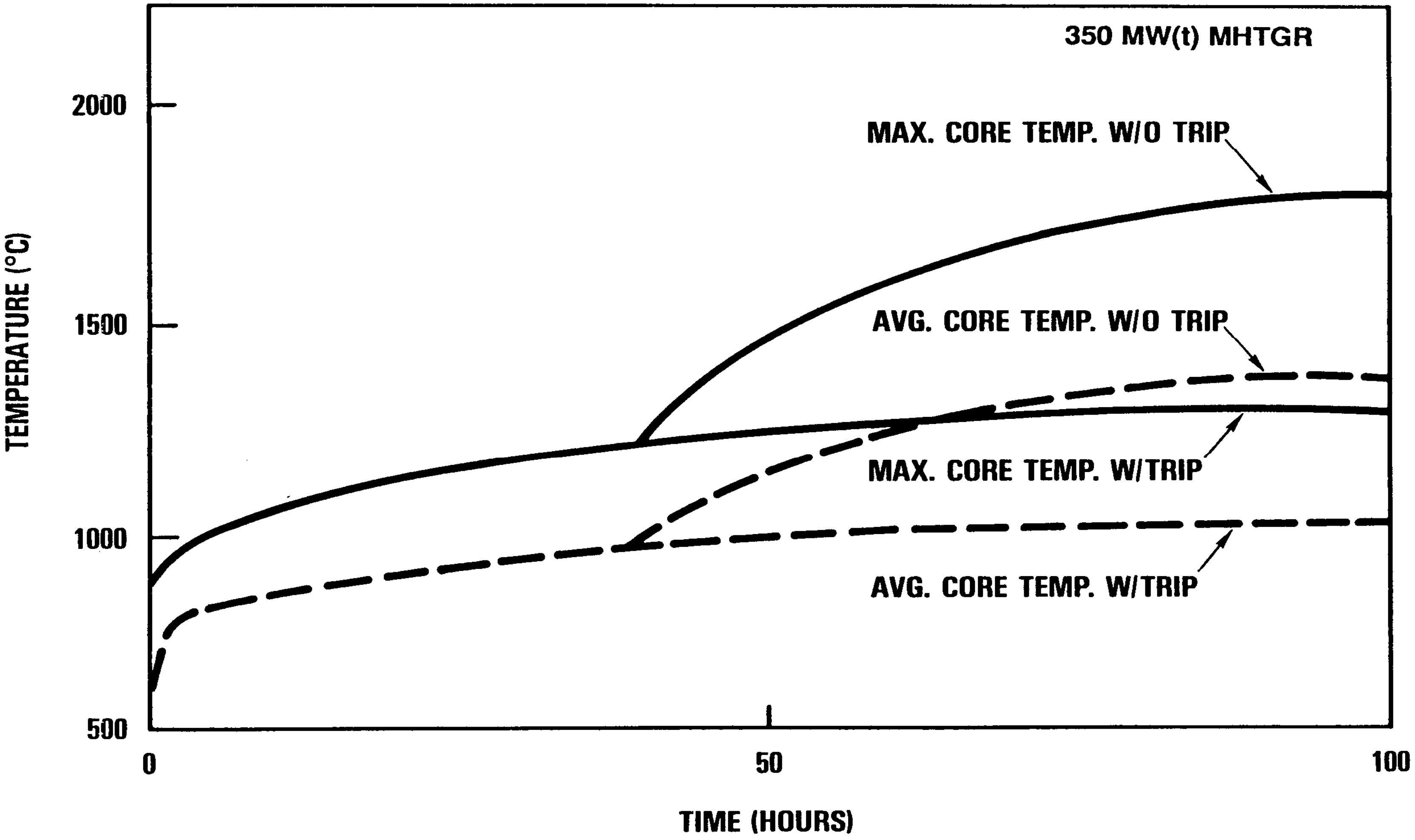
REACTOR POWER INCREASES SMOOTHLY



MAXIMUM FUEL TEMPERATURES WELL BELOW LIMITS



Prismatic Core Temperatures Maintained at Safe Levels with and without Reactor Trip



Outline

- **Licensing basis event selection process**
- **Event types and accident analysis results**
  - Challenges to core heat removal
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  - Challenges to control of chemical attack

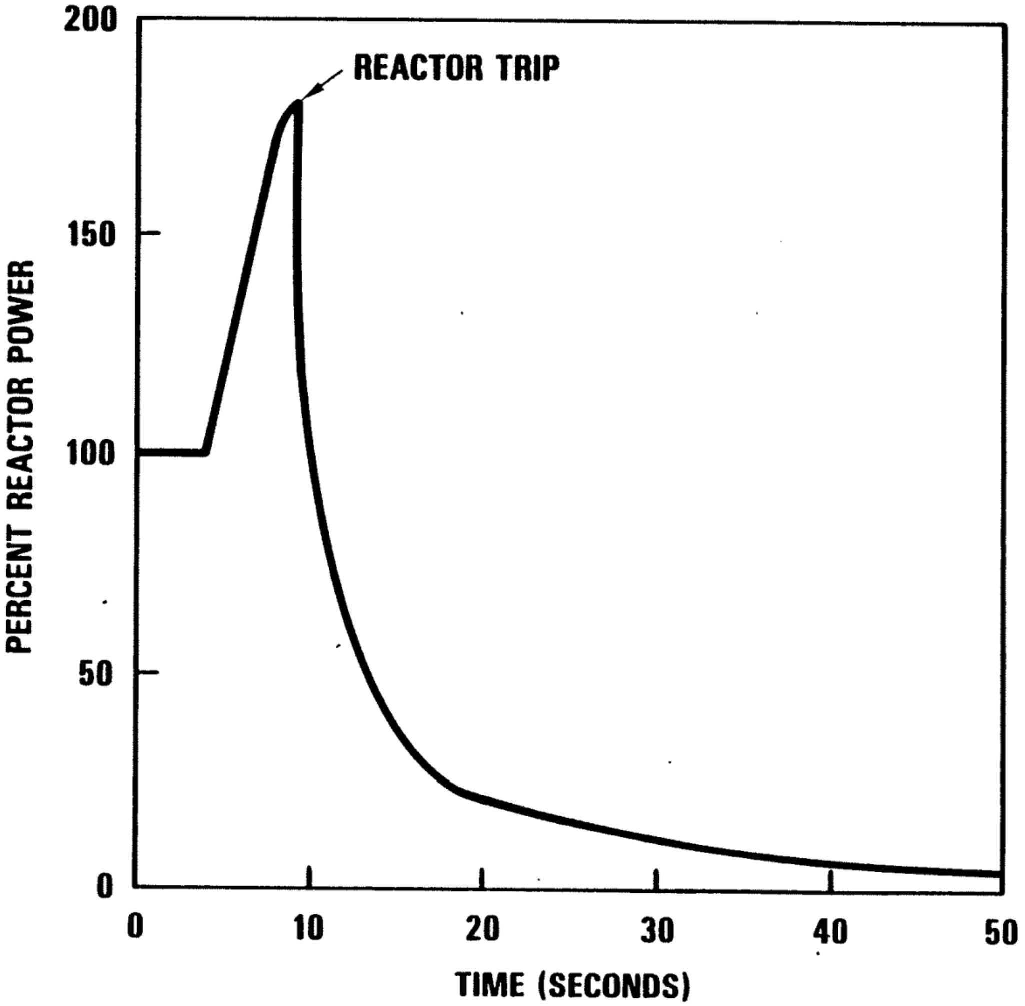
Control of Water Chemical Attack

- **Non-reacting coolant (helium)**

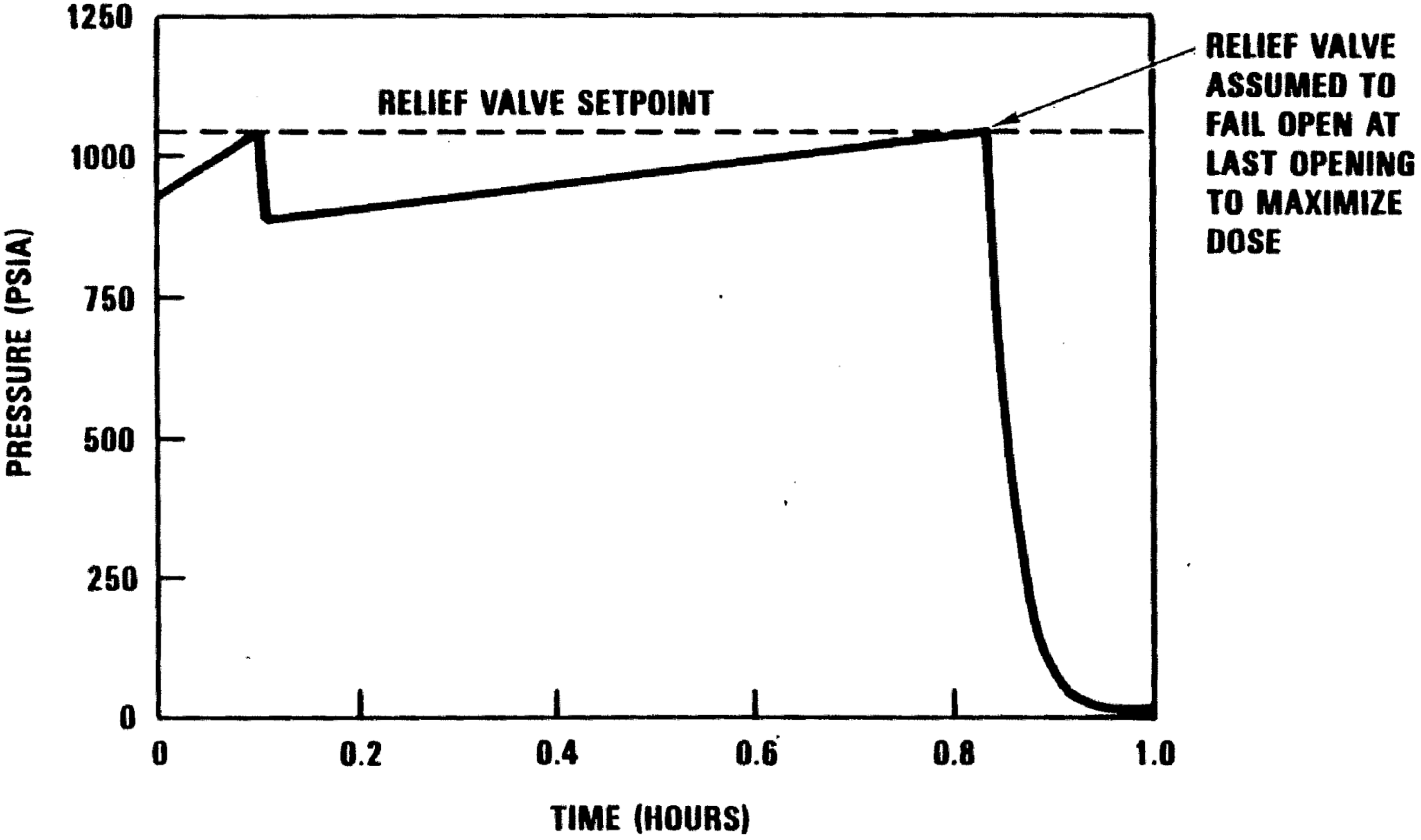
- **Water-graphite reaction:**
  - endothermic
  - requires temperatures exceeding normal operation (>700°C)
  - slow reaction rate

- **Graphite and silicon carbide coatings protect fuel**

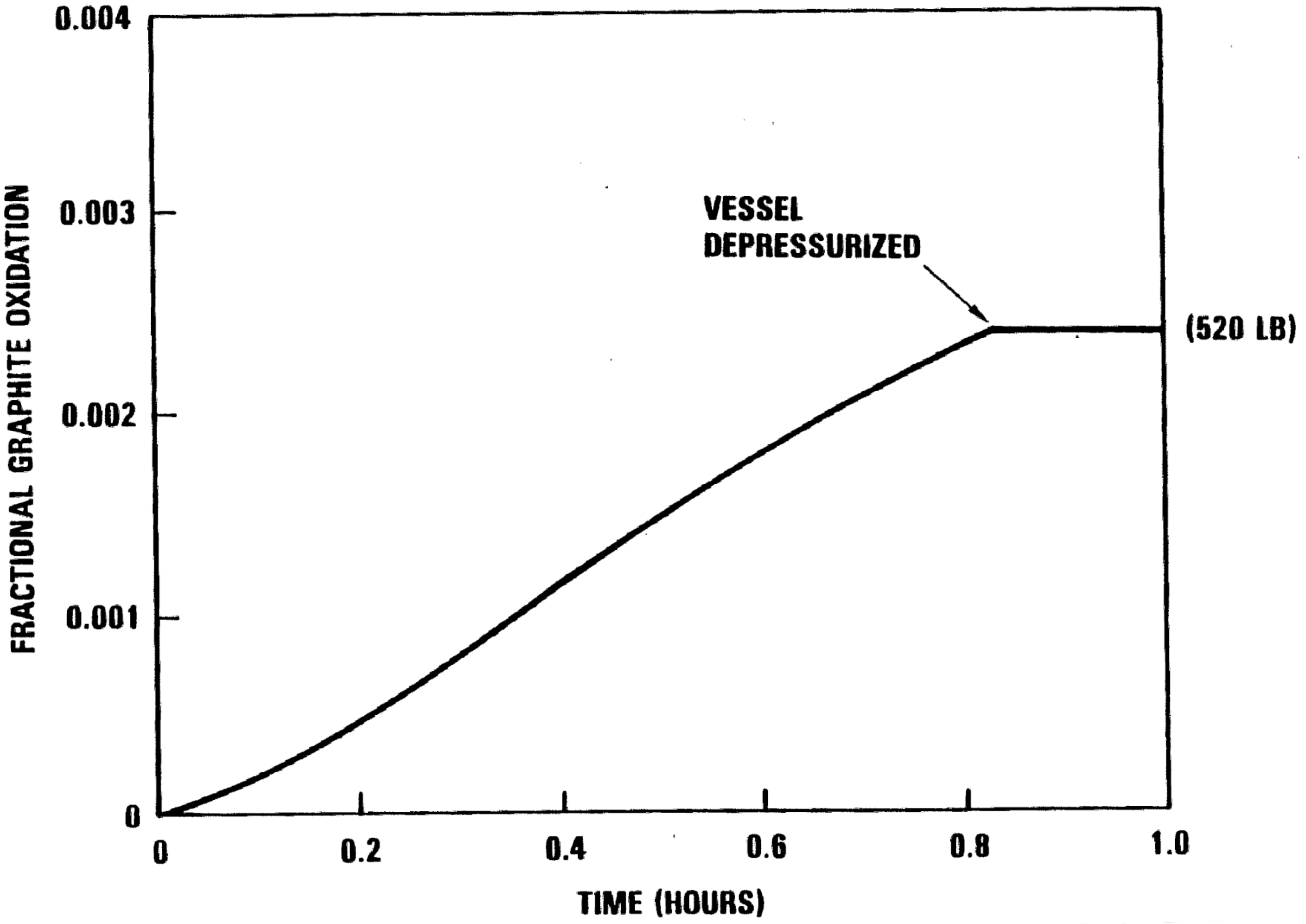
Prismatic Power During SG Tube Rupture Without Forced Cooling (350MWt)



Prismatic Pressure During SG Tube Break Without Forced Cooling (350MWt)



Prismatic Graphite Oxidation During SG Tube Break Without Forced Cooling (350MWt)



Control of Air Chemical Attack

- **Non-reacting, pressurized coolant (helium)**
- **Air ingress limited**
  - HPB configured with three Class 1 vessels
  - HPB piping diameter limited (~65mm dia)
  - HPB leaks/breaks result in venting of most RB air
- **Slow oxidation rate of core support and reflector nuclear grade graphite**
- **Ceramic coated particles embedded within fuel elements**

Conditions Required for Self-Sustained Oxidation of Nuclear-Grade Graphite

- **Heat generation from exothermic oxidation must exceed heat loss by conduction, convection, radiation**

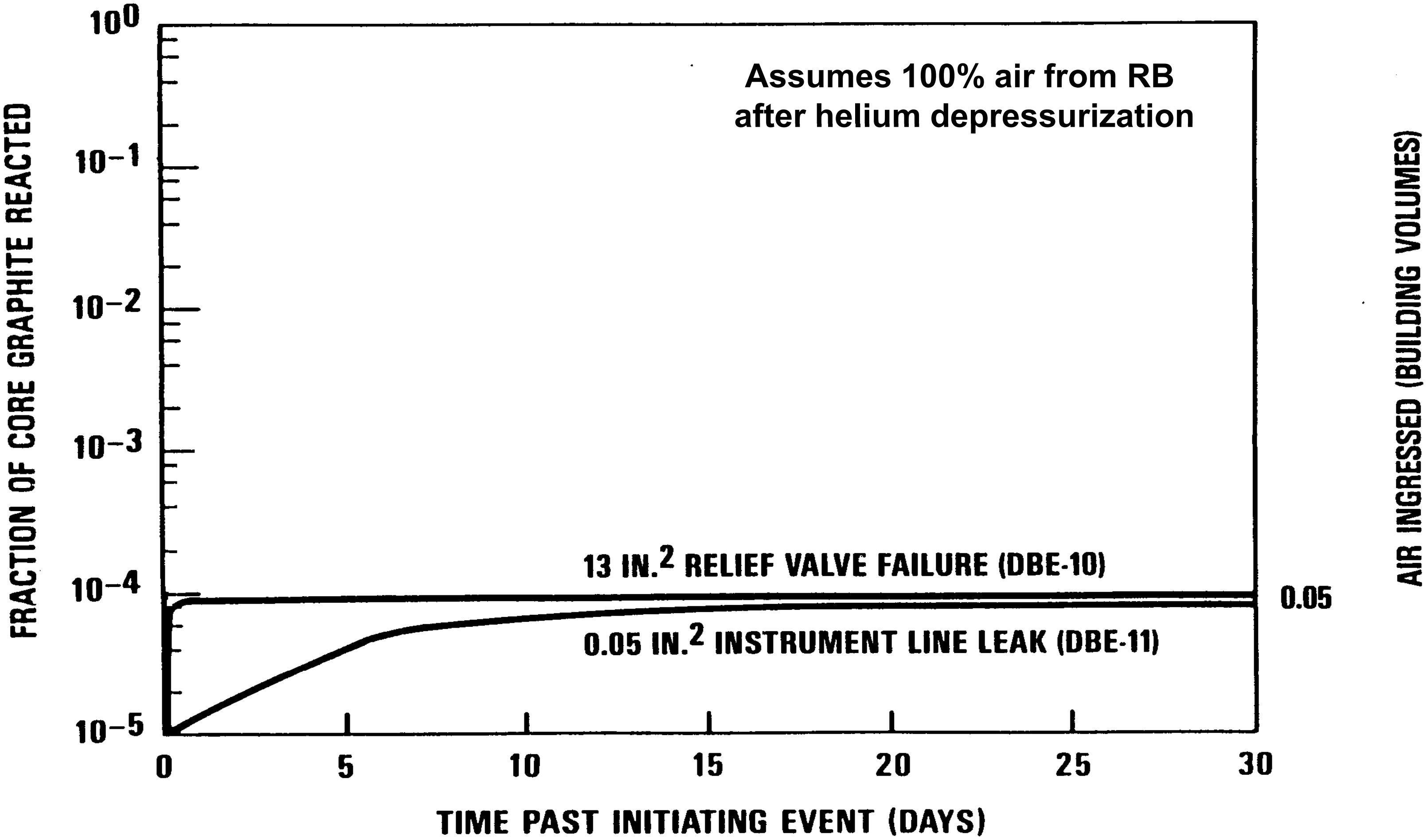
- **Heat generation rates are low because:**
  - Very low concentrations of volatiles and catalytic impurities
  - Reaction rates limited at higher temperatures by oxygen diffusion across boundary layer and into graphite

- **Heat losses are high because:**
  - High thermal conductivity and emissivity
  - Low-temperature air gas mixture provides convective cooling

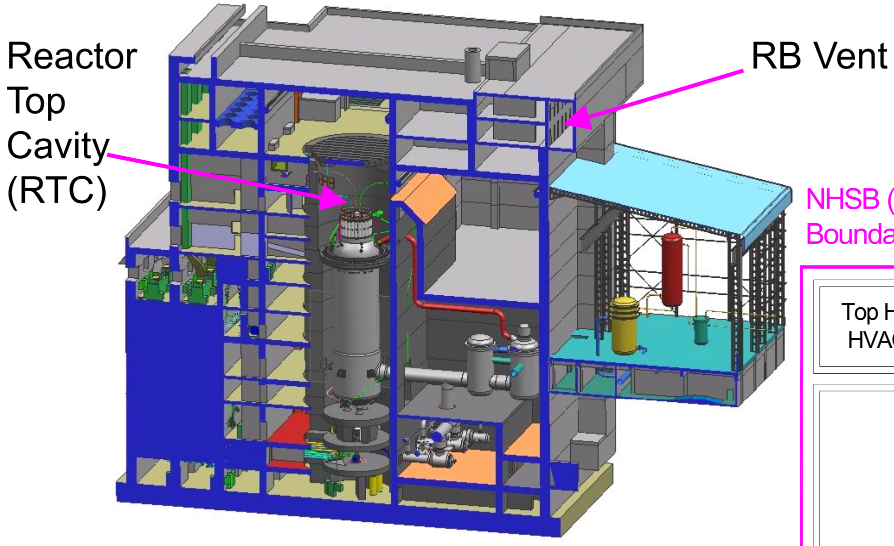
Progression of Air Ingress Events

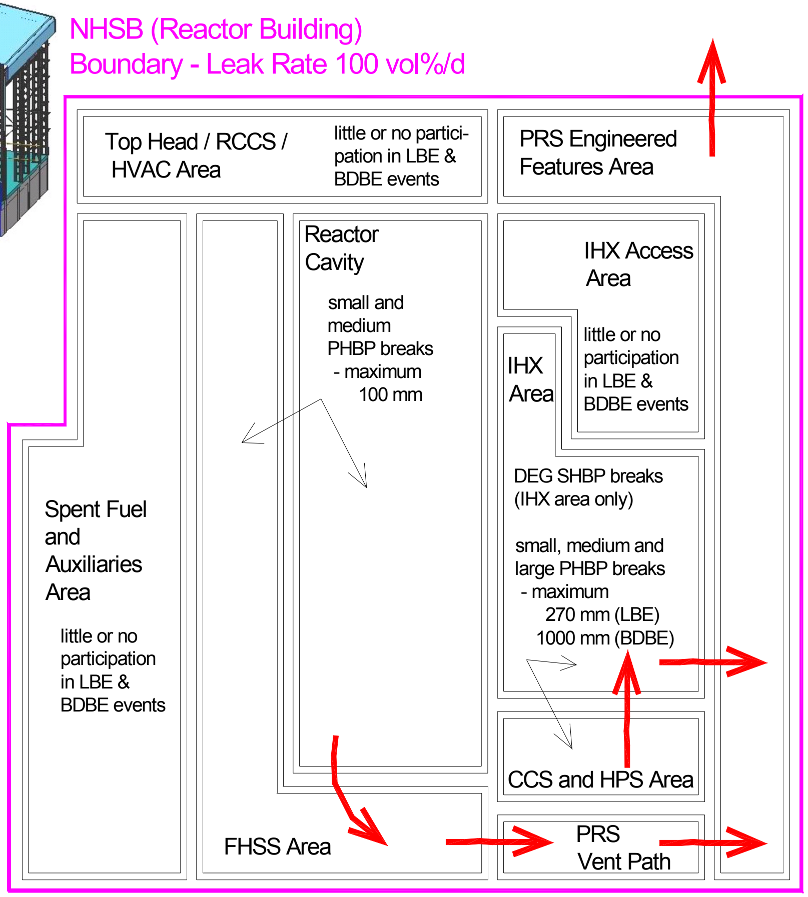
- **Overall oxidation rate determined by rate of air supply**
  - Friction greatly limits flow rate
  - Flow rate further limited as core heats up because viscosity increases with temperature
  - Eventual core cooling limits oxidation to negligible level
  - Graphite mass loss is a few percent at most and limited to lower plenum and reflectors
- **Radioactivity released by graphite oxidation is small**
  - Relatively low levels of radioactivity in graphite
  - Radiological consequences only marginally greater than conduction cooldown w/o air ingress

Prismatic Slow Oxidation of Graphite Limited by Air Mass Transfer and Core Temperataures (350MWt)



PBMR Reactor Building Vent Pathway Influence on Air Mixture Ingress (500MWt)





NHSB (Reactor Building) Boundary - Leak Rate 100 vol%/d

Top Head / RCCS / HVAC Area

little or no participation in LBE & BDBE events

PRS Engineered Features Area

Reactor Cavity

small and medium PHBP breaks - maximum 100 mm

IHX Access Area

little or no participation in LBE & BDBE events

IHX Area

DEG SHBP breaks (IHX area only)

small, medium and large PHBP breaks - maximum 270 mm (LBE) 1000 mm (BDBE)

Spent Fuel and Auxiliaries Area

little or no participation in LBE & BDBE events

CCS and HPS Area

FHSS Area

PRS Vent Path

Red Arrows show Engineered Vent Path consisting of rupture disks, dampers, and other features

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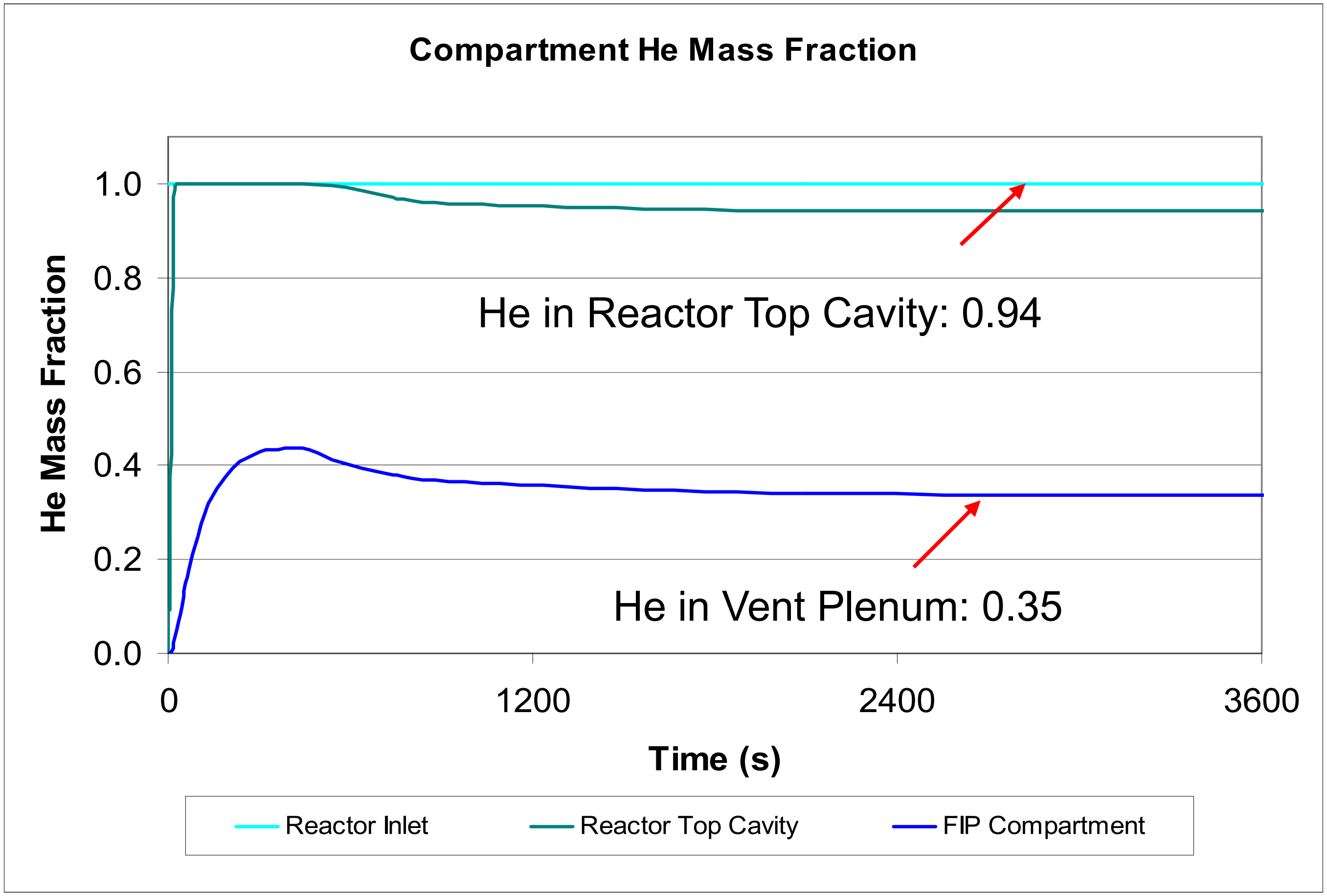
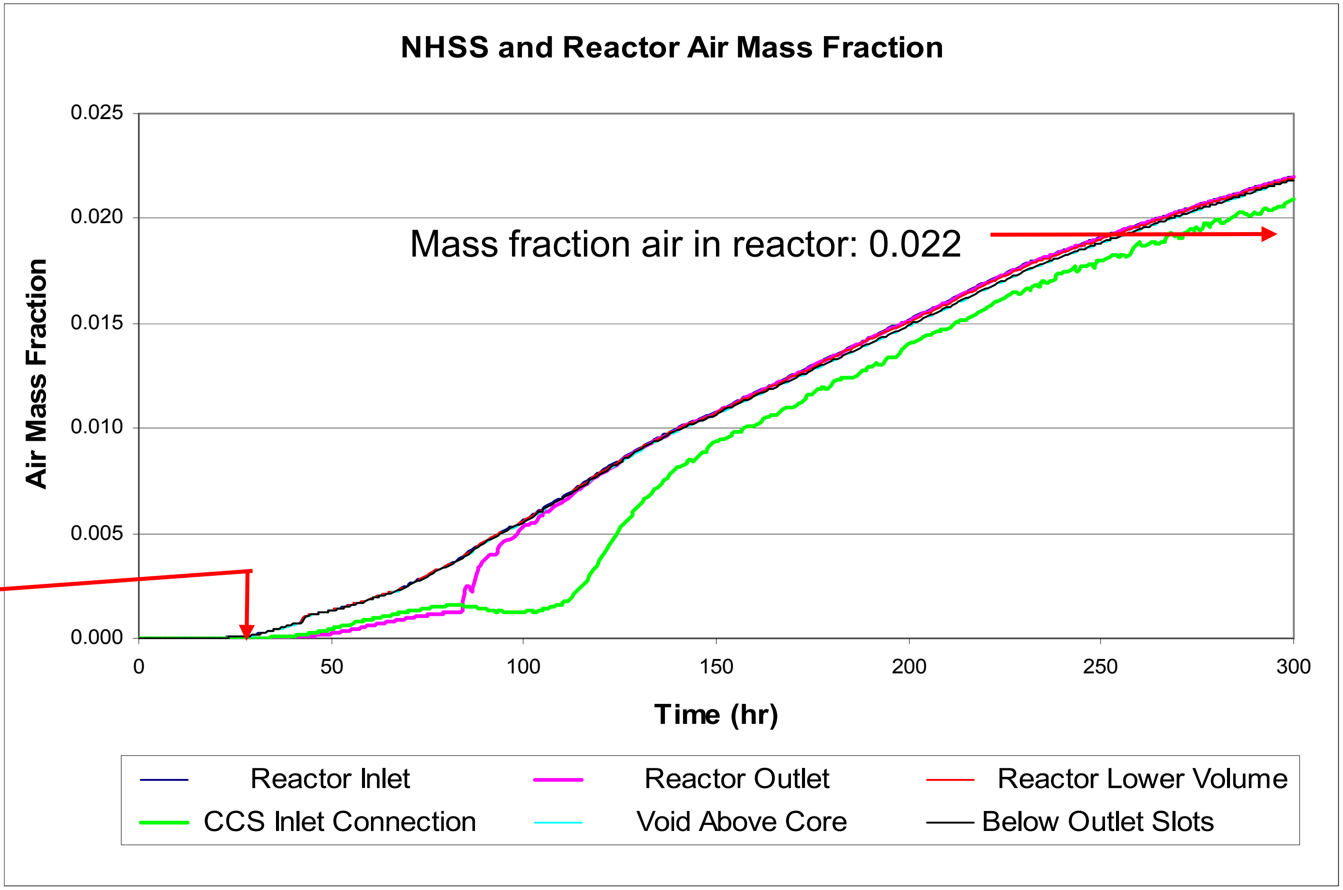
Pebble Bed Gas Mixture in RB for 100mm HPB Break
RB Vent Fails to Reclose Case



~0.9 mass fraction He (i.e.,10% air content by mass) in RTC after first hour

Pebble Bed Gas Mixture Ingress for 100mm HPB Break RB Vent Fails to Reclose Case



Mass fraction air in reactor: 0.022

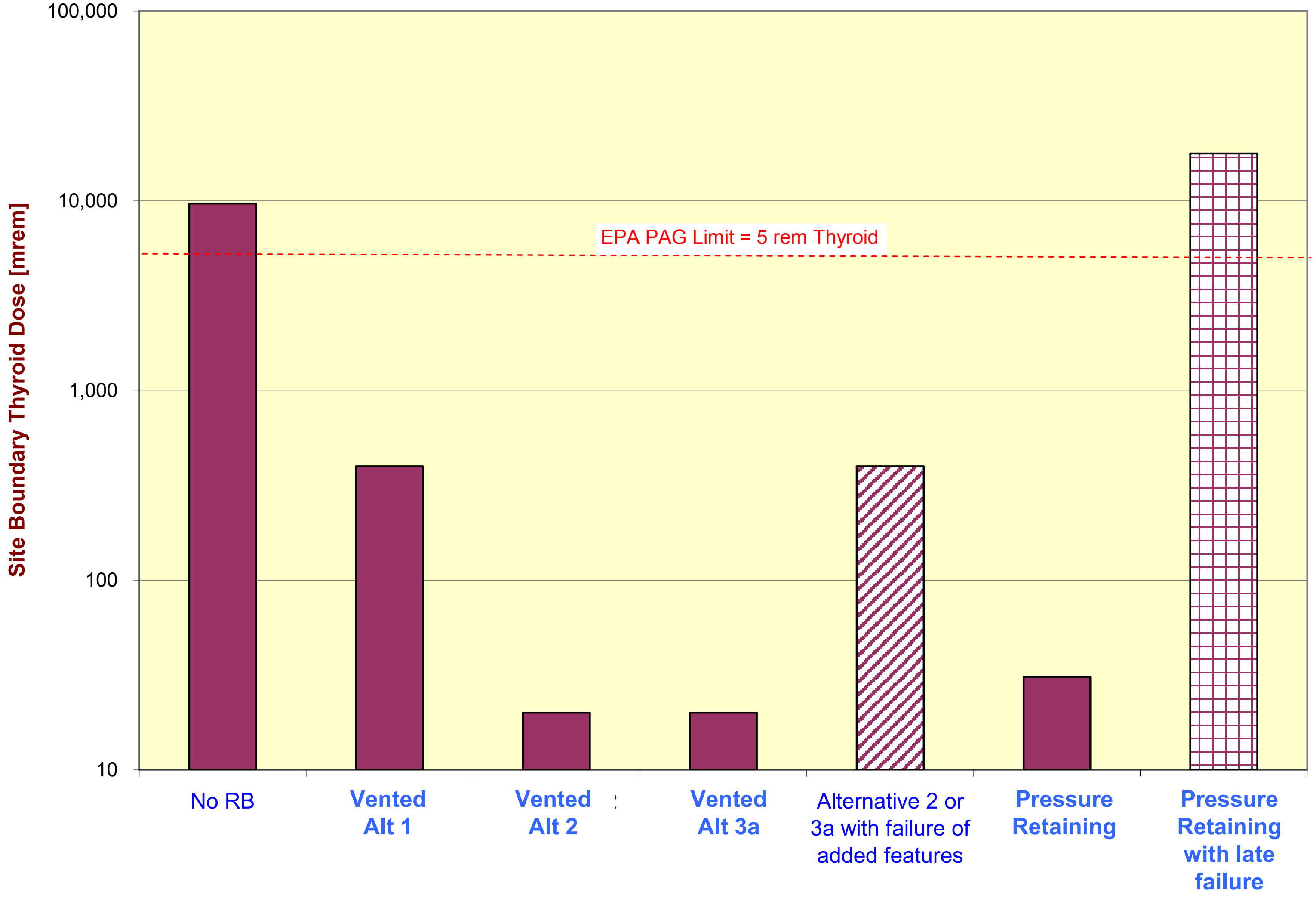
Assumed failure
to close RB damper

~2% air content by mass in Reactor after 300hrs

Role of Reactor Building in Safety Design

- **Required safety function of RB is to structurally protect HPB, Reactor, and RCCS from external events and hazards**
- **RB provides additional radionuclide retention and limits air available for ingress after HPB depressurization**
- **Vented design superior to pressure retaining design for HTGR characteristics**
  - Less air available in gas mixture for ingress to reactor after helium depressurization and venting
  - Pressurized non-condensable helium not available to transport RNs from delayed fuel release by leakage or subsequent RB failure

Comparison of RB Alternatives to PAG Sheltering Dose at EAB



Important HTGR Safety Paradigm *Shifts*

- The fuel, helium coolant, and graphite moderator are chemically compatible under all conditions
- The fuel has very large temperature margins in normal operation and during accident conditions
- Safety is not dependent on the presence of the helium coolant
- 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 HTGR has multiple, nested, and independent radionuclide barriers
- An LWR-type containment is neither advantageous nor necessarily conservative.

Summary

- HTGR LBEs selected systematically using risk insights
- Modular HTGR safety design focuses on radionuclide retention at the source within the fuel
- Challenges to the radionuclide retention grouped by the three key functions that are met with the inherent characteristics of the fuel, coolant, and moderator and the passive reactor configuration
- Modular HTGR accident time scales are long and the phenomena are amenable to mechanistic evaluations

Suggested Reading

- NGNP Licensing Basis Event Selection White Paper (~June 2010).
- "Preliminary Safety Information Document for the Standard MHTGR," DOE-HTGR-86024, Rev. 13, September 1992, ML093560560.
- "PBMR Reactor Building Functional and Technical Requirements and Evaluation of Reactor Embedment," NGNP-NHS 100-RXBLDG, Rev 0, Westinghouse Electric Company LLC, September 2008.
- "PBMR Plant Level Assessments Leading to Fission Product Retention Allocations," NGNP-FPA-RPT-001, Rev 0, Westinghouse Electric Company LLC, July 2009.