

# *Investigations of Zirconium Fires during Spent Fuel Pool LOCAs*

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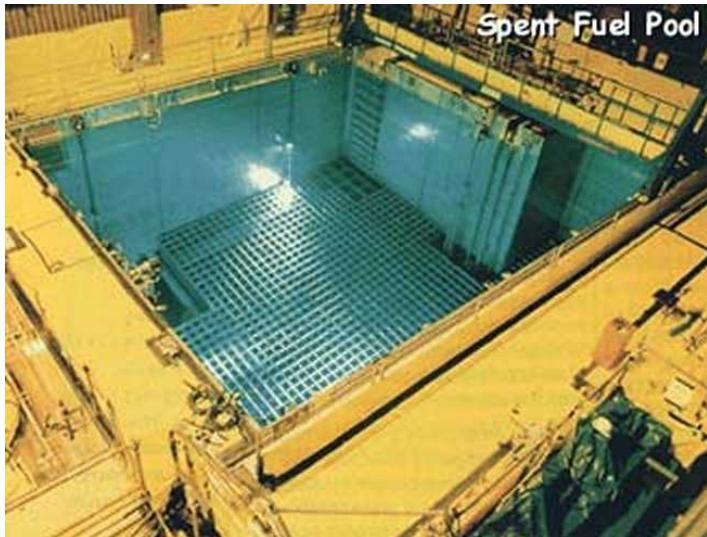
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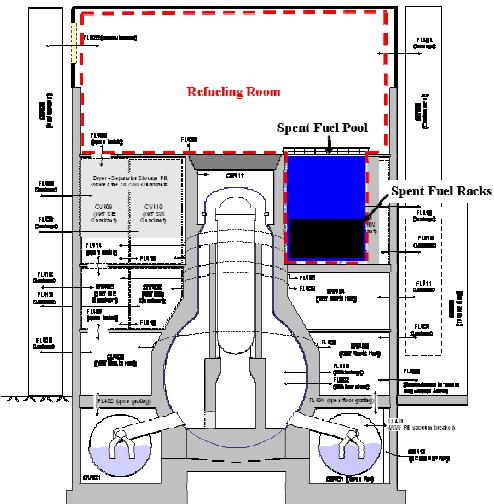
# Outline

- 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*



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- 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

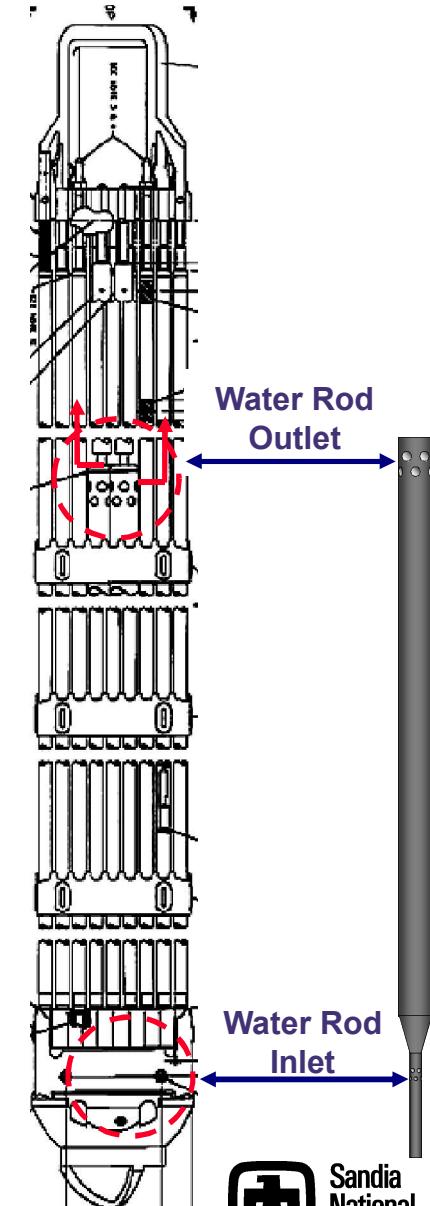
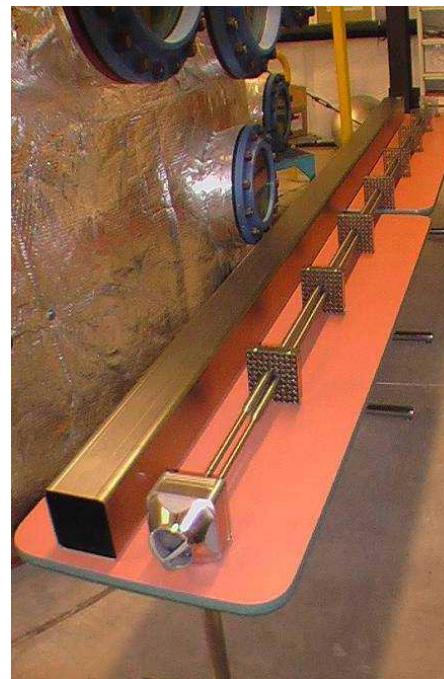
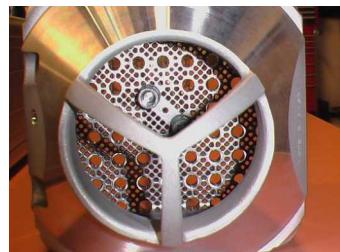
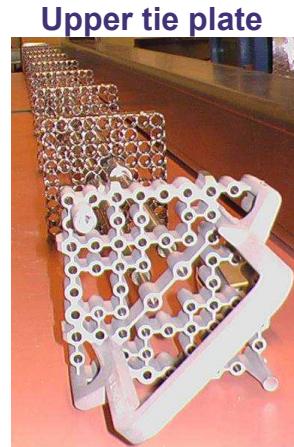


# *SFP Experiment Objectives*

- 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**





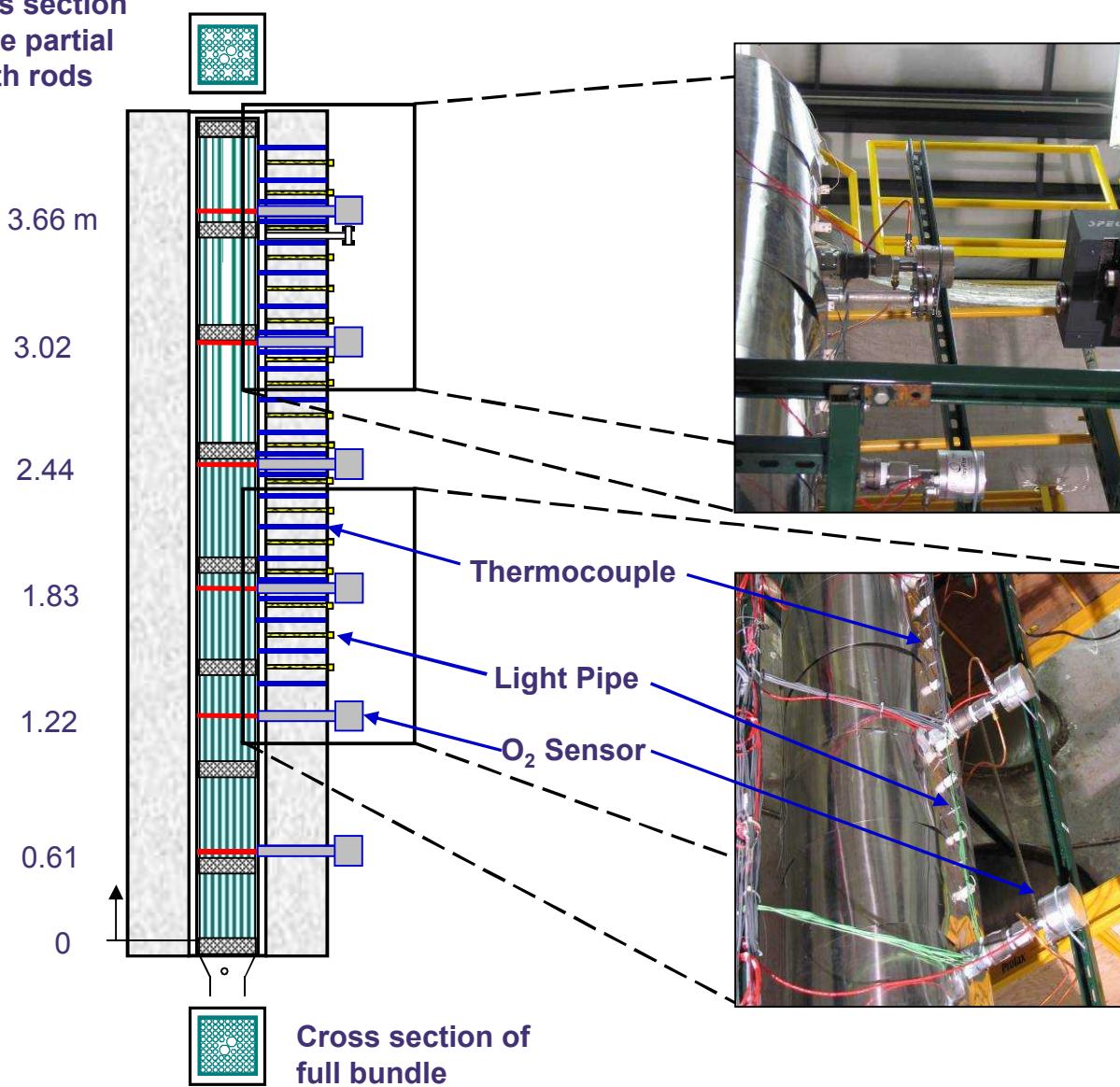
# *Integral Effects Tests*

## *(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<sub>2</sub> concentration: Determine depletion
    - Nature of fire: Initiation location & axial burn rate

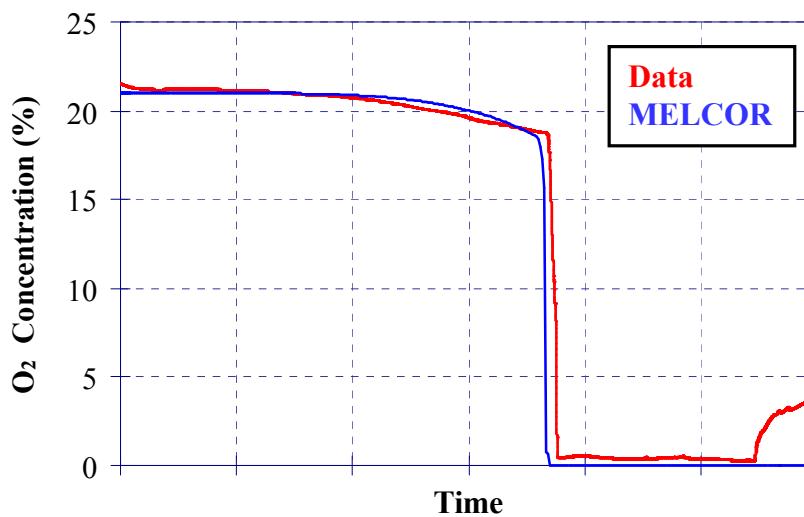
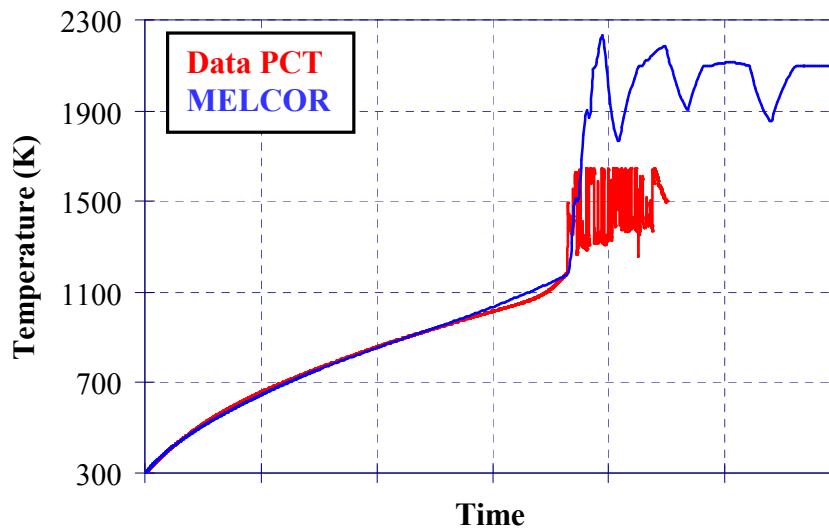
# Full Scale Zircoloy (Ignition Test Instrumentation)

Cross section  
above partial  
length rods



# 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)



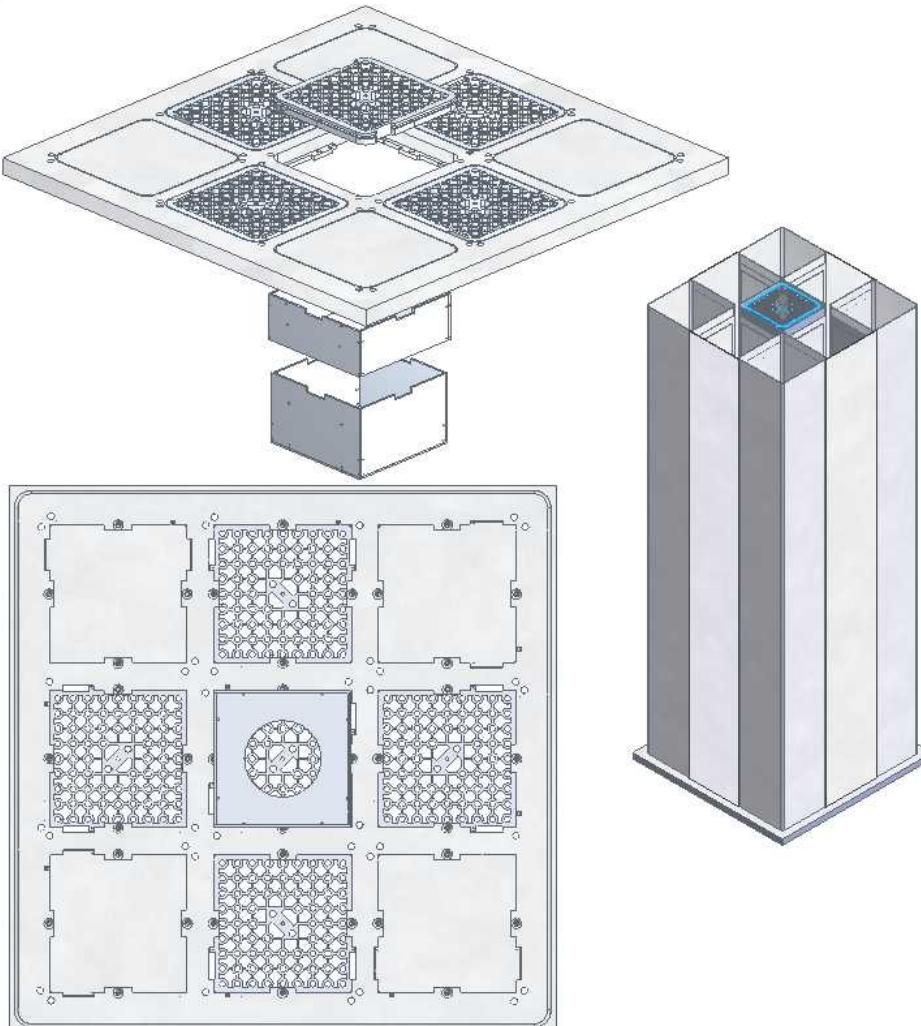
# Postmortem



Full Length  
Ignition  
Movie



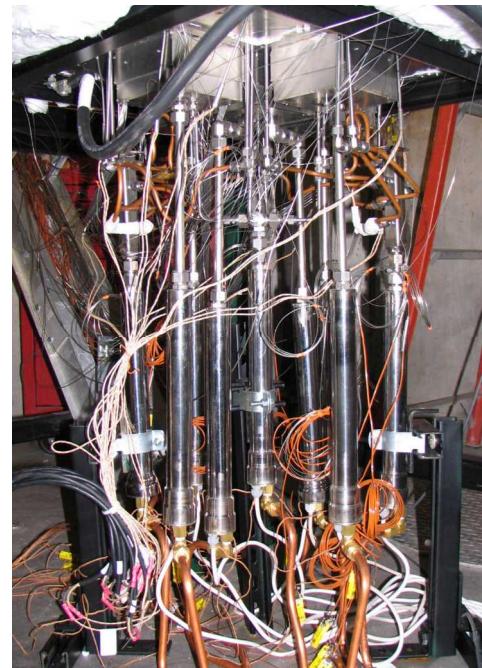
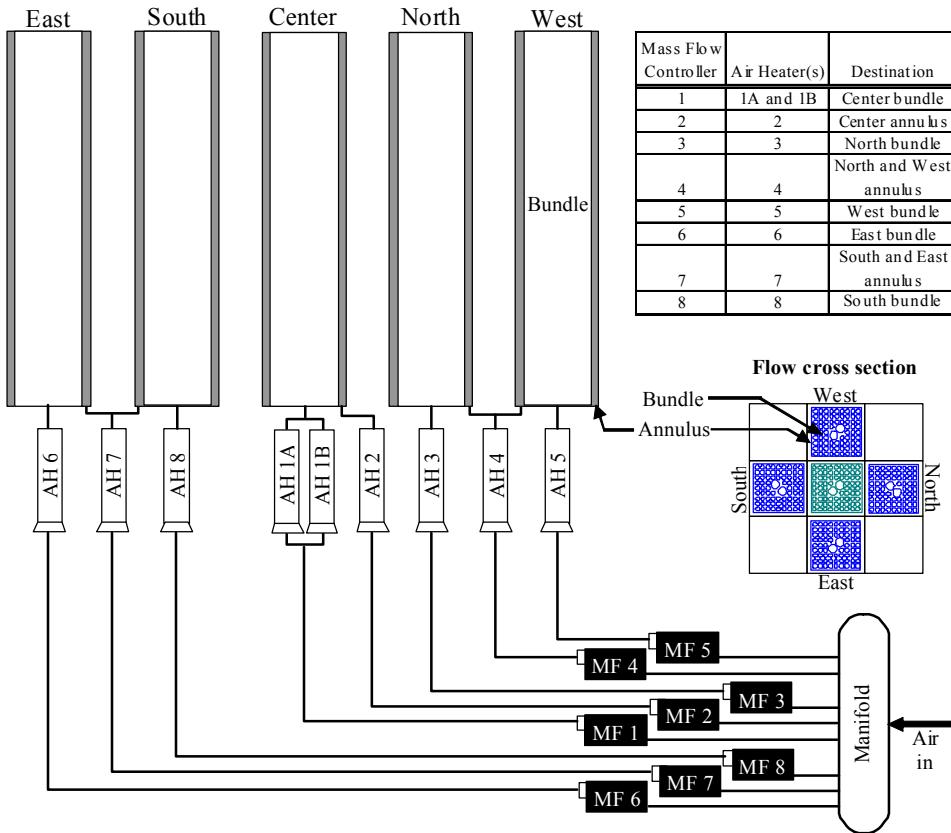
# Zircaloy Short Stack Design



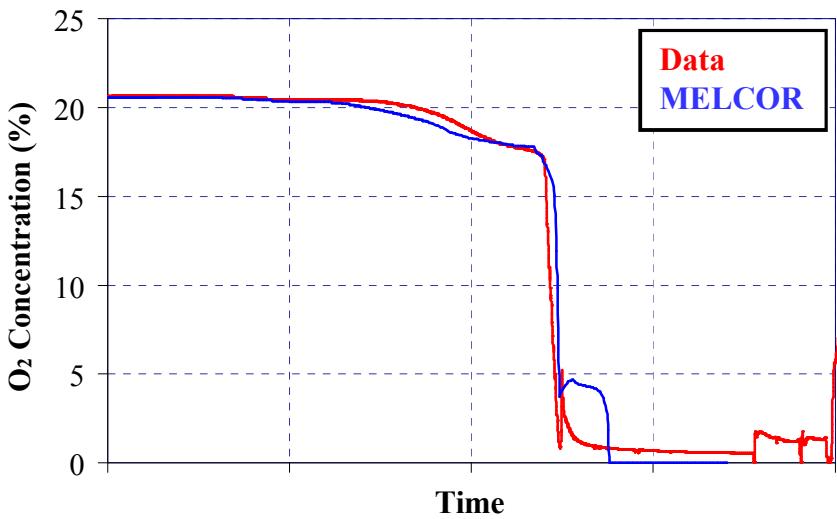
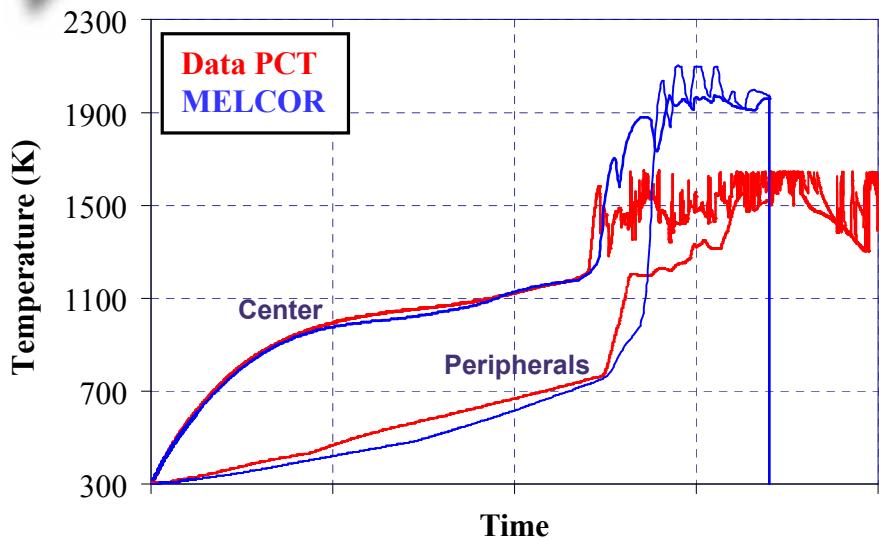
- Simulate “hot” center assembly in  $1 \times 4$  arrangement
  - Unpowered Zircaloy peripheral assemblies
  - “cold neighbor” BC
- Bottom and top tie plates allow flow
  - Bundle and annular flow rates and temperature independently controlled
- Prototypic commercial pool rack

# Inlet Condition Control

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



# Zircaloy 1 $\times$ 4 Ignition (Ignition Results)

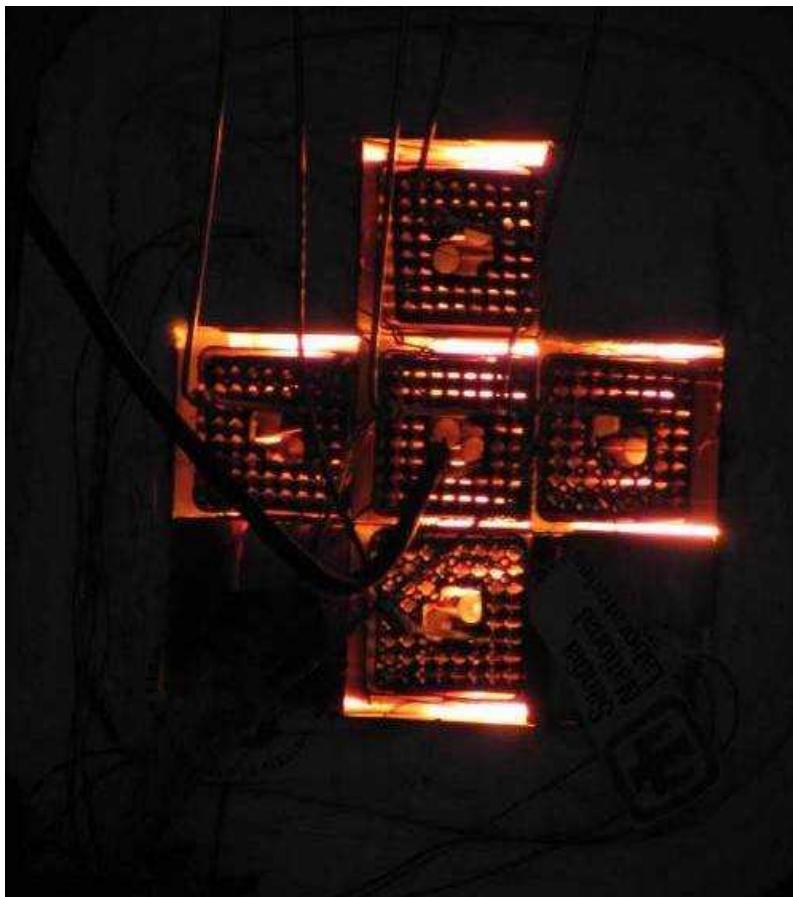


- “Hot” center assembly in  $1 \times 4$  arrangement
  - Equivalent of 15 day-old fuel surrounded by background assemblies (cold neighbor BC)
  - Air flow rates and temperatures independently controlled
  - Strong radial heat transfer to un-powered peripheral assemblies
    - Characterizing peripheral 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



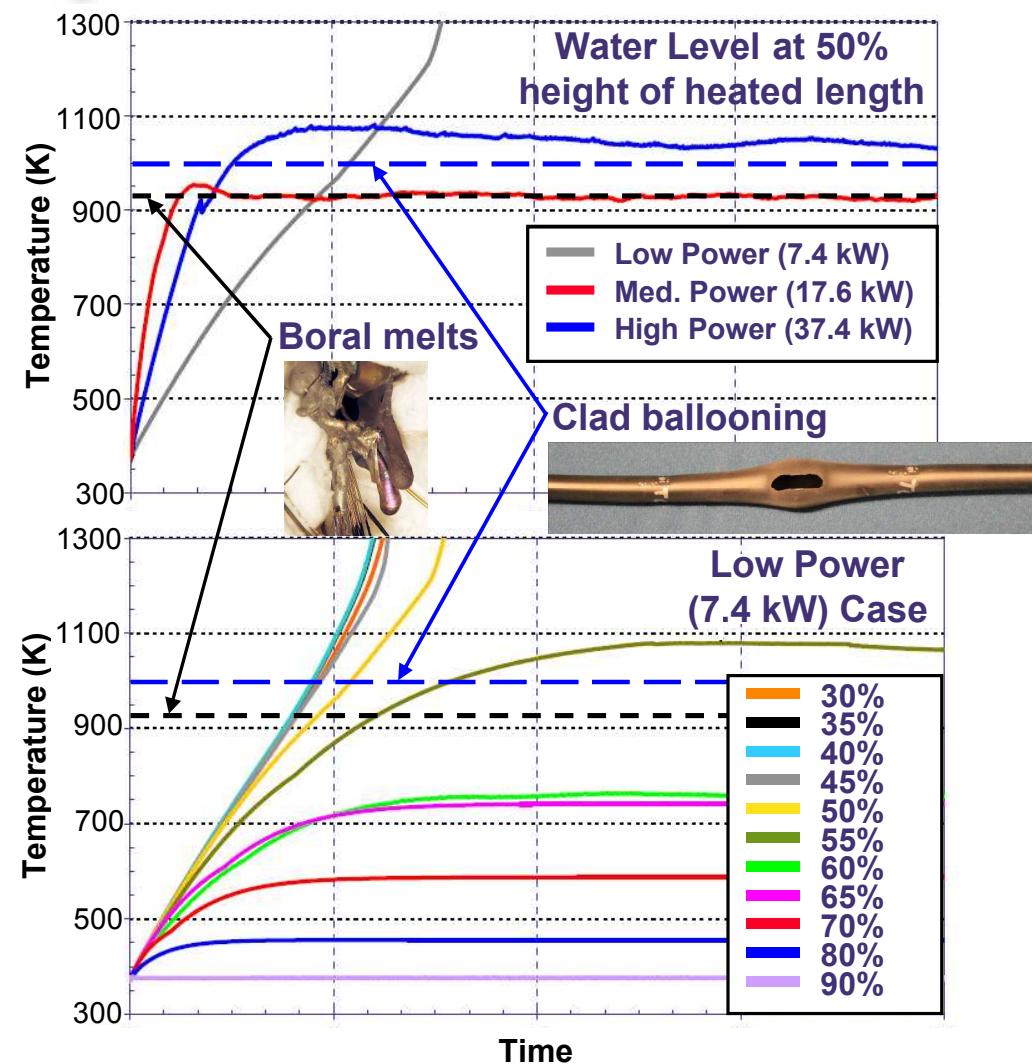
# Short Stack

## (Ignition Test)



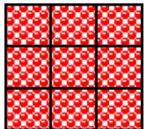
1x4  
Ignition  
Movie

# PWR Whole Pool Partial LOCA

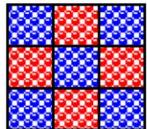


- MELCOR calculations for uniform pool loading
- Lowest powered assembly in study potentially more vulnerable
  - Less steam generated to cool upper part of assemblies
- Partial LOCAs may lead to earlier Zr ignition
  - Less coolable for water levels below ~50% of heated length

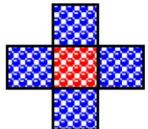
# Spent Fuel Pool Configurations



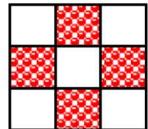
Uniform Pattern



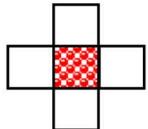
Checkerboard Pattern



1x4 Pattern



Checkerboard Pattern with Empties



1x4 Pattern with Empties



Recently discharged, high-powered assembly



Low-powered assembly discharged many years earlier



Empty rack cell

- **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



# 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<sub>2</sub> 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