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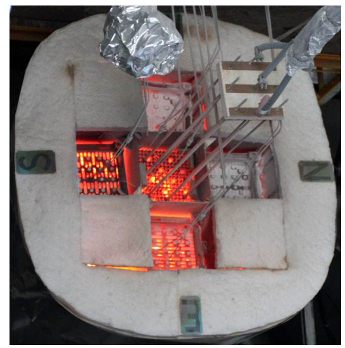

Summary of Zirconium Fire Investigations during Spent Fuel Pool Complete LOCAs

S.G. Durbin and E.R. Lindgren

BWR Test Series
Funded by USNRC

PWR Test Series
Funded by USNRC and OECD

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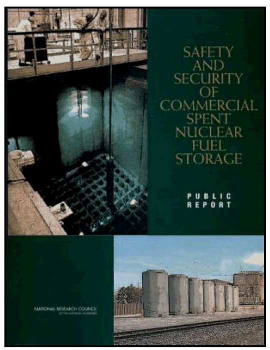
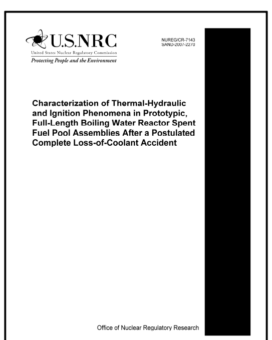
Post 9/11 Environment

Sandia National Laboratories

- 2003 – Article identifying potential vulnerabilities of current spent fuel storage
  - Highlighted possibility of zirconium cladding fires in modern, high-density spent fuel pools (SFPs)
  - Recommended transfer to dry storage within five years of discharge

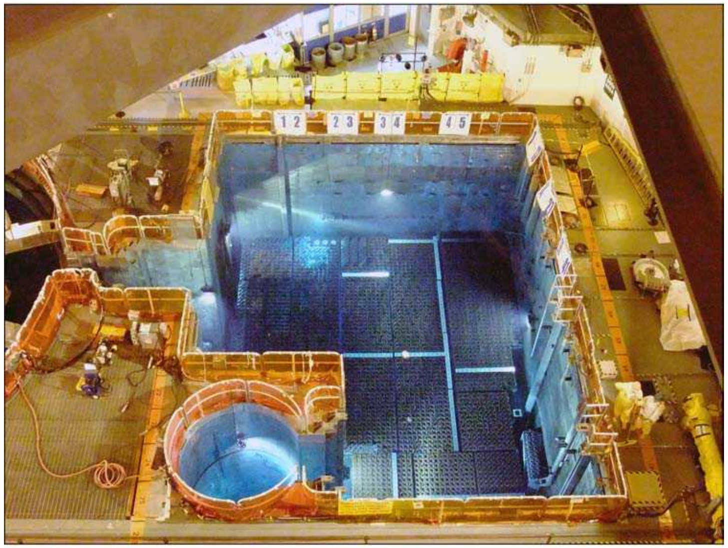


- 2004 – National Research Council produced comprehensive report for Congress on safety and security of spent fuel
  - Found a propagating zirconium cladding fire possible for some partial and complete loss-of-coolant-accidents (LOCAs) in SFPs
  - Resulting in large quantities of radioactive materials to the environment
  - Recommended that USNRC investigate vulnerabilities and consequences of LOCAs in SFPs



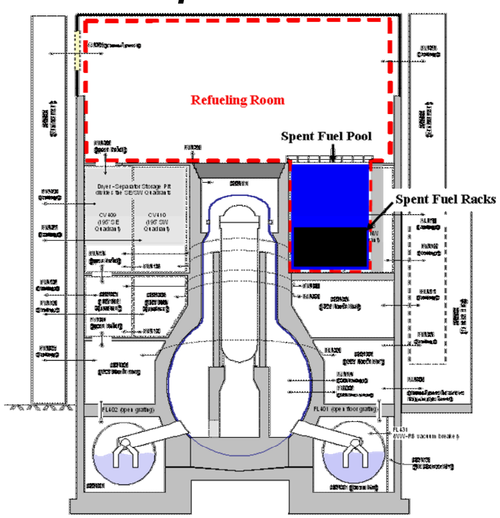
- 2005 – USNRC commissioned complete LOCA testing program for boiling water reactor (BWR) fuel
  - Demonstrated zirconium fires in near-prototypic spent fuel
  - Showed potential for propagation between assemblies
- 2009 – USNRC and OECD commissioned complete LOCA testing for pressurized water reactor (PWR) fuel
  - Two full-scale ignition tests completed
  - Clad ballooning and nitrogen depletion observed

Overview



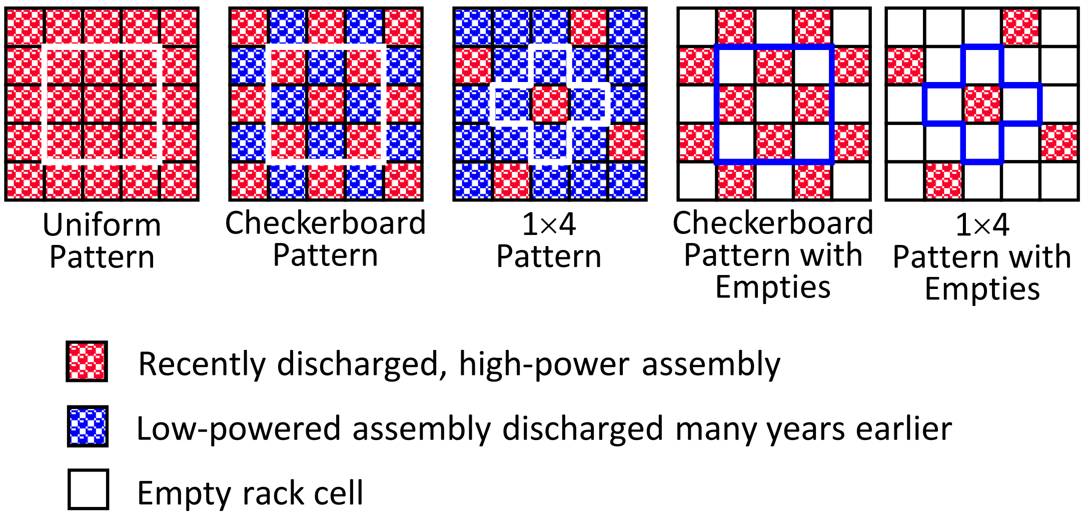
Source: Nuclear Energy Institute.

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

Spent Fuel Pool Configurations



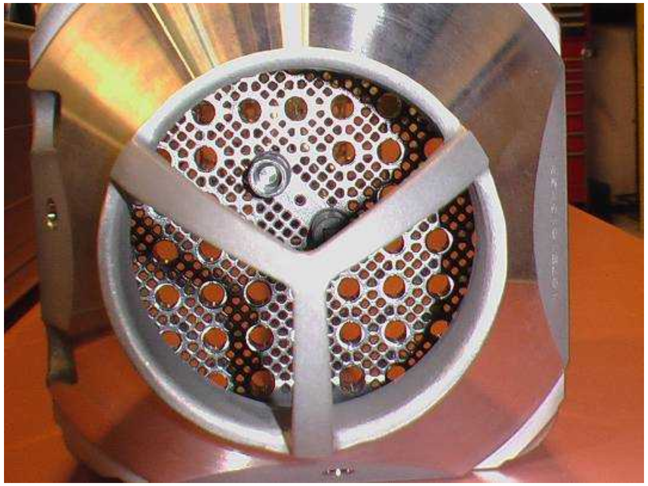
Configuration	Ranking
1×4 empties	Best
1×4	Best
Checkerboard with empties	Good
Checkerboard	Moderate
Uniform	Worst

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

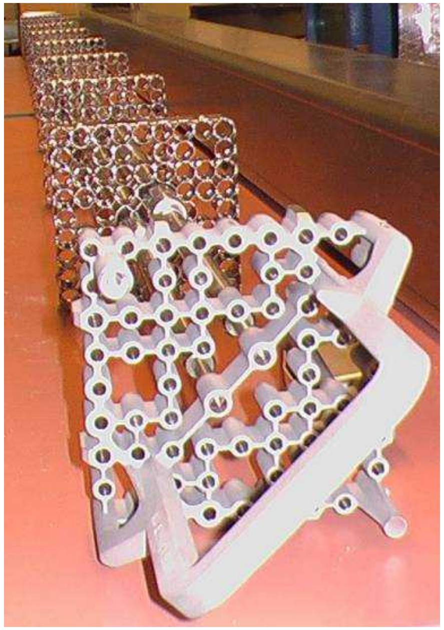
K.C. Wagner and R.O. Gauntt, "Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pools," Sandia Letter Report, Nov. 2006

BWR Hardware

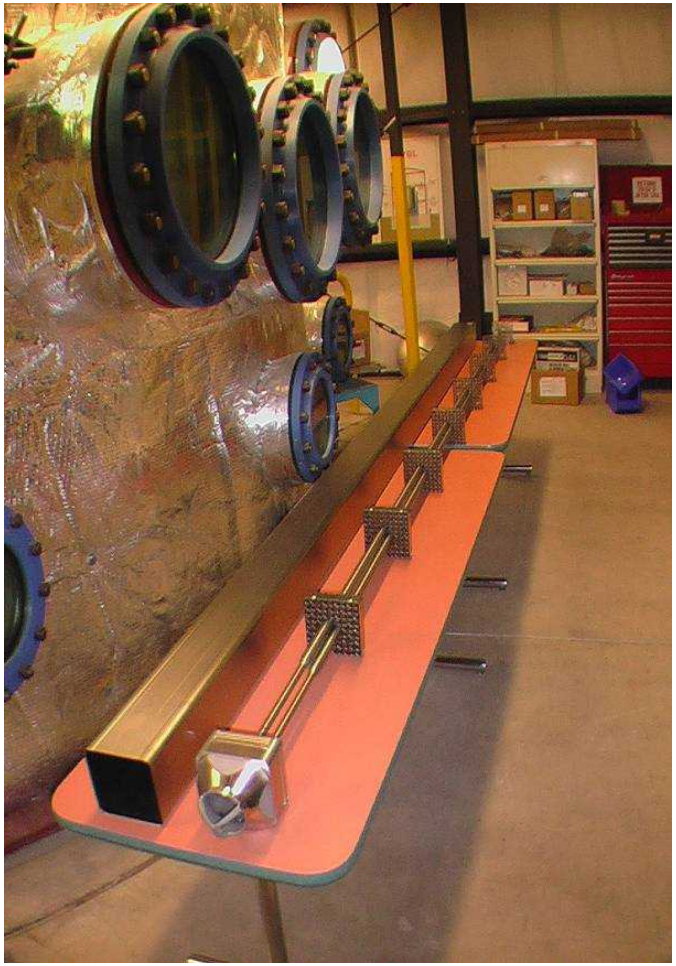
- Prototypic GE 9x9 BWR Hardware
  - Full length, prototypic GE 9x9 BWR components
  - Electric heater rods with Zr cladding for ignition testing



Nose piece & debris catcher



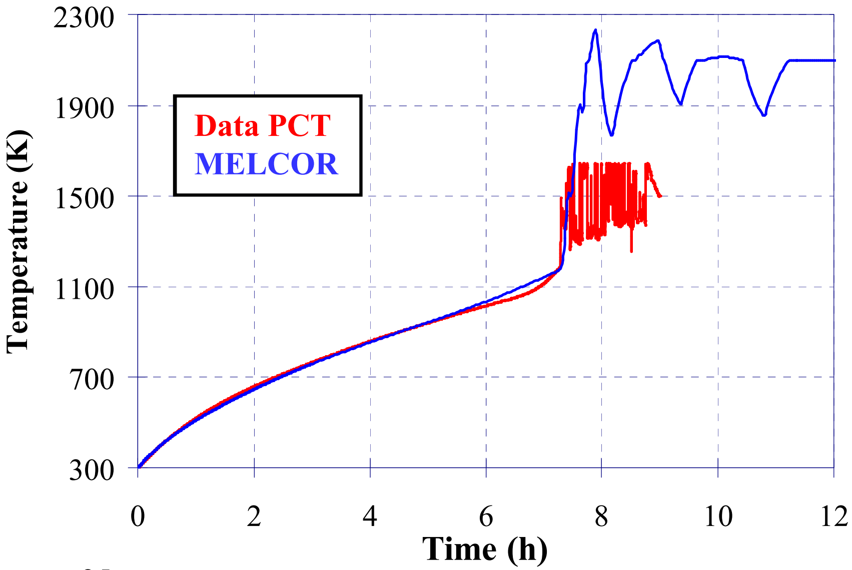
Upper tie plate

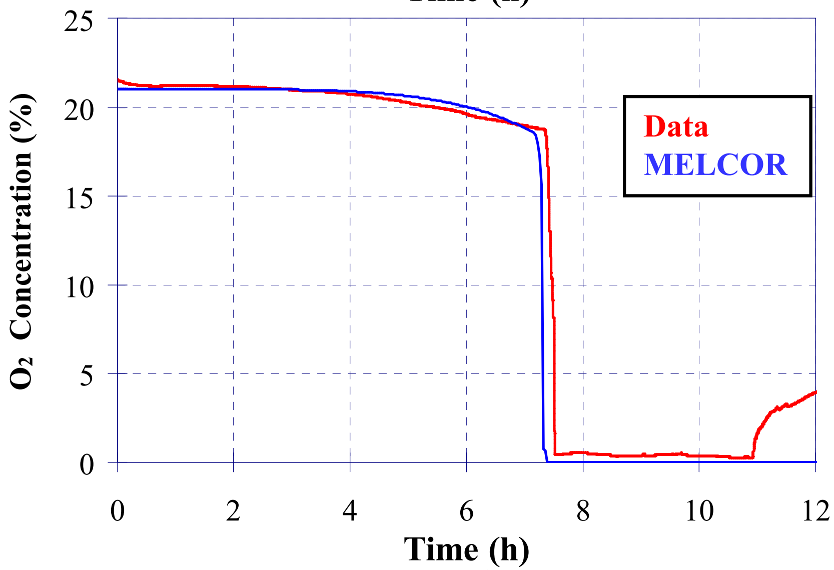


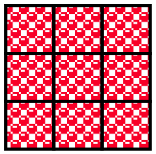
BWR channel, water tubes & spacers

Full Length Zr BWR

(Ignition Results)







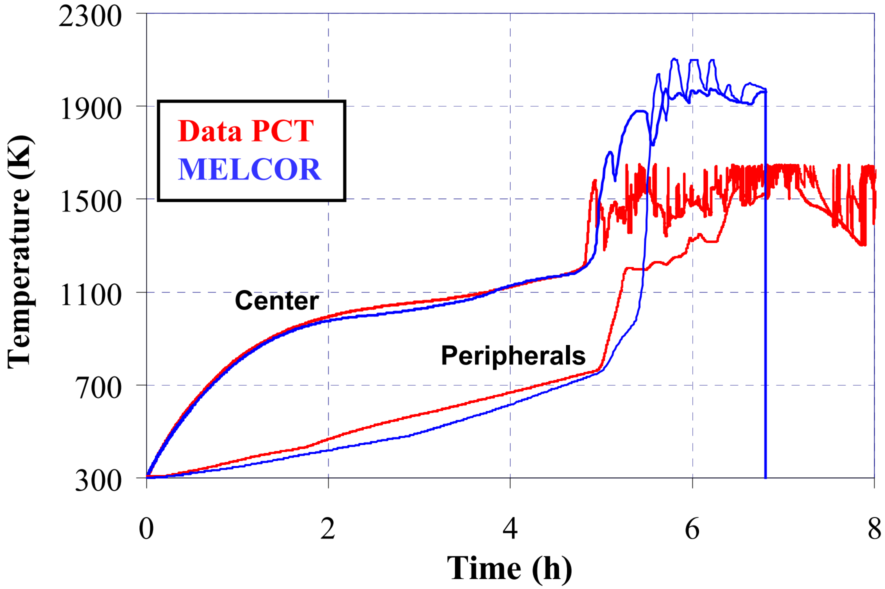
Uniform Loading

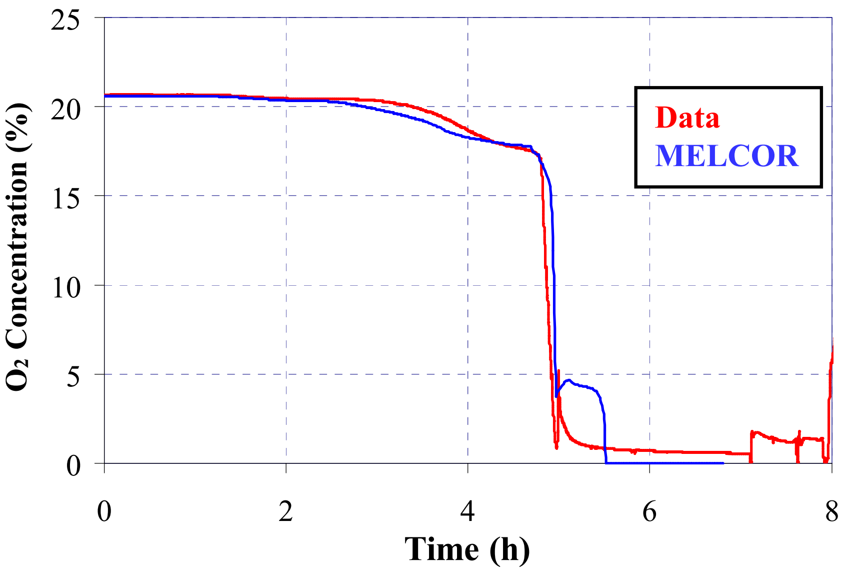
- Assembly power 5.0 kW
  - Situational equivalent of a cluster of 100 day-old assemblies
- MELCOR within 40 K
  - Ignition predicted to within 5 minutes
- Oxygen depletion accurately modeled
  - O_2 reaction kinetics adequately represented

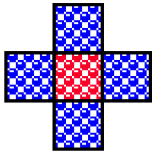
Full Length Zr BWR

(Ignition Test)

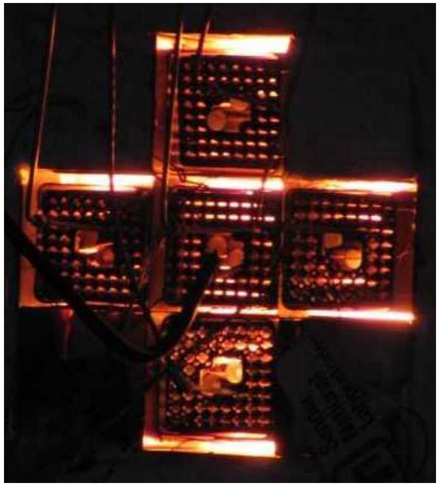
Zircaloy BWR 1×4 Ignition







1×4 Loading



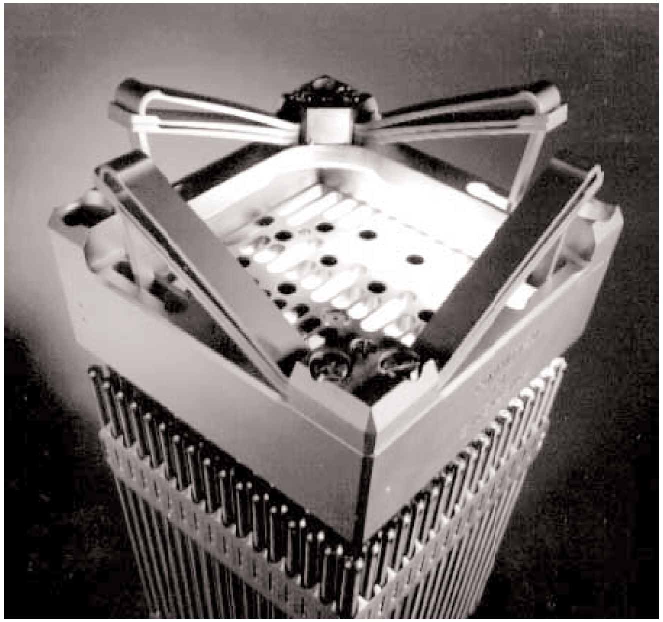
- “Hot” center assembly in 1×4 arrangement
  - Equivalent of 15 day-old fuel surrounded by background assemblies
  - Air flow rates and temperatures independently controlled
- MELCOR results within 40 K
  - Ignition modeled to within 10 minutes

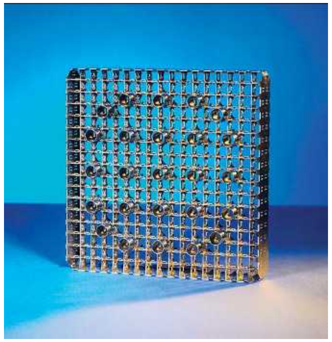
BWR 1×4 Ignition

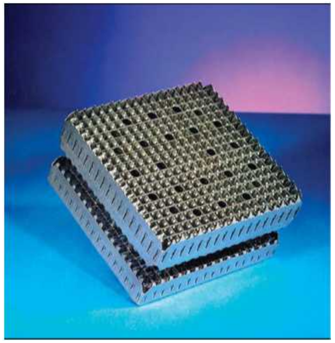
Before

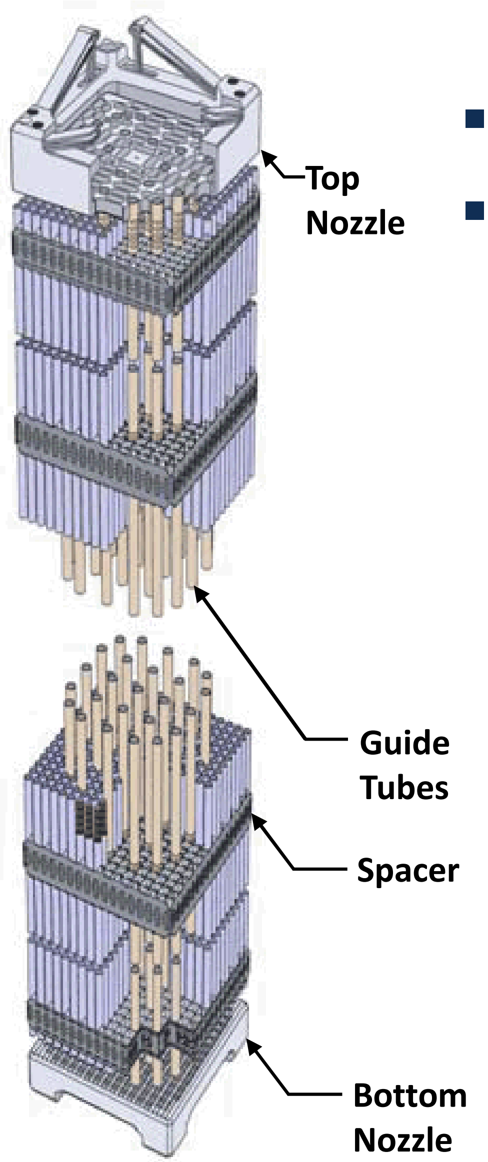
After

PWR Hardware



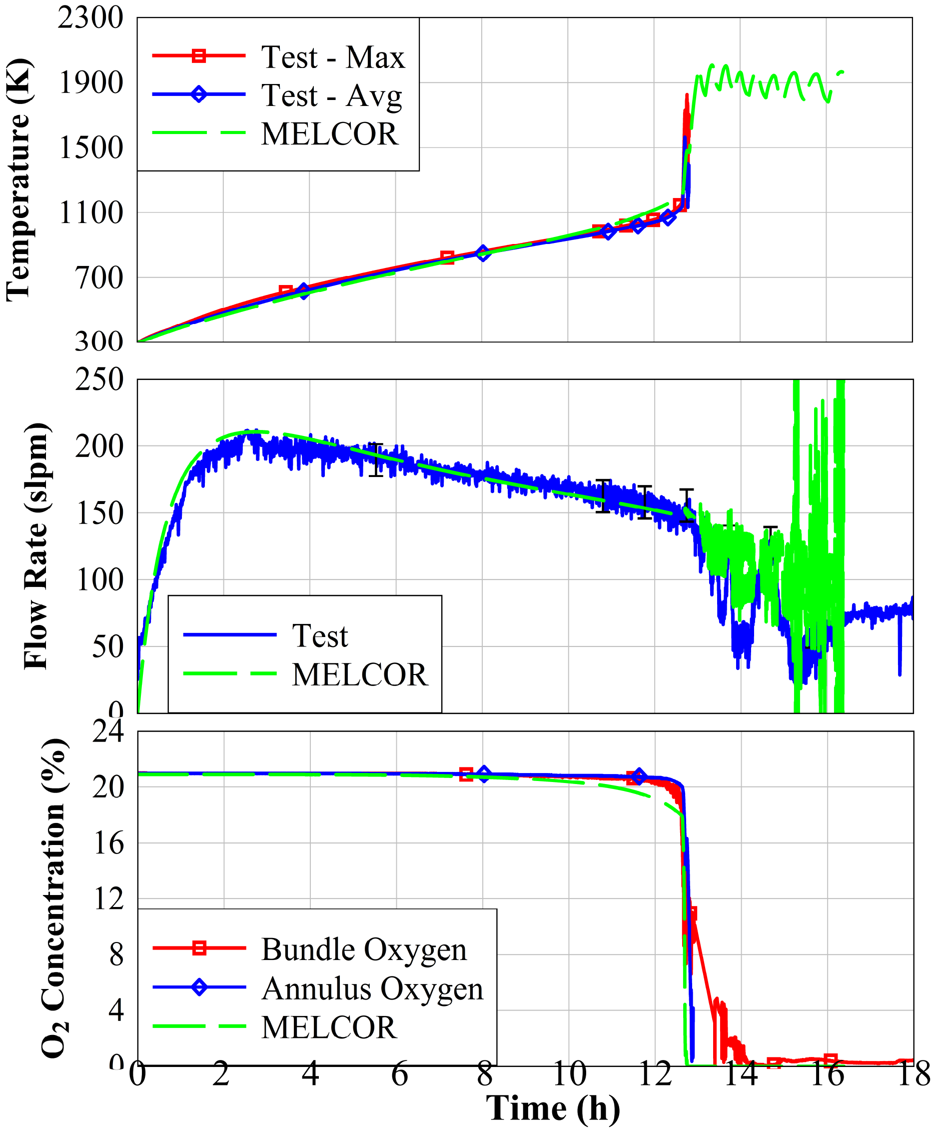




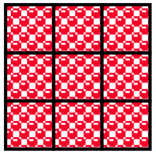


- Prototypic 17×17 PWR
- More form losses than BWR (7 spacers)
  - 8 grid spacers
  - 3 flow mixers
  - 1 debris catcher
  - 264 electric heater rods

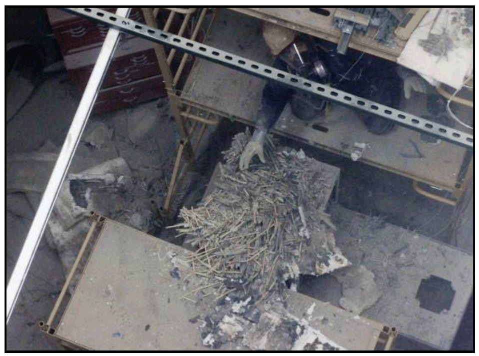
PWR Phase 1 Ignition Test Results

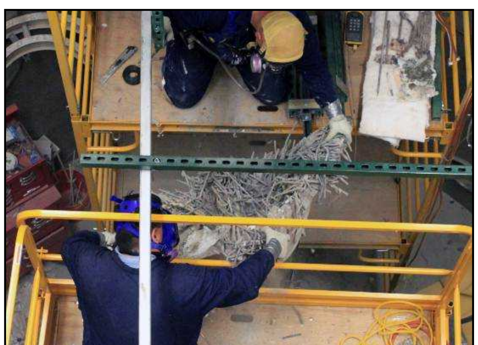


- Assembly power 5.0 kW
  - Situational equivalent of a cluster of 15 month-old assemblies (hot neighbor BC)
- Modeling predicts ignition within 10 minutes
- Thermocouples failed after ignition
  - Sharp transition to breakaway oxidation
  - Oxygen depletion at time of ignition
- Predicted flow rate within experimental uncertainty
- Interesting dynamics on burn-front movement
  - Usually downward to follow oxygen and fresh Zr

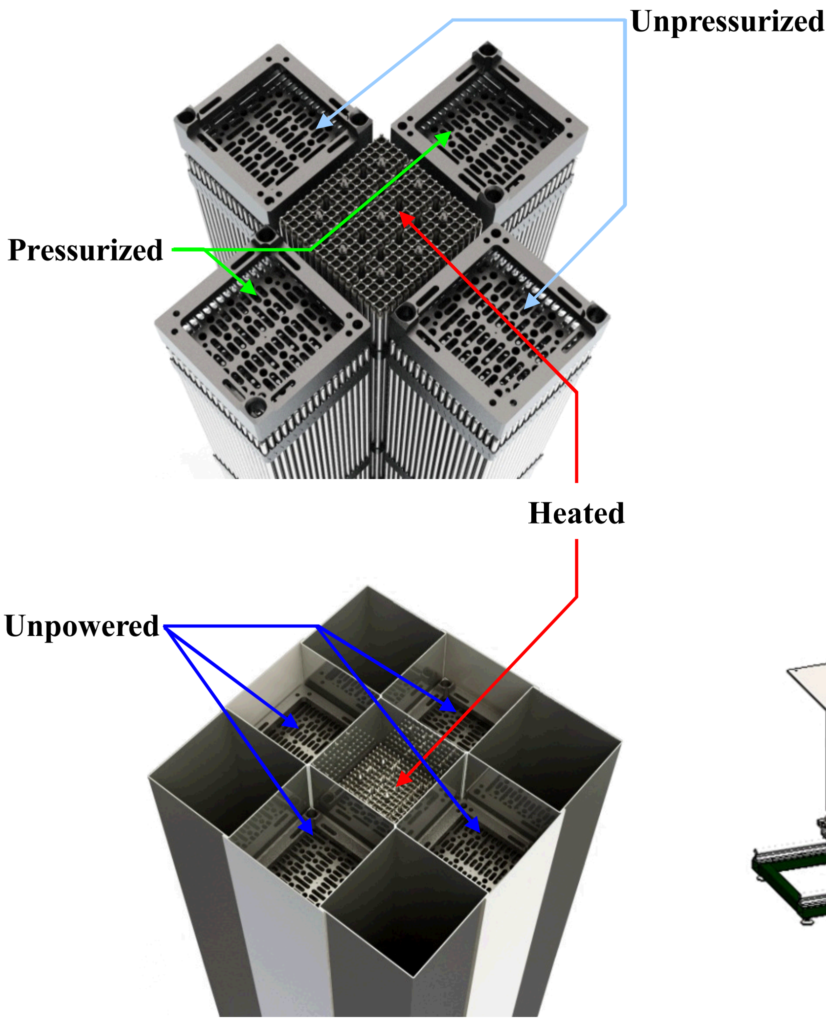
Phase 1 (Uniform Loading) = 

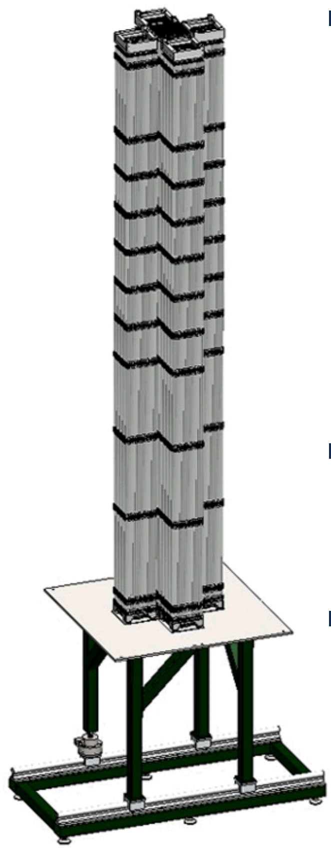
PWR Phase 1 Ignition Test



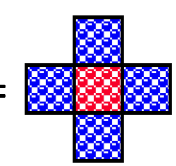


PWR Phase 2 Test Assembly

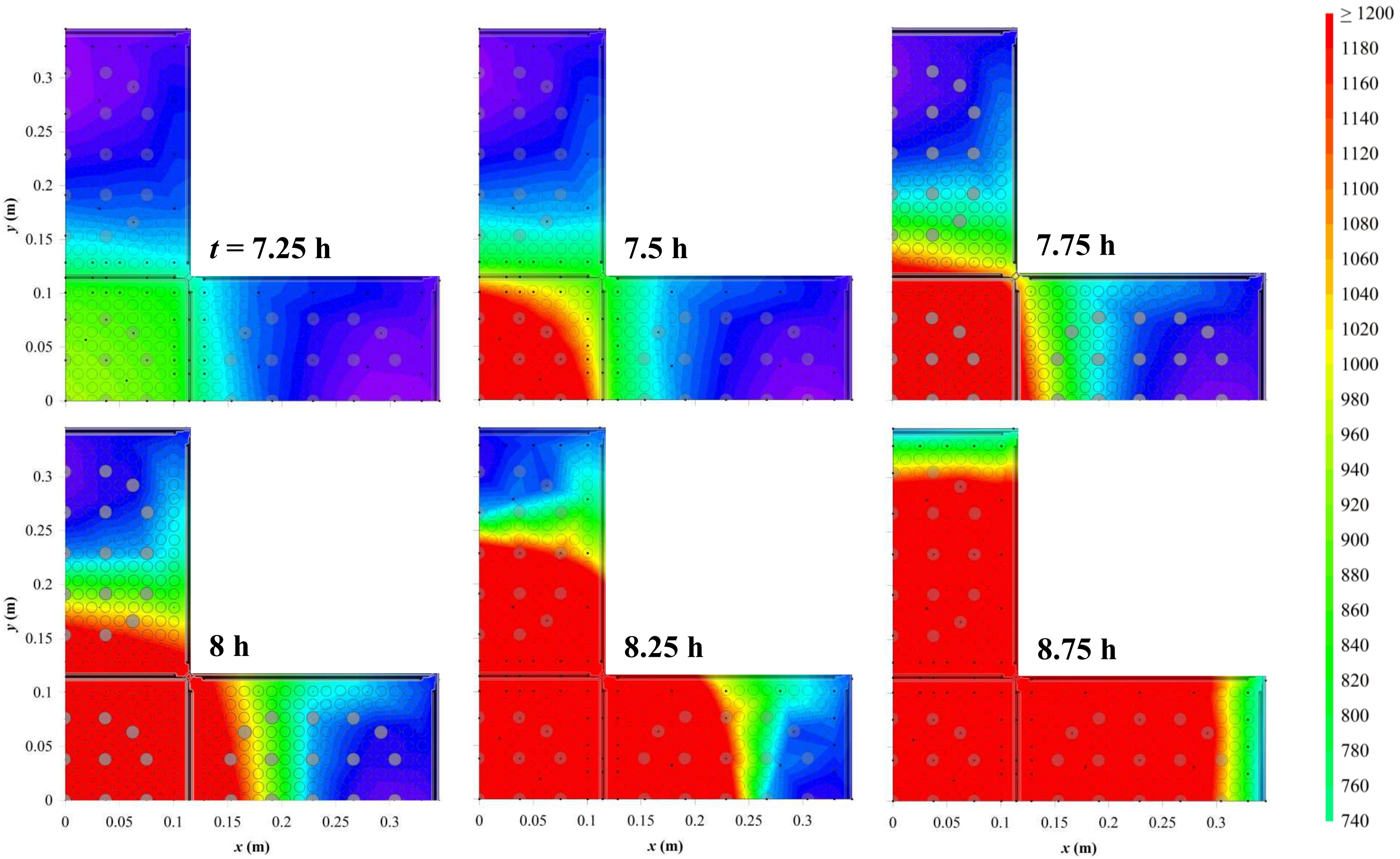




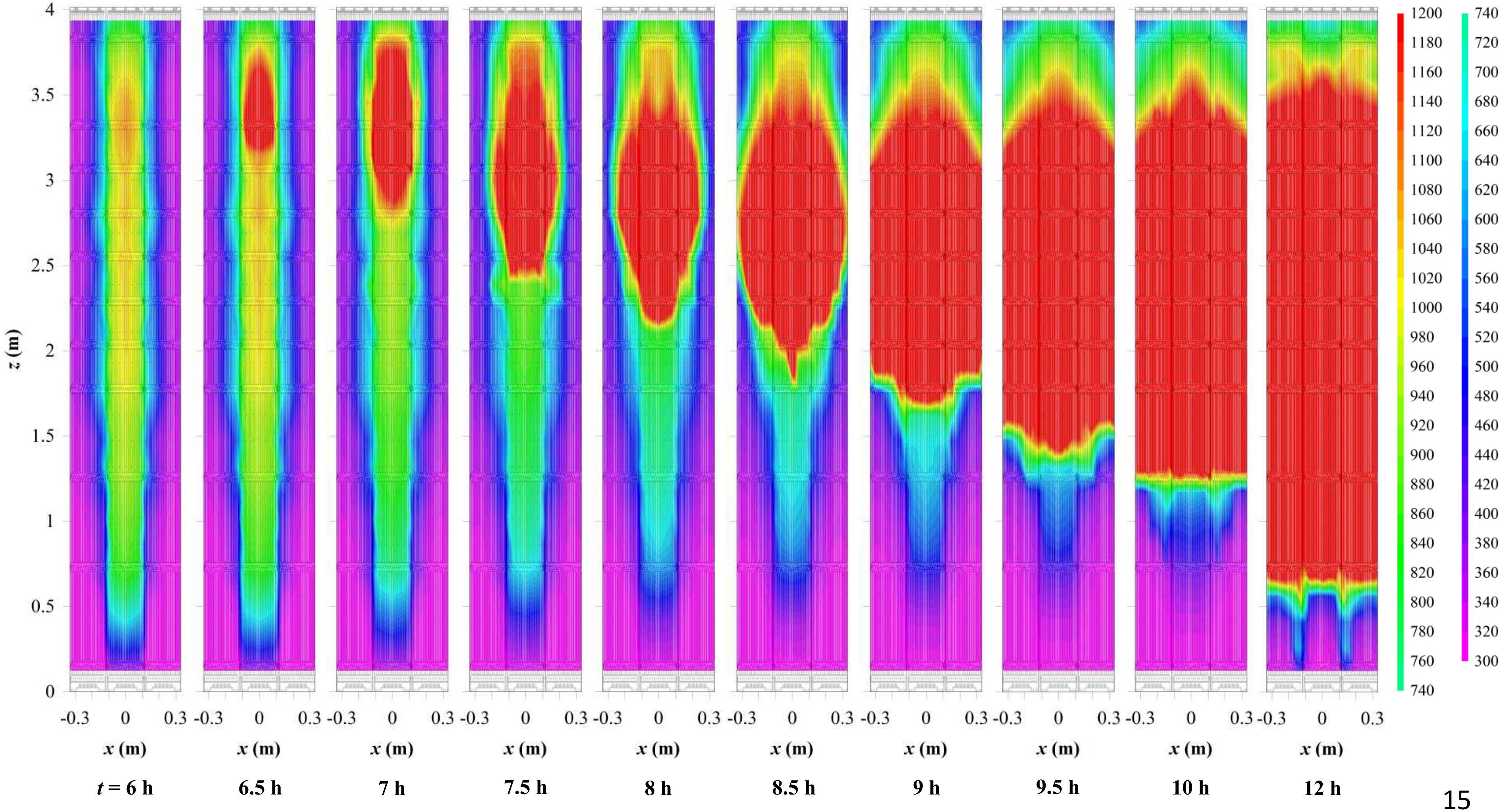
- "Cold Neighbor" Boundary
- Test Assembly
  - 5 full length assemblies in 1×4 arrangement
    - Center heated, peripheral unheated
  - Two peripheral assemblies with all pressurized rods
  - Single prototypic 3×3 pool rack
- Pre-ignition Tests
  - Measure response of different aged assemblies
- Ignition Test
  - Time to ignition for each assembly
  - Time to ballooning
  - Nitrogen reactions

Phase 2 (1×4 Loading) = 

Transverse Propagation
(z = 2.54 m)



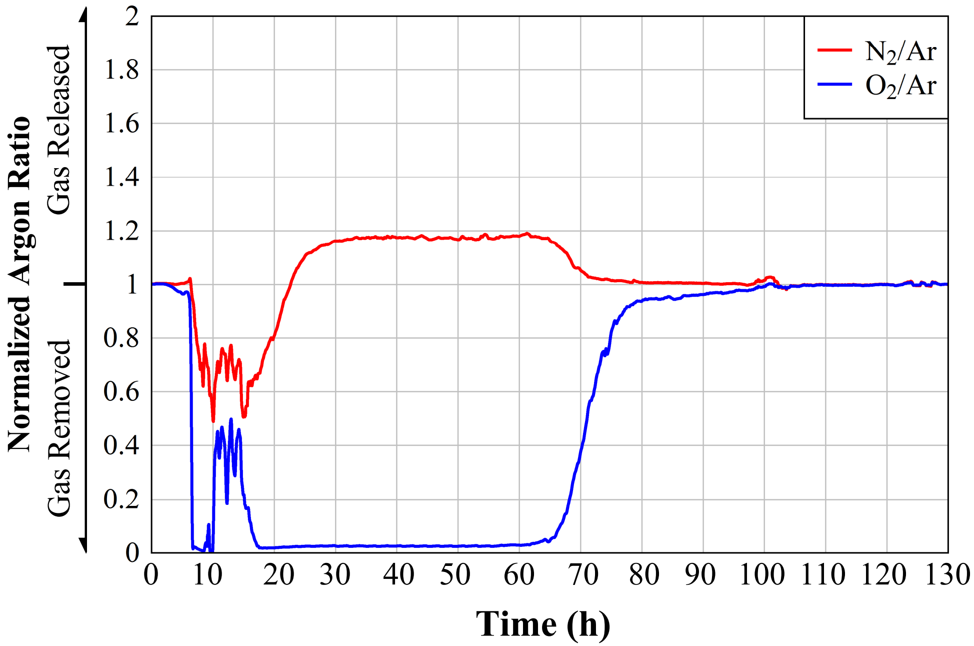
Midplane Propagation



PWR Phase 2 Ignition Test

Implications of ZrN Formation

Exhaust Gas Analysis by Mass Spectrometry



Stage 1 Oxidation

$Zr + O_2 \rightarrow ZrO_2$

$Zr + \frac{1}{2}N_2 \rightarrow ZrN$

Stage 2 Oxidation

$ZrN + O_2 \rightarrow ZrO_2 + \frac{1}{2}N_2$

- Substantial conversion to ZrN
  - After Stage 1 Oxidation
    - ~22% ZrO_2
    - ~78% ZrN
  - Doubles the energy release
- Nitrogen reactions significant
  - Greater propensity for burn propagation to adjacent assemblies
    - Higher temperatures
    - More energetic burn

Summary

- Sandia SFP complete LOCA ignition testing successfully completed
  - BWR Phase 1 (Uniform) – June 2006
  - BWR Phase 2 (1×4) – August 2006
  - PWR Phase 1 (Uniform) – March 2011
  - PWR Phase 2 (1×4) – June 2012
- Available NUREG/CRs
  - NUREG/CR-7143, "Characterization of Thermal-Hydraulic and Ignition Phenomena in Prototypic, Full-Length Boiling Water Reactor Spent Fuel Pool Assemblies After a Postulated Complete Loss-of-Coolant Accident"
  - NUREG/CR-7144, "Laminar Hydraulic Analysis of a Commercial Pressurized Water Reactor Fuel Assembly"
  - NUREG/CR-7215, "Spent Fuel Pool Project Phase 1: Pre-Ignition and Ignition Testing of a Single Commercial 17×17 Pressurized Water Reactor Spent Fuel Assembly under Complete Loss of Coolant Accident Conditions"
  - NUREG/CR-7216, "Spent Fuel Pool Project Phase II: Pre-Ignition and Ignition Testing of a 1×4 Commercial 17×17 Pressurized Water Reactor Spent Fuel Assemblies under Complete Loss of Coolant Accident Conditions"