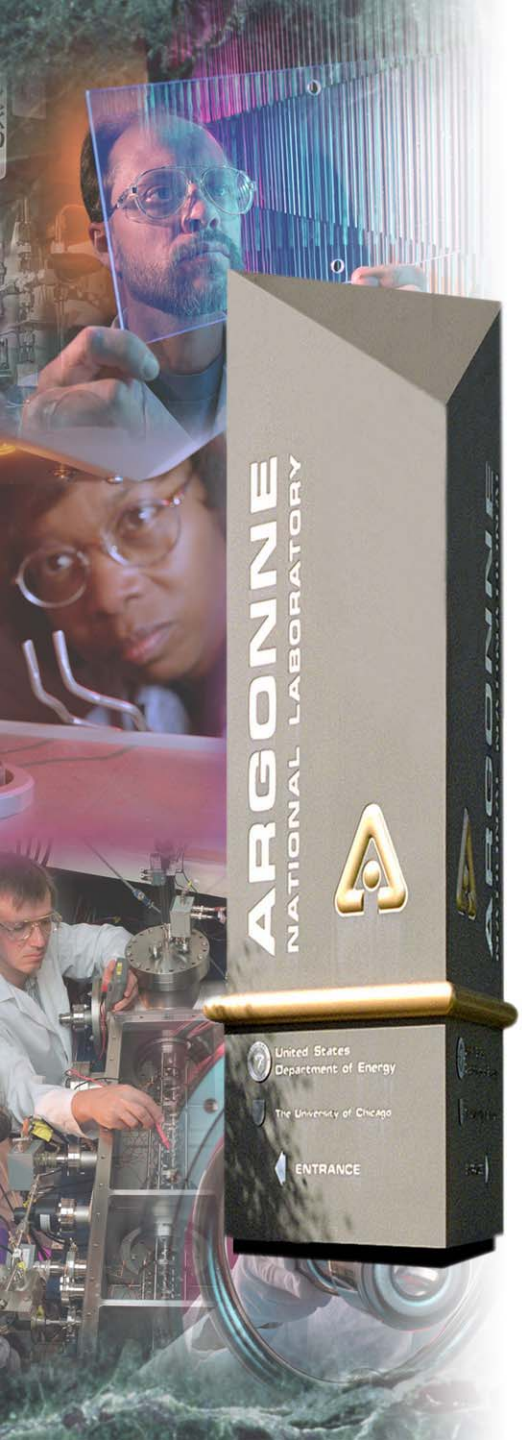

LOCA Test Results for High-Burnup BWR Fuel and Cladding

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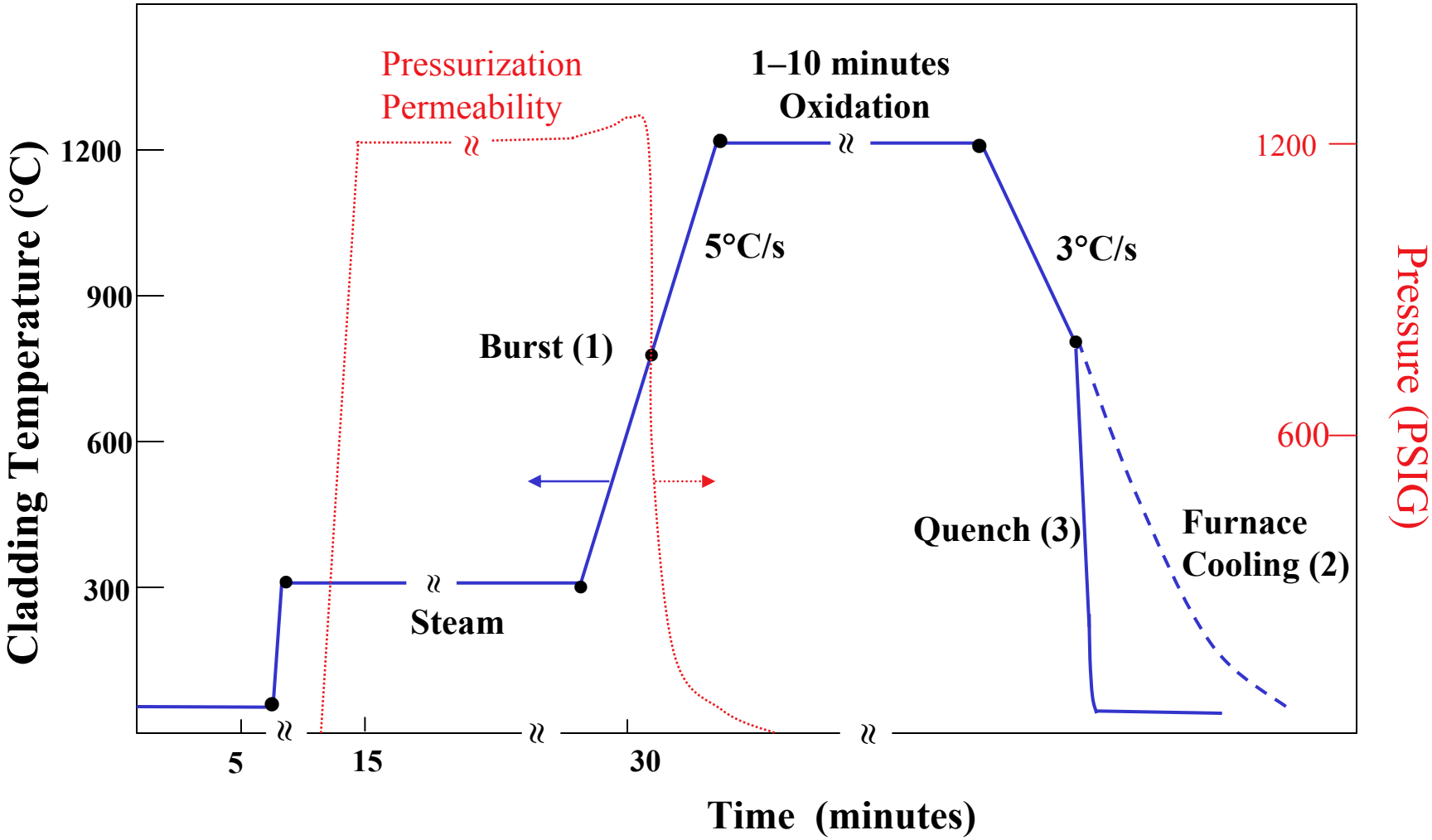
Office of Science
U.S. Department of Energy

A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago

Background

- **Objective**
  - To evaluate the influence of burnup extension on fuel behavior under LOCA conditions
- **Licensing Issues Addressed**
  - 10 CFR 50.46 embrittlement criteria for maintaining residual ductility in Zircaloy (Zry) cladding:
    - Temperature limit: peak cladding temperature (PCT) ≤ 1204ºC;
    - oxidation limit: effective cladding reacted (ECR) ≤ 17%
  - Confirming embrittlement criteria for high-burnup Zry-2 and Zry-4
- **High-Burnup Fuel Rod Segments**
  - H.B. Robinson 15×15 PWR rods at 67 GWd/MTU
    Corrosion layer ≤ 110 μm; H-content ≤ 800 wppm
  - Limerick 9×9 BWR rods at 56 GWd/MTU
    Corrosion layer ≈ 10 μm; H-content ≈ 70 wppm

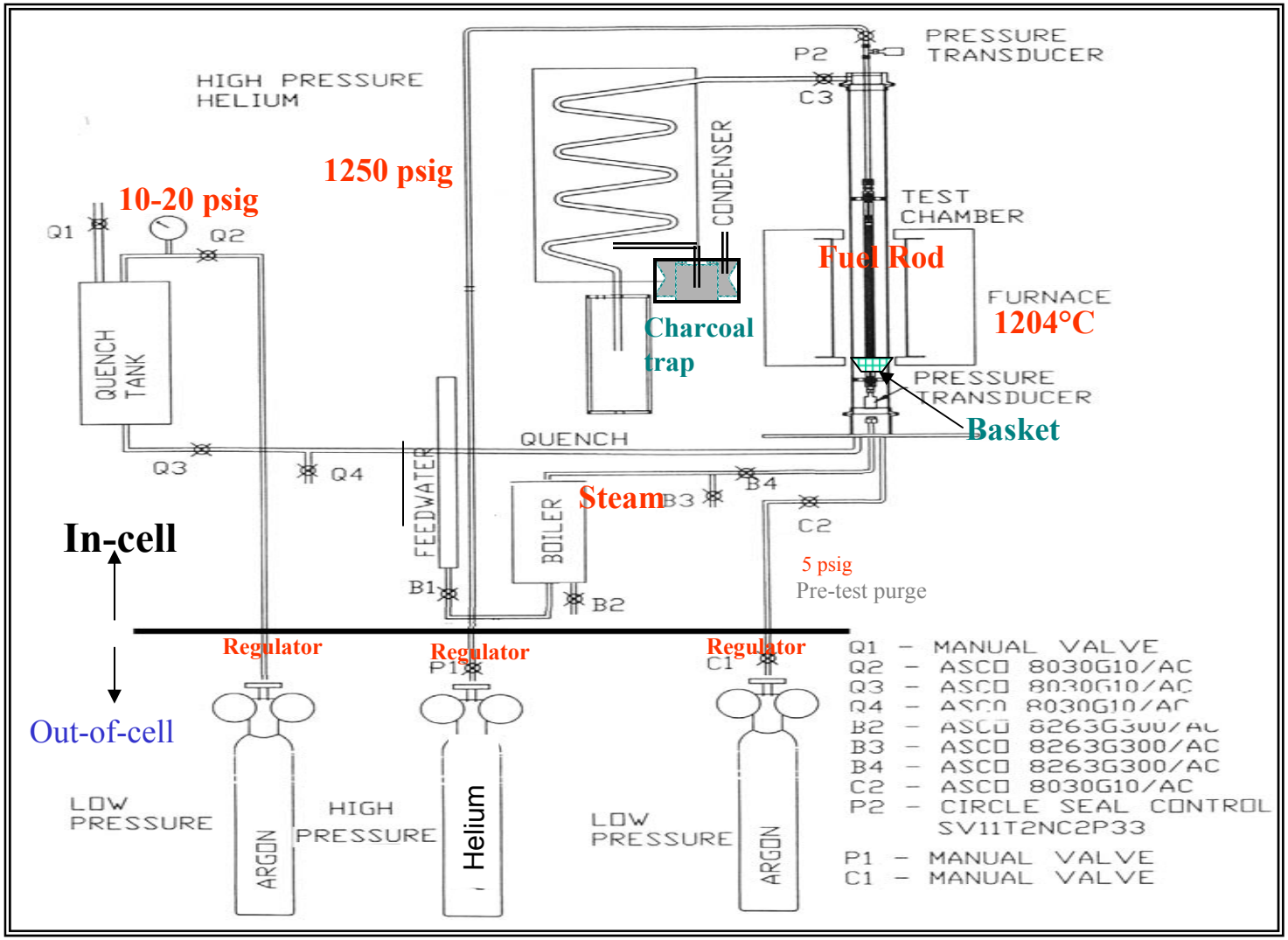
LOCA Integral Test Sequence



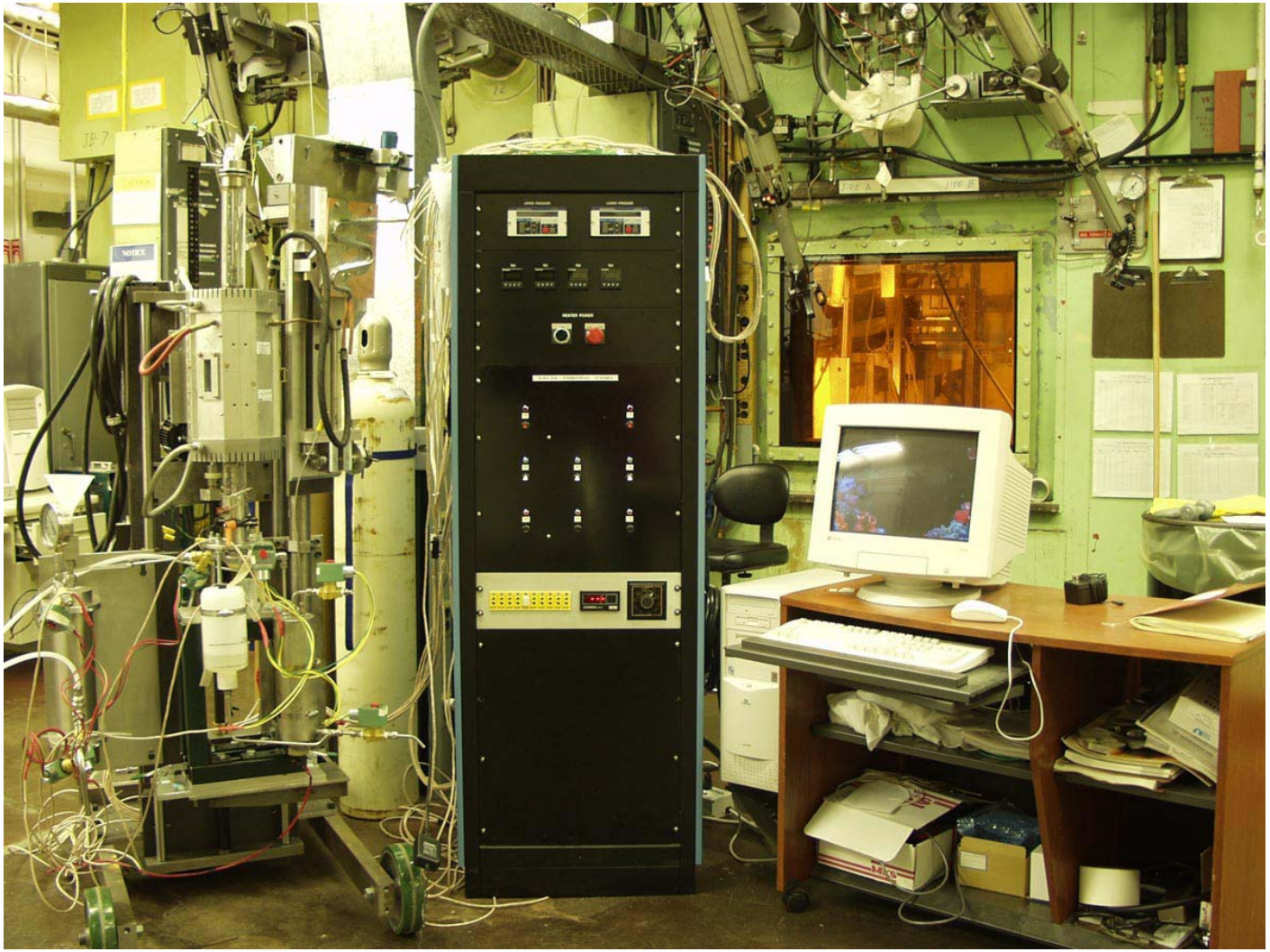
High-Burnup Phenomena Investigated

- **Fuel behavior and effects of fuel / cladding bond**
- **Effects of corrosion, hydriding, and irradiation hardening on cladding behavior:**
  - Ballooning and burst (profilometry, photography)
  - Secondary hydriding (LECO H determination)
  - Steam oxidation (Weight gain, LECO O determination, metallography)
  - Quench behavior and post-quench ductility
    - ✓ *Microhardness tests*
    - ✓ *Ring compression tests*
    - ✓ *Four-point-bend tests*
    - ✓ *Fractography*

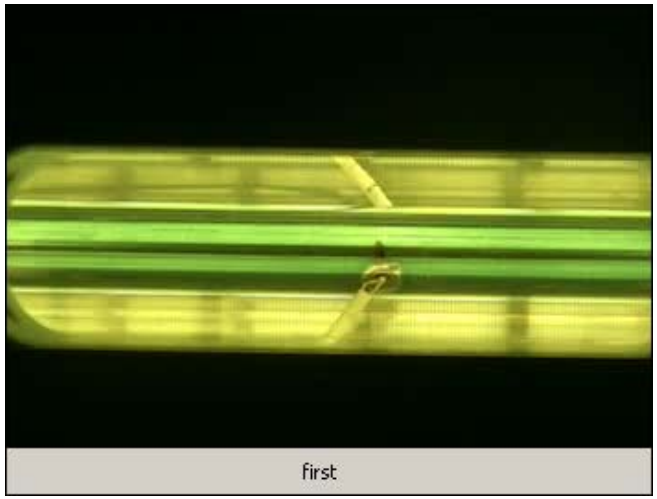
Schematic Illustration of LOCA System

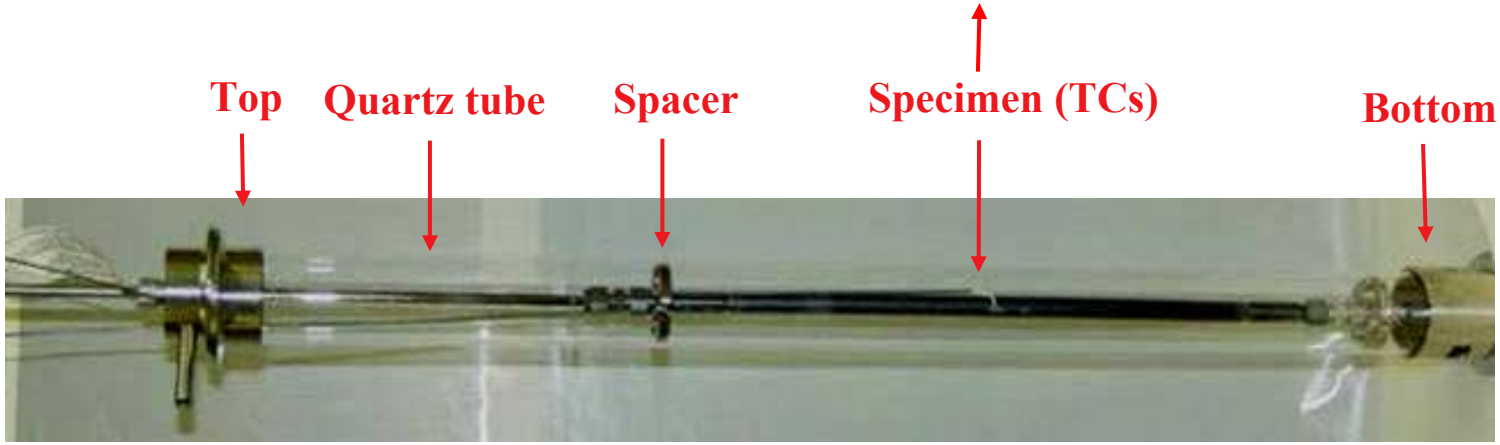


LOCA Apparatus



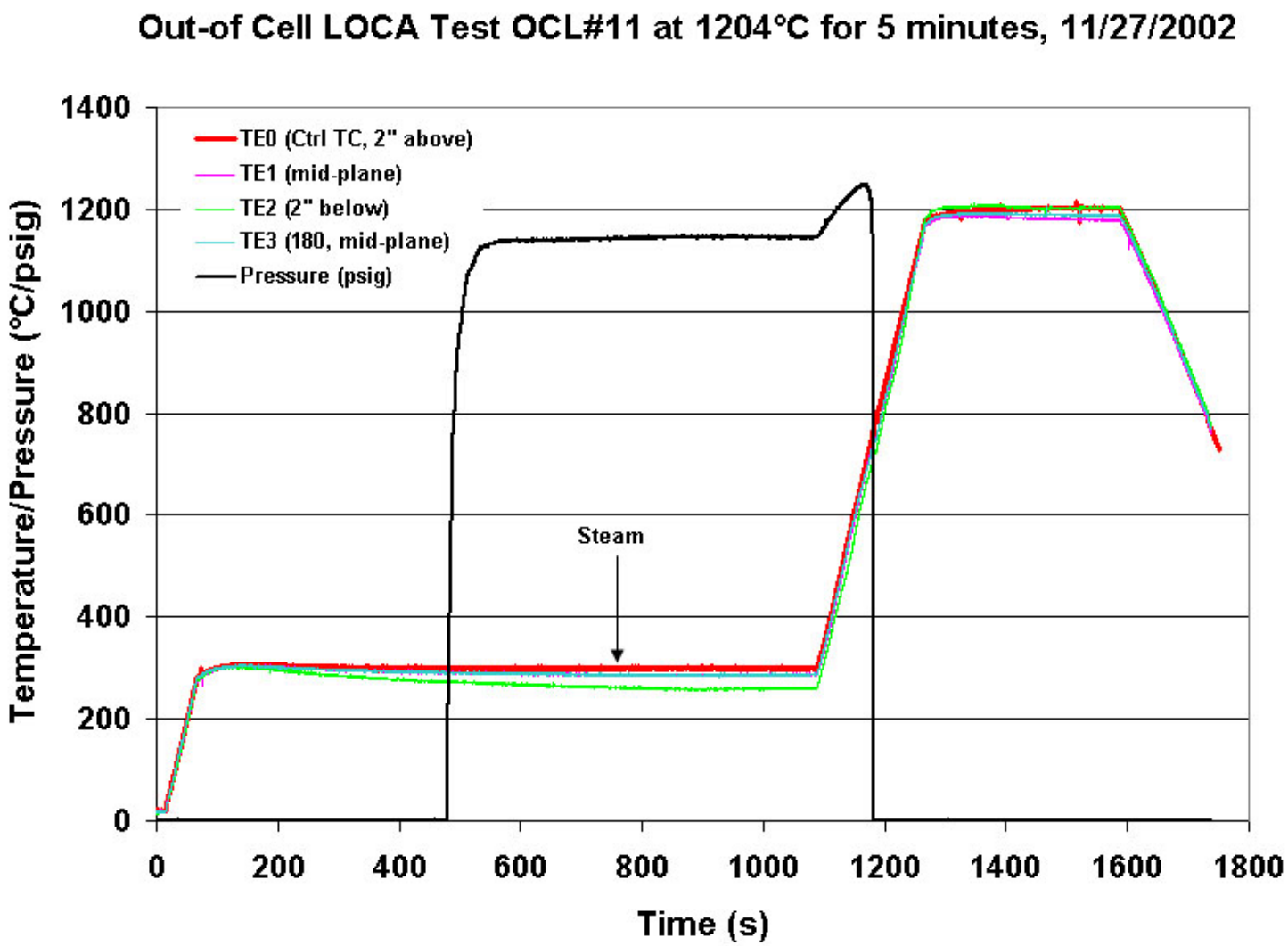
Real-time Observation of the LOCA Test



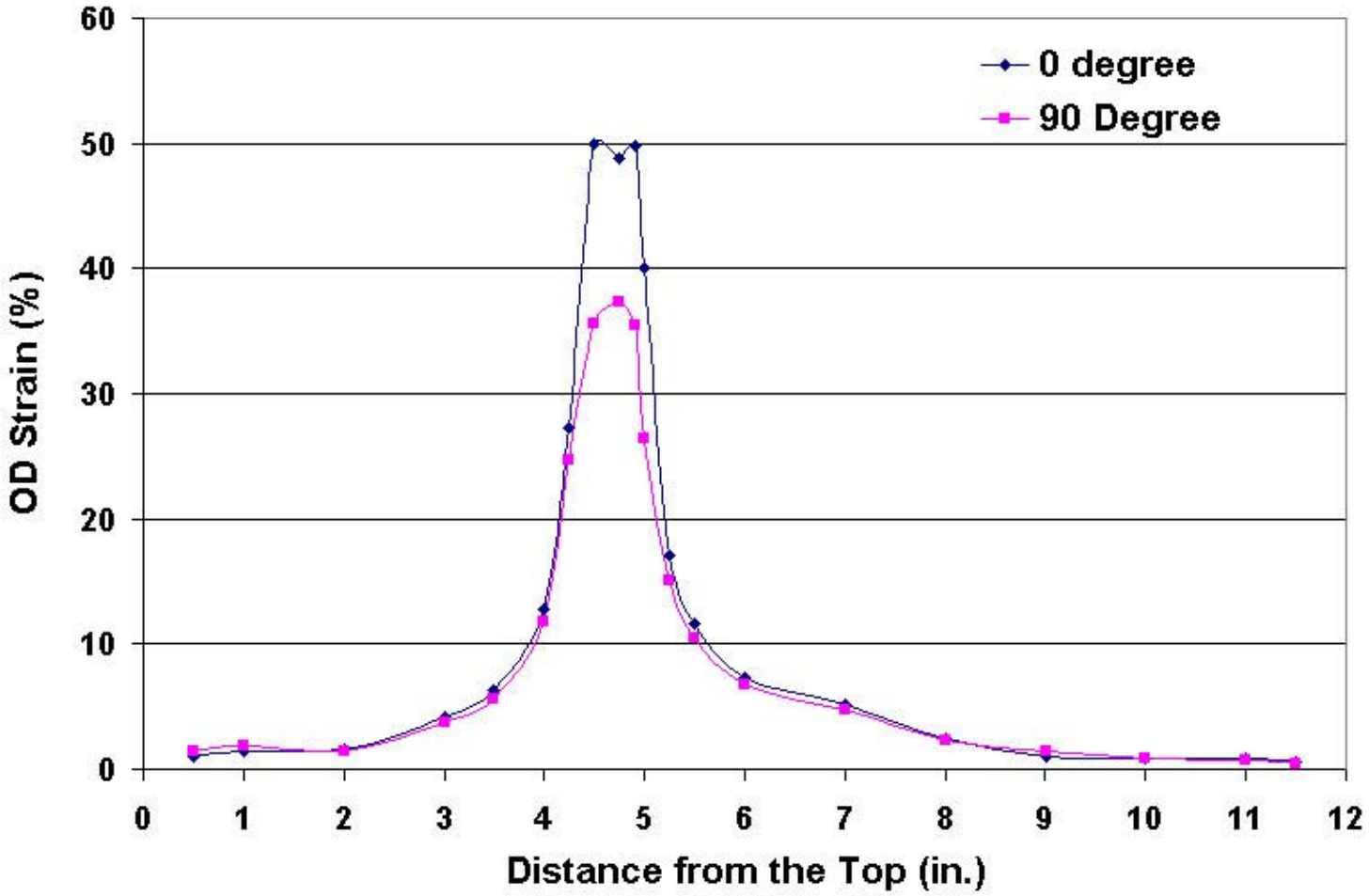


Hanging LOCA Test Train

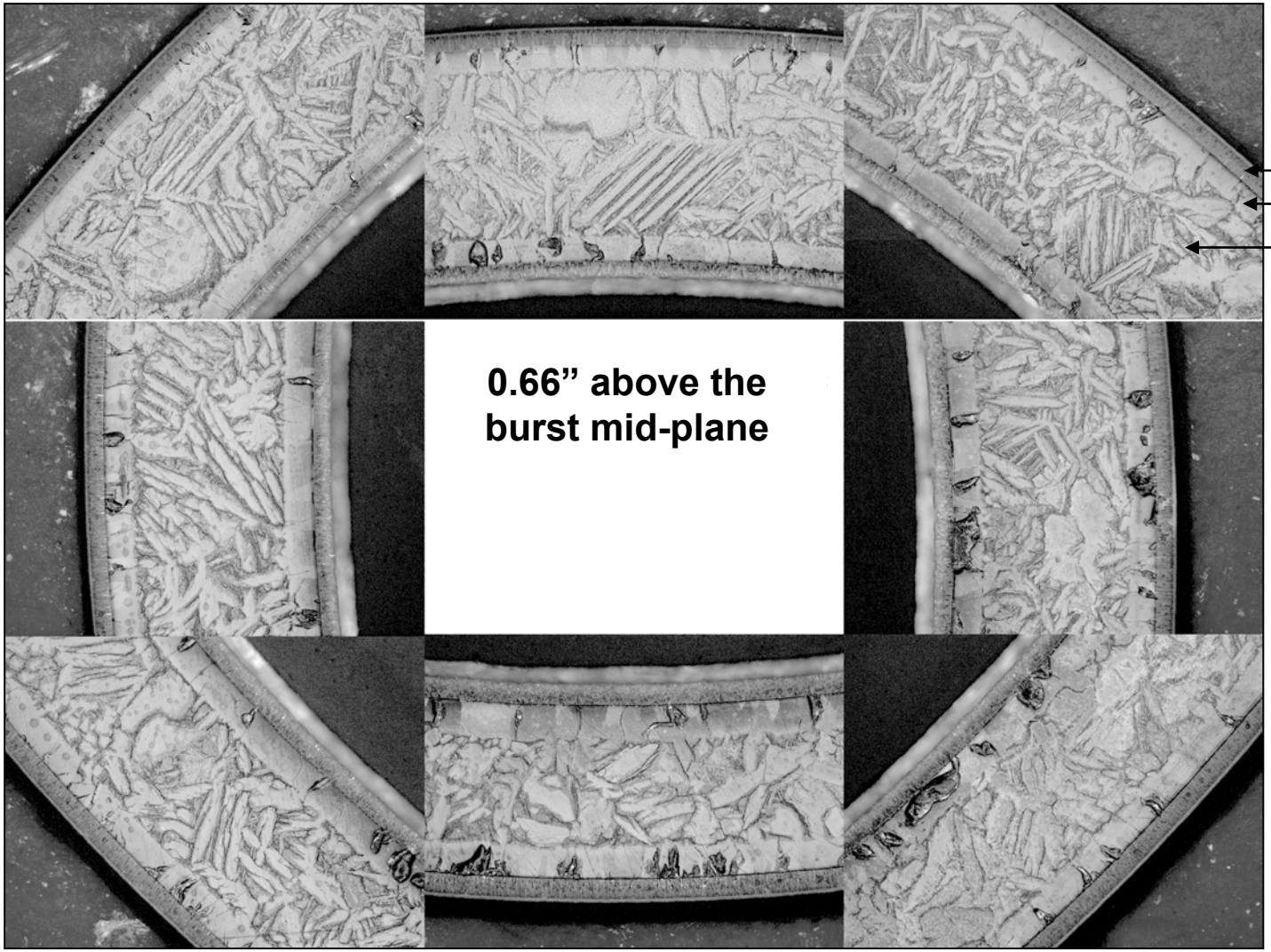
Temperature and Pressure Histories of Test OCL#11



OD Strain of OCL#11 sample (1200°C for 5 min)

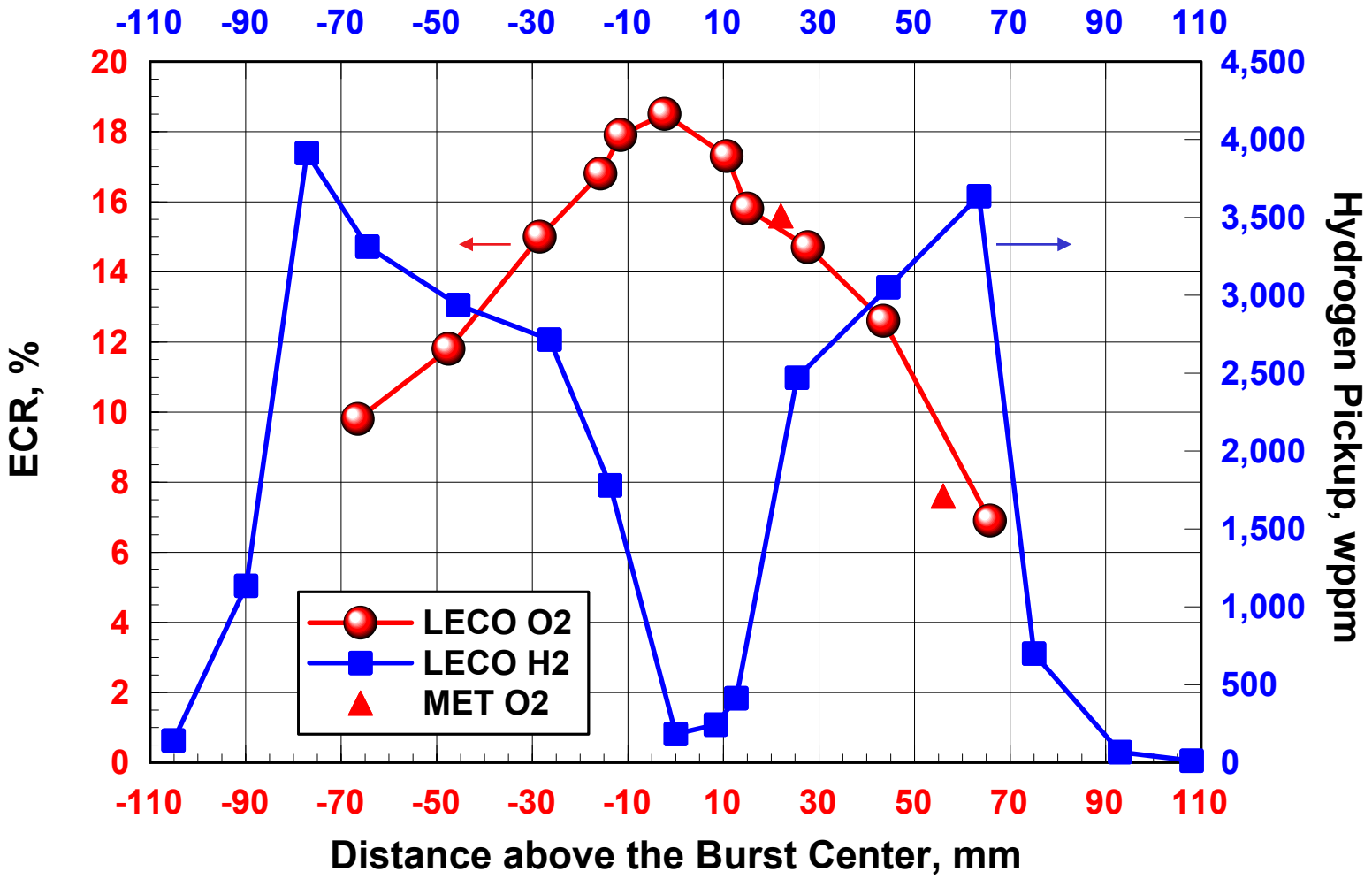


Cladding Metallographic Results for OCL#11 Specimen

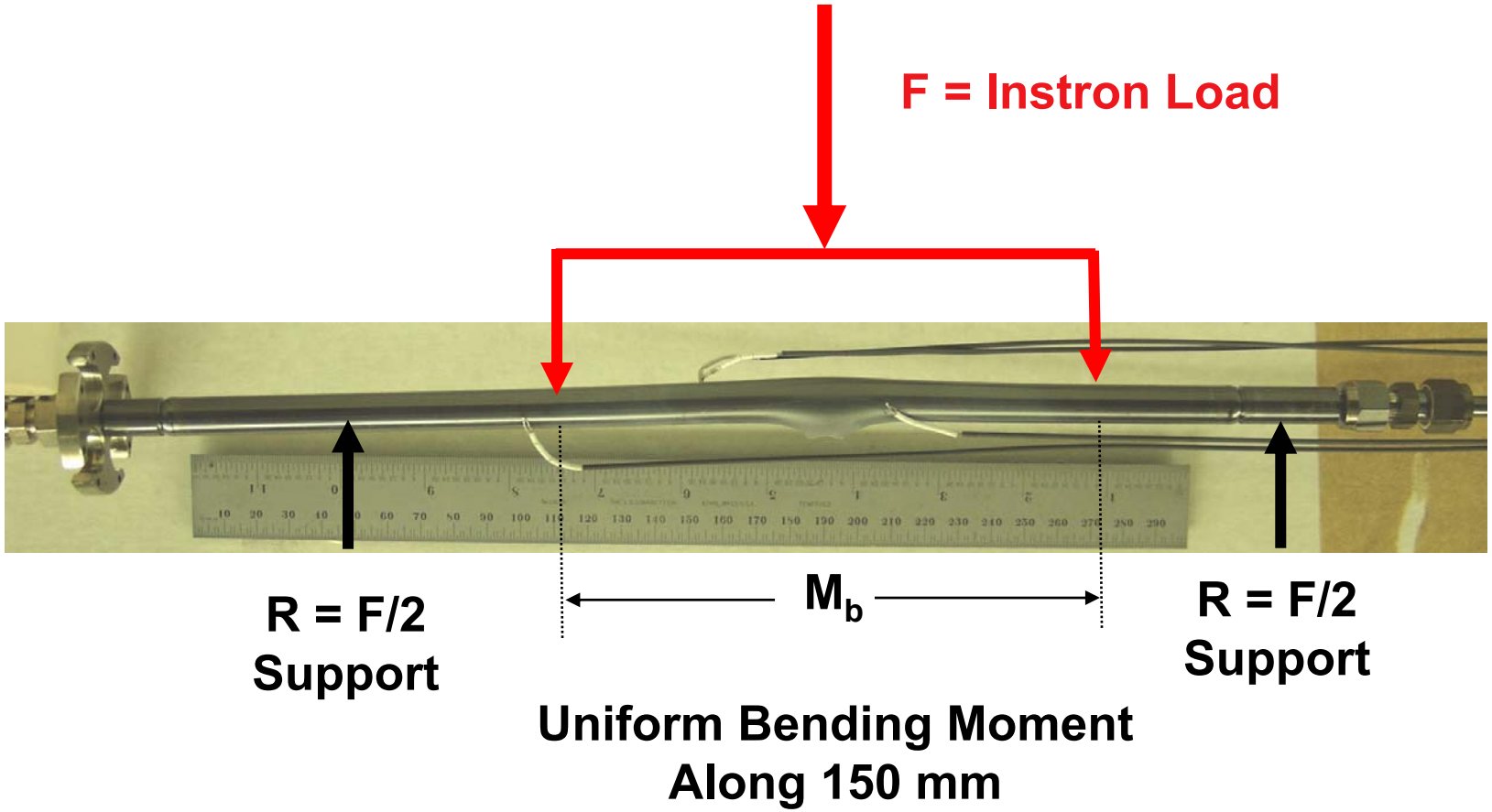


Oxide
Alpha
Prior Beta

LOCA Integral Test Results for Zry-2 (1200°C for 5 min)



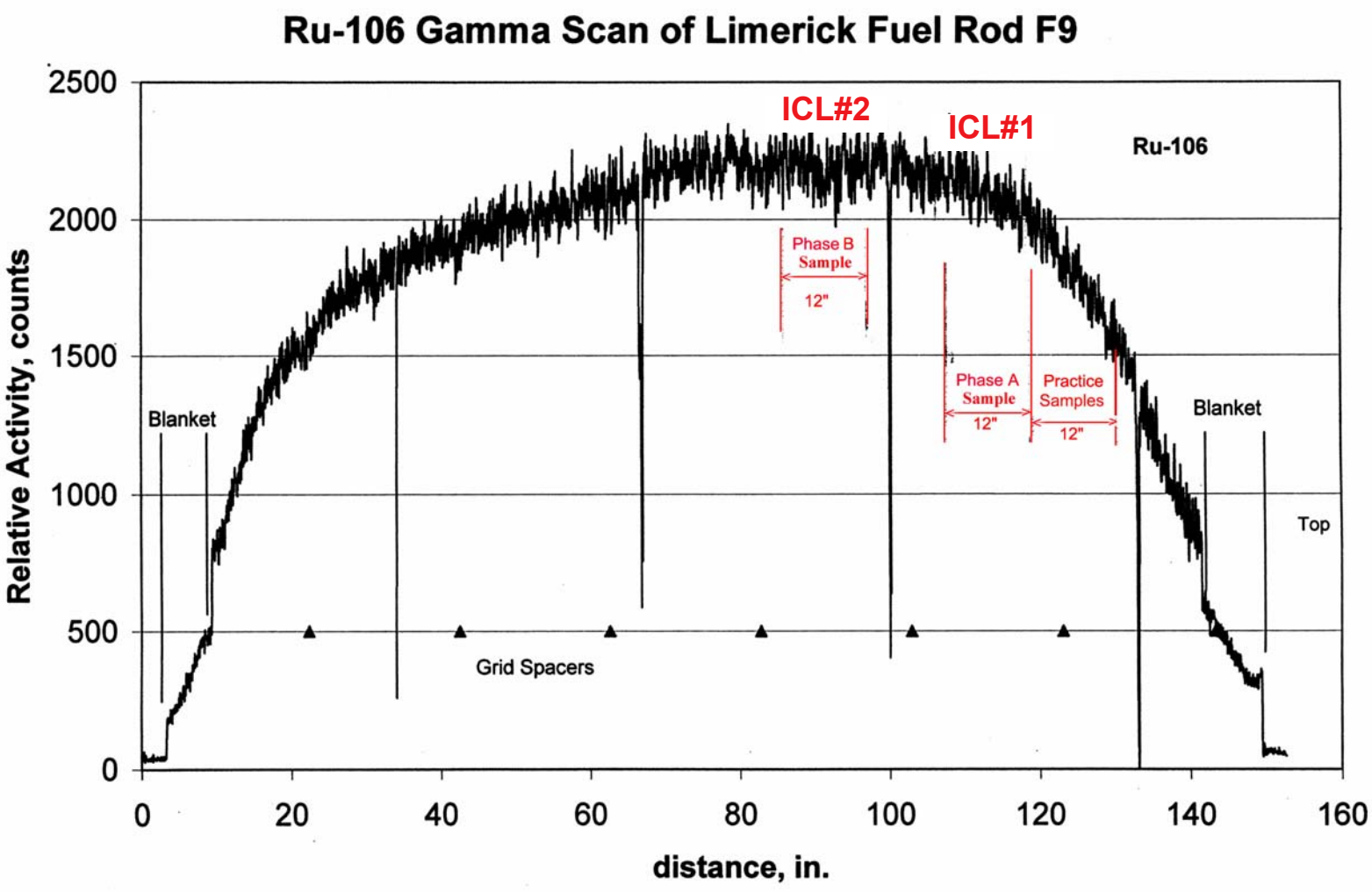
4-Point-Bend Test: Burst Area under Axial Tension



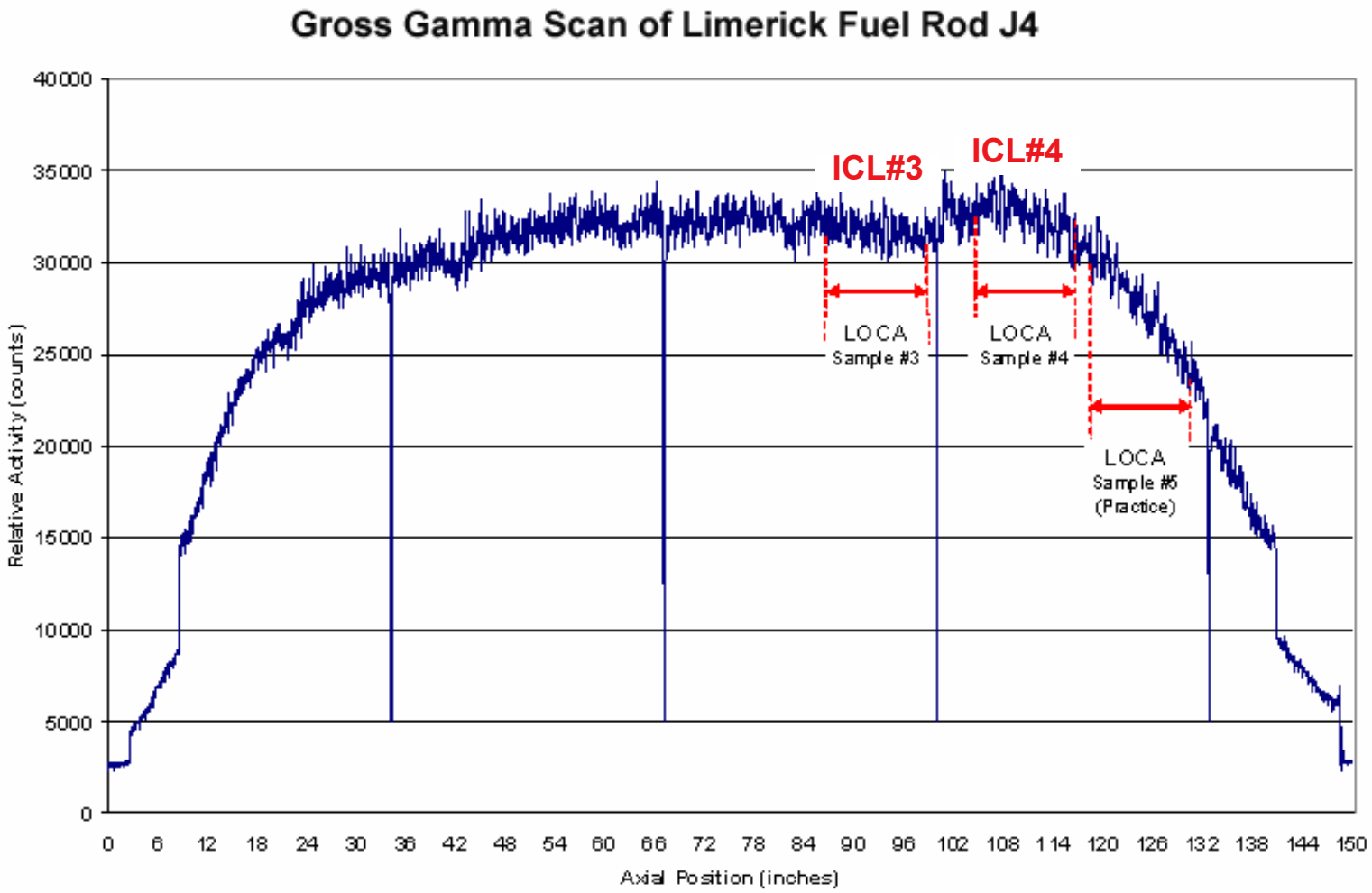
LOCA Tests with High-Burnup BWR Fuel

- **In-cell LOCA Test ICL#1**
  - Ramp-to-Burst Test Conducted in Argon
- **In-cell LOCA Test ICL#2**
  - LOCA Sequence with 5-minute Oxidation at 1204ºC and Slow-Furnace Cooling
- **In-cell LOCA Test ICL#3**
  - 5-minute Oxidation at 1204ºC Followed by Quench at 800°C (quarts tube failed at 480°C)
- **In-cell LOCA Test ICL#4**
  - Full LOCA Sequence (5-minute Oxidation at 1204ºC) with Quench at 800°C

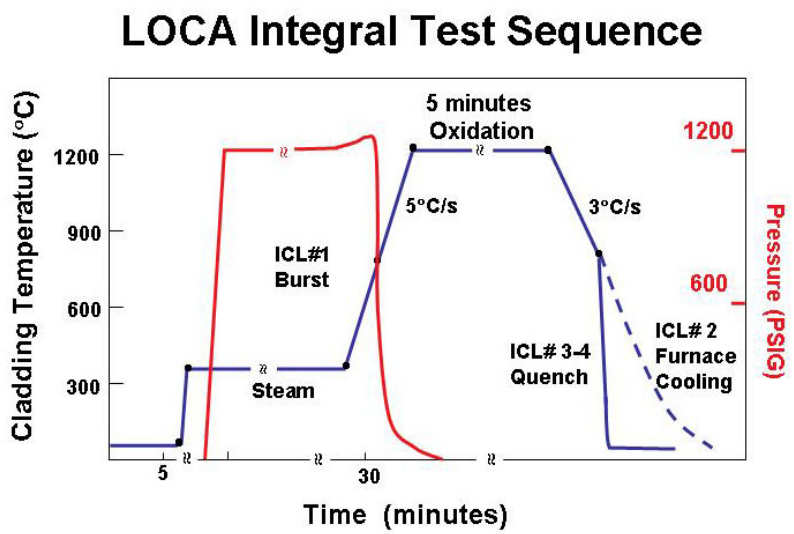
Gamma Scan of Limerick Fuel Rod F9



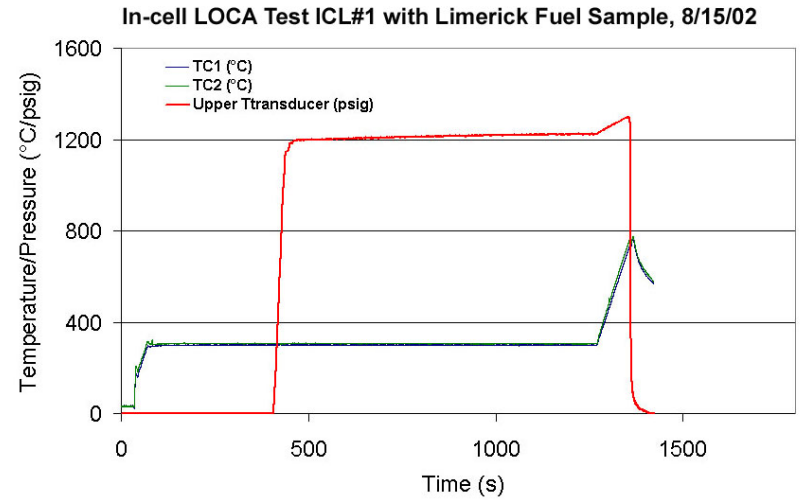
Gamma Scan of Limerick Fuel Rod J4



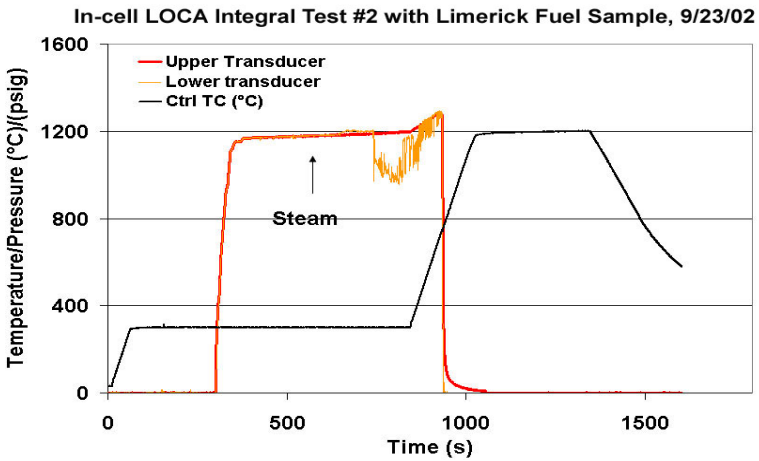
Temperature and Pressure of In-cell LOCA Tests



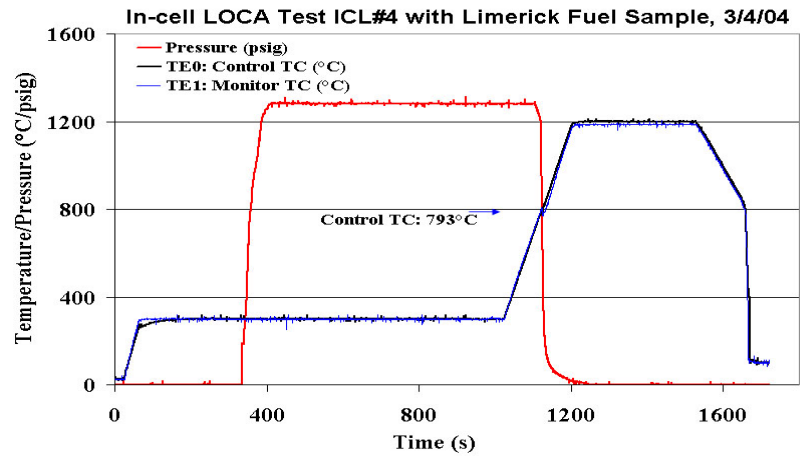
In-cell LOCA ICL#1



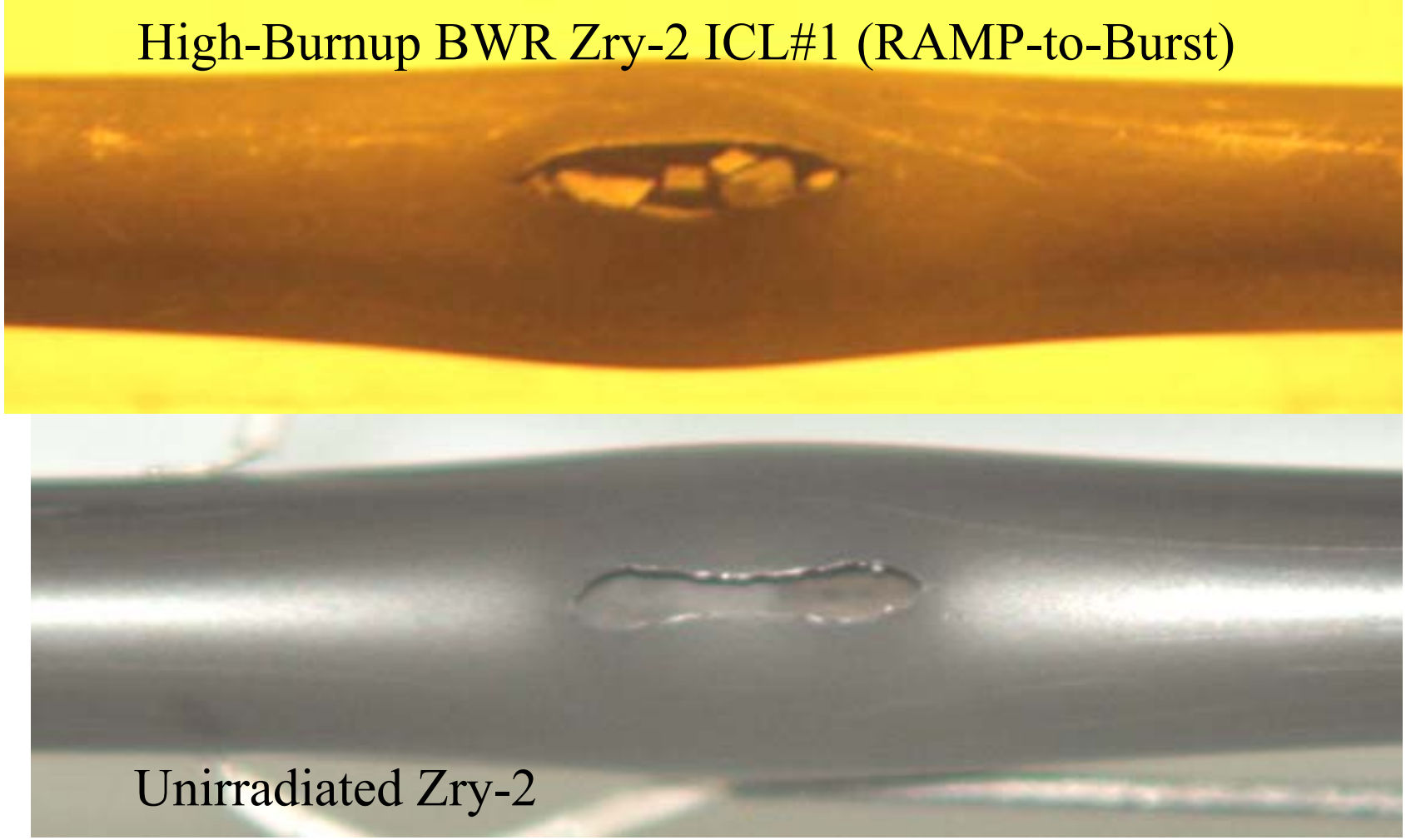
In-cell LOCA ICL#2



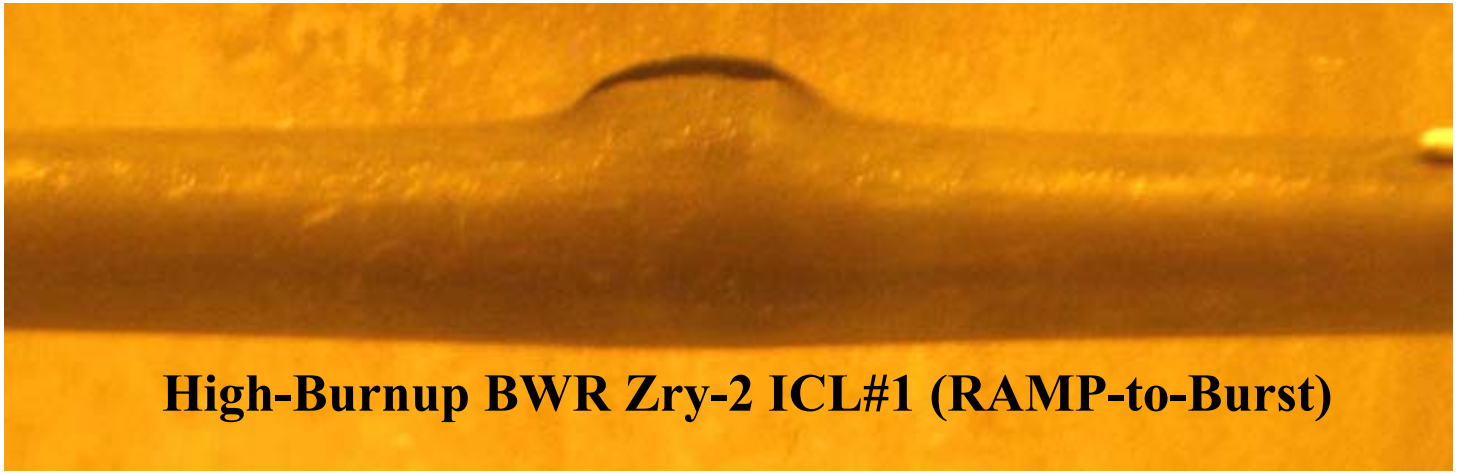
In-cell LOCA ICL#4

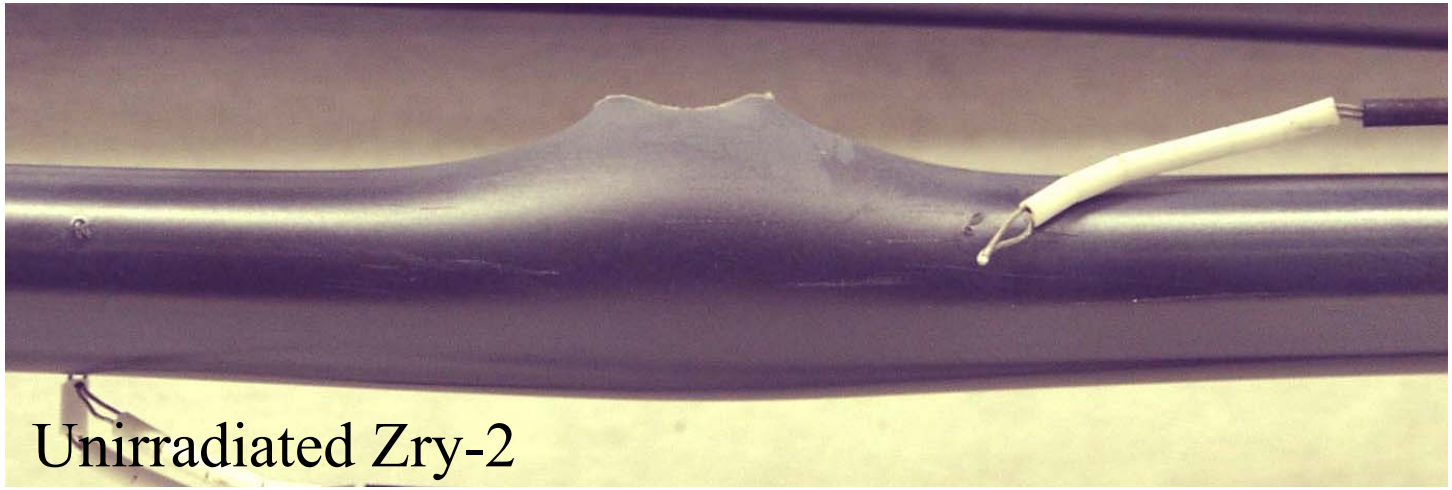


Burst Opening Comparison

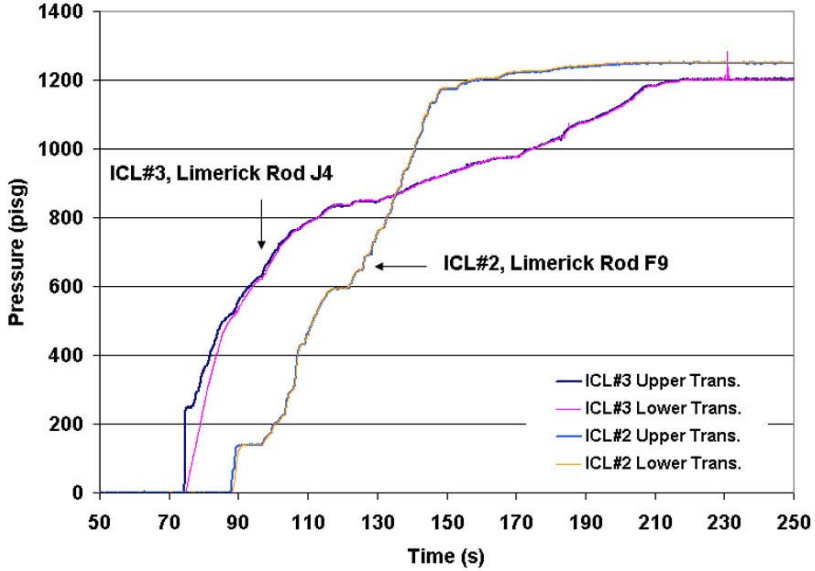


Side View of Burst Opening

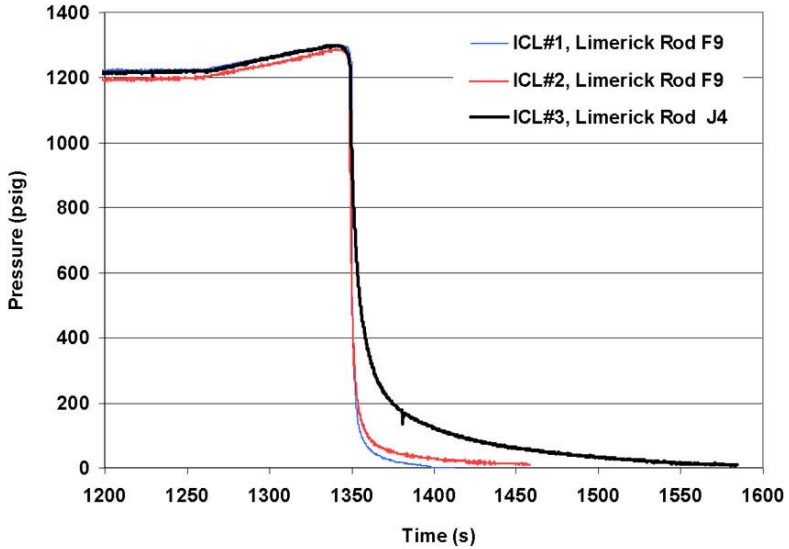




Gas Communication in High-burnup BWR Rods

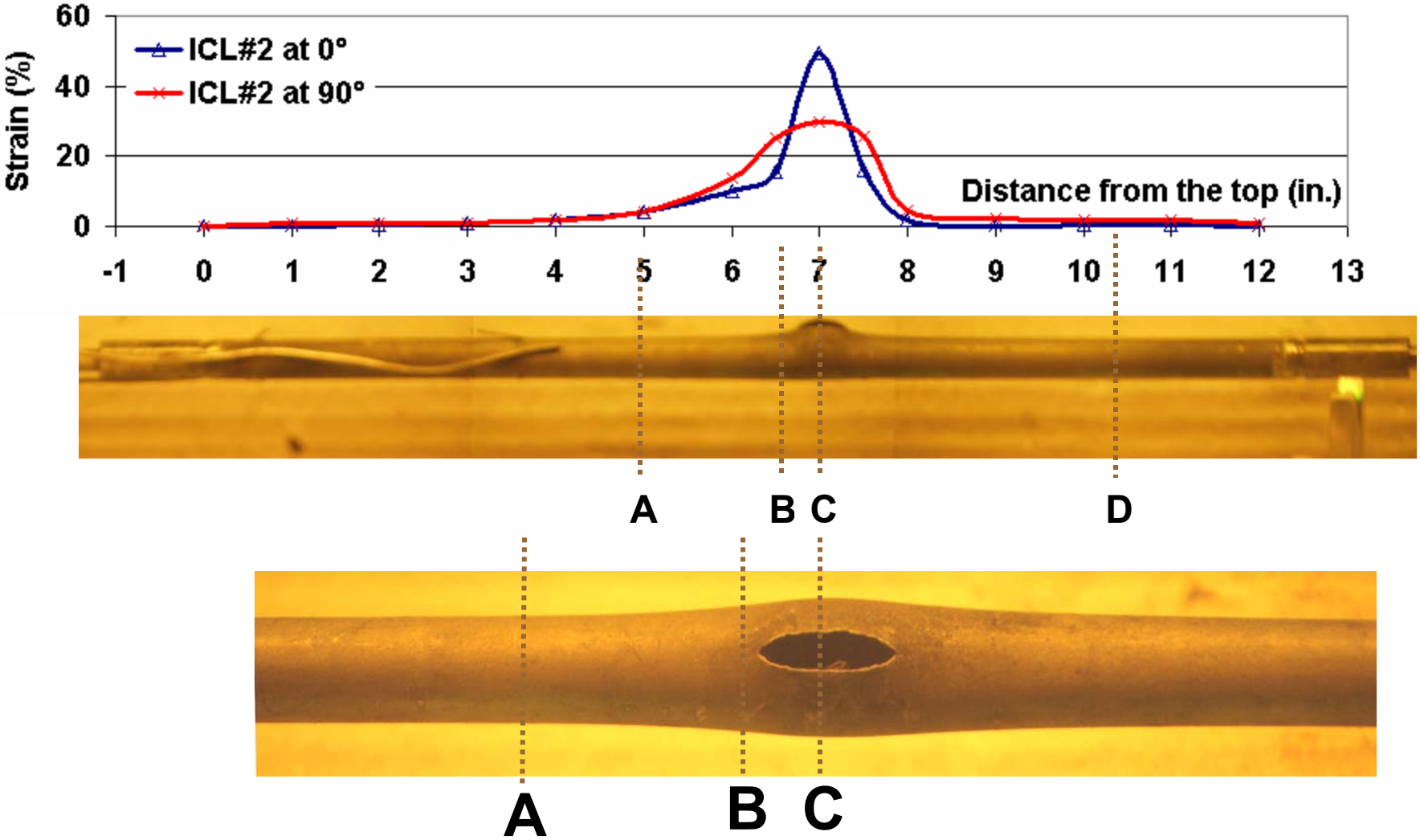


Upper and lower transducer reading at room temperature

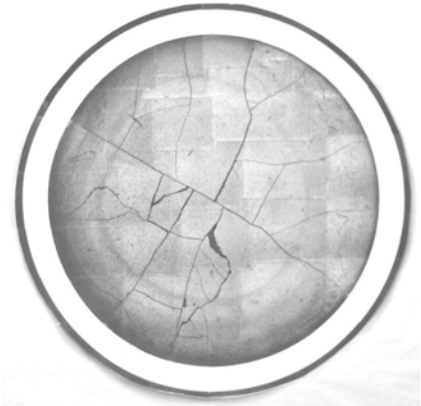


Upper transducer readings after burst

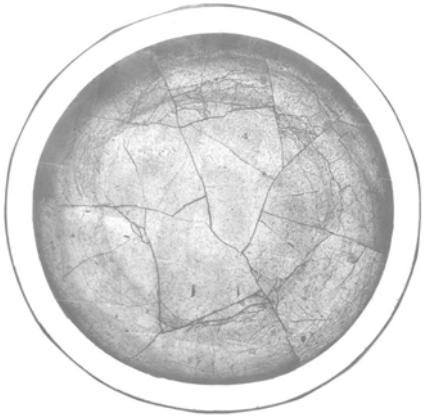
Post-test Characterization for ICL#2 Specimen



Fuel Metallographic Results for ICL#2 Specimen

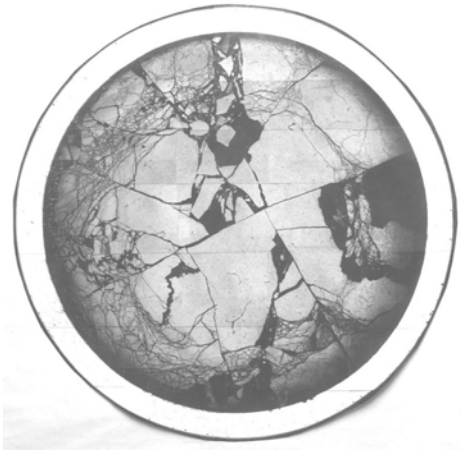


Pre-test Specimen



≈80 mm away from the burst

Post-test Specimen D, Strain: 0% - 2%



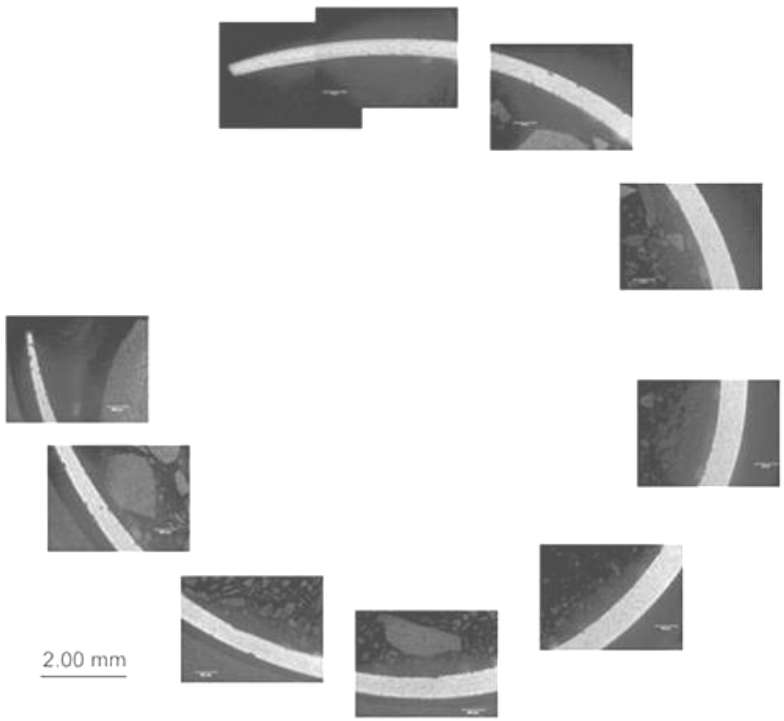
≈ 50 mm above burst mid-plane

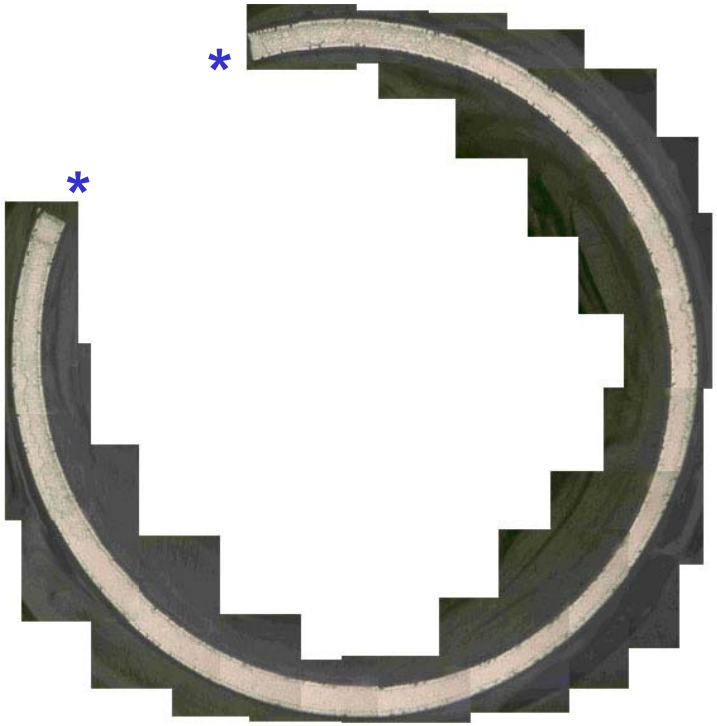
Post-test Specimen A, Strain: 2% - 4%

≈12 mm above burst mid-plane

Post-test Specimen B, Strain: 15% - 25%

Cross-Section for High Burnup LOCA Samples

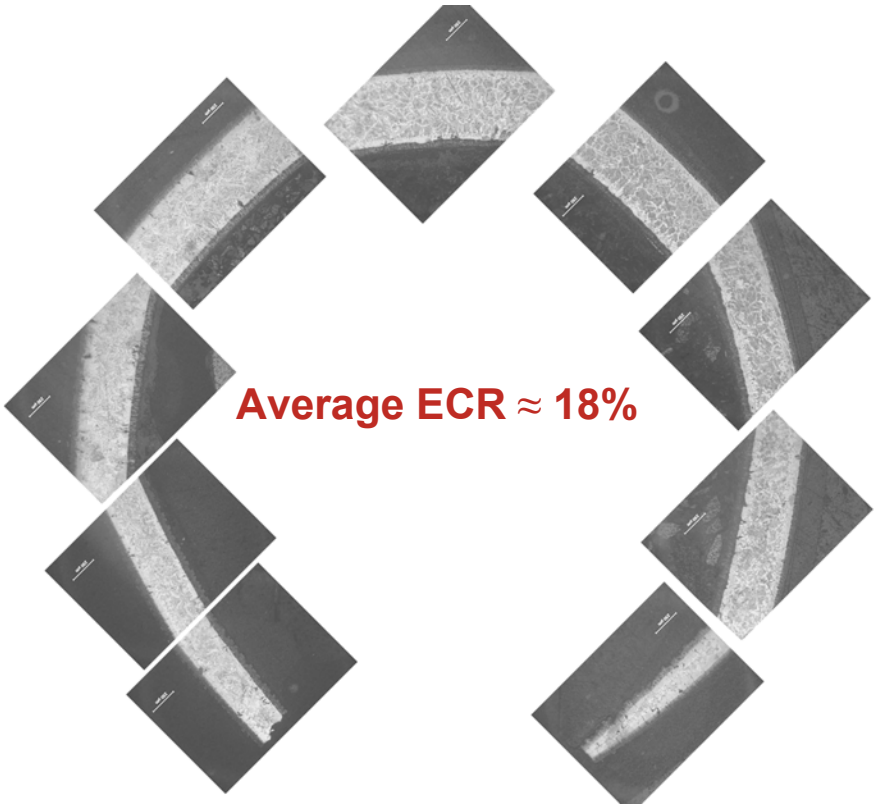


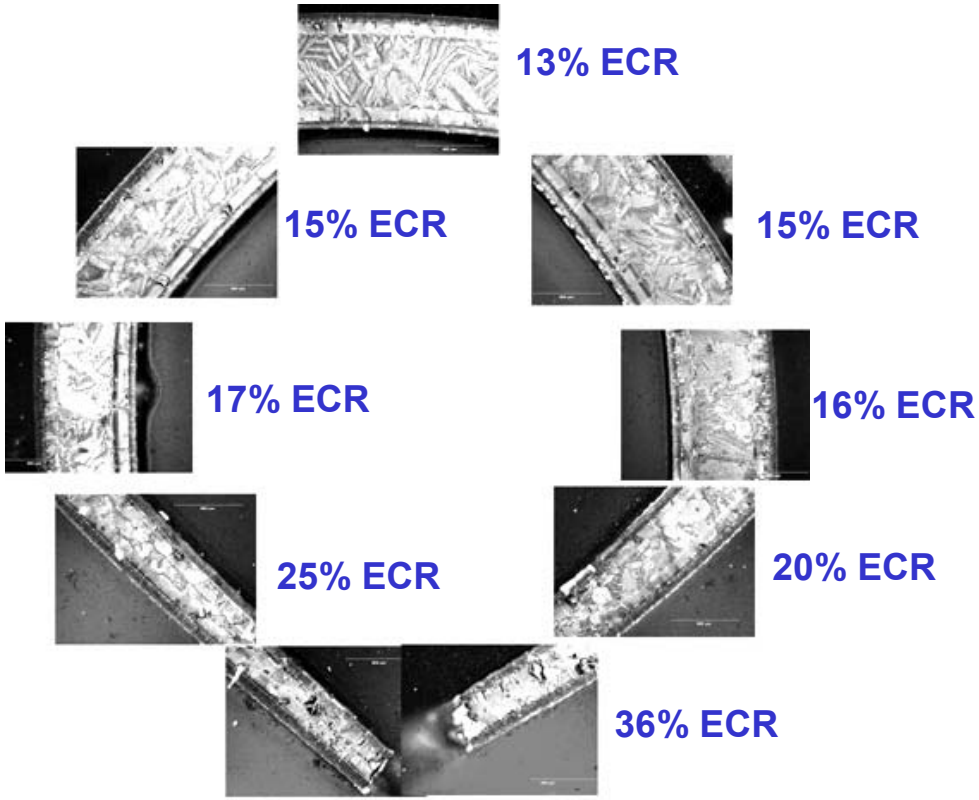


Post-test high-burnup ICL#2:
Burst mid-plane (1204°C, 5 min)
Strain: 30% - 50%
OD Oxide: 49 μm; ID Oxide: 60 μm

Post-test high-burnup ICL#3:
Burst mid-plane (1204°C, 5 min)
Strain: 36% - 52%
OD Oxide: 53 μm; ID Oxide: 56 μm
* Tip lost during sample handling

High Mag. Images of LOCA Burst Cross-Section

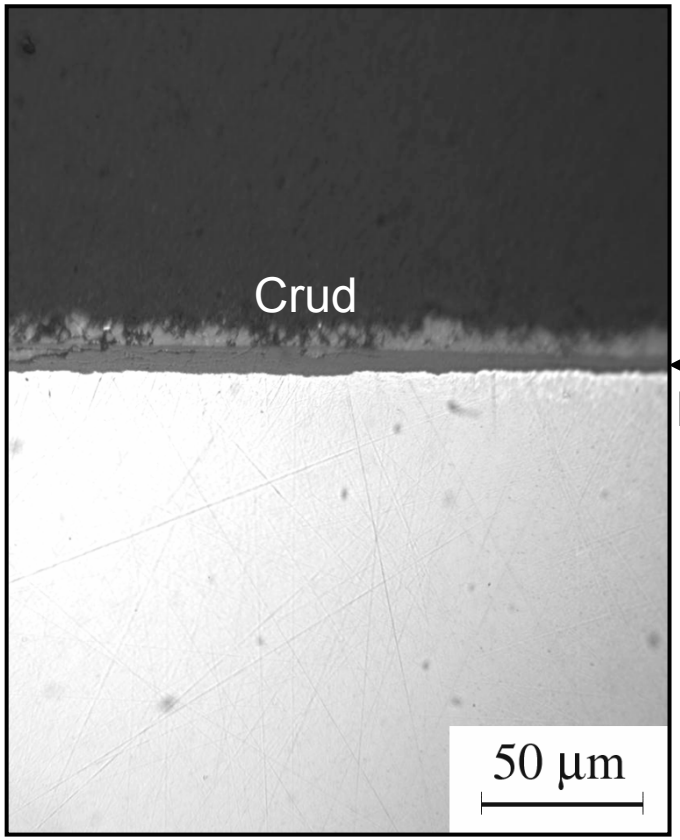




High Burnup Sample ICL#2:
Burst mid-plane (1204°C, 5 min)
Strain: 30% - 50%

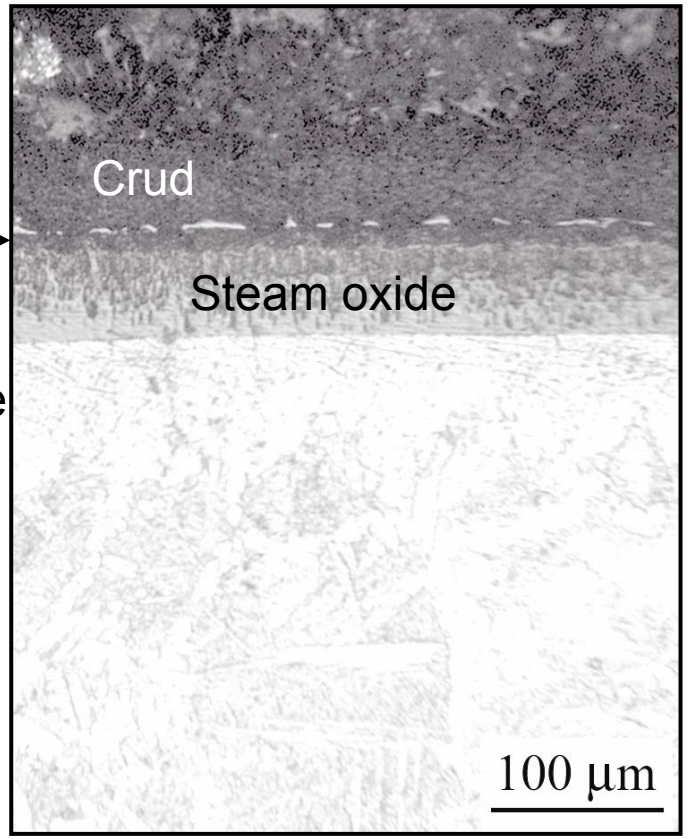
OCL#11 Sample(Unirrad. Zry-2)
Burst mid-plane (1204°C, 5 min)
Strain: 37% - 56%

Steam Oxide Layer of ICL#2 Specimen



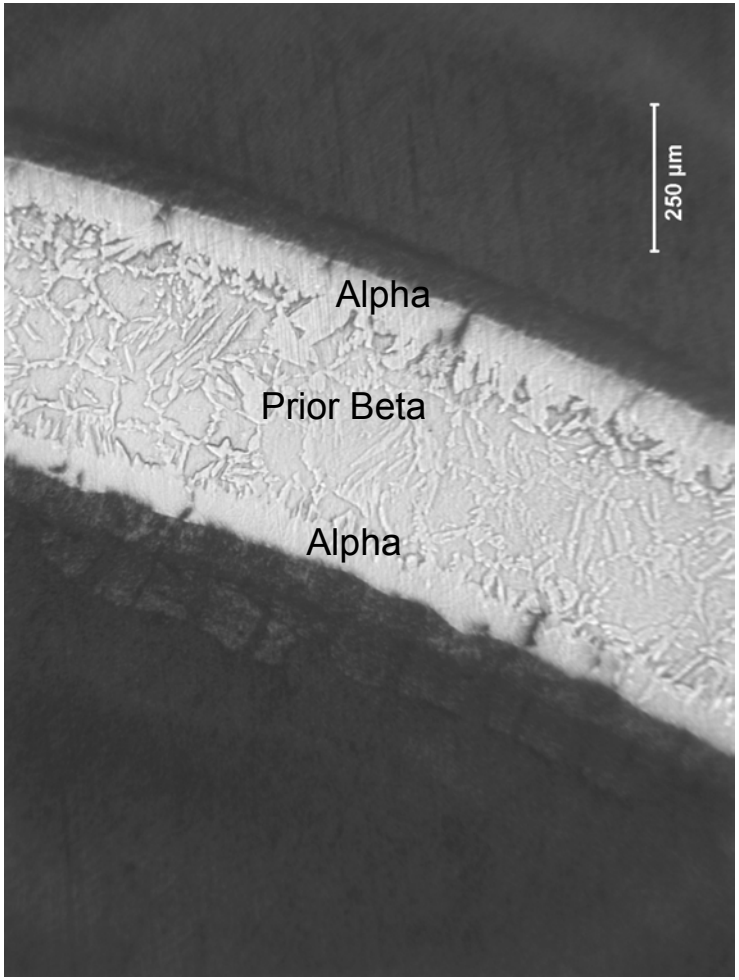
Pre-test Specimen

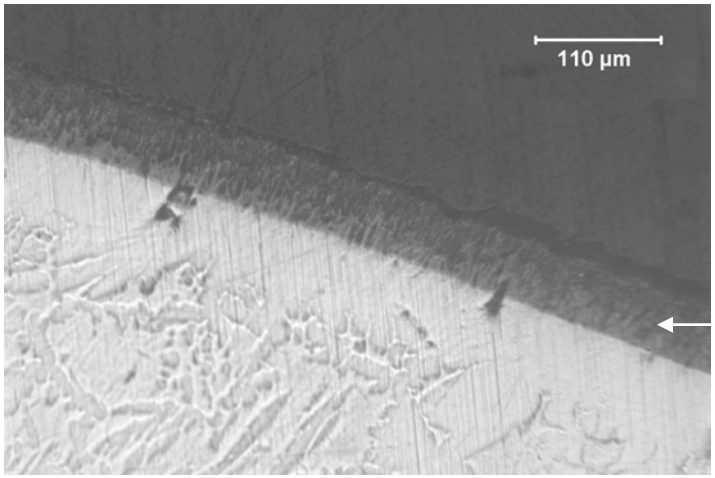
Pre-Oxide

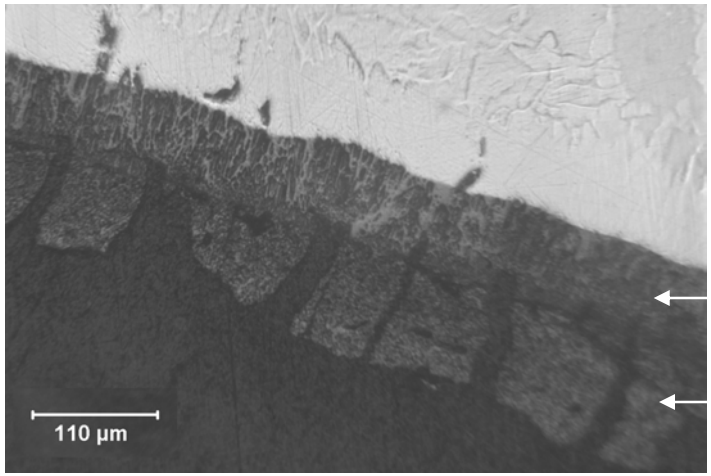


Post-test Specimen

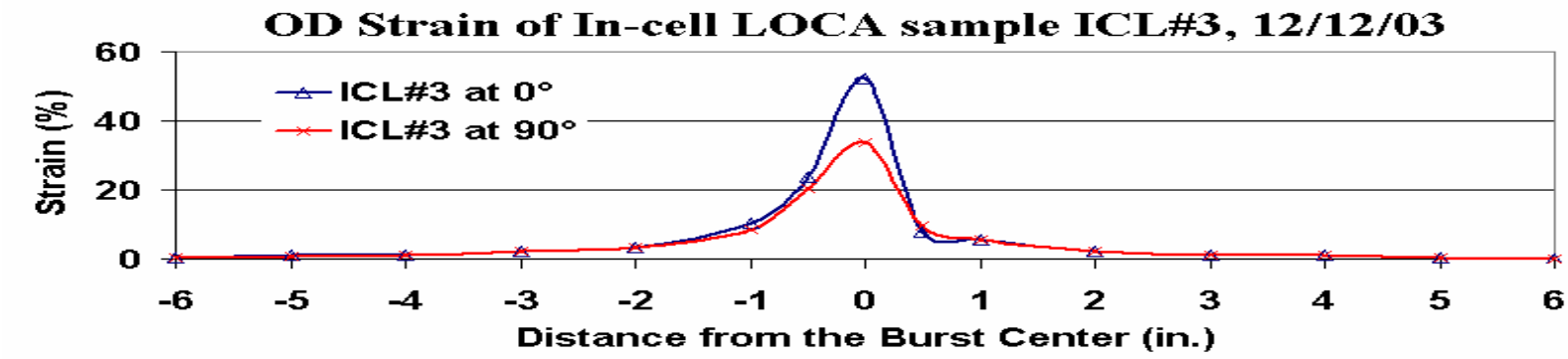
Cladding Cross-sections of ICL#3 Burst Opening

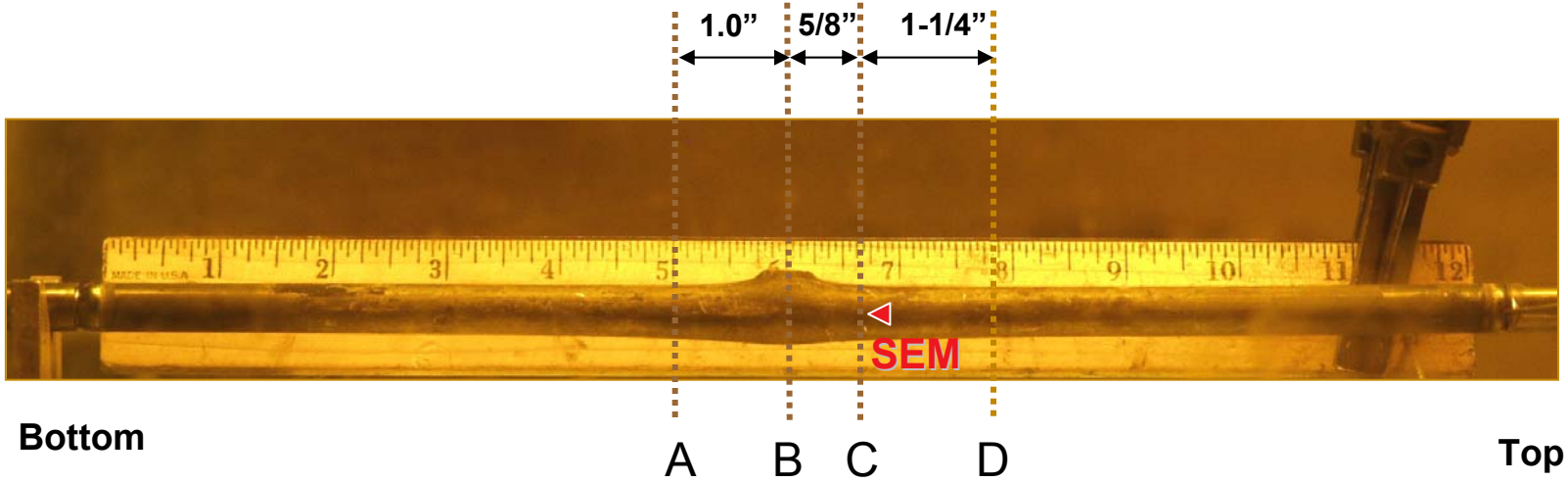






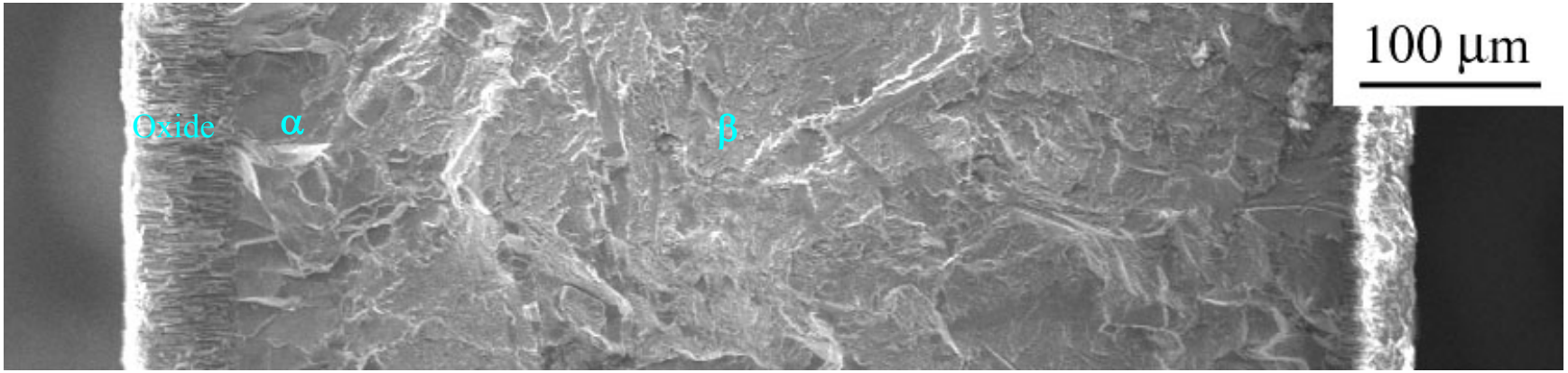
Post-test Characterization for ICL#3 Specimen

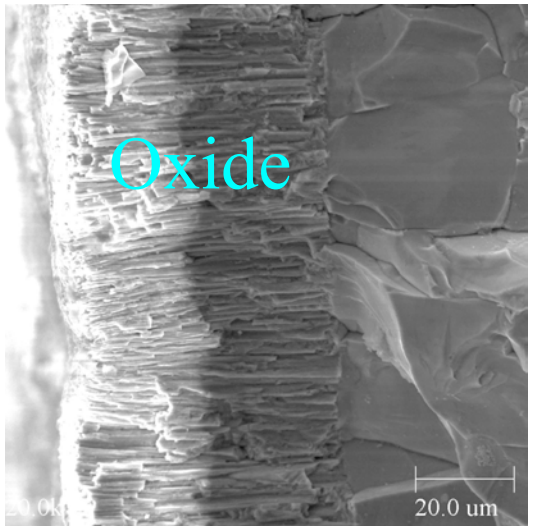




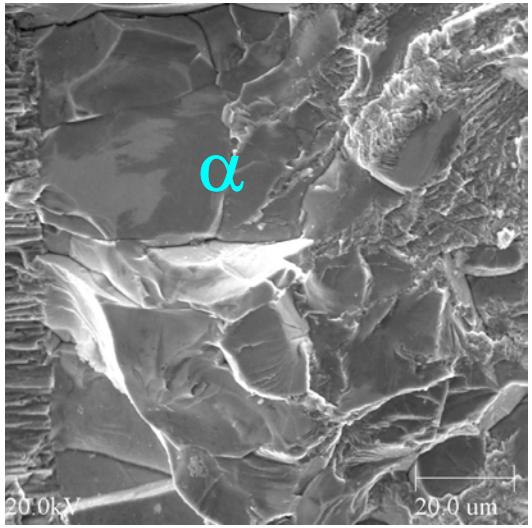
Sample ICL#3 was broken at locations A, B and C during the sample handling before the sectioning was performed at location D.

Fractography of ICL#3 Sample (20 – 30 mm to Mid-plane)

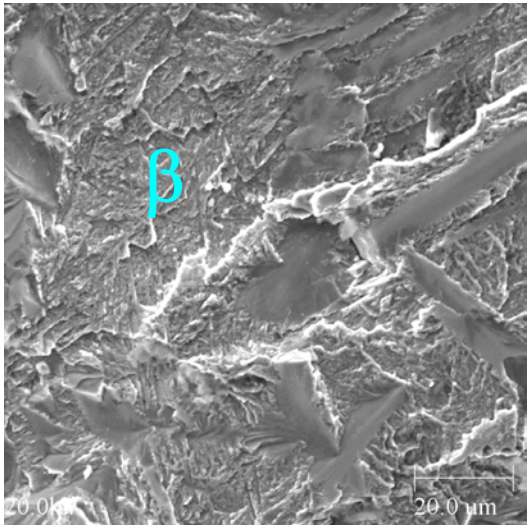




Oxide

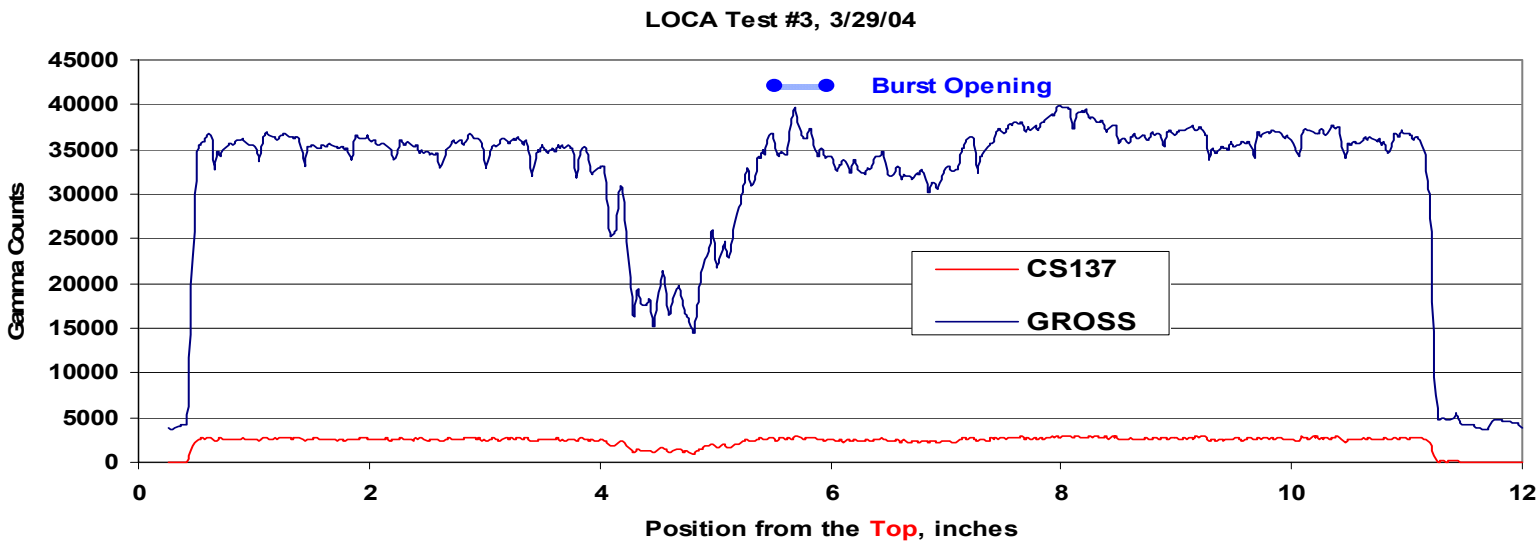


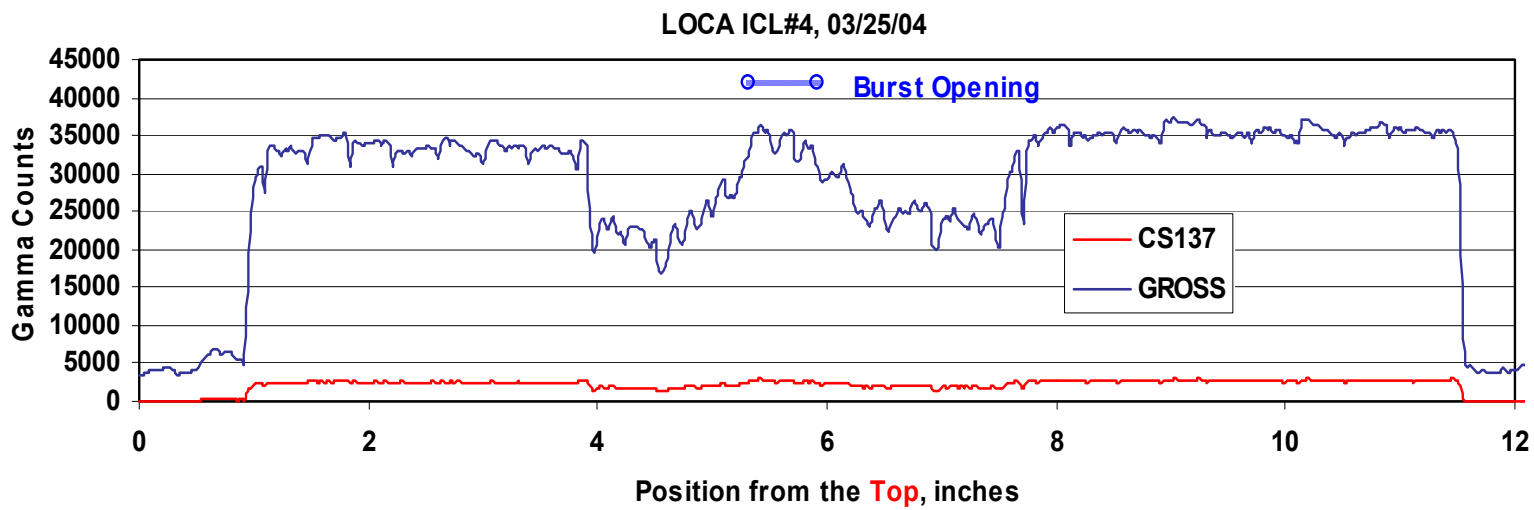
Alpha



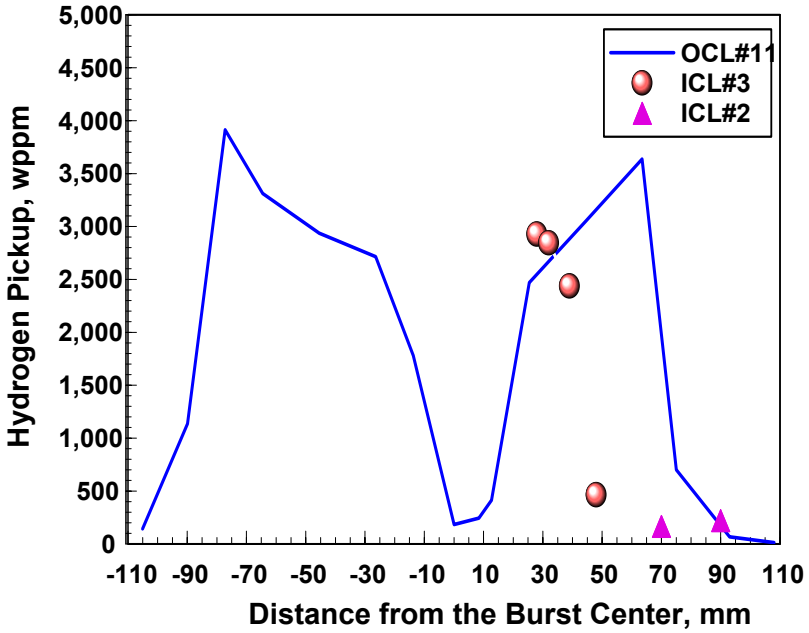
Prior Beta

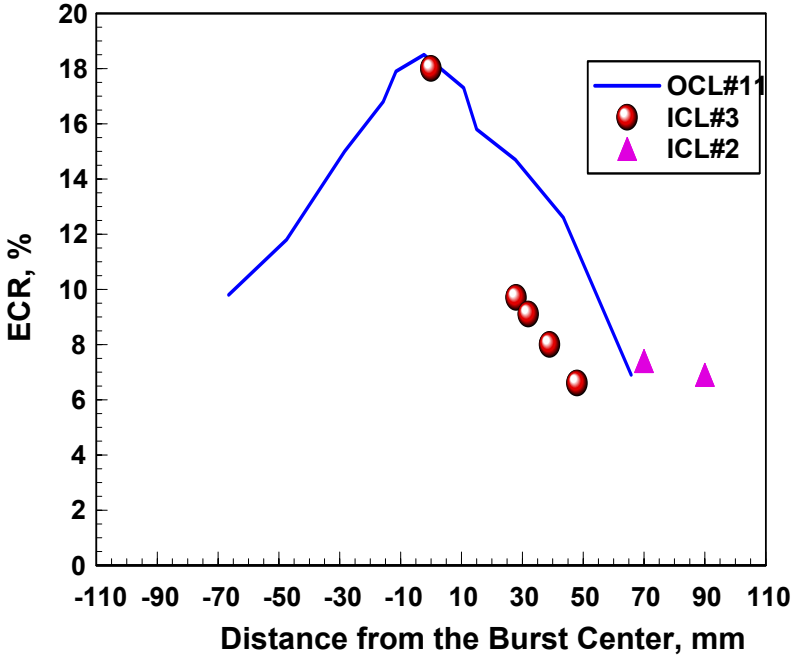
Gamma Scan Profiles for ICL#3 and ICL#4 Specimens



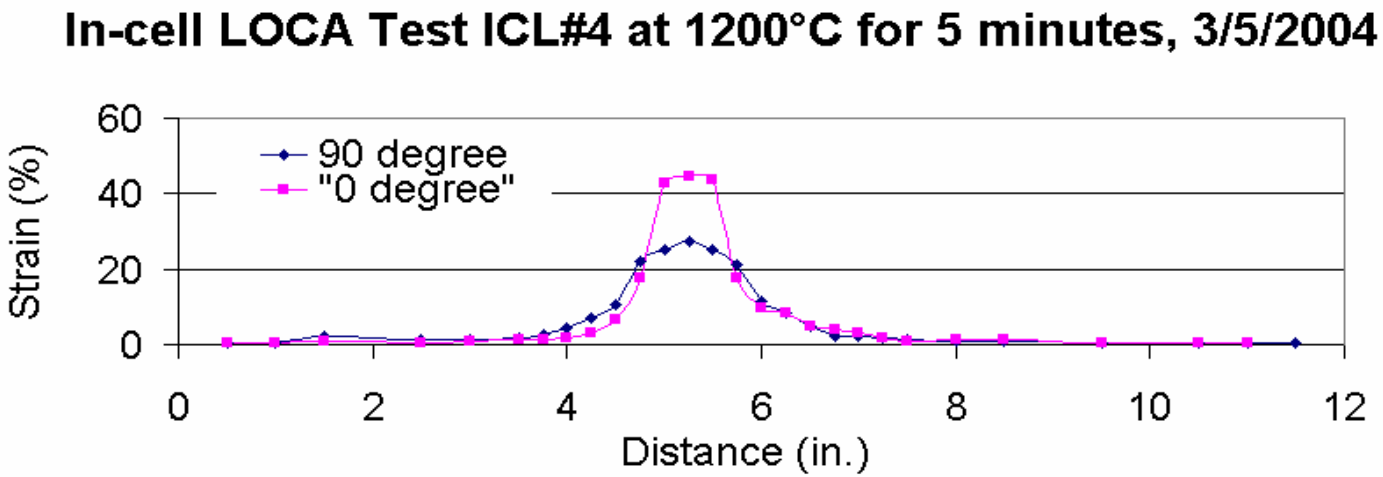


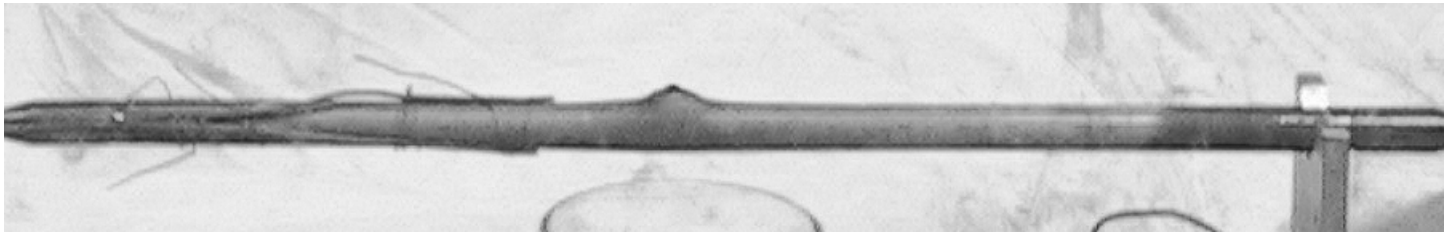
H and O Analyses of ICL#2 and ICL#3

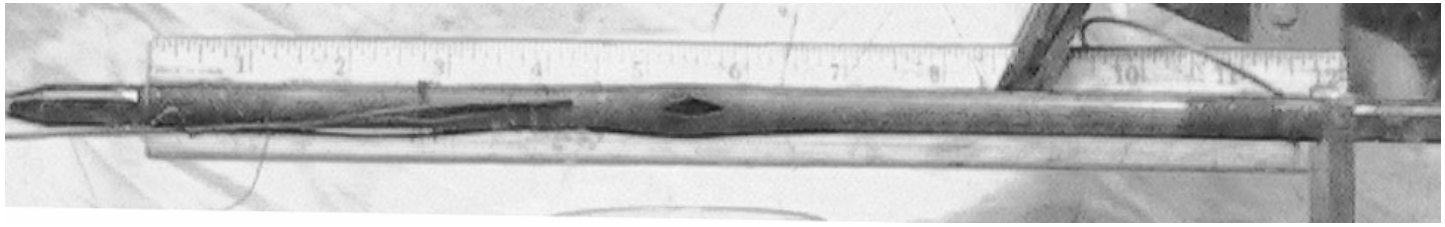




Post-test Characterization for ICL#4 Specimen







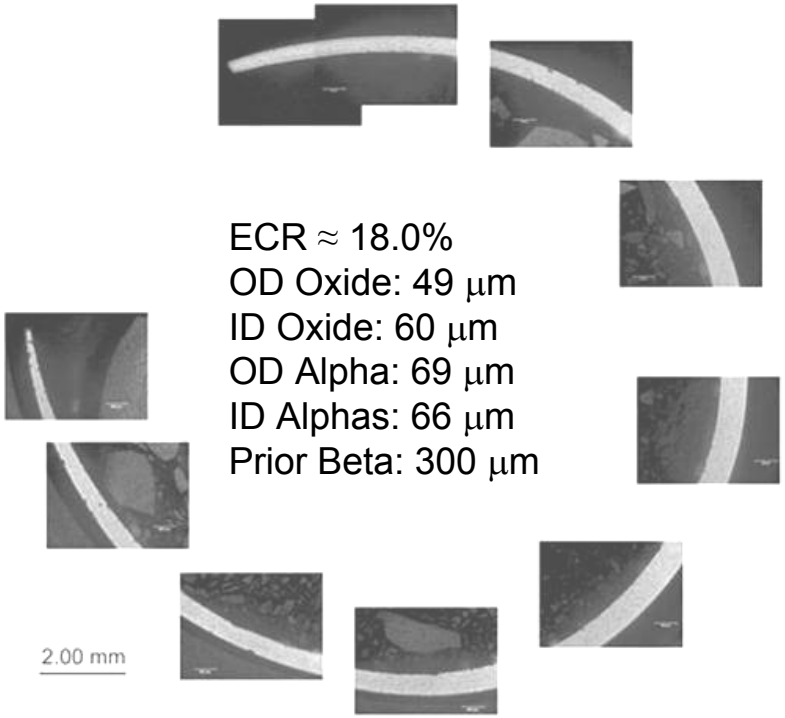
Summary of In-Cell LOCA Integral Tests with High-Burnup Limerick BWR Fueled Specimens

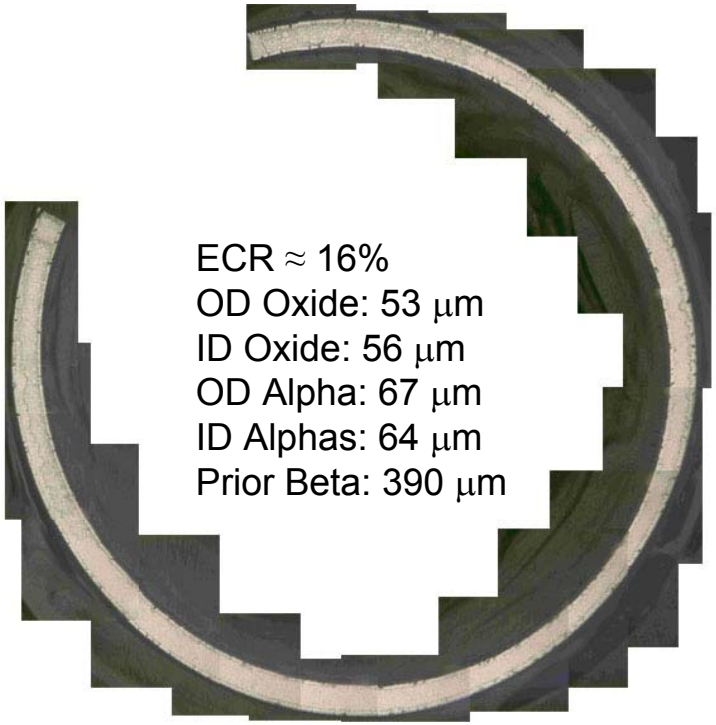
Parameter	ICL#1	ICL#2	ICL#3	ICL#4	OCL#11
Hold Time, minutes	0	5	5	5	5
Max. Pressure, MPa	8.96	8.87	9.0	8.86	8.61
Burst Pressure, MPa	≤8.61	≤8.01	8.6	8.0	≤7.93
Burst Temperature, °C	≈755	≈750	≈730	≈790	≈ 750
Burst Shape	Oval	Oval	Oval	Oval	Dog Bone
Burst Length, mm	13	14	11	15	11
Max. Burst Width, mm	3	3.5	4.6	5.1	1
Length of Balloon, mm	70	90	90	76	140
$(\Delta D/Do)_{max}$, %	38±9	39±10	43±9	36±9	43±10
Max. Calculated ECR, %	0	≈20	≈21	≈20	≈21
Max. ΔH, wppm	…	> 220	≥ 2900	TBD	3900

Summary

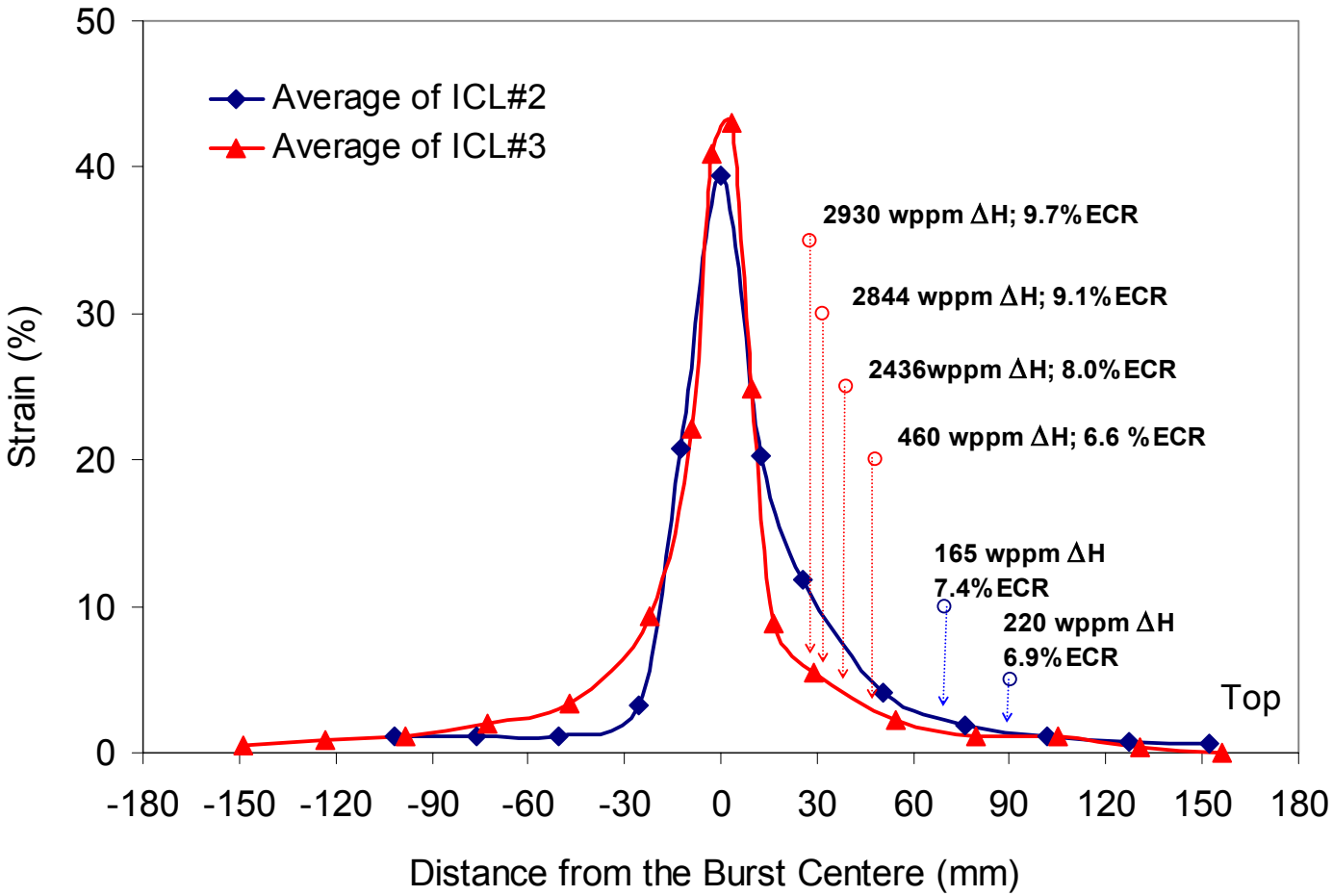
- **High-burnup BWR LOCA Test Matrix: Completed**
  - ICL#1: Ramp-to-burst test conducted in argon
  - ICL#2: LOCA sequence with 5-min. oxidation at 1204ºC and slow cooling
  - ICL#3 and ICL#4: Full LOCA sequence with quench
- **Future Work with High-Burnup Samples**
  - Perform bend test on post-quench fueled samples
  - Conduct ring compression tests on defueled samples
  - Initiate Robinson PWR oxidation and LOCA tests

Cross-Section for High Burnup LOCA Samples





Post-test high burnup ICL#2:
Burst mid-plane (1204°C, 5 min)
Max. Strain: 30% - 50%

Post-test high burnup ICL#3:
Burst mid-plane (1204°C, 5 min)
Max. Strain: 36% - 52%

Secondary Hydriding of ICL#2 and ICL#3