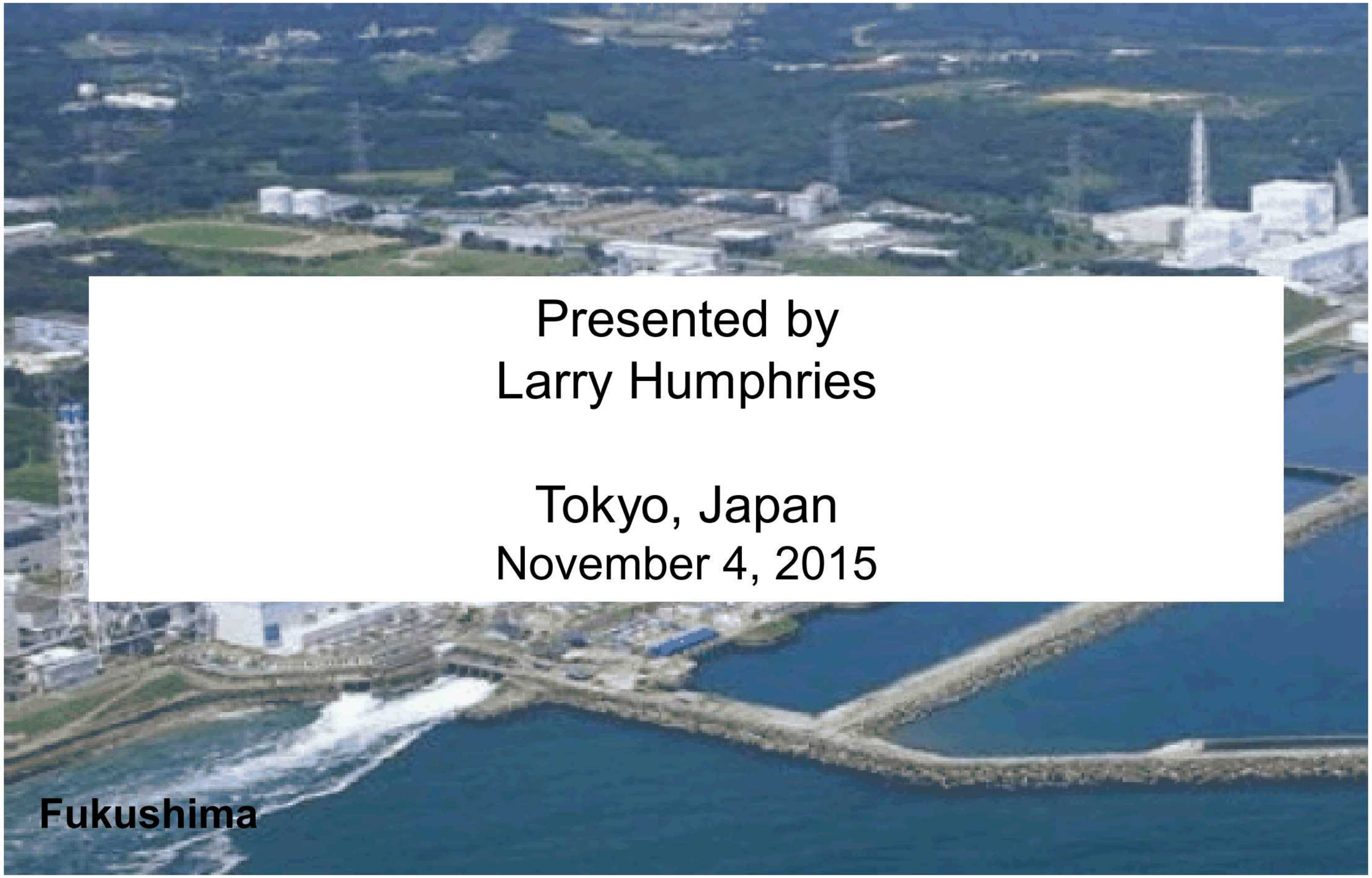
# Overview of MELCOR COR Package

SAND2015-9561PE




Presented by
Larry Humphries

Tokyo, Japan
November 4, 2015

Sandia National Laboratories

# MELCOR COR Modeling Introduction

- **MELCOR COR package models core-specific structures in the core and lower plenum**
  - Fuel assemblies
    - Fuel rods (and grid spacers), BWR canisters
  - Control elements
    - PWR rods, BWR blades
  - Structural elements
    - Core plate
    - BWR control-rod guide tubes
    - Vessel lower head
      - Including penetrations
- **It *does not* model boundary structures**
  - Core shroud, barrel, vessel, upper internals

# MELCOR Core Modeling Phenomenological Models

- **Nuclear heat sources in core**
  - Fission power from models in COR package
  - Decay power from decay heat (DCH) package
- **Thermal response of core**
  - Temperature and stored heat in core structures and debris
  - Conduction and radiation between them
  - Convective and radiative heat transfer to CVH fluids
  - Radiation to boundary structures in HS package
- **Oxidation behavior**
  - Oxidation of Zircaloy and steel by water vapor and/or $O_2$
  - Oxidation of boron carbide ($B_4C$) in BWRs
  - Heat generation by oxidation
  - Release of hydrogen (and other gases) to CVH package

Sandia National Laboratories

# MELCOR Core Modeling Phenomenological Models (2)

- Failure of core and lower plenum structures
  - Local failure by loss of integrity
    - Melting, oxidation, materials interactions
  - Local failure of supporting elements under load
  - Failure of other elements by loss of support
- Creation of debris beds
  - Contain material from failed original structures
- Relocation of core materials
  - Downward flow of molten debris, “candling”
  - Downward relocation of solid debris
  - Radial spreading (leveling) of molten and/or solid debris, when appropriate
  - Changes in volume distribution communicated to CVH
- Response of vessel lower head
  - Failure of penetrations
  - Gross failure of lower head

# MELCOR Core Modeling Basic Approach

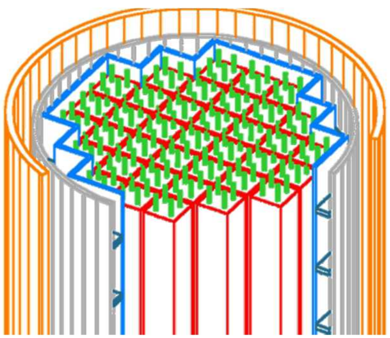
- Take boundary conditions from CVH and HS
  - Standard approaches and heat transfer correlations
- Nodalization may be more detailed than hydro
  - Local temperature profiles inferred where necessary
- Build core structures from "components"
  - Limited number of "building blocks"
  - Components have temperature (enthalpy), mass, composition, surface area
- Use lumped mass treatment for each component in each cell
  - Single temperature
  - Multiple materials
    - Distinguish original ("intact") masses from melted/refrozen masses ("conglomerate debris")
- Unified approach for PWR and BWR

# MELCOR Core Modeling
# Channel and Bypass

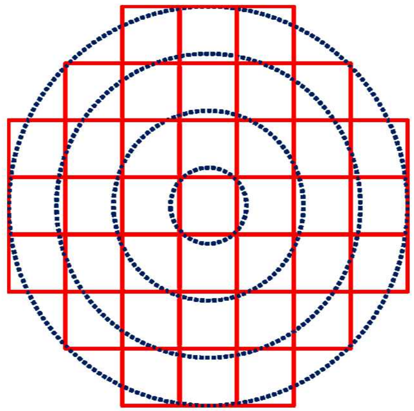
- **Same representation used for PWR and BWR**
  - In a BWR, MELCOR calls the region outside the canisters (channel boxes) in the core region the "bypass"
  - In a PWR, MELCOR calls the region outside the core shroud the "bypass"
  - Everything else is called the "channel"
    - In a BWR, "channel" includes the interior of canisters and the lower plenum
- **Input specifies the CVH volume representing channel and bypass for each core cell**
  - Distinction only in core region of a BWR or outer peripheral core ring of PWR
  - Common to interface several cells to a single CVH volume

# MELCOR Core Modeling
# Core Nodalization

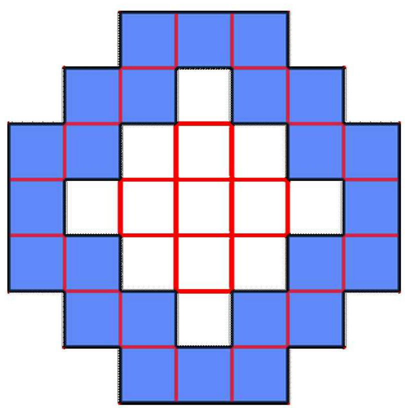
- **Core and lower plenum divided axially and radially into cells**



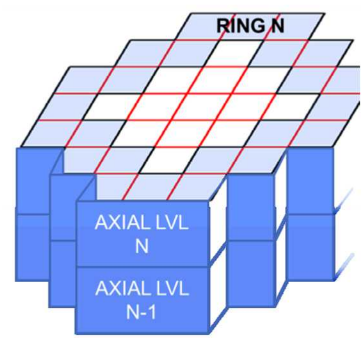
Core Geometry

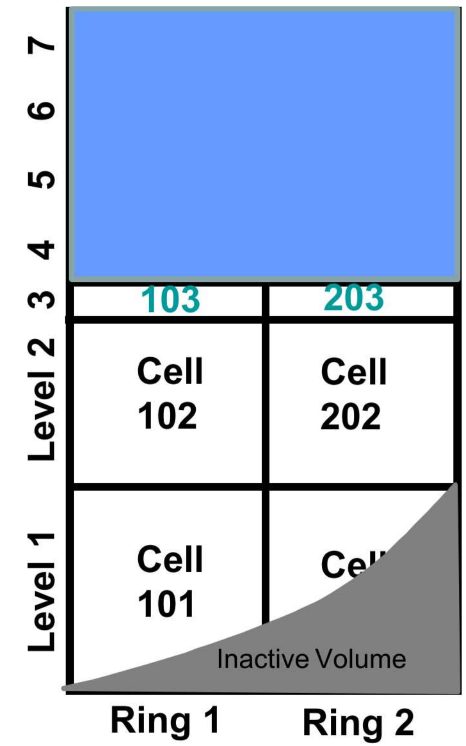


Conceptual Rings



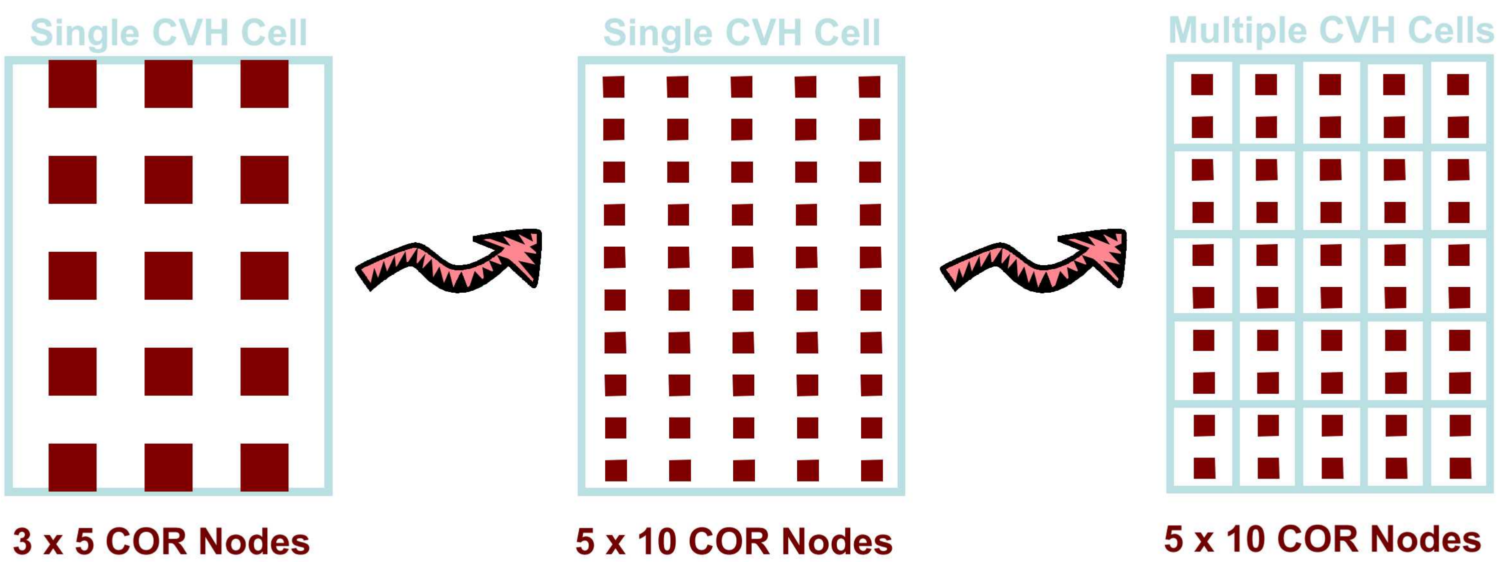
Modeled 'rings'



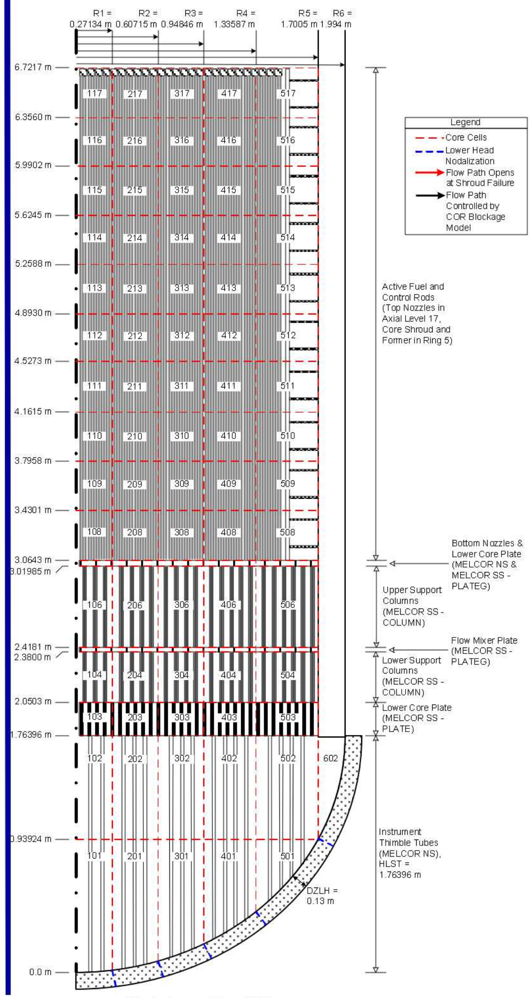
# Evolution of the core nodalization

- **Increased fidelity in modeling of core damage progression**
  - Greater resolution in melt progression accounting for "phased" events
  - Ability to account for timing effects of support structure failure, blockages created by core debris, and other important phenomena

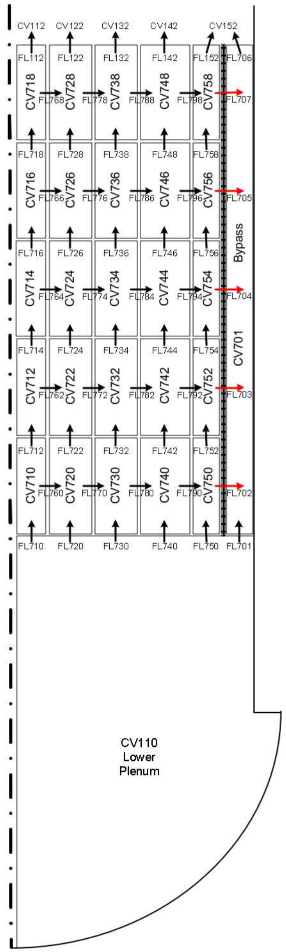



COR representation can be large as desired by the user
Constrained by code performance and effort in building deck
Can have more than 9 rings

# Surry – Initial Nodalization



Westinghouse 3-Loop PWR
Core Nodalization

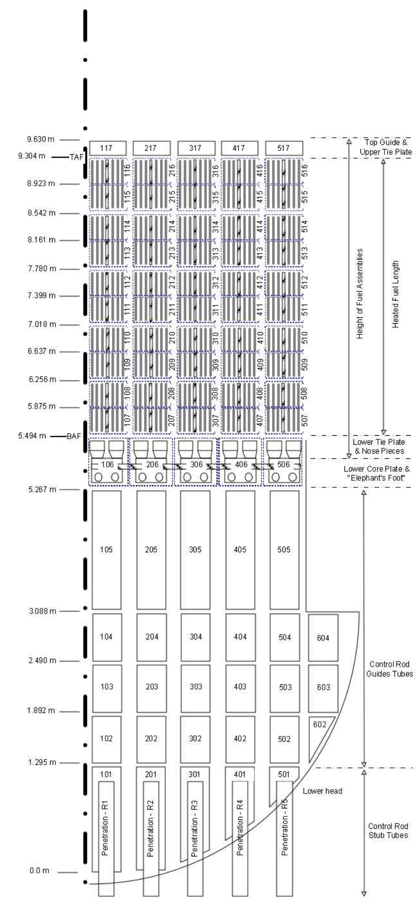


Westinghouse 3-Loop PWR
CVH/FL Nodalization

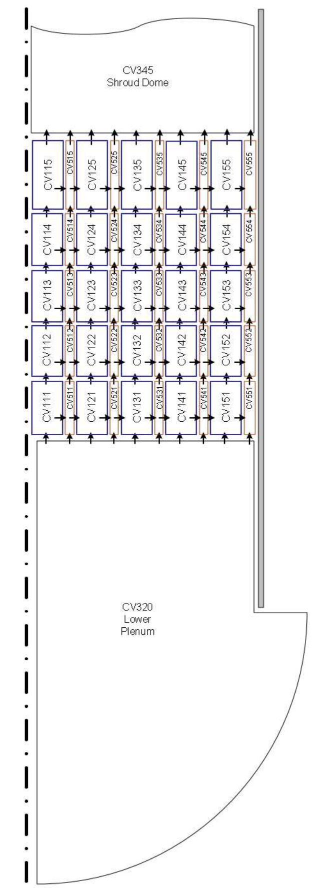
- **Westinghouse 3-loop PWR**
- **2,546 $MW_{th}$**
- **Active core – 5 radial rings, 10 axial levels, 2 core cells per CV**

# Fukushima Unit 1 – Initial Nodalization

- **General Electric, Mark I BWR-3**
- **460 MW$_e$**
- **Active core – 5 radial rings, 10 axial levels, 2 core cells per CV**
- **Note – Diagram shown is for Peach Bottom, which the Fukushima model was developed from. The nodalization is the same, but the elevations will be different**



BWR/4 Core Nodalization



CVH Nodalization accompanying COR Nodalization

Sandia National Laboratories

# MELCOR Core Modeling
# Core Components

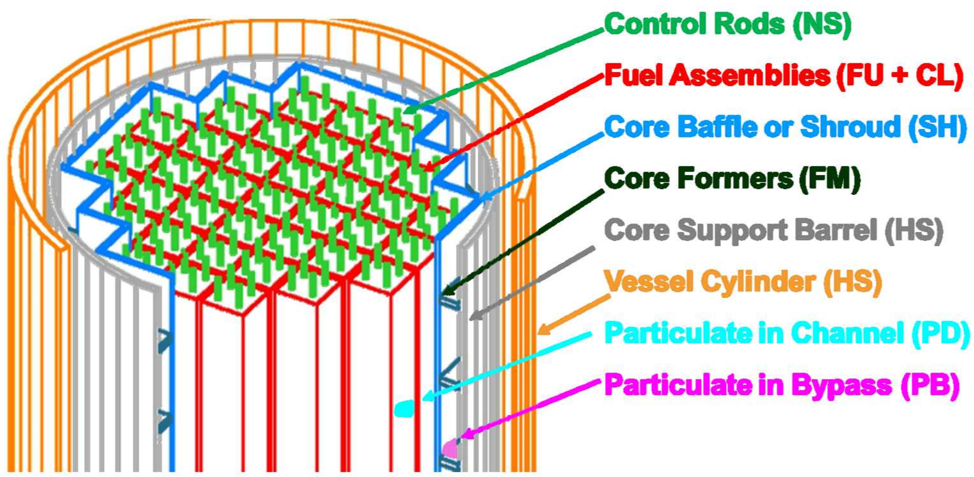
**Each core cell may contain one or more of a set of permitted core components (or none)**

| | | |
|---|---|---|
| 1 | FU | intact fuel component |
| 2 | CL | intact cladding component |
| 3 | CN | intact canister component (portion not adjacent to control blade |
| 4 | CB | intact canister component (portion adjacent to control blade) |
| 4 | SH | Intact PWR core shroud (baffle) |
| 5 | FM | Intact PWR core formers |
| 6 | PD | particulate debris component (portion in the channel for a BWR) |
| 7 | SS | supporting structure component |
| 8 | NS | Non-supporting structure component |
| 9 | PB | particulate debris component in the bypass (for a BWR) |
| 10 | MP1 | Oxide or mixed molten pool component (portion in channel for a BWR) |
| 11 | MB1 | Oxide or mixed molten pool component in bypass (for a BWR) |
| 12 | MP2 | Metallic molten pool component (portion in channel (for a BWR) |
| 13 | MB2 | Metallic molten pool component in bypass (for a BWR) |
| - | - | The lower head is a unique structure associated with the COR package |

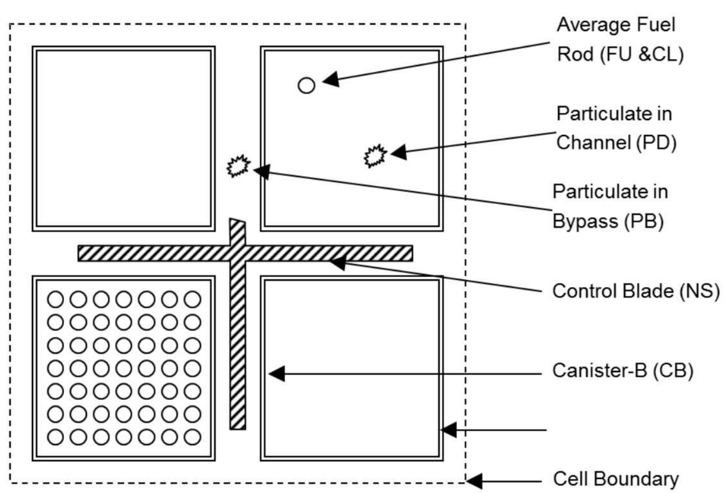
Components in green are specific to BWRs
Components in red are specific to PWRs
Components in yellow are created when intact components fail.

# MELCOR CORE Representation
# COR Components

PWR Core




BWR Assembly




Sandia National Laboratories

# Location of COR Components

| Reactor Type | Volume: CH<br>Surface: CH<br>Single-sided | Volume: CH<br>Surface: CH/BY<br>2-sided | Volume BY<br>Surface BY<br>Single-sided |
|---|---|---|---|
| PWR | FU, CL, PD, SS, NS, MP1, MP2 | SH | FM, PB, MB1, MB2 |
| BWR | FU, CL, PD, MP1, MP2 | CN, CB | SS, NS,, PB, MB1, MB2 |
| SFP-PWR | FU, CL, PD,SS, NS, MP1, MP2 | | RK, |
| SFP-BWR | FU, CL, PD, MP1, MP2 | CN, CB, | SS, RK, PB, MB1, MB2 |
| PMR | FU, CL, PD, SS, NS, MP1, MP2 | RF | PB, MB1, MB2, |
| PBR | FU, CL, PD, SS, NS, MP1, MP2 | RF | PB, MB1, MB2 |

# Conglomerate On Components

- Each component has an intact mass field
  - User typically defines intact masses only (before onset of core degradation)
  - User also defines surface areas of intact components
  - Intact material has never melted (though it may have resulted from failure of intact component, i.e., intact particulate debris)
- Each component has a conglomerate mass field
  - Material has melted but may have refrozen on surfaces
    - Can be molten in molten pool component
  - Can fill interstitials in particulate debris
  - Different Composition
    - Can have materials that are not available in the intact field
  - Intact and conglomerate mass in thermal equilibrium (same temperature)
  - Affects surface area exposed to fluid convection, oxidation, radiation, and further refreezing
  - Affects thermal conductivity of particulate debris

Sandia National Laboratories

# Special Components Created During Core Degradation

## Particulate Debris (PD, PB)

- Formed when an intact component fails or when molten pool freezes
- Has both intact & conglomerate fields
  - Unique composition but same temperature
- "Intact" mass
  - Porosity assumed from user input & conglomerate mass
  - Has never melted
- Conglomerate mass
  - Fills interstitials first
    - Affects effective thermal conductivity, heat surfaces for oxidation and radiation, and fluid flow
  - Excess assumed above

## Molten Pool (MP1, MP2, MB1, MB2)

- Formed when other components melt
  - molten material blocked during candling
  - Melting PD
- All mass resides in the conglomerate field.
- Freezing MP is moved to the PD component and equilibrated
- Can form contiguous molten pool
  - Special routines for convection and freezing (Stefan model)
- Non-contiguous cells
  - Does not participate in convecting molten pool calculation (more later)
  - Heat transfer similar to PD

Sandia National Laboratories

# MELCOR Core Modeling Non-Supporting Structures

- Non-supporting structure (NS) can support only other NS
- User input defines treatment in each core cell
  - Type of structure modeled
  - Failure criteria
- Three basic input options
  - 'ABOVE', like a PWR control rod
  - 'BELOW', like a BWR control blade
  - 'FIXED', like the stiffeners in Phebus experiments
    - NS in a cell will not collapse until it fails locally.
- More general global options
    - 'BLADE' (default for BWR) ≡ 'BELOW'
    - 'ROD' (default for PWR) ≡ 'FIXED' at upper end, 'ABOVE' elsewhere

PWR Control Rod Assembly



Sandia National Laboratories

# MELCOR Core Modeling Input for Cell Contents

- **User input defines the components initially present in each core cell**
  - **Masses of materials in each component**
    - **Can contain one or more of a list of 7 materials defined in the material properties package**
      - **Restricted list for most components**
      - **PD, MP, and conglomerate can contain any of them,**
      - **User can redefine materials**
  - **Initial temperature of each component**
  - **Surface areas of components**
    - **Except debris and molten pool which are Internally calculated from surface/volume ratio**
  - **Hydraulic diameters**
  - **PD porosity**

| COR name | MP name |
| --- | --- |
| UO2 | 'URANIUM DIOXIDE' |
| ZR | 'ZIRCALOY' |
| ZRO2 | 'ZIRCONIUM DIOXIDE' |
| SS | 'STAINLESS STEEL' |
| SSOX | 'STAINLESS STEEL OXIDE' |
| CRP (control rod poison) | 'BORON CARBIDE' for BWR *or*<br>'SILVER INDIUM CADMIUM' for PWR |
| INC (Inconel) | 'STAINLESS STEEL' |

Sandia National Laboratories

# Heat Transfer
# Axial Conduction

- **Like components in adjacent axial cells**
- **Plate supporting structure and all components supported by it**
- **Component and particulate debris in adjacent cells if**
  - **component exists in only one of the two adjacent cells**
  - **physical contact between debris and component is predicted.**
    - **assumed if the debris resides in the overlying cell where it is presumed to rest on components in the underlying cell**
- **Heat transfer from convecting molten pool components handled separately**

$$q_{ij} = K_{eff}\left(T_i - T_j\right)$$

$$K_{eff} = \frac{1}{{}^{1}\!/_{K_i} + {}^{1}\!/_{K_j}}$$

$$K_i = \frac{k_i A_i}{\Delta x_i}$$

$$A_i = \frac{V_{tot,comp,i}}{\Delta z_i}$$

$$\Delta x_i = \tfrac{1}{2}\Delta z_i$$

# Heat Transfer
# Conduction - Other

- **Radial**
  - Conduction is calculated between elements of supporting structure (SS) modeling contiguous segments of a plate in radially adjacent core cells.
  - Conduction is also calculated between particulate debris in radially adjacent core cells unless the path is blocked by intact canisters
- **Intracell**
  - debris and any remaining intact core components.

Intracell

$$A_i = A_j = \frac{V_{tot,PD}}{V_{tot,PD} + V_{free}} A_{intact}$$

$$\Delta x_{PD} = \frac{V_{bed}}{2\,A_{bed}}$$

$$\Delta x_{intact} = \frac{V_{tot,intact}}{2\,A_{intact}}$$

Sandia National Laboratories

# Heat Transfer
# Convection

- **Heat transfer rates calculated for each component using heat transfer coefficients**
  - **Uses Local cell temperature predicted from dT/dz model**

$$q = h_{rlx} \; A_s \; (T_s - T_f)$$

- **Does not use a critical Reynolds number to determine laminar or turbulent flow regimes**
  - **Maximum of laminar and turbulent Nusselt number is used**
  - **Maximum of forced and free used**
  - **Alleviates some numerical difficulties associated with discontinuities in Nu**
- **Convective heat transfer from contiguous molten pools treated separately**
  - **Heat transfer only at pool surfaces in contact with fluid**

Sandia National Laboratories

# Radiative Exchange Factors

- **Simple model for radiant heat exchange between COR cells.**
  - **Radiation Exchange Factors**

$$A_1F_{12} \equiv A_2F_{21} \equiv AF = \min(A_1, A_2, A_{cell,x})F_{cell,x}$$
$$= A_{cell,x}F_{cell,x}\min(A_1/A_{cell,x}, A_2/A_{cell,x}, 1)$$

- where $F_{cell,x}$ is the effective inter-cell view factor input by the user and x may be r (radial) or a (axial),
- $A_1$ is the surface area of the component in cell 1,
- $A_2$ is the surface of the component in cell 2, and
- $F_{12}$ is the actual view factor between components in cells 1 and 2.
- Effective Exchange Factors
  - Exchange factor also accounts for the fact that for thick cells radiation at the cell boundary "sees" only a fraction of the average temperature difference between cells.

| View factor | Default Value | Notes |
|---|---|---|
| FCNCL | 0.25 | Radiative exchange factor for radiation heat transfer from the canister wall to the fuel rod cladding surfaces. |
| FSSCN | 0.25 | Radiative exchange factor for radiation from NS (e.g., control blades) to the adjacent canister walls or to fuel rods and debris if canister is not present.<br><br>Redefined in the spent fuel pool model as a view factor for radiation heat transfer from cladding surfaces to the rack surfaces (if applicable) within a ring. |
| FCELR | 0.1 | Radiative exchange factor for radiation heat transfer radially outward from the cell/node boundary to the adjacent cell/node boundary. |
| FCELA | 0.1 | Radiative exchange factor for radiation heat transfer axially upward from the cell/node boundary to the next adjacent cell/node boundary. |
| FLPUP | 0.25 | Radiative exchange factor for radiation from the liquid pool to the core components. |

Sandia National Laboratories

# Geometric Radiative Exchange Factors

Not Validated Yet

- **Geometric view factor only (no accounting for temperature effects)**
  - **The view factor between a cell of thickness of $L_1$ and one of thickness $L_2$ may be calculated as**

$$A_1F_{12} = \int_{-L_1}^{0} dx_1 A_{cell} \left(\frac{A}{V}\right)_1 e^{\alpha_1 x_1} \int_{0}^{L_2} dx_2 \alpha_2 e^{-\alpha_e x_2}$$

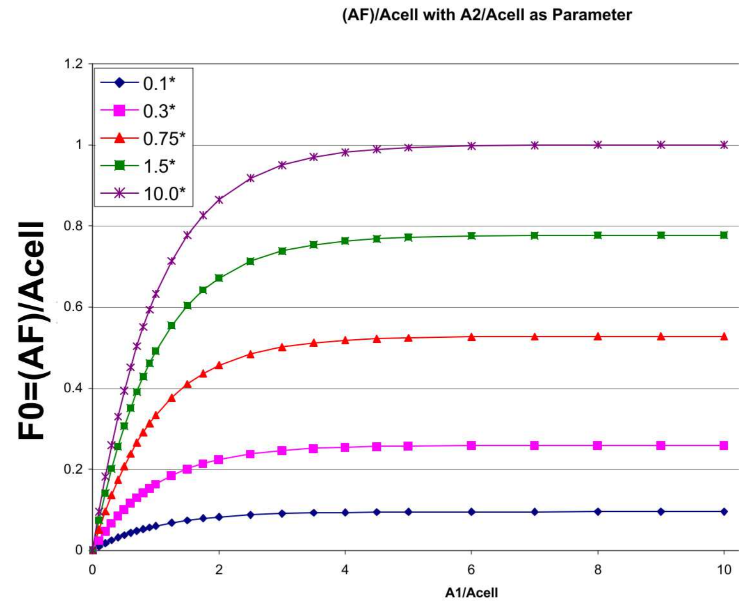
  - **In terms of dimensionless variables**

$$A_1F_{12} = A_{cell} \left(\frac{A}{\alpha V}\right)_1 \int_{-\alpha_1 L_1}^{0} dy_1 e^{y_1} \int_{-\alpha_2 L_2}^{0} dy_2 e^{y_2} = A_{cell} \left(\frac{A}{\alpha V}\right)_1 \left(1 - e^{-\alpha_1 L_1}\right)\left(1 - e^{-\alpha_2 L_2}\right)$$

  - **By reciprocity**

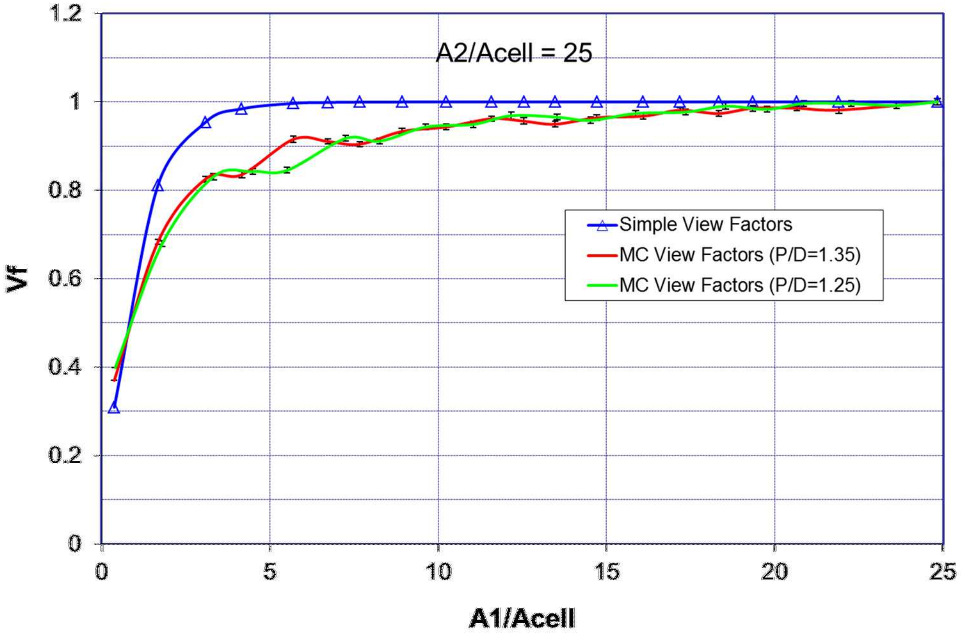
$$A_2F_{21} = A_2F_{21} = AF = A_{cell}F_0 = A_{cell}K\left(1 - e^{-\alpha_1 L_1}\right)\left(1 - e^{-\alpha_2 L_2}\right) \quad where \quad \alpha_i L_i = \frac{A_i}{KA_{cell}}$$

  - **In limits (reasonable therefore to assume K = 1)**
    - **Both cells large** $AF \rightarrow A_{cell}K$
    - **Cell 1 small and cell 2 large** $AF \rightarrow A_1$
    - **Both cells small** $AF \rightarrow \frac{A_1 A_2}{KA_{cell}}$



# Geometric Radiative Exchange Factors - Validation

- **Simple geometric radiation exchange factors compared to Monte Carlo evaluated view factors.**
  - Simple model is adequate for A/Acell > 10
- **Monte Carlo utility was created for calculating both FCELR and FCELA exchange factors from fuel rod arrays.**
  - Partially implemented as an option for PWR at MELGEN



# Effective Radiative Exchange Factors

Not Validated Yet

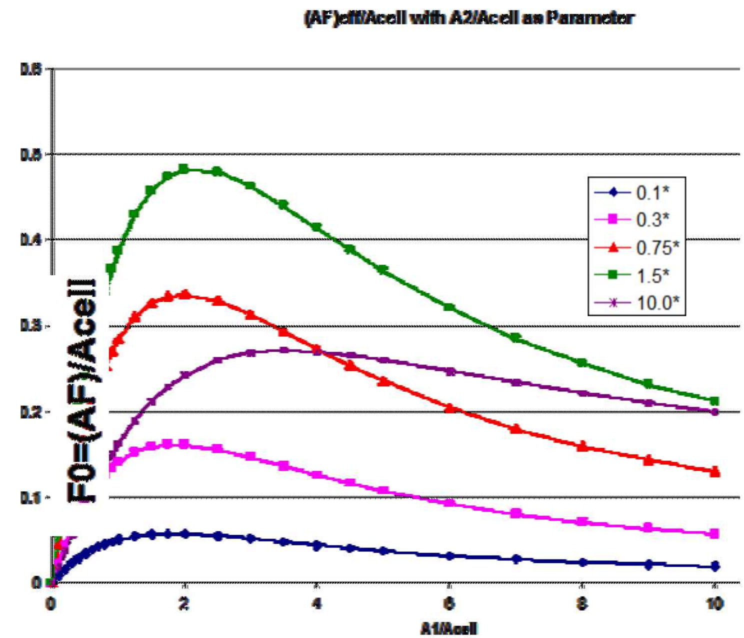
- **Accounting for temperature variation in cell**

$$(AF)_{eff} = -A_{cell} K \int_{-\alpha_1 L_1}^{0} dy_1 e^{y_1} \int_{-\alpha_2 L_2}^{0} dy_2 e^{y_2} \frac{2(y_1 + y_2)}{\alpha_1 L_1 + \alpha_2 L_2}$$

  - **where the fraction in the integrand is the fraction of the average difference in $T^4$ between point 1 and point 2.**

- **Using K=1 defined for geometric exchange factor and simplifying**

$$(AF)_{eff} = 2\frac{(A_{cell})^2}{A_1 + A_2}$$
$$\left\{\left[1-(1+\alpha_1 L_1)e^{-\alpha_1 L_1}\right]\left(1-e^{-\alpha_2 L_2}\right)+\left(1-e^{-\alpha_1 L_1}\right)\left[1-(1+\alpha_2 L_2)e^{-\alpha_2 L_2}\right]\right\}$$

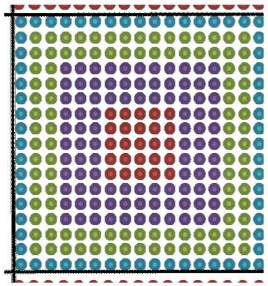



- **Limits for Exchange factors**
  - **both cells large** $(AF)_{eff} \rightarrow 4\frac{(A_{cell})}{A_1 + A_2}$
  - **cell 1 small and cell 2 large** $(AF)_{eff} \rightarrow \frac{A_1 A_{cell}}{A_1 + A_2}$
  - **both cells small** $(AF)_{eff} \rightarrow \frac{1}{2}\frac{A_1^2 + A_2^2}{A_1 + A_2}$

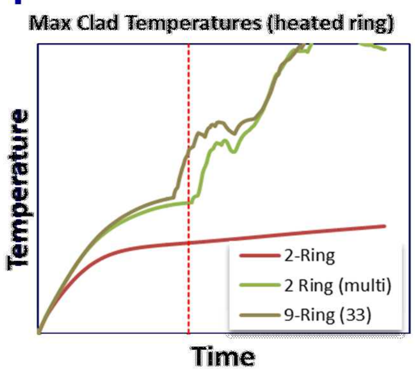
Sandia National Laboratories

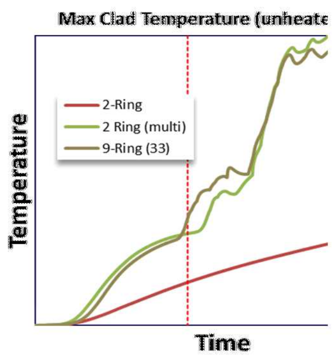
# Multi-Rod Model

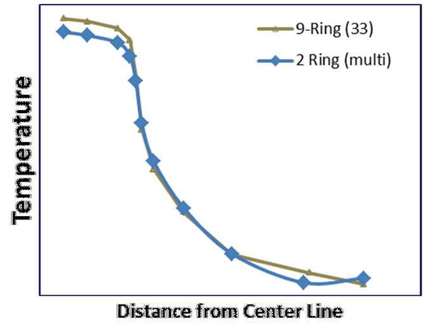
- **Motivation**
  - **It is desirable to model an entire assembly within a single MELCOR ring**
- **Challenge**
  - **When hot assembly reaches ignition, heat transfer to cold assembly is problematic**

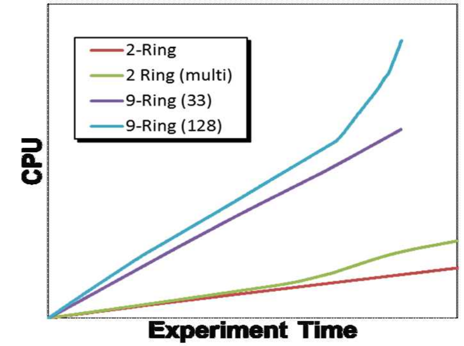


Color represents rod types




- Validation
  - Validation was performed against the Sandia PWR Spent Fuel Pool Experiments
  - Comparisons between 2-ring (2 rods) model; 2-ring, (9 rods) model; and 9-ring model.
- CPU time is greatly reduced for multi-rod model
- Simplified input requirements

# Oxidation Models - General

- **Objects that can oxidize**
  - COR components
    - Metals include Zr, SS, and B4C
  - Debris in CAV package
- **Objects that cannot oxidize**
  - Heat structures
- **Oxidation behavior for COR components**
  - Oxidation of Zircaloy and steel by water vapor and/or $O_2$
  - Oxidation of boron carbide ($B_4C$) in BWRs
  - Heat generation by oxidation
  - Release of hydrogen (and other gases) to CVH package

# Oxidation Reactions

- **Specific models for each oxidizing material**
- **Reaction Kinetics**
- **Zircaloy**
  - **Reactions**
  - **Kinetics**
- **Steel**
  - **Reactions**
  - **Kinetics**
- **Boron Carbide**
  - **Reactions**

Solid-state diffusion of oxygen through an oxide layer to unoxidized metal is represented by the parabolic rate equation:

$$\frac{d\,(W^2)}{dt} = K(T)$$

Where W is the mass of the oxidized metal per unit surface areaThis is integrated over a timestep:

$$(W^{n+1})^2 = (W^n)^2 + \mathrm{K}\,(T^n)\;\Delta \mathrm{t}$$

Urbanic Heidrich evaluation of rate constant, K

For very low oxidant concentrations, gaseous diffusion may limit the reaction rate.

$$\frac{\mathrm{d\,W}}{\mathrm{dt}} = \frac{\mathrm{MW}\;k_c\;P_{ox}}{\mathrm{n\;R}\;T_f}$$

The gaseous diffusion oxidation rate is used if it is less than the rate calculated from the parabolic rate equation.

# Other Oxidation Models

- **MELCOR original oxidation modeling is still available**
- **PSI model improves flexibility for steam oxidation**
  - **New steam oxidation models are available to users:**
    - **Cathcart-Pawel/Urbanic Heidrick**
      - **CP when T< 1853K**
      - **U-H when T> 1873 K**
    - **Leistikov-Schanz/Prater-Courtright**
    - **Leistikov**
    - **Urbanic-Heidrick**
    - **Sokolov**
- **Several Air oxidation models to choose from**
- **Several options for enabling breakaway**

**COR_OX** – PSI Oxidation model of Zircaloy-4 for cladding

Optional.
The user may activate and set parameters for PSI cladding oxidation model.

(1) MODEL – Key for PSI oxidation model activation:
0 – MELCOR oxidation model is used;
1 – PSI oxidation model is used.
(type = integer, default = 0, units = none)

The following data must be input if MODEL = 1 only:

(2) STEAM – Steam oxidation model:
<0 – Use parameters from sensitivity cards
0 – Cathcart-Pawel/Urbanic-Heidrick;
1 – Leistikov-Schanz/Prater-Courtright;
2 – Leistikov;
3 – Urbanic-Heidrick;
4 – Sokolov;
5 – Grosse.
(type = integer, default = 0, units = none)

(3) AIR – Air oxidation model:
<0 – Use parameters from sensitivity cards
0 – Hofmann-Birchley;
1 – Hayes-Roberson/Leistikov-Berg (NUREG1);
2 – Powers (NUREG2) (Birchley);
3 – Melcor (Birchley);
4 – Mozart (Birchley).
(type = integer, default = 0, units = none)

(4) OXYGEN – Oxygen oxidation model:
<0 – Use parameters from sensitivity cards
0 – Hofmann

(5) NOBRK – Breakaway switch:
0 – switch on for steam and air;
1 – switch off for steam, on for air;
2 – switch off for steam and air.
(type = integer, default = 0, units = none)

Sandia National Laboratories

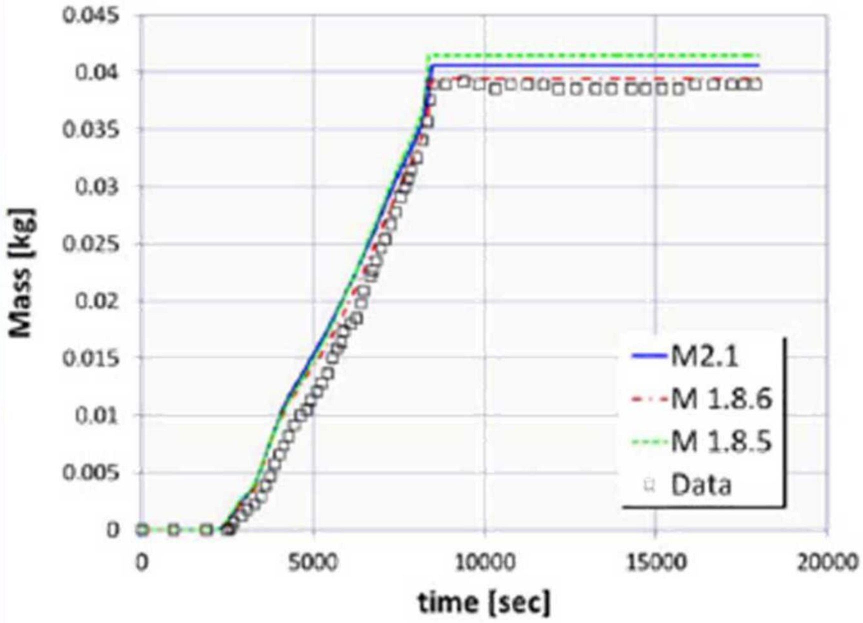
# Oxidation
# Additional Considerations

- Refrozen conglomerate (candled) material blocks intact surface (including PD) from oxidation
- Surface areas must be defined consistently with component mass since they are used in calculating thickness.
- Two-sided components residing in channel with a surface in contact with bypass can oxidize
  - Volume expansion accommodated through borrowing virtual volume from bypass
- Zirconium emissivity is calculated as a function of oxide thickness
- Oxidation calculated for submerged surfaces
  - Gas film between unquenched surfaces and pool
- Debris surface area is partitioned between Zr, SS, and other materials
  - Surface area for Zr oxidation from volume fraction of Zr + ZrO2
    - Modeled as layers with ZrO2 outer layer
  - Surface area for SS oxidation from volume fraction of SS + SSOX
    - Modeled as layers with SSOX outer layer

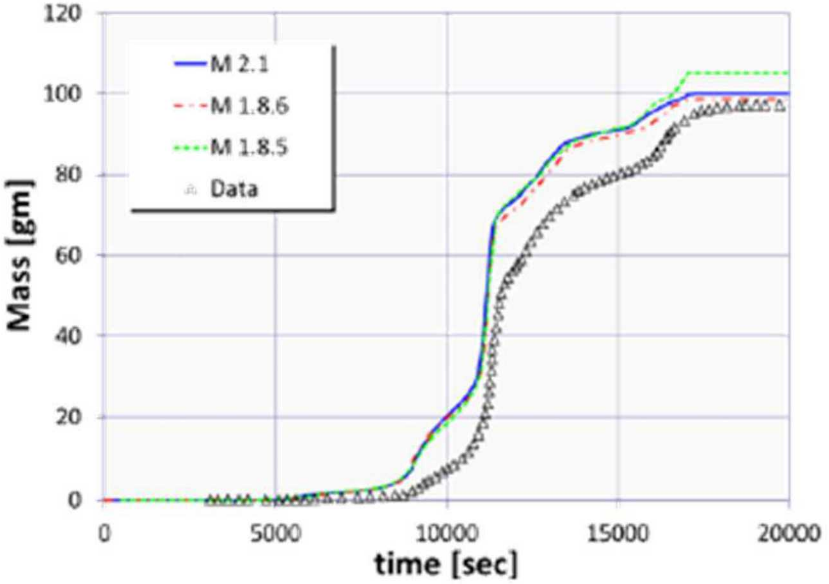
Sandia National Laboratories

# Validation of Hydrogen Generation

PHEBUS-B9



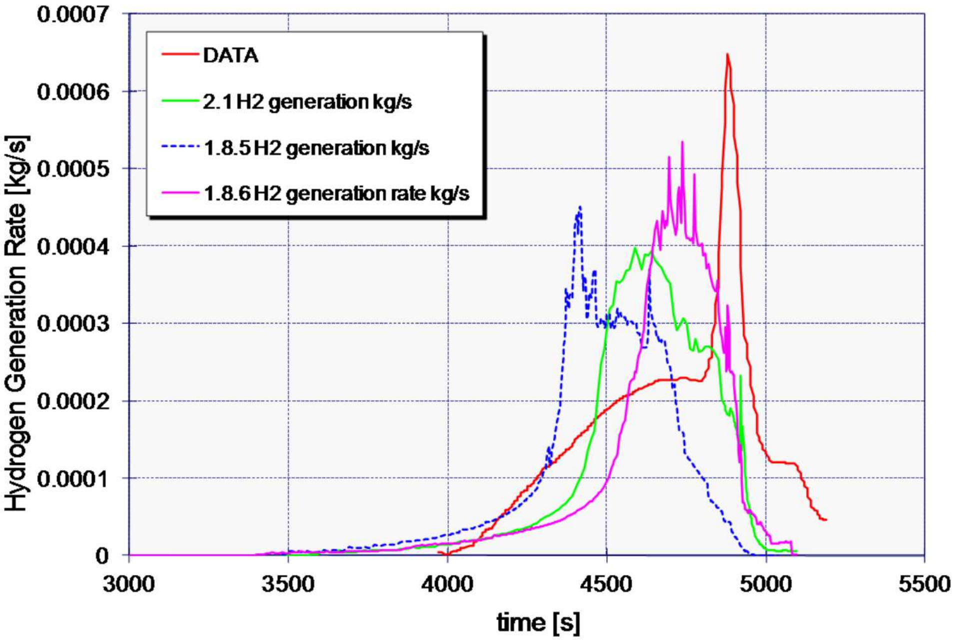

FPT-1




Sandia National Laboratories

# Complications to validation of oxidation modeling

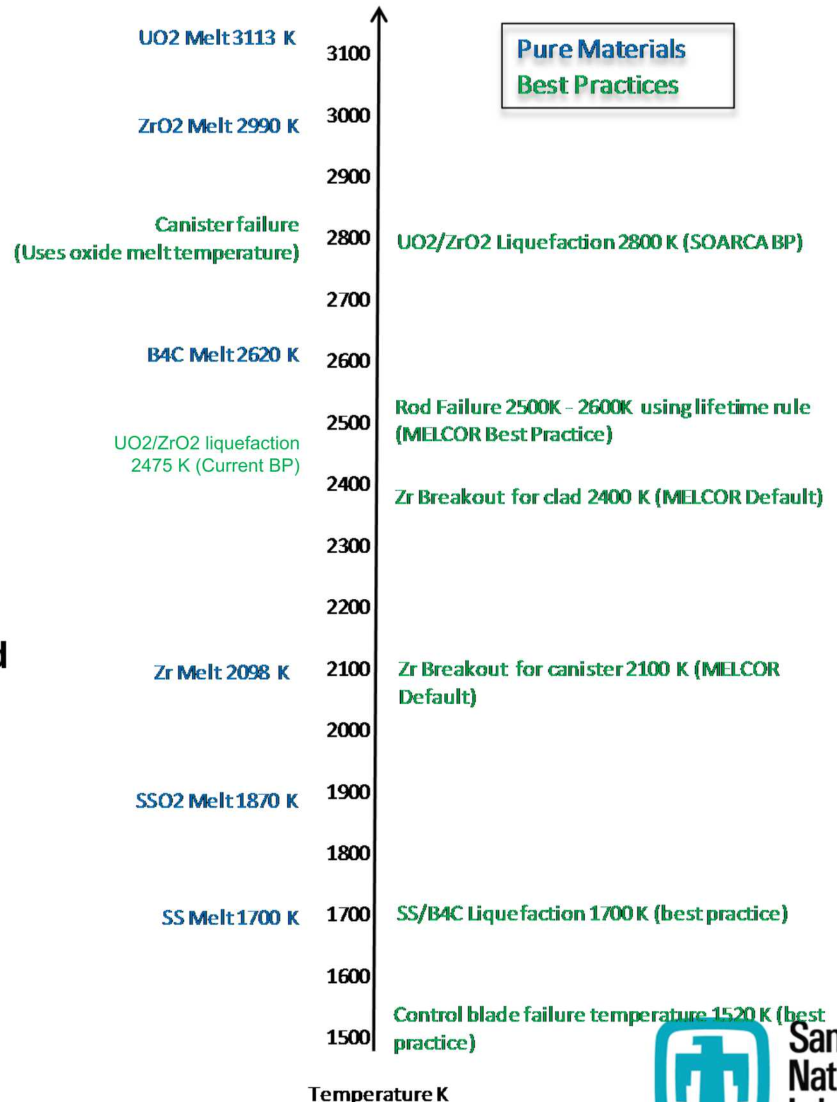
- **CORA-13 Validation does not predict the spike in hydrogen production during the rapid quench**
  - **No modeling for possible damage to oxide layer from thermal stress**
- **During core degradation, changes in exposed surface area and blocked flow are more important than nuances in the rate equations**




Sandia National Laboratories

# Order of Component Failure and Temperature (Though Other Failure Mechanisms are Operative)

- **MELCOR does not have a built-in phase diagram**
  - MELCOR eutectic model has been disabled
- **Order of component failure depends on component failure and melt temperatures**
  - Control blade fails first at ~1500 K
  - Canister melts next and candles at 2100 K
    - In reality, control blade material and canister wall would interact leading to possibly earlier liquefaction
    - Such interactions can lead to perforation of channel boxes
      - Currently not modeled in MELCOR
  - Fuel rods fail by 2600 K
- **Solid $UO_2$ transport with candling Zr**
  - Fractional proportion to its existing fraction in a component
  - 20%




Sandia National Laboratories

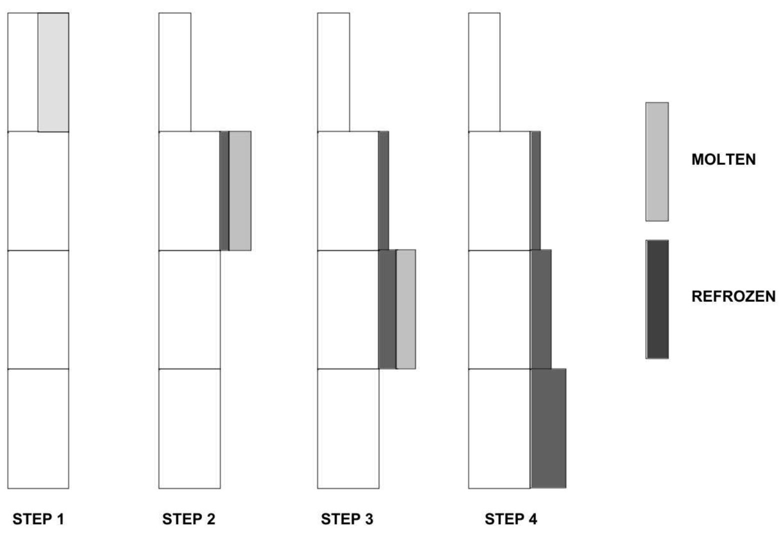
# COR Degradation Models

- **Ballooning Model**
  - There is no comprehensive model for clad ballooning in the code though MELCOR provides limited capabilities for simulating the effects.
    - Gap release model
      - Gap release at user temperature (1173 K default)
- **Candling**
  - Thermal-hydraulic based
    - (does not account for viscosity or surface tension)
    - Does not have a separate field (temperature)
  - Simple holdup model for melt inside an oxide shell
  - Formation of blockages from refrozen material
- **Formation of Particulate debris**
  - Failure temperature / component thickness / CF / support structures
  - Clad optional time at temperature modeling (best practice)
  - Downward relocation of (axial and radial) by gravitational settling
    - not modeled mechanistically but through a logical sequence of processes through consideration of volume, porosity, and support constraints.
    - Time constants associated with leveling
    - Fall velocity that limits axial debris relocation rates
  - Support structure modeling for COR components leads to failure of supported intact components when support structure is lost
- **Molten Pool Modeling**
  - Forms when downward candling molten material reaches a blockage and still has superheat
    - Settling similar to particulate debris but particulate debris displaces molten pool
    - Time constants associated with leveling
    - Fall velocity that limits axial debris relocation rates

Sandia National Laboratories

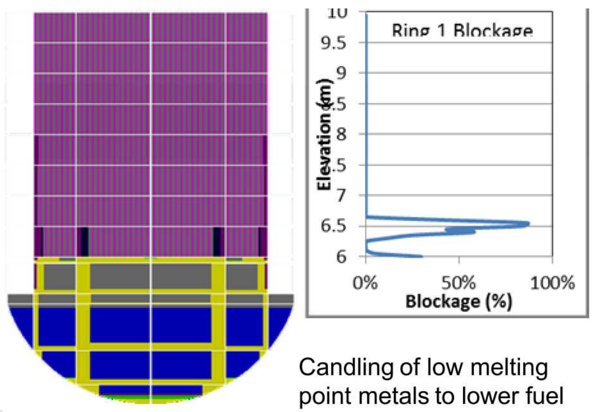
# Downward Relocation of Molten Material

- Candling - Downward flow of molten core materials
  - Subsequent refreezing (creation of ‘conglomerate’)
  - Blockage (creation of molten pool)
  - Solid material transport of secondary materials
    - Thin oxide shells or dissolution of UO2 by molten Zr
- Semi-mechanistic
  - Based on fundamental heat transfer principles
  - Assumptions
    - Steady generation and flow of molten material
      - Does not solve a momentum equation for velocity
      - All material generated in a time step reaches its final destination in that step
        - » There is no separate field for conglomerate and must equilibrate with a component
      - relatively independent of time step history
    - Molten material is held up behind oxide shell or retained behind blockage.
      - For breakaway melt, assumption of steady generation no longer valid
    - Freezes on originating component or alternate component



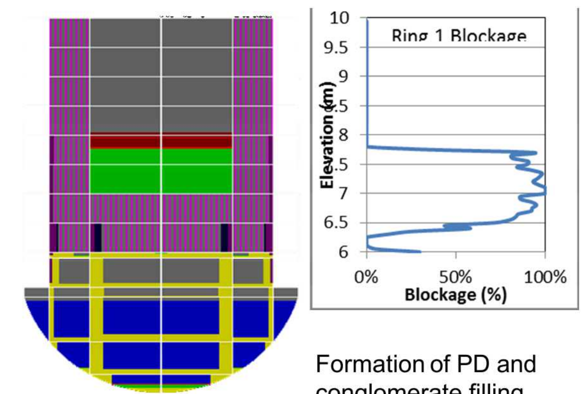

Sandia National Laboratories

# Sub-Grid Model Prediction of Blockages



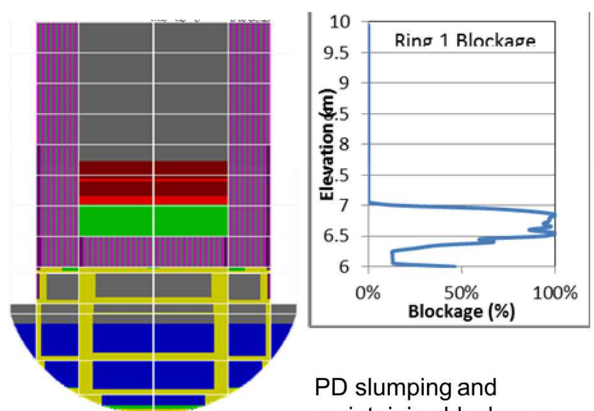

1998 (sec)

Candling of low melting point metals to lower fuel rods



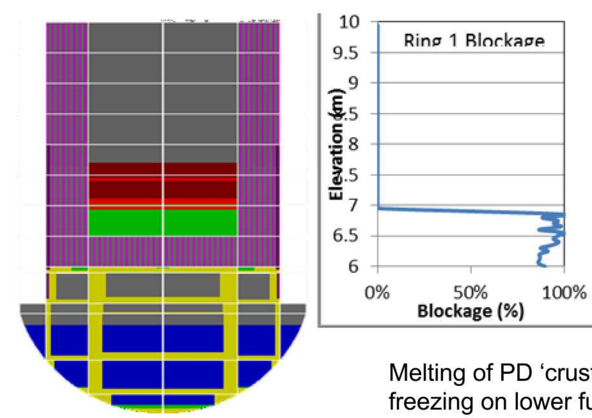

2008 (sec)

Formation of PD and conglomerate filling interstitials




2414 (sec)

PD slumping and maintaining blockages




2462 (sec)

Melting of PD 'crust' and freezing on lower fuel rods

Sandia National Laboratories

# MELCOR Core Modeling
# Supporting Structures

- **Supporting structure can support itself, other components (including particulate debris)**
- **There are five named options for basic model**
  - 'PLATE', 'PLATEG', 'PLATEB', 'COLUMN', and 'ENDCOL'
  - Each has different properties, 'PLATEG' is default
- **Two classes of failure models**
  - Parametric, as in versions before 1.8.5 (default)
    - Failure on maximum temperature (default, at 1273.15 K)
    - Failure defined by value of a LOGICAL control function
  - Stress-based structural models
    - Load and stress calculations depend on basic model
      - Engineering handbook equations, based on simple parameters
    - Failure by creep rupture, yielding, or buckling (COLUMN)

Sandia National Laboratories

# Supporting Structure Models

| | PLATE | PLATEG | PLATEB | COLUMN |
|---|---|---|---|---|
| **Typical Application** | PWR edge supported plate | PWR grid support | BWR | BWR CRGTs |
| **Supported Components** | - itself<br>- fuel assemblies<br>- particulate debris | - itself<br>- fuel assemblies<br>- particulate debris | - itself<br>- particulate debris | - columns above<br>- Carries transferred load of fuel assemblies |
| **Dependencies** | Outer rings support inner rings<br><br>Outermost ring is self-supporting | Rings fail independently | Rings fail independently | Upper columns and any transferred loads<br>Bottom ring is self-supporting |
| **Disposition at failure** | On failure in a ring, 'PLATE' and everything supported by it (including inner rings) *collapses as particulate debris* | On failure in a ring, supported components and particulate collapse, but *'PLATEG' remains in place until it melts* | On failure in a ring, supported particulate collapses, but fuel assemblies remain supported by CRGTs, and *'PLATEB' remains in place until it melts* | On failure in a ring, 'COLUMN' and everything supported by it *collapses as particulate debris* |

Sandia National Laboratories

# Mechanical Failure of Components (Formation of Particulate Debris)

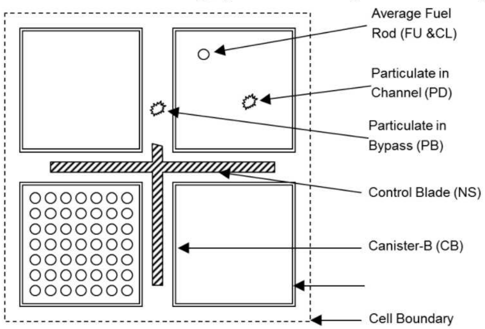
- **Particulate debris**
  - Channel and Bypass
  - Debris Behavior
  - Debris Porosity and Surface Area
  - Debris Exclusion :
- **Formation from failed fuel rods:**
  - Failure of oxidized rods
  - Failure of unoxidized fuel rods
    - Inert environment or candling of all ZrO2
    - Metal thickness < DRCLMN
  - Or failure by control function
    - Possible failure based on a cumulative damage function)
- **From Failure of BWR fuel canisters (channel box)**
  - Metal thickness < DRCLMN or
  - Temperature > canister oxide melt point
  - Or failure by control function

- **Molten materials can freeze in the pores (as conglomerate debris), reducing the porosity**
  - Thermal equilibrium between 'Intact' PD and conglomerate
- **Geometric considerations may exclude solid particulate from volume available to fluids**
  - Too large to occupy spaces between intact rods, canisters

Sandia National Laboratories

# Particulate Debris Characteristics

- **Porosity of particulate debris**
  - 0.4 (defined by elevation)
- **Particulate debris equivalent diameter**
  - Core 0.01 m
  - Lower Plenum 0.002 m
    - Tuned to get appropriate end-of-pour debris temperature.
    - 2mm based on FARO fragmented debris size.
- **Particulate debris excluded from spaces**
  - Between fuel rods and the bladed bypass in BWR
    - Melt is allowed to relocate into interstitials and candle
  - In unbladed portion of bypass (BWR) when canister present
  - In bladed portion of bypass (BWR) when blade is present



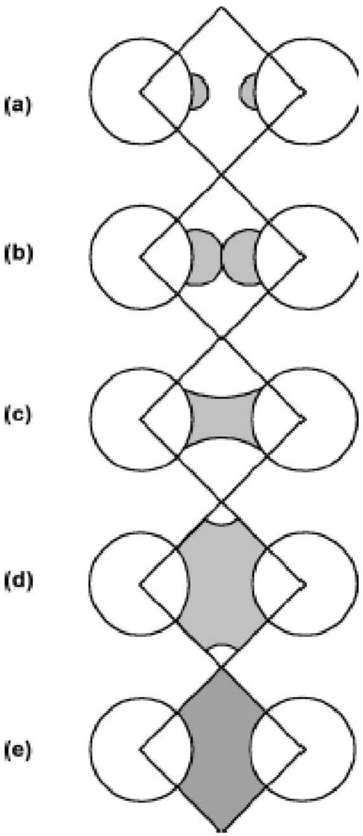

Sandia National Laboratories

# Evolving Surface Areas During Core Degradation

- **Particulate debris surface areas**

$$A_{s,pd} = \frac{6\ V_{px}}{D_{px}}$$

- **Surface area changes from freezing conglomerate**
  - **Assumption of rivulets freezing in rod lattice**
    - During the first stage, the surface area of the conglomerate debris grows as the square root of its volume up to some critical volume.
    - During the third stage, beyond some critical volume, the surface area of the conglomerate debris decreases as the square root of the empty volume
    - During the second stage, the surface area of the conglomerate debris is interpolated linearly with volume between $A^{c1}$ and $A^{c2}$.
  - **Applied to particulate debris geometry**
    - **Alternate model developed but not validated or implemented by default**



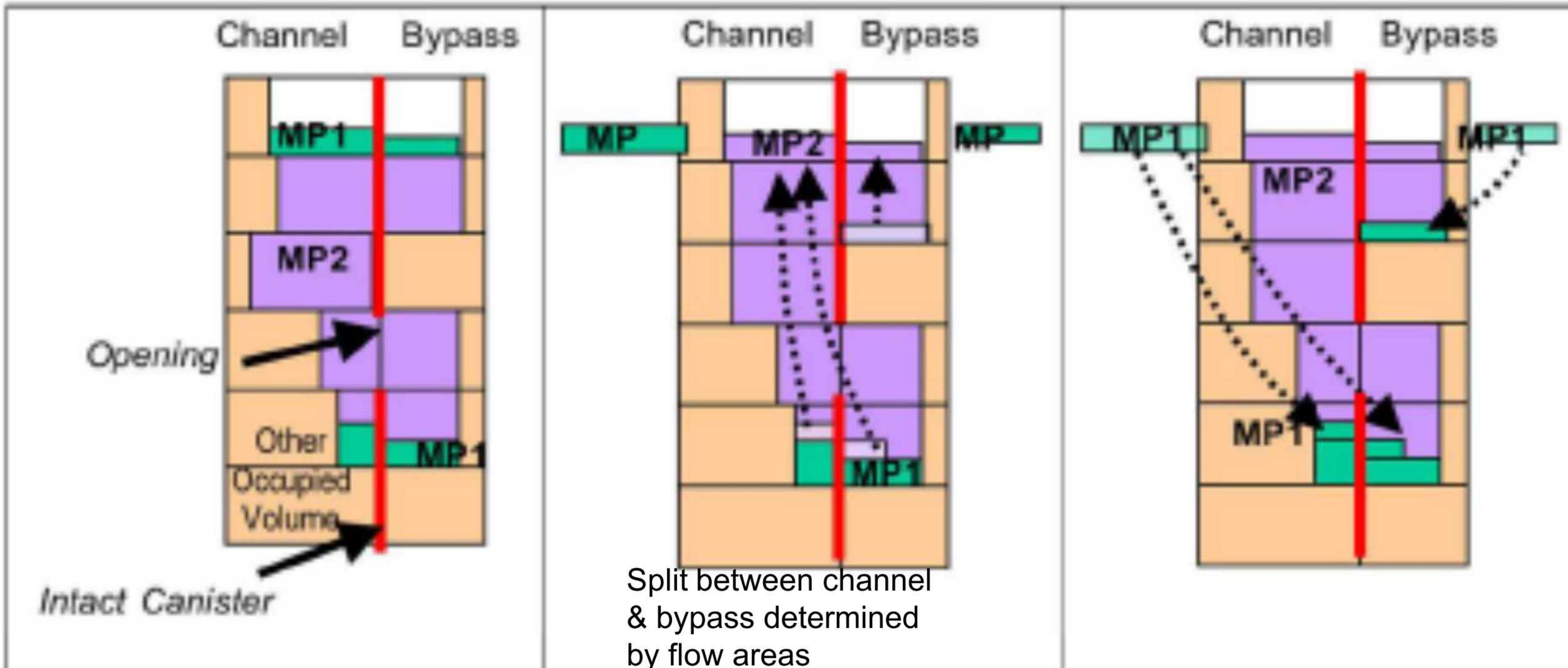

Sandia National Laboratories

# Gravitational Settling of PD and MP components

- **Gravitational settling occurs at constant velocity (VFALL) for both particulate debris and molten pool**
  - PD displaces MP
- **Each ring is calculated separately, starting at the center (radial spreading occurs later)**
  - Calculation proceeds from the bottom up
    - Determine how far source mass can move in time step
      - Limited by available space and support
    - Moves mass from source to that level and above
    - Moves up to next source cell
  - Distinction between channel and bypass
    - PD stays in channel & PB stays in bypass
  - Relocation to elevation where channel box has failed,
    - PD & PB are mixed
  - Relocation from an elevation where channel box has failed to one where it hasn't
    - PD & PB split based on available cross-sectional area

Sandia National Laboratories

# Displacement of Molten Pool by PD during Gravitational Settling



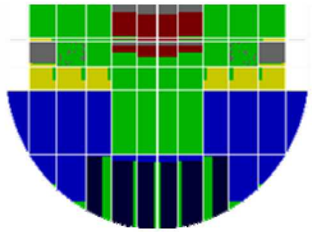

| Overall: Configuration at start of the time step | Step 1: Movement of MP2 upward into vacated MP1 volume | Step 2: Movement of MP1 downward into vacated MP2 volume |
|---|---|---|

# Radial Spreading of Debris

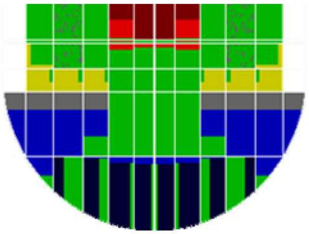
- Two radial relocation models. Both models are intended to simulate the gravitational leveling between adjacent core rings that tends to equalize the hydrostatic head in a fluid medium.
  1. Relocation of molten core material that still exists following the candling/refreezing algorithm.
     - Ad hoc time constant for relocation is 60 s (C1020(2))

$$V_{rel} = V_{eq} \left[1 - \exp\left(-\Delta t_c / \tau_{spr}\right)\right]$$

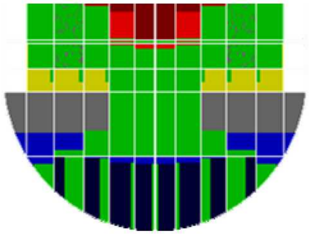
  2. Relocation of particulate debris, is essentially similar.
     - Ad hoc time constant for relocation is 360 s (C1020(1))
  - Particulate debris is permitted to displace molten pool material in adjacent rings, and molten material will backfill volume previously occupied by slumping solid particulate debris.
  - **Must take into account the volume vs elevation relation for cells adjacent to lower head**



20040 (sec)



20820 (sec)

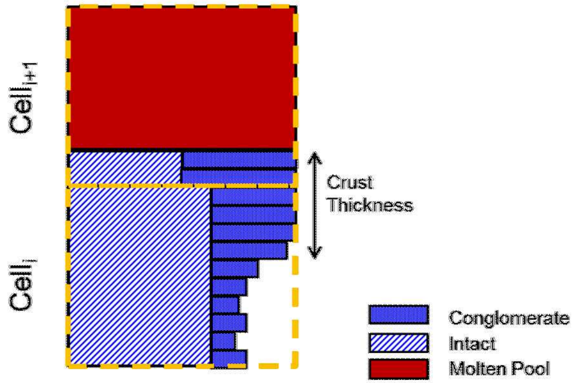


21540 (sec)

Sandia National Laboratories

# MELCOR Crust

- **There is no separate component to model crust**
  - Crust is represented as PD component
  - No distinct temperature for crust
  - Crust thickness is inferred from sub-grid model
- **Blockage associated with 'crust' obstructs downward relocation of molten pool**
- **Radial Crust**
  - Crust calculated for cells adjacent to lower head
    - intact PD is always available to spreading routine
    - Fraction of conglomerate associated with crust is frozen to lower head
  - No radial crust modeled for molten pool in upper core
    - Time constant for radial spreading of molten pool component into fuel rod region is 10 times longer than elsewhere



# MELCOR Modeling Experience in Re-flood Conditions


Presented by
Larry Humphries

Tokyo, Japan
November 4, 2015

Sandia National Laboratories

# Axial Conduction

- **Like components in adjacent axial cells**
- **Plate supporting structure and all components supported by it**
- **Component and particulate debris in adjacent cells if**
  - **component exists in only one of the two adjacent cells**
  - **physical contact between debris and component is predicted.**
    - **assumed if the debris resides in the overlying cell where it is presumed to rest on components in the underlying cell**
- **Heat transfer from convecting molten pool components handled separately**

$$q_{ij} = K_{eff}\left(T_i - T_j\right)$$

$$K_{eff} = \frac{1}{\frac{1}{K_i} + \frac{1}{K_j}}$$

$$K_i = \frac{k_i A_i}{\Delta x_i}$$

$$A_i = \frac{V_{tot,comp,i}}{\Delta z_i}$$

$$\Delta x_i = \tfrac{1}{2}\Delta z_i$$

# Axial Conduction – Quench Front

- **Three temperature regions of interest**
  - **above the pool surface,**
  - **unquenched below pool surface,**
  - **below quench front,**
- **Modeled as**
  - **two temperature regions and**
  - **three regions of heat transfer**
- **Details within the quench front are not modeled**

Cold (Quenched) region:

$$\frac{d}{dt}\left(x_c C T_c\right) = x_c\left[\dot{Q} - h_c A\left(T_c - T_{f,c}\right)\right] + \frac{C}{L} v_q T_c$$

Submerged (Un-quenched) region:

$$0 = k\frac{V}{L}\left.\frac{\partial T}{\partial z}\right|_{q+} - x^* h^* A\left(T^* - T_{f,q}\right)$$

Hot (Un-submerged) region:

$$\frac{d}{dt}\left(x_h C T_h\right) = -k\frac{V}{L}\left.\frac{\partial T}{\partial z}\right|_{q+} + x_h\left[\dot{Q} - h_h A\left(T_h - T_{f,h}\right)\right] - \frac{C}{L} v_q T_c$$

# Quench Front Velocity

- **Quench front velocity, $u^*$, determined by correlation**
  - **extended to allow for the unquenching of surfaces with large internal heat sources, resulting in regression of the quench front**
- **Uses COR and CVH data to calculate a velocity**
- **Energy changes implied by front movement used to define terms in CVH and COR energy balance**

Dimensionles Quench Velocity (Peclet Number)

$$Pe = u^* = \frac{u\delta}{\alpha}$$

Dua –Tien Correlation †

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

where

$$\overline{B} = Bi\left(1 - \Theta\right)^2 / \Theta$$

Biot Number

$$Bi = \frac{h^*\delta}{k}$$

Dimensionless Temperature

$$\Theta = \frac{T_h - T_{sat}}{T_{Q,max} - T_{sat}}$$

Note: • $\delta$ is the volume of the component divided by its surface area.
• Items in red are model parameters (next slide)

†Dua and Tien
Intl. J. Heat and Mass Transfer 20l, pp 174-176 (1977)

Sandia National Laboratories

# MELCOR Quench Model Parameters

- **SC1260(1)**
  - 600 K
  - $\Delta T_{Q,max}$
- **SC1260(2)**
  - 40.0 K
  - $\Delta T_{Q,min}$
- **SC1260(3)**
  - $1.5 \times 10^5$ W/m$^2$K
  - $h^*$
- **SC1260(4)**
  - 125.0 W/m$^2$K
  - $h_{pre}$

- **$T_{Q,max}$ is the maximum surface temperature against which the quench front can advance**

$$T_{Q,max} = T_{sat} + \Delta T_{Q,max}$$

- **$T_{Q,min}$ is the minimum surface temperature against which the quench front can advance**

$$T_{Q,min} = T_{sat} + \Delta T_{Q,min}$$

- **Heat transfer coefficient associated with the quench front movement**
  - Used only for correlation, not for heat transfer
- **Heat transfer coefficient for unquenched, submerged surfaces**

Sandia National Laboratories

# Generalization for Receding Quench Front

Advancing Quench front

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

where

$$\overline{B} = Bi\left(1 - \Theta\right)^2 / \Theta$$

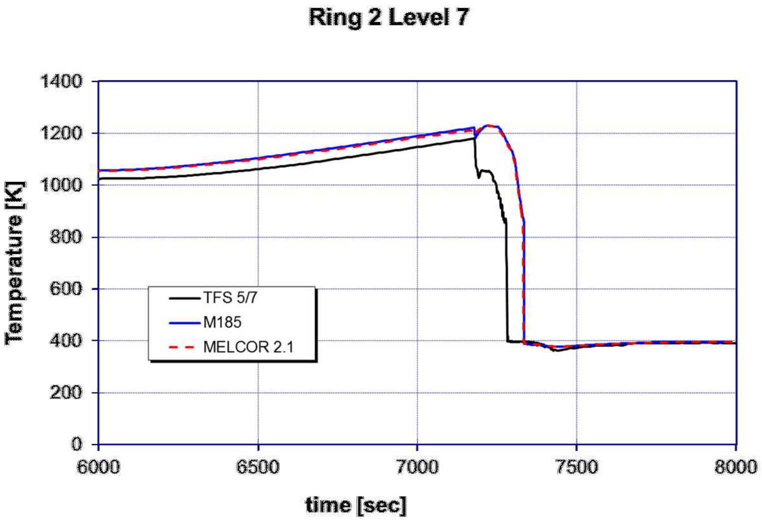
Receding Quench front

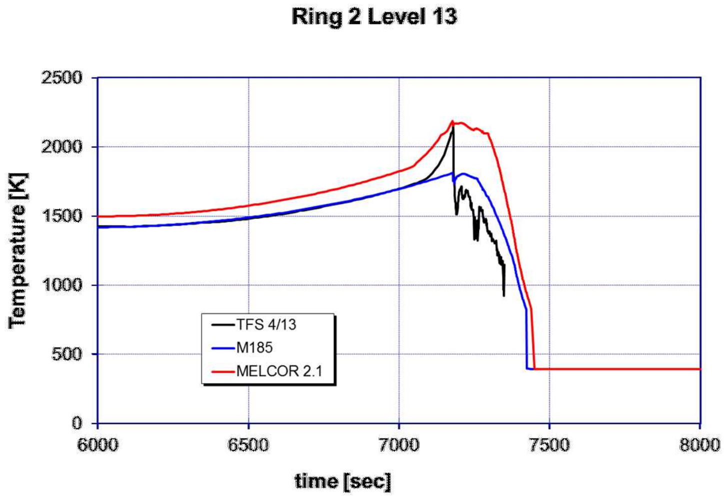
$$Pe = -|\overline{B}|^{\frac{1}{2}} = (1 - \Theta)\left(\frac{Bi}{\Theta}\right)^{1/2}$$

- **MELCOR model must allow for negative quench front velocity when $T_h > T_{q,max}$**
- **Generalization of the correlation using the thin-surface limit gives a reasonable result.**

# Predicted Transient Response to Quench Quench 06

- **Quench model has not changed since implemented in M1.8.5**
  - Changes in shroud modeling
    - New shroud component
  - Changes to electric heater models.
- **Temperature response is similar between code versions but noticeable differences**
  - Quench phase appears identical at lower elevation
  - Oxidation phase appears to be under predicted for M186 calculation.
    - Should lead to differences in hydrogen generation during quench



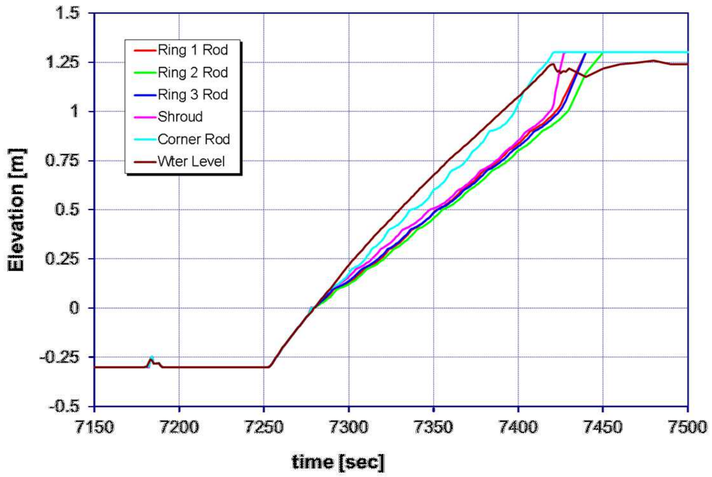




National Laboratories

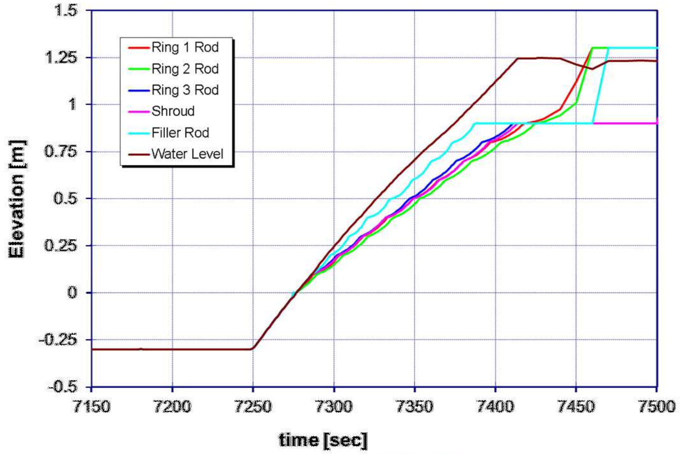
# MELCOR Calculated Quench Height QUENCH-06

- **MELCOR calculation shows the quench front lags below the water level**
- **Differences between M2.1 and M185**
  - Corner rod shows more lag in M21
  - Quench appears to stop near top of rods
- **Is it possible to extract similar trends from data?**

M185



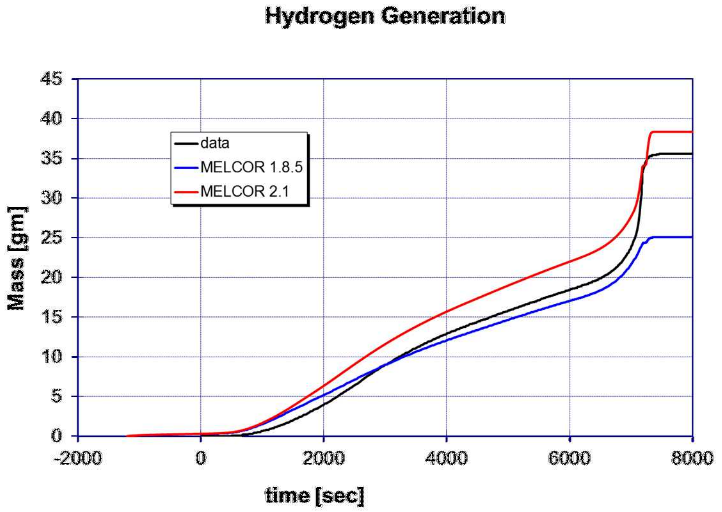

M 2.1

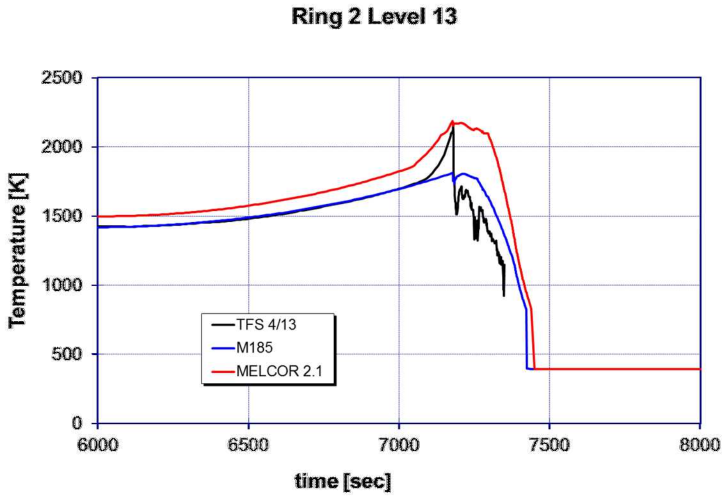



Sandia National Laboratories

# Quench 06 – Predicted Transient Response to Quench

- **Improved Hydrogen generation during quench.**
- **Improved temperature response during quench.**
- **Perhaps related to reduced energy losses to shroud**
- **This is just a first look at this validation case for M2.1**




Sandia National Laboratories

# MELCOR Core Phenomenon
# Core Fluid Flow Blockage Modeling

- **Destruction of original structures, formation of debris will alter flow resistances in core**
  - Debris bed resistance different from rod bundle resistance
    - Ergun equation is used for debris bed
      - New core blockage enhancement factor (multiplier on porosity for resistance calculation)
      - As a core cell becomes completely filled, flow resistance will approach infinity
    - Initial (intact) resistance used until then
      - Small area correction for possible conglomerate debris or changes in clad expansion from oxidation
  - Failure of BWR canisters or PWR shroud opens path between channel and bypass volumes
- **Model connects open area and resistance in a flow path to state of core in specified cells**
  - Flow can be axial or radial
  - For BWR, can restrict to channel or bypass region only
    - Can open path on failure of BWR channel box

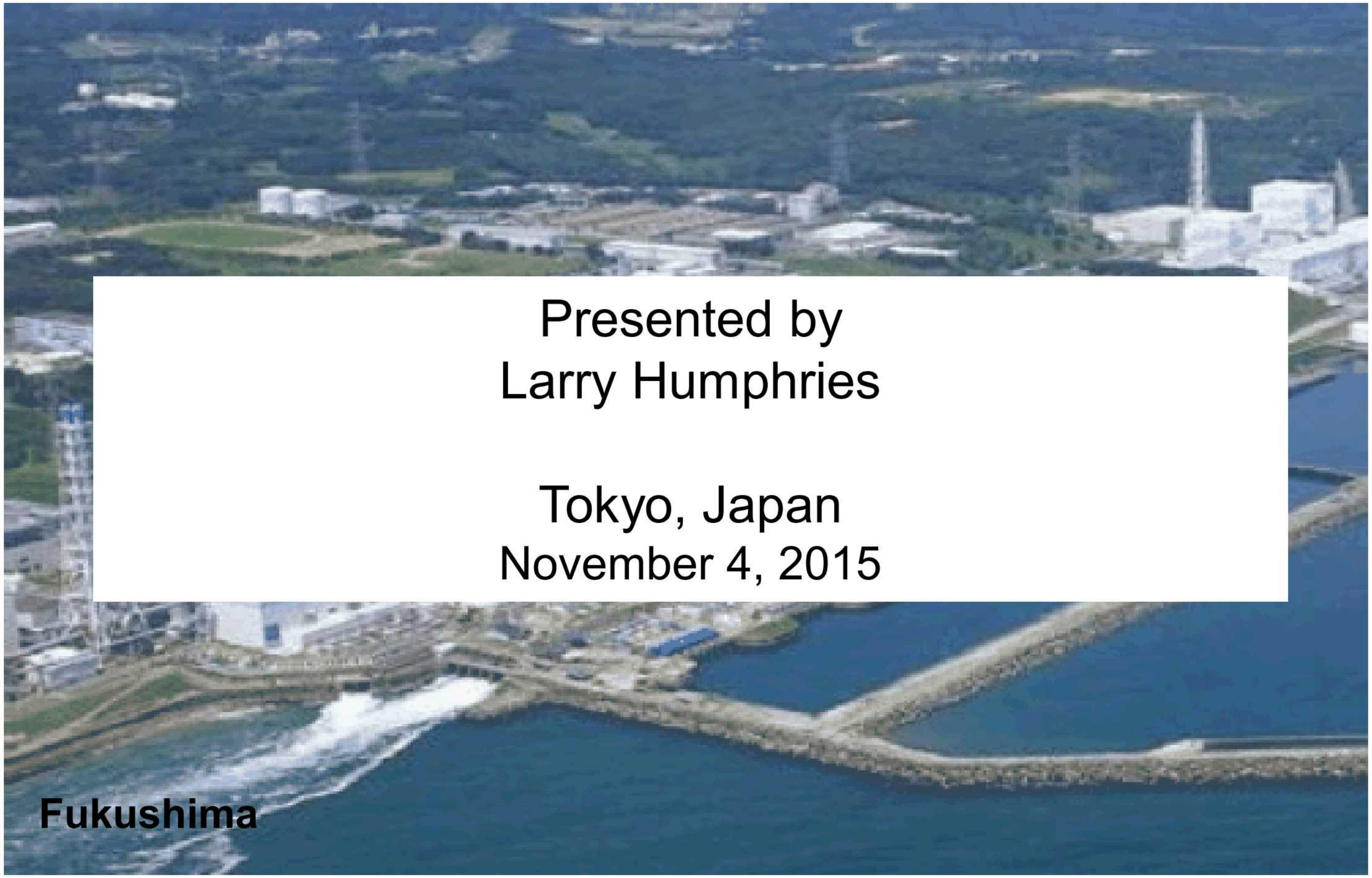
Sandia National Laboratories

# Special Considerations Limiting CV Blockage

- **SC1505(1) - Minimum porosity to be used in calculating the flow resistance in the flow blockage model.**
  - Default is 0.05 (can be modified by user) was 0.001 in M186
- **SC1505(2) - Minimum porosity to be used in calculating the area for heat transfer to fluid.**
  - Default is 0.05 (can be modified by user) was 0.001 in M186
- **SC4414(1) Minimum Hydrodynamic Volume Fraction**
  - This parameter defines a fraction of the initial hydrodynamic volume in each segment of the volume/altitude table of a control volume that will be considered as available to hydrodynamic materials. This volume is preserved, regardless of virtual volume changes resulting from relocation of non-hydrodynamic materials such as core debris.
  - Default is 0.01 (can be modified by user)
- **Implication is that blockages are not impermeable.**
  - Recognition that volume represents a large number of fuel rods for which it may be difficult to imagine complete blockage.
  - Oxidation continues as well as heat transfer

Sandia National Laboratories

# MELCOR Lower Plenum Processes



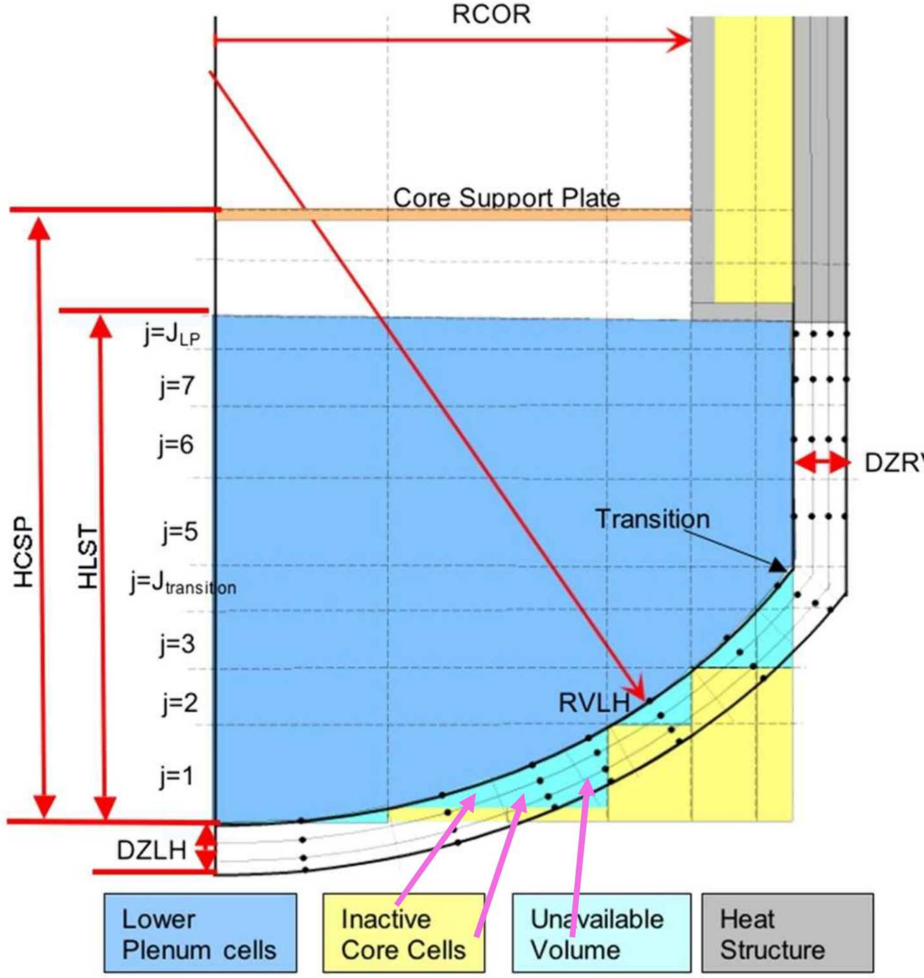

Presented by
Larry Humphries

Tokyo, Japan
November 4, 2015

Sandia National Laboratories

# MELCOR Core Modeling
# Lower Head Geometry

- Lower head defined in segments
  - Outer radius defined independently of core cells
    - Used to calculate area and inclination
  - Each communicates with core cell above, control volume outside, and adjacent segments
- Total thickness DZLH with NLH nodes
  - Default is CARBON STEEL, equally-spaced nodes
    - Can modify to add liner or insulation
- Unavailable volume
  - Cells that lie below the curved lower head surface can be specified as "Null" cells



# MELCOR Core Phenomenon
# Falling Debris Quench Model, Sequence of Events

- **Core Support Failure**
  - —Debris falls into lower plenum
  - —Falls with user defined velocity, VFALL
  - —Candling, spreading, and dissolution deactivated
- **Debris reaches pool**
  - —Surface area inferred from DHYPD
  - —Constant heat transfer coefficient (HTC) from input
- **Leading edge of debris reaches lower head**
  - —Decay factor applied to HTC to simulate reduction in heat transfer during transition from quench period to stationary period.
    - —Based on radial spreading time constant
    - —Significant continued relocation delays decay

$$f(t+\Delta t) = \min\left[1, f(t)\exp(-\Delta t/\tau_{spr}) + V_{cor}/V_{LP}\right]$$

  - —Candling, spreading, and dissolution activated

# MELCOR Core Modeling
# Supporting Structures

- **Supporting structure can support itself, other components (including particulate debris)**
  - **Load and stress calculations depend on basic model from engineering handbook equations**
  - **Failure by creep rupture, yielding, or buckling**
  - **Failure by melting**
- **In a BWR, two support structures are of particular interest**
  - ‘PLATEB’ models the core support plate
    - Supports itself and debris but not assemblies
    - Does not fail when support plate in neighboring rings fail
    - Remains in place after failing but melts
  - ‘COLUMN’ models the CRGTs
    - Supports the assemblies and canisters
    - Failure in any cell leads to failure of all contiguous COLUMN elements higher
- Other support structures available

Sandia National Laboratories

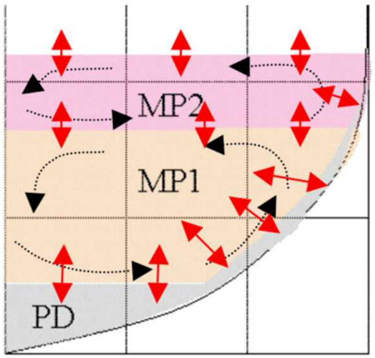
# Stationary Debris Dryout

- Stationary state assumed when decay factor < 0.01
- Debris bed dryout
  - MELCOR uses Lipinski zero- dimensional model
    - Downward flow of water and upward flow of vapor
    - At some total bed-heat flux (incipient dryout), the vapor prevents further liquid from reaching the debris.
    - Currently disabled in best practices (SOARCA)
      - Vessel failure occurred when there was still a large reservoir of water above
  - NEA/CSNI/R(2015)
    - "This benchmark showed that some "cliff-edge" effects still exist, e.g. for the quenching of a much degraded core where some codes predict success of quenching whereas other codes predict the impossibility of stopping melt progression and thus the occurrence of vessel failure."

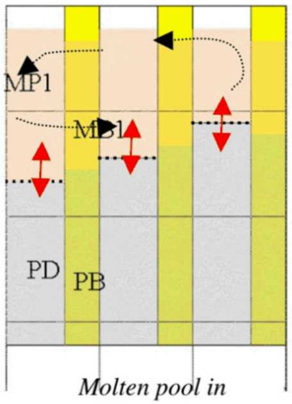
Sandia National Laboratories

# MELCOR Core Phenomenon
# Stratified Molten Pool Model

- **Treat molten pools, both in core and lower head**
  - Can contain oxidic and metallic materials
  - May be immiscible, and separate by density
  - Same approach in core and lower head
    - Requires distinguishing pool in channel from that in bypass
- **Stratified melt pool - Additional material relocation models**
  - Downward and radial flow of molten pools
  - Sinking of particulate debris in molten pool
    - Particulate displaces pool
  - Stratification of molten pools by density
    - Denser pool displace less dense
      - Currently oxide pool is assumed denser
  - Partitioning of fission products between metallic and oxidic phases
    - Can affect heat generation and natural convection in core molten debris.



*Molten pools in lower plenum*



*Molten pool in upper core*

Sandia National Laboratories

# Molten Pool Convective Heat Transfer

Energy Balance on MP1:

$$MC_{P,MP1}\frac{T^{n}_{MP1}-T^{o}_{MP1}}{\Delta t} = \dot{Q}_{MP1,decay}$$

$$-\sum_{s\in seg} h_{MP1\to s}A_s\left(T^{n}_{MP1}-T_s\right)-h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right)$$

$$-\left\langle h_{MP1-fluid}\,A_f\left(T_{MP1}-T_{fluid}\right)-\sigma\varepsilon_{eff}\,A_{up}\left(T^{4}_{MP1}-T^{4}_{ambient}\right)\right\rangle$$

Energy Balance on MP2:

$$MC_{P,MP2}\frac{dT^{n}_{MP2}}{\Delta t} = \dot{Q}_{MP2,decay}$$

$$-\sum_{s\in seg} h_{MPs\to s}A_s\left(T^{n}_{MP2}-T_s\right)+h_{MP1\to MP2}A_{1,2}\left(T^{n}_{MP1}-T^{n}_{MP2}\right)$$

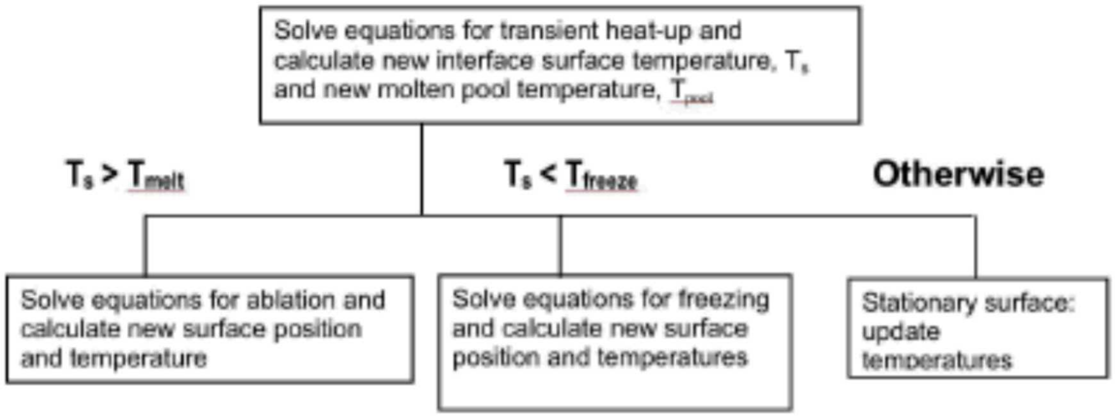
$$-h_{MP2-fluid}\,A_f\left(T^{n}_{MP2}-T_{fluid}\right)-\sigma\varepsilon_{eff}\,A_{up}\left(T^{4}_{MP2}-T^{4}_{ambient}\right)$$

- Heat Transfer coefficients from empirical Rayleigh coefficients obtained for steady state conditions correlating Ra number with internal heat generation rate
- Correlations adapted to transient conditions based on the average of the decay heat and the boundary heat losses
  - Solved recursively
  - Approaches steady state in limit
- Time constant for establishing convective currents
  - Arbitrarily set to 1 sec to smooth transition but not based on any physical significance

Sandia National Laboratories

# Integral Solution to Stefan Problem

- Convective molten pool supported by solid substrate
  - May be PD, lower head, or core support plate
  - Thermal properties vary greatly between phases
  - Temperature gradient in substrate may be highly nonlinear within the dimension of a COR cell
  - Position of the interface may move (Stefan Problem)
  - Determines crust thickness in lower plenum
- Integral model for transient calculation
  - Does not require many nodes
  - Assumes a shape for the temperature profile (quadratic) in the substrate
  - Integration of the conduction equations over the spatial domain
  - Impose convective boundary condition at interface




Sandia National Laboratories

# Lower Head Failure Mechanisms

- **Creep-rupture failure of a lower head ring occurs**

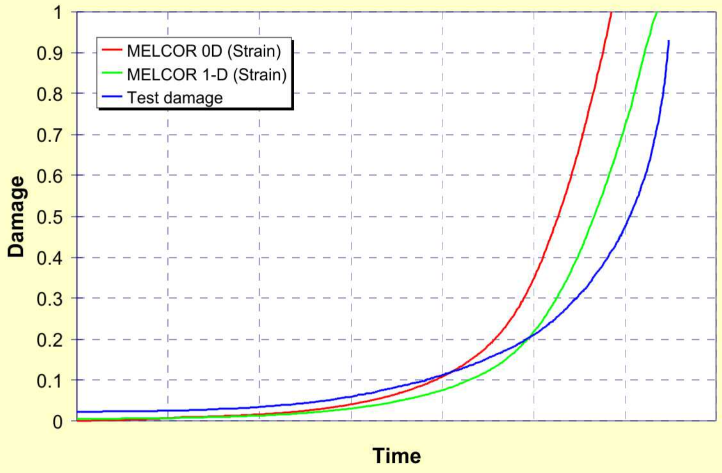
$$t_R = 10^{\left(\frac{P_{LM}}{T} - C\right)} \qquad P_{LM} = \min\left[a_1 \log_{10}(\sigma_e) + b_1, a_2 \log_{10}(\sigma_e) + b_2\right]$$

  - **2-D internal model to account for stress and temperature distribrution through the vessel**
    - **Load redistributed to cooler nodes**
  - **Failure occurs when damage = 1.0**
    - **Strain at failure is defined as 18%**
- **Penetration failure**
  - **Failure Temperature, TPFAIL, or**
  - **Control function for penetration failure**
    - **OLHF and LHF tests suggest strain-based failure criteria**
- **Overpressure from the falling-debris quench model**
  - **Default failure criterion is 20 MPa**
    - **Redefine on record** COR_LP**, but not greater than $P_{crit}$**
- **Load on vessel includes weight of debris and structures in ring above supported by vessel in addition to hydrodynamic pressure.**

Sandia National Laboratories

# MELCOR Lower Head Failure Models

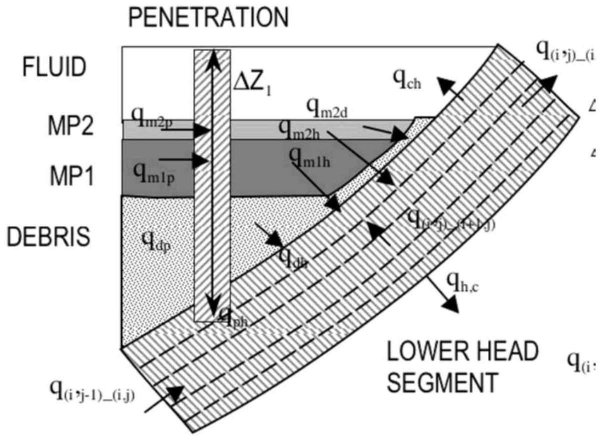
- **Failure based on Robinson's Rule, i.e., lifetime rule from Larson-Miller parameter**
- **Two models are available in MELCOR:**
  - **Zero-Dimensional Model**
    - **Default Model**
  - **One-Dimensional Model**
    - **Selected by setting sensitivity coefficient SC1600(1) = 1**
    - **Recommended Model**
  - **Part of thickness can be non-load-bearing (e.g., insulation)**
    - `NINSLH` **(from record** `COR00000`**) outer meshes, with default 0, will be excluded from the calculation**




Assessment of models with LHF and OLHF test results

# MELCOR Core Modeling
# Modeling of Lower Head Penetrations (2)

- **Each "penetration" represents the aggregate of all like penetrations in a single segment**
  - **Can have up to three distinct types in a single segment**
    - **Allows for instrumentation tubes, control rod guide tubes, and drain plugs**
  - **Can have a maximum of 19 distinct penetrations**
- **Failure defined by failure temperature or LOGICAL control function**
  - **Initial hole size, discharge coefficient for debris defined**
    - **Discharge rate calculated from Bernoulli equation**
  - **Ejection of debris may be delayed,**
  - **During debris ejection, ablation increases hole size (Pilch and Tarbell)**
    - **Ablated material is *not* added to debris**




**Curved Lower Head**

# MELCOR Core Modeling
# Vessel Failure Consequences (2)

- **Failure of penetration or lower head provides path for debris to reach cavity**
  - Threshold imposed to avoid problems in CAV package
  - No ejection until 5000 kg debris in lowest core cell (or molten material fills more than 10% of its volume)
- **Ejected debris is "handed off" to Transfer Process (TP) package**
  - Input must specify number of appropriate transfer process

```
! COR_TP defines transfer process to receive debris
!        NTPCOR is name of 'IN' transfer process or NO
COR_TP   NTPCOR
```

  - NTPCOR=0 is allowed, even though it is not an acceptable transfer process number
    - Calculation will be terminated if ejection is predicted
    - MELGEN will issue a warning to this effect



Sandia National Laboratories