SAND2015-7163PE

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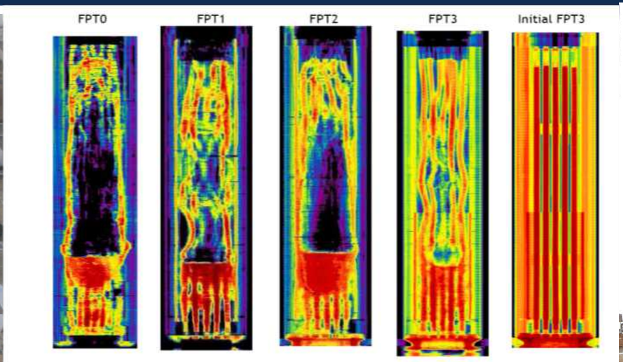

Severe Accident Phenomena

TSG Skill Set

Spend Fuel Pool Phenomena

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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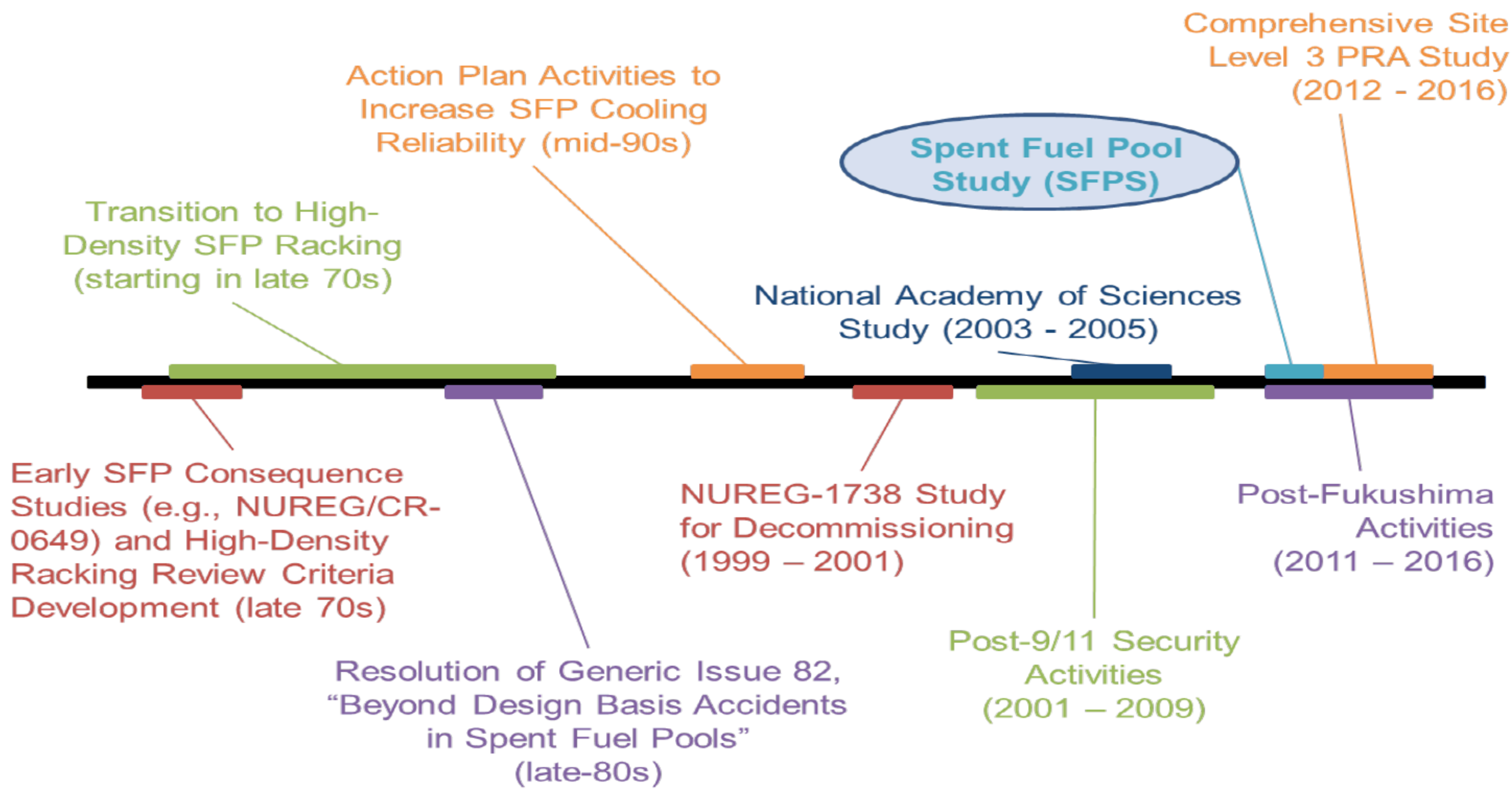
Timeline of Significant SFP Studies (NUREG-2161)



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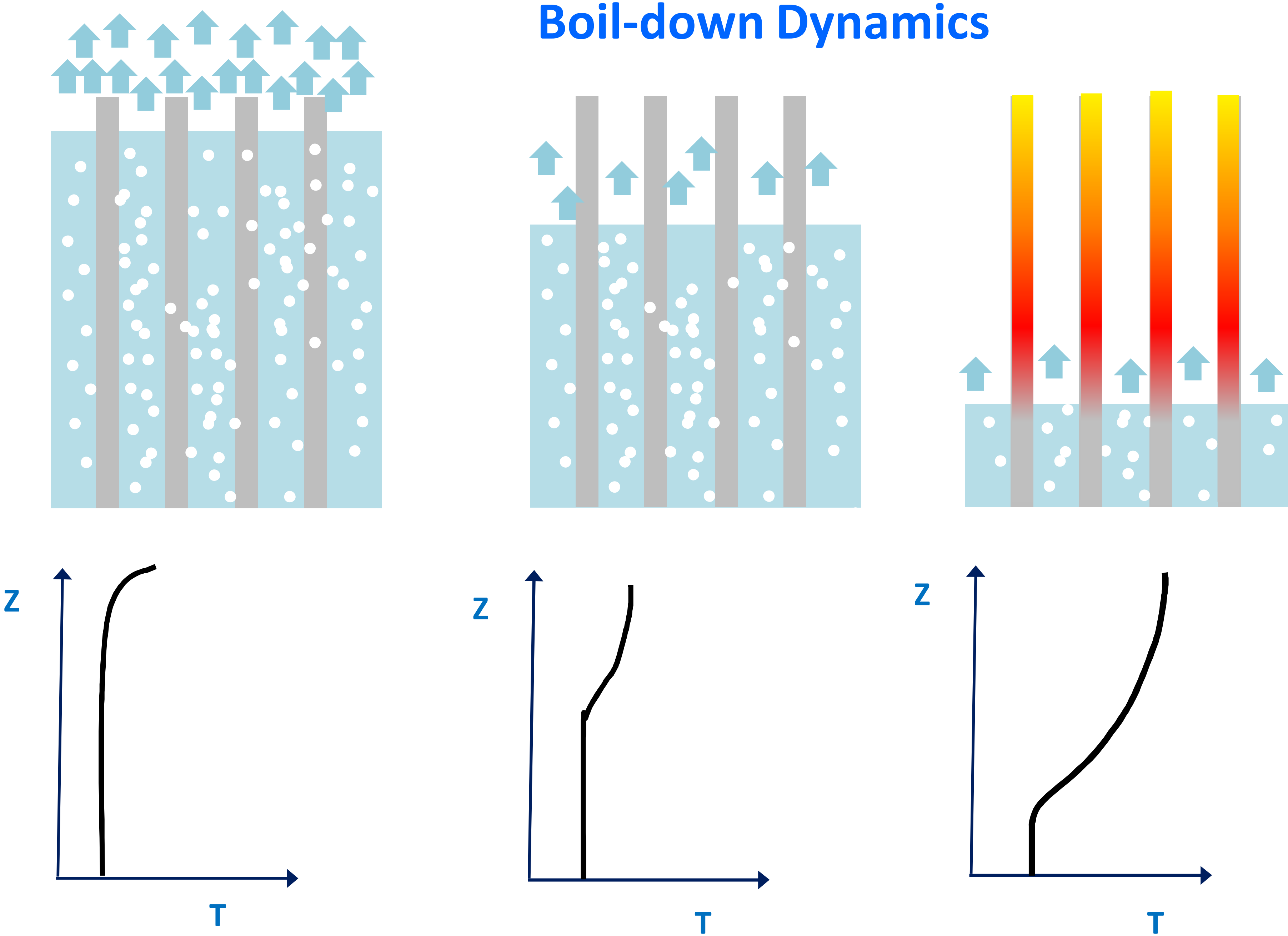
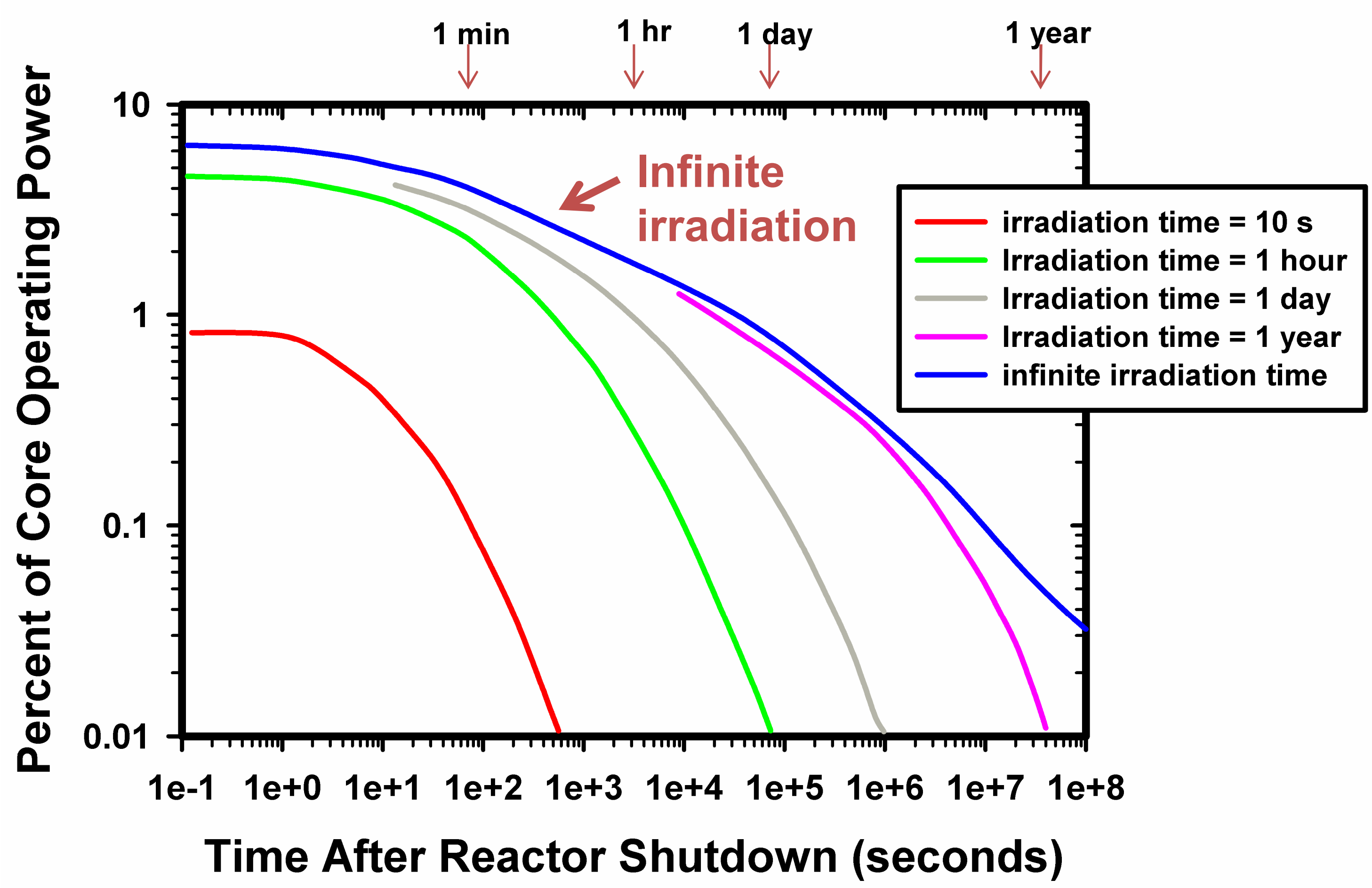
Boil-down Dynamics



Decay Heat



An Infinite period is considered to occur when all fission products have reached saturation levels.

EARLY STAGES OF REACTOR ACCIDENTS

Boiloff, Heatup, and Clad Oxidation

Stages of Reactor Accidents

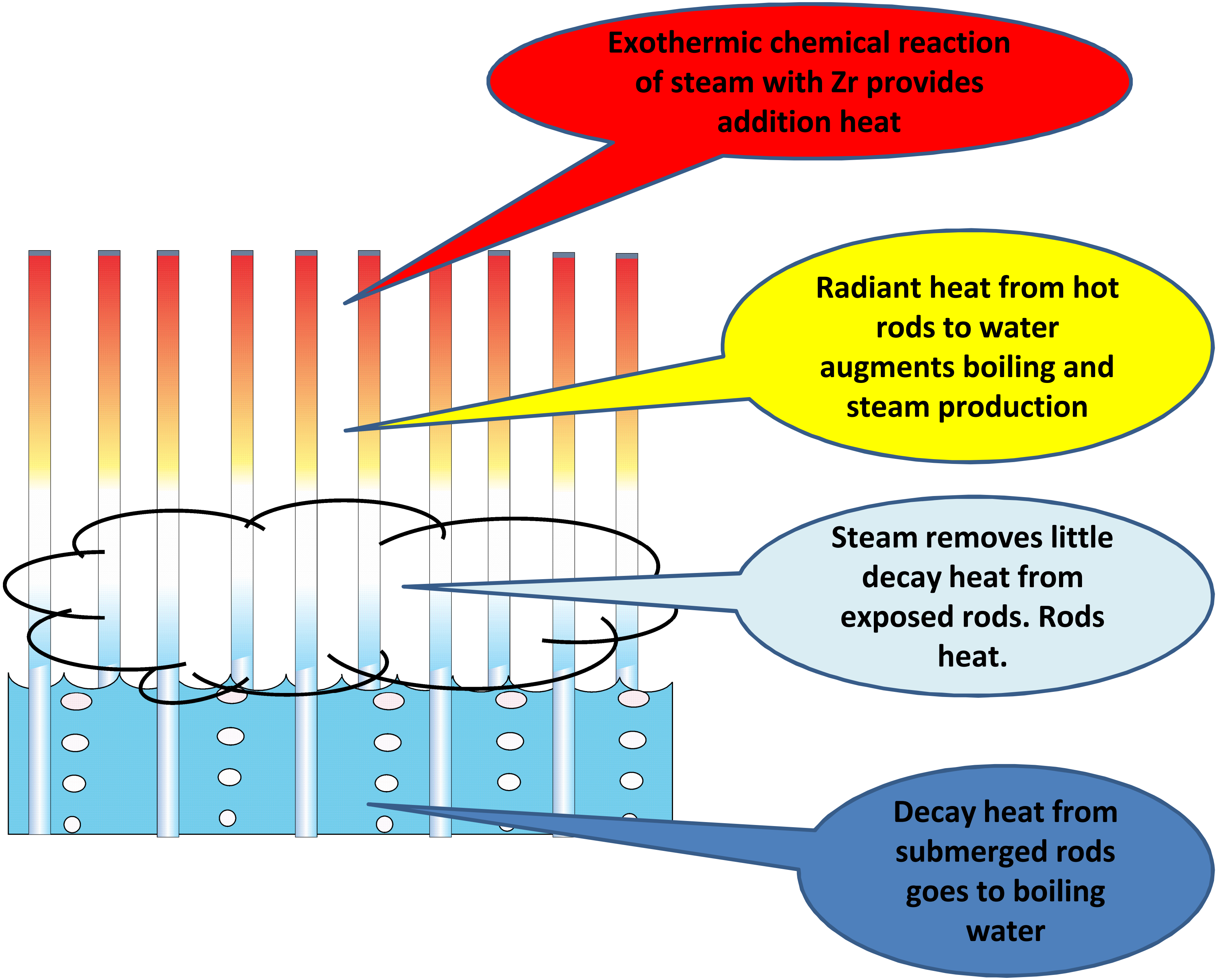
- *Accident initiation and discharge of coolant to TAF.*
- *Stages:*

1. *boildown of coolant and fuel heatup*
2. *clad balloon and rupture*
3. *clad oxidation and temp. transient*

DBA & SA (stages 1–2)

4. *clad melting and fuel liquefaction*
5. *candling and accumulation of core debris*
6. *relocation of debris from core region*
7. *debris interactions with vessel*

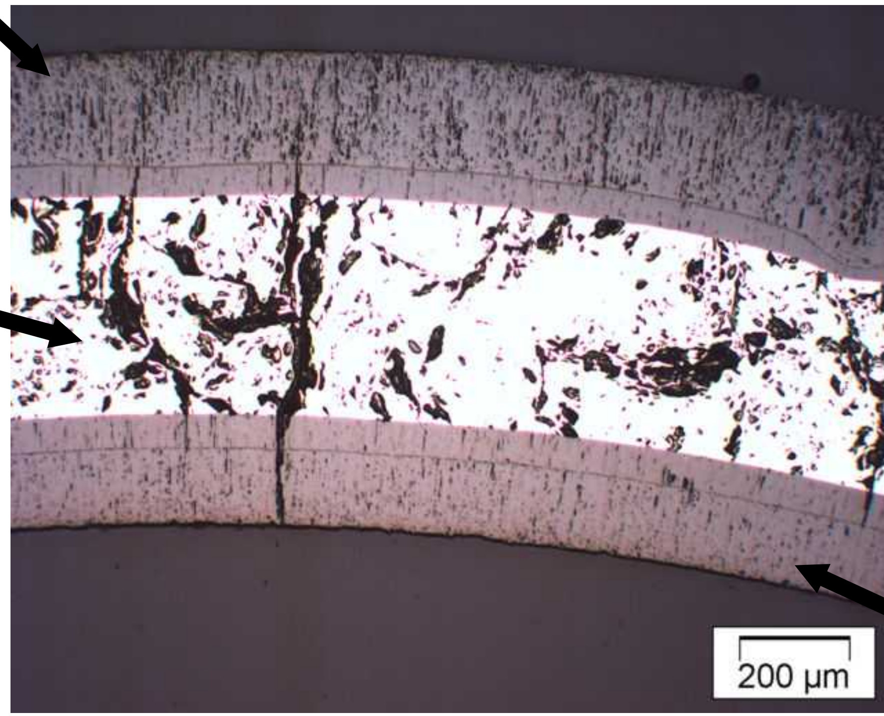
SA (stages 3–7)


Exothermic chemical reaction of steam with Zr provides addition heat
Radiant heat from hot rods to water augments boiling and steam production
Steam removes little decay heat from exposed rods. Rods heat.
Decay heat from submerged rods goes to boiling water

Steam Oxidation of Zircaloy Cladding

Outer Cladding

Residual oxygen saturated metal



Inner Cladding

Oxidation Kinetics

- Zr Oxidation rate measured experimentally through weight gain measurements on small coupons held at constant temperature in an oxidizing furnace
  - tests show that $(\text{weight gain})^2 = K \times \text{time}$ where K is a function of temperature

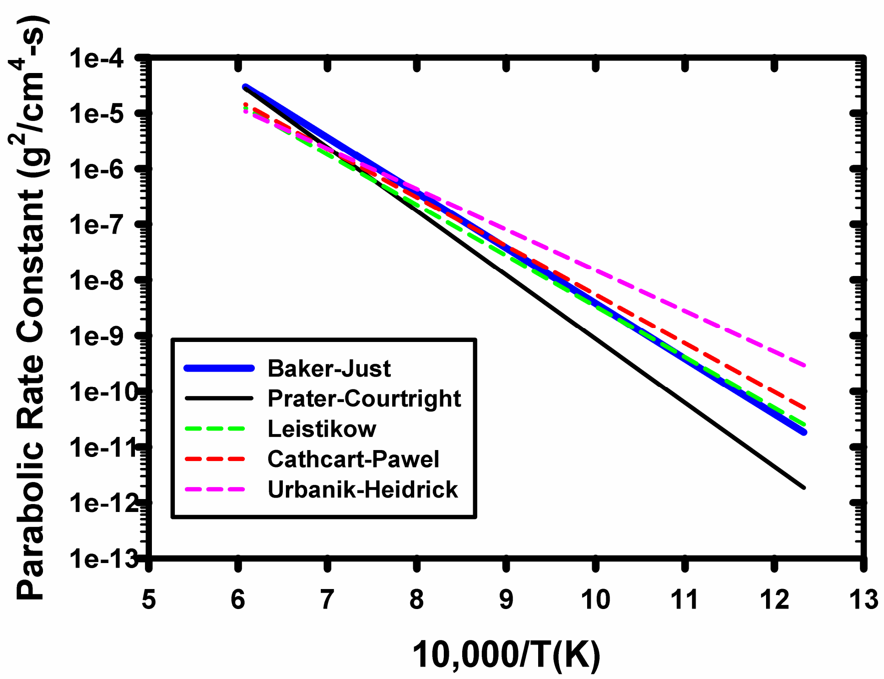
$$W_{Zr} = \sqrt{A e^{(-B/RT)} t}$$

  - W_{Zr} is mass of Zr oxidized per unit area exposed to steam at absolute temperature T for time t
  - A,B are empirically determined constants
  - R is universal gas constant

Steam Oxidation Kinetics Parameters

Parabolic Rate Constant = $Ae^{-B/RT}$

Authors	A g^2/cm^4-s	B J/mole
Baker-Just	33.6	190372
Prater Courtright	268	219835
Leistikow	4.26	174288
Cathcart Pawel	2.94	167121
Urbanik Heidrick	0.3	139800



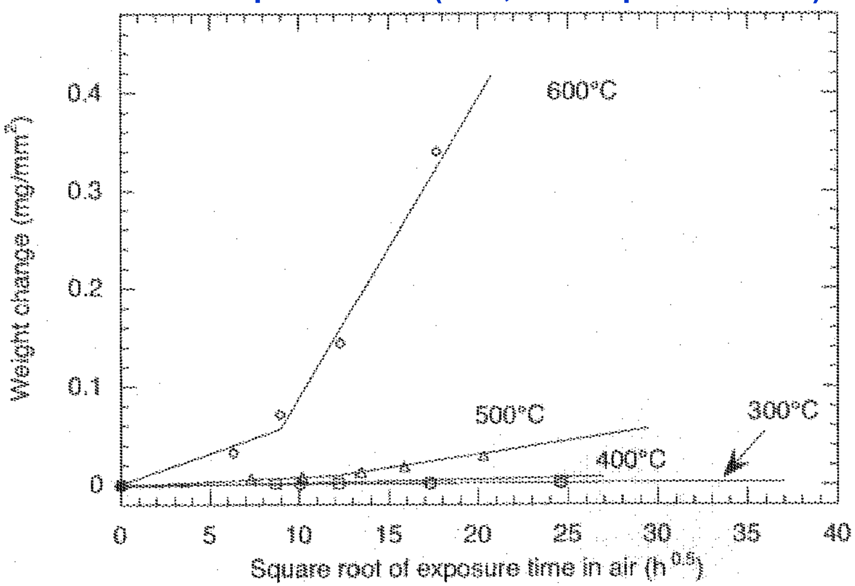
ANL Air Oxidation Experiments

- Principal investigators, K. Natesan and W. Soppet
  - NUREG/CR-6846, "Air Oxidation Kinetics for Zr-Based Alloys"
- Initial tests (low temperature)
  - Thermogravimetic test apparatus (TGA) used to measure specimen weight change
    - Bare samples
    - Steam pre-oxidized (25-30 μm oxide layer thickness)
  - Oxidation in dry air or steam
    - Weight gain recorded as a function of sqrt(time)
  - All-purpose Correlation from range of data (Zircaloy-4)
    - Bare (i.e., no initial oxide layer) samples in air
    - Bare samples in steam
    - Steam pre-oxidized in air

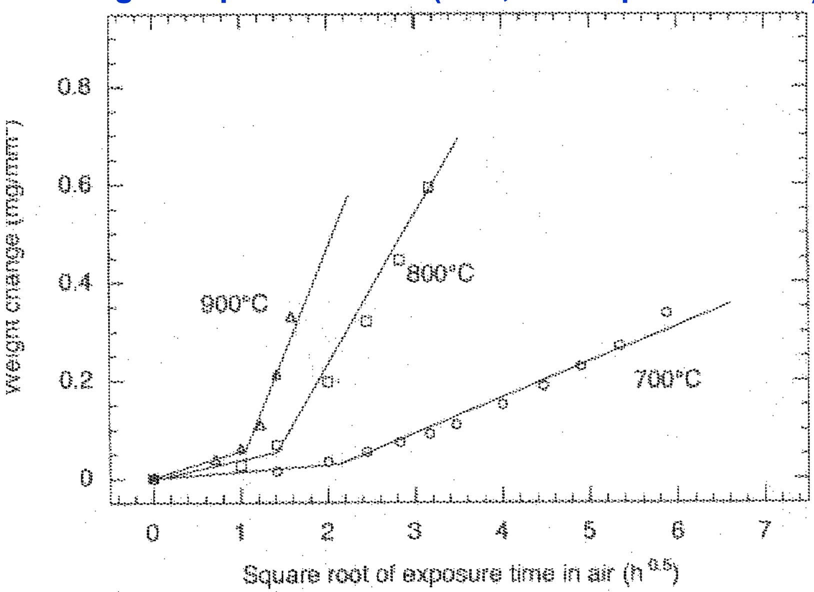
ANL Air Oxidation Experiments

- **Consistently observed in all ANL oxidation tests**
  - **Whether bare or pre-oxidized**
  - **Not a function of oxide thickness**
  - **Correlate breakaway timing with sample temperatures**

Low temperate data (Zr-4,steam pre-oxidized)



High temperature data (Zr-4,steam pre-oxidized)



Ref: NUREG/CR 6846

SNL Lifetime Breakaway Model

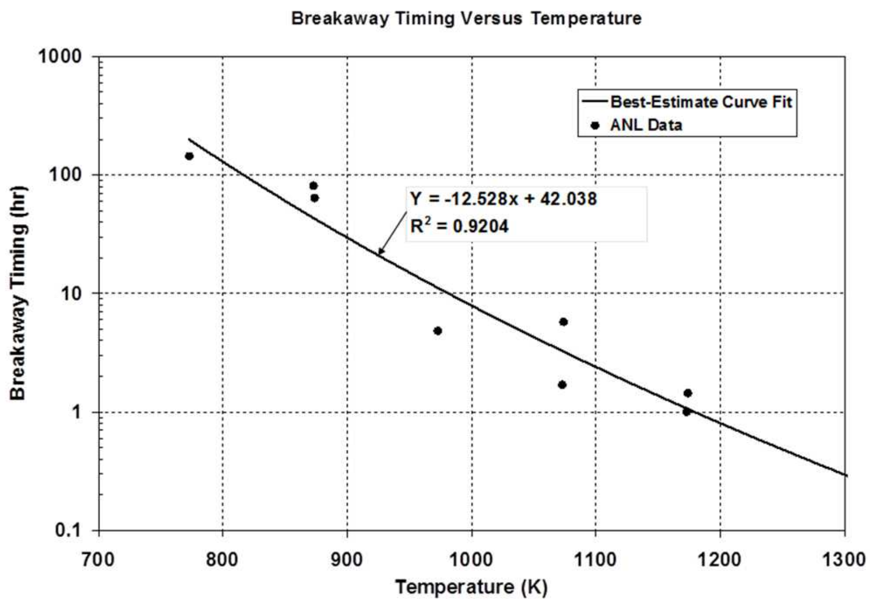
- Lifetime rule similar to Larson-Miller creep
  - Used to capture the time-at-temperature characteristics of breakaway
- Local damage is tracked for all Zircaloy components

$$LF = \int_0^t dt' \frac{t'}{\tau(T)}$$

where,

$$\tau(T) = 10^{P_{LOX}}$$

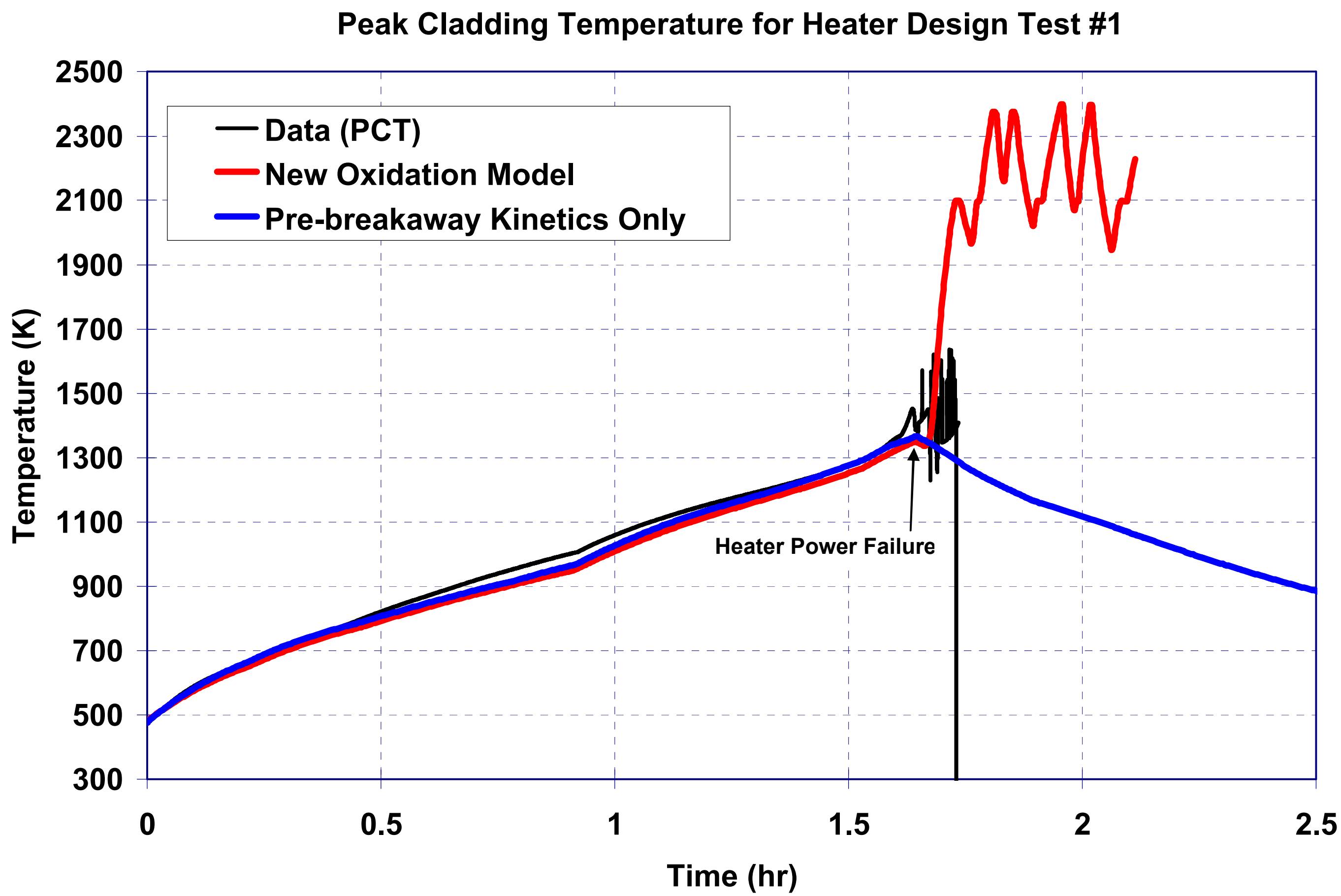
$$P_{LOX} = -12.528 \cdot \log_{10} T + 42.038$$



- Parameters come from experimental curve fit
- Failure occurs when damage function reaches 1

Breakaway effect in Air Oxidation

- Comparison calculations with and without breakaway kinetics



SFP Nodalization (1)

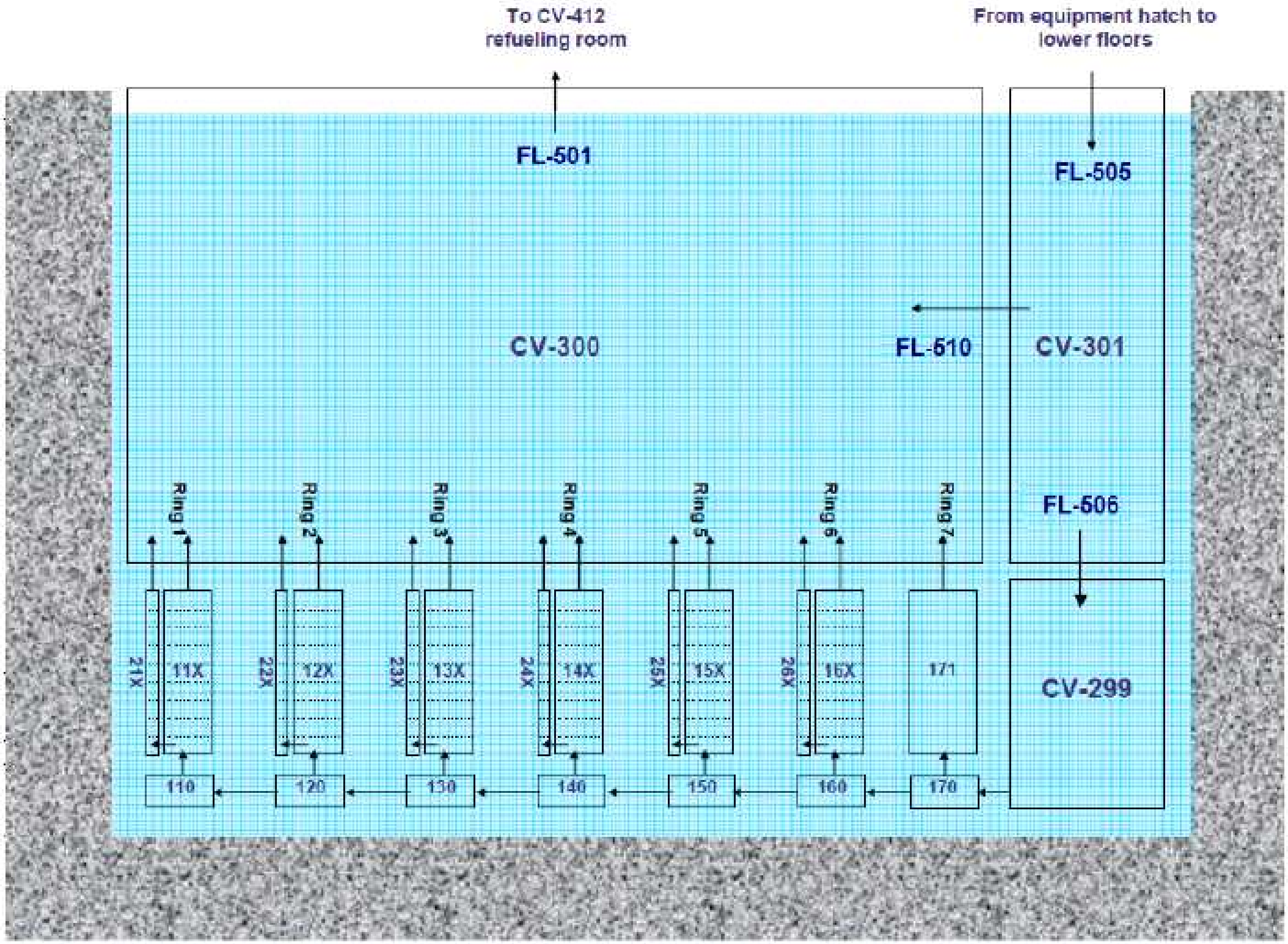
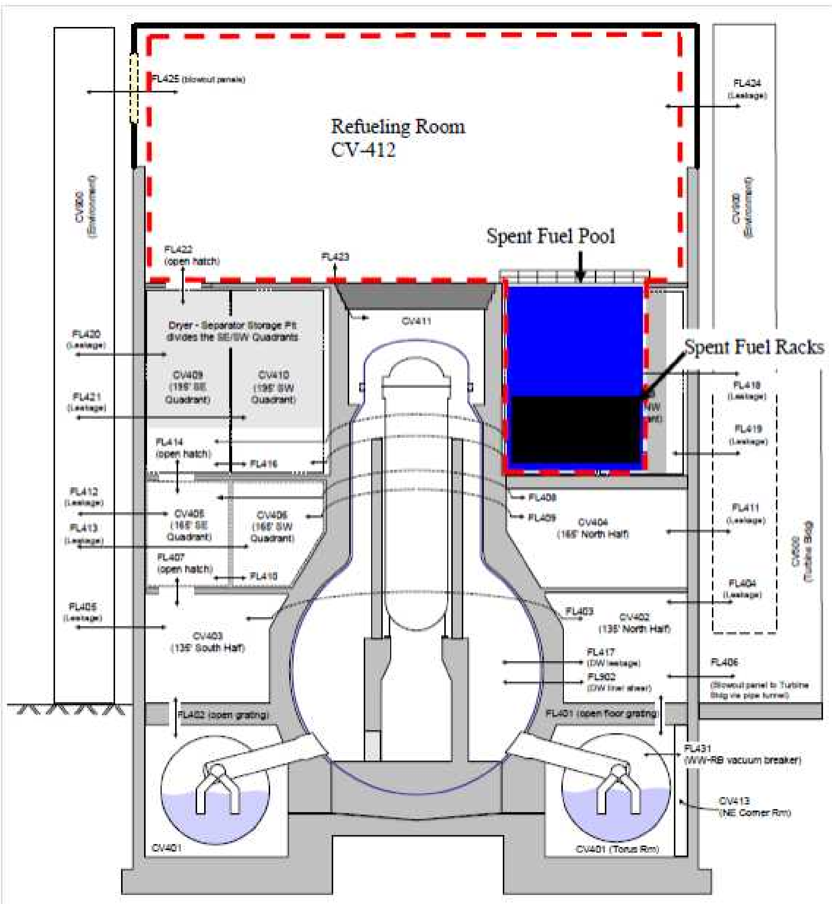
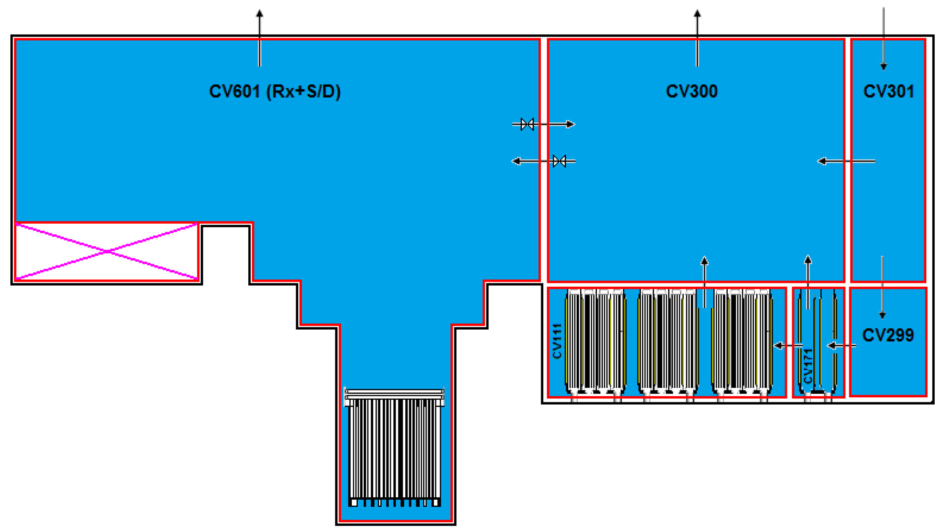


Figure 40 MELCOR nodalization of the whole pool high density model

Ref: NUREG 2161

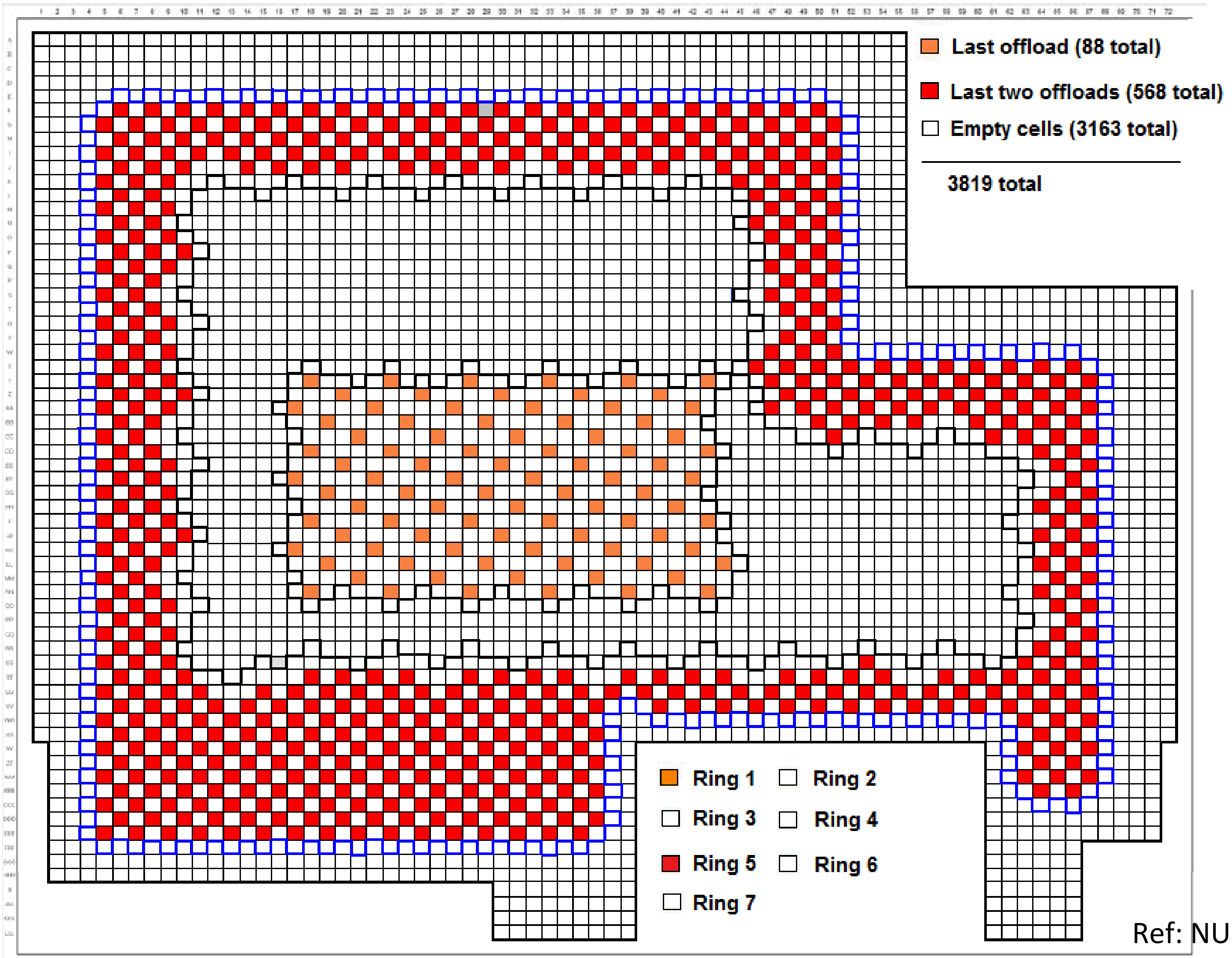
SFP/Building Nodalization





Ref: NUREG 2161

Low Density Racking



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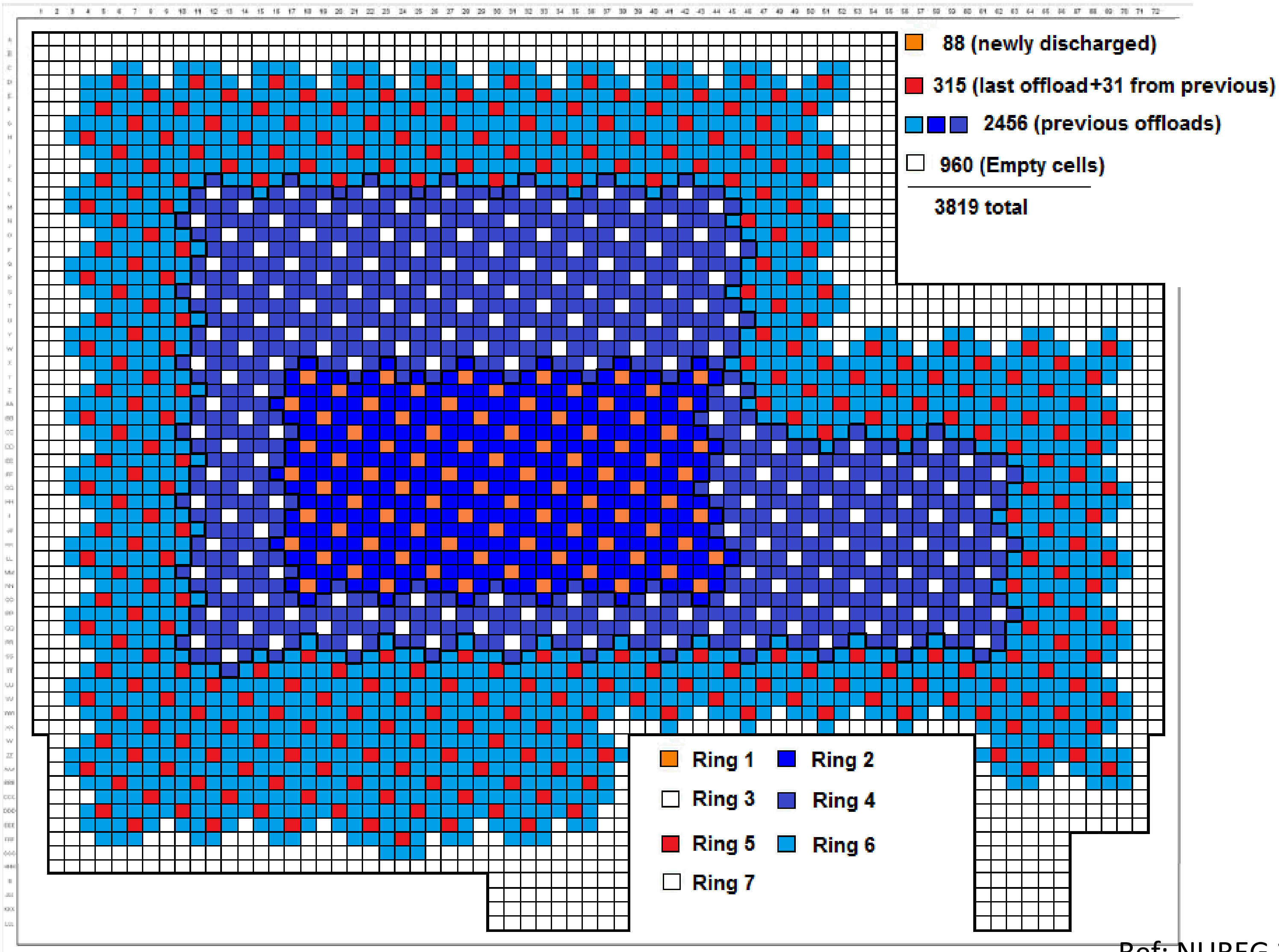
High Density Racking



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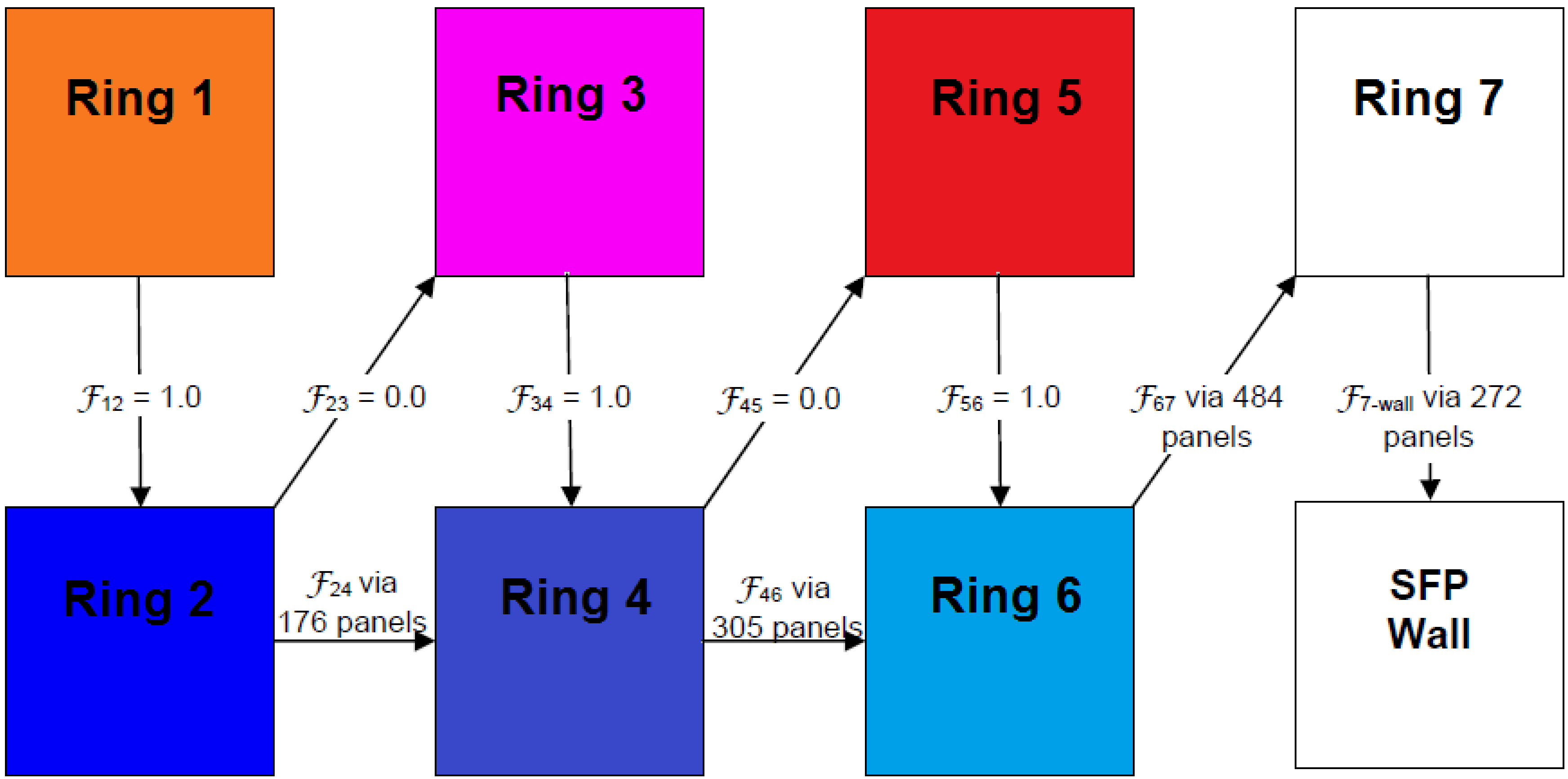
Radiant Heat Exchange Between Classes of Fuel Assemblies



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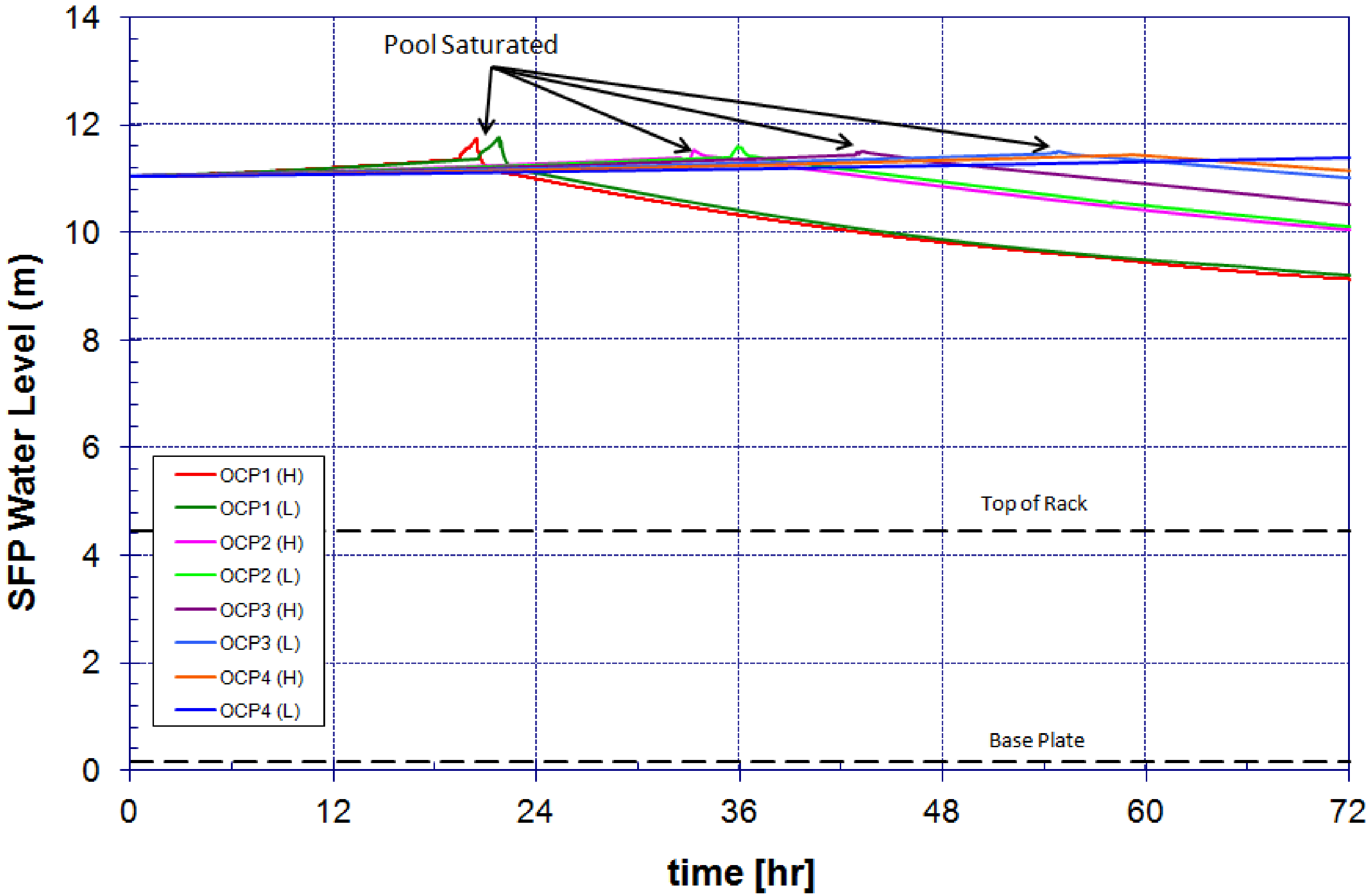
Pool Response to Loss of Heat Rejection



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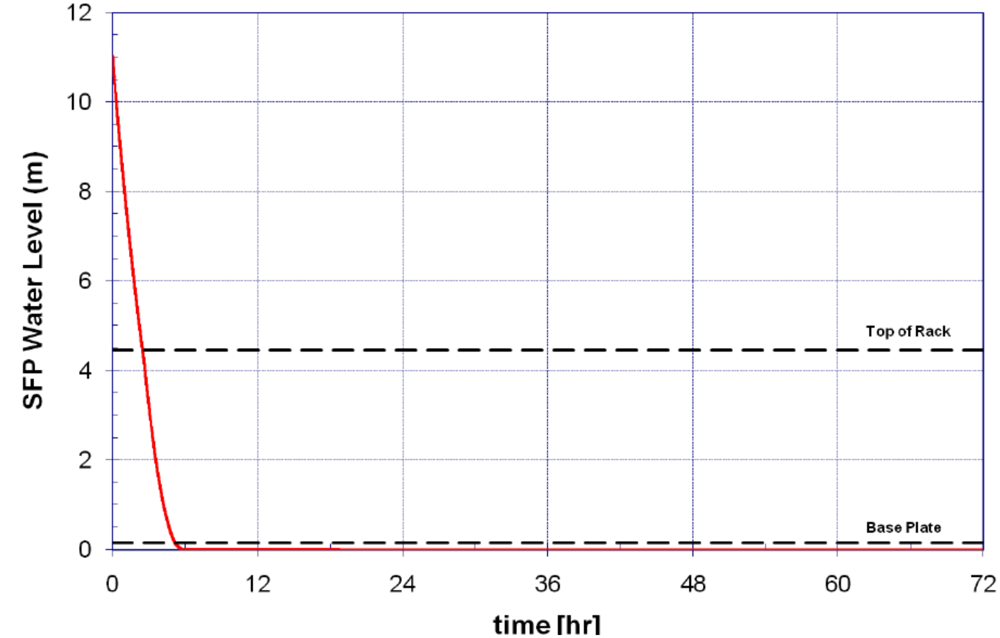
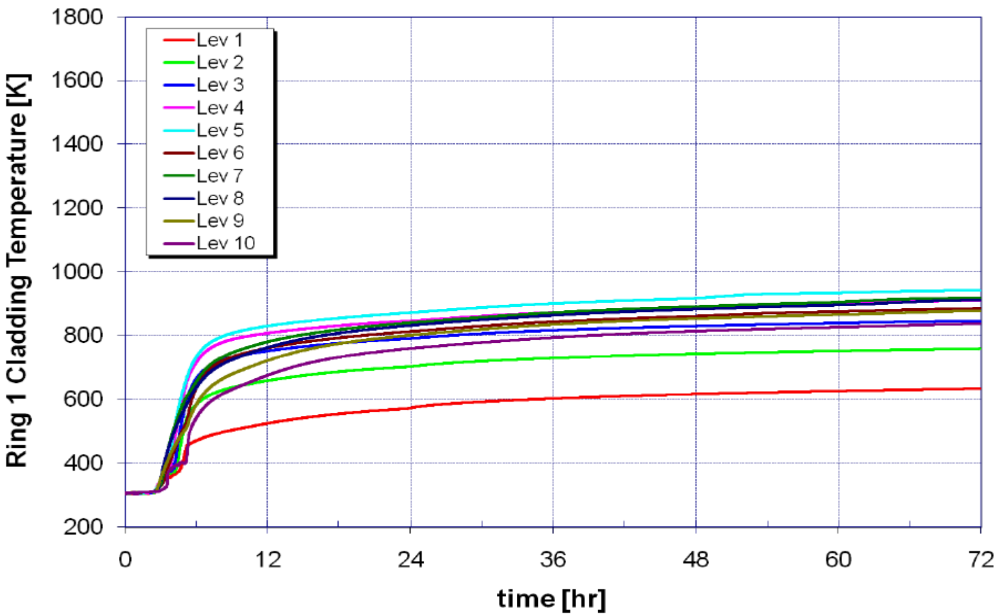
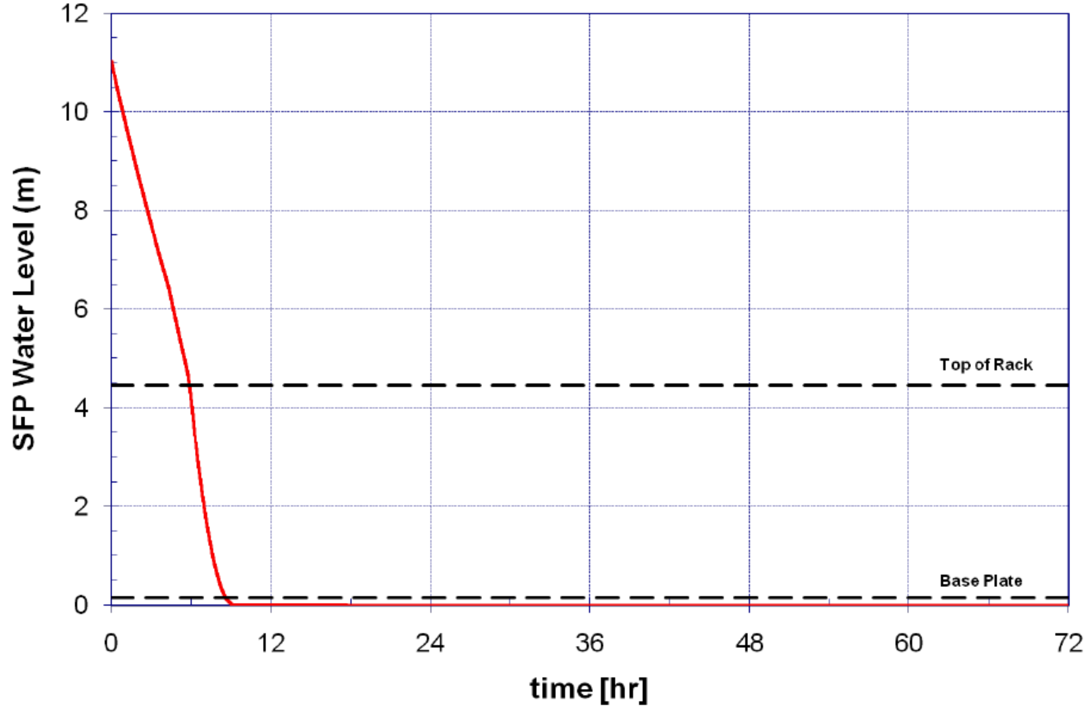
Low Density Racking

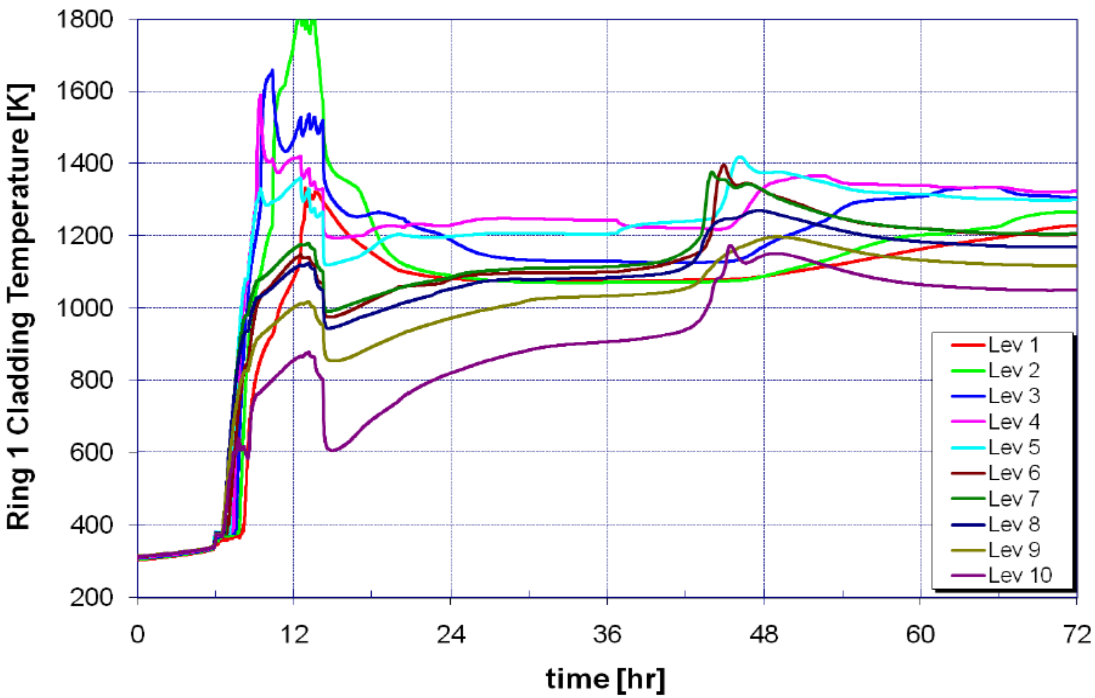




- Assumed pool leak due to seismic event
- Low density racking provides loose thermal coupling between assemblies
- Uncovered fuel is heated but no Zr-fire results

Ref: NUREG 2161

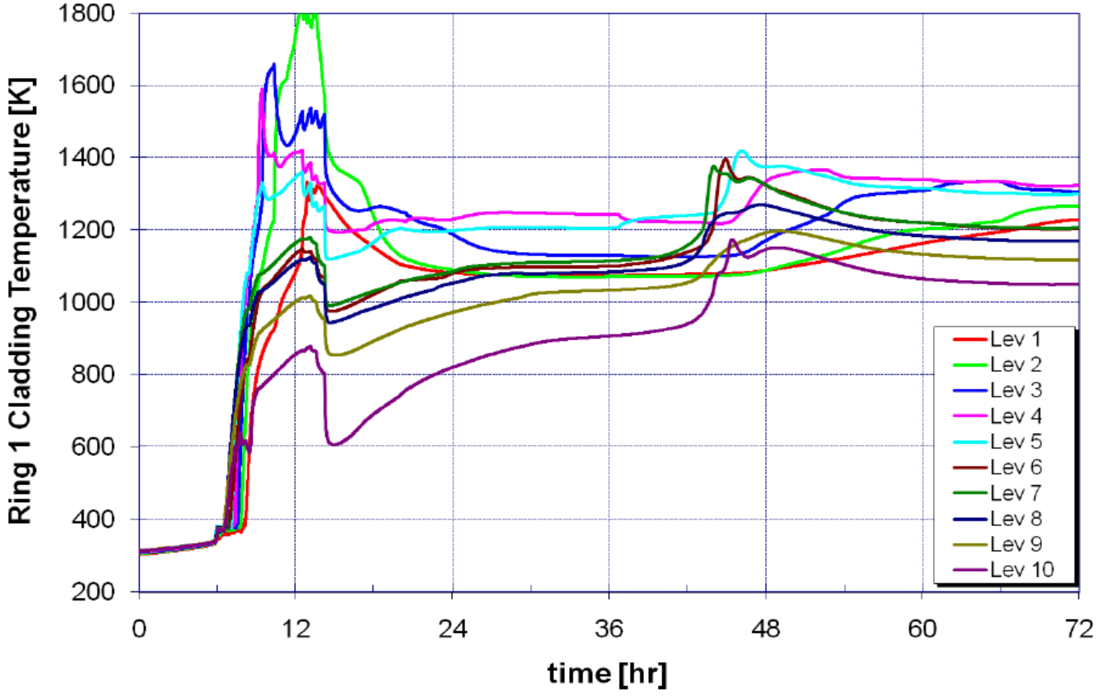


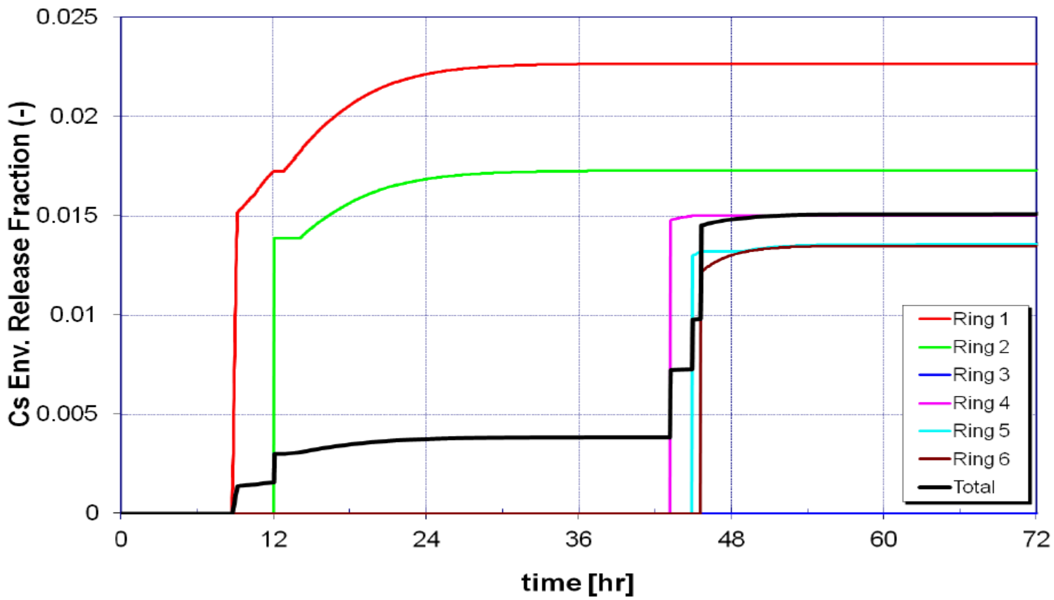


High Density Racking

- Tighter thermal coupling produces larger thermal response
- Oxidation energy produces higher fuel temperatures and cladding failures
- Hydrogen generation from steaming period
- Fission product releases

Ref: NUREG 2161



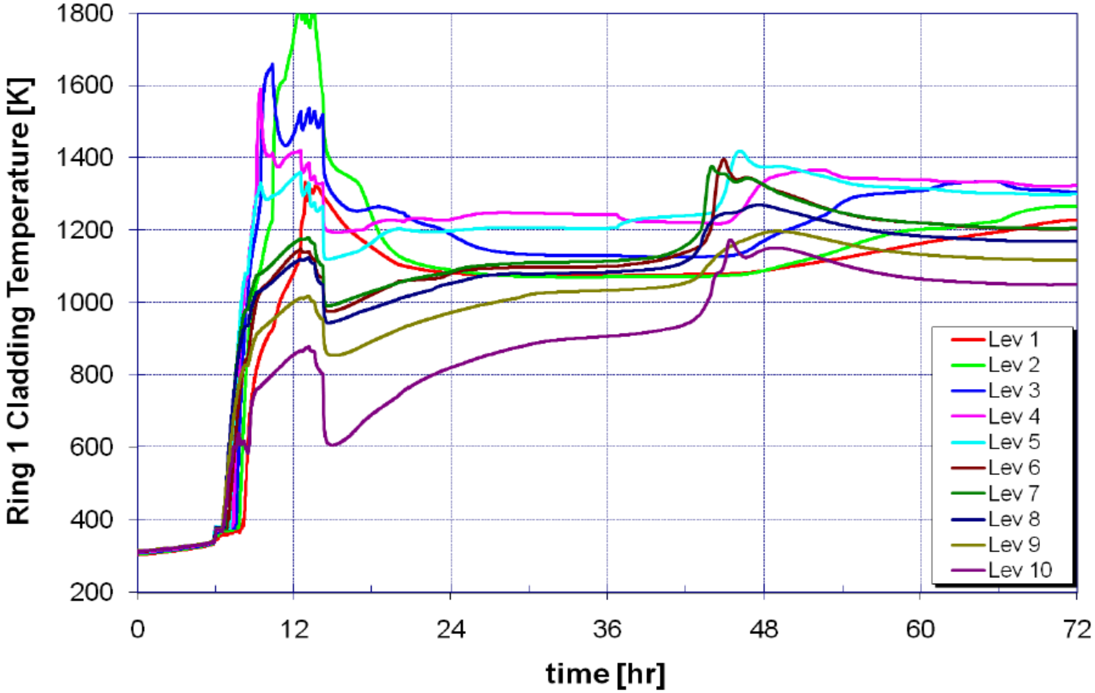


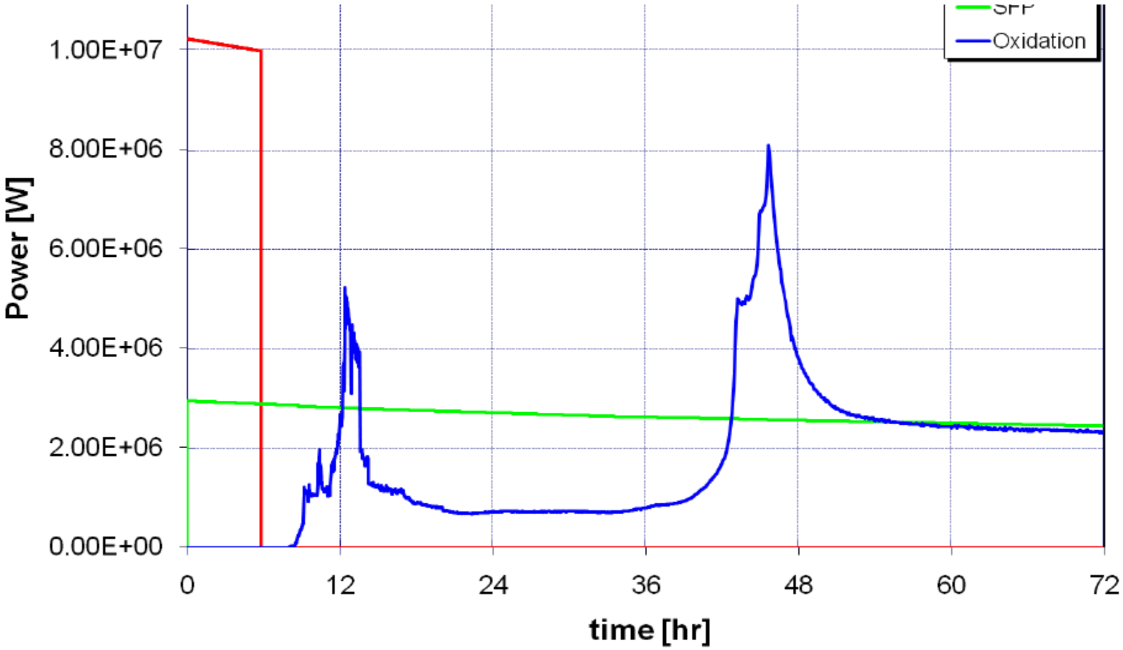
Fission Product Release

- Fuel heating drives release of fission products
- Second thermal transient driven by air oxidation

Ref: NUREG 2161

Oxidation Power

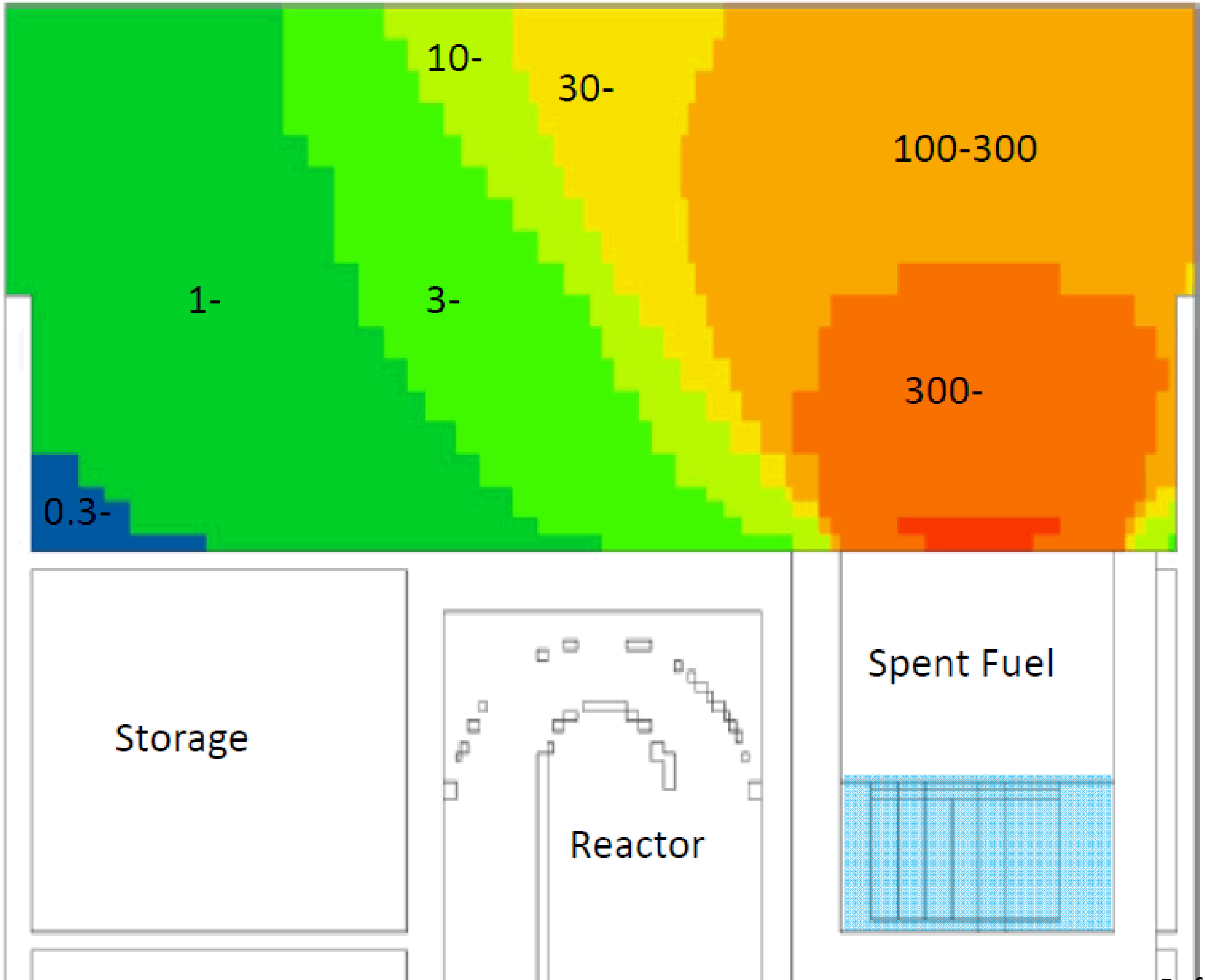




- Exothermic oxidation (Zr-fire)
- Energy release exceeds that from decay power significantly

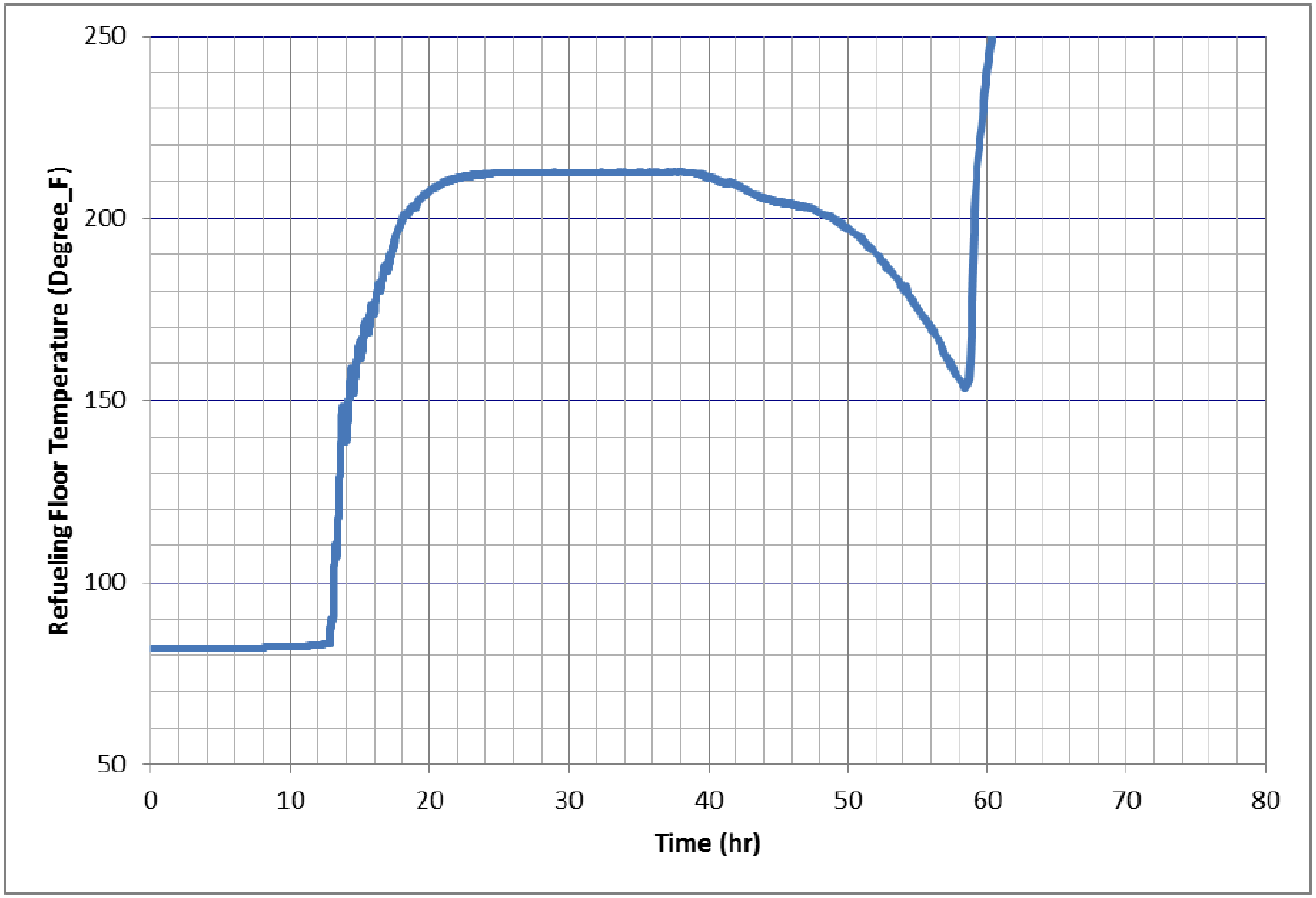
Ref: NUREG 2161

Radiation Field from Uncovered Fuel



Ref: NUREG 2161

Potential Temperatures on Refueling Floor



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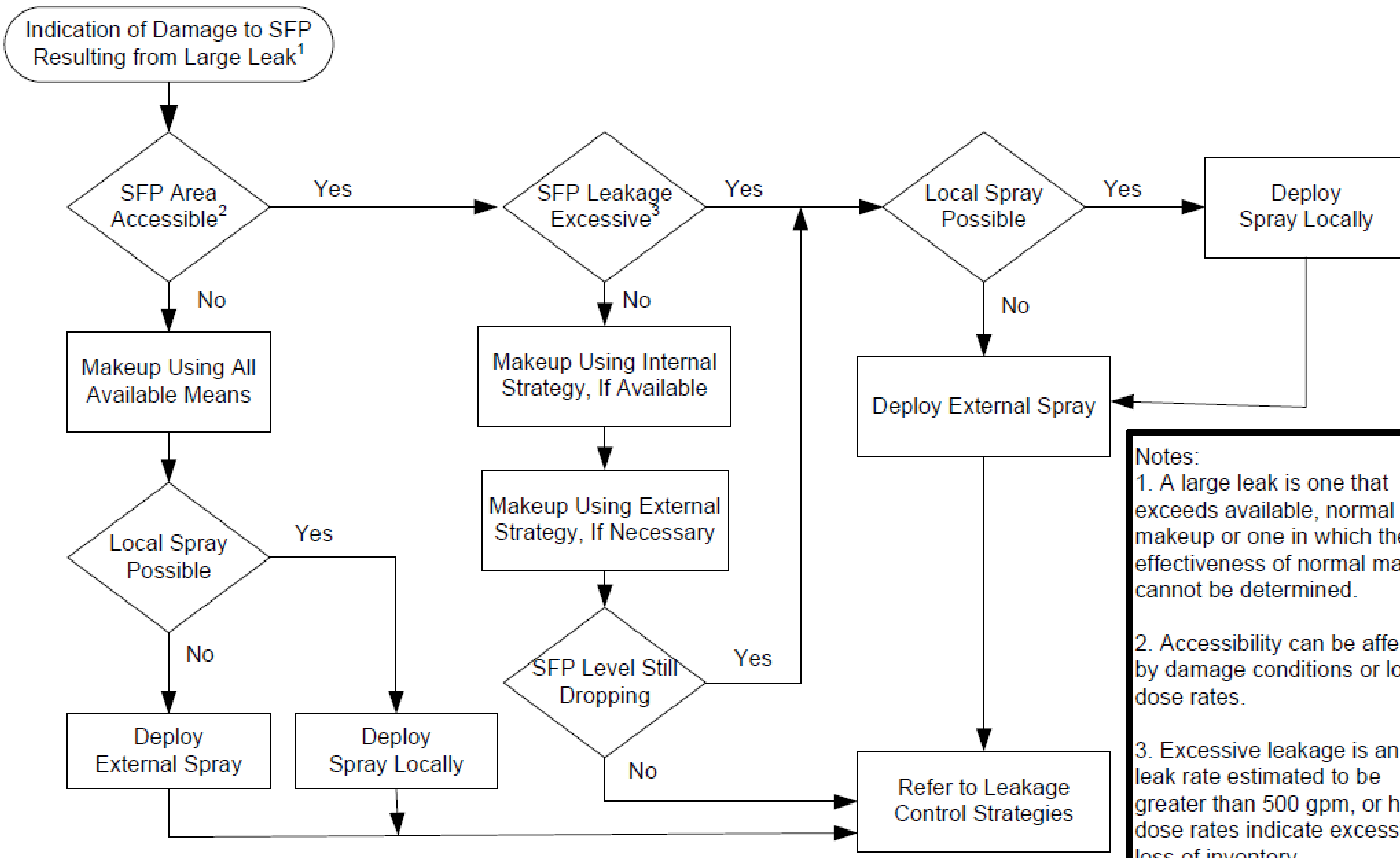
SFP Mitigation Using Sprays
NEI 06-12 TSG 4.1



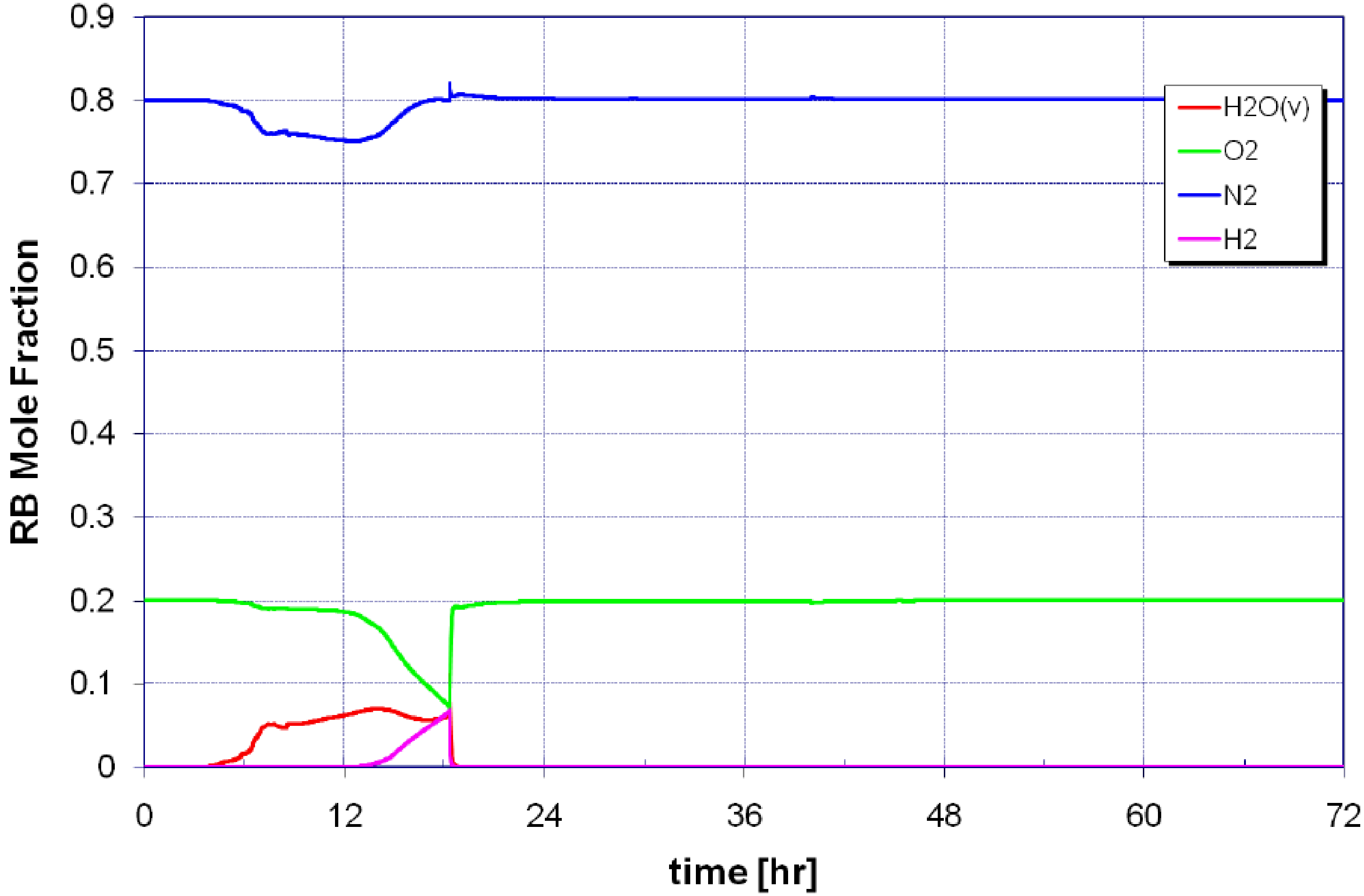
Notes:
1. A large leak is one that exceeds available, normal makeup or one in which the effectiveness of normal makeup cannot be determined.

2. Accessibility can be affected by damage conditions or local dose rates.

3. Excessive leakage is an SFP leak rate estimated to be greater than 500 gpm, or high dose rates indicate excessive loss of inventory.

Ref: NUREG 2161

Hydrogen Behavior on Refueling Floor



Ref: NUREG 2161

Spent Fuel Pool Accidents

- Protracted loss of heat sink generally not an issue until many days
- Zr-fire risk a function of fuel loading strategies
  - High density, low density, salt & pepper
- Environmental conditions are harsh
  - Thermal and radiation
- Spray and reflood mitigation measures can further reduce Zr-fire potential
- Zr-fire can propagate among assemblies and result in environmental release of fission products

Ref: NUREG 2161