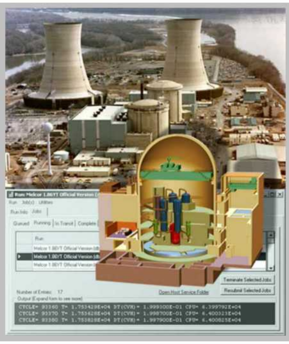
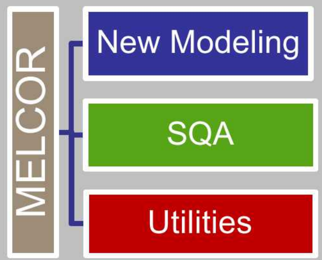
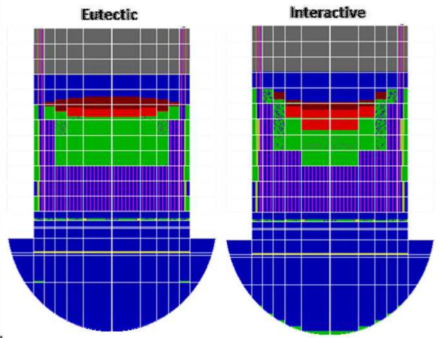
SAND2019-0531PE







MELCOR Core Degradation Overview

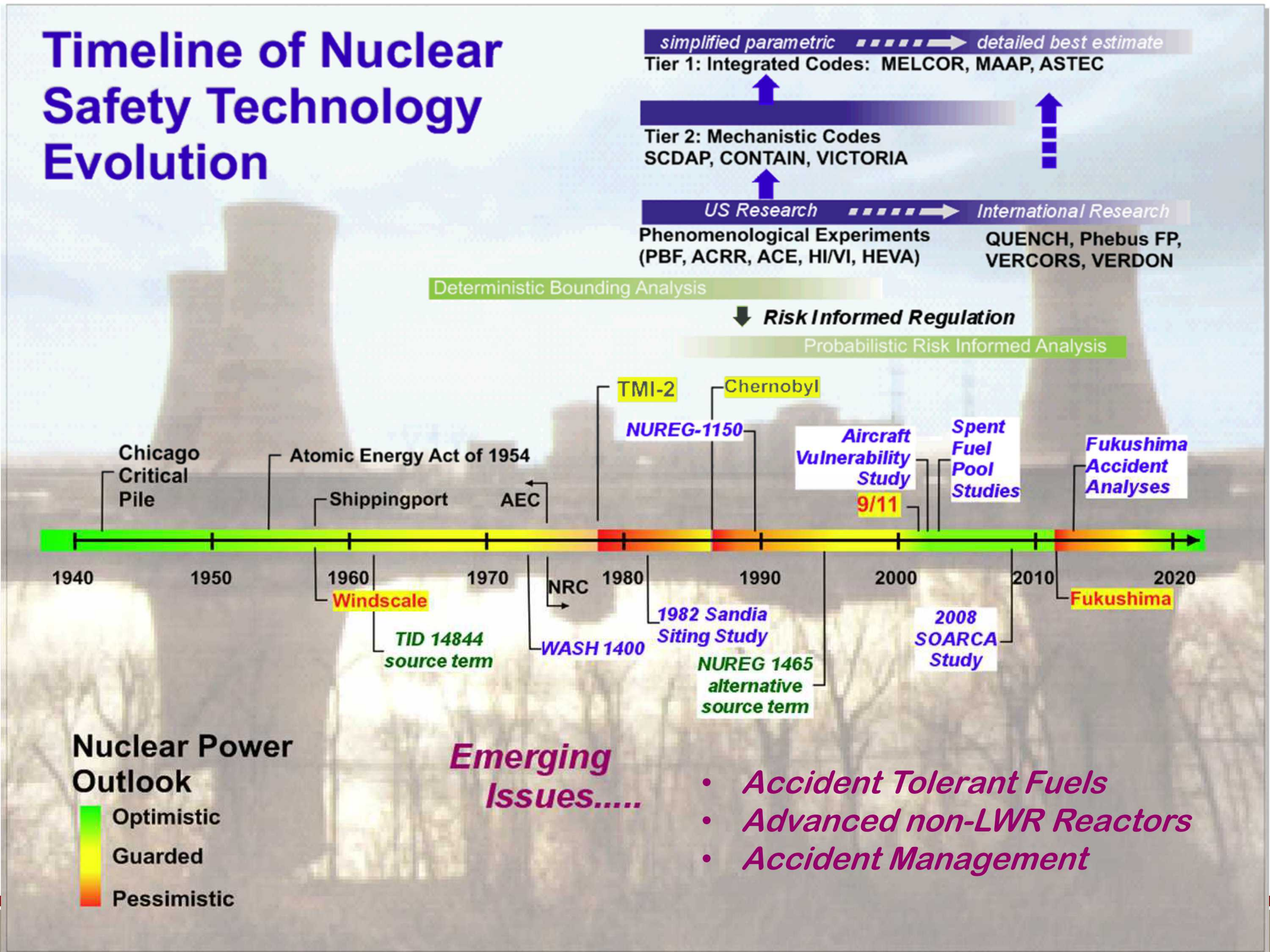
TCOFF Meetings

January 31/February 1 2019

Presented by Larry Humphries

llhumph@sandia.gov

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., , for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525

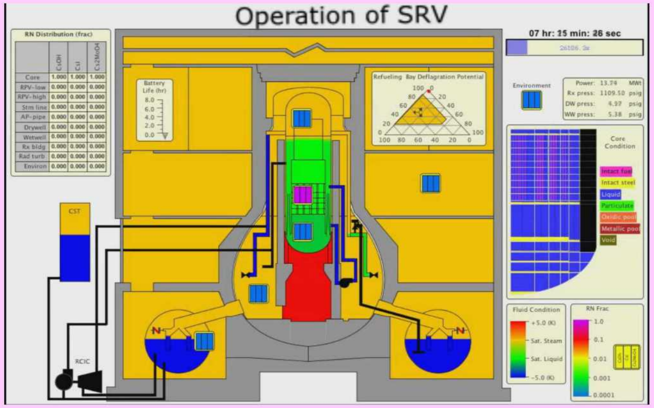


Timeline of Nuclear Safety Technology Evolution
simplified parametric
detailed best estimate
Tier 1: Integrated Codes: MELCOR, MAAP, ASTEC
Tier 2: Mechanistic Codes
SCDAP, CONTAIN, VICTORIA
US Research
International Research
Phenomenological Experiments
(PBF, ACRR, ACE, HI/VI, HEVA)
QUENCH, Phebus FP,
VERCORS, VERDON
Deterministic Bounding Analysis
Risk Informed Regulation
Probabilistic Risk Informed Analysis
TMI-2
Chernobyl
NUREG-1150
Aircraft Vulnerability Study
Spent Fuel Pool Studies
Fukushima Accident Analyses
Chicago Critical Pile
Atomic Energy Act of 1954
Shippingport
AEC
9/11
1940
1950
1960
1970
1980
1990
2000
2010
2020
NRC
Windscale
Fukushima
TID 14844 source term
WASH 1400
1982 Sandia Siting Study
NUREG 1465 alternative source term
2008 SOARCA Study
Nuclear Power Outlook
Optimistic
Guarded
Pessimistic
Emerging Issues.....
• Accident Tolerant Fuels
• Advanced non-LWR Reactors
• Accident Management

Requirements of an Integrated Severe Accident Code

- Fully Integrated, multi-physics engineering-level code
  - Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings;
  - Core heat-up, degradation, and relocation;
  - Core-concrete attack;
  - Hydrogen production, transport, and combustion;
  - Fission product release and transport behavior
- Diverse Application
  - Multiple 'CORE' designs
  - User constructs models from basic constructs
  - Adaptability to new or non-traditional reactor designs
    - ATR, Naval Reactors, VVER
- Validated physical models
  - ISPs, benchmarks, experiments, accidents
- Uncertainty Analysis & Dynamic PRA
  - Relatively fast-running
  - Reliable code
  - Access to modeling parameters
- User Convenience
  - Windows/Linux versions
  - Utilities for constructing input decks (GUI)
  - Capabilities for post-processing, visualization
  - Extensive documentation

Multi- Physics

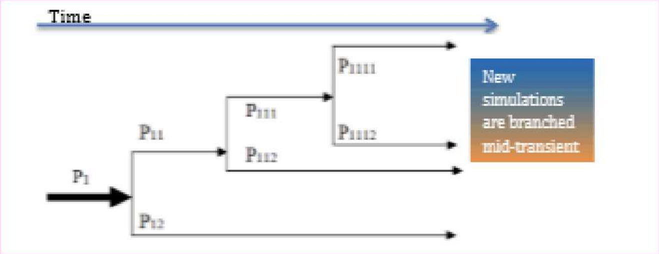


SOARCA LTSBO

Diverse Application

Advanced Test Reactor

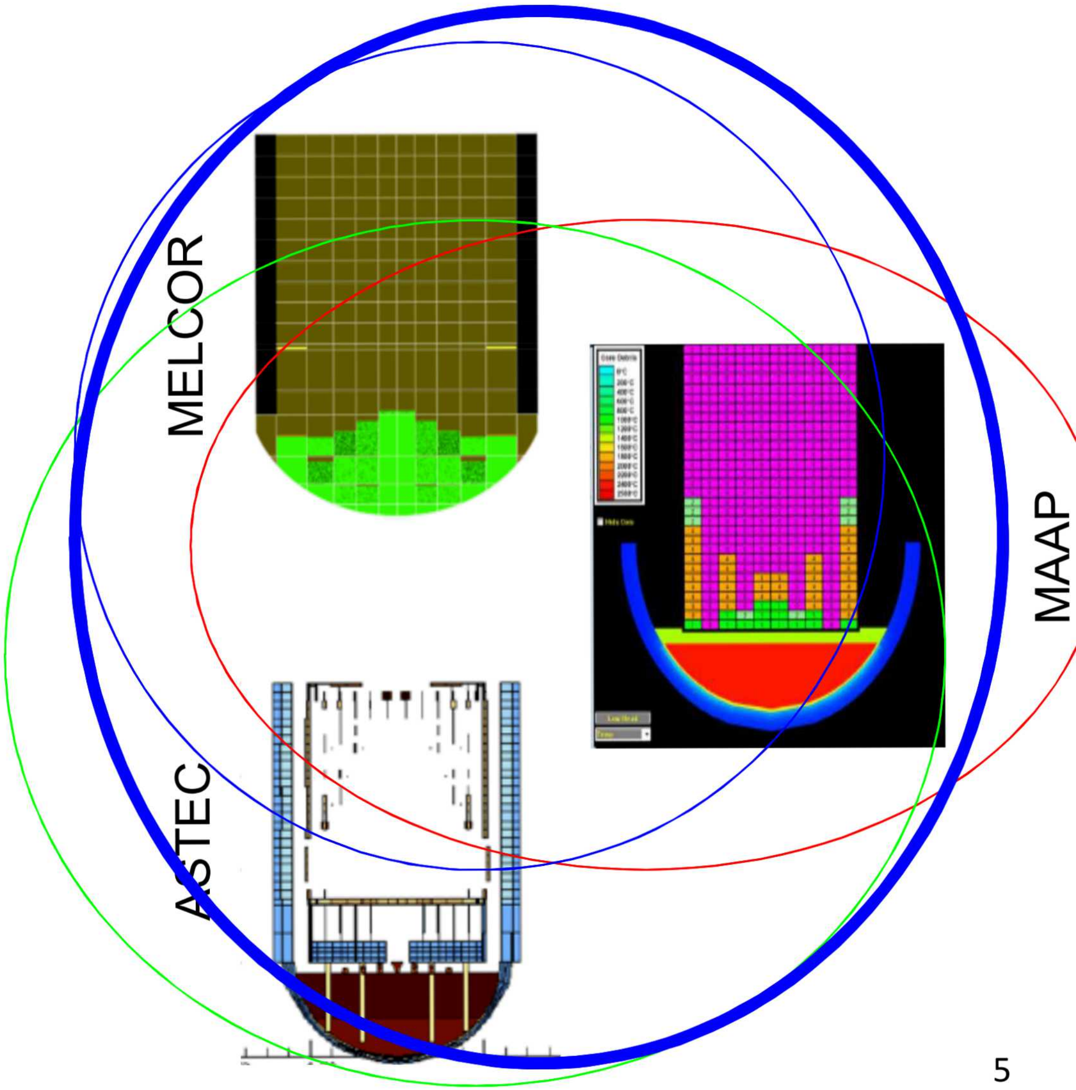
Uncertainty & Dynamic PRA



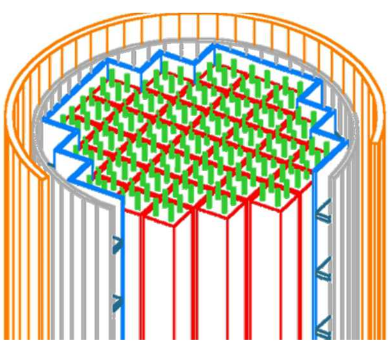
Dynamic Event Tree

Degradation Model Uncertainty

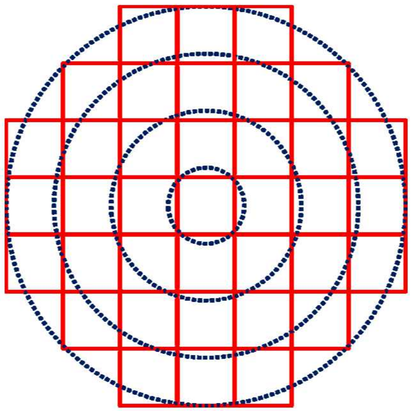
- Where validation data exists, codes give reasonable agreement
- During core degradation, codes diverge
  - Distinct core degradation models
    - ASTEC – Melting only
    - MELCOR – minimum porosity
    - MAAP – molten-pool crust



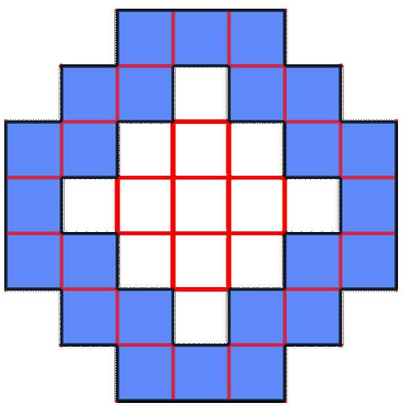
MELCOR Core Modeling
Core Nodalization



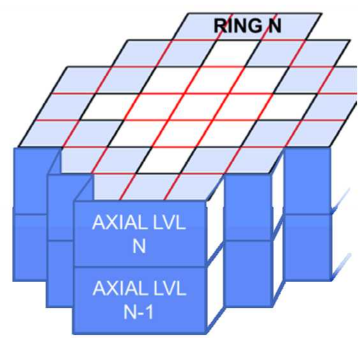
Core Geometry



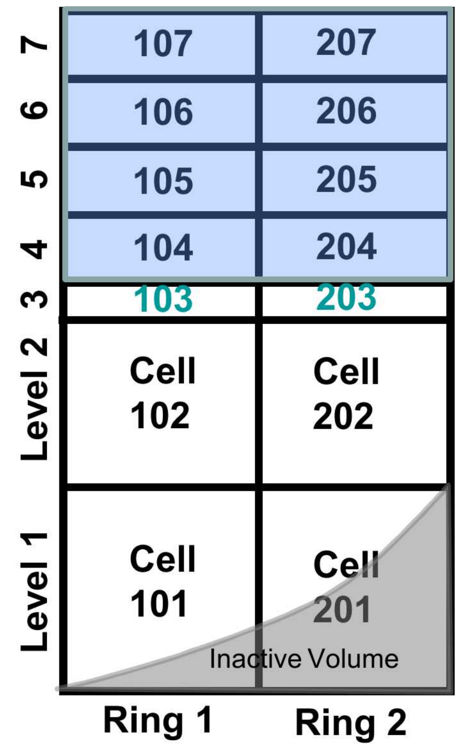
Conceptual Rings



Modeled 'rings'

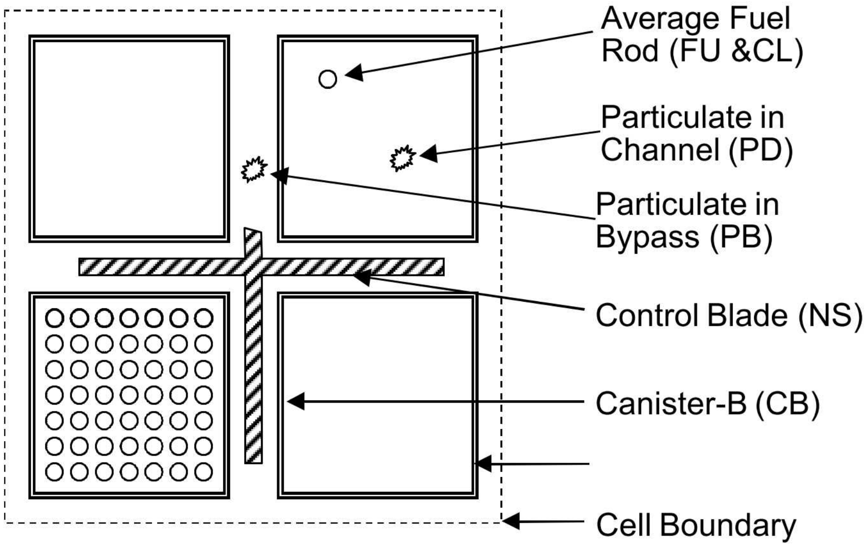


- Core and lower plenum divided axially and radially into cells

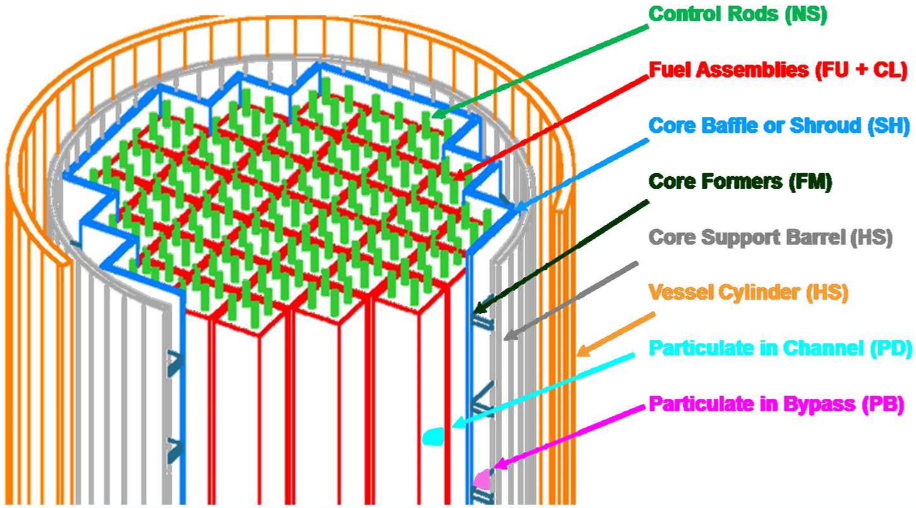


MELCOR Core Modeling
Visualization of Core Components

- BWR



- PWR

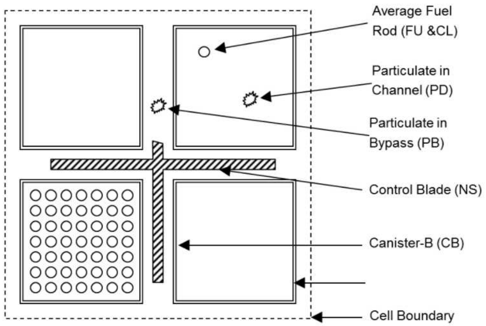


MELCOR Core Modeling
Supporting Structures

- 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)

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



MELCOR Core Modeling
Core Components

Sandia National Laboratories

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.

Location of COR Components

Reactor Type	Volume: CH Surface: CH Single-sided	Volume: CH Surface: CH/BY 2-sided	Volume BY Surface BY 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

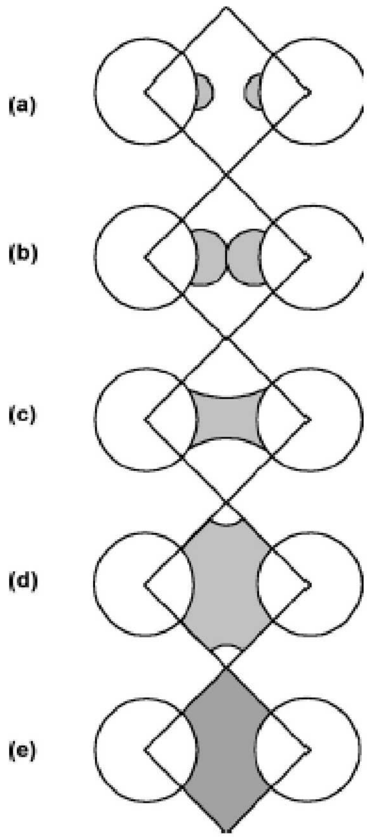
- Each component has an intact mass field
  - User typically defines intact masses only (before onset of core degradation)
  - User also defines surface areas of intact components
  - Intact material has never melted (though it may have resulted from failure of intact component, i.e., intact particulate 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

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



MELCOR Core Modeling
Core Flow Blockage Model Input

Sandia National Laboratories

FL_BLK OPTION ICORCR1 ICORCR2 ICORCA1 ICORCA2 FLMPTY

OPTION - Flow geometry for this path

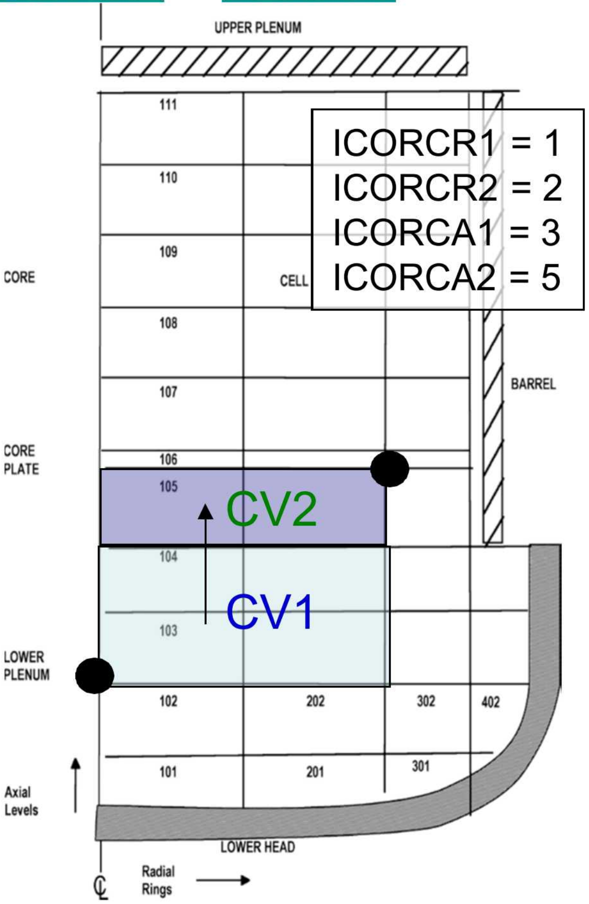
Flow geometry to be modeled in this path.

'AXIAL', 'AXIAL-C', 'AXIAL-B', 'RADIAL', 'RADIAL-C', 'RADIAL-B', 'CHANNEL-BOX', OR 'CORE-SHROUD'

(type = character, default = none, units = dimensionless)

CHANNEL-BOX

Connection between channel and bypass of a BWR that opens when the channel box fails.



Note: The FL_BLK record table is analogous to the FLnnBK record type.

Oxidation Models - General

- Objects that can oxidize
  - COR components
    - Metals include Zr, SS, and B4C
  - Debris in CAV package
- 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
- Available Oxidation Models
  - Cathcart-Pawel/Urbanic Heidrick
  - Leistikov-Schanz/Prater-Courtright
  - Leistikov
  - Urbanic-Heidrick
  - Sokolov

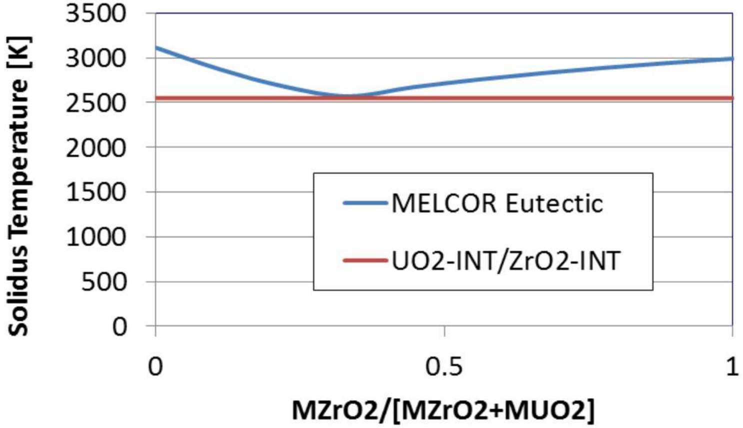
MELCOR Effective Melt Temperature

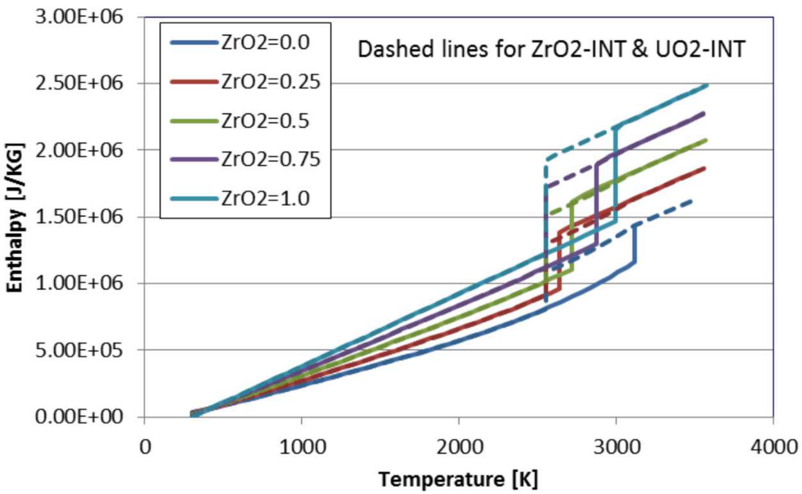
UO2-INT/ZRO2-INT

- Melt temperature for UO2 & ZrO2 is the same for intact materials as it is for conglomerate.
- Does not depend on composition
- **With this model it was impossible to enforce lower effective melting temperature through default in source code**
  - User was required to modify UO2-INT and ZRO2-INT melt temperatures through input

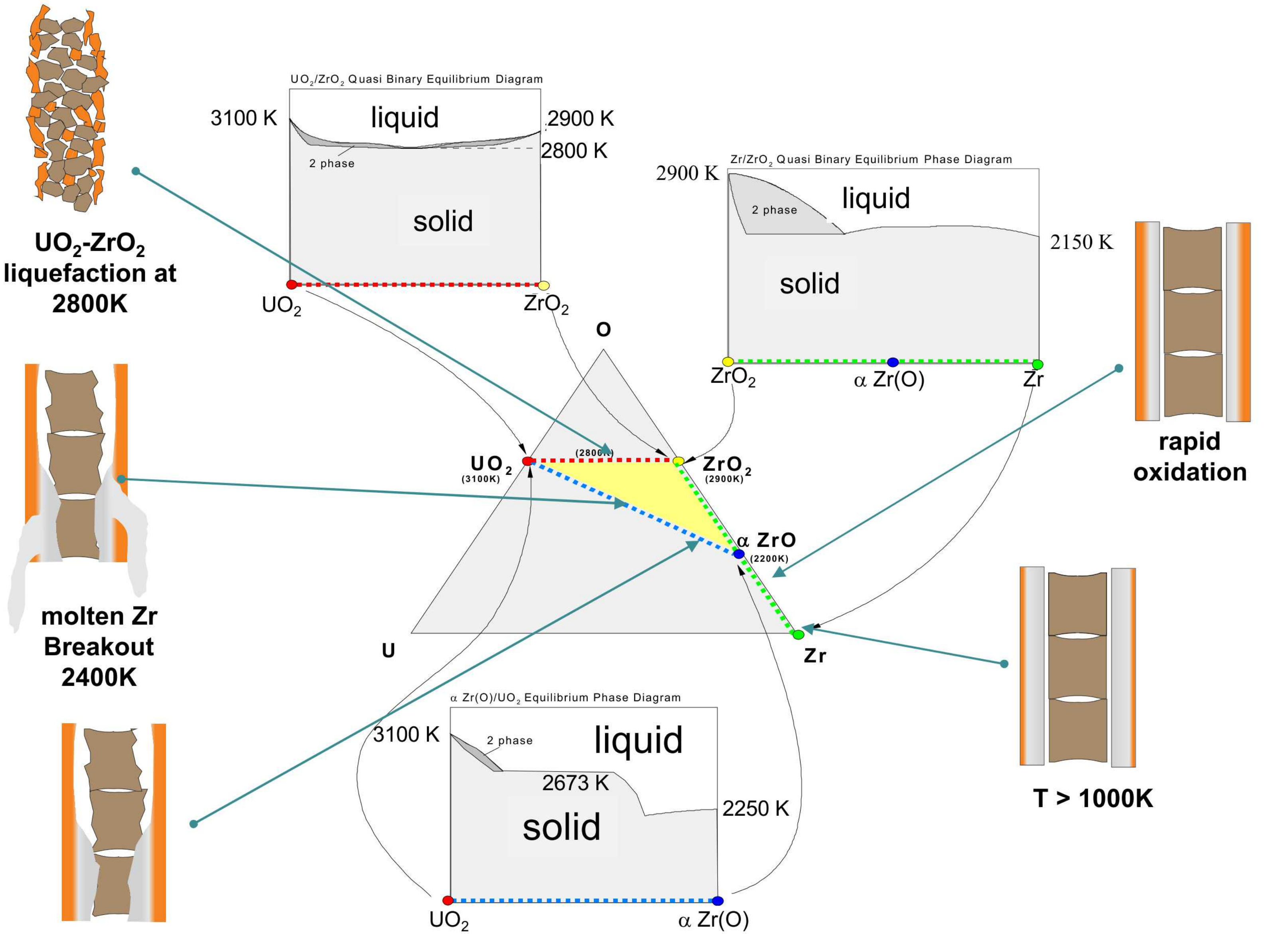
Eutectic Model

- **Melt temperature of intact material uses elemental melting points while conglomerate uses eutectic temperature**
  - Liquefaction of solids in contact from calculated rates
- Melt temperature dependent on composition





U/Zr/O Ternary Phase Diagrams



Eutectic Mixtures

- Eutectic mixture composition
  - Conglomerate debris materials associated with any component are treated as part of a coherent mixture.
    - Some materials are treated as mutually miscible
    - Others are considered mutually immiscible
      - treated as they are when the model is inactive (i.e. they melt and relocate independently of one another).
  - As currently implemented, when the model is active all the materials are part of the miscible mixture.
- Formation of eutectic mixtures
  - Normal liquid formed when an intact solid reaches its melting point
  - Eutectic reaction product formed when two intact solids in mechanical contact within a core component reach their eutectic temperature
  - Dissolution of an intact solid by an existing liquid mixture in the same core cell
    - Example: the dissolution of UO_2 fuel by the liquid mixture associated with the cladding in the same core cell as the fuel.
    - At most two distinct solids
      - Hierarchy for dissolution

Dissolution of solids by molten mixture

- Dissolution will proceed until the addition of solid lowers the updated gross mixture enthalpy to the liquidus enthalpy associated with the updated mixture composition
- Or until the parabolic rate limitation associated with the dissolution reaction has been exceeded for the given timestep.
- The solution is iterative

Component	Solids Dissolved by Mixture
Cladding	UO2 from intact fuel
	ZrO2 from intact cladding
Canister	ZrO2 from intact canister
	ZrO2 from intact cladding
	UO2 from intact fuel
Other structure SS or NS (steel only)	steel oxide from the same other structure
Other structure NS (BWR control rod)	steel oxide from the same other structure
	ZrO2 from intact canister
	Zr from intact canister
Other structure NS (PWR control rod)	steel oxide from the same other structure
	Zr from the same other structure
	ZrO2 from intact cladding
	UO2 from intact fuel
Particulate debris	UO2 from particulate debris
	ZrO2 from particulate debris
	ZrO2 from intact cladding
	UO2 from intact fuel

$$(x_j^f)^2 = (x_j^i)^2 + K_j \Delta t$$

$$K_j = A_j \exp\left(B_j / T\right)$$

where

x_j^f = final mass fraction of material j,

x_j^i = initial mass fraction of material j,

Δt = timestep (s), and

$A_{ZrO2} = 1.47 \times 10^{14}$ $A_{UO2} = 1.02 \times 10^{15}$

$B_{ZrO2} = 8.01 \times 10^{4}$ $B_{UO2} = 8.14 \times 10^{4}$

Secondary Candling Model

- Eutectics model off
  - Simple model to allow transport of unmolten secondary materials
    - ZrO_2, UO_2, steel oxide, control poison
    - Dissolution of UO_2 by molten Zr or breaking off of pieces of thin oxide shells
  - Fraction of secondary material carried with candling molten material
    - Input fraction F1 of the molten mass

$$\Delta M_s = F_1 \ \Delta M_m$$

    - Fractional proportion to existing fraction within a component

$$\Delta M_s = F_2 \ \frac{M_{s,total}}{M_{m,total}} \ \Delta M_m$$

- Eutectic model on
  - Secondary candling is inactive
  - Material interactions predicted by eutectics model

Calculation of the Solidus/Liquidus Temperatures of a Mixture

- *Determined by considering every binary combination of material pairs in the mixture (molar weighted combination of solidus temperatures*

$$TS_{mix} = \frac{\sum_j \sum_{i \neq j} f_i \quad f_j \quad TS_{ij}}{\sum_j \sum_{i \neq j} f_i \quad f_j}$$

  - *Eutectic pairs*
    - Lever Rule
      - The solidus temperature is given by the mole-weighted average of the eutectic temperature and solidus temperature of the component present in excess of the eutectic molar composition.

Material Pairs		Molar Ratio	Eutectic Temperature
Zr	Inconel	0.76 / 0.24	1210
Zr	steel	0.76 / 0.24	1210
ZrO_2	UO_2	0.50 / 0.50	2800
Zr	B_4C	0.43 / 0.57	1900
Steel	B_4C	0.69 / 0.31	1420
Zr	Ag-In-Cd	0.67 / 0.33	1470

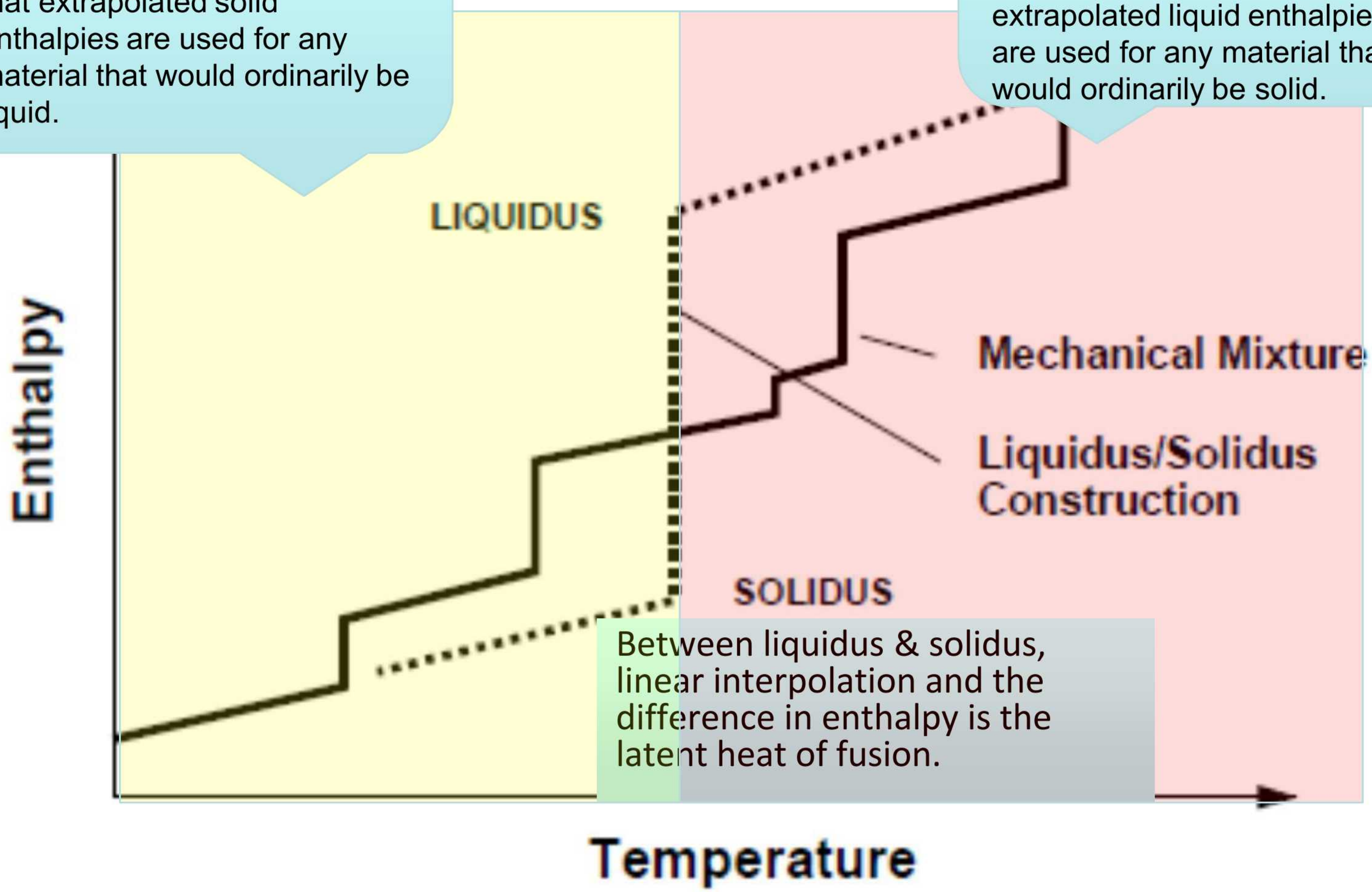
  - *Non-Eutectic Pairs*
    - TS_{ij} is given by the mole-weighted average of the two solidus temperatures.

The liquidus temperature is set equal to the solidus temperature plus 0.01 K

Enthalpy of Eutectic Mixture

For temperatures less than the calculated solidus, the mass-weighted individual enthalpies are summed with the exception that extrapolated solid enthalpies are used for any material that would ordinarily be liquid.

For temperatures greater than the calculated liquidus, the mass-weighted individual enthalpies are summed with the exception that extrapolated liquid enthalpies are used for any material that would ordinarily be solid.

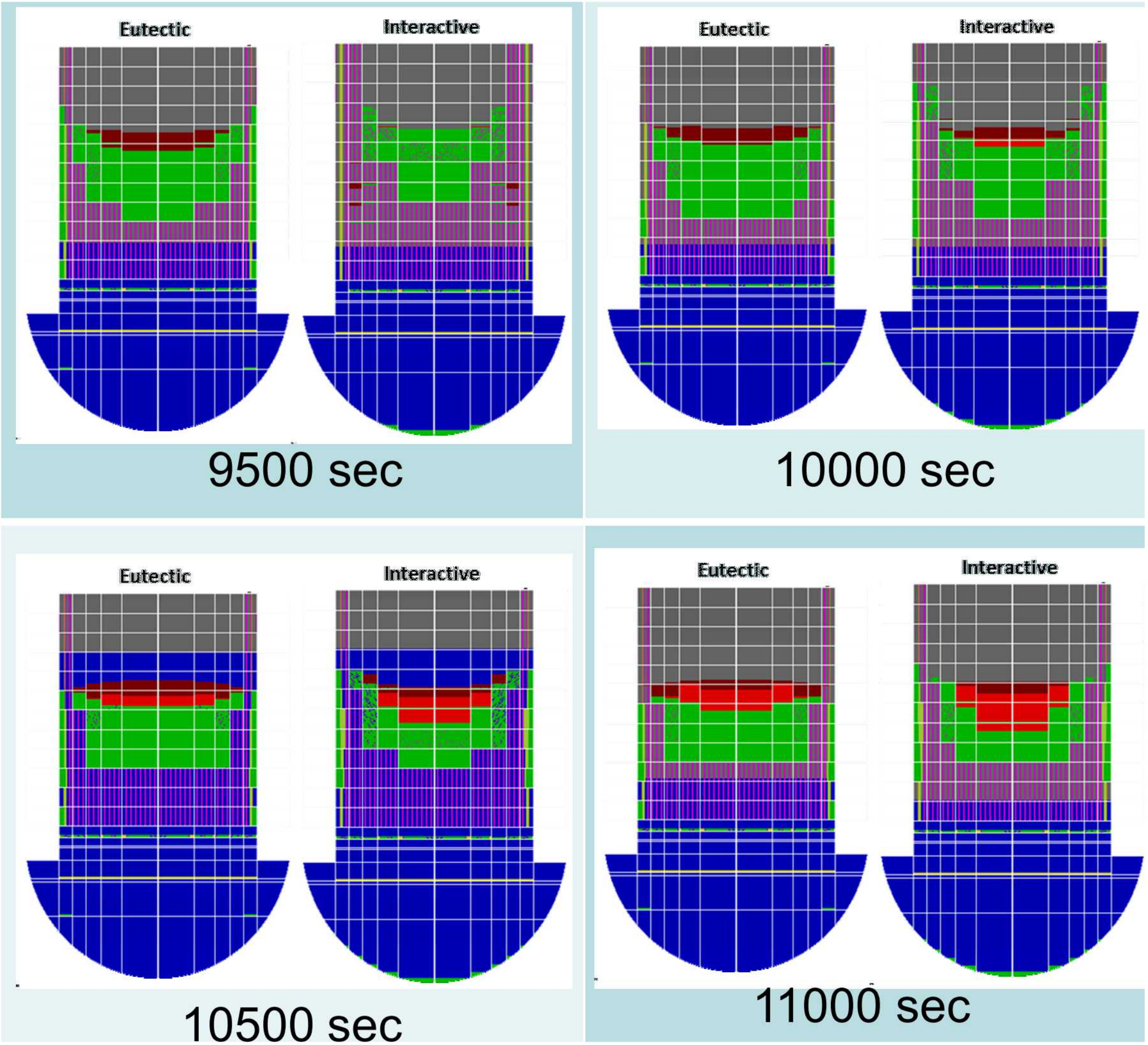


Between liquidus & solidus, linear interpolation and the difference in enthalpy is the latent heat of fusion.

TMI Melt Progression –Preliminary Results

Sandia National Laboratories

- Compare two TMI-2 test cases
  - Eutectics point = 2550 K
  - Interactive UO2-INT/ZRO2-INT 2550 K
- Similarities but notable differences
  - Core damage
    - Greater for eutectics
  - Size of Molten pool
    - Early: Greater for interactive
    - Later: Greater for eutectics
  - Material relocating to lower plenum
    - Greater for interactive
- Results are preliminary



Holdup Behind ZrO2 layer

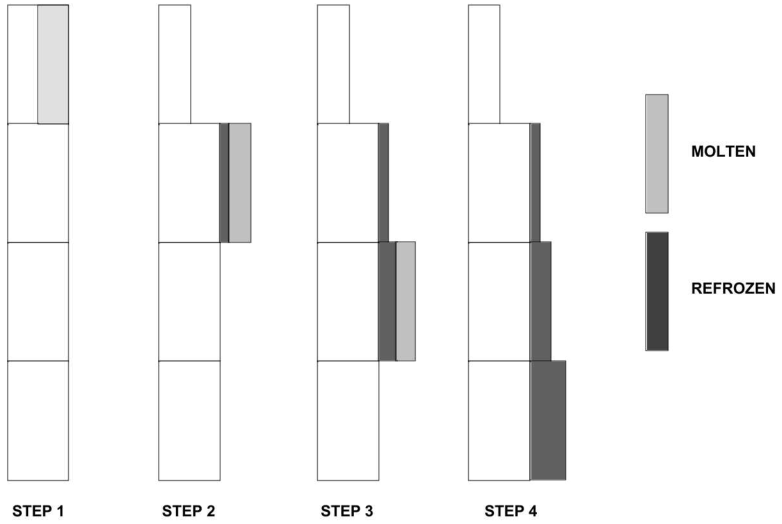
- Molten material is held up within a component
  - if the oxide thickness is greater than a critical value Δr_{hold}
  - if the component temperature is less than a critical value T_{breach}
  - if no candling from the component in that cell has yet taken place.
- Eutectic model protects materials from dissolution when they are behind an oxide layer

Component	Solids Dissolved Effected by Oxide Layer
Canister	ZrO2 from intact cladding (A)
Other structure NS (BWR control rod)	ZrO2 from intact canister (A)
	Zr from intact canister (A)
Other structure NS (PWR control rod)	Steel oxide from the same other structure (B)
	ZrO2 from intact cladding (A)
	UO2 from intact fuel (A)

A. solid is attacked only if there is no holdup of the mixture in the component.
B. solid is attacked only if the mixture is being held up by the component

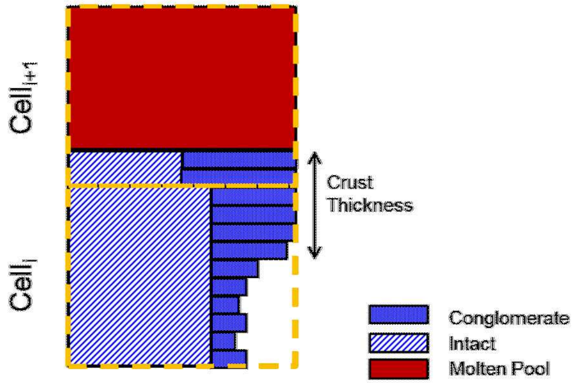
Downward Relocation of Molten Material

- Candling - Downward flow of molten core materials and subsequent refreezing (creation of ‘conglomerate’)
  - Semi-mechanistic
    - Based on fundamental heat transfer principles with user-specified refreezing heat transfer coefficients for each material
  - 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 if non-existent at lower elevation

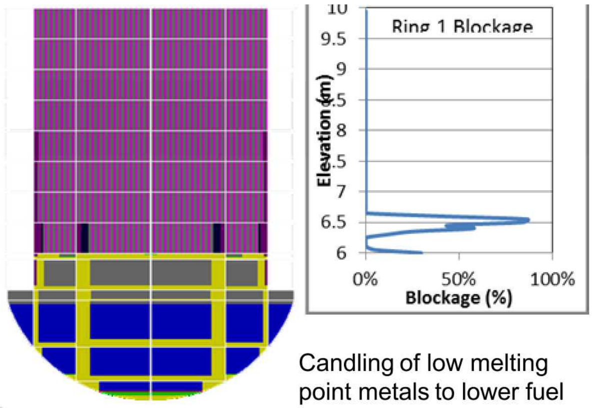


MELCOR Crust

- 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

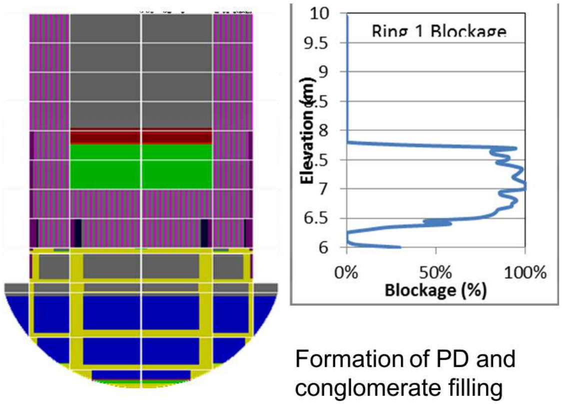


Sub-Grid Model Prediction of Blockages



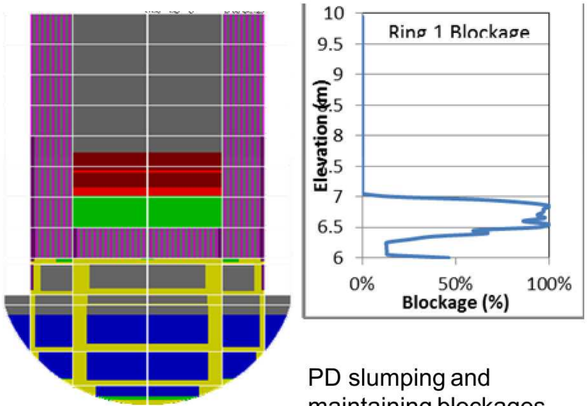
1998 (sec)

Candling of low melting point metals to lower fuel rods



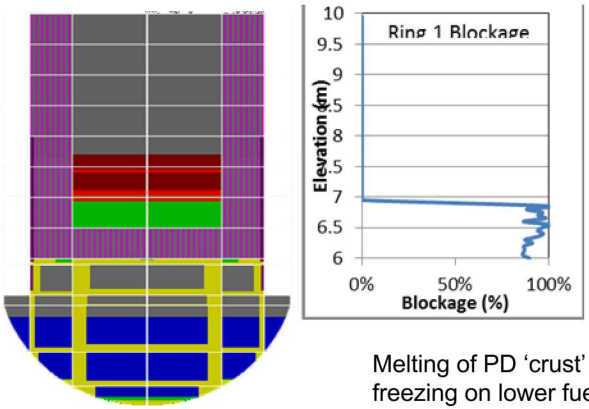
2008 (sec)

Formation of PD and conglomerate filling interstitials



2414 (sec)

PD slumping and maintaining blockages

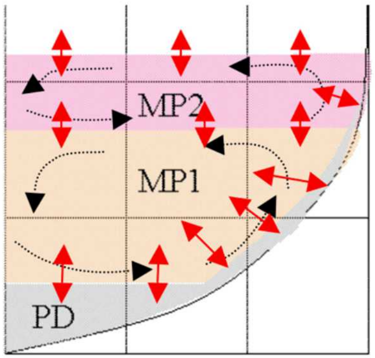


2462 (sec)

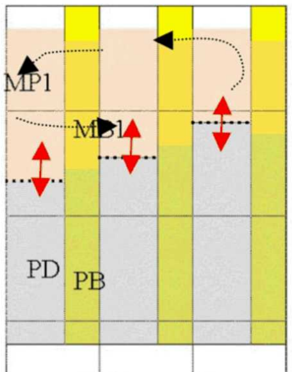
Melting of PD ‘crust’ and freezing on lower fuel rods

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