



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

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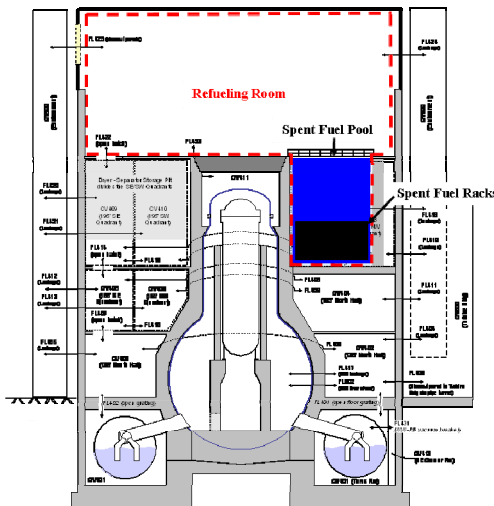
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# *Outline*

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



- **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**



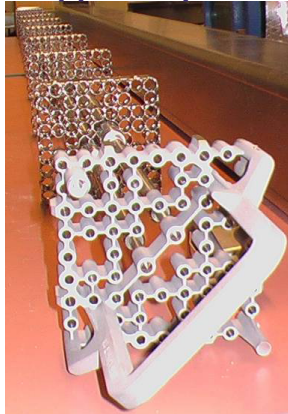
# ***SFP Experiment Objectives***

- 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**

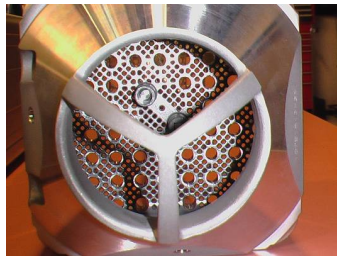
# Actual Hardware

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

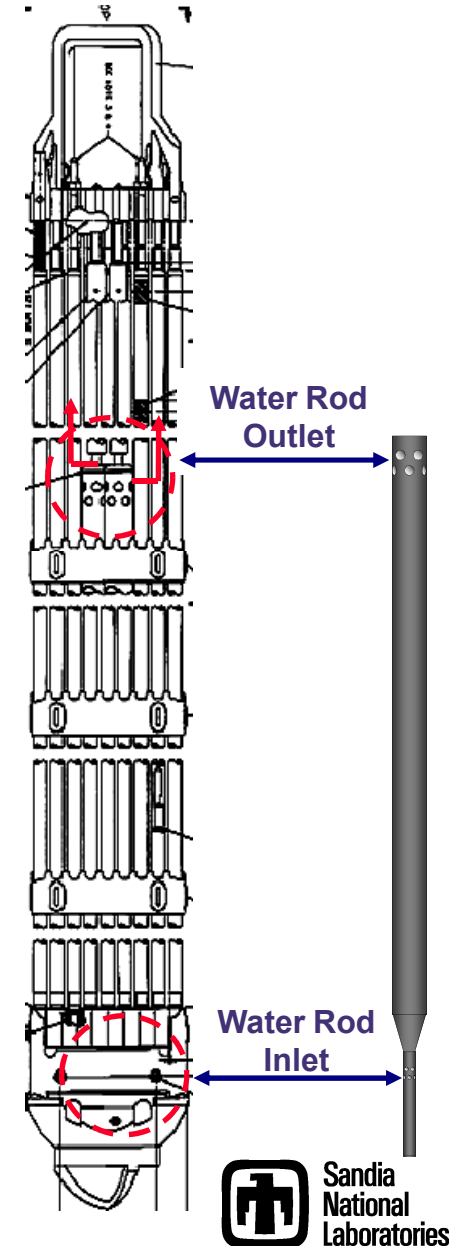
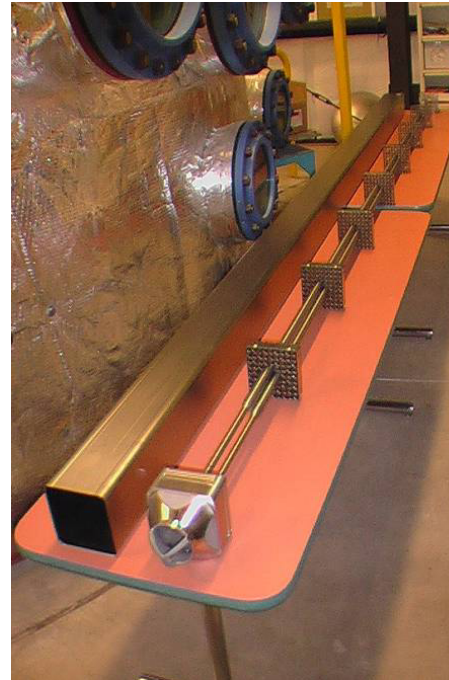
Upper tie plate



Nose piece & debris catcher



BWR channel, water tubes & spacers





# ***Integral Effects Tests***

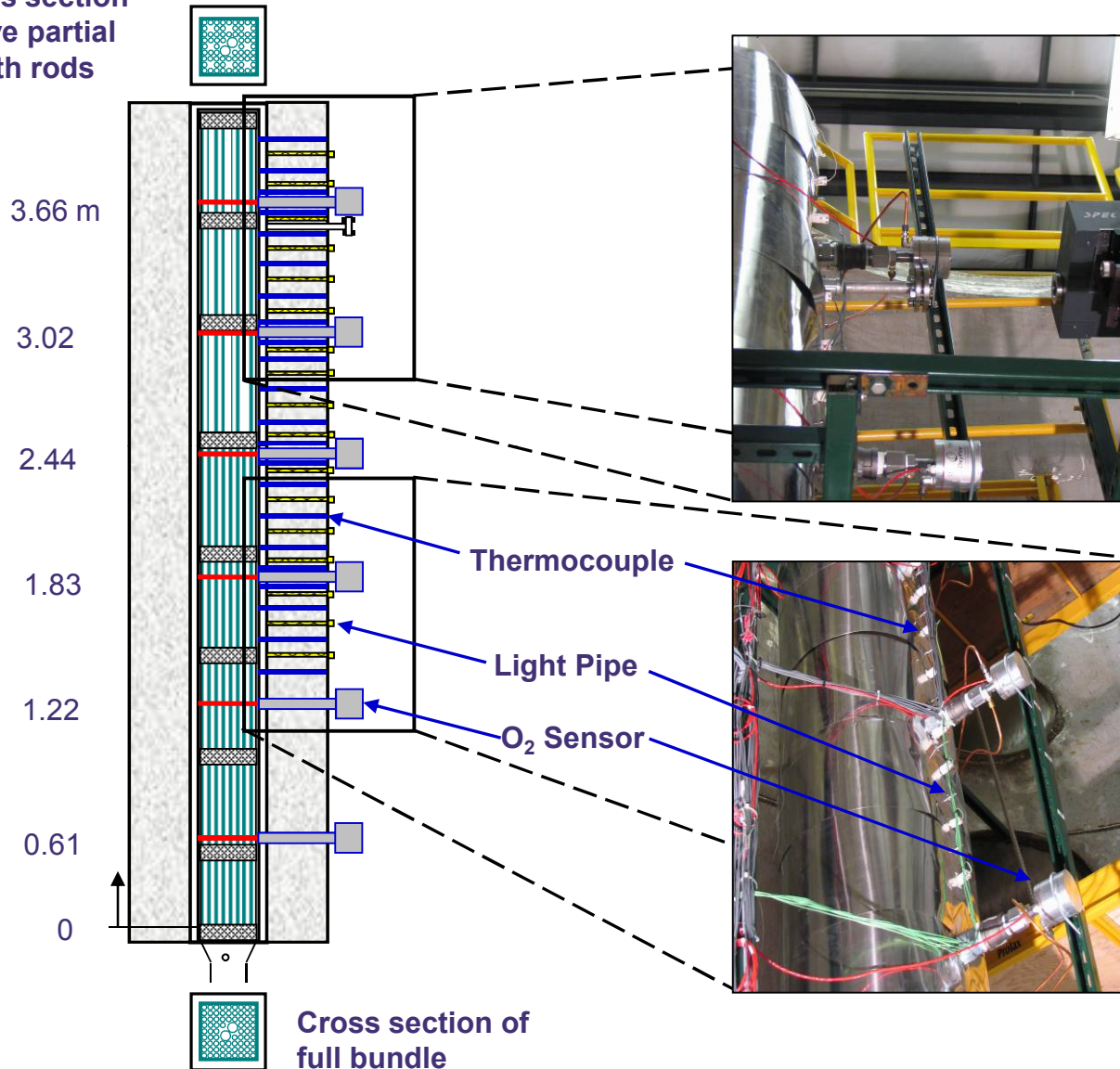
## ***(Single, Full Length)***

- **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**

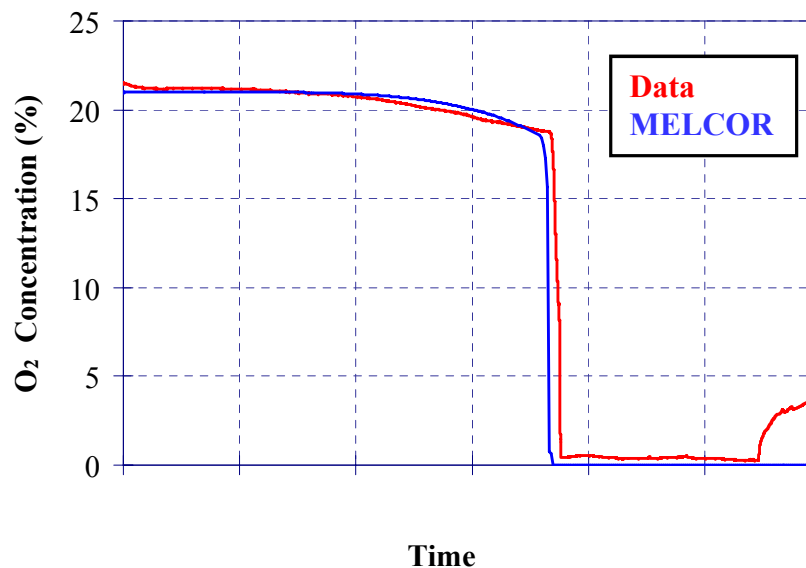
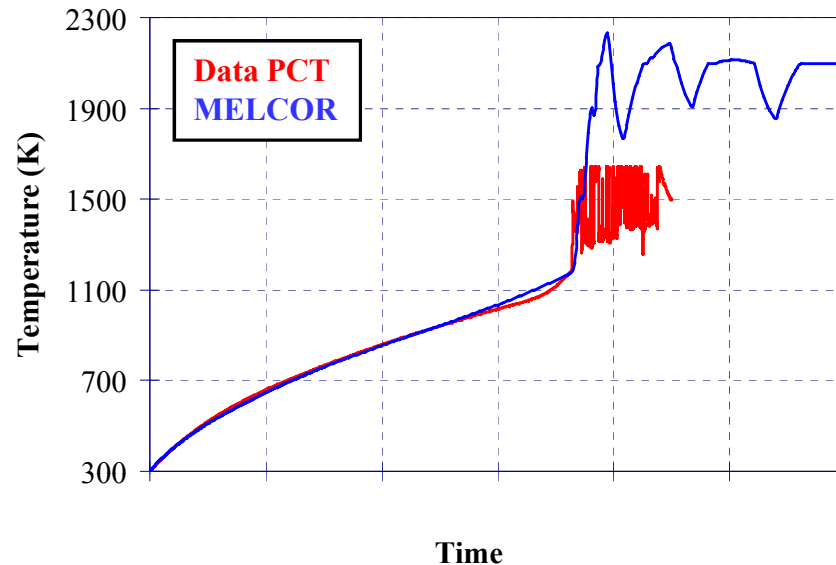


# Full Scale Zircoloy (Ignition Test Instrumentation)

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)

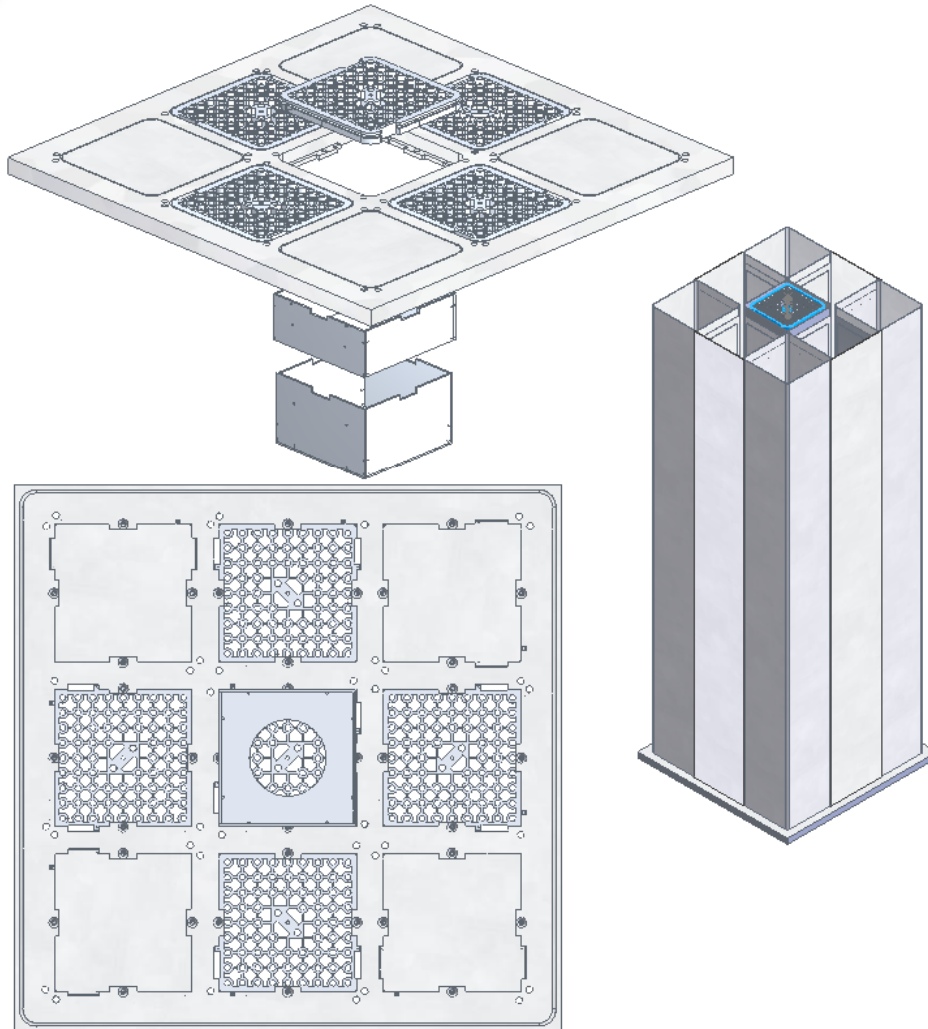


# Postmortem





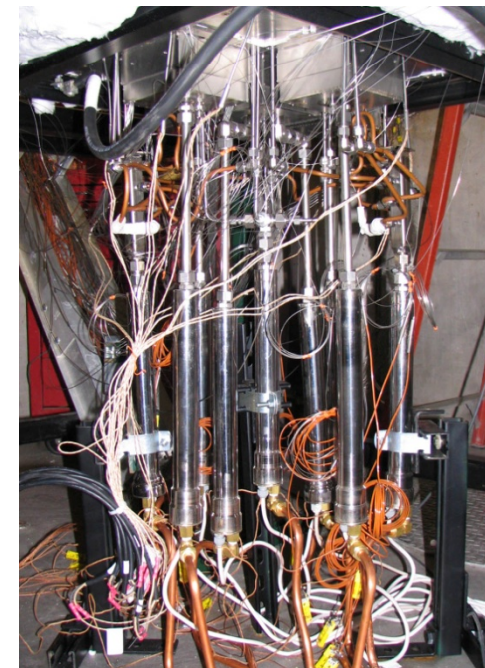
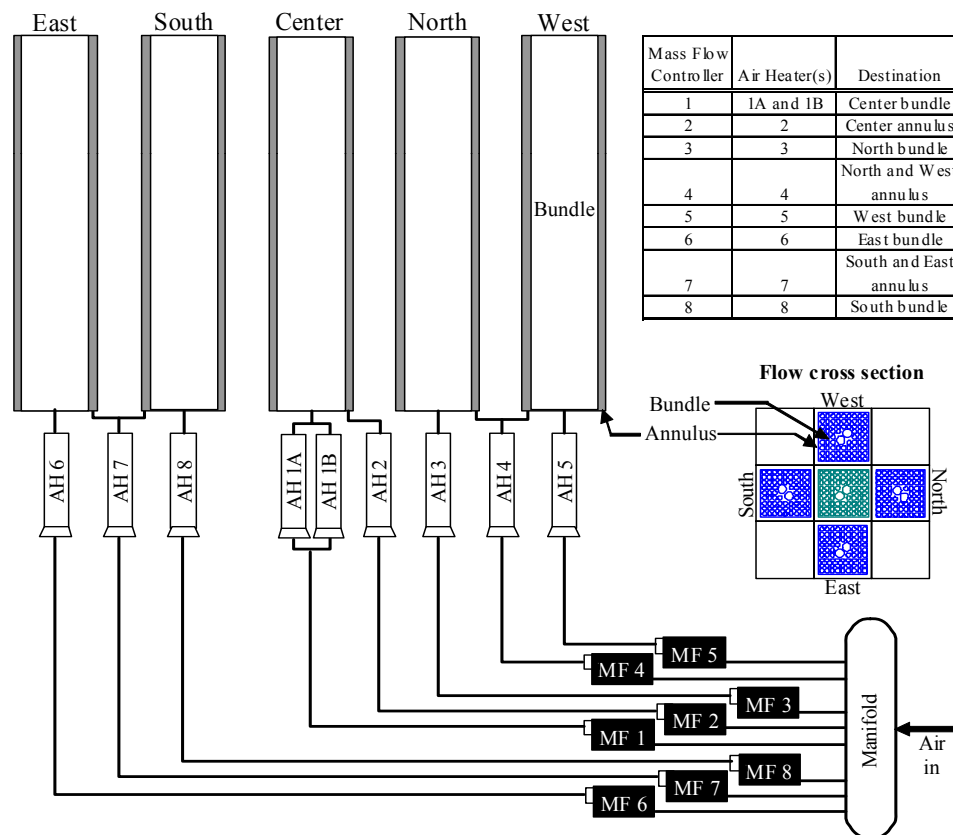
# ***Zircoloy Short Stack Design***



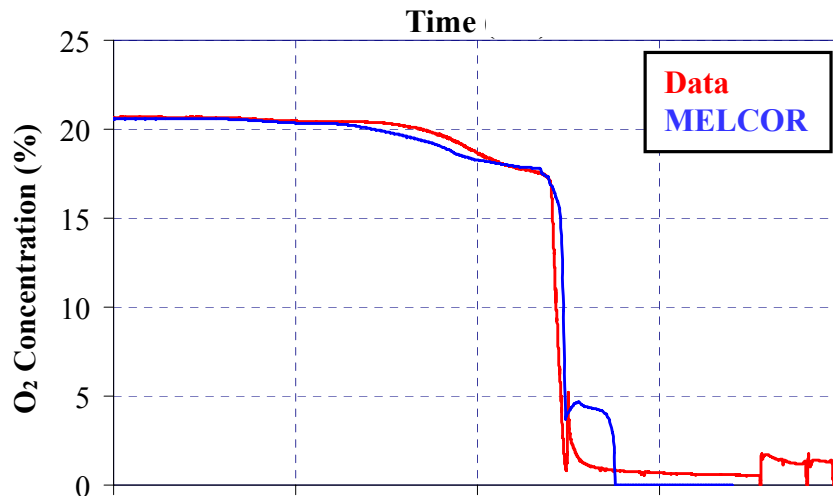
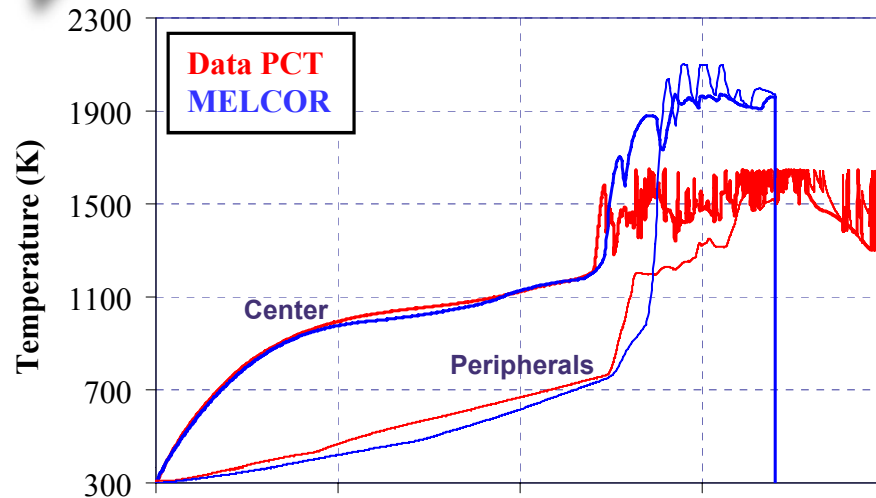
- **Simulate “hot” center assembly in  $1 \times 4$  arrangement**
  - **Unpowered Zircaloy peripheral assemblies**
  - **“cold neighbor” BC**
- **Bottom and top tie plates allow flow**
  - **Bundle and annular flow rates and temperature independently controlled**
- **Prototypic commercial pool rack**

# Inlet Condition Control

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



# Zircaloy 1 × 4 Ignition (Ignition Results)



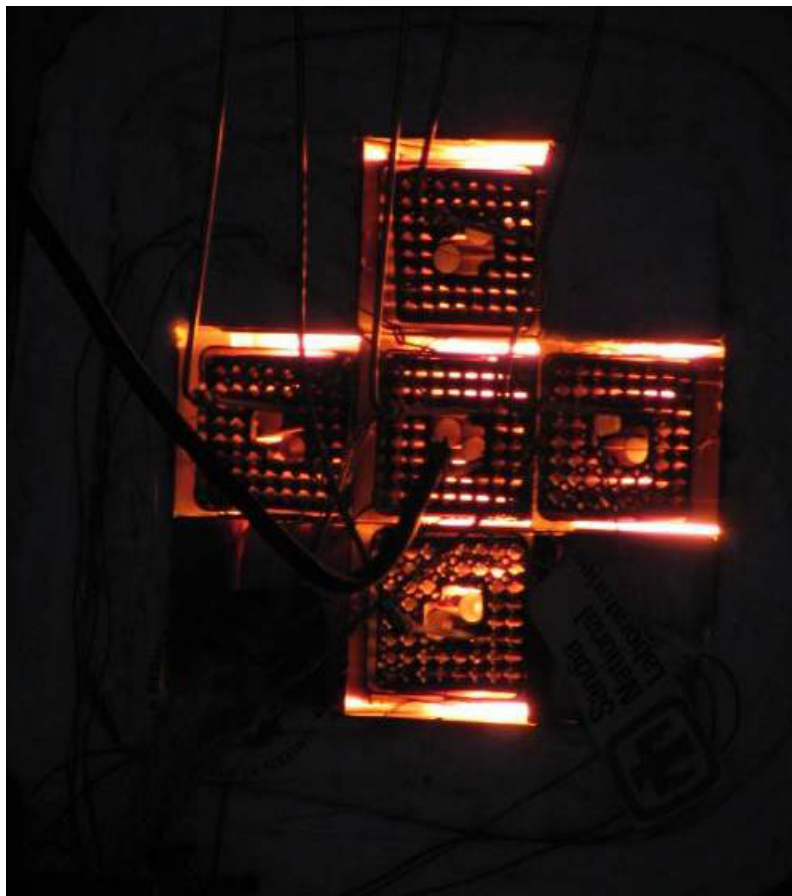
- “Hot” center assembly in 1 × 4 arrangement
  - Equivalent of 15 day-old fuel surrounded by background assemblies (cold neighbor BC)
  - Air flow rates and temperatures independently controlled
  - Strong radial heat transfer to un-powered peripheral assemblies
    - Characterizing peripheral rod emissivity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





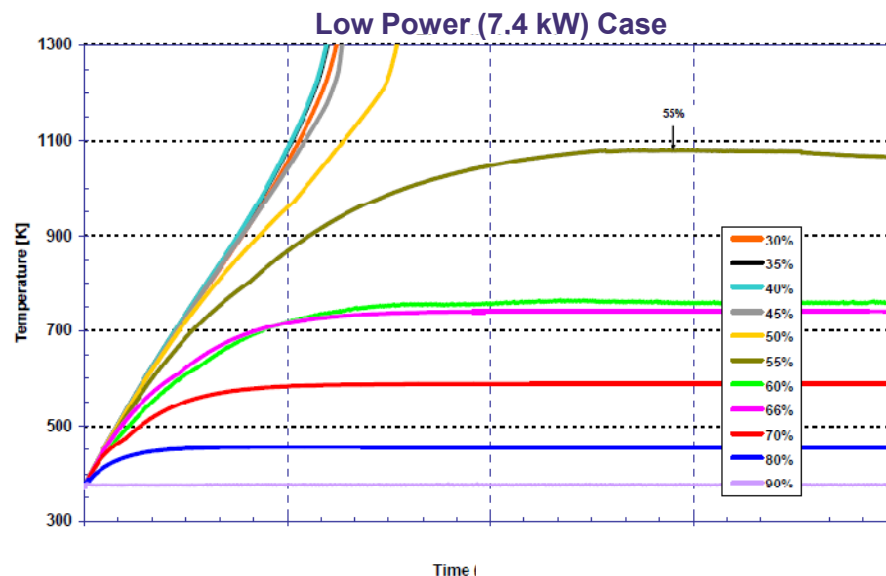
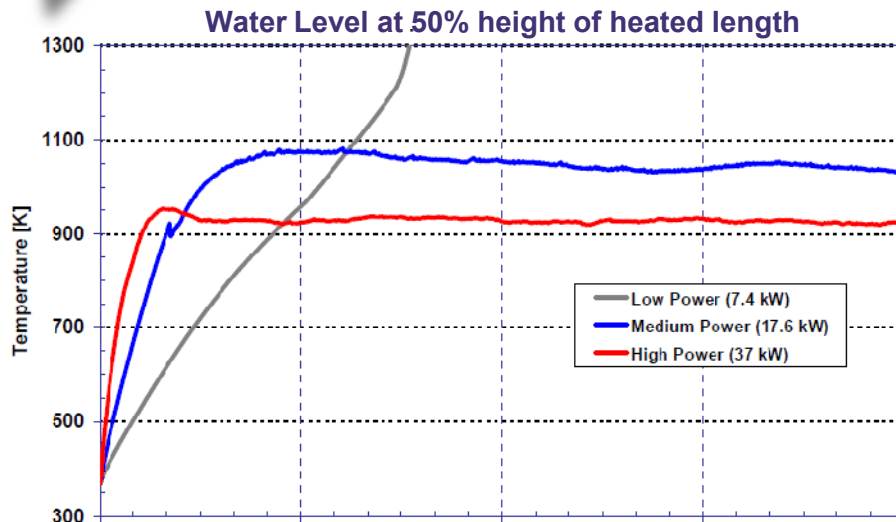
# ***Short Stack***

## ***(Ignition Test)***



1x4  
Ignition  
Movie

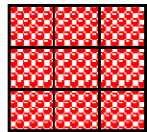
# PWR Whole Pool Partial LOCA



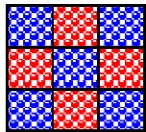
- MELCOR calculations for uniform pool loading
- Lowest powered assembly in study potentially more vulnerable
  - Less steam generated to cool upper part of assemblies
- Partial LOCAs may lead to earlier Zr ignition
  - Less coolable for water levels below ~50% of heated length



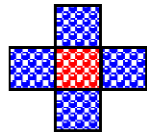
# Spent Fuel Pool Configurations



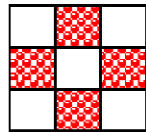
Uniform Pattern



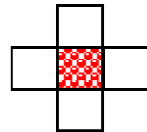
Checkerboard Pattern



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