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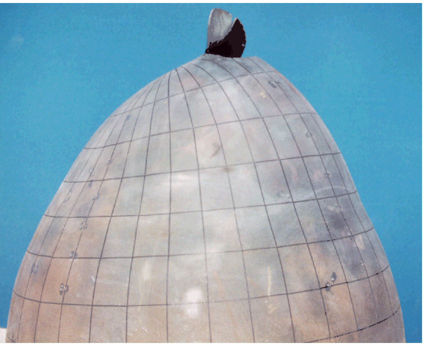

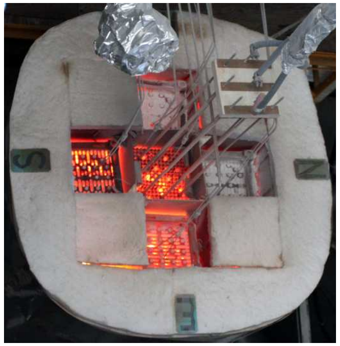


Investigations of Zirconium Fires during Spent Fuel Pool LOCAs

Sam Durbin and Eric Lindgren

Funded by
USNRC and OECD
JCN# N6777 and F6898

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Post 9/11 Environment

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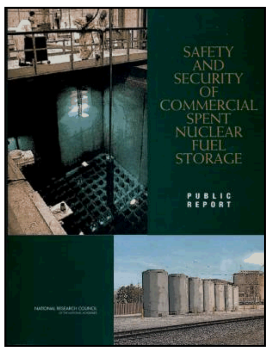
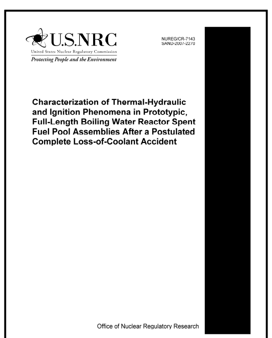
- 2003 – Critics produced article identifying potential vulnerabilities of current spent fuel storage
  - Highlighted possibility of zirconium cladding fires in modern, high-density spent fuel pools (SFPs)
  - Recommended transfer to dry storage within five years of discharge



- 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

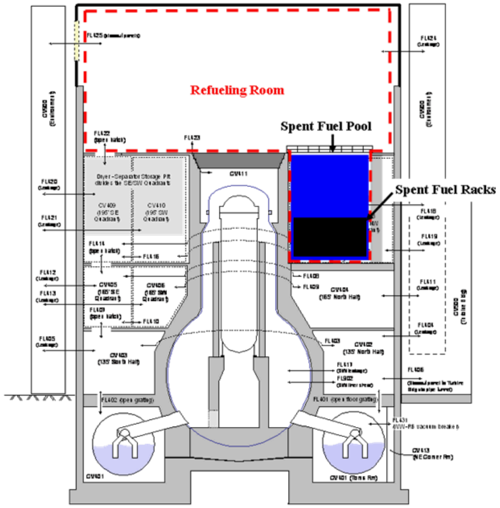


- 2005 – USNRC commissioned complete LOCA testing program for boiling water reactor (BWR) fuel
  - Demonstrated zirconium fires in near-prototypic spent fuel
  - Showed potential for propagation between assemblies
- 2009 – USNRC and OECD commissioned complete LOCA testing for pressurized water reactor (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

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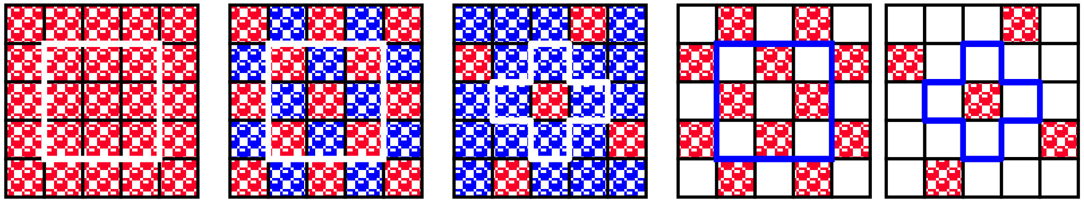


Recently discharged, high-power assembly

Low-powered assembly discharged many years earlier

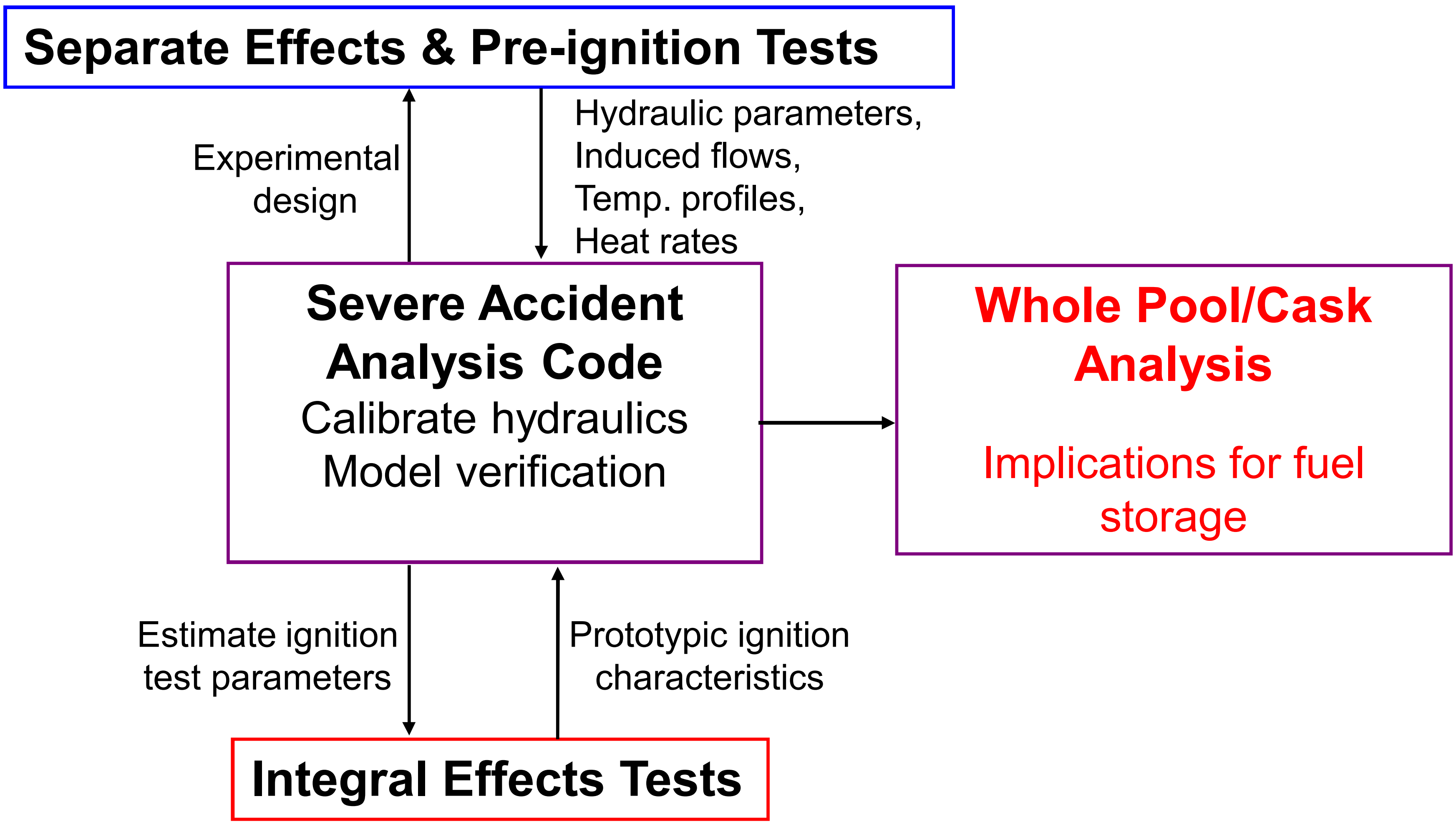
Empty rack cell

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

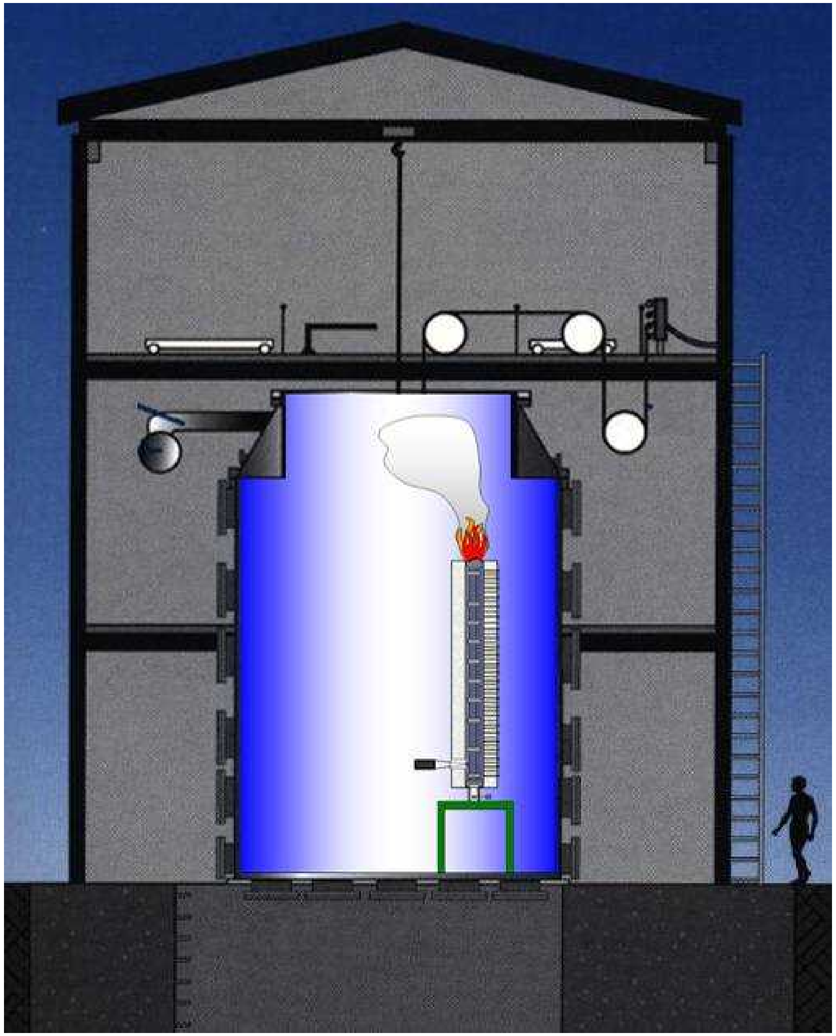
Configuration	Ranking
1×4 empties	Best
1×4	Best
Checkerboard with empties	Good
Checkerboard	Moderate
Uniform	Worst

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

Integrated Testing and Modeling

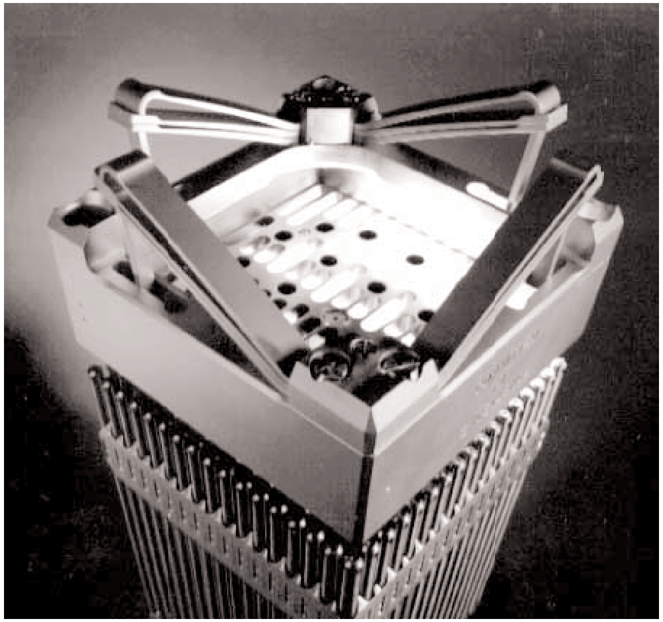


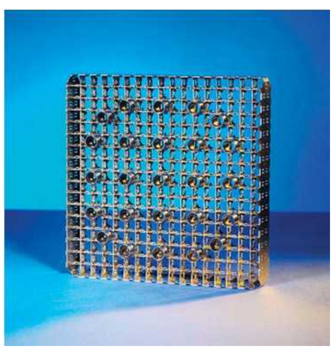
CYBL Test Facility

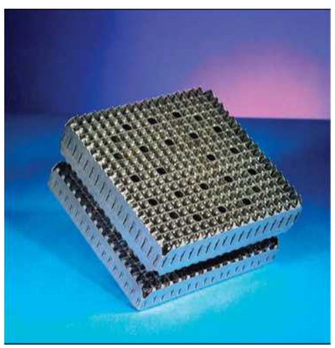


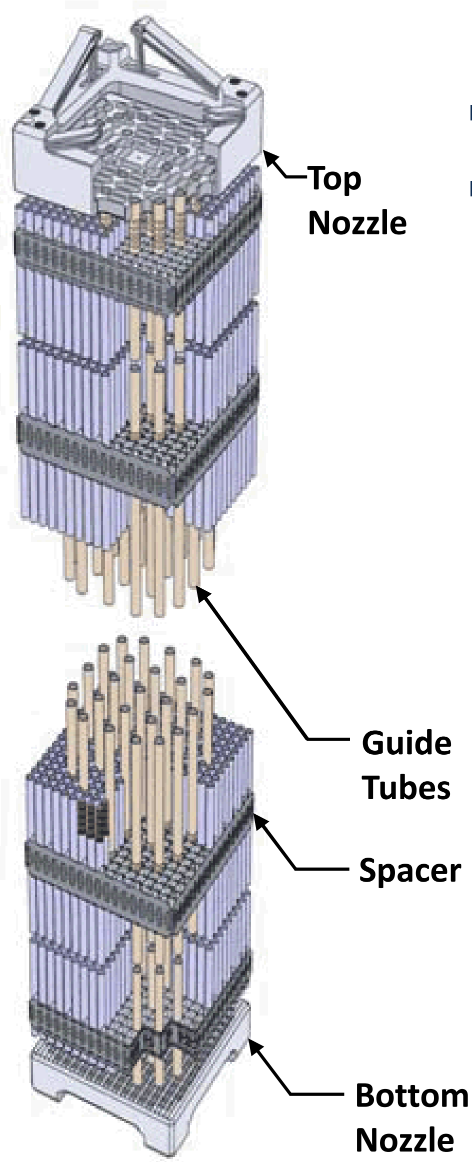
- Large stainless steel containment
  - Repurposed from earlier CYLINDRICAL BOILING Testing sponsored by DOE
  - Excellent general-use engineered barrier for isolation of high-energy tests
    - 3/8 in. stainless steel
    - 17 ft diam. by 28 ft cylindrical workspace
- Part of the Nuclear Energy Work Complex (NEWC)

PWR Hardware



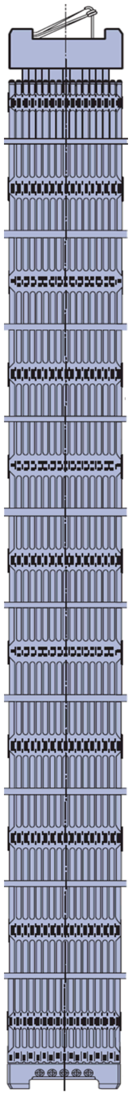


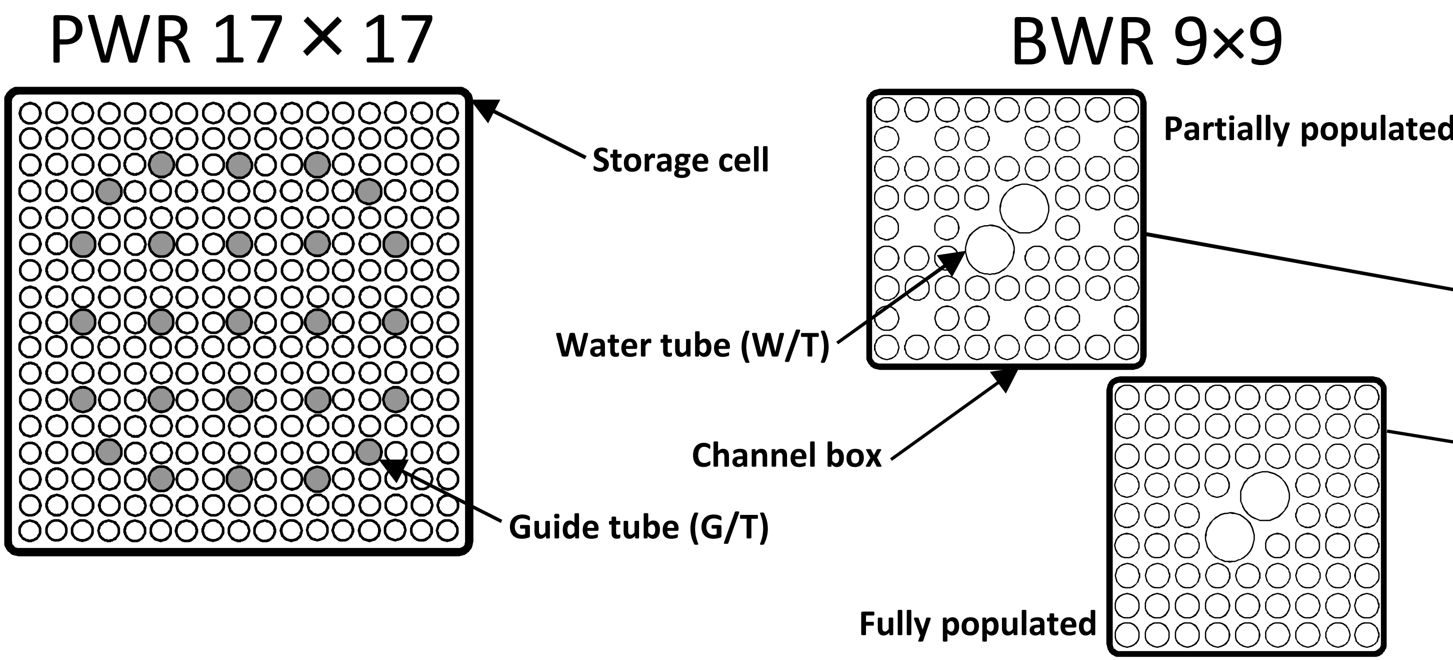


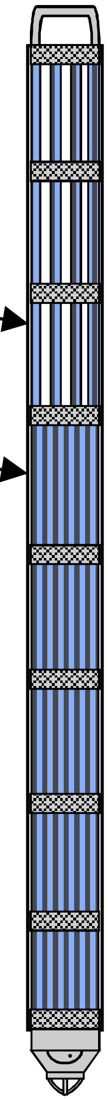


- Prototypic 17×17 PWR
- More form losses than BWR (7 spacers)
  - 8 grid spacers
  - 3 flow mixers
  - 1 debris catcher
  - 264 electric heater rods

Fuel Geometry Differences

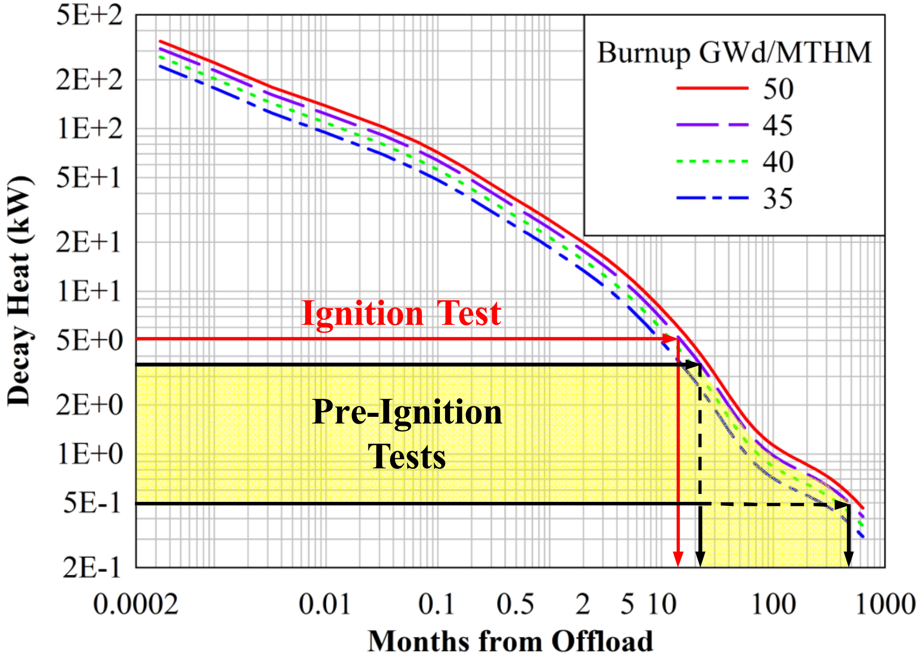




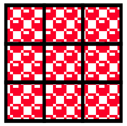


- Significantly different geometries
  - Prevents hydraulic scaling between assemblies
- Testing of PWRs more complex
  - Approximately 3.5× more fuel rods
  - Longer construction and instrumentation times

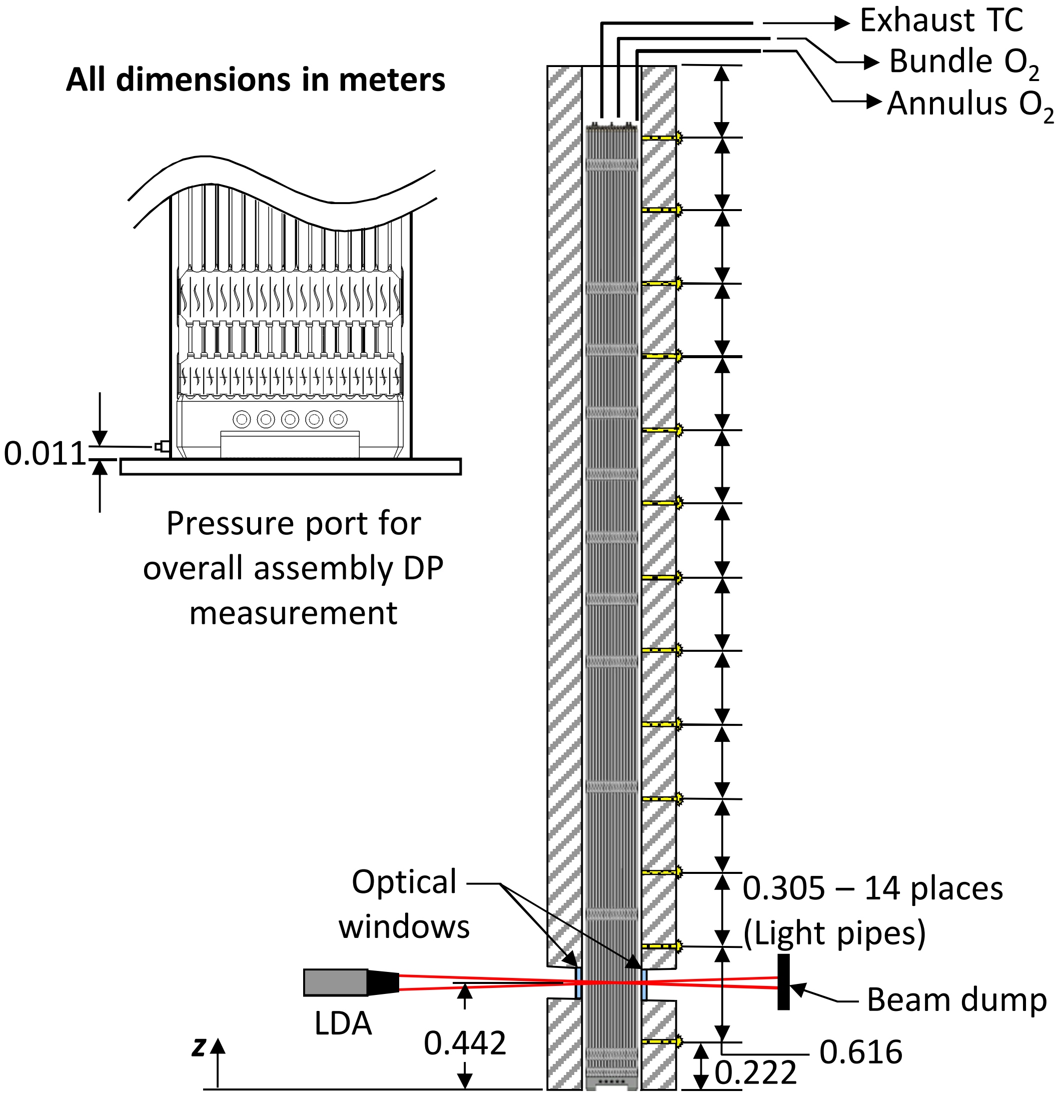
Phase 1 Simulated Decay Heat



- Pre-ignition tests
  - Decay heats 0.5 to 3.5 kW
  - Simulate 45 GWd/MTHM fuel 23 mo. to 40 yrs from offload
- Ignition test
  - Decay heat = 5 kW
  - Fuel age 15 months (457 days) at 45 GWd/MTHM

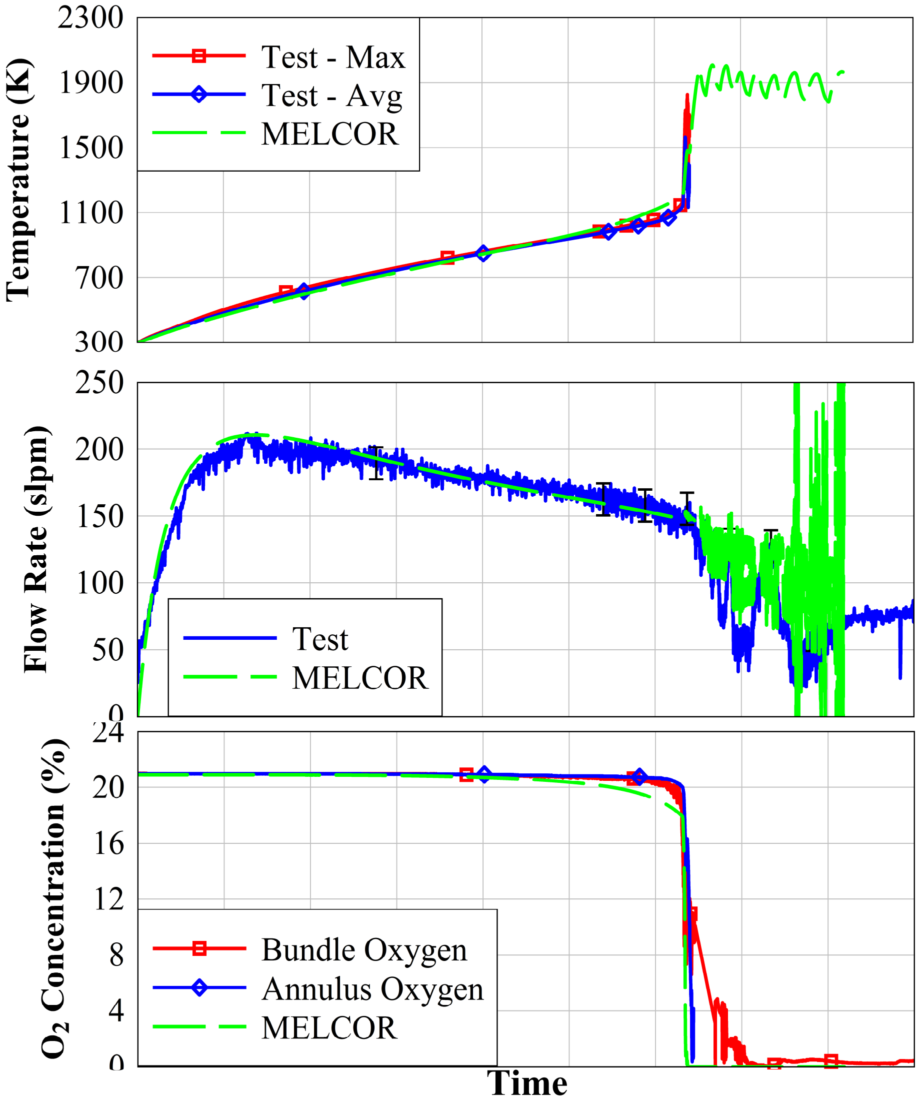
Phase 1 (Uniform Loading) = 

Phase 1 Test Assembly



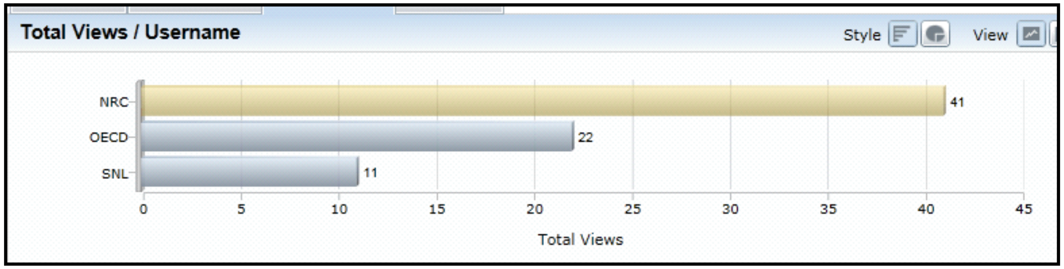
- Hydraulic characterization
  - Pressure port for overall assembly ΔP
- Burn front tracking
  - Quartz light pipes at 0.305 m (12 in.) intervals
- Bundle velocity profiles
  - Laser Doppler anemometer (LDA) and optical windows
- Internal temperature monitoring
  - 131 thermocouples (TCs) at 0.152 m (6 in.) axial increments
- Additional temperature tracking
  - Pool cell & outer skin TCs at 0.61 m (24 in.) levels

Phase 1 Ignition Test Results

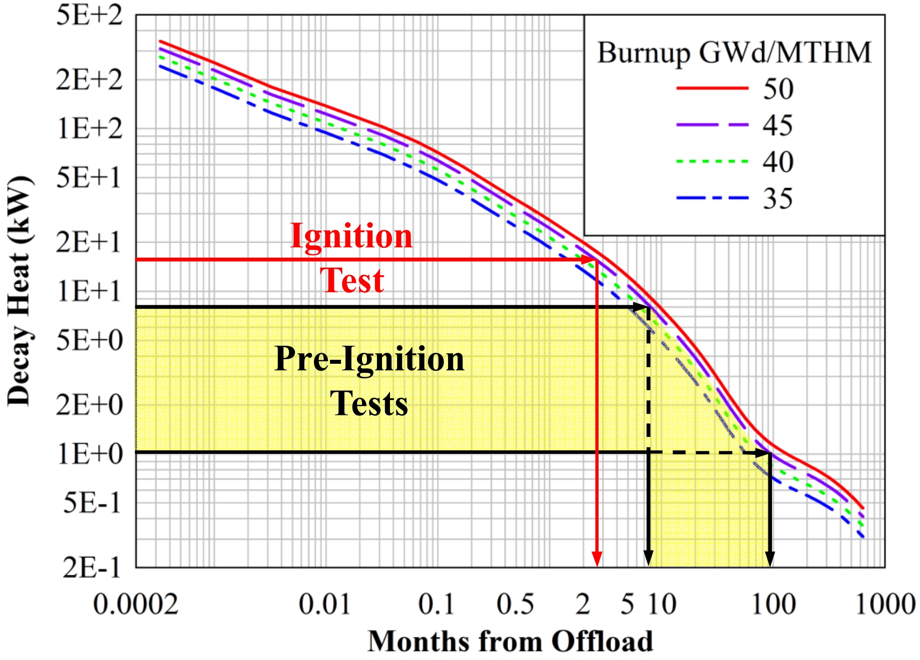


- Assembly power 5000 W
  - Situational equivalent of a cluster of 15 month-old assemblies (hot neighbor BC)
- Modeling predicts ignition within 10 minutes
  - Based on Peak Cladding Temp. = 1200 K
  - PCT within 40 K of test max at all times up to ignition
- Thermocouples failed after ignition
  - Sharp 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

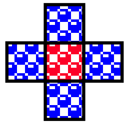
Phase 1 Ignition Test



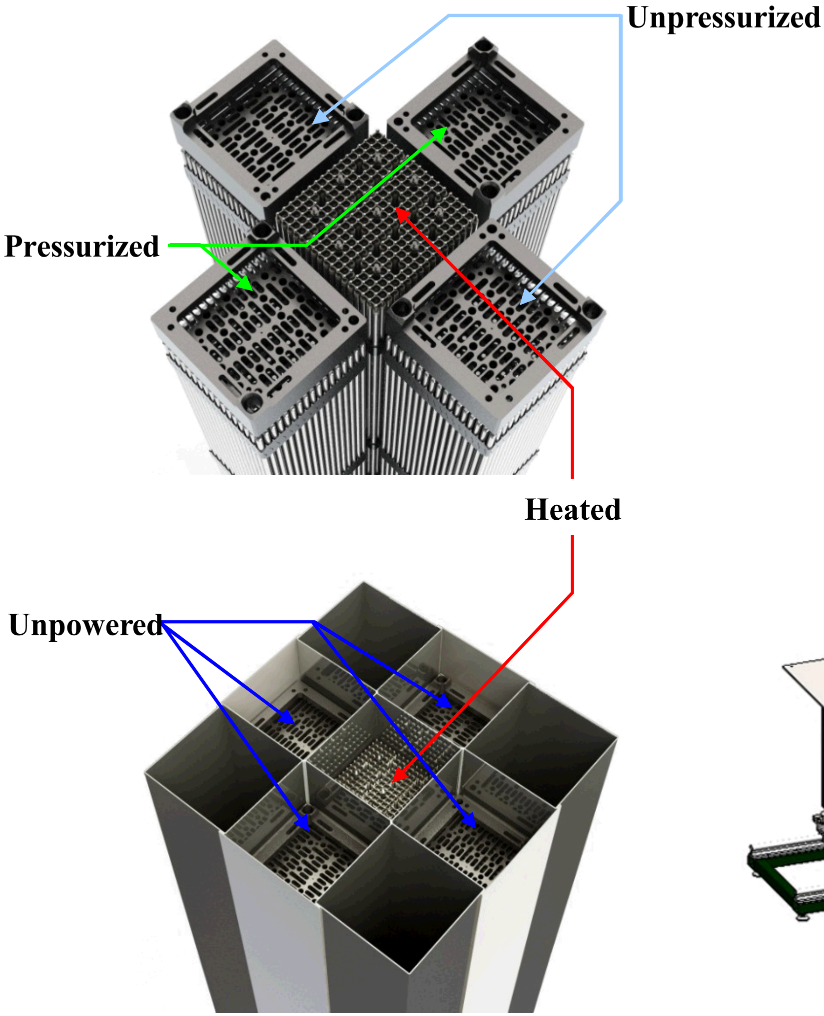
Phase 2 Simulated Decay Heat

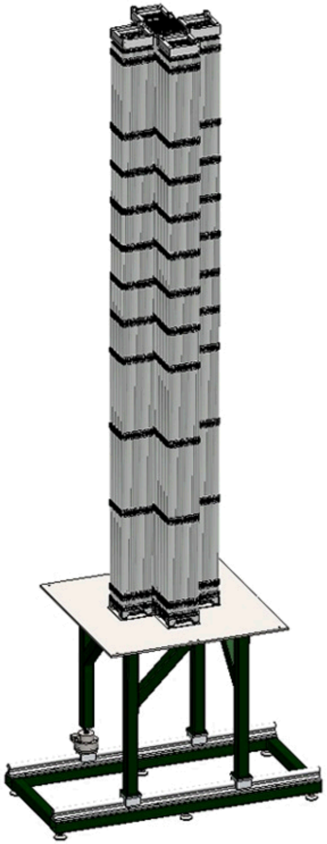


- Pre-ignition tests
  - Decay heats 1 to 8 kW
  - Simulate 45 GWd/MTHM fuel 8 mo. to 8 yrs from offload
  - Transient data to *t* = 12 hrs
    - For 1 and 4 kW, up to *t* = 24 hrs
- Ignition test
  - Decay heat = 15 kW
  - Fuel age 2.8 months (86 days) at 45 GWd/MTHM

Phase 2 (1×4 Loading) = 

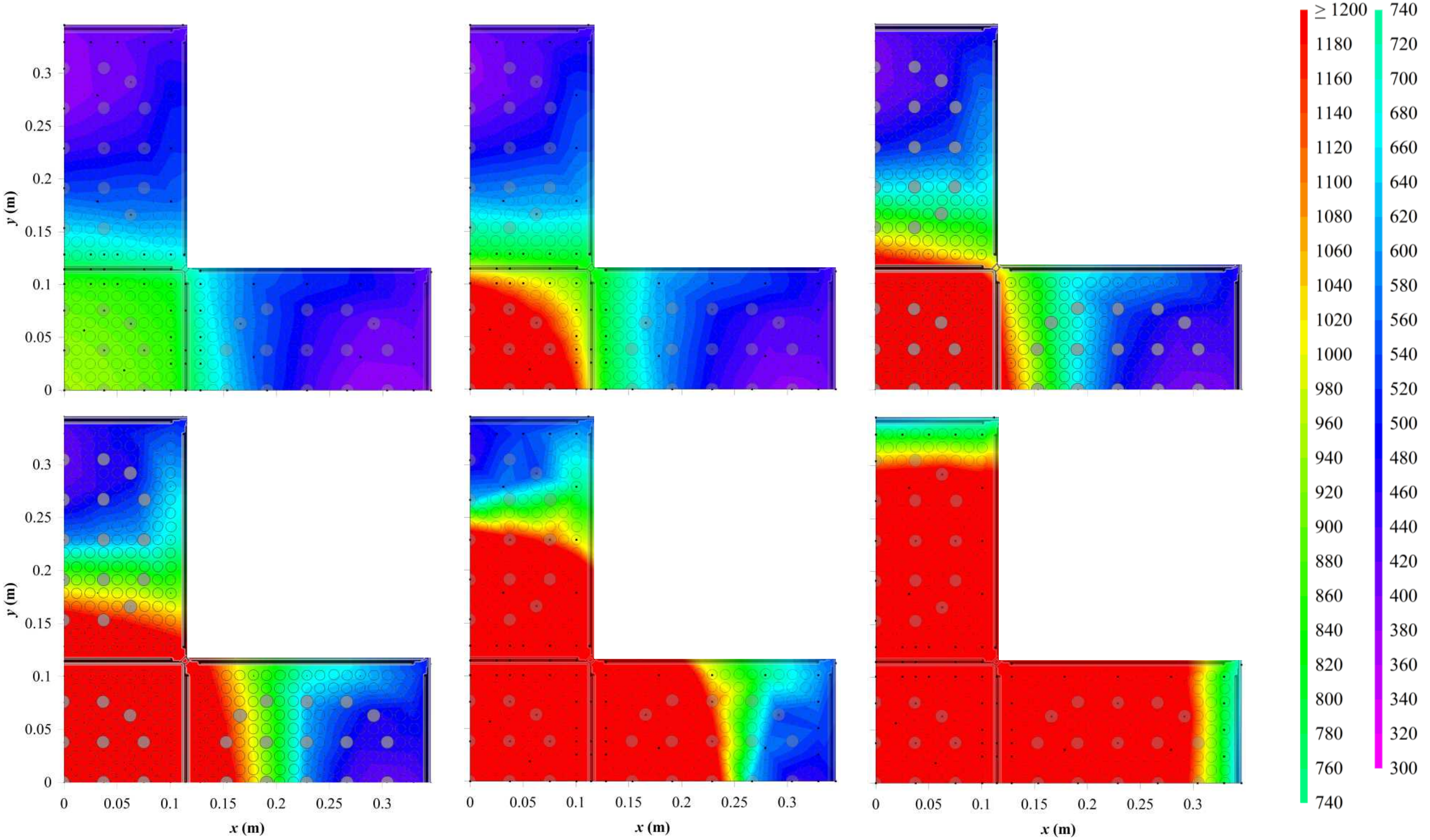
Phase 2 Test Assembly



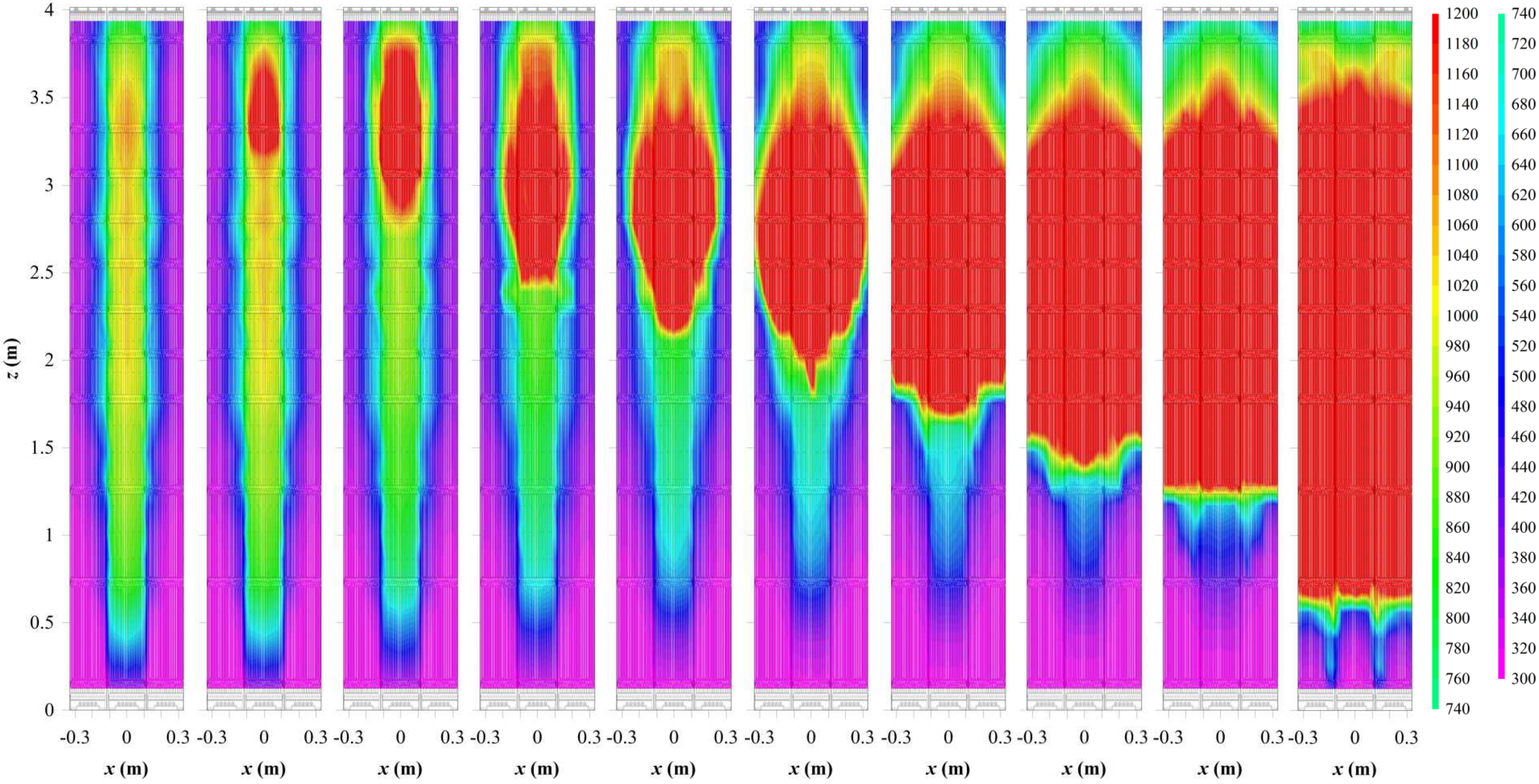


- "Cold Neighbor" Boundary
- Test Assembly
  - 5 full length assemblies in 1×4 arrangement
    - Center heated, peripheral unheated
  - Two peripheral assemblies with all pressurized rods
  - Single prototypic 3×3 pool rack
- Pre-ignition Tests
  - Measure response of different aged assemblies
- Ignition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

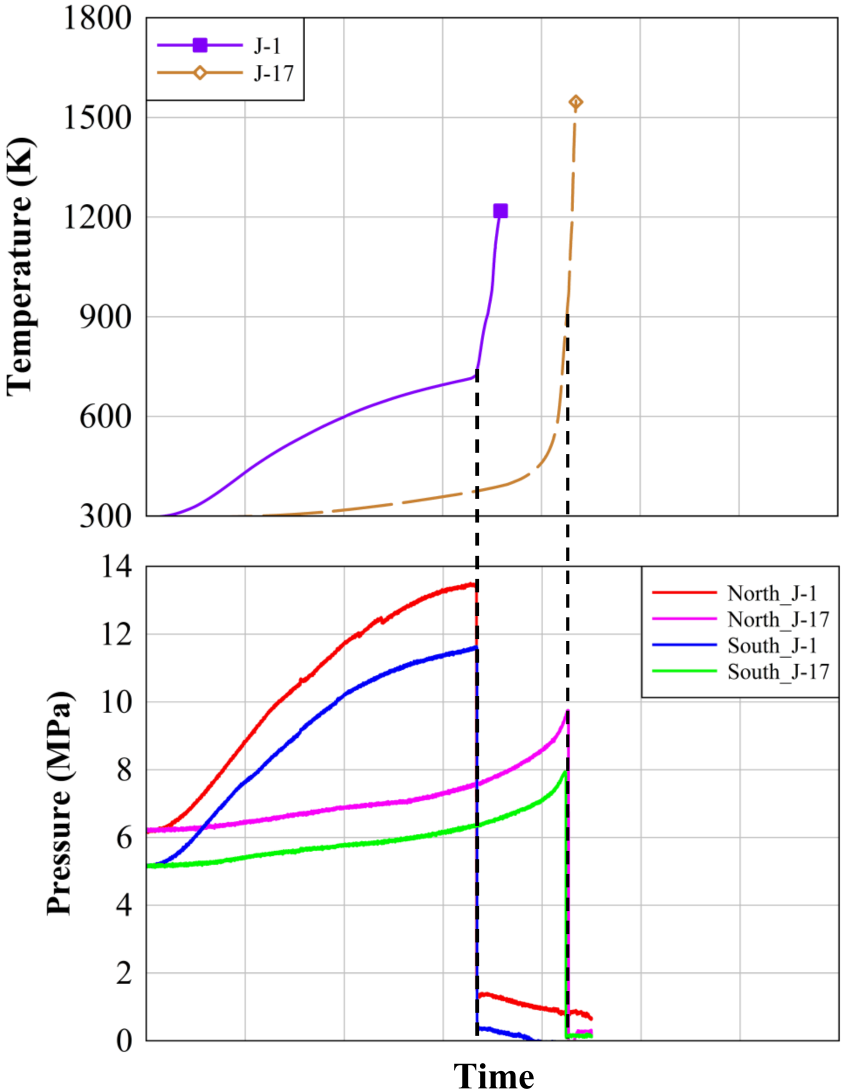
Transverse Propagation
(z = 2.54 m)



Midplane Propagation



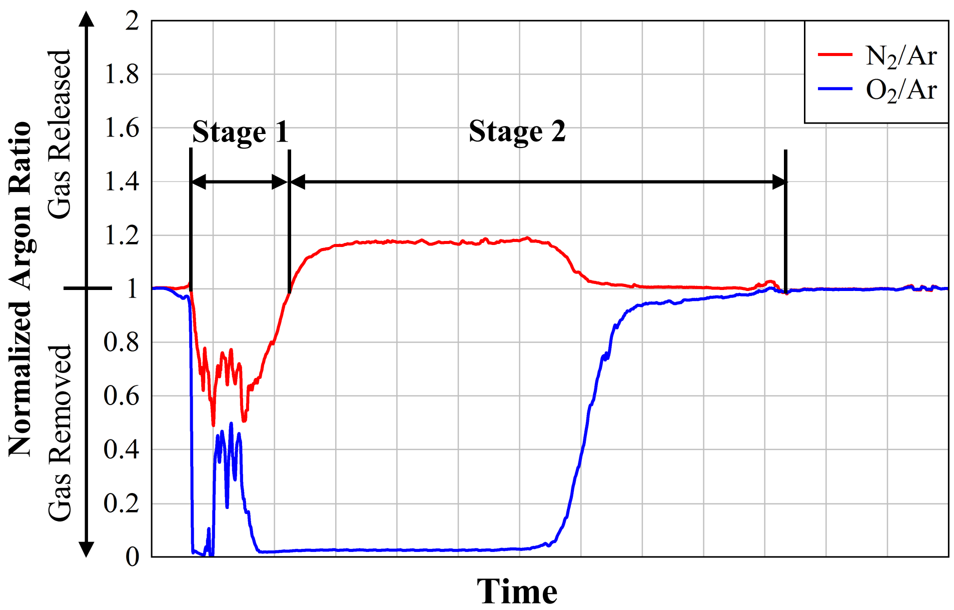
Clad Ballooning



- First ballooning event shortly after ignition in center
- Initial pressure not significant
  - Within 3 minutes of each other
- No measureable difference between assemblies w/ and w/o ballooning
- Ballooning likely between z = 2.692 and 3.302 m

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
- Models must incorporate the nitrogen reactions
  - Greater propensity for burn propagation to adjacent assemblies
    - Higher temperatures
    - More energetic burn

Phase 2 Ignition Test

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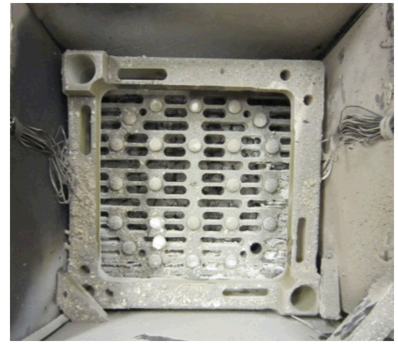


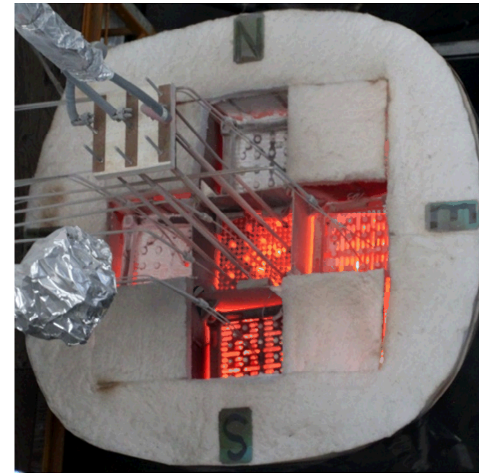

Summary

- All Sandia Fuel Project testing successfully completed
  - Phase 1 (Uniform loading) – Sixteen pre-ignition (Feb. 2011) and one ignition test (March 2011)
  - Phase 2 (1×4 loading) – Nine pre-ignition (May 2012) and one ignition test (June 2012)
  - Ignition tests broadcasted live on web to project members
- Successfully demonstrated and quantified phenomena dominant during spent fuel pool complete LOCAs
  - Burn initially propagated near the top of the fuel assemblies
    - Primarily burned down to the assembly inlet
  - Cladding fire breached the pool rack and propagated into the peripheral assemblies
  - Significant depletion of nitrogen during initial stage of ignition
    - More energetic burn than previously modeled
  - Severe thermal environment caused all pressurized fuel pins to balloon
    - No measureable thermal-hydraulic impact from ballooning