SAND2019-3568PE

# MELCOR COR Nodalization

2019 European MELCOR User Group Meeting

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# OVERVIEW

# Objectives

- Examine effects of enhanced/decreased fidelity of COR package to contribute to MELCOR best-practices

- Approach:
  - Used 3 core nodalization schemes to represent coarse, typical, and fine nodalization
  - Coarse – 12 axial levels, 4 radial divisions
  - Typical – 17 axial levels, 6 radial divisions
  - Fine – 22 axial levels, 8 radial divisions

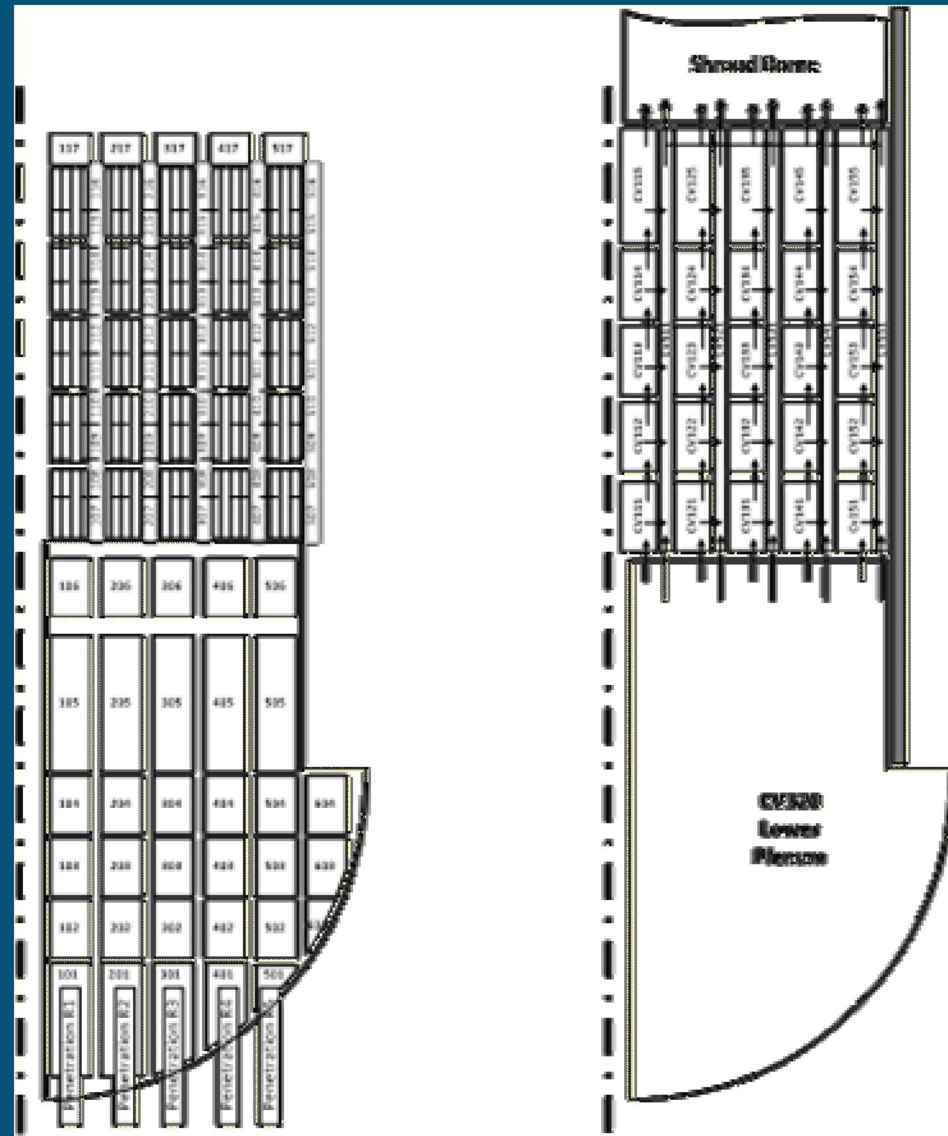
- Challenges:
  - Creating new methodology to easily renodalize core
  - Evaluating magnitude and timing of core response to scheme
  - Incorporating findings into best practices

- Missing from this analysis
  - Modification of radiation modeling to reflect opacity of fuel rings.

# Typical SNL MELCOR Nodalizations

Fukushima Example

- 10 axial elevations (COR cells) in active core
- 5 radial rings (COR cells) in active core (6th ring for lower plenum)
- 2 COR cells/ CV in active core (dt/dz model)
- 5 axial elevations in lower plenum



# Core Cell Nodalization Considerations

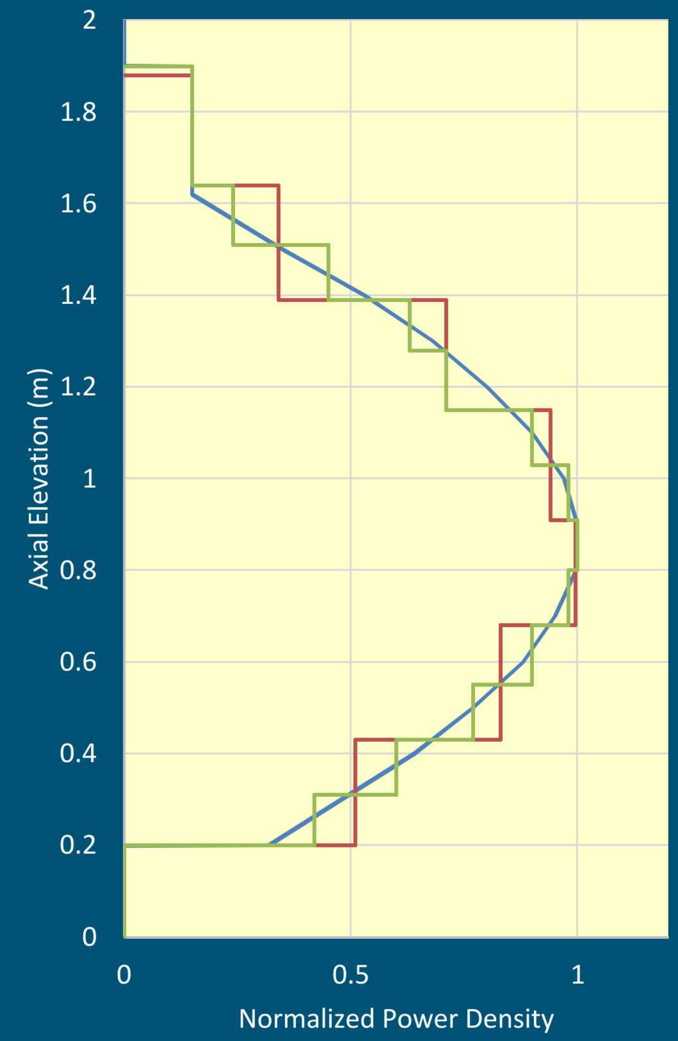
## Potential issues

Coarse nodalization

- Inability to accurately match power density
- Averaging temperatures across larger fuel areas can impact damage progression
  - Oxidation
  - Quenching
  - Heat transfer

Fine nodalization

- Run time
- Models that do not scale (i.e., bubble rise model)



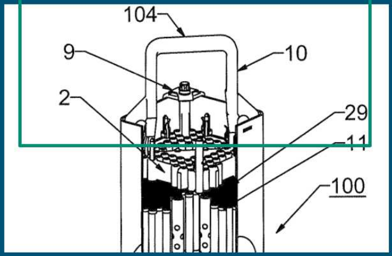
# NODALIZATION APPROACH

# Active Fuel Core Cells

- Original goal was to automate process – therefore, approach needed to be relatively simple
  - i.e. no counting fuel assemblies to divide rings

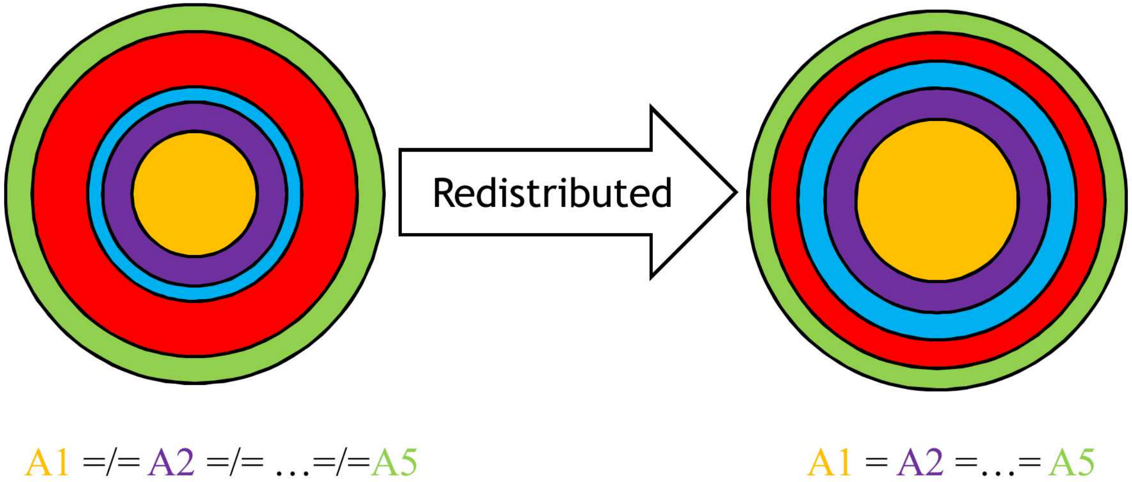
- Equiareal Concept
  - Only variation between COR cells is mass
  - If core region is divided equally radially, segments with same height will have same volume
  - Dividing height equally means <u>identical COR cells across active fuel region</u>!
  - **ONLY NEED TO GENERATE ONE REPEATING CELL FOR FUEL REGION**

- Above TAF
  - Additional COR cell level above active fuel to represent additional canister mass
  - Mass was redistributed across new radial areas <u>but</u> height was left unchanged




- Bypass volumes treated same as COR cells (equiareally redistributed)

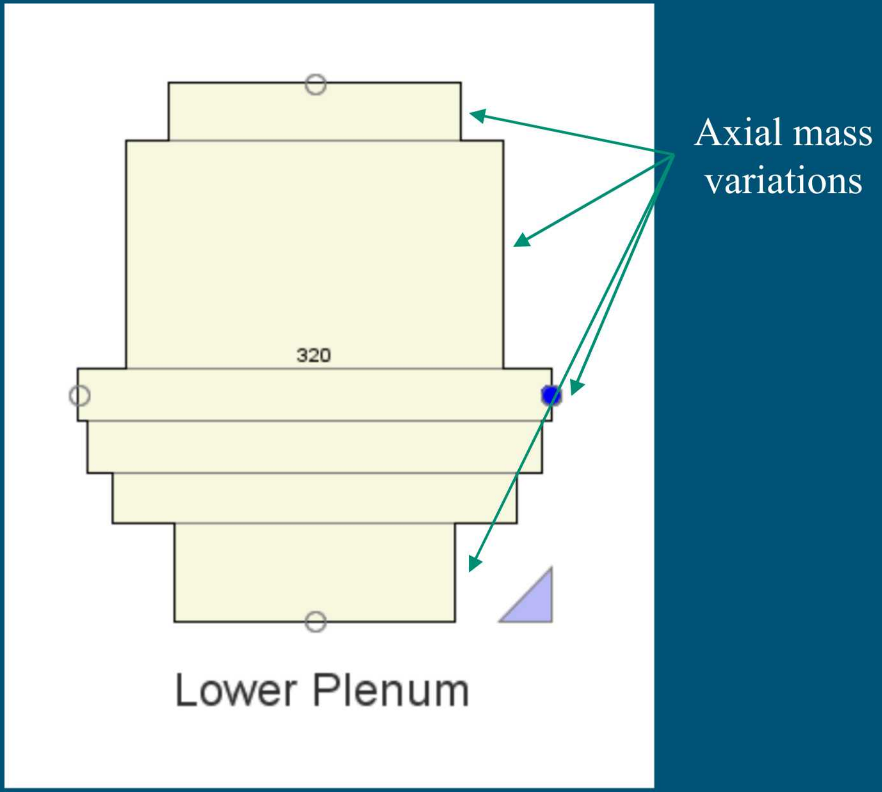
# Active Fuel – Equiareal Modeling




Volume = Area x Height → A1=A2=…=An, H1=H2=…=Hn → V1=V2=…=Vn

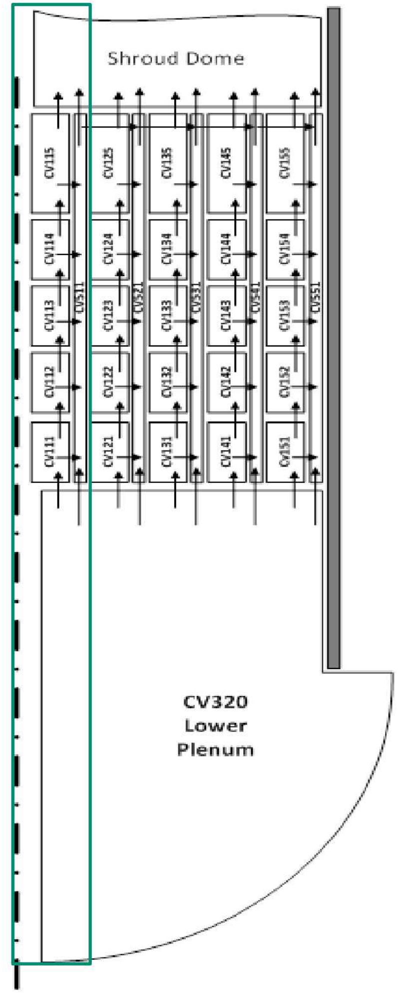
# Lower Plenum

- 6 axial levels with varying heights
  - Mass varies across levels
- Redistributing axial mass is impractical
  - Would require function for spatial mass distribution
- Lower Plenum radial nodalization is tied to fuel region though
- Therefore, mass was preserved on an <u>axial</u> basis and <u>redistributed radially</u>



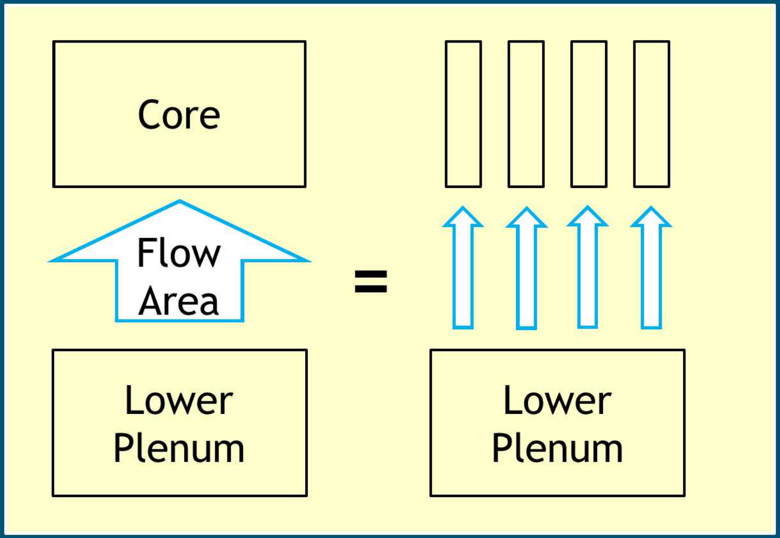
# Control Volume Scheme

- Total core volume conserved
  - Lower plenum
  - Fuel channels
  - Bypass volume
- 1 fuel channel per ring
- 5 control volumes per fuel channel
  - Not a hard requirement
  - Chosen because base model had 5
- 1 bypass volume per fuel channel



# Flow Areas

- Six unique flow paths for each ring
  - Lower plenum to fuel channel
  - Lower plenum to bypass
  - Intra-fuel channel
  - Fuel channel to bypass
  - Fuel channel to shroud
  - Bypass to shroud




- Total flow area is conserved and redistributed equally radially
  - Loss coefficients, friction factors preserved

- ONLY NEED TO CREATE SIX UNIQUE FLOW PATHS PER RING

# Takeaways

- Equiareal approach greatly simplifies nodalization
  - 1 new active fuel cell
  - 1 new cell for canister above TAF
  - 1 unique bypass volume
  - 6 new cells for lower plenum axial levels
  - 6 new flow paths

- Total flow area is conserved and redistributed equally radially
  - Loss coefficients, friction factors preserved

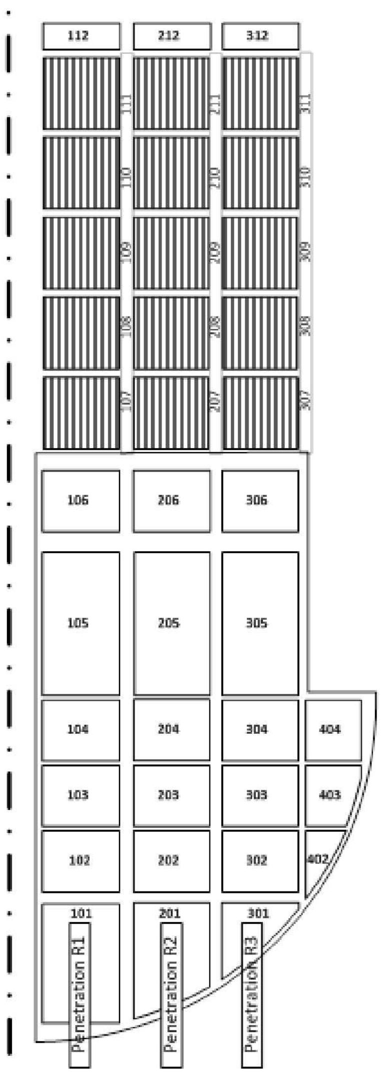
- Only need to create one ring and duplicate it over entire core
  - Applies to COR cells and CV/FPs

# Accident Sequence

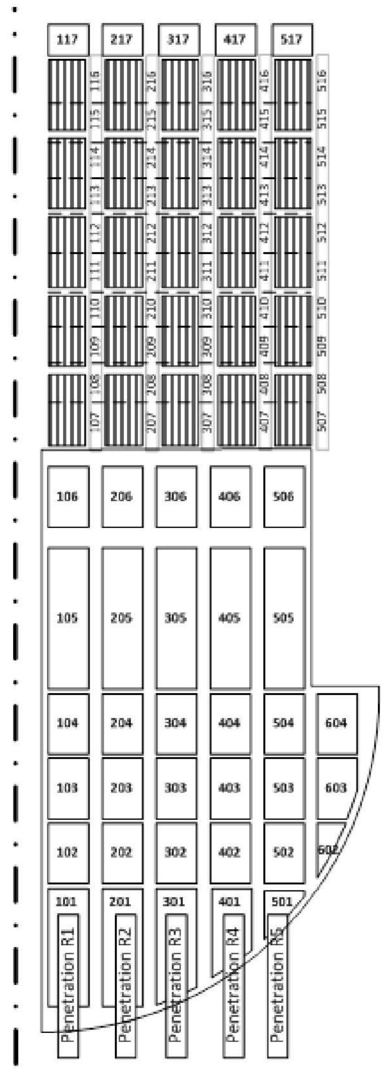
- Loosely based on Fukushima Unit 1 accident sequence
  - Inputs are modifications of BSAF Unit 1 decks
  - Sequence begins with full station blackout conditions
  - SRV releases steam from RPV
  - MSL fails based on Larson-Miller creep function
- No enforced failures
  - Original input is tuned to match TEPCO data by enforced failure timings (e.g. lower head)
  - Conditions were removed to study nodalization effects on event timings
- Simulation terminates at 24 hours
  - Arbitrary limit
  - Long term release not considered as part of work

# RESULTS AND DISCUSSION

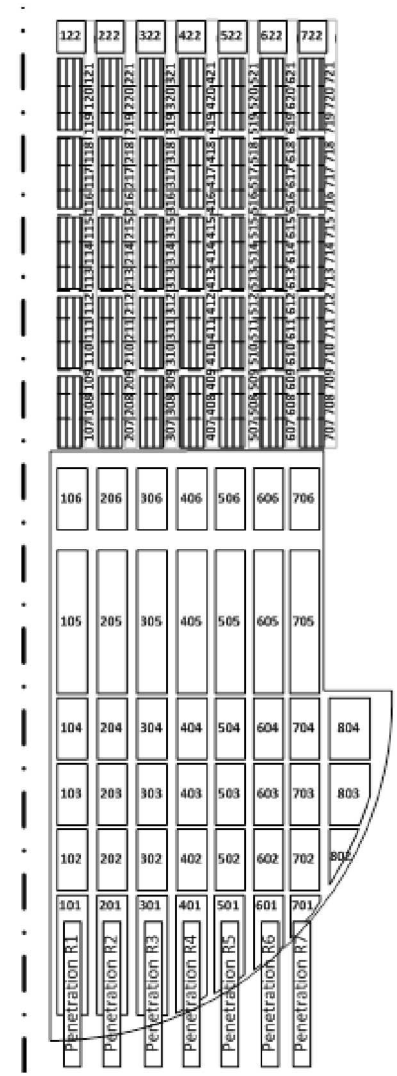
# COR Nodalizations (coarse to fine)




3-ring

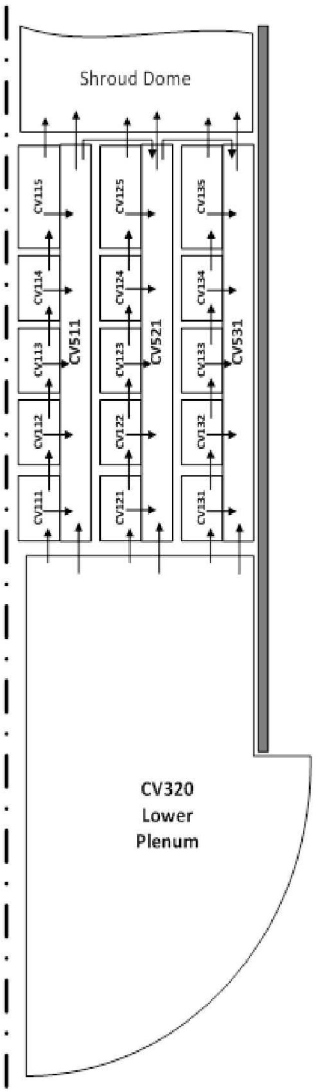



5-ring

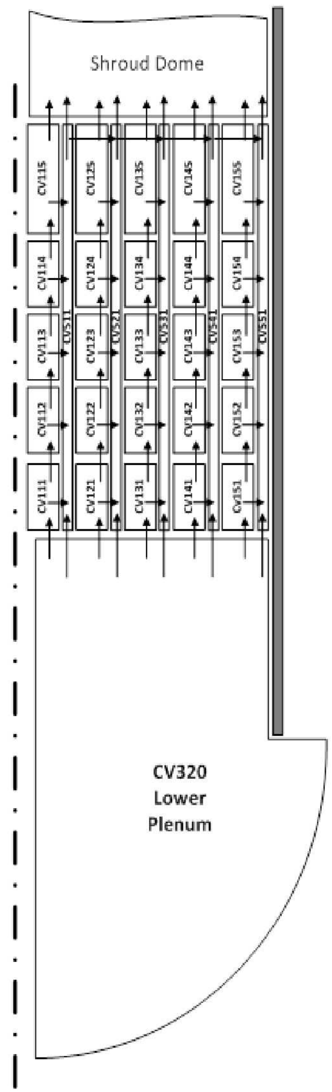



7-ring

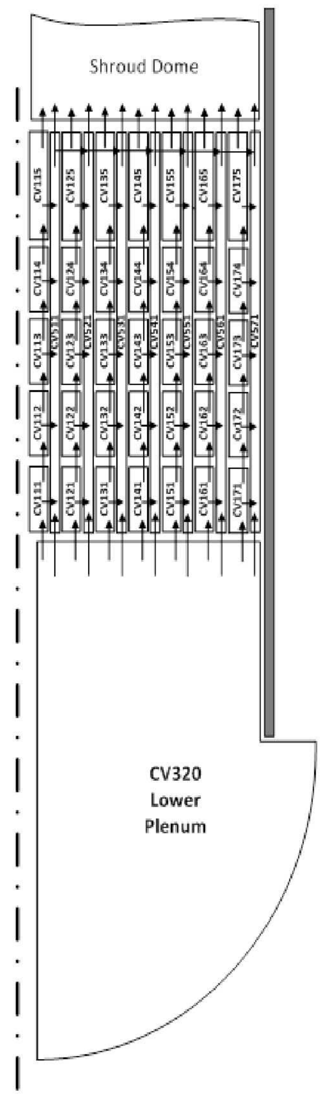
# CVH Nodalizations (coarse to fine)




3-ring




5-ring




7-ring

# Event Timing Table

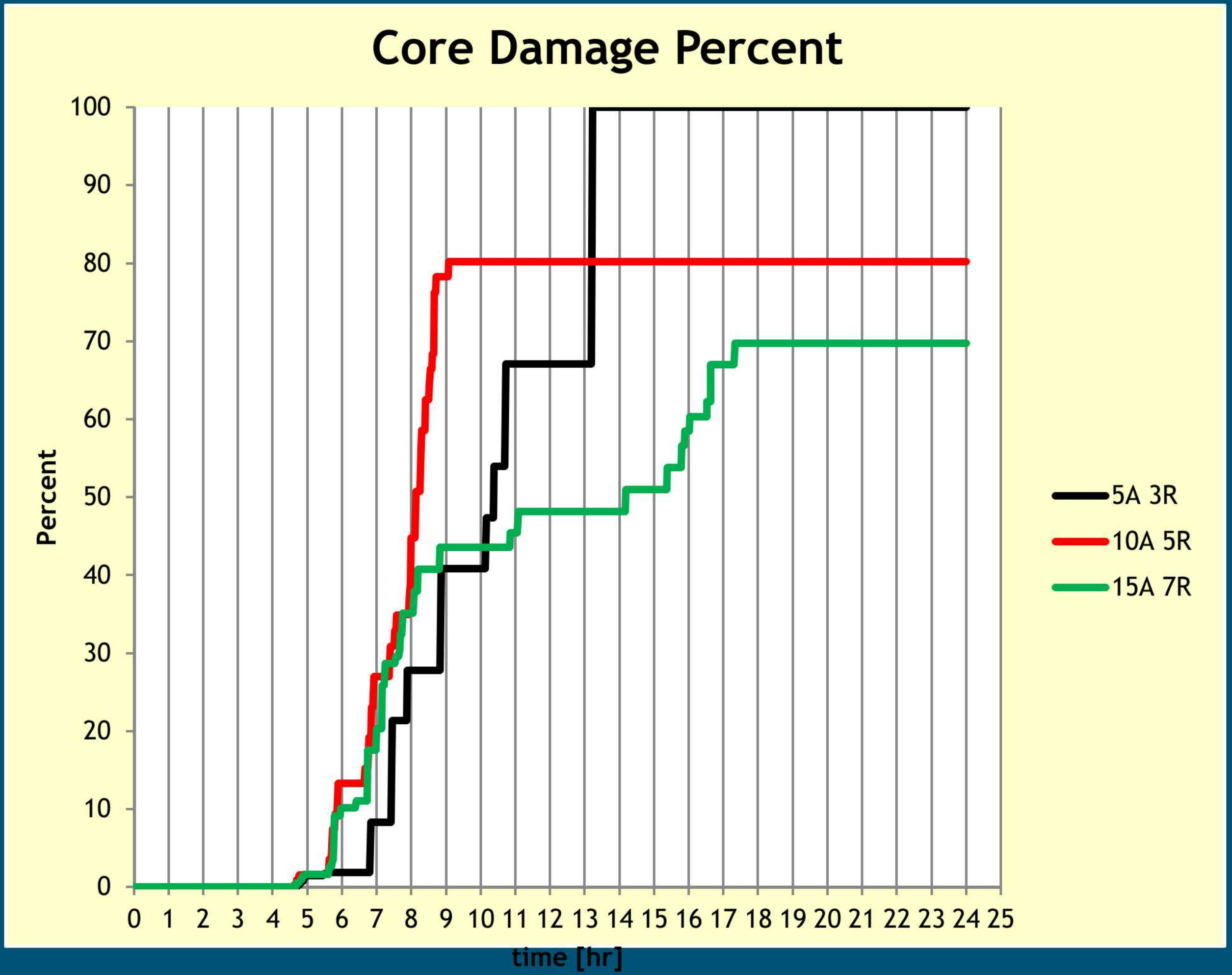
| Event | Time [h] | | |
|---|---|---|---|
| | 5A/3R | 10A/5R | 15A/7R |
| Water at Top of Active Fuel | 2.7 | 2.6 | 2.6 |
| Onset of Fuel Damage | 3.9 | 3.8 | 3.8 |
| Water at Bottom of Active Fuel | 4.2 | 4.0 | 4.1 |
| Initial Core Support Plate Failure | 4.6 | 4.5 | 4.5 |
| Main Steam Line Rupture | 5.8 | 5.2 | 5.2 |
| Greater Than 5% Fuel Damage | 8.0 | 6.2 | 6.3 |
| Core Slump | 15.1 | 7.7 | 7.1 |
| Greater Than 90% Fuel Damage | 19.5 | 17.8 | - |
| Lower Head Failure | 20.4 | 17.9 | 15.8 |
| Drywell Liner Melt-Through | 21.3 | - | - |

# RESULTS AND DISCUSSION – CORE DEGRADATION

# Core Damage

- Fine nodalization shows more continuous collapse
  - Other nodalizations exhibit start-stop behavior

- Coarse nodalization leads to 100% core damage
  - Outer rings (approximately 30% of fuel) survives in fine case



# Hydrogen Generation

H2 production shows correlation with core collapse

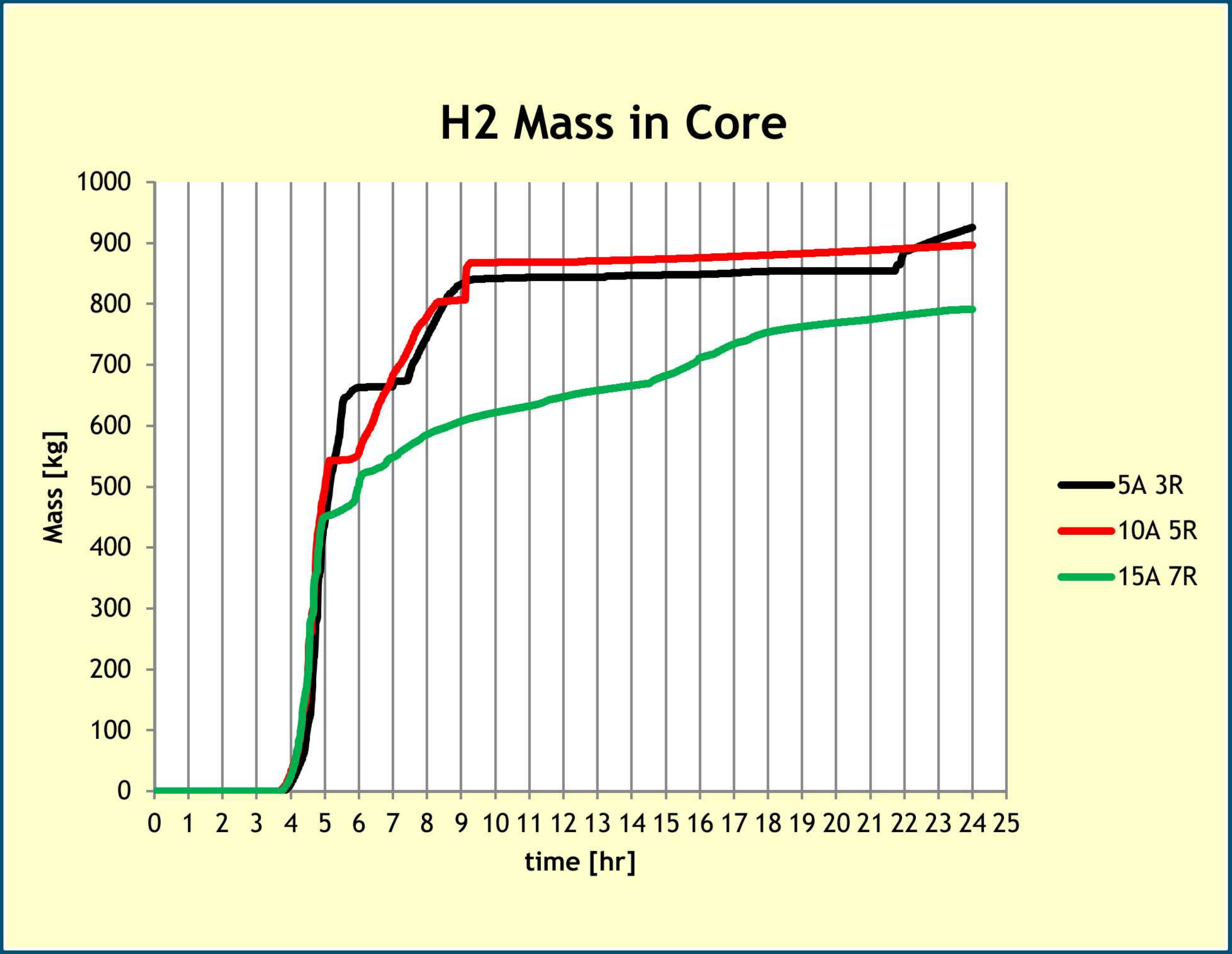
- Heat from oxidation contributes to fuel failure

Coarse nodalization has highest initial H2 inventory

- Possibly related to oxidation of surviving fuel
- Fuel relocates in other simulations, inhibiting oxidation

Fine nodalization produces approximately 200 kg less H2 than typical nodalization

- May have implications for deflagrations and reactor building release



# RESULTS AND DISCUSSION – ENERGY BALANCE

# Total Energy

Total energy is very consistent

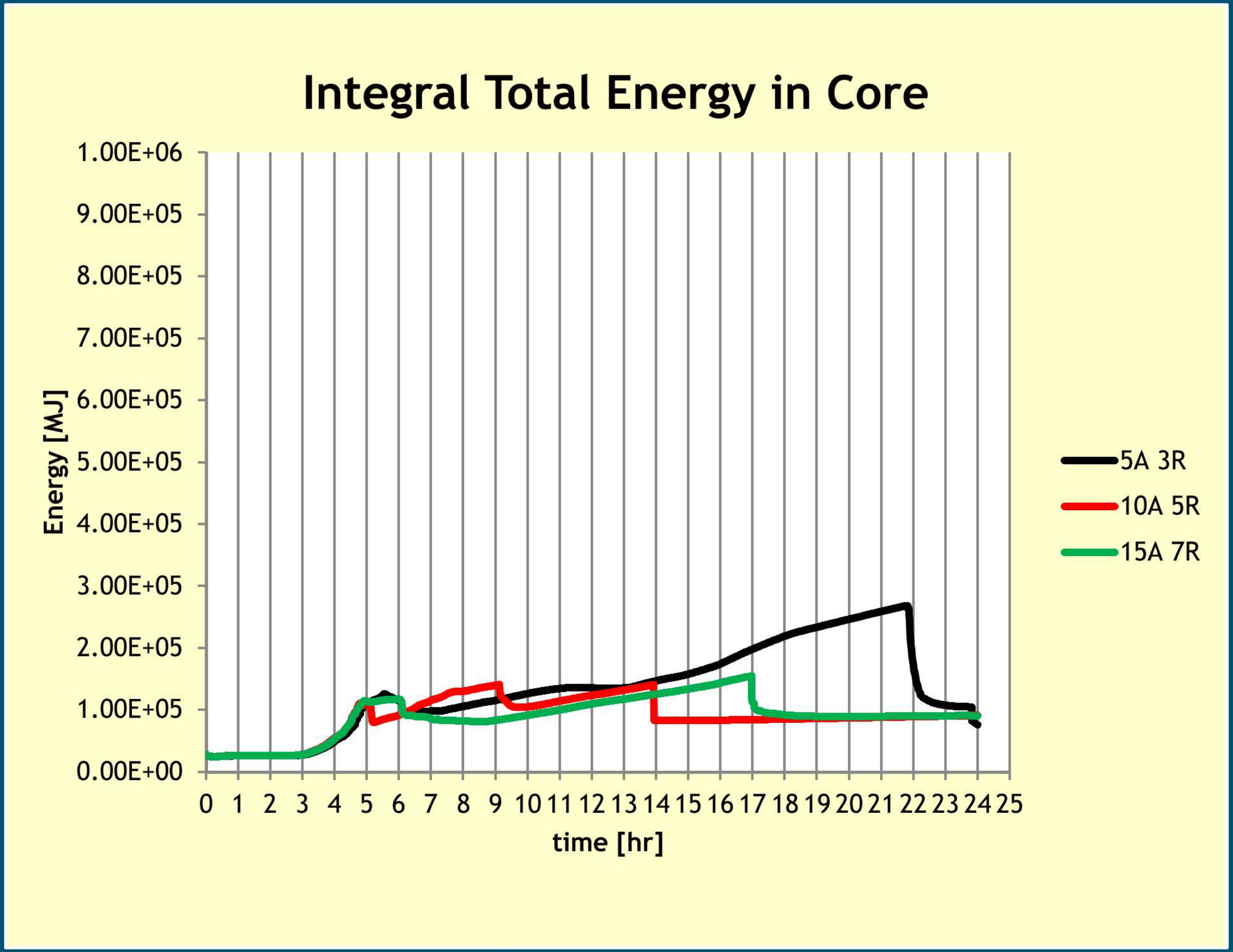
- Simulations diverge with start of core collapse

Highly impacted by lower head failure timing

- More energy accumulates in lower head during late stage of accident

More total energy means higher debris temperatures

- Impacts debris composition and MCCI response



# Decay Energy

Decay heat is uniform across all inputs

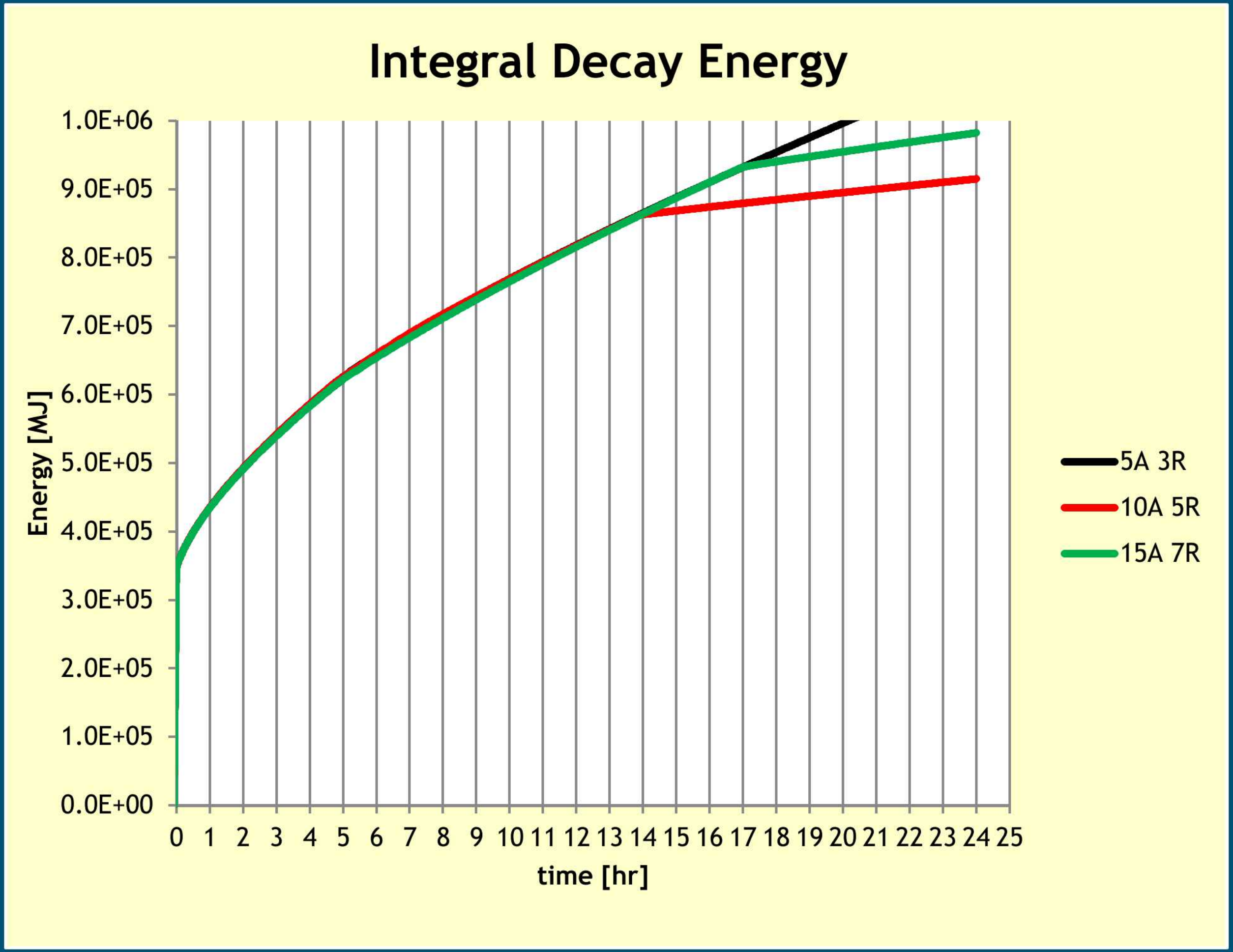
- Governed by hardwired function

Energy plateaus upon lower head failure

- Decay energy in fuel is no longer tracked by COR package once fuel leaves core region

Fine nodalization has some surviving fuel

- Decay energy remains in core

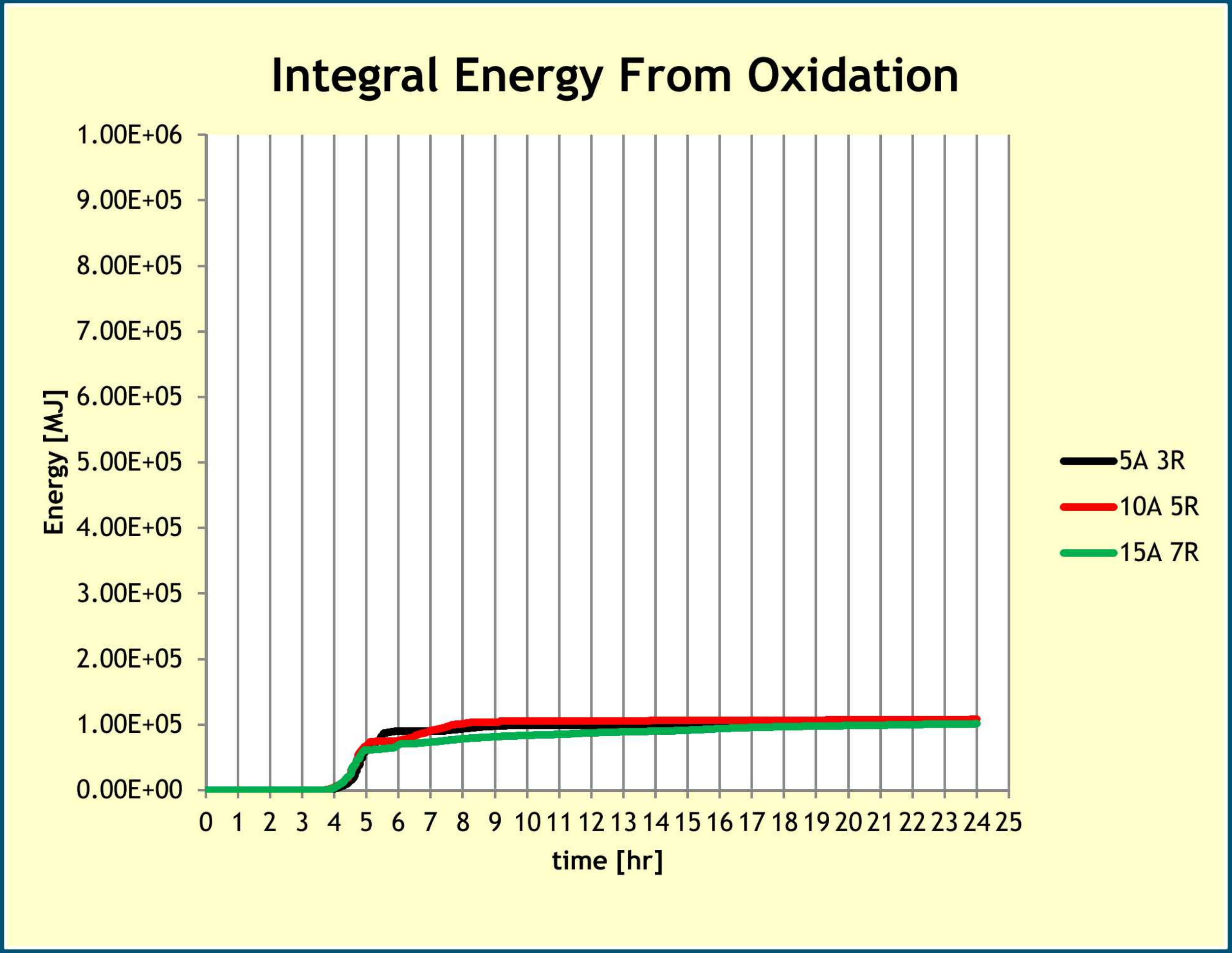


# Oxidation Energy

Oxidation energy is in very close agreement

Suggests that despite differences in core collapse, oxidation energy may not be sensitive to nodalization

No apparent relationship between oxidation energy and $H_2$ production



# Convective Energy Removal

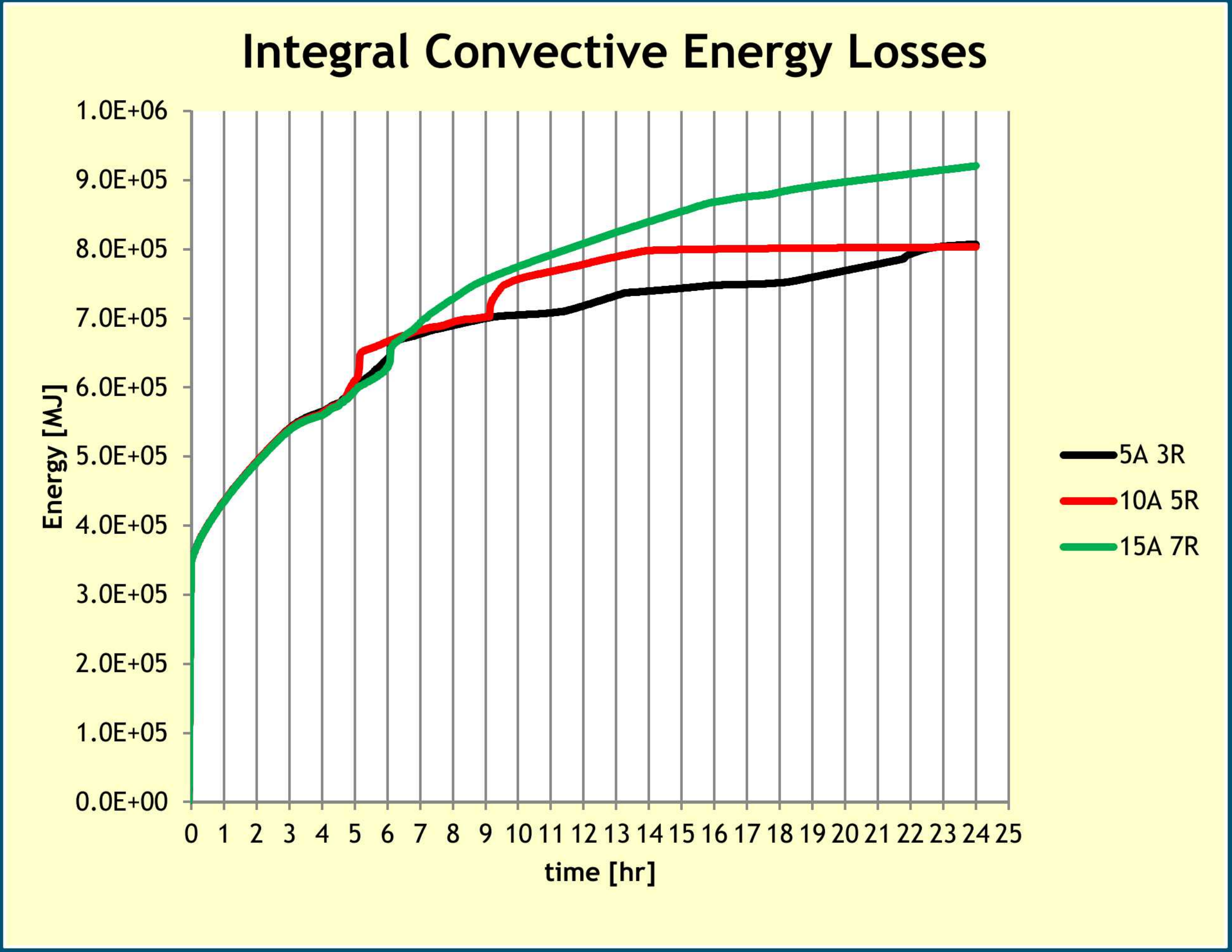
All nodalizations show increase in convective losses when MSL fails

Typical and fine cases show close agreement until 9.0 hours

- Very close MSL failure times
- Similar RPV water inventories before core slump

Convective losses impacted by radiative losses

- Simulations with more surviving fuel exhibit more radiative loses
- Enhanced radiation would reduce energy losses from convection



# Radiative Energy Losses

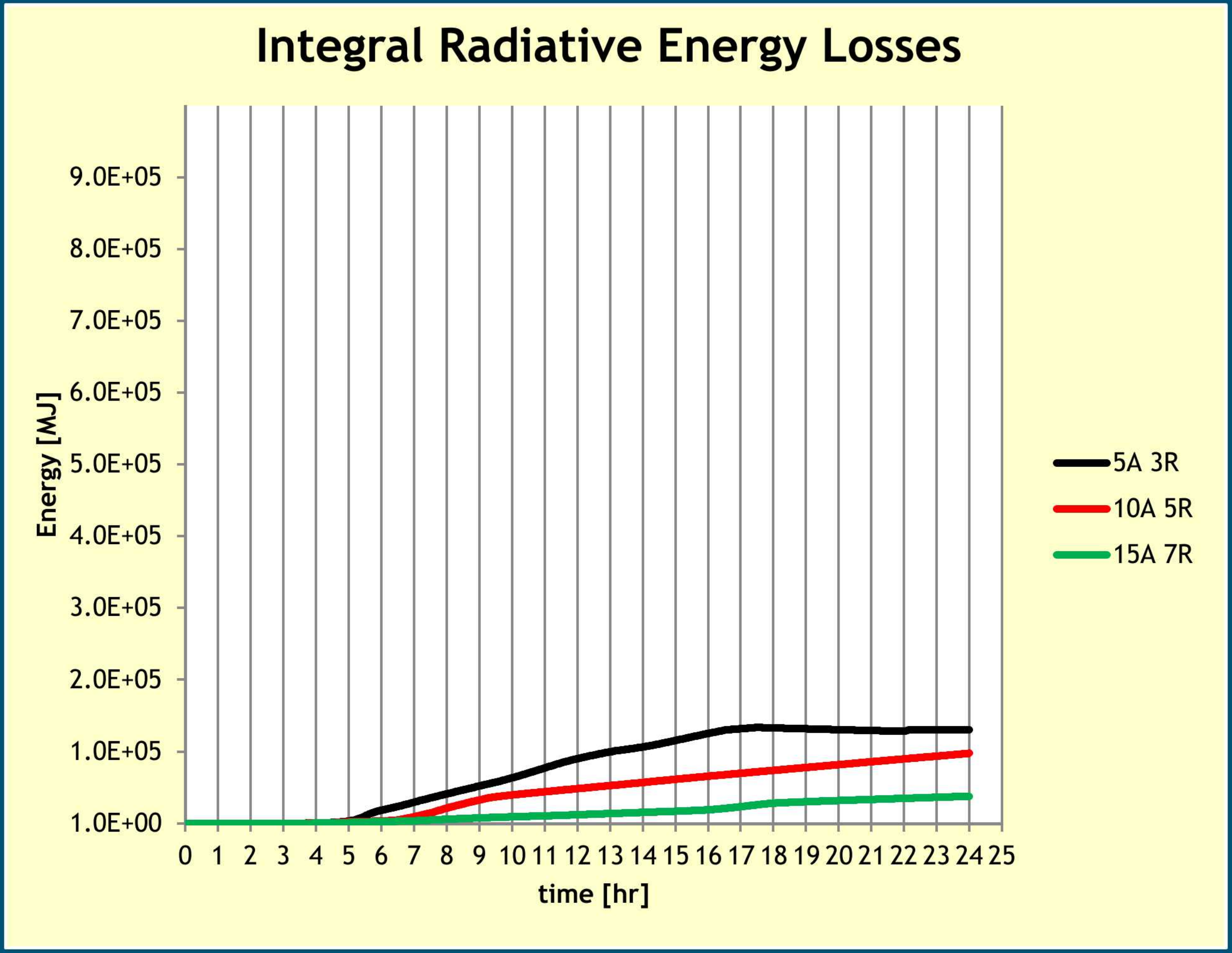
Inverse relationship with convective losses

Radiative losses increase with reduced COR fidelity

- Coarse nodalization has nearly twice as much radiative transfer as fine nodalization

Onset of radiative losses corresponds to upper tie plate failure

- Slower core degradation in coarse nodalization could enhance radiative losses from surviving fuel



# RESULTS AND DISCUSSION – THERMAL-HYDRAULIC RESPONSE

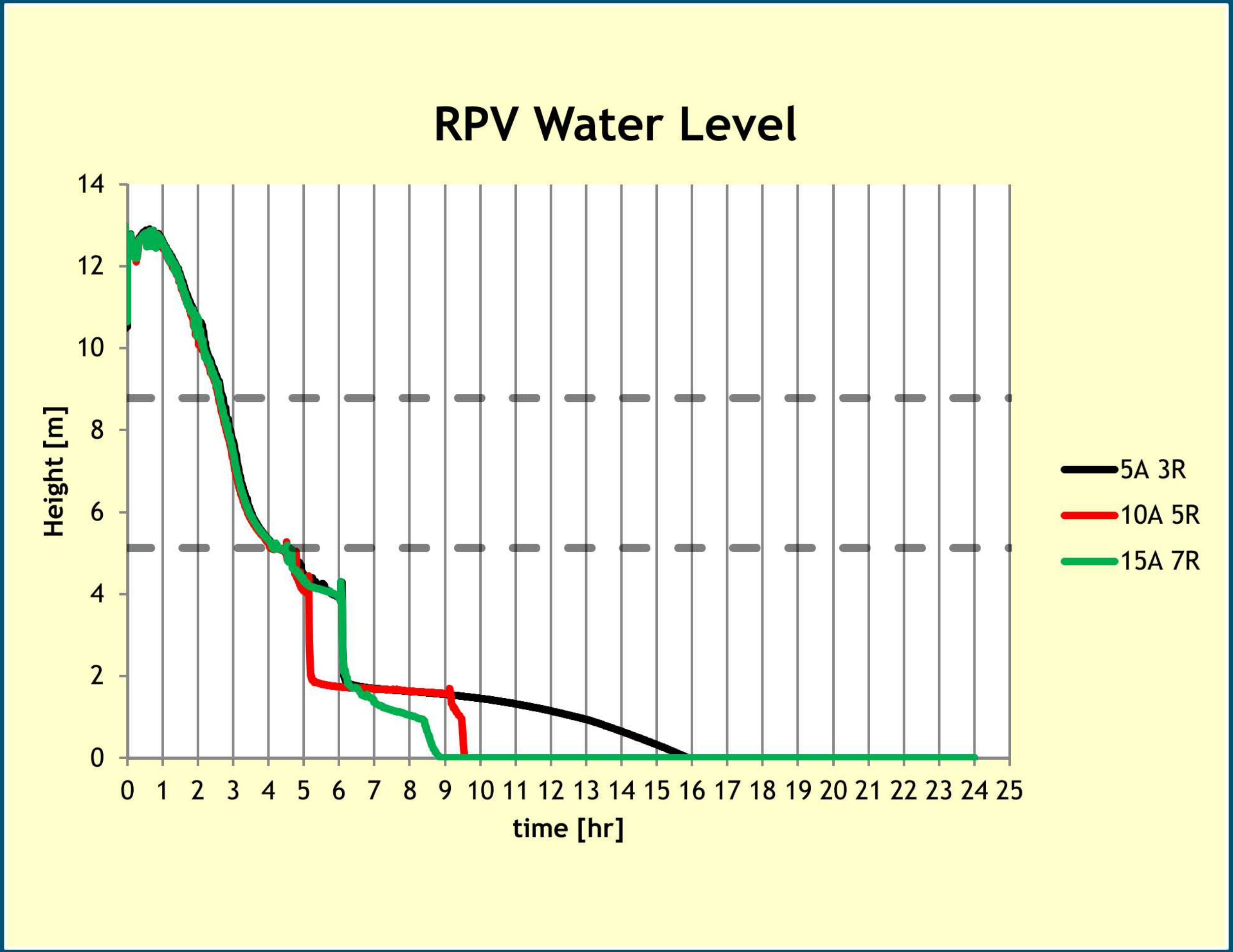
# RPV Water Level

Closely correlates to core degradation

All nodalizations show effectively identical boiloff rates prior to full core uncovery

Delayed slumping in coarse nodalization prolongs RPV inventory

- Impacts pressure response as less water vaporizes during slump

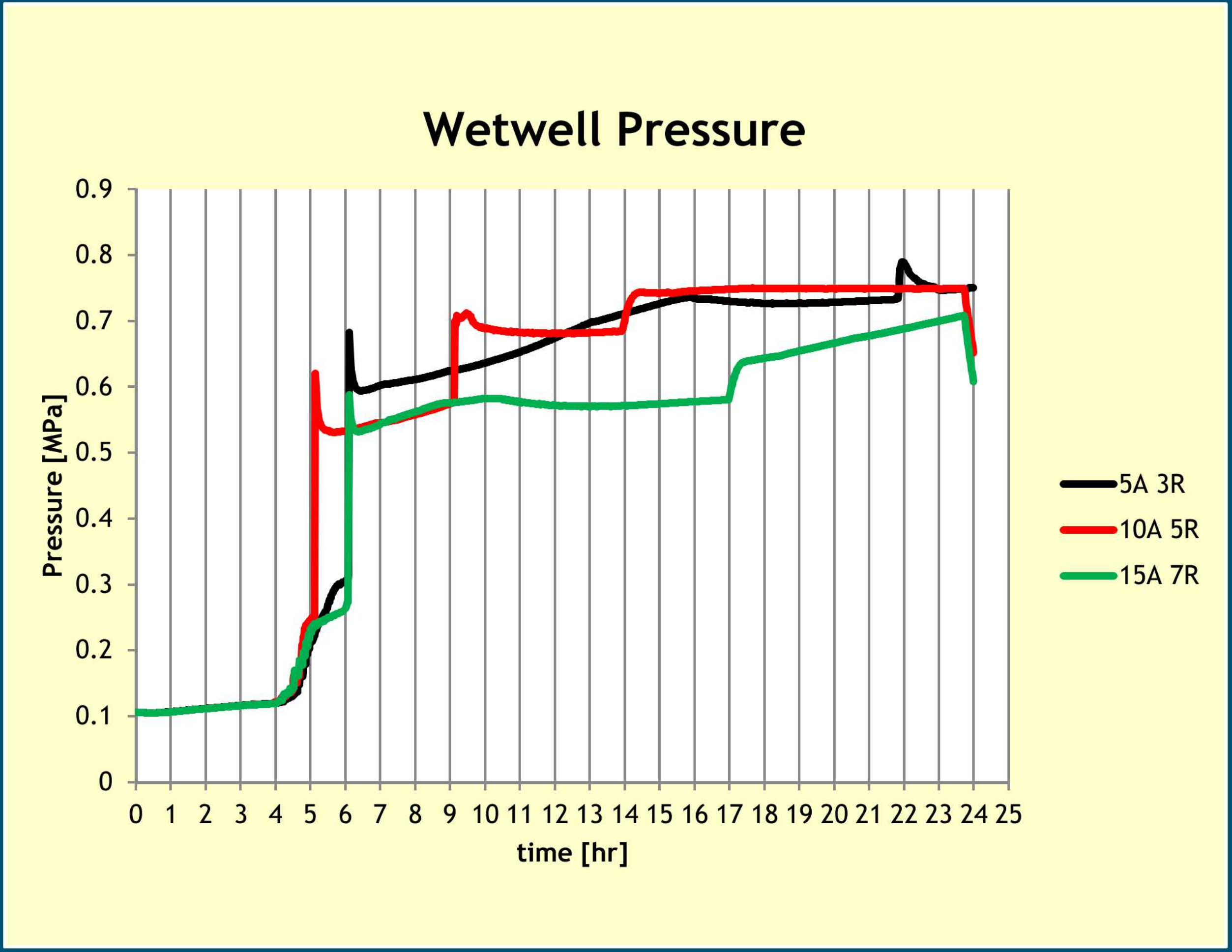


# Wetwell Pressure

No strong variation between nodalizations
- All trends within 0.1 MPa

Simulations converge towards end of simulation time
- Suggest insensitivity to nodalization

No strong CVH connection between drywell and wetwell
- Wetwell is insensitive to drywell transients



# Steam Dome Temperature

Temperatures show high variance until 9.0 hours in all cases

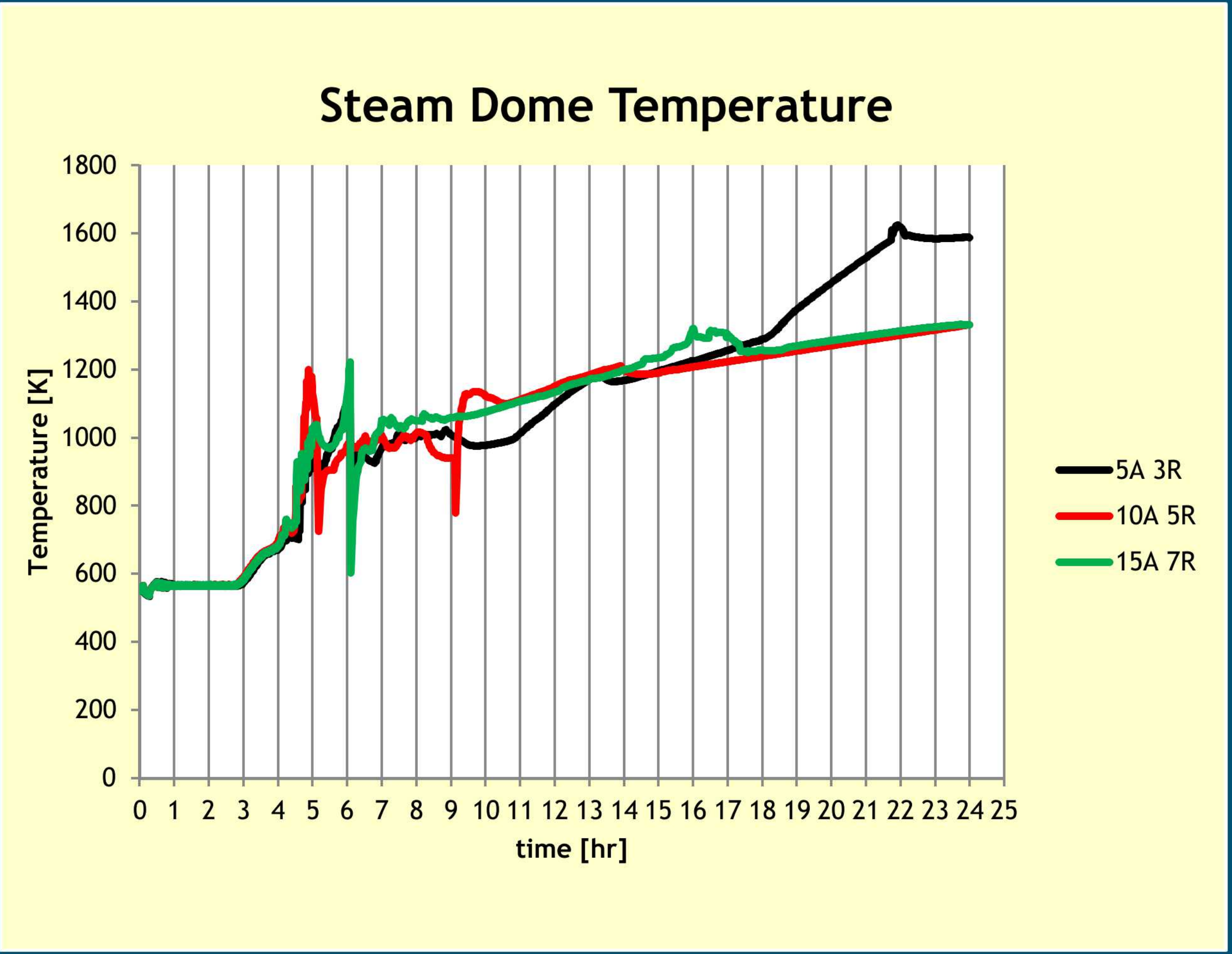
- Core is undergoing rapid geometry changes

No strong correlation to nodalization

- Typical and fine cases show higher initial temperatures
- Result of debris energy transfer to RPV water

Temperatures diverge at 11.0 hours

- Present cause unknown



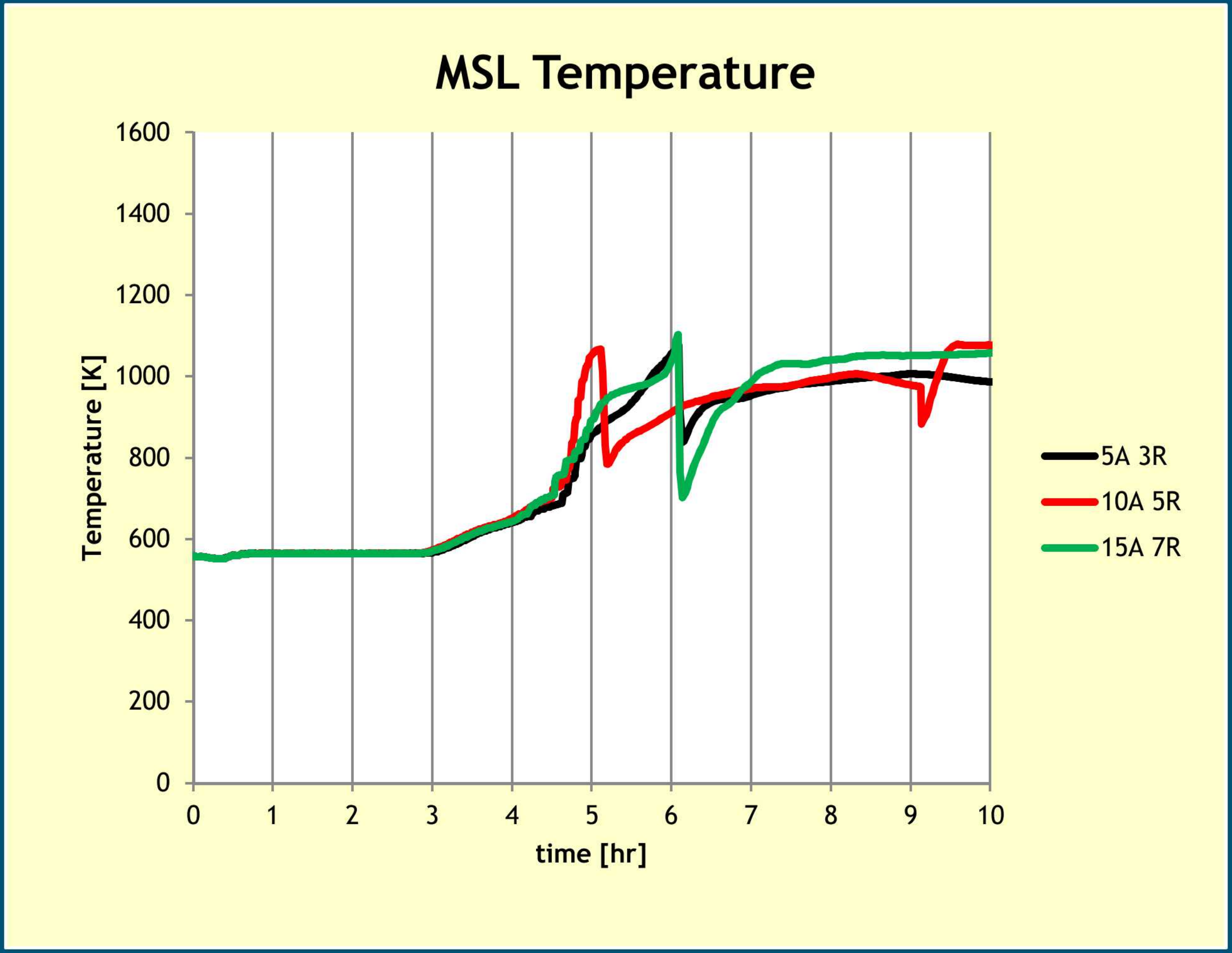
# MSL Temperature

Typical and fine cases have identical pre-failure response

Coarse nodalization has prolonged heatup

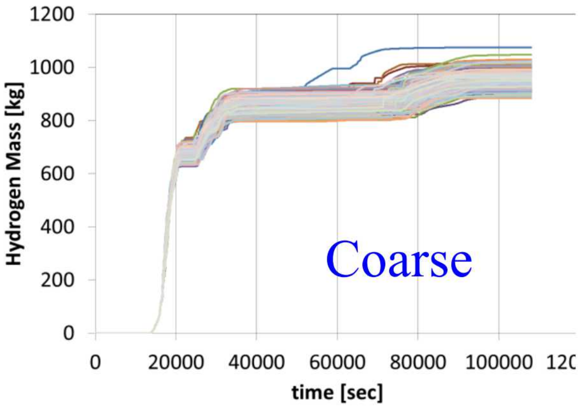
- Results of less steam generation in lower plenum from debris quenching

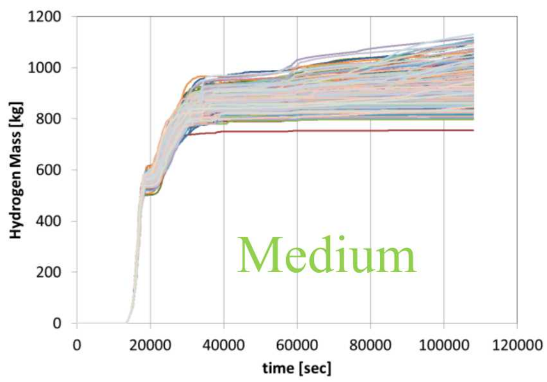
Temperature at time of failure is agreeable across all schemes (~1100 K)

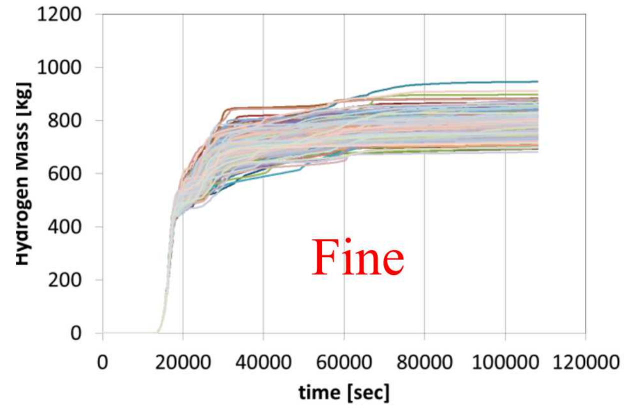


# RESULTS AND DISCUSSION – NUMERICAL VARIANCE

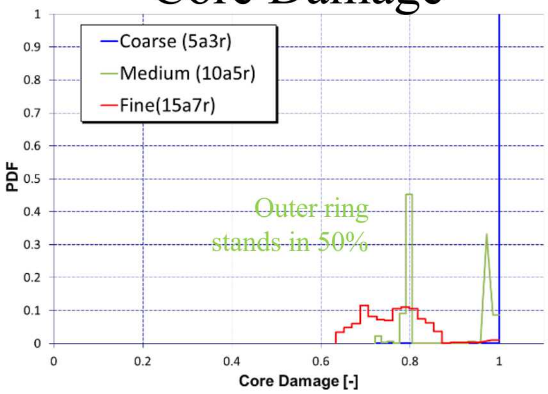
# Numerical variance associated with nodalization



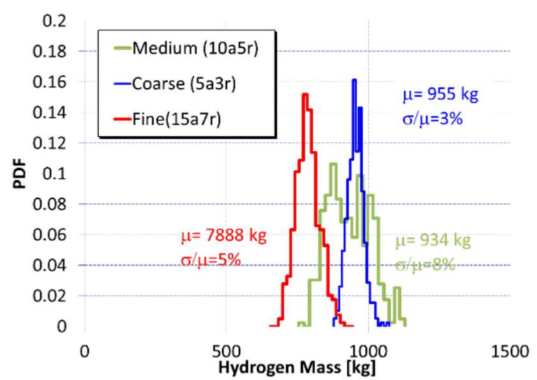



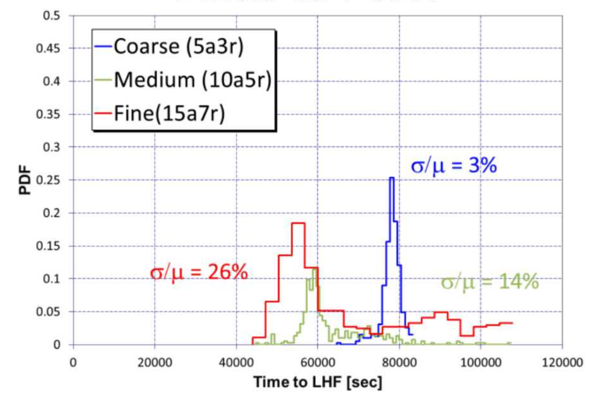

Core Damage




Hydrogen Mass




Time to LHF

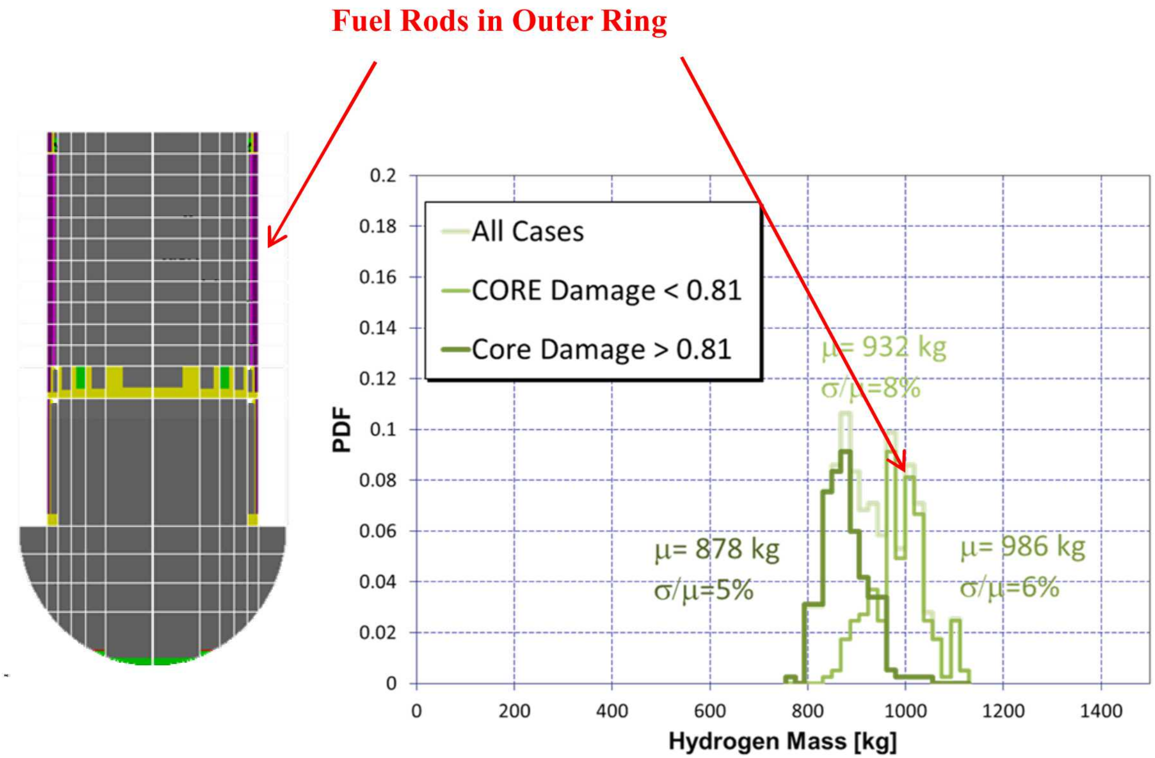


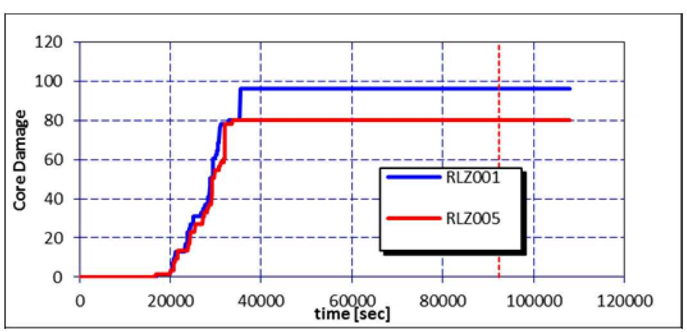
# Hydrogen variance in medium nodalization Case

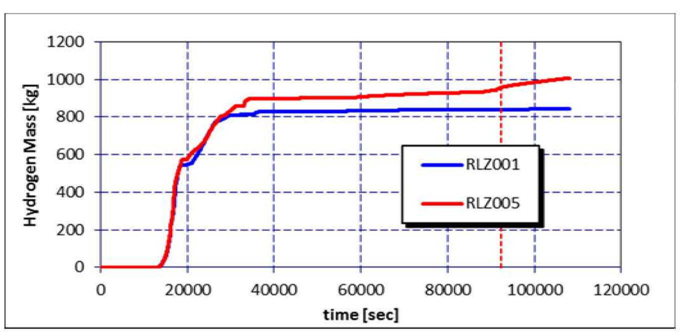
Hydrogen variance strongly dependent on failure of outer ring.

- Hydrogen distribution and core damage are highly correlated.

Cases where outer rod survives results in more overall hydrogen generation in core after vessel failure and more variance



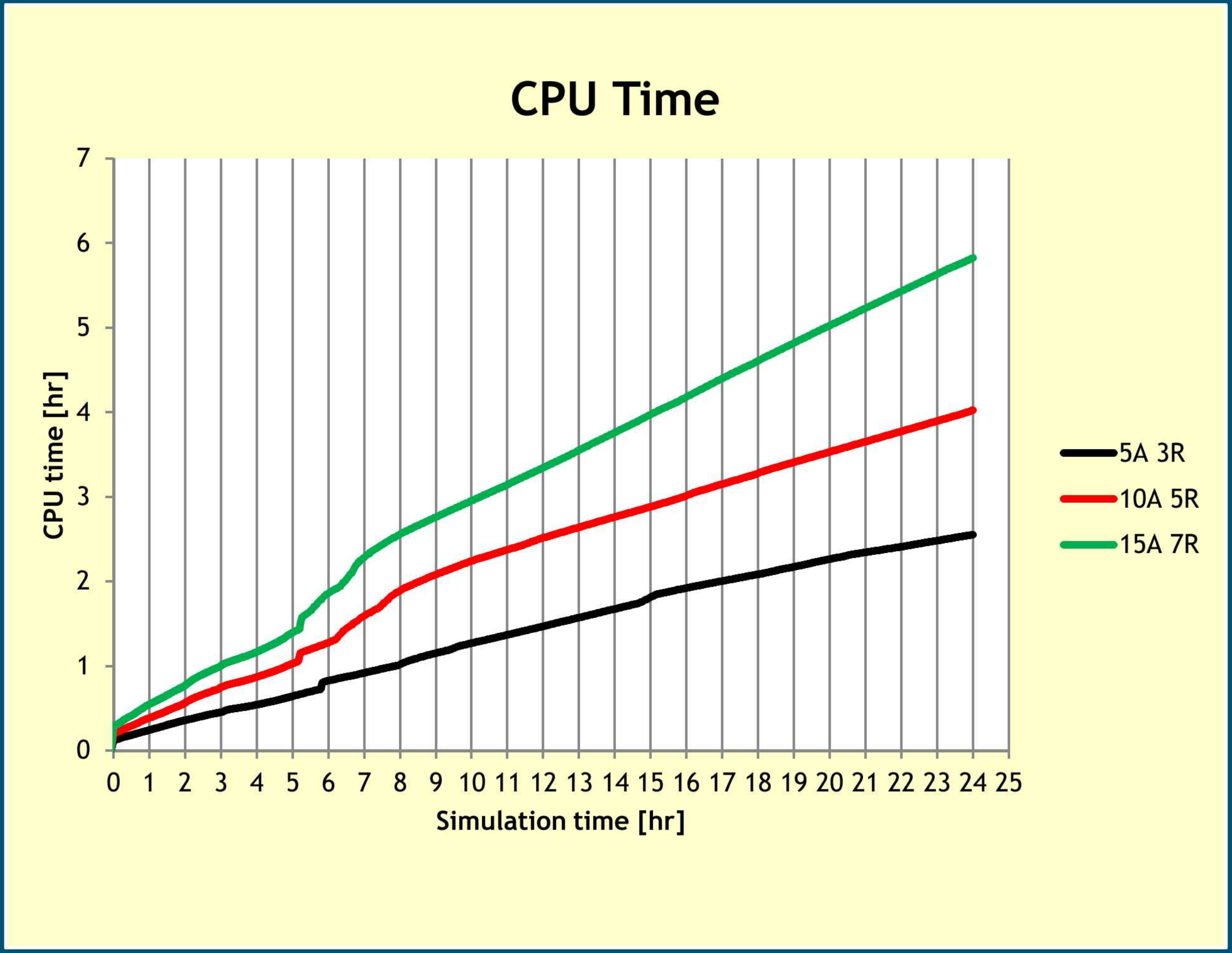



# RESULTS AND DISCUSSION – COMPUTATIONAL COSTS

Computational time scales proportionally to COR fidelity

24 hour run times are not computationally expensive

Further sensitivity studies can easily be run



# SENSITIVITY OF CONSTITUTIVE RELATIONS

# Reflood Quench Model

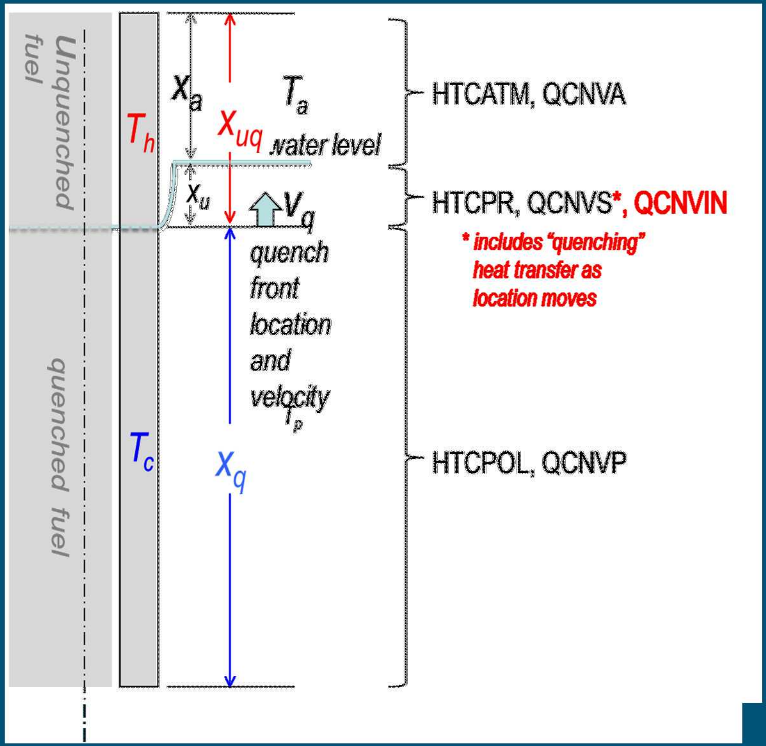
MELCOR computes a quench velocity, distinct from pool water level

- The quench velocity correlation implemented is that of Dua and Tien[1]

$$Pe = \left[ \bar{B}(1+0.4\bar{B}) \right]^{1/2}$$

- Where
  - Pe is the dimensionless quench velocity or Peclet number
  - $\bar{B}$ is a dimensionless Biot number

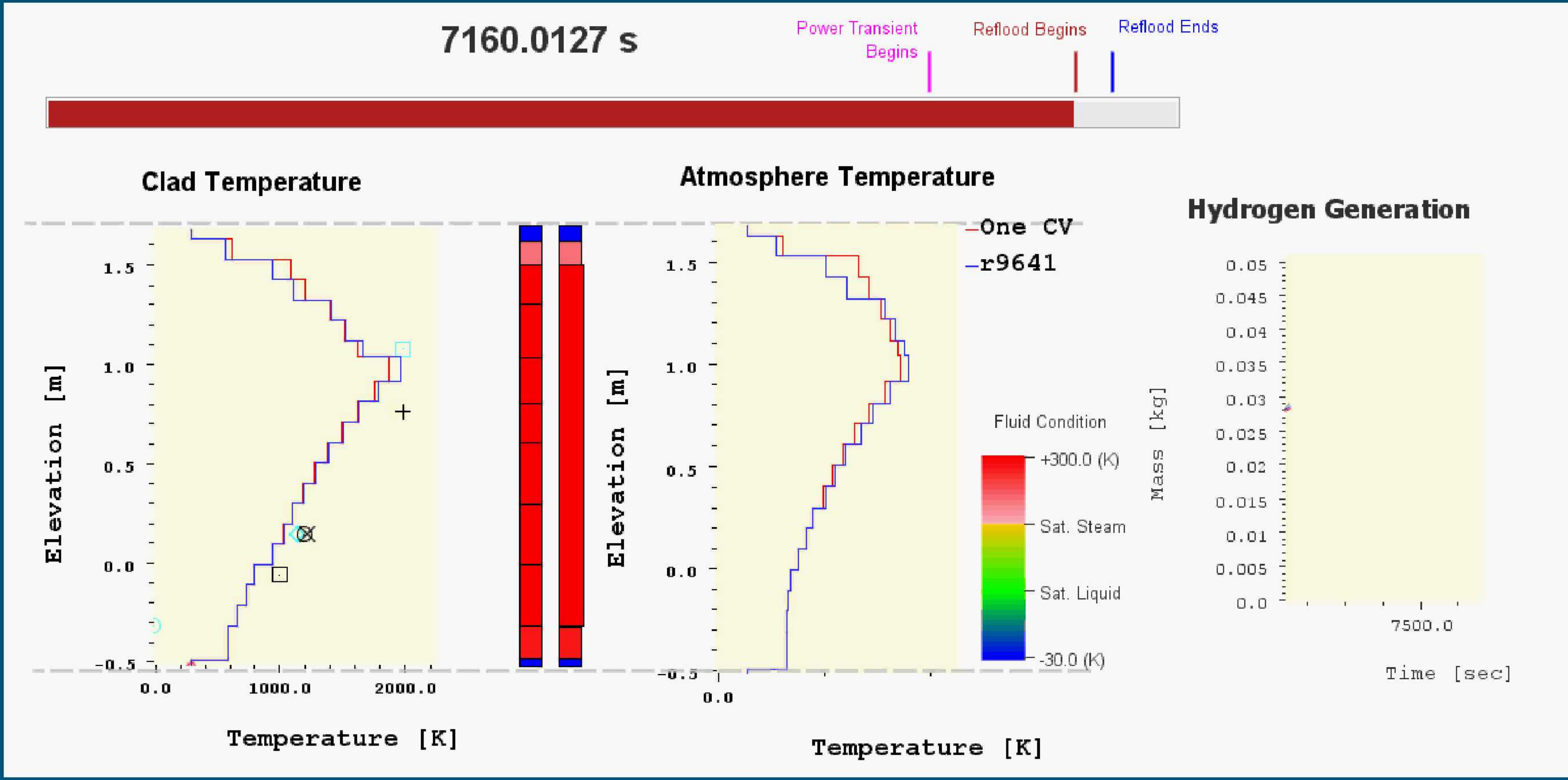
- May be thought of as an interpolation between a result based on one-dimensional conduction in thin surfaces (small Bi), and one based on two-dimensional conduction in thick surfaces (large Bi).




**Question: How sensitive is the quench model to the number of CV volumes?**

[1] *S. S. Dua and C. L. Tien, Intl. J. Heat and Mass Transfer 20, pp.174-176 (1977).*

# Quench model - Nodalization




Quench 6 test– Compare Single CV to CV stack

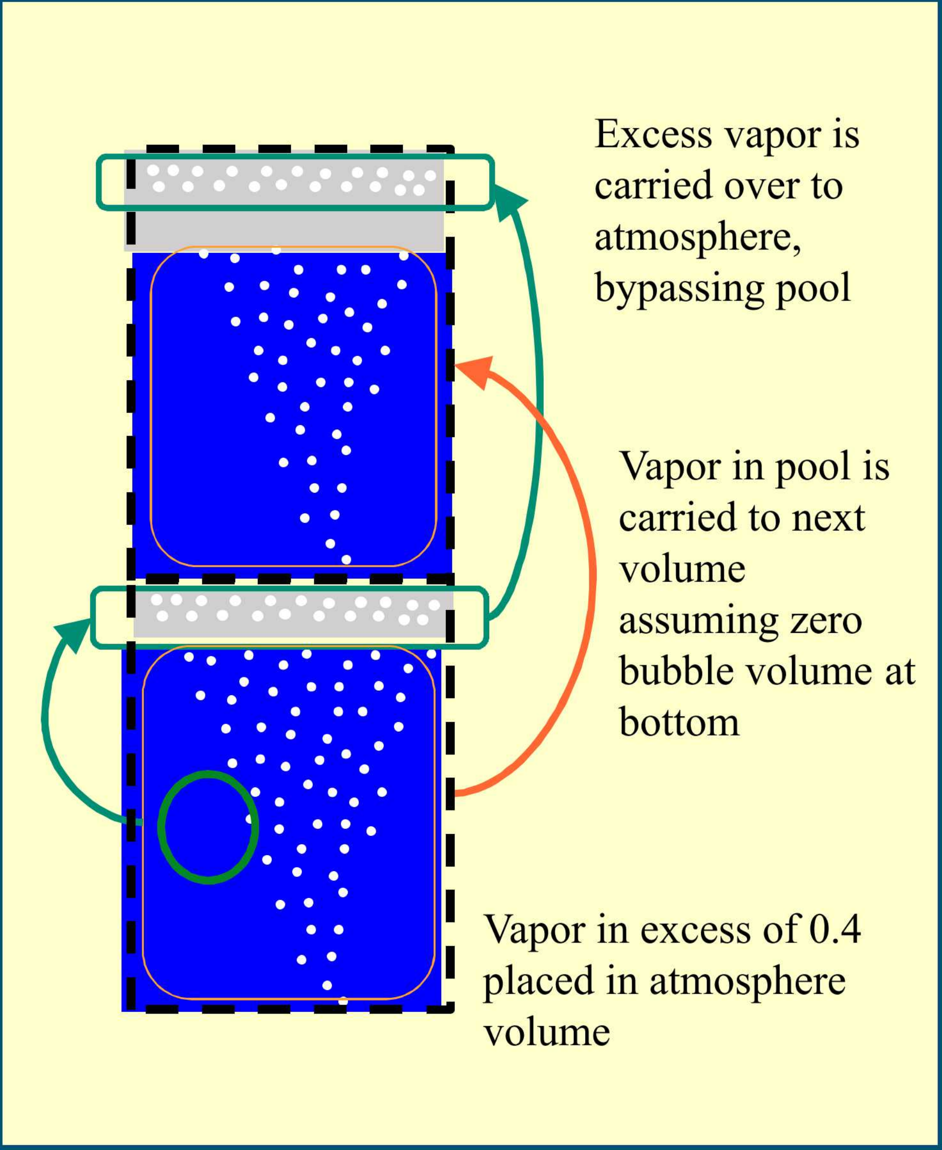
# Bubble Rise Model

Boiling may cause vapor bubbles to appear in a pool

- Either as a result of flashing or heat deposition in the pool
- Only occurs with non-equilibrium model since NCG not present in pool.

Bubble rise model

- Volume flow of bubbles varies linearly from zero at bottom of CV to a value of $J_{max}$ at the top
- Constant rise velocity, $v_o = 0.3$ (SC4407)
- Maximum void fraction in pool is 0.4 (SC4407)
- Formulated for a single CV volume
  - Excess bubbles placed in atmosphere carry over to atmosphere in receiving volumes, bypassing pool

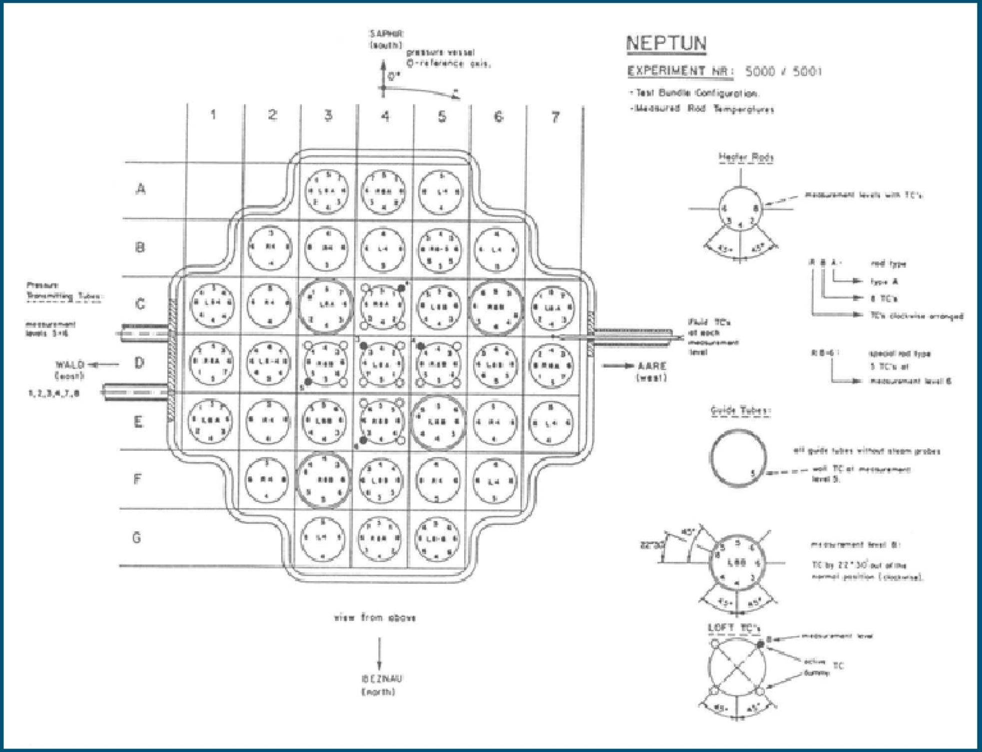


# NEPTUN Experiment

Boil-off from a simulated fuel assembly

Assembly (37 rods, 33 heated, 4 unheated) flooded, coolant preheated under pressure, then power ramped to test level

Experiment 5006 – Pressure at 5 bar, 12 K preheating, power held at 42.1 kW for 380 seconds

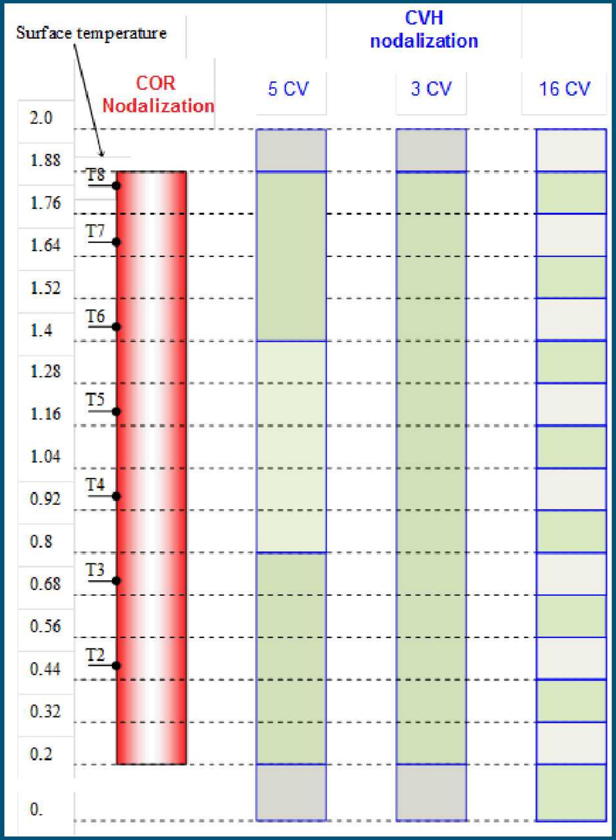


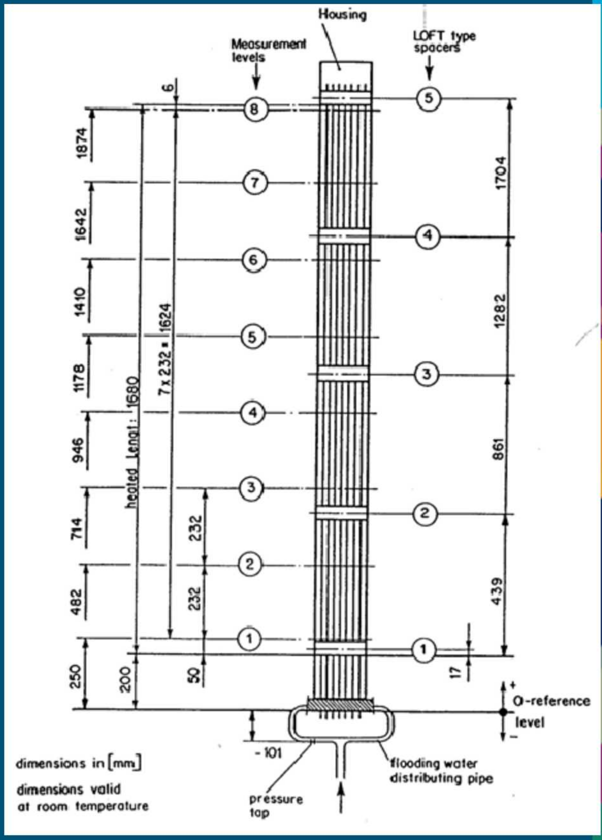
# MELCOR Nodalization

Rods modeled using COR package, with heated rods as fuel and cladding and unheated guide tubes as non-supporting structure

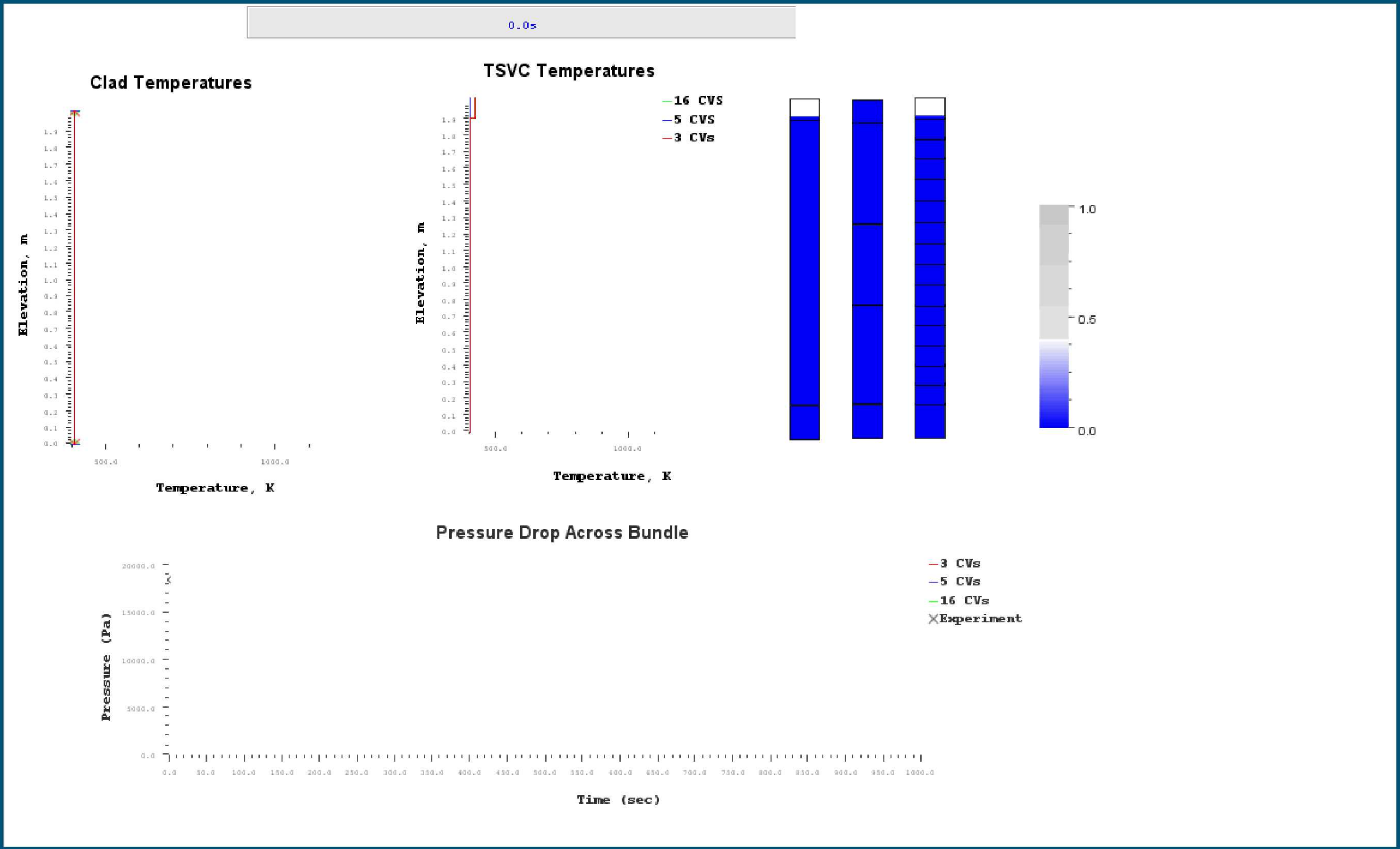
Sidewall modeled as heat structure

Any water or steam leaving the assembly is assumed to be lost to the environment



# NEPTUN Nodalization Results



# CONCLUSIONS

# Effects of Nodalization

- Core degradation primarily drives other transients
  - Coarse nodalization prolongs core degradation
  - Typical and fine nodalizations show faster collapse
- Nodalization impacts final core state
  - Fine nodalization showed least damage to core
  - Conversely, coarse nodalization had most damage to fuel and supporting structures
- Nodalization impacts numerical variance
  - Cliff edge effect when rings fail
  - Survival of rods in outer ring impacts hydrogen
  - Should be considered when analyzing uncertainty analysis
- Relationship to best practices
  - Final core state could impact nodalization chosen
  - Certain nodalizations may align better with available transient data
  - Continued nodalization refinement leads to diminishing returns (CPU time)

# QUESTIONS?