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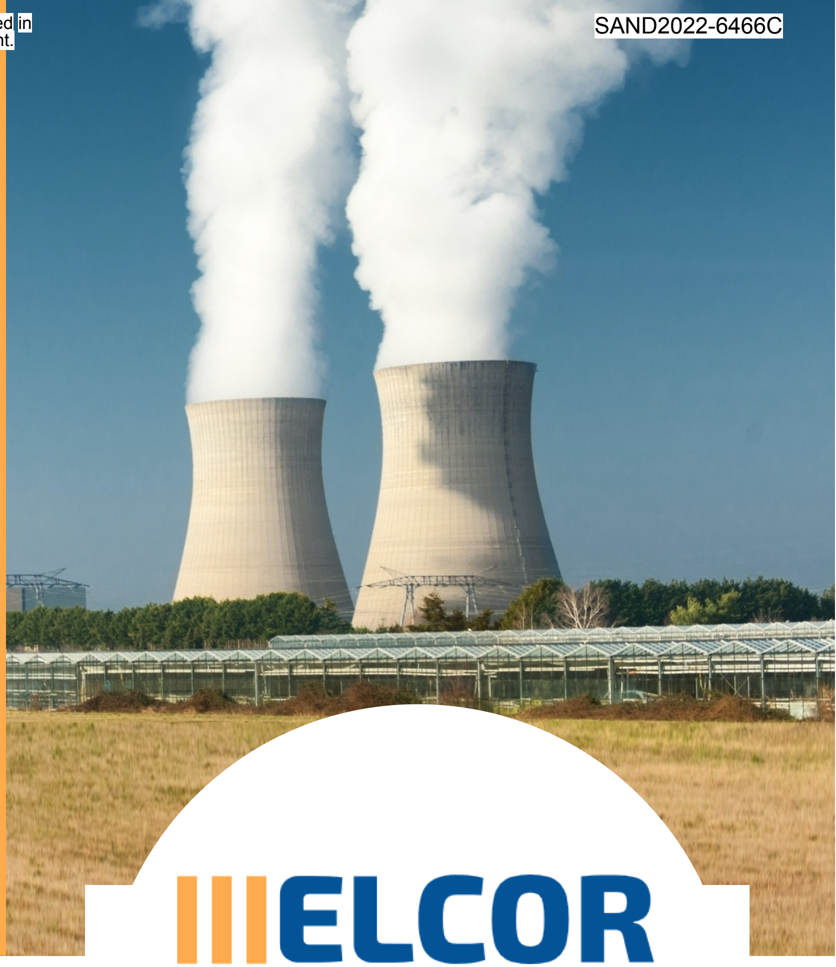


MELCOR

MELCOR Integrated Severe Accident Code Demonstration and Sensitivity Study of Heat Pipe Reactor Accident Progression

K.C. Wagner, C. Faucett, R. Schmidt, and D.L. Luxat
Nuclear Energy Safety Modeling and Analysis (8852)

Evolving Knowledge of Advanced Reactor Radiological Releases

Radiological releases from reactors generally similar to current plants

- Species of importance (e.g., I and Cs) similar
- May be additional activation products of interest (e.g., tritium or activated sodium)

Designs likely have improved safety margins relative to current plants

- Inherent and passive safety provides reactivity control and decay heat removal
- Longer time required from start of an event to radiological release to environment (>1day)
- Magnitude of core inventory released to environment may be lower by an order of magnitude or more for most events

Potentially greater range of radiological material available to be released from processing or off -gas systems outside reactor

Traditional reactor containment structures are not being pursued for many of these advanced reactor concepts

- Reactor enclosures not "leak tight" and exhibit strong coupling to wind

Requests to have no requirement for emergency planning (i.e., no Emergency Planning Zone)

Uncertainties still relatively large

- Consensus around range of credible beyond design basis (i.e., severe accident) scenarios developing
- Comparisons between designs should not be made currently

MELCOR Heat Pipe Reactor Modeling: 1

When present, HPs replace conventional convective heat transfer between the fuel and coolant channel with the energy transfer from the fuel to the evaporative region of the HP.

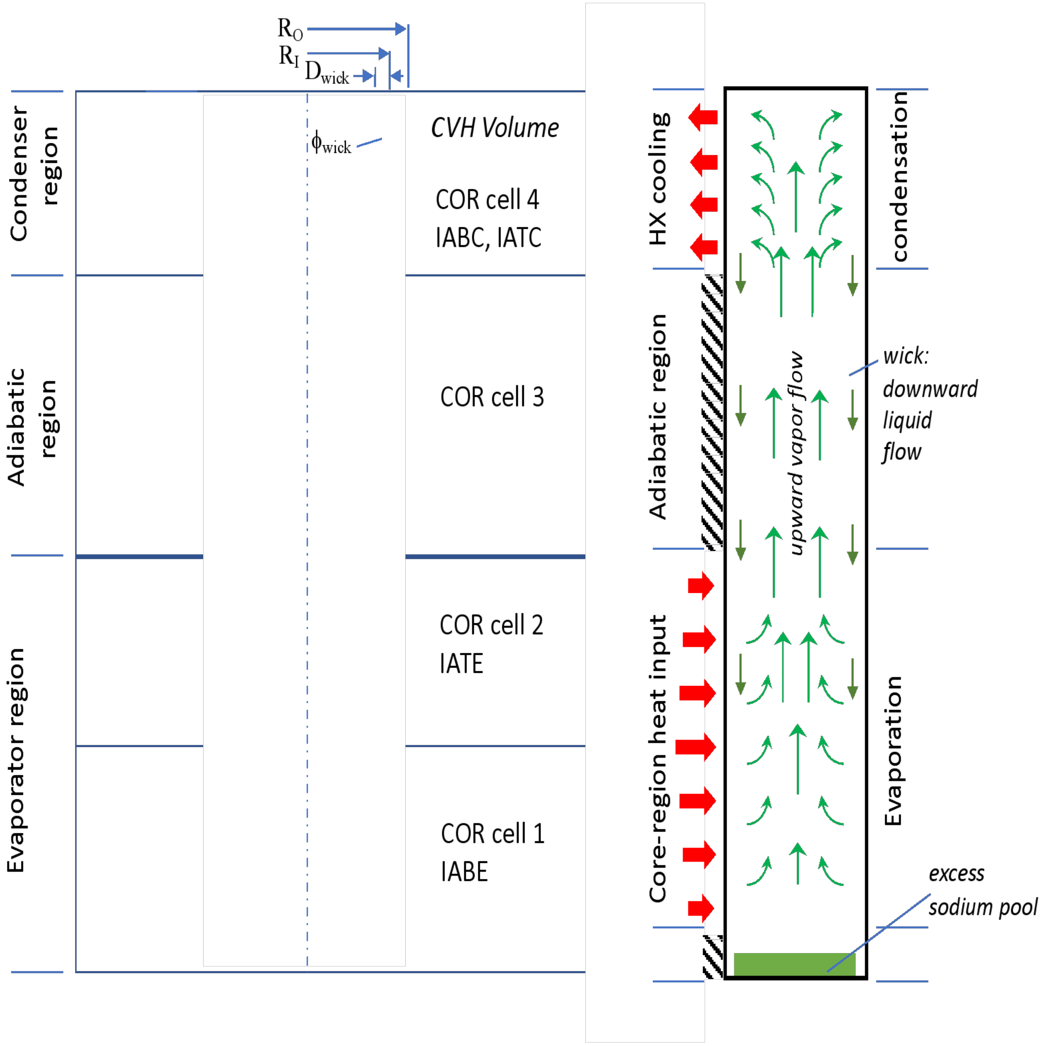
HP models are special components within the COR package.

Heat rejection from the HP model at the condensation interface is transferred to the CVH package.

Basic geometry of a heat pipe is assumed to be a circular cylinder characterized by a relatively small set of geometric values, e.g.:

- R_O outside radius of heat pipe wall (m),
- R_I inside radius of heat pipe wall (m),
- D_{wick} thickness (or depth) of the wick (m), and
- ϕ_{wick} porosity of the wick (-).

Axial lengths of the condenser, adiabatic, and evaporator sections are implicitly defined by the COR package cells that these regions are associated with.



A Generic Heat Pipe

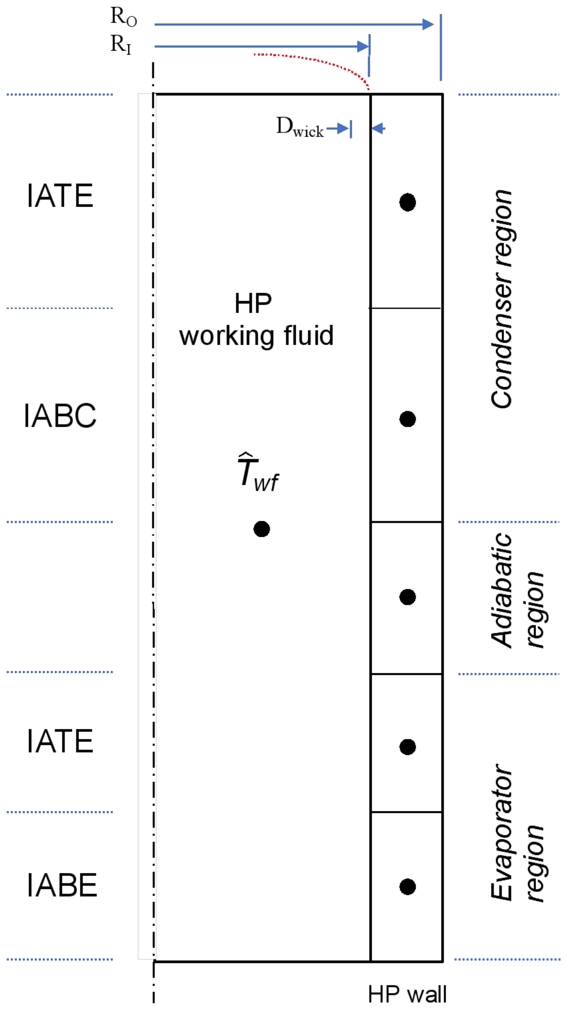
MELCOR Heat Pipe Reactor Modeling: 2

HP modeling approaches within MELCOR reflect the purpose and constraints of the systems-level integrated code that it is.

MELCOR accommodates HP models of different fidelity through a common interface and a specified wall and working fluid region nodalization.

- Model 1: working fluid region modeled as high thermal conductivity material.
- Model 2: thermodynamic equilibrium of working fluid (sodium or potassium EOS). P, T and liquid/vapor fraction evolve in time. Sonic, capillary and boiling limits enforced.
  - Accepts experimental or design-specific performance limit curves
- Flexible implementation allows for multiple HP definitions in the same MELCOR input deck and multiple HP regions

Time-dependent conservation-of-energy equations are solved within the HP component and include boundary conditions linking them with the neighboring fuel (evaporator region) and coolant (condenser region)

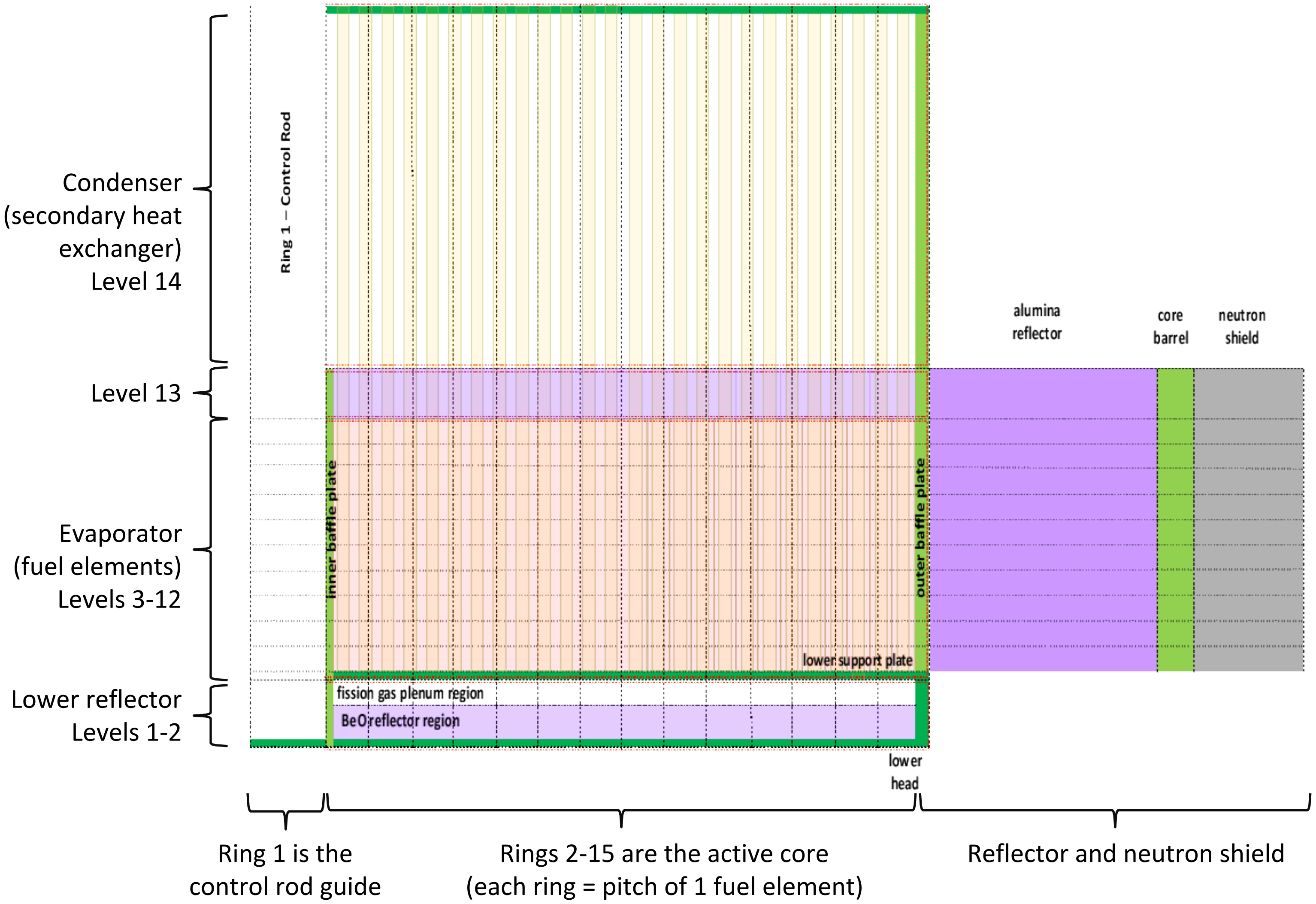


Illustrative MELCOR HP component nodalization to define MELCOR variables. Actual nodalization has more nodes.

MELCOR model of INL Design A – Reactor

Reactor modeling

- 2-D reactor nodalization
  - 14 axial levels
  - 15 radial rings
- 14 concentric rings of heat pipes (width of ~1 fuel assembly)
- Center ring models the emergency control rod guides
- Top and bottom reflectors are in axial levels 1 and 13
- Heat pipes transfer heat to the secondary Brayton air cycle in axial level 14
- Core region is surrounded by stainless steel shroud, alumina reflector, core barrel, and B_4C neutron shield



Reactor vessel – release pathways

Release from fuel to reactor vessel

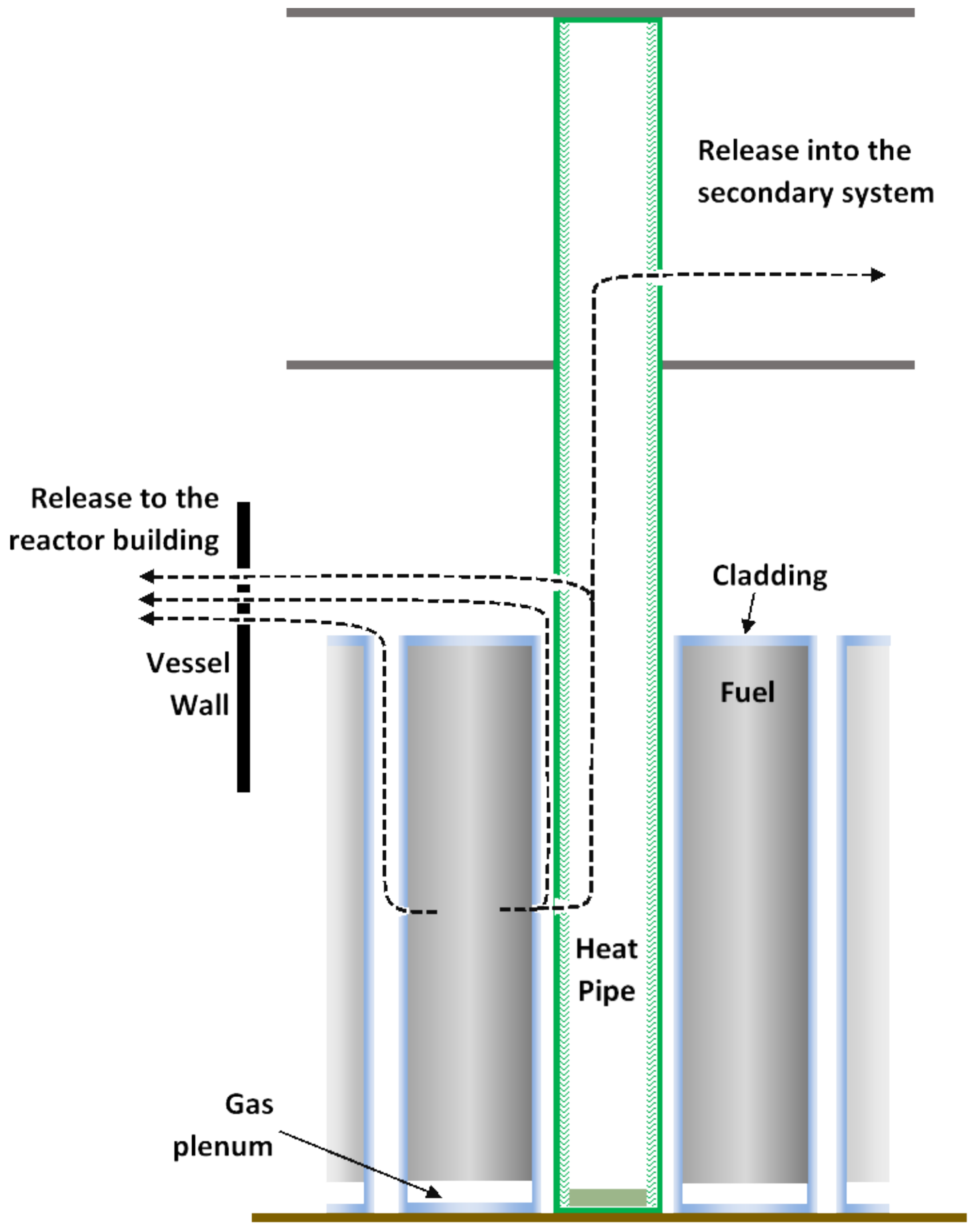
- Stainless-steel cladding failure at 1650 K

Release from reactor vessel to reactor building

- Assumed reactor vessel leakage

Heat-pipe release path

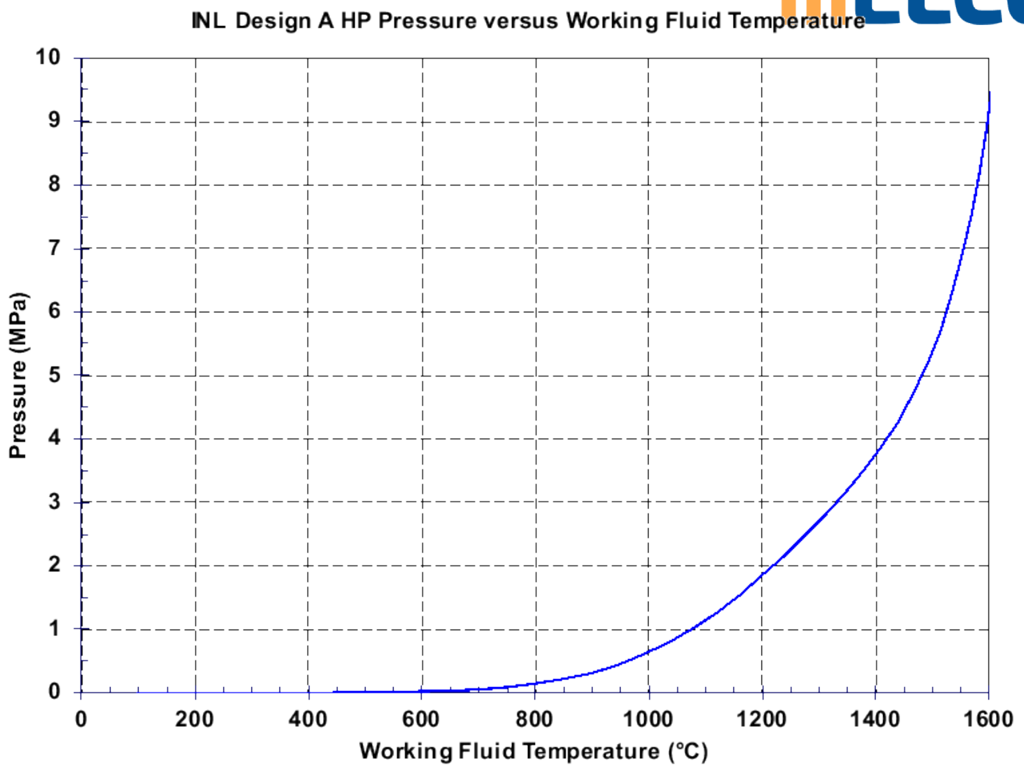
- Requires heat-pipe wall failure in two places
  - Creep rupture followed by melting
- Creep rupture failure in the heat-pipe condenser region (secondary system region) could lead to reactor building bypass



MELCOR HP failure modeling

MELCOR

- HP temperature excursion leads to working fluid pressurization and HP wall creep failure
  - Larson-Miller model used for wall failure
  - Subsequent response includes HP failure and depressurization
- Alternate user-specified criteria for HP wall failure
  - HP wall failure can be a specified event (e.g., initiating event) or as an additional failure following a creep rupture failure (i.e., creep failure is predicted before wall melting)
- Optional user features to dynamically control or disable HP evaporator or condenser wall heat transfer and to start the fuel cell radionuclide leakage



Enclosure building nodalization

ELCOR

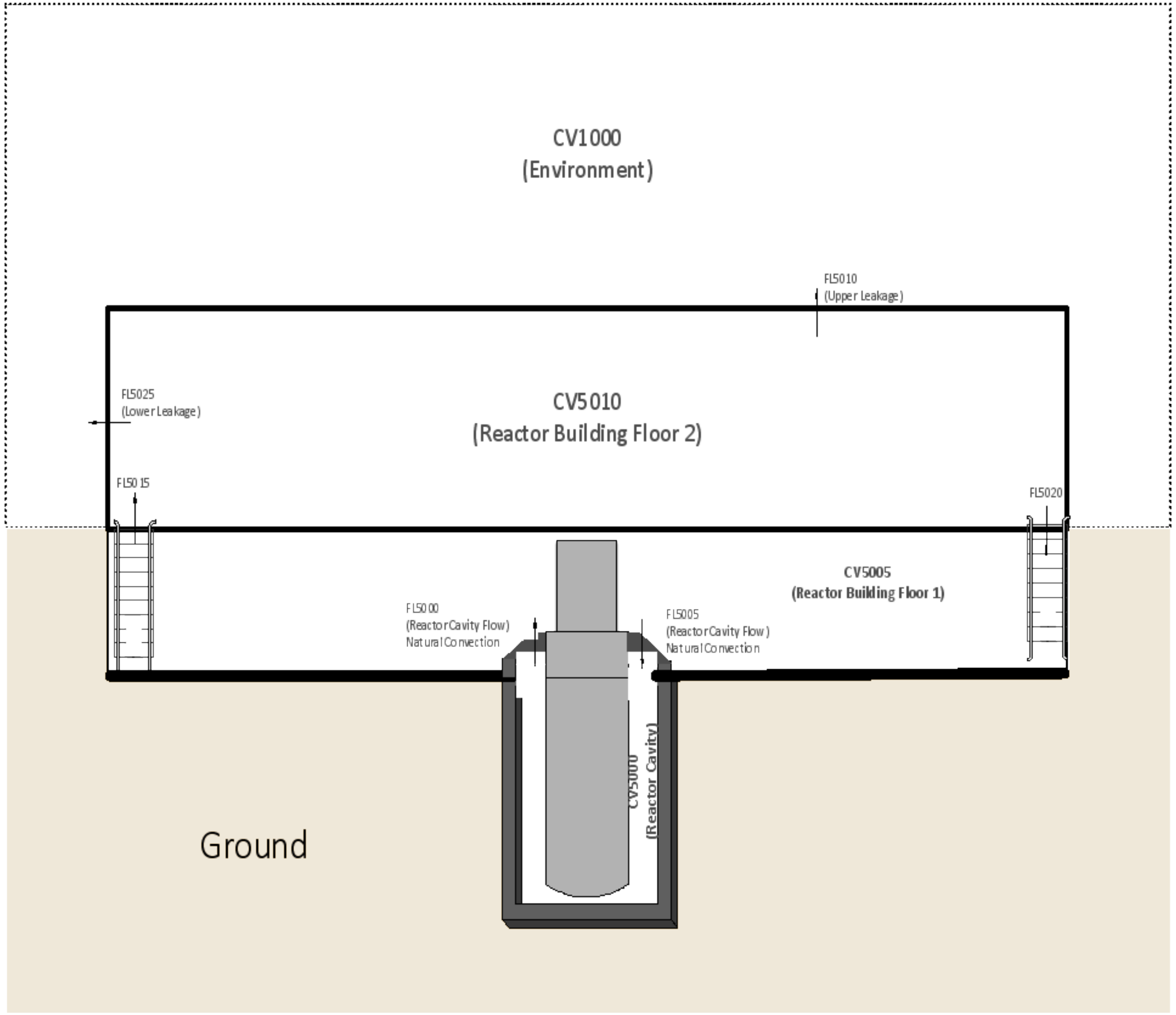
LANL and INL HPR descriptions did not address the enclosure building

Modeling includes internal building circulation flow paths

- Natural circulation into and out of the reactor cavity
- Natural circulation within the building

Building leakage addressed parametrically

- Base leakage similar to the reactor building surrounding the BWR Mark I containment



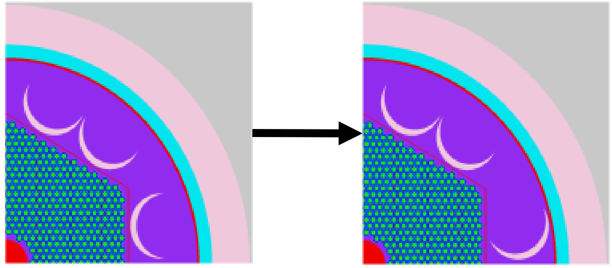
Description of the TOP scenario

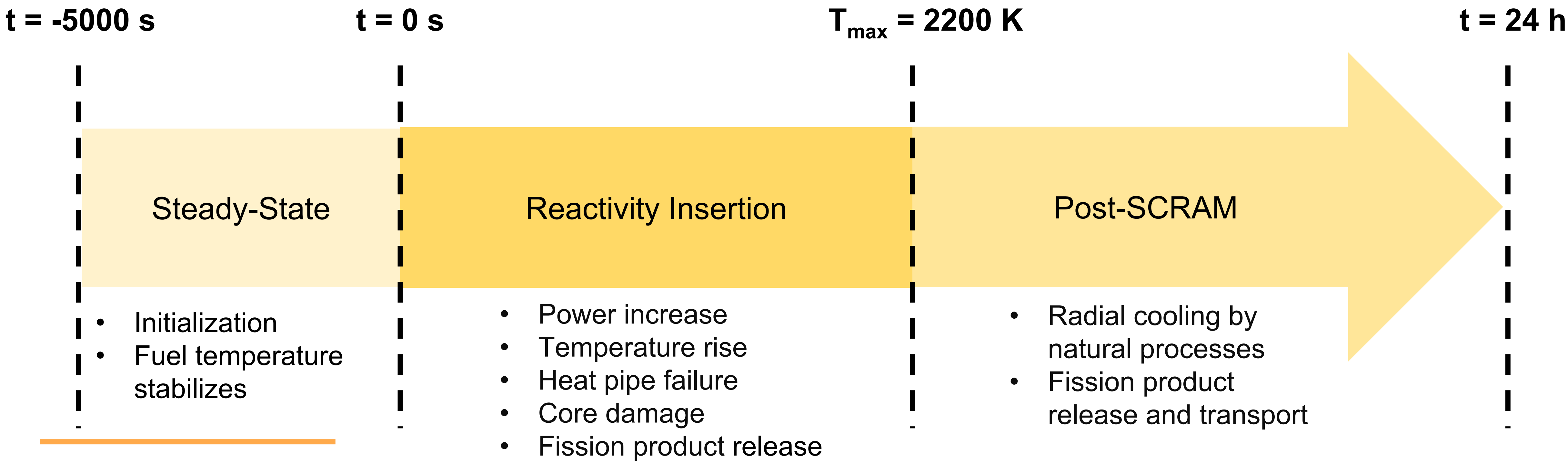
MELCOR

Transient Overpower (TOP) scenario selected for demonstration calculations
- Control drums malfunction and spuriously rotate “outward”

Modeled as linear reactivity insertion rate in $/second
- Safety control rods assumed to insert when peak fuel temperature exceeds 2200 K
- Strong feedback coefficient creates linear power increase

Performed sensitivity analysis to show how MELCOR could be used to gain insight into key source term drivers
- Sensitivities focused on source term and HPR parameters
- Previous LWR parameters do not necessarily translate to HPR uncertainties





Transient Overpower (TOP) base scenario (1/7)

The control drums start rotating at t=0 sec, which leads to an increase in the core power over 0.9 hr

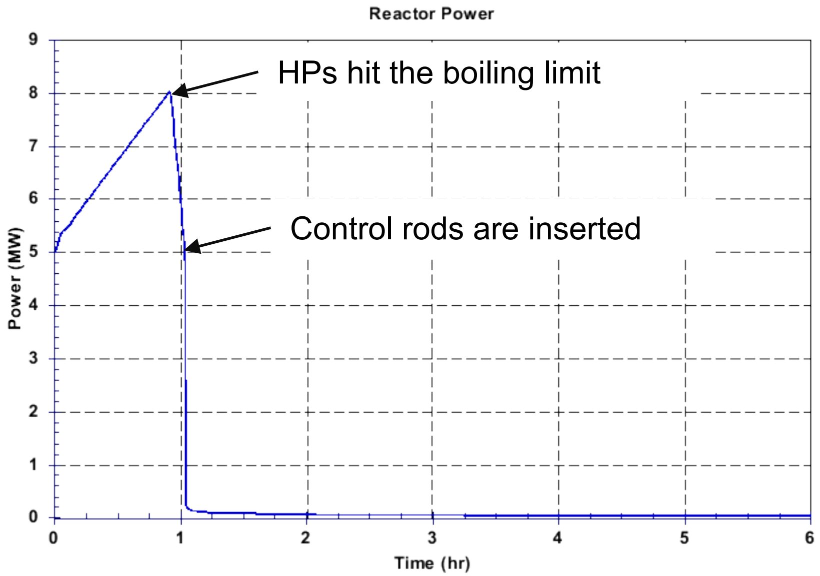
- Negative fuel temperature reactivity feedback limits the rate of power increase

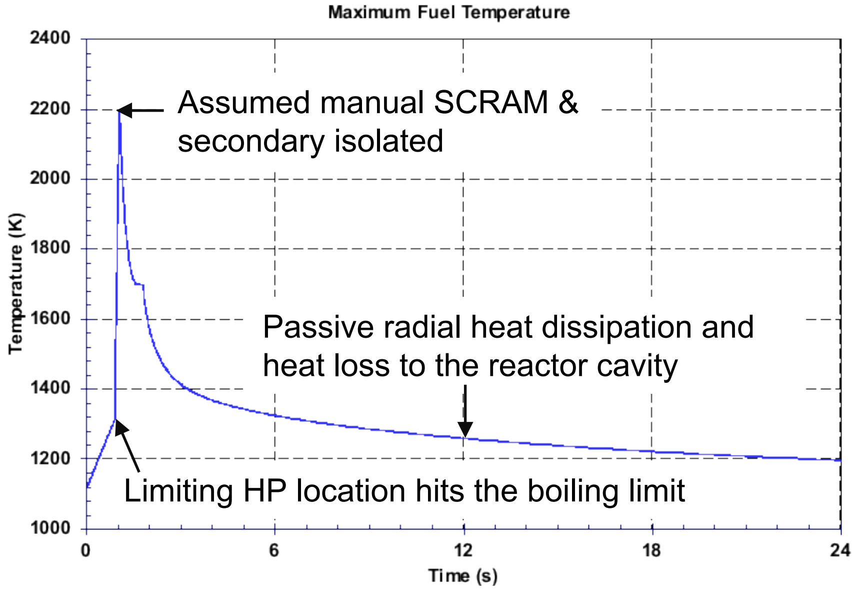
The core steadily heats until the maximum heat flux location reaches the boiling limit

- The heat transfer rate is limited above the boiling limit, which leads to a rapid heatup rate
- The SS cladding is assumed to fail at 1650 K (just below its melting point), which starts the fission product releases into the reactor
- The reactor is assumed to trip at 2200 K

Radial heat dissipation and heat loss to the reactor cavity passively cools the core

- No active heat removal (secondary system trips and isolates)

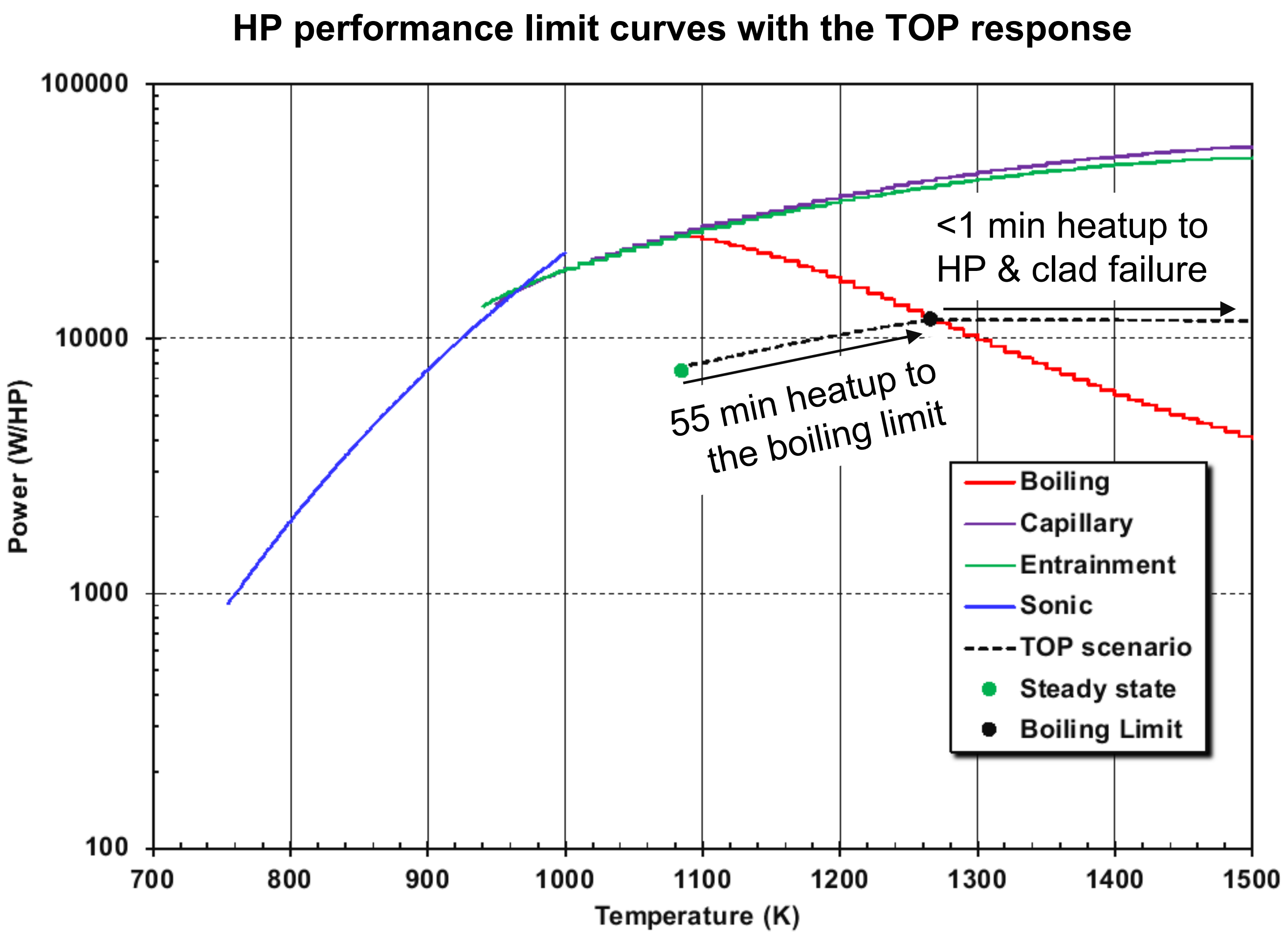




Transient Overpower (TOP) base scenario (2/7)

The HP performance limits at the highest heat flux location show a steady heatup to the boiling limit

- Once the boiling limit is reached, there is a rapid heatup over the next minute
  - The fuel rapidly heats to melting conditions
  - SS cladding fails at 1650 K
  - SS HP wall also fails at 1650 K
- The start of the fission product release occurs through the failed cladding locations



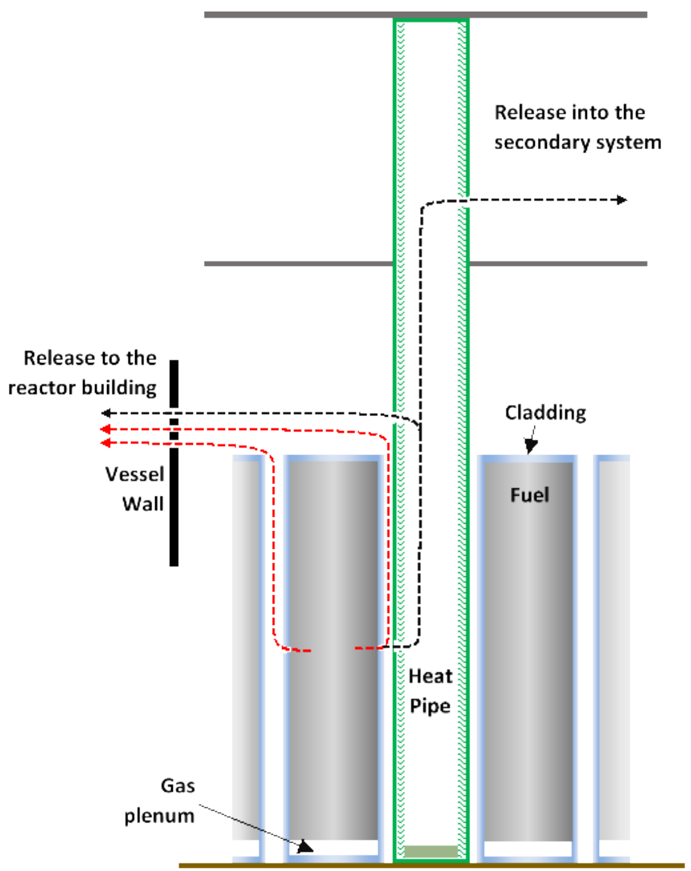
Transient Overpower (TOP) base scenario (3/7)

Cladding failure at 1650 K resulting in fission product release

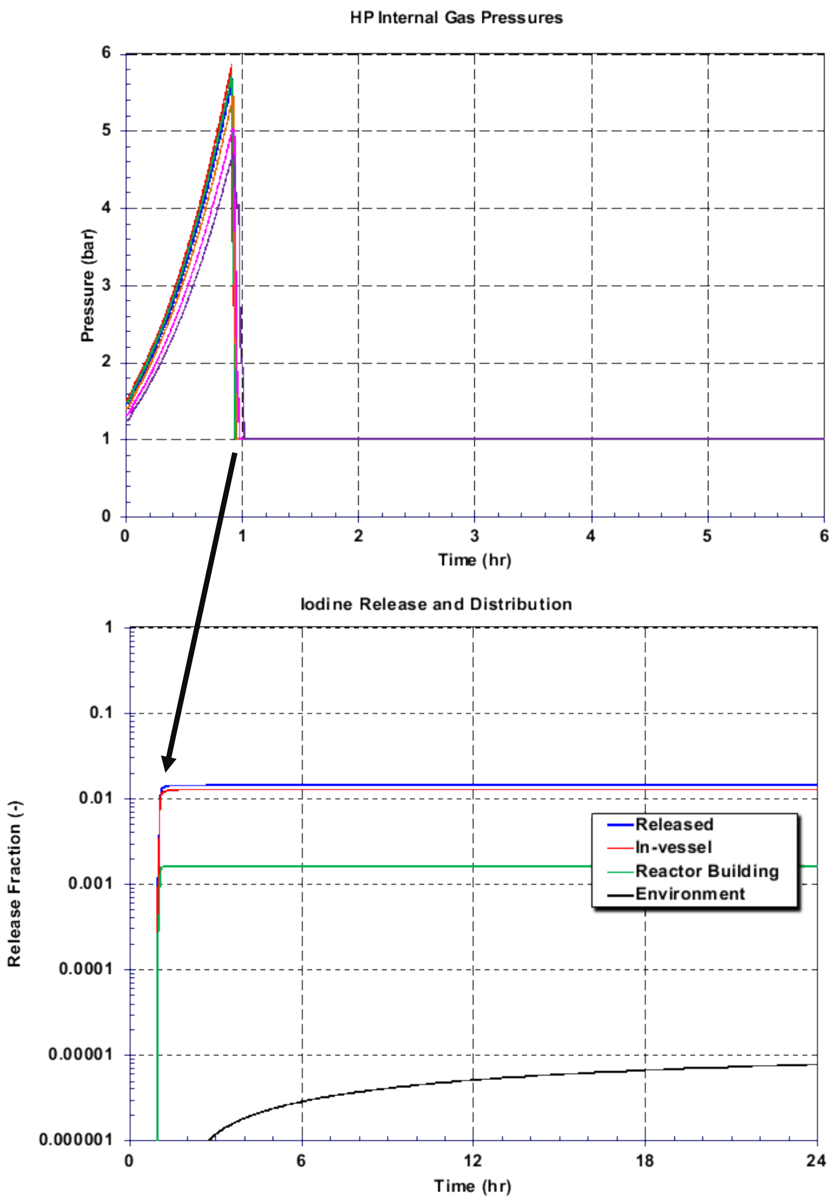
- HPs that exceeded the boiling limit rapidly heat to cladding failure (1650 K)
- ~20% of the 1134 HPs and fuel elements failed
- HP depressurization on failure drive release from the vessel

Iodine releases also depend on time at temperature

- Fuel release – 1.4% of core inventory
- Environmental release – 0.0008% of core inventory



- Vessel leakage is 1.6 in^2
- Building leakage is 1.8 in^2



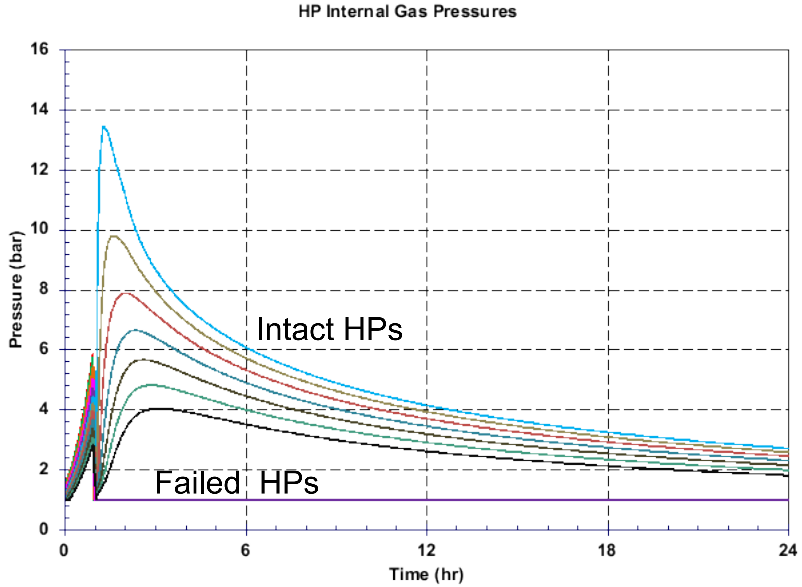
Transient Overpower (TOP) base scenario (4/7)

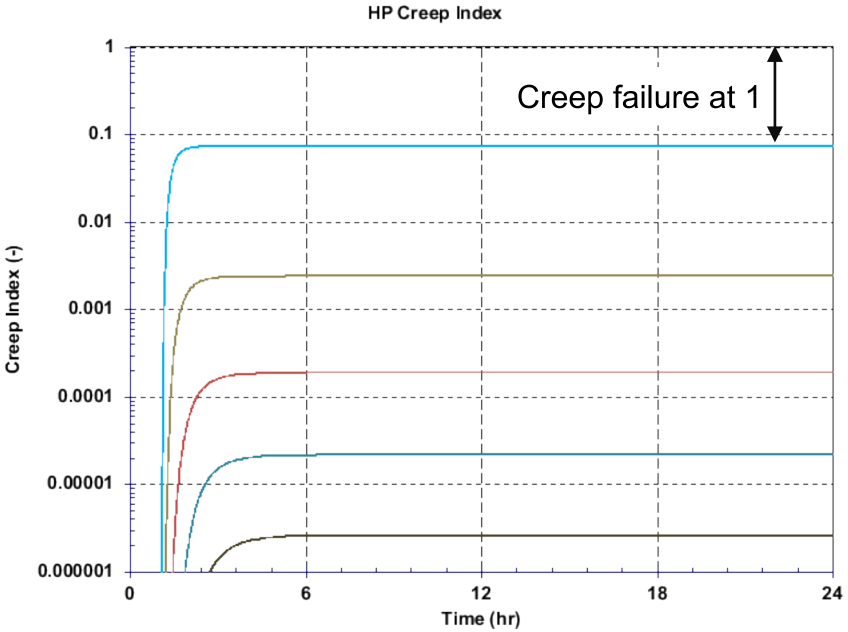
The HPs could be challenged by creep failure at high temperature and pressure

- The HP gas heats and pressurizes during the TOP scenario
- The HP depressurizes after the wall fails shortly after reaching the boiling limit
  - Creep accumulation effectively stops upon HP wall failure without ΔP stress
- For HPs that do not reach the boiling limit, the HP pressure initially drops due to secondary system removing heat

HP creep failure is monitored using Larson-Miller correlations

- TOP base scenario shows maximum creep is ~0.07 (failure = 1)
- Creep failures in the condenser can create a bypass leak path to the environment

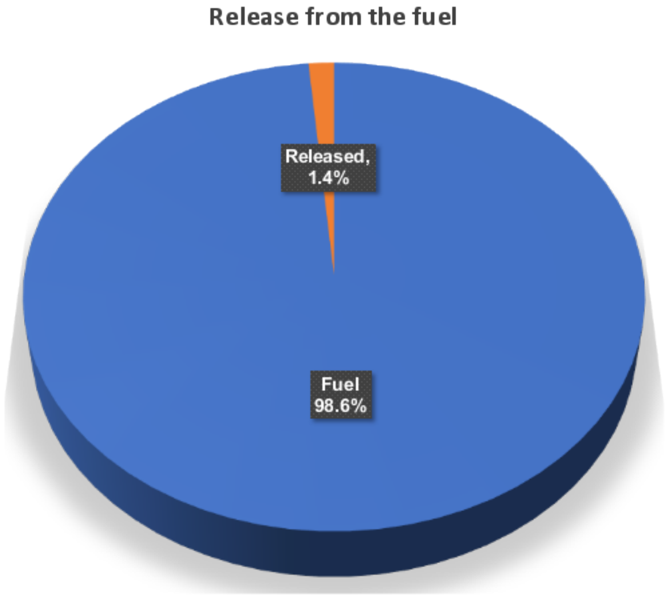




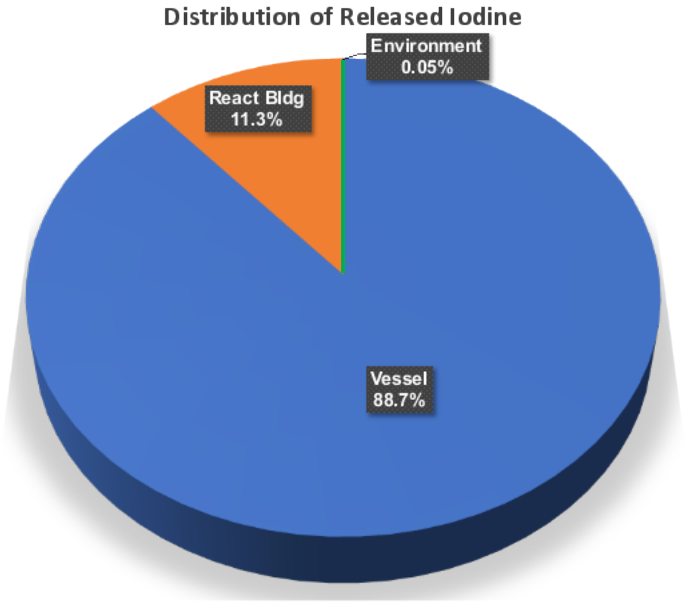
Transient Overpower (TOP) base scenario (5/7)

Fission products are retained in the fuel or deposit on their way to the environment

- The cladding remained intact for ~80% of the fuel elements
- 98.4% of the iodine fission product inventory is retained in the fuel due to limited time at high temperature



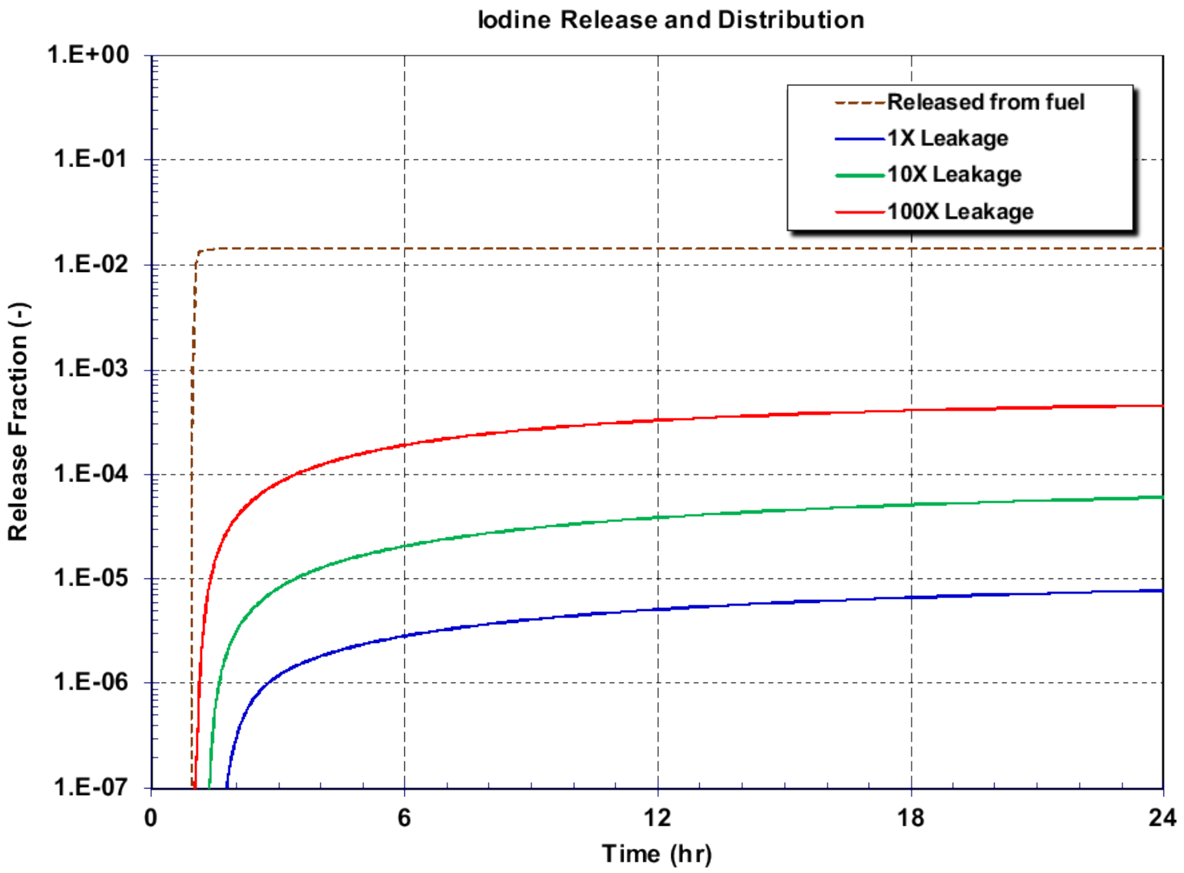
- The vessel retains 89% of the released iodine radionuclides
  - HP depressurization after failure is primary release mechanism
- The reactor building retains 11% of the radionuclides in the base case
  - BWR reactor building leak tightness used for the base case
  - No strong driving pressure to cause leakage



Transient Overpower (TOP) base scenario (6/7)

A series of calculations were performed to investigate the sensitivity of the source term magnitude to reactor building leakage effects

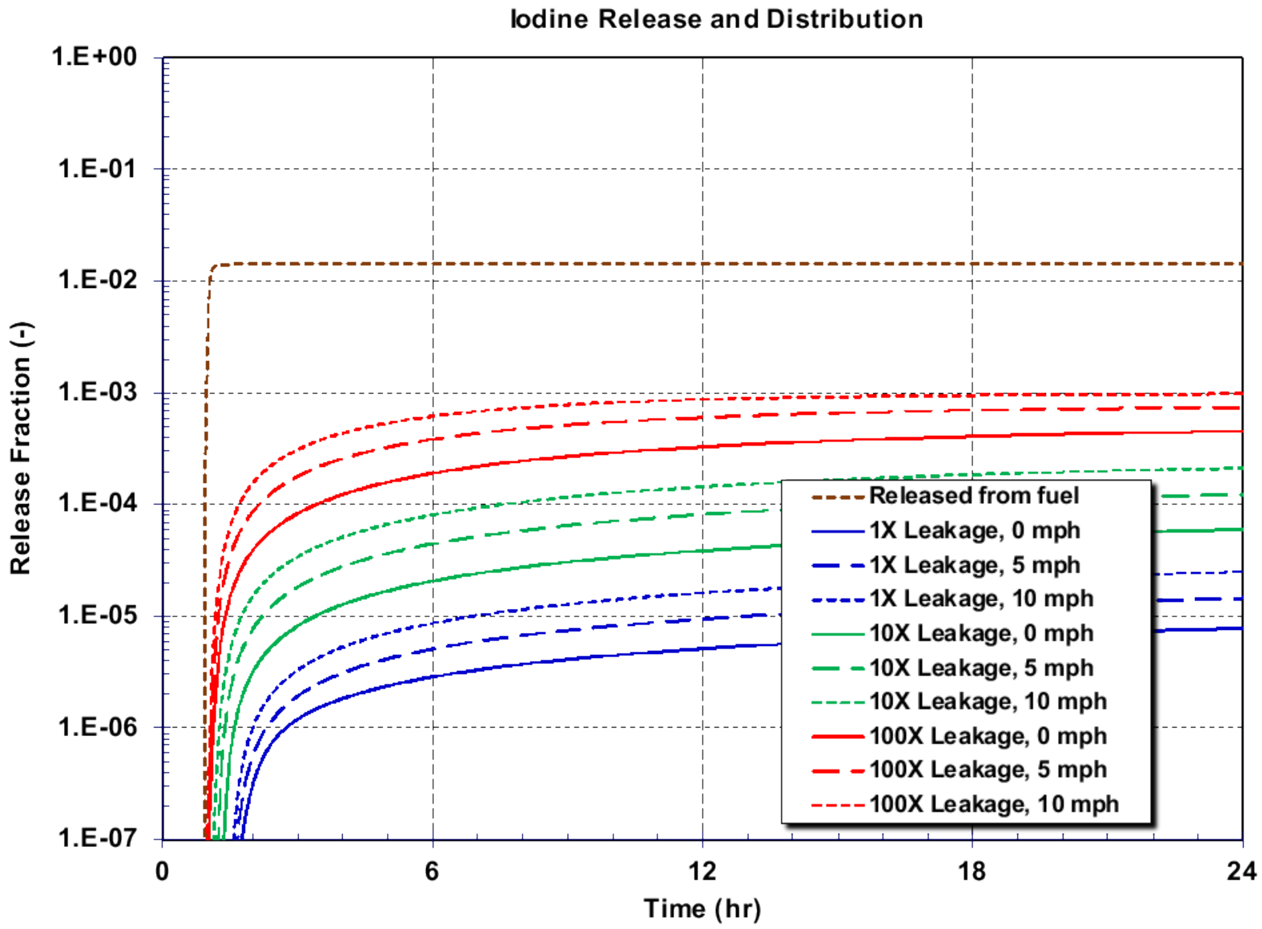
- The design specifications of the reactor building were assumed
  - The base result (1X) assumed a BWR reactor building value
  - 10X and 100X reflects higher design leakage and/or building damage
- Building leakage is driven by a very small temperature gradient to the environment (~5 -7 °C)
  - Leakage is approximately linear with leakage area (1X is ~1.8 in^2)



Transient Overpower (TOP) base scenario (7/7)

A series of calculations were performed to investigate the impact of an external wind

- External wind effects are included in DOE facility safety analysis where there also are not strong driving forces
  - Wind increases building infiltration and exfiltration
  - Upwind and downwind leakage pathways
- Wind effects are modeled as a Bernoulli term
  - $dP = \frac{1}{2}\rho C_p v^2$
  - ASHRAE building wind-pressure coefficients



External wind modeling ref:

“MELCOR Computer Code Application Guidance for Leak Path Factor in Documented Safety Analysis,” U.S. DOE, May 2004.

Building wind pressure coefficients.

ASHRAE, 1977, Handbook of Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 1997.

Parametric Uncertainties – Capability Demonstration

Component	Parameter	Ranges
Heat Pipes	Heat Pipe Failure Location	Condenser (50%) / Evaporator (50%)
	Initial non-functional HPs	0% - 5%
Core	Gaseous Iodine Fraction (-)	0.0 - 0.05
	Reactivity Insertion Rate ($/s)	0.5×10^{-4} - 1.0×10^{-3}
	Total reactivity feedback	-0.0015 to -0.0025
Vessel	Fuel Element Radial View Factor Multiplier (-)	0.5 - 2.0
	Vessel Emissivity (-)	0.125 - 0.375
	Total Leak Area (m^2)	2×10^{-5} - 2×10^{-3}
	Vessel and Vessel Upper Head HTC (W/m-K)	1 – 10
Confinement	Cavity entrance open fraction	100% (90%) - 1% (10%)
	Cavity Emissivity (-)	0.125 – 0.375
	Wind Loading (m/s)	0 – 10
	Total Leak Area Multiplier (-)	1 - 100
Scenario	Peak fuel temperature for safety rod insertion (K)	1300 – 2200

Characterization of Uncertainty in Event Evolution

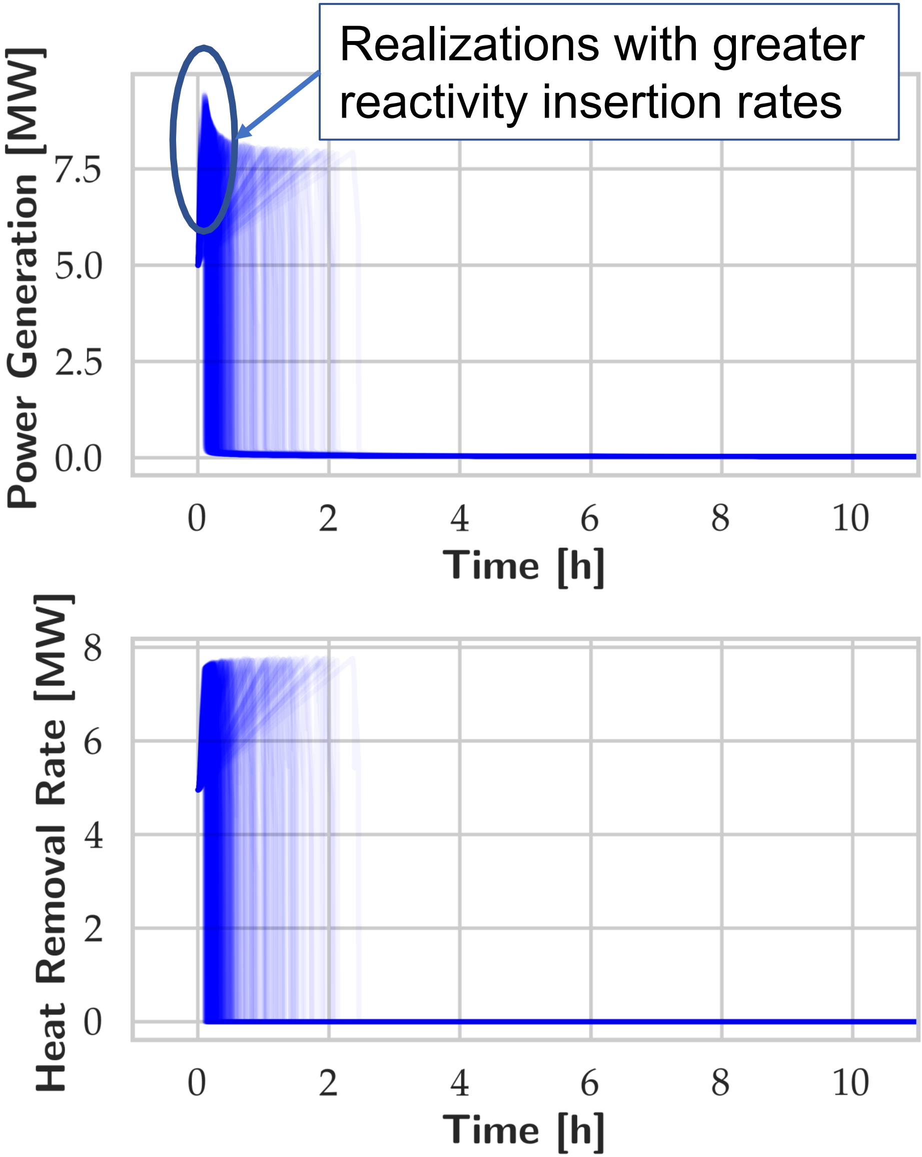
Traditional event scenario evolution for LWRs dominated by active system performance

Event scenarios evolved based often on binary decisions

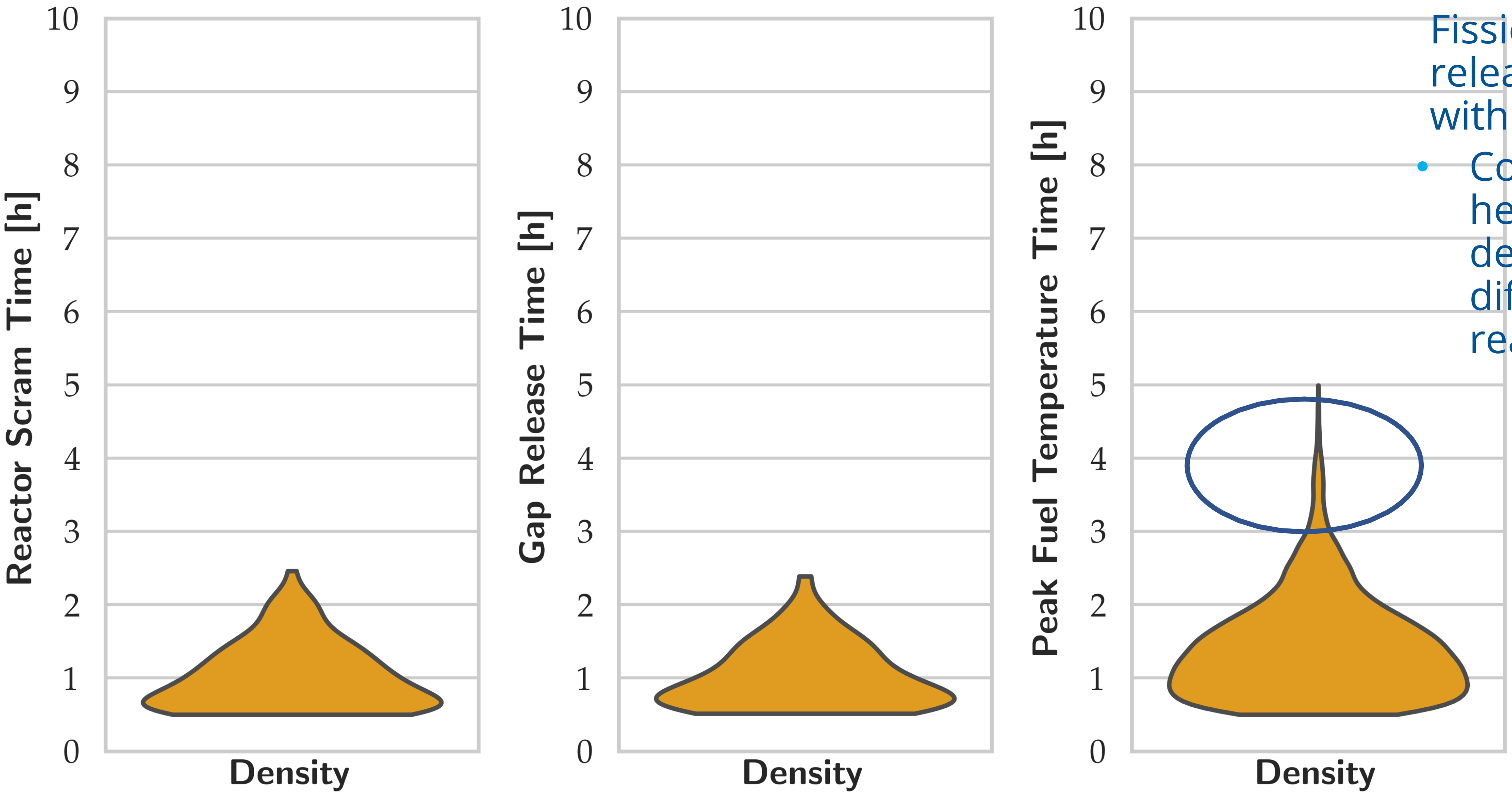
- SSC performance often characterized as success or failure
- Risk profile could be adequately characterized or bounded by success or failure of SSCs

HPR accident scenario evolution will be unique, like other advanced non-LWRs

- Limited operational experience
- Broader range of operation for passive systems
- Consideration of degraded modes of operation
- What is the true margin to failure under accident conditions?



Overall Timing of Event Evolution



Fission product release commences with cladding failures

- Continued fuel heatup can occur as deposited energy diffuses following reactor trip

Evaluating Heat Pipe Response

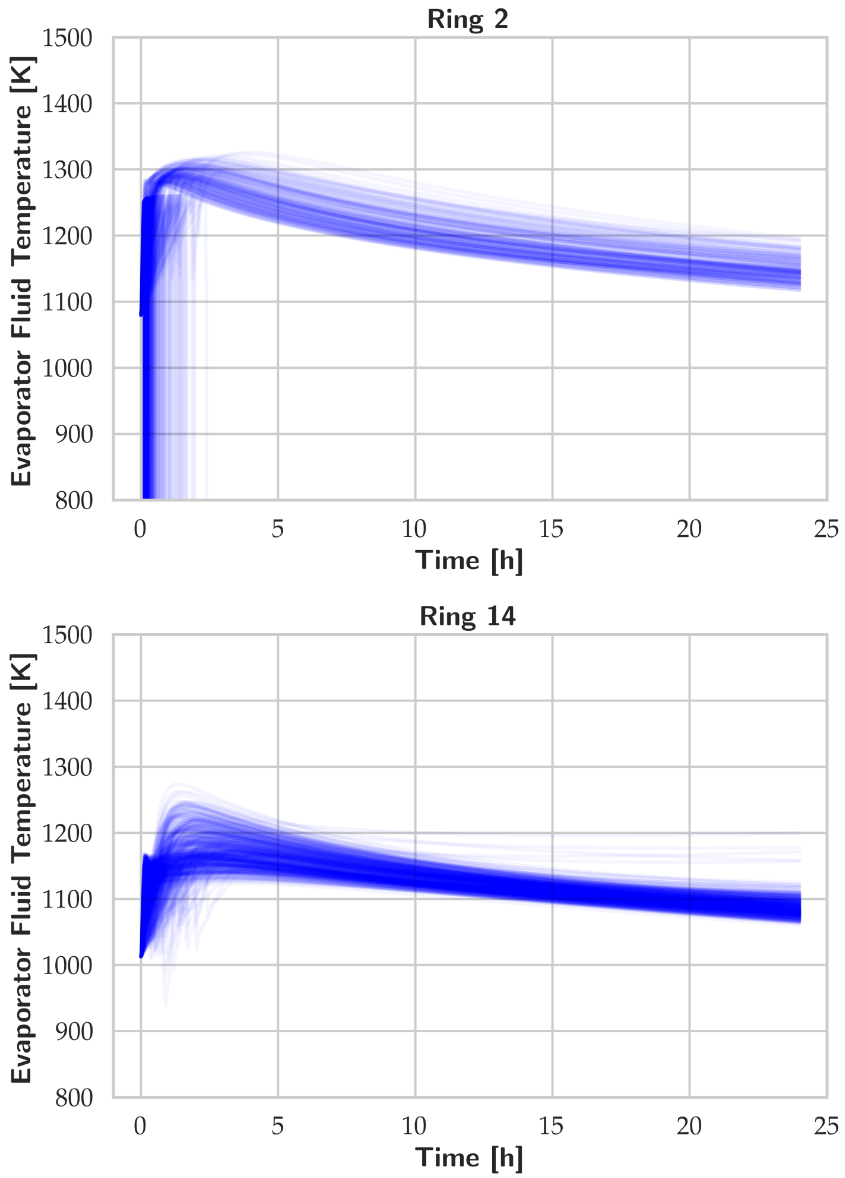
Spectrum of accident scenarios give rise to range of plant conditions

- Relevant to assessing potential and magnitude of consequences

Evaluation of SSC performance and margin in performance under accident conditions

HPRs rely on passive heat removal through capillary flows in heat pipes

- Sensitive to operating range of heat pipes
- Operating limits could for example be challenged under overpower conditions



Fuel Response by Ring

Highest powered rings off-center

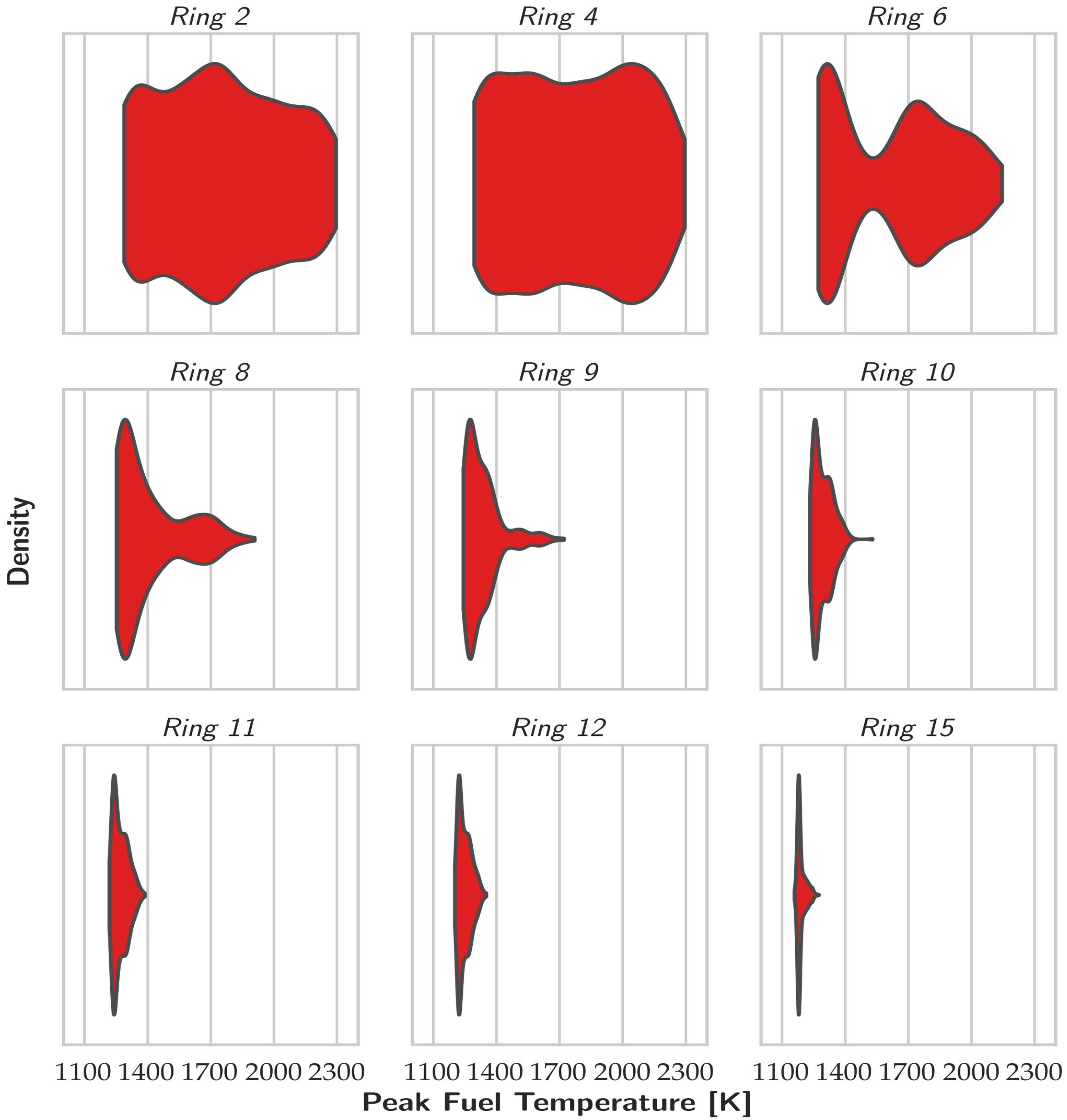
Energy deposited in reactor during reactivity transient diffuses to lower power rings after reactor trip

Heatup of fuel in peripheral rings influenced by

- Lower decay heat levels
- Energy loss to confinement through vessel wall

Heatup of fuel in central rings influenced by

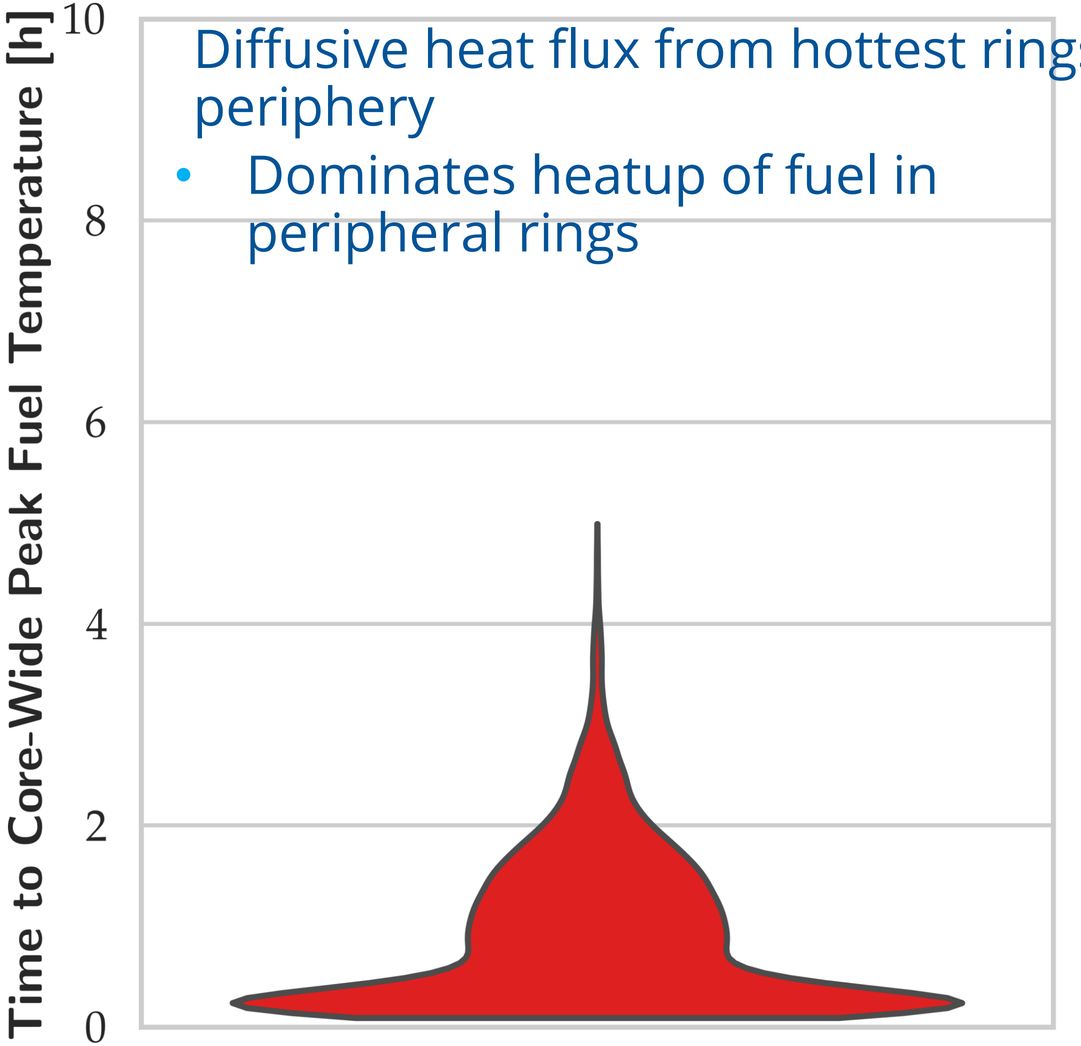
- Diffusion of energy from hottest fuel rings
- Limited heat sinks to which to dissipate energy

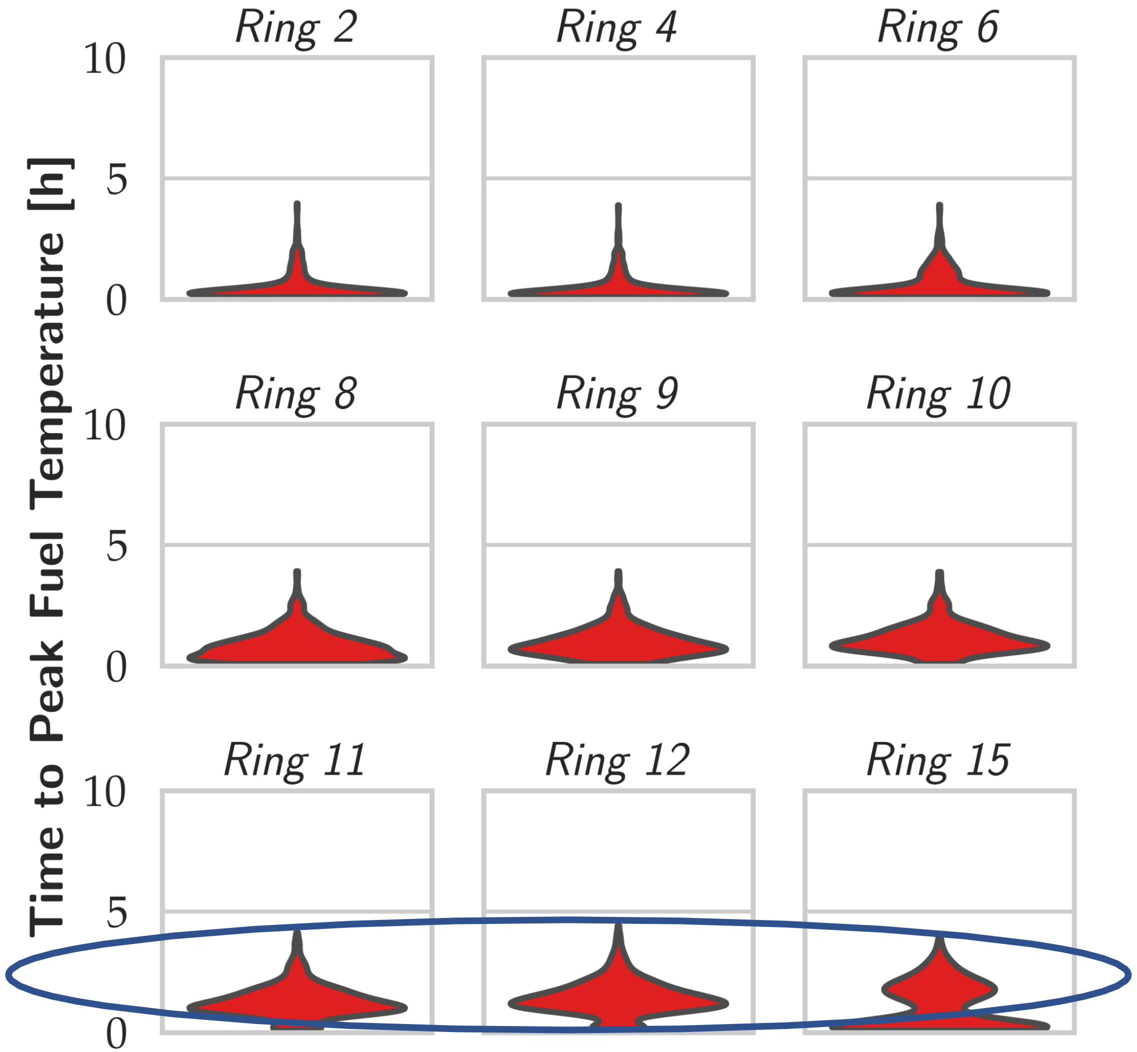


Thermal Inertia in Fuel Response

Diffusive heat flux from hottest rings to periphery

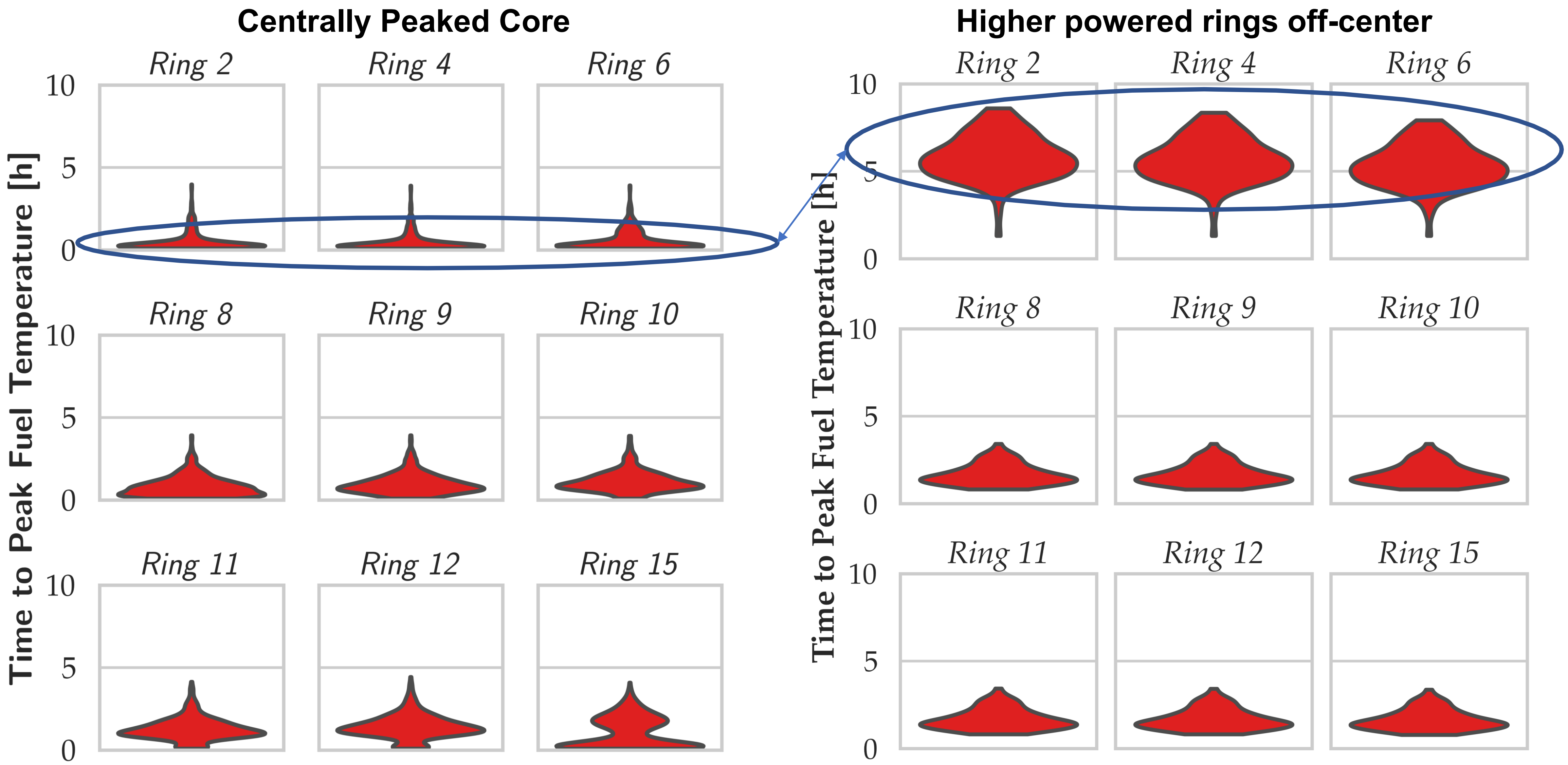
- Dominates heatup of fuel in peripheral rings



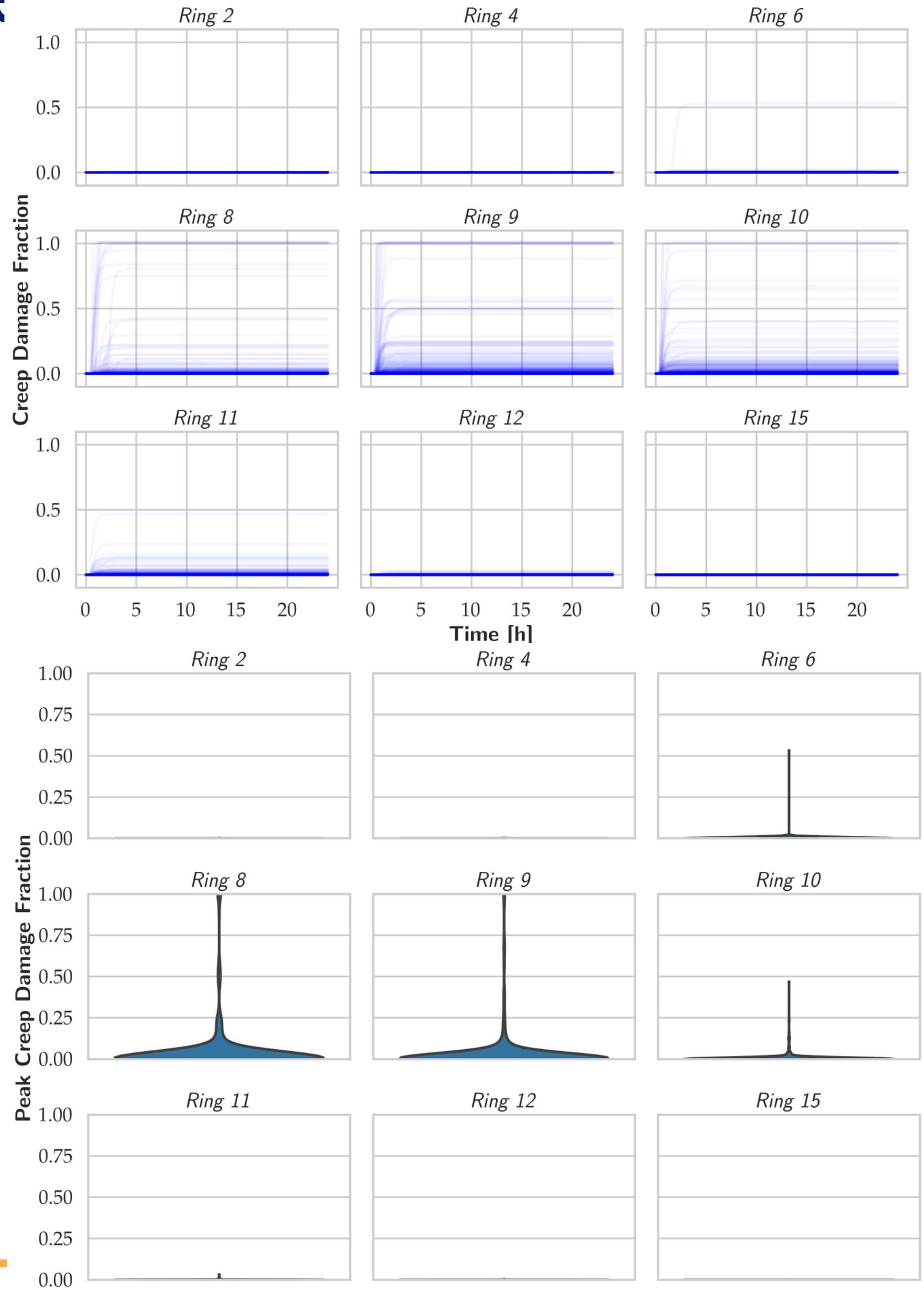


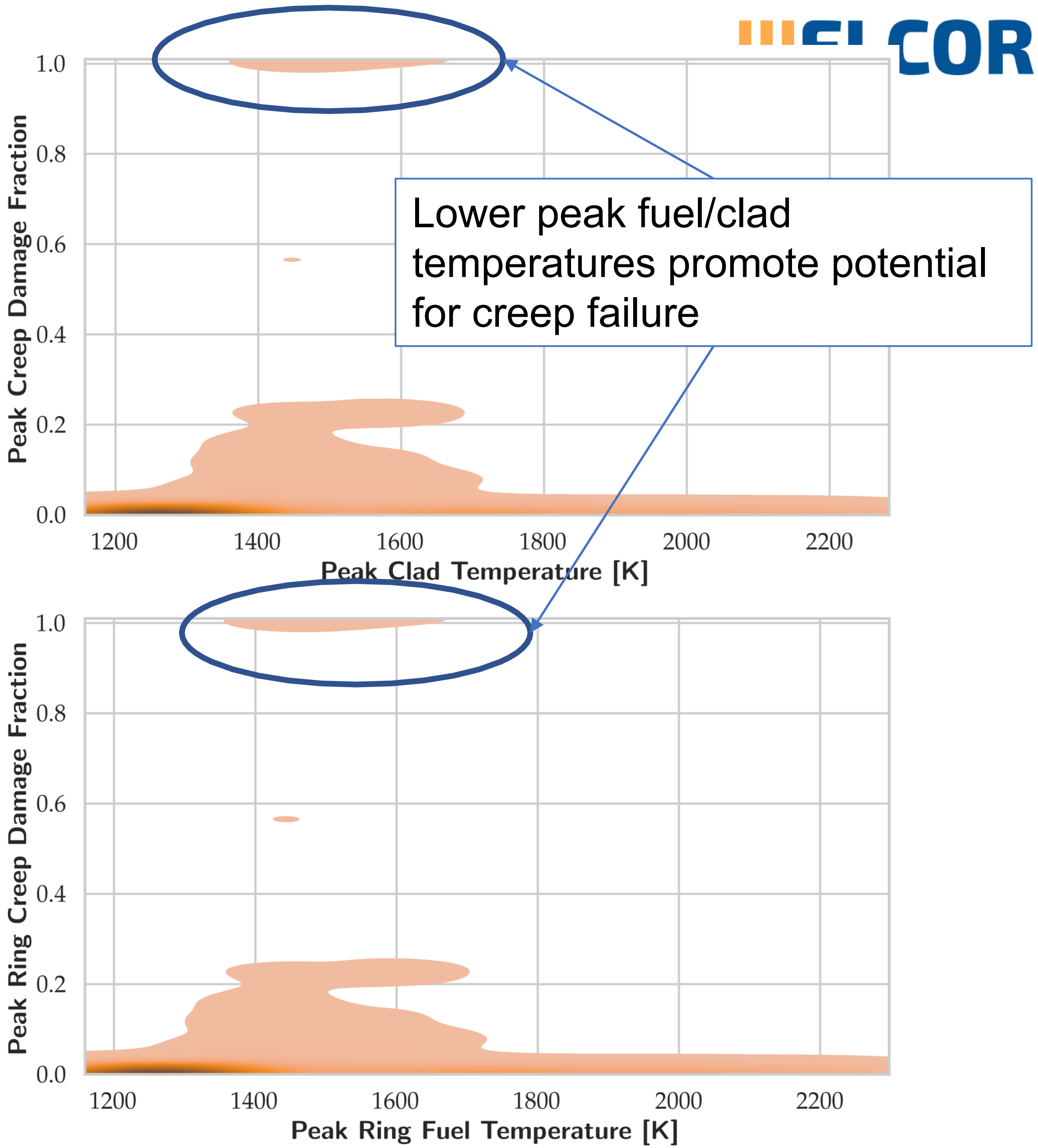
Most realizations dominated by early energy deposition into fuel prior to reactor trip

Thermal Inertia in Fuel Response

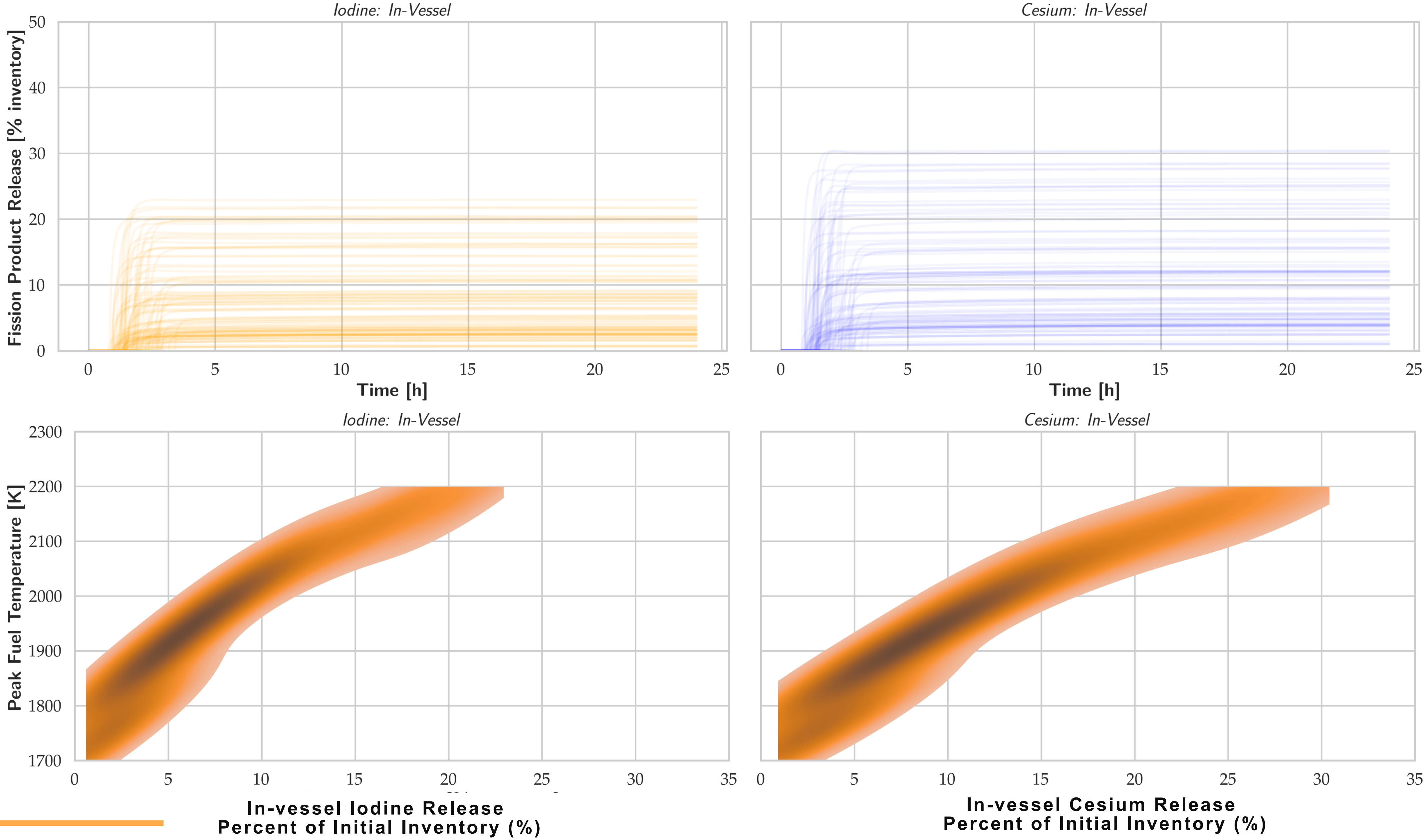


Heat Pipe Response

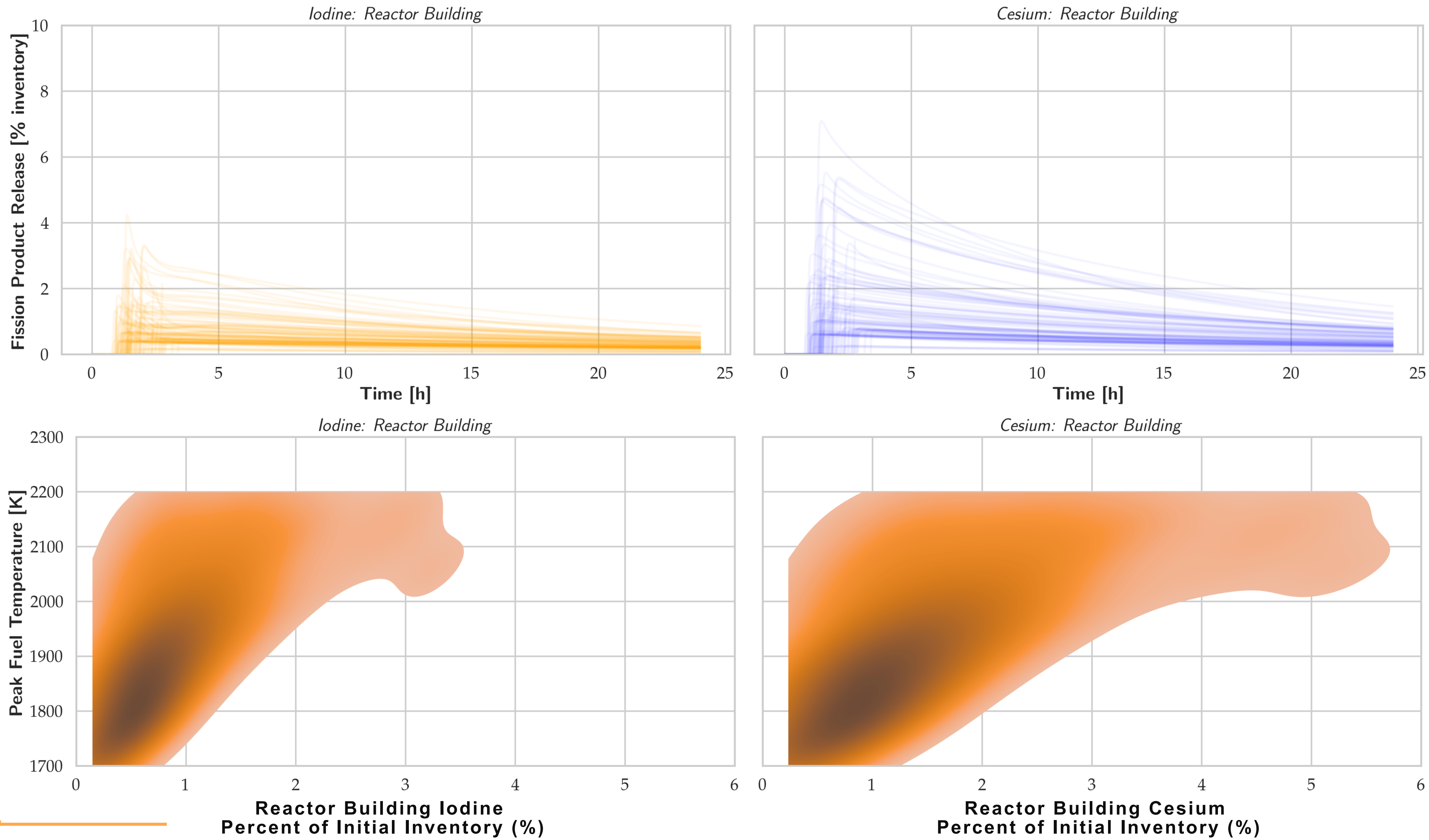




Fission Product Release from Fuel Characterization



Fission Product Transport Characterization



Fission Product Release to Environment