Investigations of Zirconium Fires during Spent Fuel Pool LOCAs

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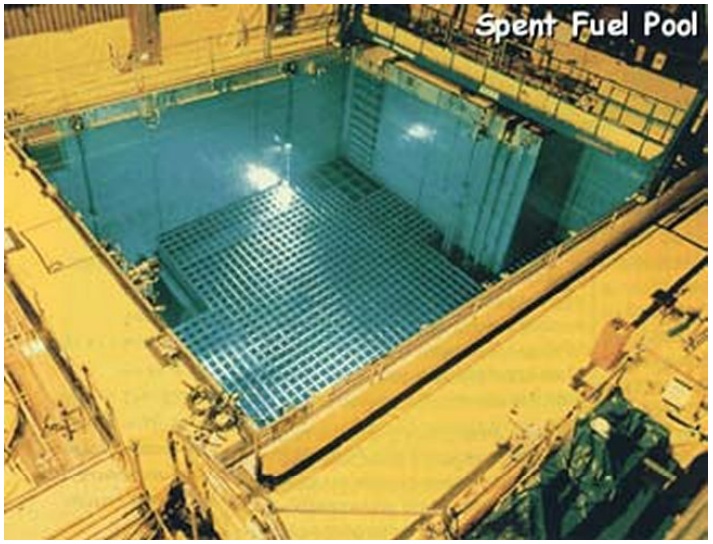
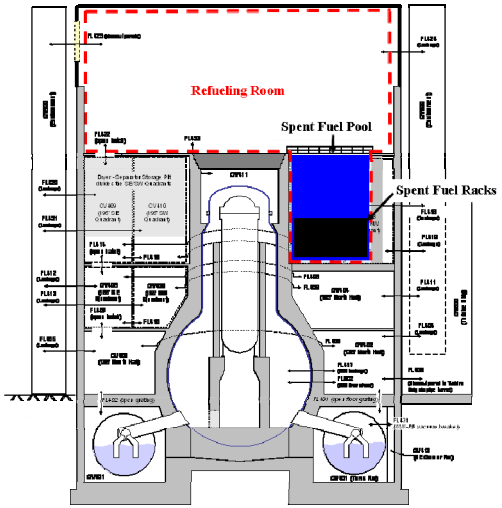
Outline

- Overview
- Objective
- Experimental Approach
- Hardware
- Experiments
  - Single, full length assembly with “hot” neighbor BC
  - 1×4 arrangement – Central “hot” assembly with cold neighbors
- Summary

Overview



BWR Spent Fuel Pool



- Validate severe accident codes for whole pool LOCA analyses
- Phased experimental approach
  - Study physical phenomena separately
    - Provide input parameters to accident codes
  - Examine nature of Zircaloy fires in prototypic assemblies
    - Validate predictive capability
    - Develop mitigation strategies

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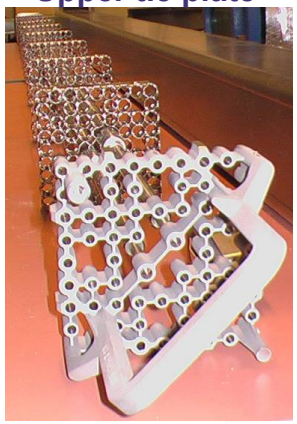
SFP Experiment Objectives

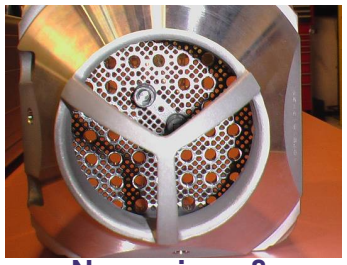
- Provide full scale thermal hydraulic and zirconium ignition data
  - Prototypic components
    - Eliminate scaling arguments
    - Represents fuel design intricacies
  - Gas flow conditions
    - Spent fuel pool complete loss of coolant accident (LOCA)
    - Dry cast storage performance
    - Air ingress during late stages of core melt-down
  - Code validation
    - Closely coupled into experimental design
  - Improve whole pool source term simulations for safety and consequence analyses

Actual Hardware

- Prototypic 9×9 BWR hardware
  - Full length, prototypic 9×9 BWR components
  - Electric heater rods with Zr-2 cladding

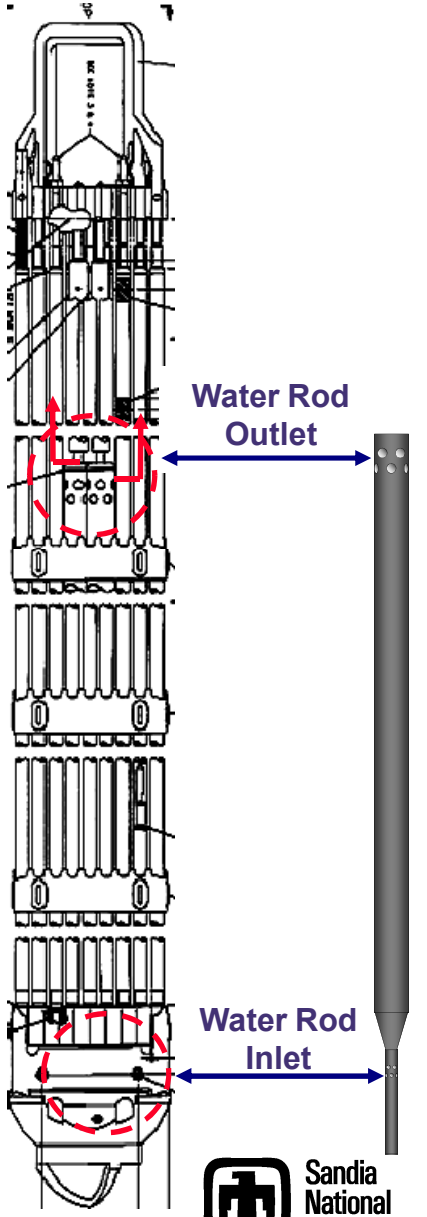
Upper tie plate





Nose piece & debris catcher

BWR channel, water tubes & spacers



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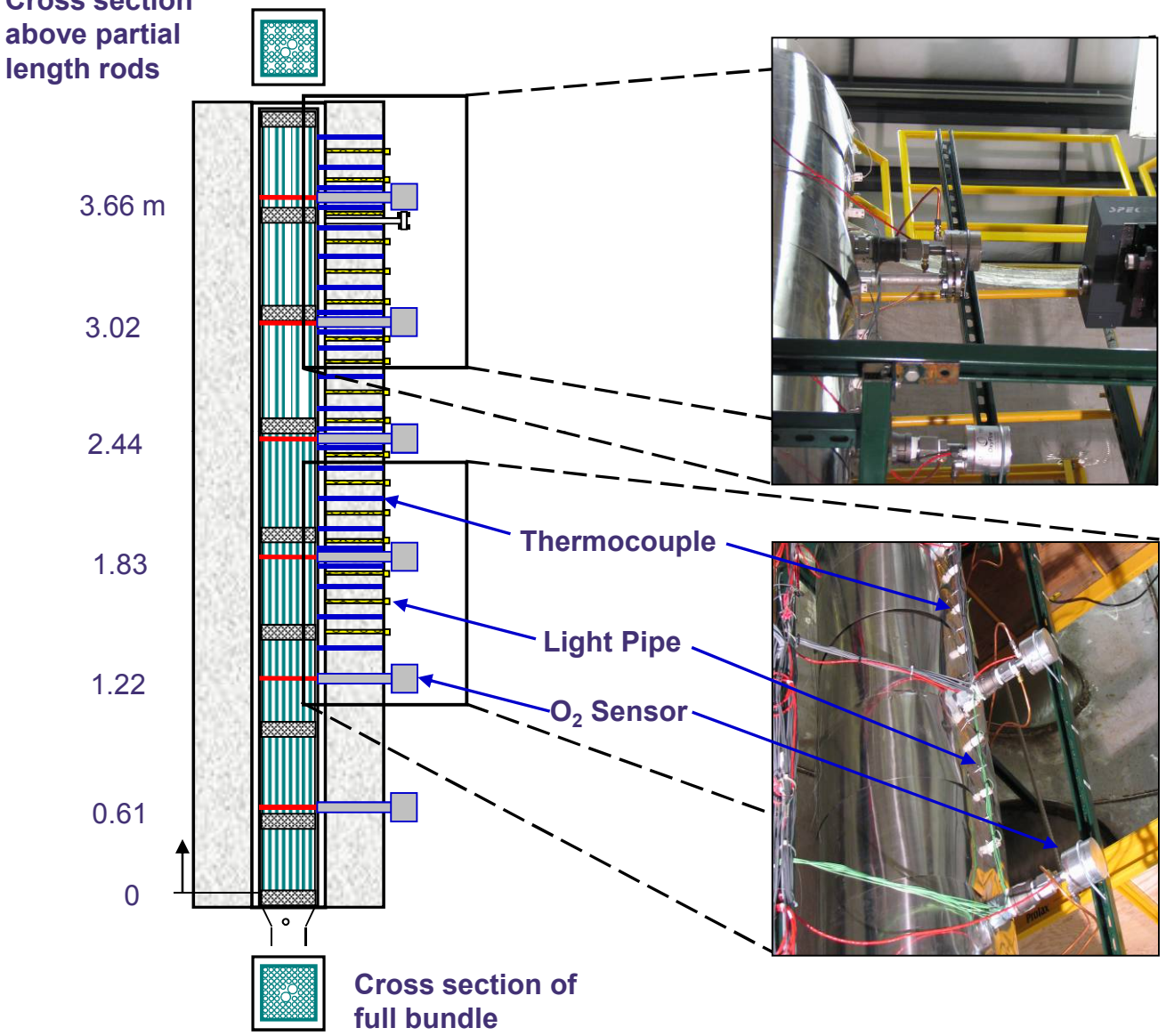
Integral Effects Tests
(Single, Full Length)

- Single, full length, prototypic 9×9 BWR assembly
  - 5000 W simulating a 100 day old assembly
  - 74 Zr heater rods
    - Eight partial length
  - Prototypic hardware:
    - Upper & lower tie plates
    - Seven spacers
    - Water tubes and channel box
    - Single pool rack cell
  - Measurements
    - Temp profiles: Axial and radial
    - Induced flow: Effect of ignition on flow
    - O_2 concentration: Determine depletion
    - Nature of fire: Initiation location & axial burn rate

Full Scale Zircoloy
(Ignition Test Instrumentation)



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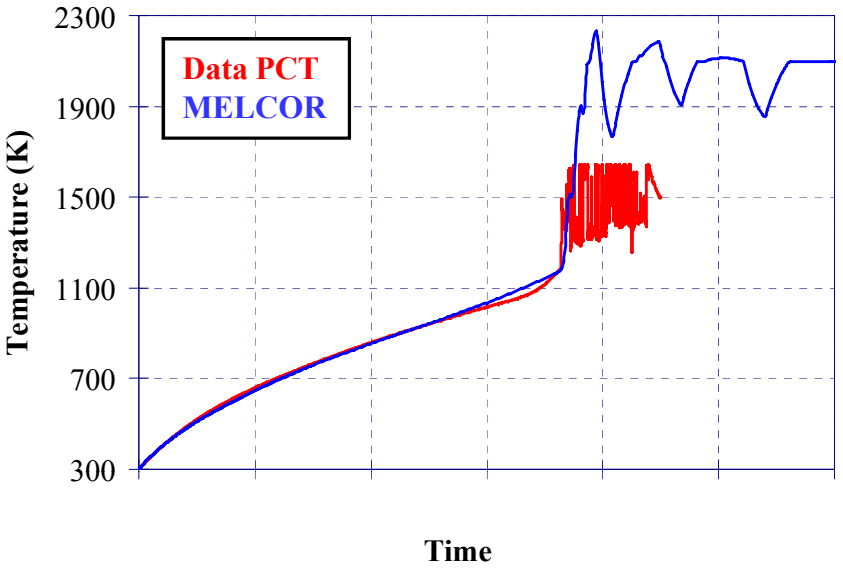
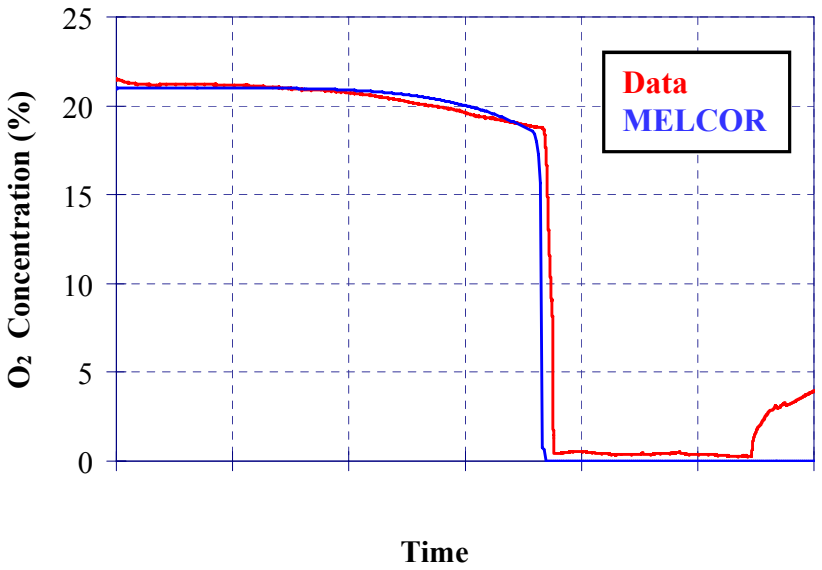
Full Length Zr
(Ignition Results)





- Assembly power 5000 W
  - Situational equivalent of a cluster of 100 day-old assemblies
    (hot neighbor BC)
- Thermocouples failed after ignition
  - Sharp transition to breakaway oxidation
  - Oxygen depletion
  - Requires breakaway reaction kinetics
- Interesting dynamics on burn-front movement
  - Usually downward to follow oxygen and fresh Zr
  - Late phase ignition above the initial ignition location
  - Saw tooth pattern on code max temperature response (ignition front movement to new node)

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Postmortem

Full Length Ignition Movie

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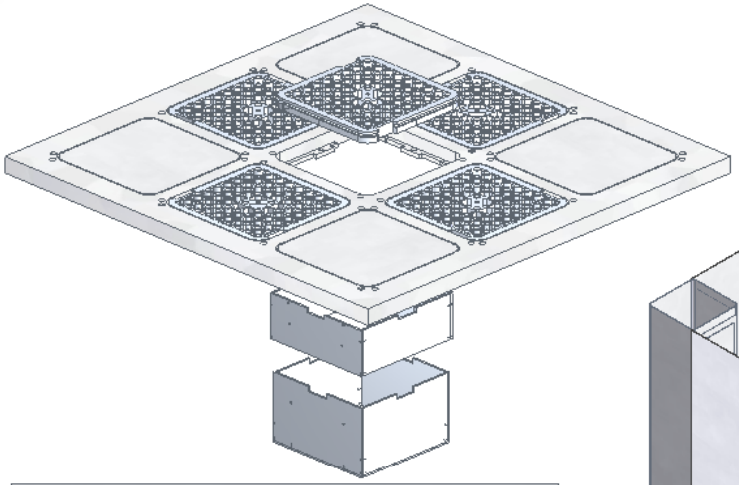
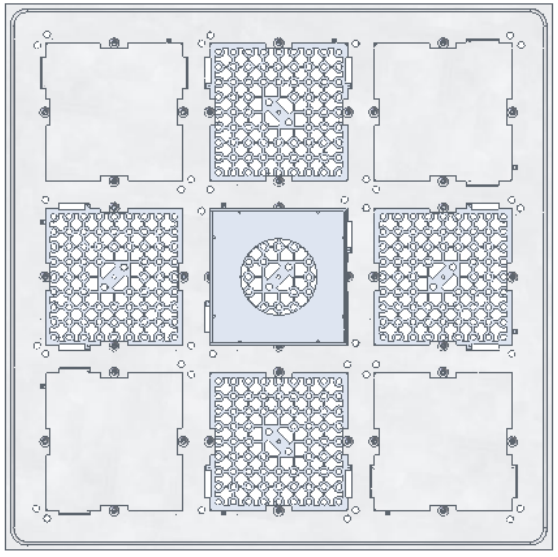
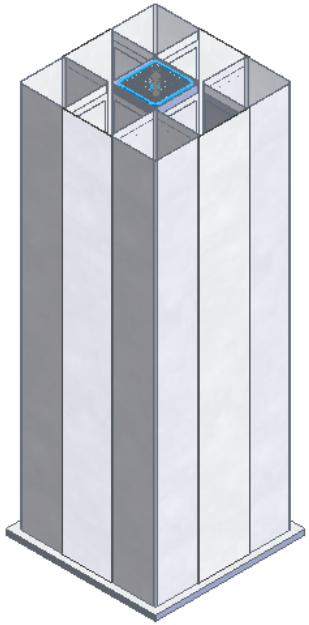
Zircoloy Short Stack Design



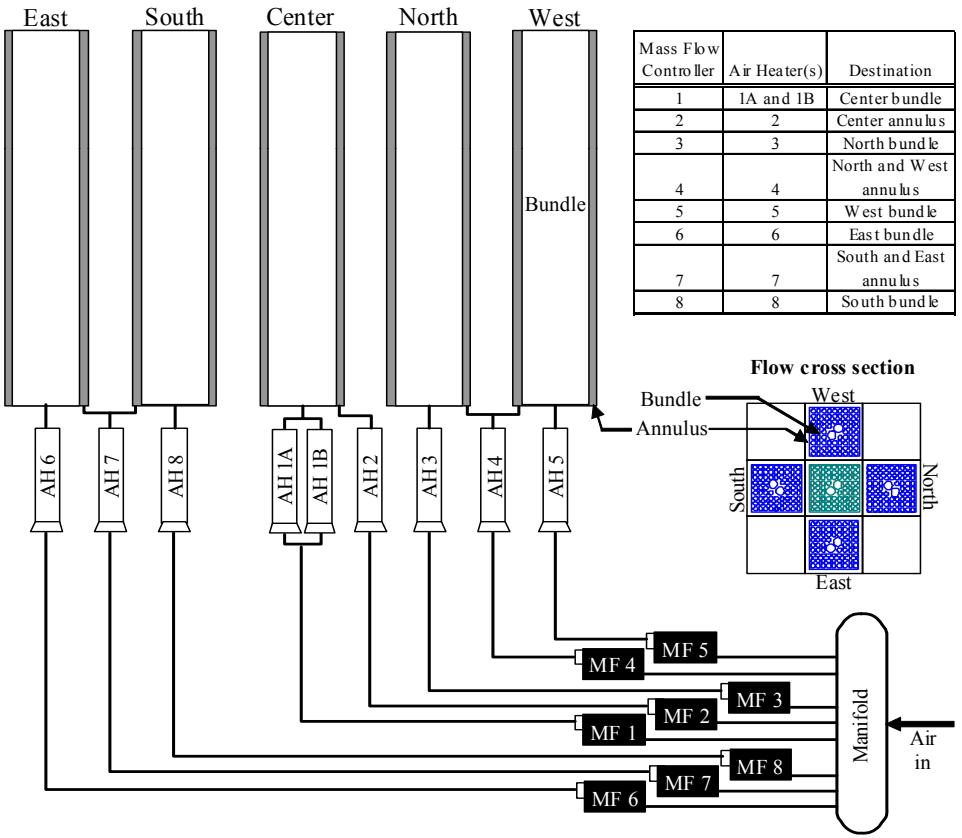




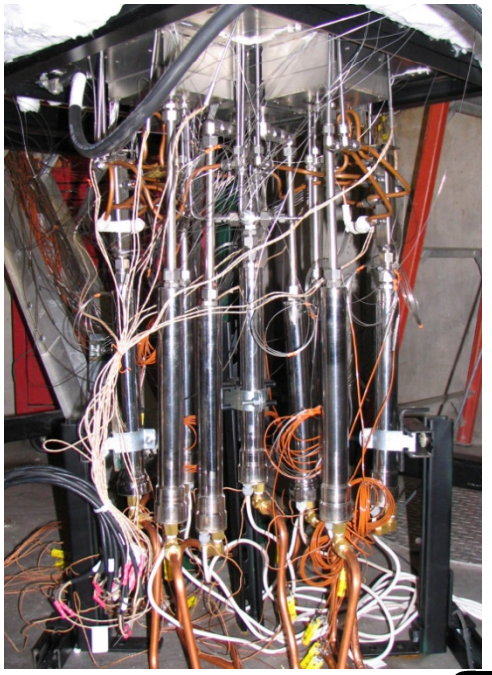
- Simulate “hot” center assembly in 1 × 4 arrangement
  - Unpowered Zircaloy peripheral assemblies
  - “cold neighbor” BC
- Bottom and top tie plates allow flow
  - Bundle and annular flow rates and temperature independently controlled
- Prototypic commercial pool rack

Inlet Condition Control

- Simulate segment of full length assemblies
  - Temperature and flow histories independently controlled
    - Based on previous experimental and modeling results



Mass Flow Controller	Air Heater(s)	Destination
1	1A and 1B	Center bundle
2	2	Center annulus
3	3	North bundle
4	4	North and West annulus
5	5	West bundle
6	6	East bundle
7	7	South and East annulus
8	8	South bundle



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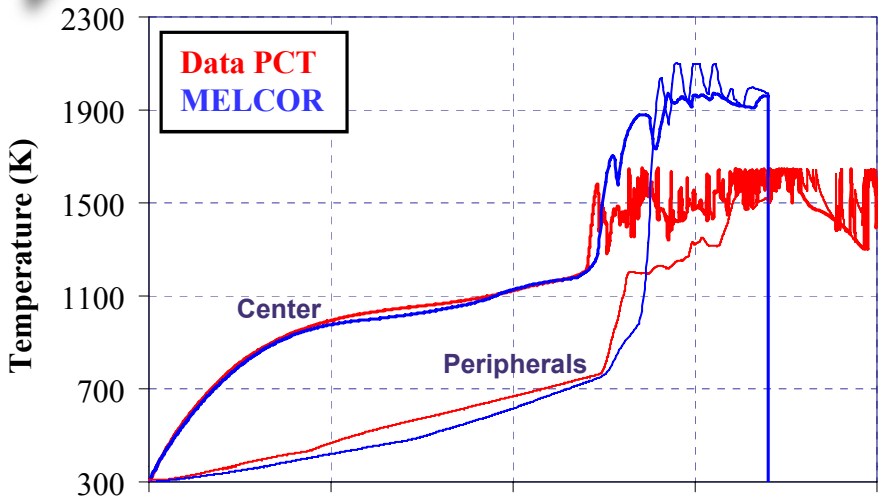
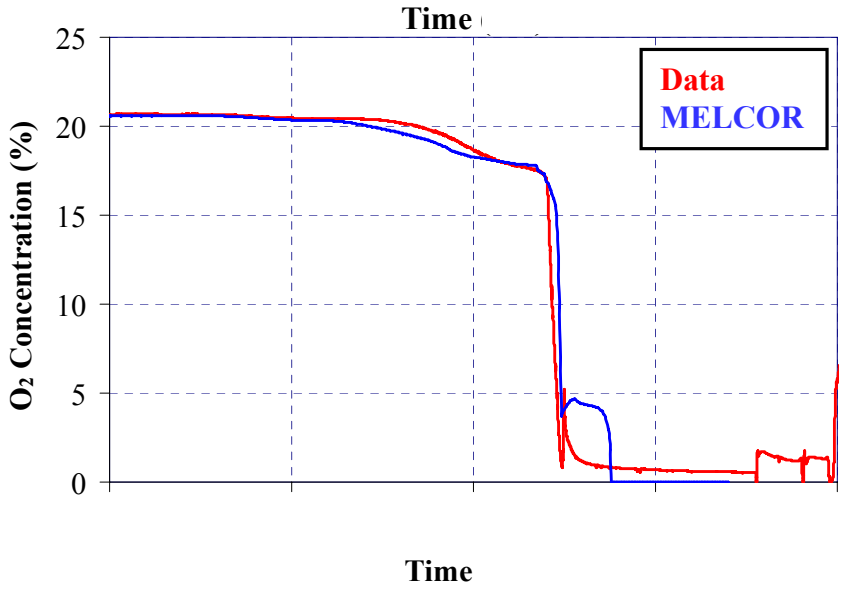
Zircaloy 1 × 4 Ignition
(Ignition Results)





- "Hot" center assembly in 1 × 4 arrangement
  - Equivalent of 15 day-old fuel surrounded by background assemblies (cold neighbor BC)
  - Air flow rates and temperatures independently controlled
  - Strong radial heat transfer to un-powered peripheral assemblies
    - Characterizing peripheral rod emissivity important
  - Investigated sensitivity to reaction kinetics
    - Increased heat rate and oxygen consumption prior to sharp breakaway oxidation behavior
    - Possible connection to phase change in Zr at 1090 K

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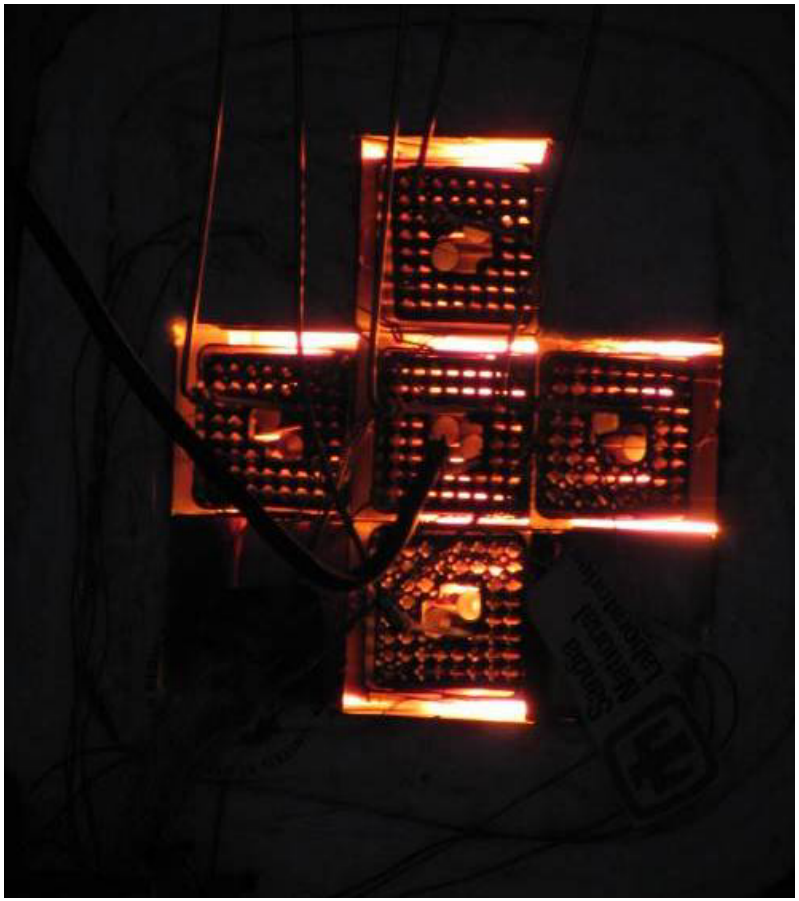
Short Stack
(Ignition Test)



1×4
Ignition
Movie

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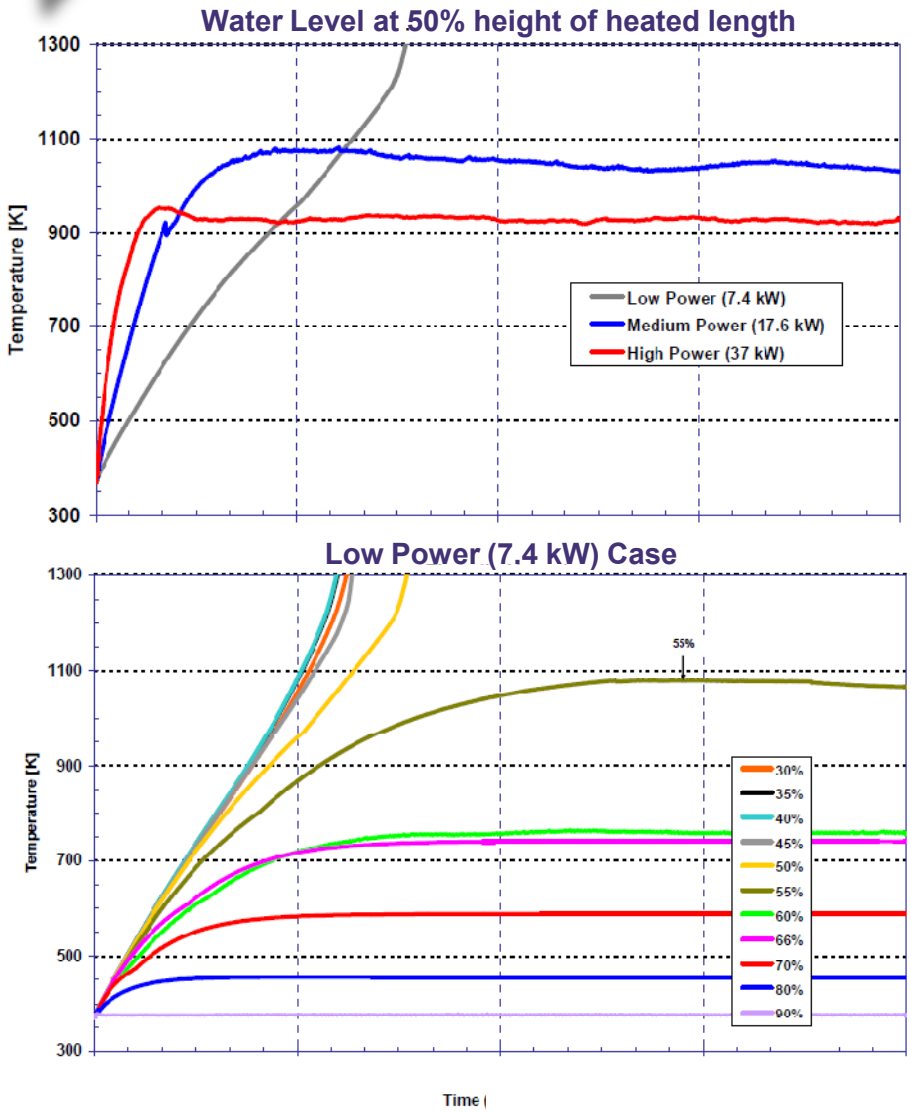
PWR Whole Pool Partial LOCA



- MELCOR calculations for uniform pool loading
- Lowest powered assembly in study potentially more vulnerable
  - Less steam generated to cool upper part of assemblies
- Partial LOCAs may lead to earlier Zr ignition
  - Less coolable for water levels below ~50% of heated length

K.C. Wagner and R.O. Gauntt, "Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pools, Sandia Letter Report," Nov. 2006

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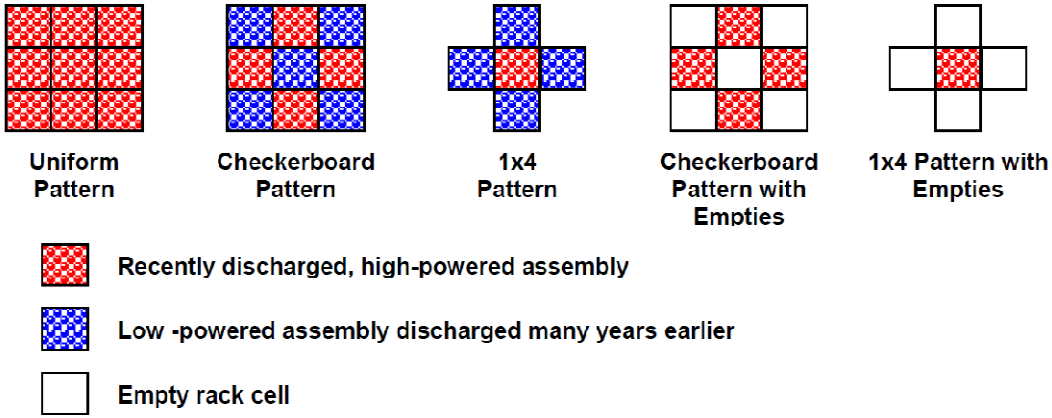
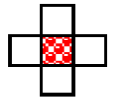
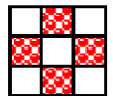
Spent Fuel Pool Configurations



- **Low-density racking least vulnerable**
- **High-density racking with interspersed high and low powered assemblies is best practice for pools near capacity**

Configuration		Ranking
1x4-empties		Best
1x4		
Checkerboard with empties		Good
Checkerboard		Moderate
Uniform		Worst

K.C. Wagner and R.O. Gauntt, "Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pools, Sandia Letter Report," Nov. 2006

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BWR Summary

- Integral ignition tests
  - Full-Scale Assembly Ignition Test:
    - Represents uniform distribution of 100 day old assemblies
    - Prototypic heat-up and ignition response
    - Breakaway phenomena important
      - Evident in both temperature and O_2 measurements
  - 1×4 Ignition Test:
    - Represents 15 day old assembly with old neighbors
    - Confirmed delayed ignition
      - Potential for radial propagation
      - Showed importance of radial heat transfer