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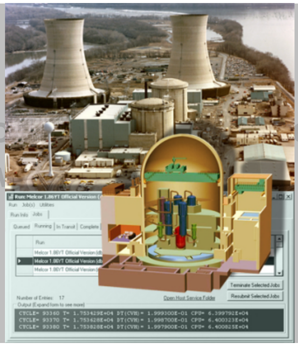

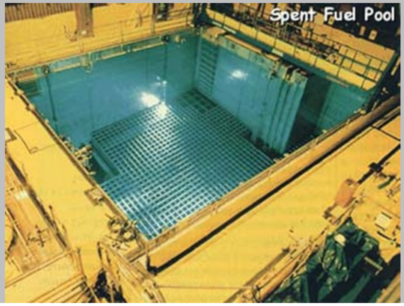

MELCOR Spent Fuel Pool Modeling

2017 ANS Winter Meeting

SFP Panel Discussion

November 2017

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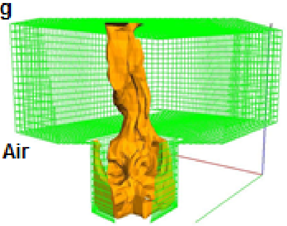
Timeline of SFP Model Development

BWR SFP Accident Analysis

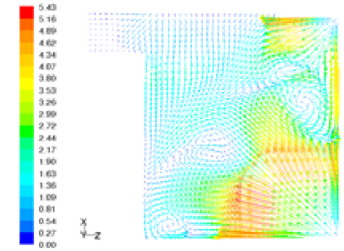
- **NRC Research into SFP Accidents (post-9/11)**
  - Air Oxidation Experiments (ANL)
  - BWR SCALE/ORIGEN decay heat analysis
  - Whole Pool BWR SFP Analysis using MELCOR
  - Separate Effects BWR SFP Analysis using MELCOR
  - BWR spray mitigation analysis
  - CFD Analysis of BWR SFPs and RB
    - Complete Loss-of-Coolant RB/SFP Air Patterns
    - Partial Loss-of-Coolant Assembly Flow Patterns
    - Hot Gas Layer Heat Transfer Analysis



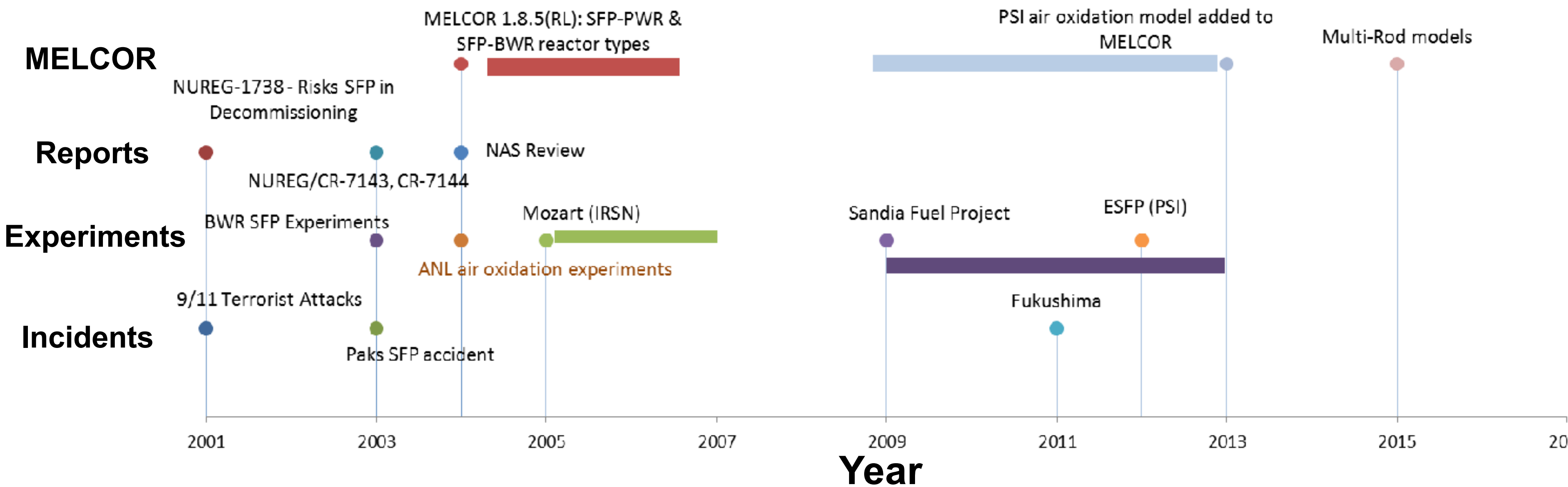
900 K Iso-Therm from 5 MW "Fire"

PWR SFP Accident Analysis

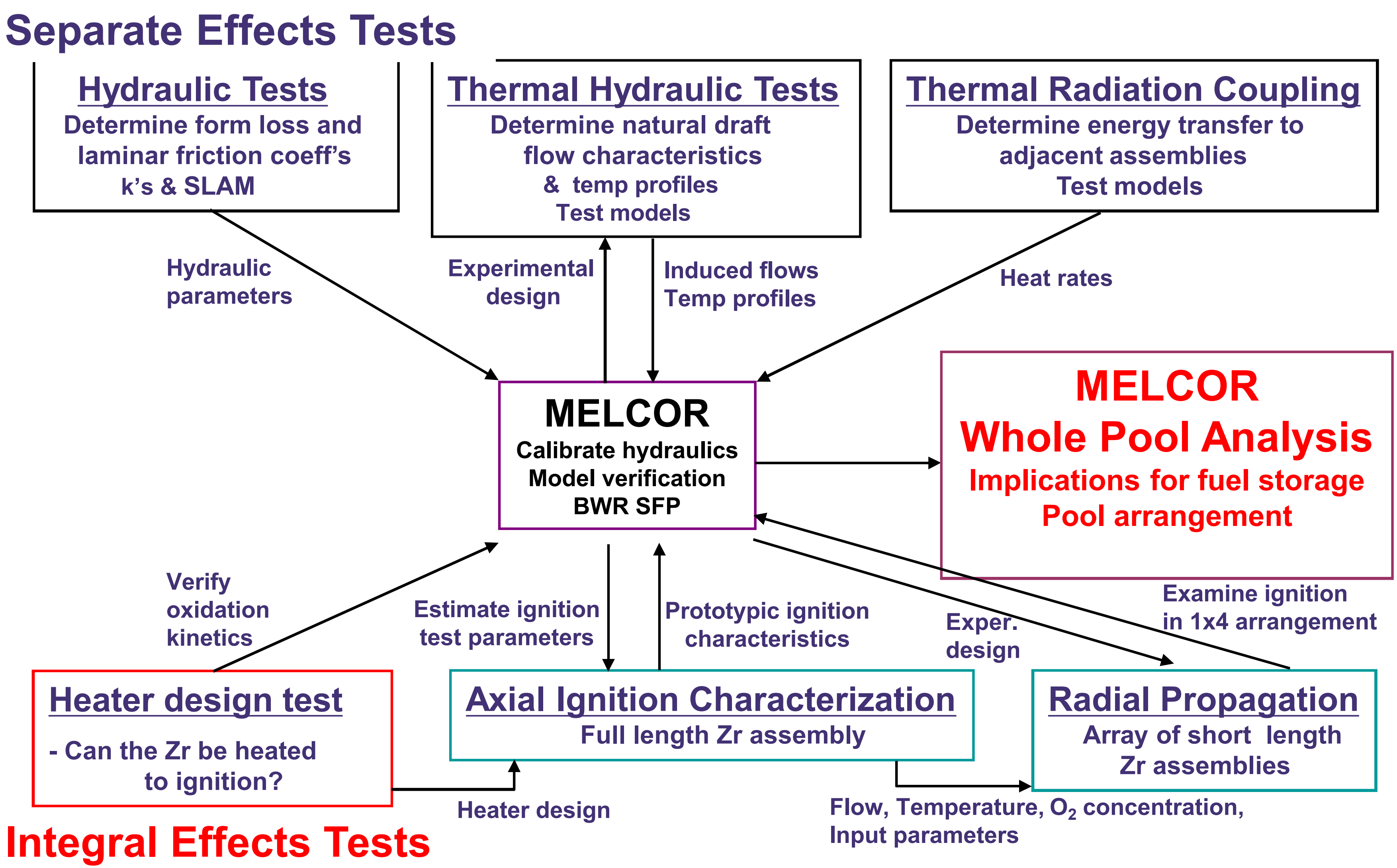
- **NRC Research into SFP Accidents (post-9/11)**
  - PWR SCALE/ORIGEN decay heat analysis
  - PWR Whole Pool SFP Analysis using MELCOR
  - PWR Separate Effects Analysis using MELCOR
  - CFD Analysis of PWR SFPs and Fuel Storage Buildings
    - Complete Loss-of-Coolant FSB/SFP Air Patterns
    - Hot Gas Layer Heat Transfer Analysis



PWR Air Flow Patterns using Fluent



SFP Accident Analysis

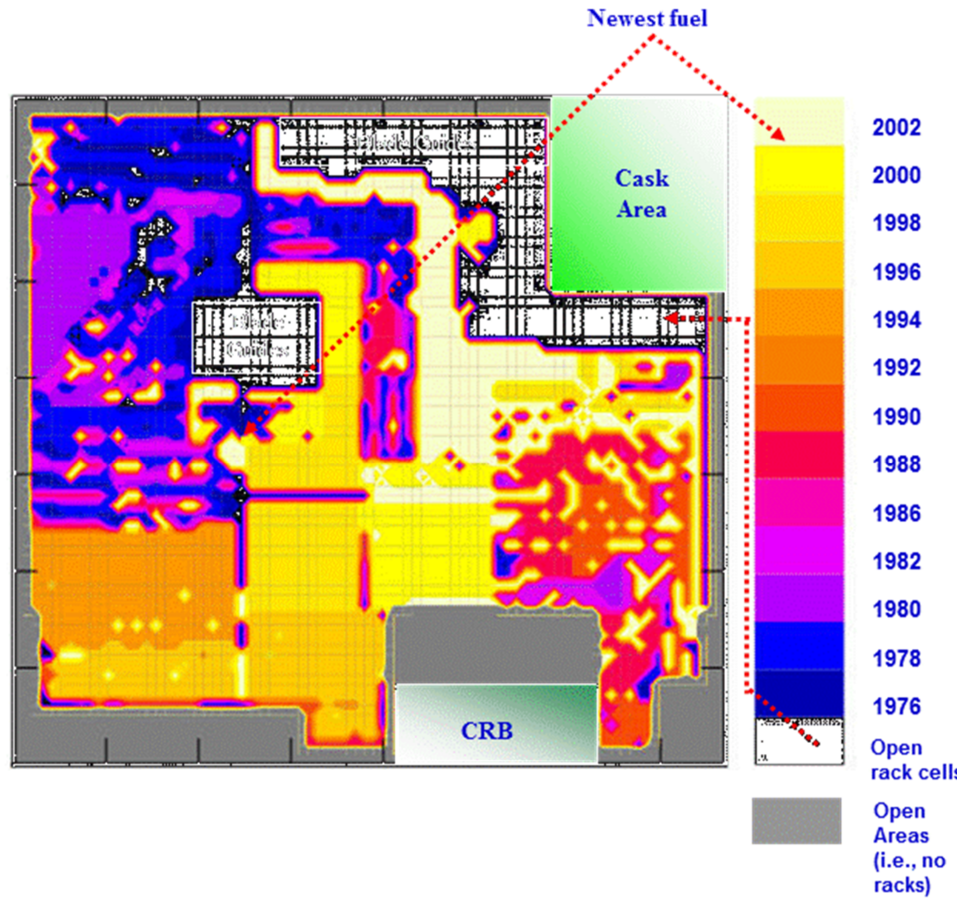


MELCOR SFP Models

- SFP is just another reactor type available to MELCOR users
  - BWR, PWR, SFP-BWR, SFP-PWR,ACR-700, PBR, PMR
- Components available for SFP modeling
  - Fuel rods, cladding, canisters (SFP-BWR), control rods (SFP-PWR), racks, support structure, particulate debris, molten pool
- Decay Heat Modeling
  - Many, hugely different fuel-loadings in a SFP.
  - Models for tracking radionuclide release by zone have been added.
- Thermal Hydraulics
  - SLAM Models
- Radiant heat transfer
  - User-defined heat transfer paths
  - Multi-rod model
- Air Oxidation
  - Air oxidation
  - Break-away modeling

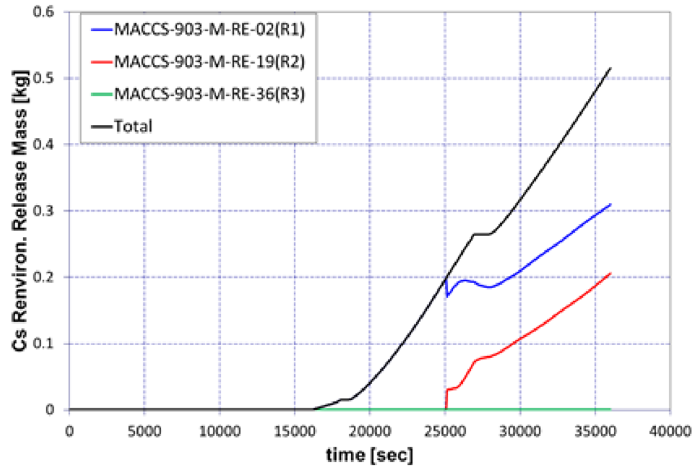
Decay Heat Modeling

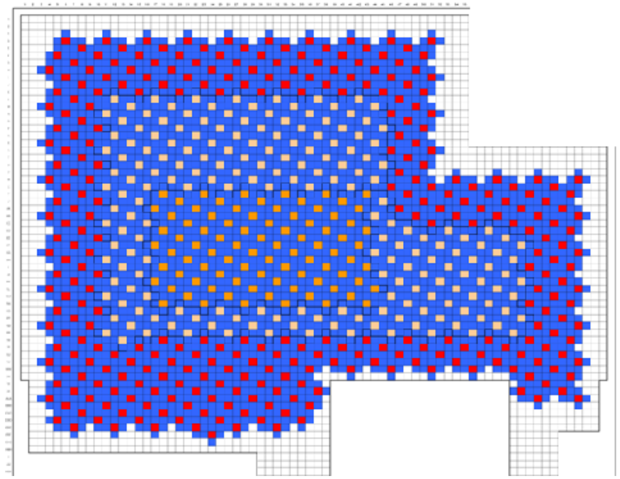
- SCALE/ORIGEN analysis practical
- Preserve decay heat per offload
- Grouping will be necessary
  - Power and Layout
  - Empties
- Power distribution
  - Zone power distribution
  - Axial power distribution
- Two Options for modeling decay heat
  - Specifying unique classes (burnup) for each zone
    - Additional classes slow down calculations
  - Specify same classes (burnup) for each zone but track releases for post-processing activities.



SFP Class MACCS Releases by Offload Batch (MELCOR Ring)

- Motivation
  - Burnup and therefore activity for distinct rings may be vastly different. Recently, MACCS has been modified to allow it to distinguish masses provided by MELCOR by batch (ring). MACCS then will associate different activities for a class, dependent on the ring of origination
  - The problem is that once RN mass is released, it can no longer be distinguished by originating ring.
- New variable for approximating mass release by offload batch (ring)
  - This is an approximation in obtaining a plot variable
- Previously implemented through use of control functions.
  - Control function description can be quite lengthy even for a two-ring model

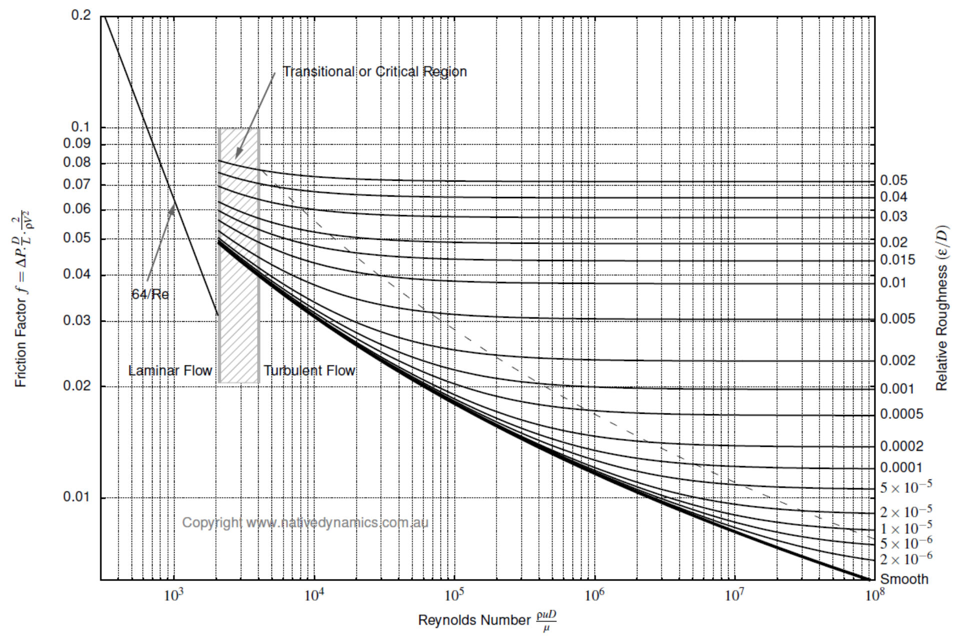




Thermal-hydraulic Modeling

Sandia National Laboratories

- **MELCOR includes models for laminar and turbulent flow**
  - Default laminar "SLAM" coefficient not appropriate for bundle geometry
    - Nuclear Systems Volume II: Thermal Hydraulic Fundamentals, by Neil E. Todreas and Mujid Kazimi
  - SNL/SFP Experimental Characterization very good reference



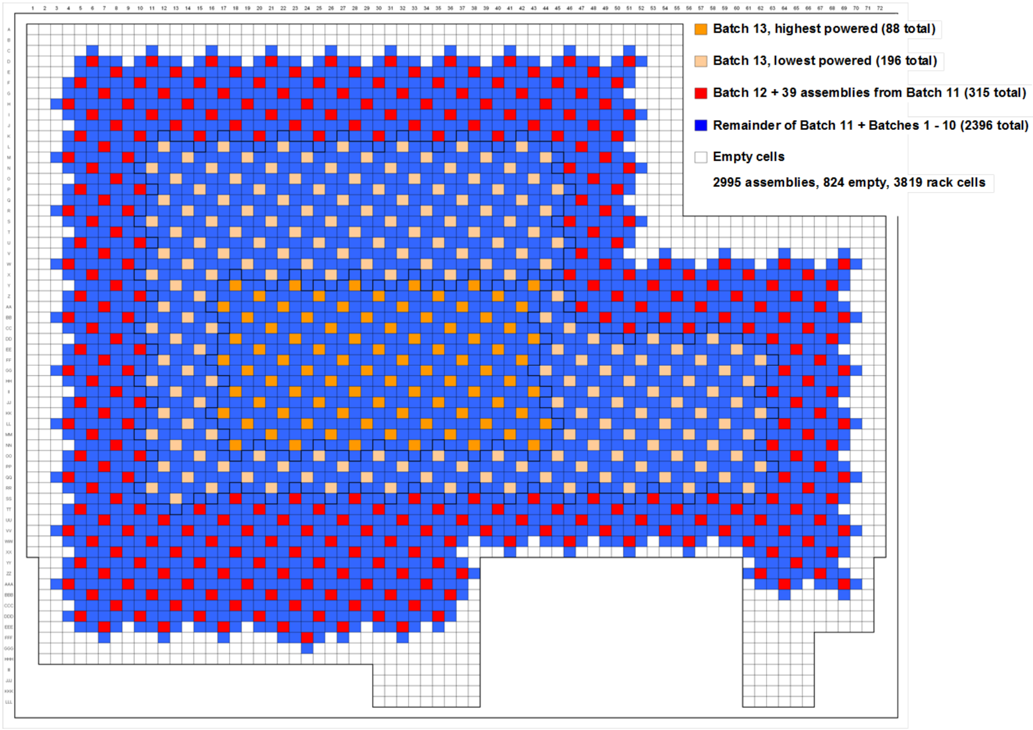
4404 – Friction Factor Parameters

A two-phase friction factor is calculated for each flow path segment. Laminar flow is assumed if the Reynolds number is less than C4404(14), turbulent flow is assumed if the Reynolds number is greater than C4404(15), and a transition region is assumed for Reynolds numbers between these values. The friction factor for laminar flow is determined by dividing the value of the variable SLAM by the value of the Reynolds number. The default value of SLAM is C4404(13). The Colebrook-White equation

$$\frac{1}{\sqrt{f}} = C4404(1) - C4404(2)\log_{10}\left(C4404(3)\frac{e}{D} + \frac{C4404(4)}{\mathrm{Re}\sqrt{f}} \right)$$

is used to define the friction factor, f, for turbulent flow, where e is the surface roughness and D is the hydraulic diameter.

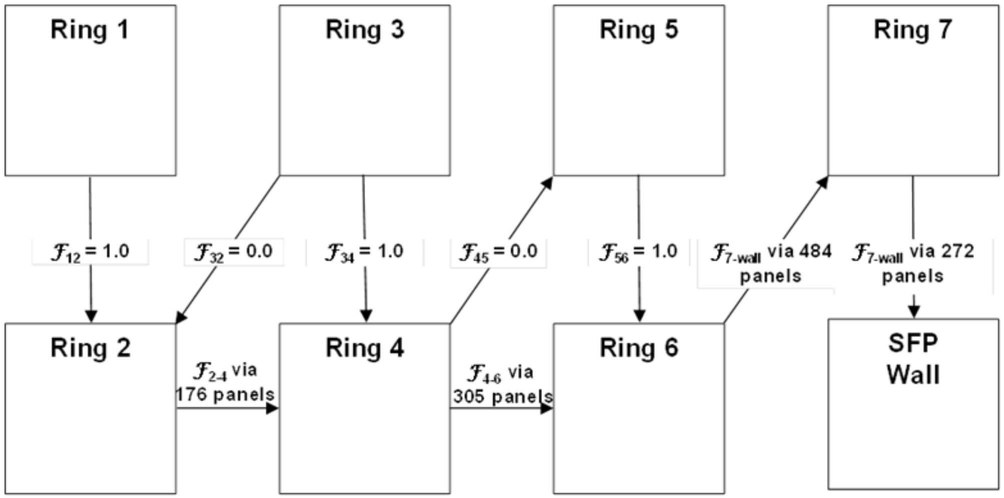
Thermal Radiation Modeling



- User defined heat transfer paths
  - Most general method
  - Many records are required to define heat transfer
  - Single, lumped parameter temperature for fuel rods in a cell
  - User provides product of viewfactor and area for each radiant heat transfer path

User Defined Arbitrary Heat Transfer Paths

- COR_HTR
  - Allows the user to define arbitrary heat transfer paths
    - Radiation
    - Conduction
  - Constant or Control Function
    - Conduction: Total conductance (KA/dx)
    - Radiation: product of the view factor and area (VF x A)
  - User can specify heat transfer from any core component at any cell location to another core component or to a heat structure
    - Rack to rack radiation conduction
    - Radiation to concrete walls
    - Unique degradation based radiative heat transfer

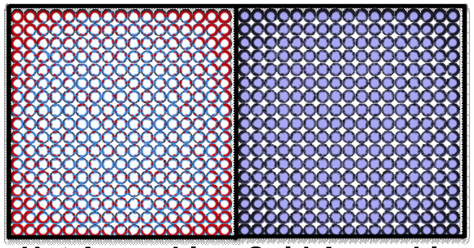


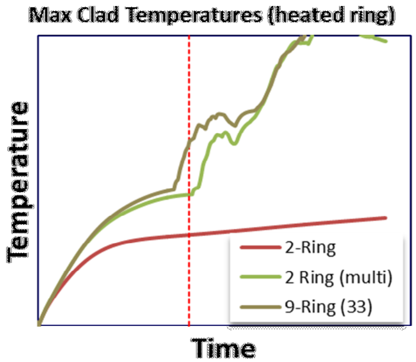
$$\dot{Q} = \sigma_B \frac{(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1-\epsilon_2}{A_2\epsilon_2} + \frac{1}{F_{1-2}A_1}}$$

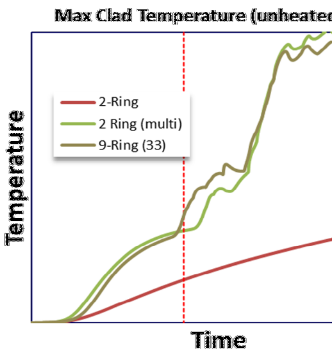
Quantity in red is supplied by user. All other areas determined from components

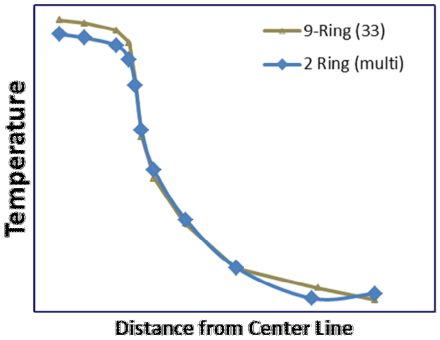
Multi-Rod Model

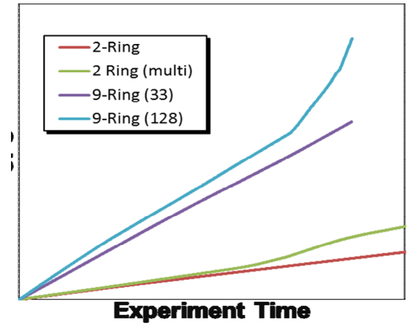
- Motivation
  - It is desirable to model an entire assembly within a single MELCOR ring
- Challenge
  - When hot assembly reaches ignition, heat transfer to cold assembly is problematic











- **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.**

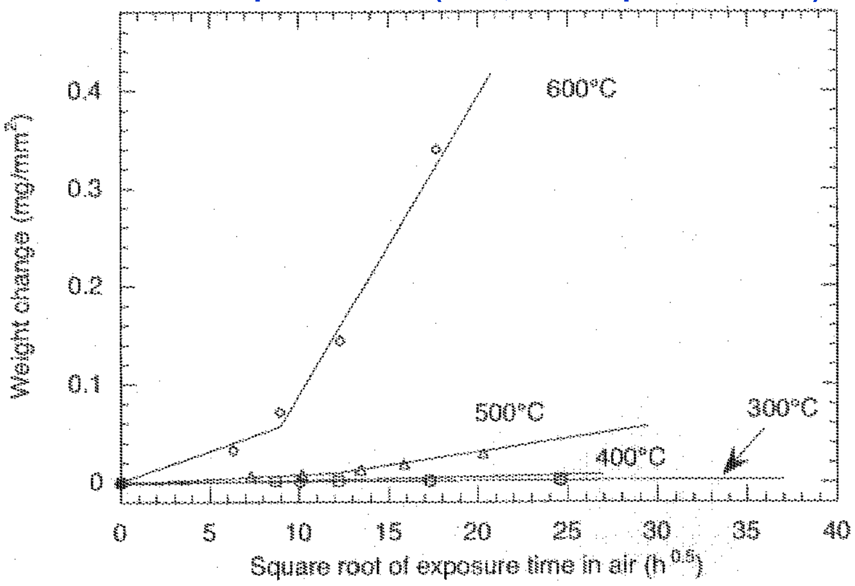
ANL Air Oxidation Experiments

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

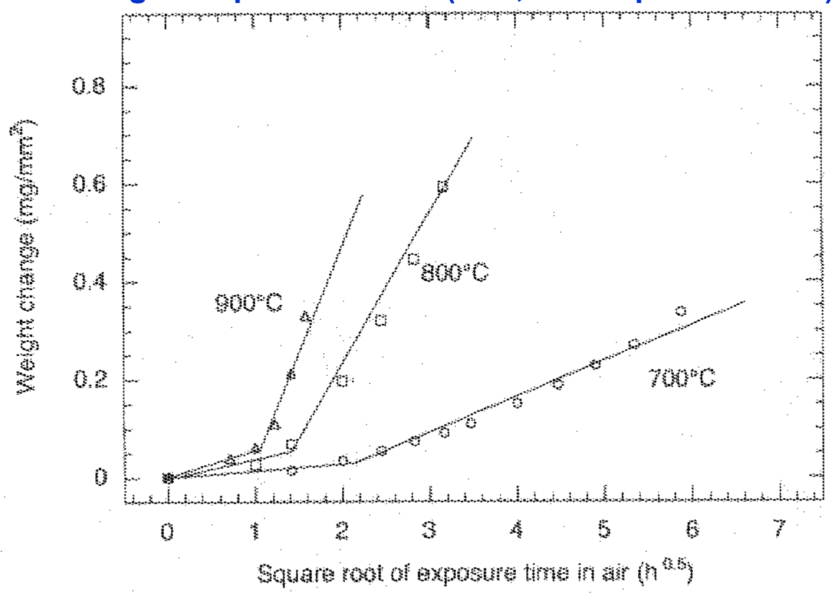
ANL Air Oxidation Experiments

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

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



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



SNL Lifetime Breakaway Model

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

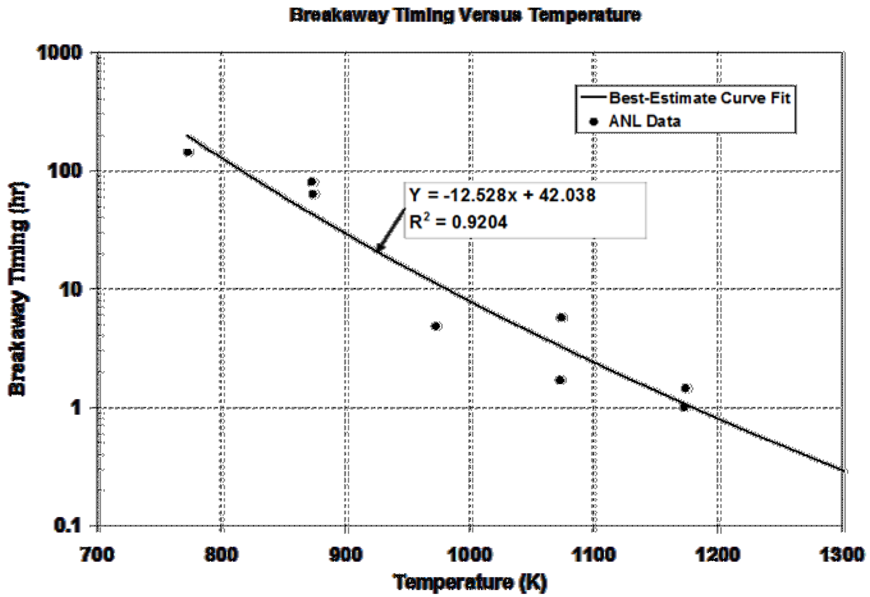
$$LF = \int_0^t dt' \frac{t'}{\tau(T)}$$

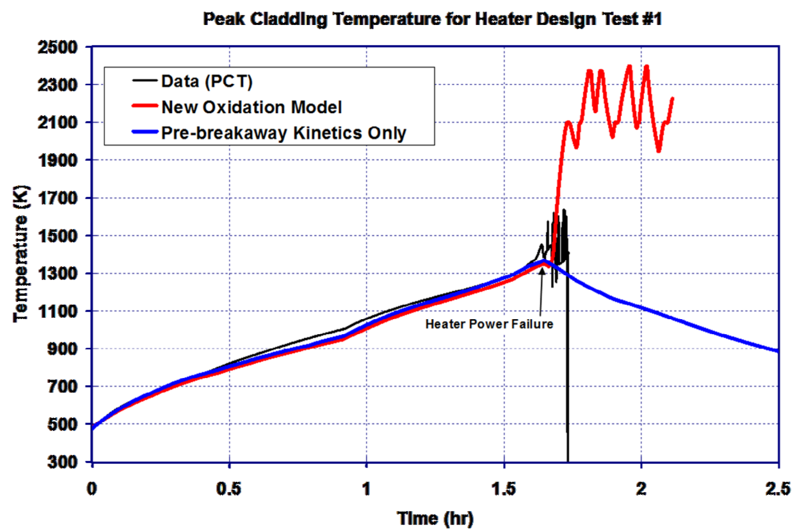
where,

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

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

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





PSI Air Oxidation Model

- Initially, oxidation kinetics follows a parabolic law
  - Uses Arrhenius law similar to default MELCOR

$$C = A \exp(-B/T)$$

  - Oxide Thickness
    - Does not account for oxygen dissolved in metallic zirconium, α(Zr-O)

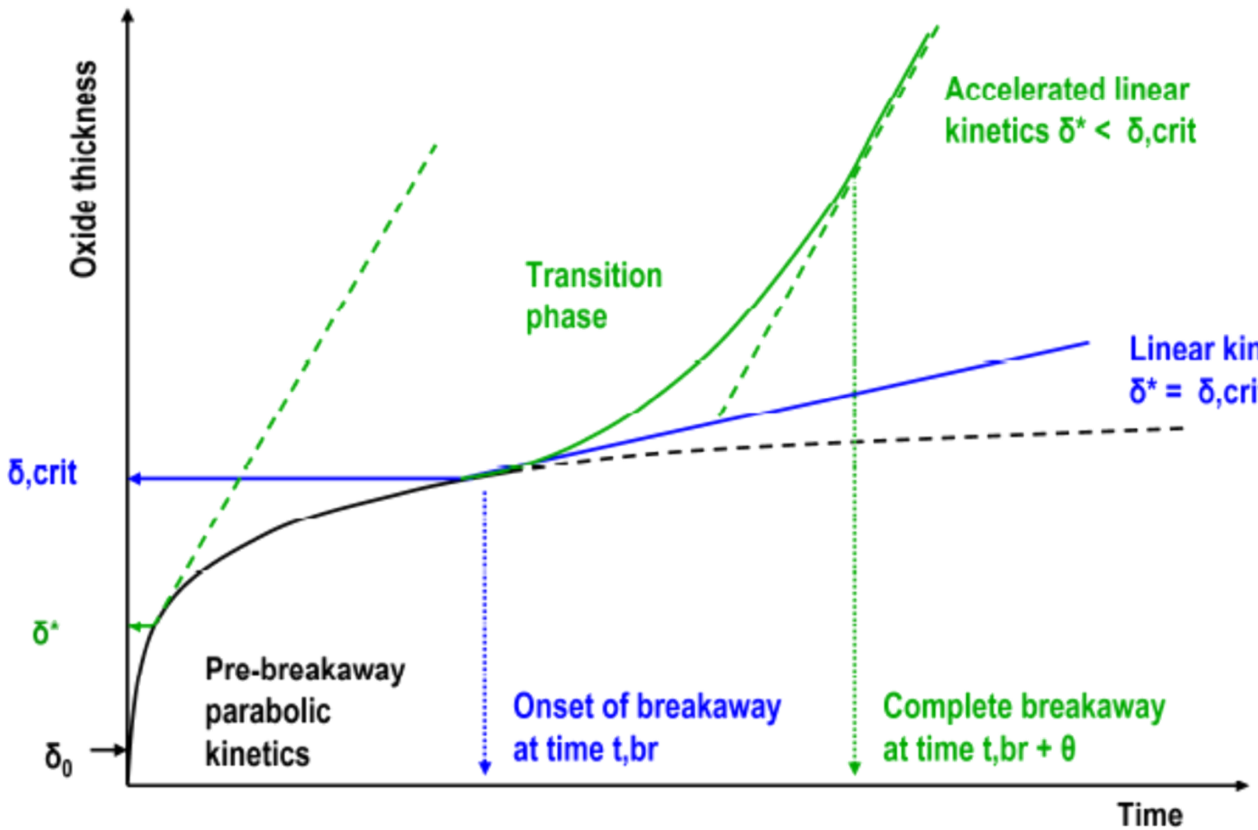
$$d(\delta)/dt \sim C' / \delta_{eff}$$

$$\delta = \Delta m \frac{M(ZrO_2)}{\rho(ZrO_2) M(O_2)}$$

Δm is the mass gain / area
M(X) is the molecular weight of species X

  - Alternate oxidation models are available to user
    - i.e., (Urbanic-Heidrick, etc)
- Transition to linear initiates at critical thickness
  - When δ reaches δ,crit transition to linear (breakaway) is initiated
  - The 'effective' oxide thickness (more porous microstructure) decreases from δ,crit to δ* during transition
  - When oxide thickness reaches δ*, transition is complete
    - Empirical fits to δ,crit and δ*
    - Empirical fit for rate of change in δ_{eff} during transition

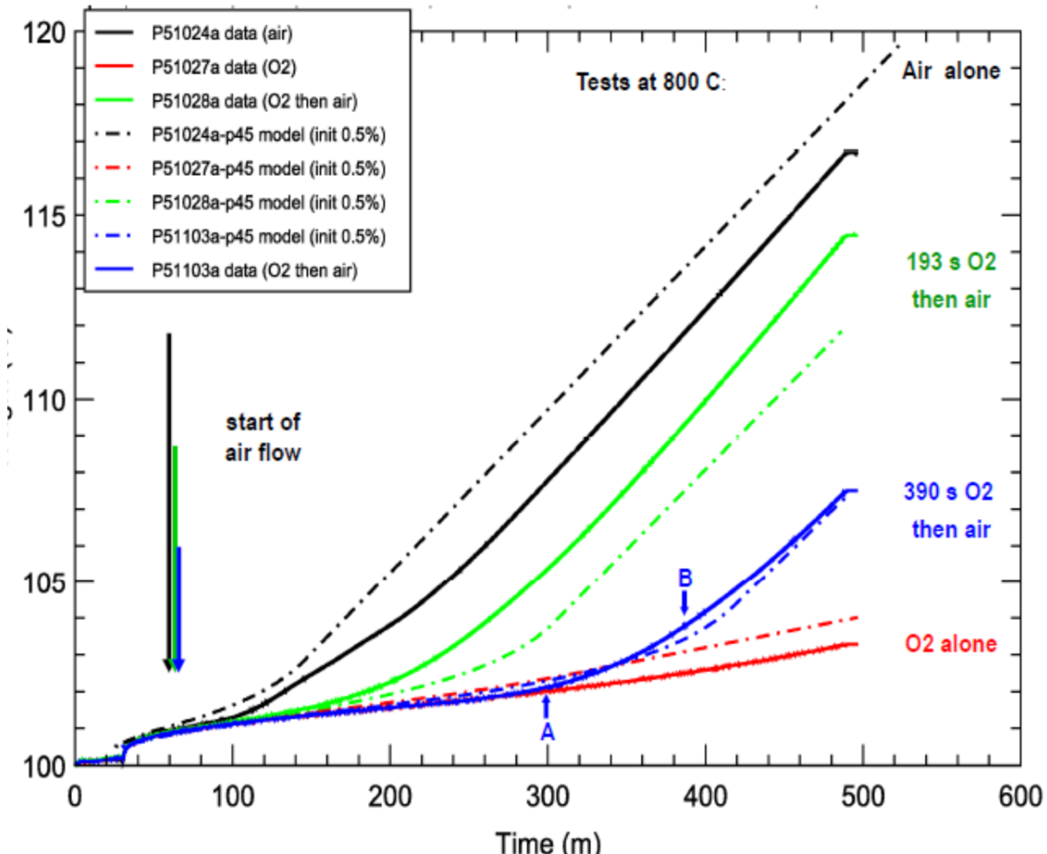
PSI Air Oxidation Model



Jonathan Birchley, Leticia Fernandez-Moguel, Simulation of air oxidation during a reactor accident sequence: Part 1 – Phenomenology and model development, Annals of Nuclear Energy, Volume 40, Issue 1, February 2012, Pages 163-170, ISSN 0306-4549

PSI Assessment with SET data

- Model uses a criterion for onset of breakaway (A) and a timescale for full transition (B)
- The oxide thickness formed during preoxidation provides a protective layer when cladding is later exposed to air
  - Breakaway would start at δ^* without protective layer



Fernandez-Moguel, "Status of PSI air Oxidation Model," From EMUG 2014 Meetings

Summary

- MELCOR has undergone an evolutionary development of SFP models over two decades
  - Code has been used in designing experiments and scoping studies
  - Information from experiments has been used in developing models
- New models specific to spent fuel pool application
  - Rack components
  - Radiant heat transfer models
  - Air oxidation models
  - New multi-rod model
  - Tracking fuel release by zones

Questions