



LOCA Integral Test Results

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*Review of ANL LOCA and Dr-Cask-Storage Programs
Argonne National Laboratory
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Argonne National Laboratory



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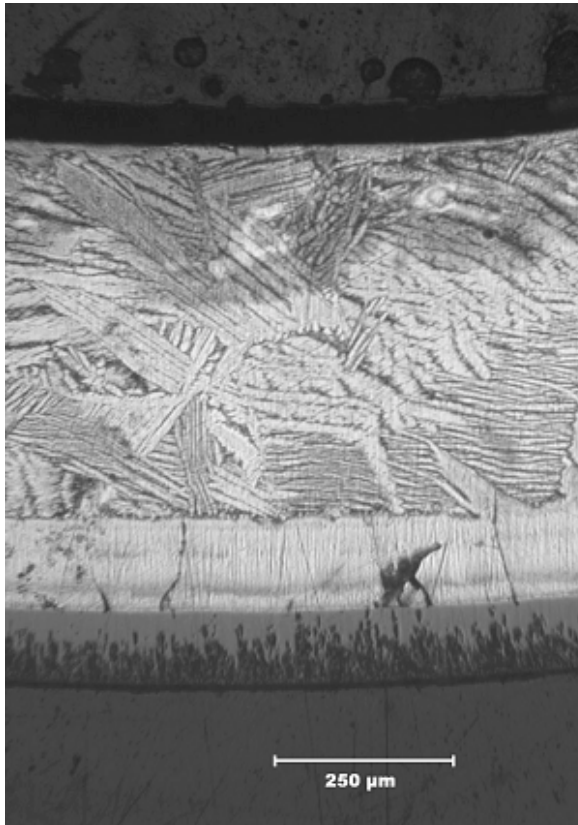
LOCA Issues for High-Burnup Fuel

- **BWR Fuel Rods (≤ 57 GWd/MTU, ≈ 10 μm OD Oxide)**
 - Effects of fuel-cladding bond and restricted gas flow on ballooning and burst, on inner-surface **oxidation/hydrogen** pickup, and on subsequent **post-quench ductility**
 - Effect of irradiation on high temperature oxidation in steam
 - Effect of fuel-cladding mechanical interaction on fragmentation resistance during water quench
- **PWR Fuel Rods (≤ 67 GWd/MTU, ≤ 100 μm OD Oxide)**
 - Similar fuel-cladding issues as for BWR
 - Effect of in-reactor oxide layer on oxidation kinetics and ECR
 - Effects of **hydrogen** content (up to ≈ 800 wppm) on oxidation kinetics, quench fragmentation-resistance and **post-quench ductility**

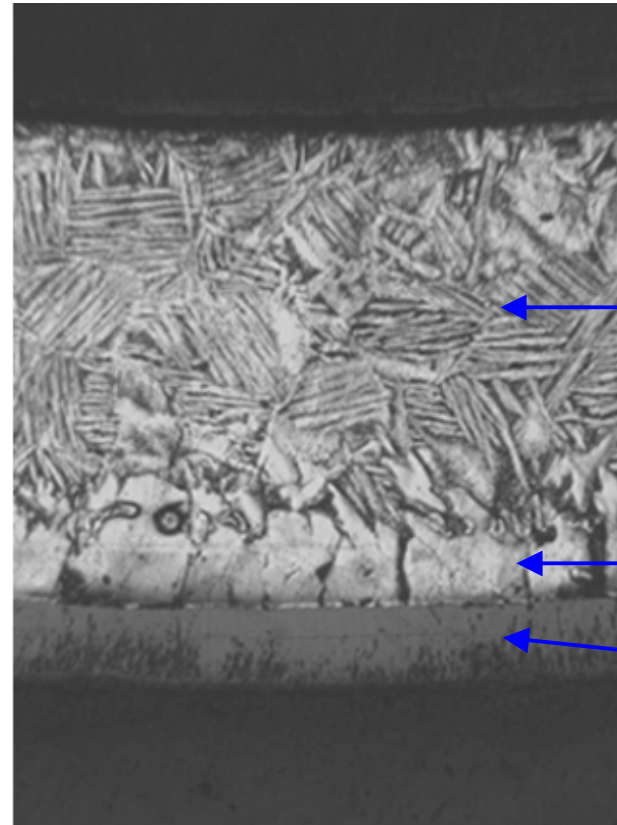
LOCA-Relevant Tests for High-Burnup Fuel

- **Steam Oxidation Kinetics Studies (One-Sided Tests)**
 - 900-1300°C, emphasis on 1204°C for 5-20 minutes
 - Kinetics of weight gain, (oxide + α) layer growth rate, effective β layer thickness vs. time at temperature, ECR
- **LOCA Integral Tests (1204°C)**
 - Test adequacy of 10CFR50.46 ECCS licensing criteria (**ECR \leq 17%, T \leq 1204°C**) for high burnup fuel
 - Determine if “measured” 17% ECR specimen has adequate post-quench ductility; if not, reduce oxidation test time
- **Post-Quench Ductility Tests**
 - Four-point bend tests: uniform bending moment along specimen
 - ring compression tests of samples outside the balloon region

Oxide, α and Prior- β Layer Characteristics for Zry-2 (in Steam at 1204°C for 10 Minutes; ECR = 11%)



unirradiated Zry-2



irradiated Zry-2

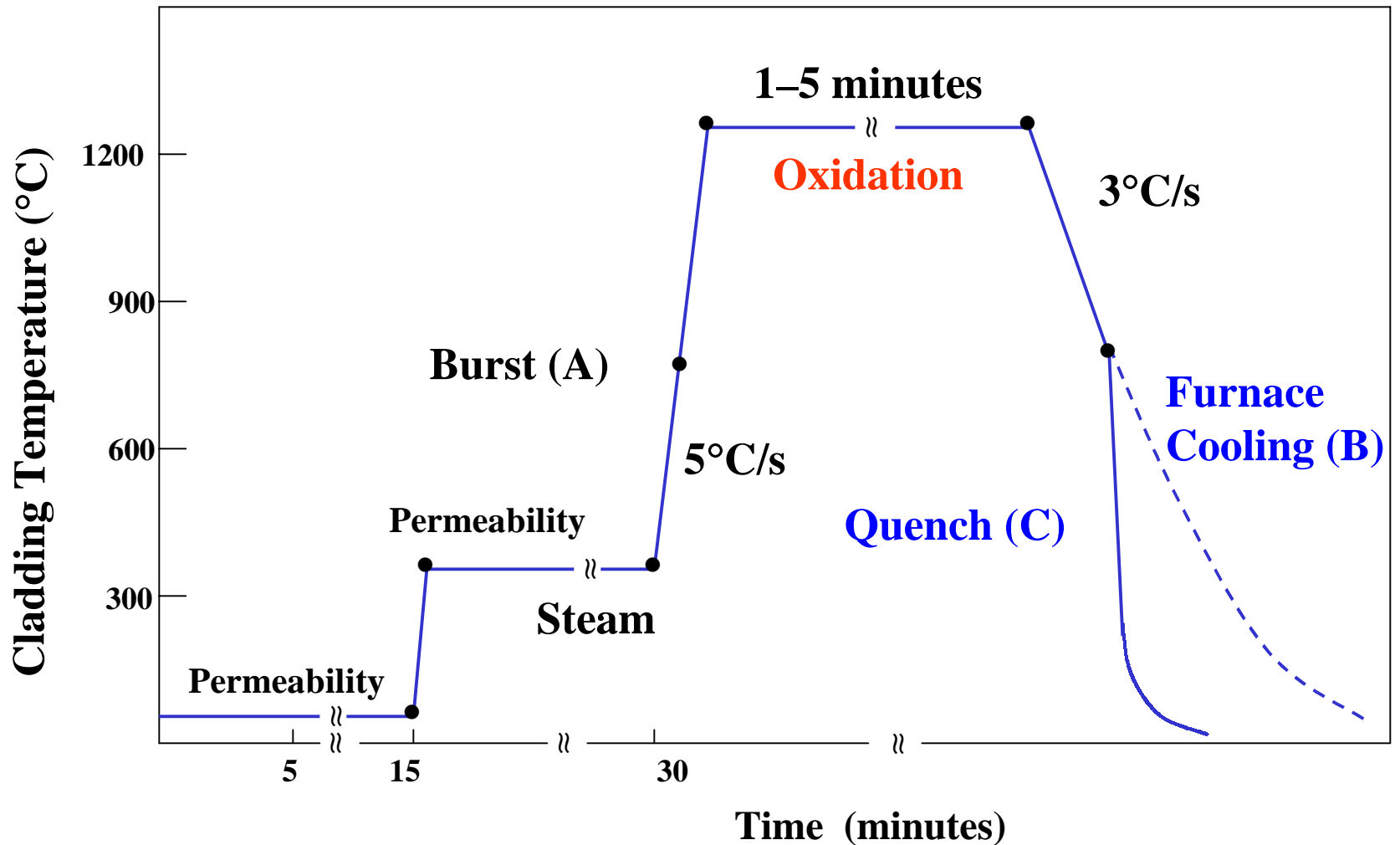
LOCA Integral Testing Scope

- **Parameters Common to BWR and PWR Tests**
 - **Fuel-cladding samples** = 305-mm long; fueled region = 270 mm
 - **Peak cladding temperature (PCT) = $1204 \pm 20^\circ\text{C}$**
 - **“Plenum” Volume $\approx 10\text{ cm}^3$** (most of it outside heating zone)
 - **Best-estimate and “measured” ECR $\approx 17\%$ for 5 min. hold time**
- **High Burnup BWR Rods (Limerick)**
 - **Heating rate = 5°C/s , cooling rate = 3°C/s , quench at 800°C**
 - **Cladding $\Delta P \leq 8.6\text{ MPa}$ (1250 psig): gives large balloon and burst temperature $< 800^\circ\text{C}$ (alpha phase)**
- **High Burnup PWR Rods (H. B. Robinson)**
 - Same test conditions as for BWR
 - Note: both BWR and PWR cladding thickness $\approx 0.7\text{ mm}$ after in-reactor corrosion; primary difference is H (≈ 70 vs. ≤ 800 wppm)

Limerick BWR LOCA Integral Tests

- **Test 1 (Phase A): Fuel Permeability, Ballooning and Burst**
 - Permeability at 30°C and 300°C
 - Ramp (5°C/s) to burst in high purity argon
 - Slow furnace cool from burst temperature
- **Test 2 (Phase B): Above Plus Oxidation**
 - Permeability (30°C and 300°C); ramp to 1204°C in steam
 - Hold (5 min.) at 1204°C; cool to 800°C at 3°C/s
 - Slow furnace cool from 800°C to RT
- **Test 3 (Phase C): Above Plus Quench at 800°C**
 - Repeat Phase B through cooling to 800°C; quench at 800°C

LOCA Integral Test Sequence



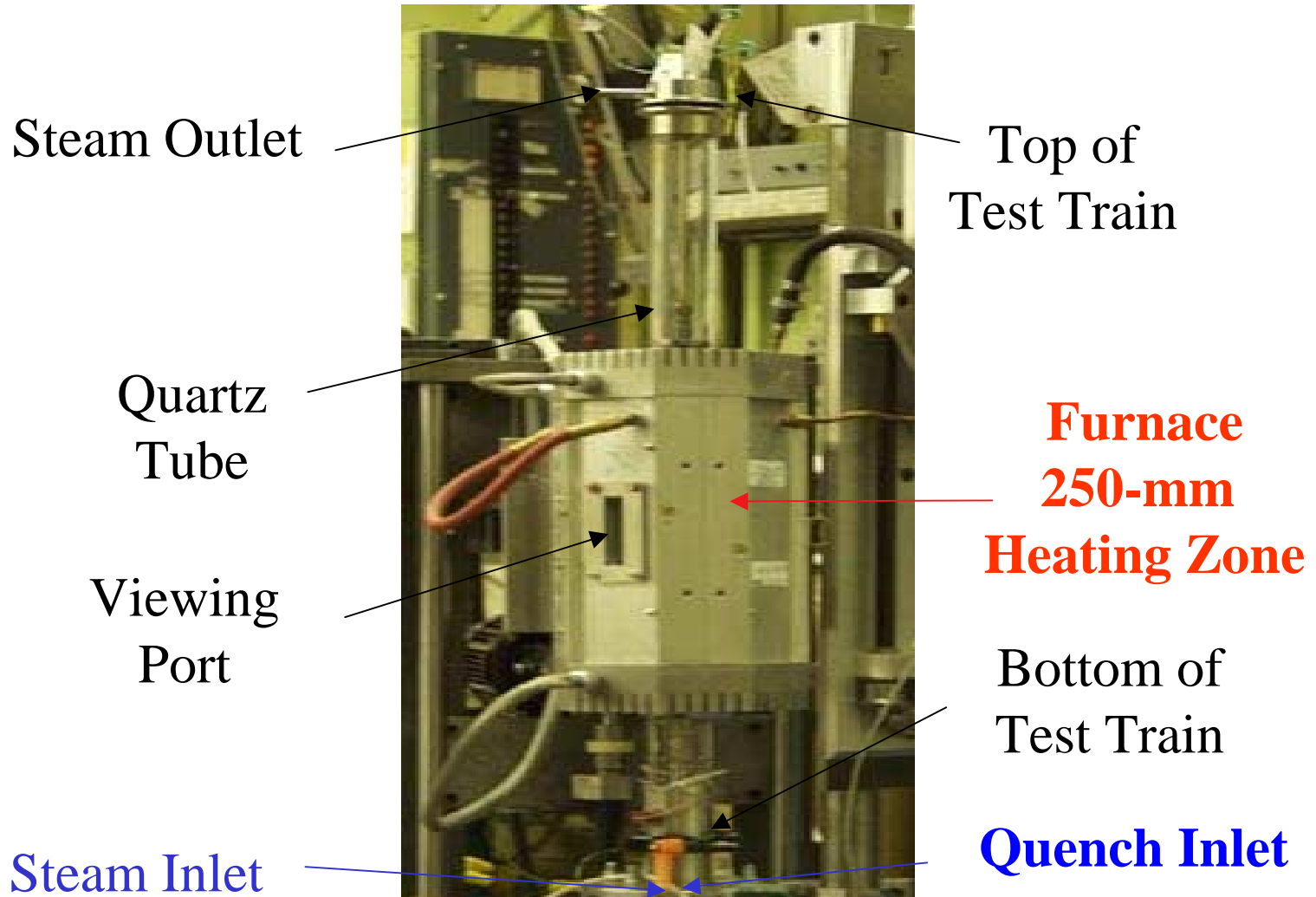
LOCA Integral Test Apparatus

- **Out-of-Cell LOCA Integral Test Apparatus**
 - Same design as in-cell apparatus
 - Baseline data for unirradiated, archival cladding (Zry-2 completed)
 - Useful for testing modifications prior to doing them in-cell
 - Oxidation and LOCA Integral tests of cladding alloys (ongoing)
- **In-cell LOCA Integral Test Apparatus**
 - Same design and control system (shared) as out-of-cell apparatus
 - **All components are in-cell except quench unit**
 - **Limerick Test 1 (Phase A) Test (completed 8-15-02)**
 - **Limerick Phase B Test (completed 9-23-02)**
 - Full LOCA Integral Test with Limerick sample (August 2003)
 - H.B. Robinson PWR tests will follow Limerick BWR tests

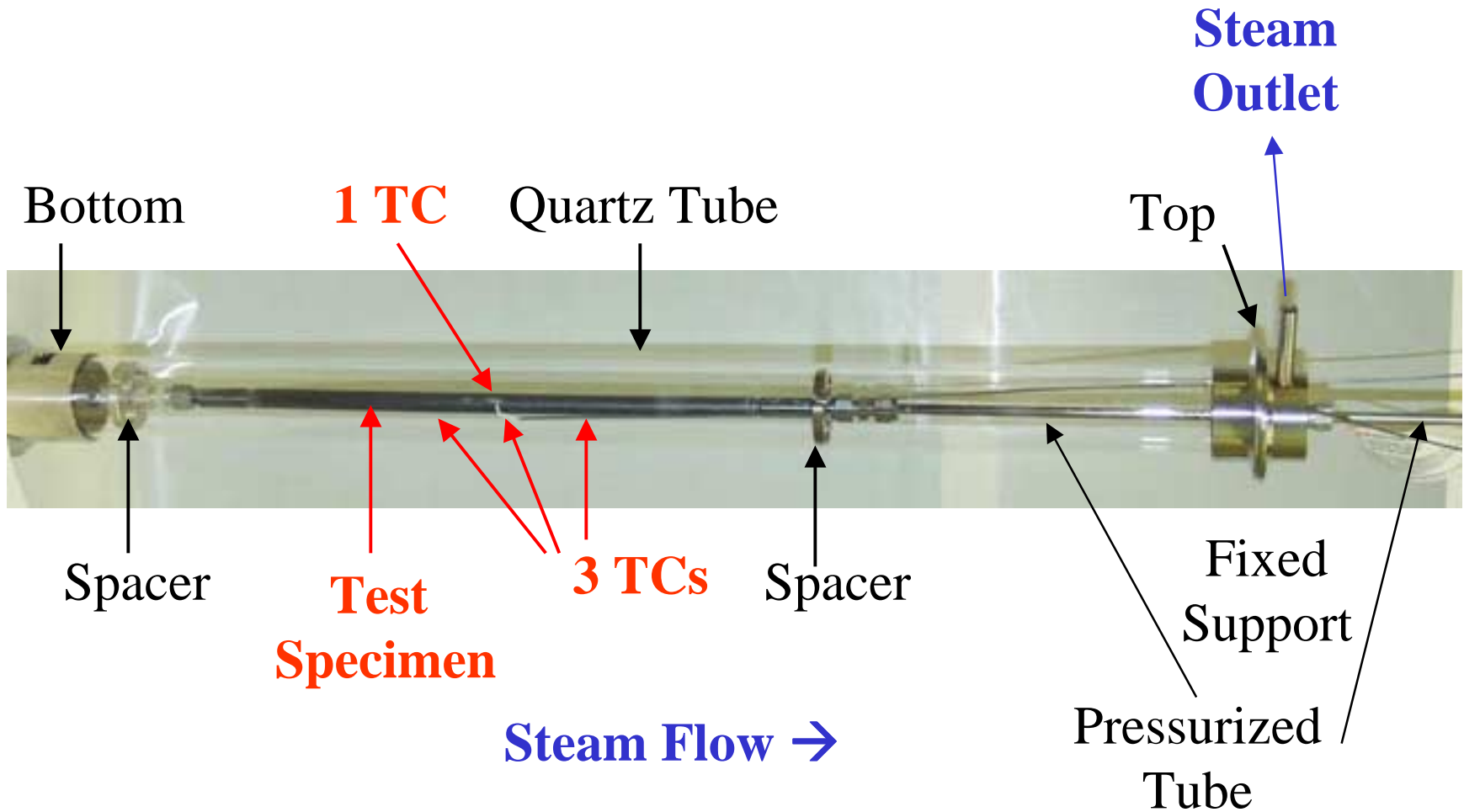
Out-of-Cell Oxidation/LOCA-Integral-Test Apparatus



Out-of-Cell LOCA Apparatus (Enlarged View)



LOCA Test Train Assembly



Out-of-Cell LOCA Integral Test Results

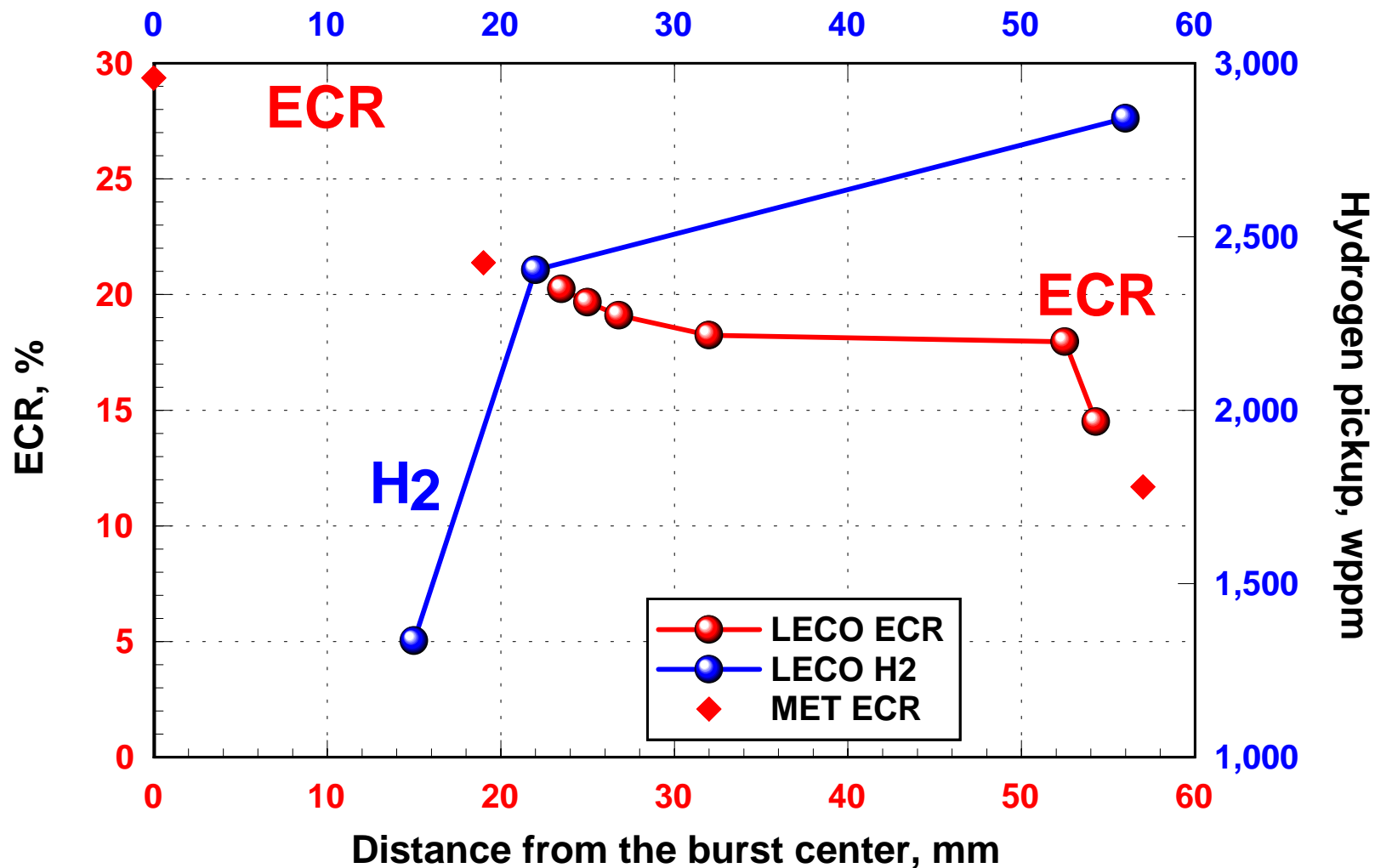
Unirradiated Zry-2 with 10-minute Hold at 1204°C

- **Test #3 Results (10 min. in steam at 1204°C)**
 - Peak $\Delta P = 9.24$ MPa, burst $\Delta P \approx 8.4$ MPa, **burst T $\approx 760^\circ\text{C}$**
 - “Dog-bone-shaped” burst opening; ≈ 13 -mm long (**ECR = 29%**)
 - **Peak $\Delta D/D_o \approx 60\%$** ; axial extent of balloon 150 mm
 - Specimen survived thermal quench & post-quench handling
- **Test #4 Results (10 min. in steam at 1204°C)**
 - Peak $\Delta P = 10.28$ MPa, burst $\Delta P \approx 9.42$ MPa, **burst T $\approx 730^\circ\text{C}$**
 - Similar burst opening and ballooning strain as in Test #3
 - **Sample failed across mid-burst region at 100°C after quench**
- **Based on Results, Hold Time at 1204°C for High-Burnup BWR LOCA Integral Test Set at 5 Minutes**

OCL#3: 10-Minute Hold Time at 1204°C

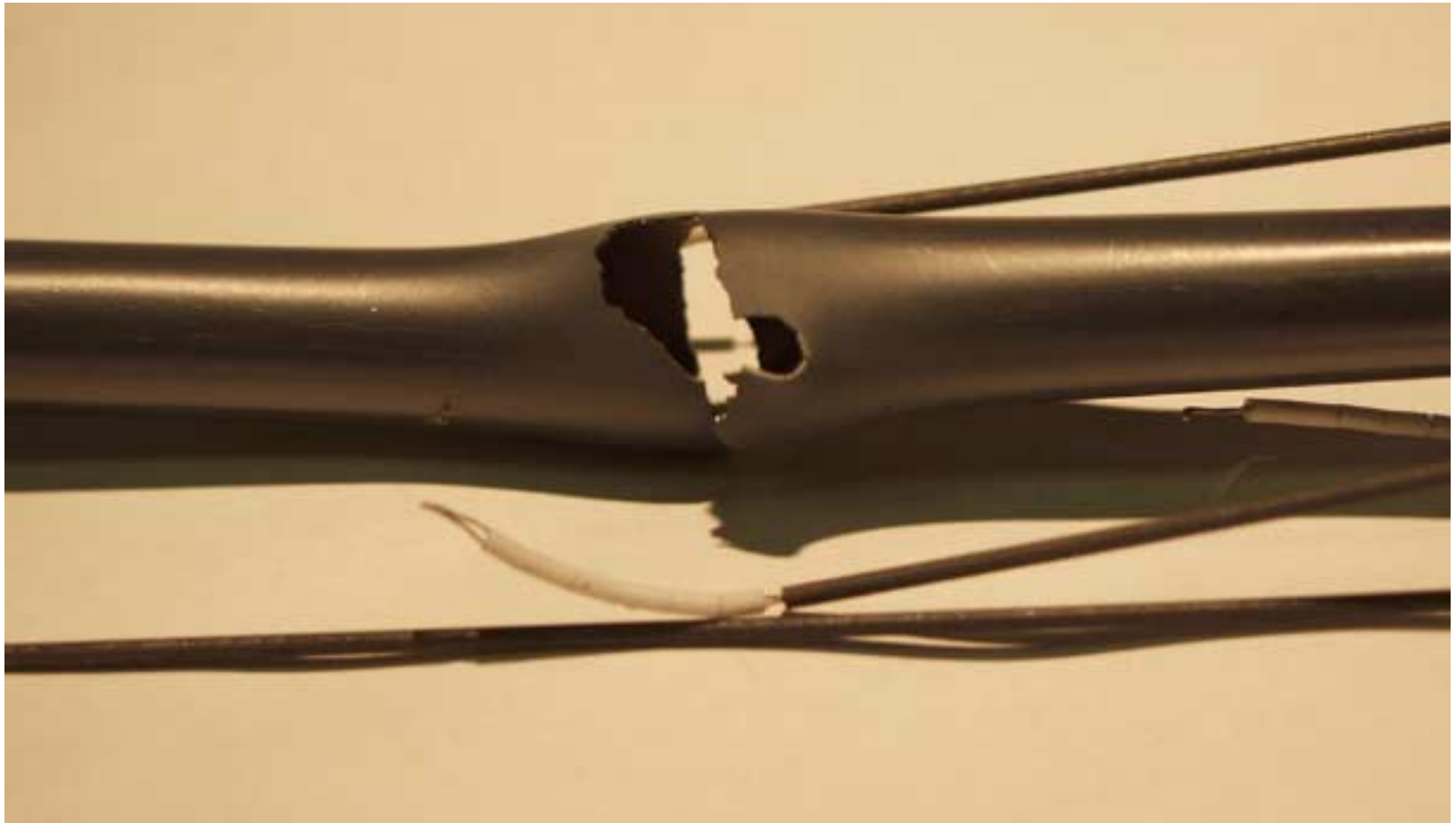


LOCA Integral Test Results for Zry-2: 1204°C for 10 Min.



OCL#4: 10 min. at 1204°C, C-P ECR \approx 30%

Survived Quench; Failed under Dead-Weight Loads at $\approx 100^\circ\text{C}$



In-Cell LOCA Integral Test Results

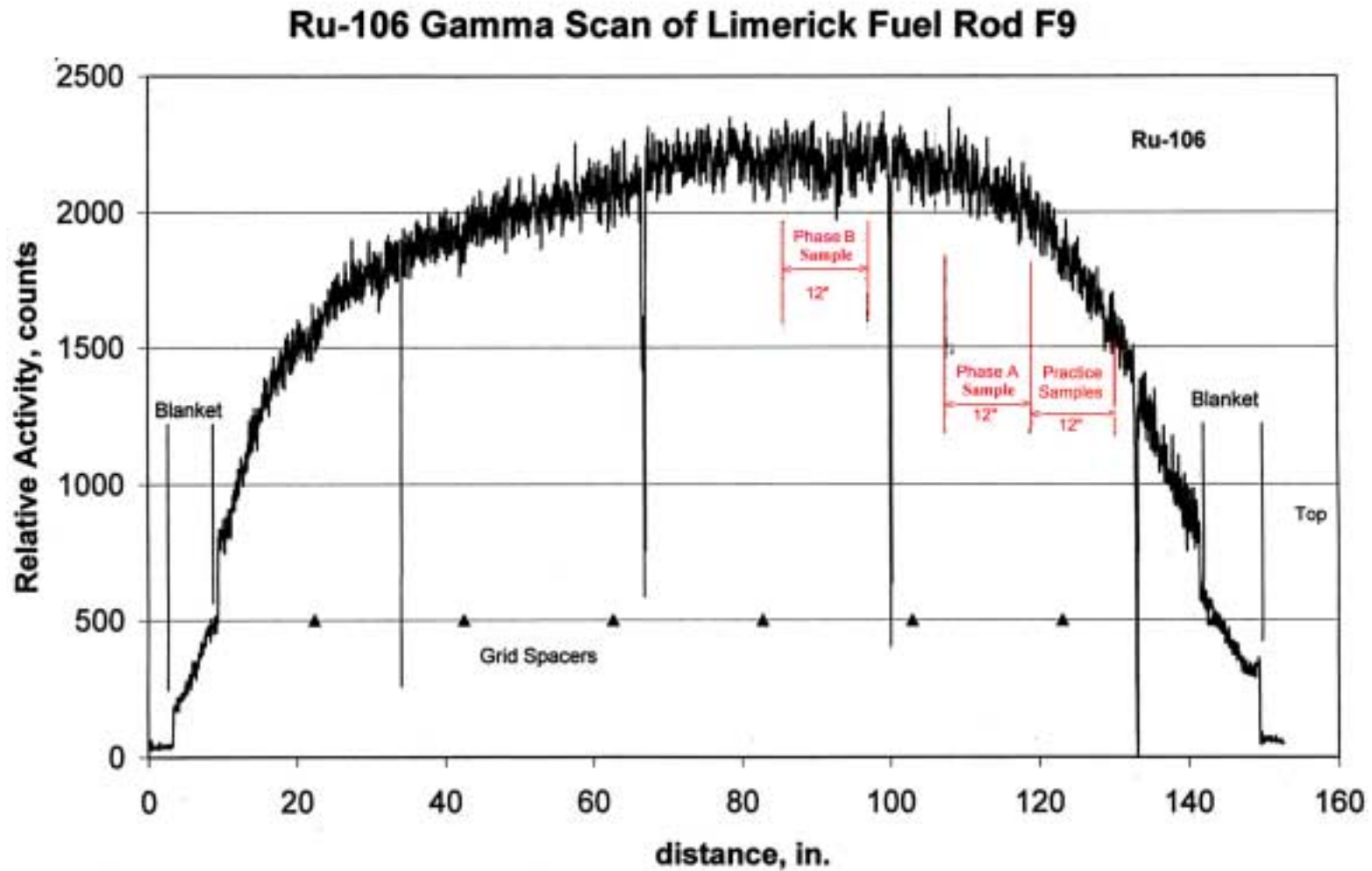
- **Limerick Specimens**

- **Phase A: middle of Grid Span #6; 0.94-1.24 m above fuel MP**
- Phase B: middle of Grid Span #5; 0.46-0.76 m above fuel MP
- Phase C: to be prepared from GS #5 & 6 of Rod J4

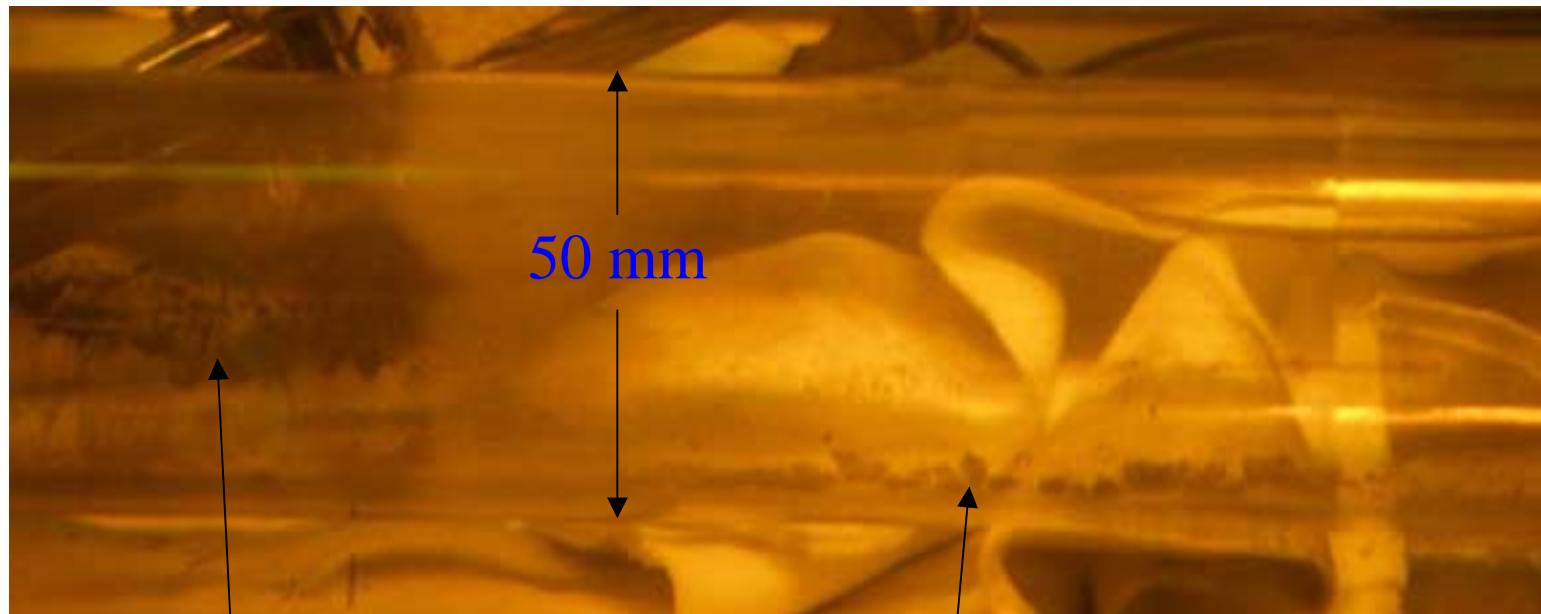
- **Test 1 (Phase A) Completed on August 15, 2002**

- Ramp temperature to burst in Ar; slow furnace cool
- Out-of-cell companion test (OCL#5) run under same conditions
- Interesting fuel particle and fission product behavior (NSRC-2002)
- Results suggest good fuel permeability

Axial Location of Limerick BWR LOCA Samples



Fuel Deposit and Particles within Quartz Tube



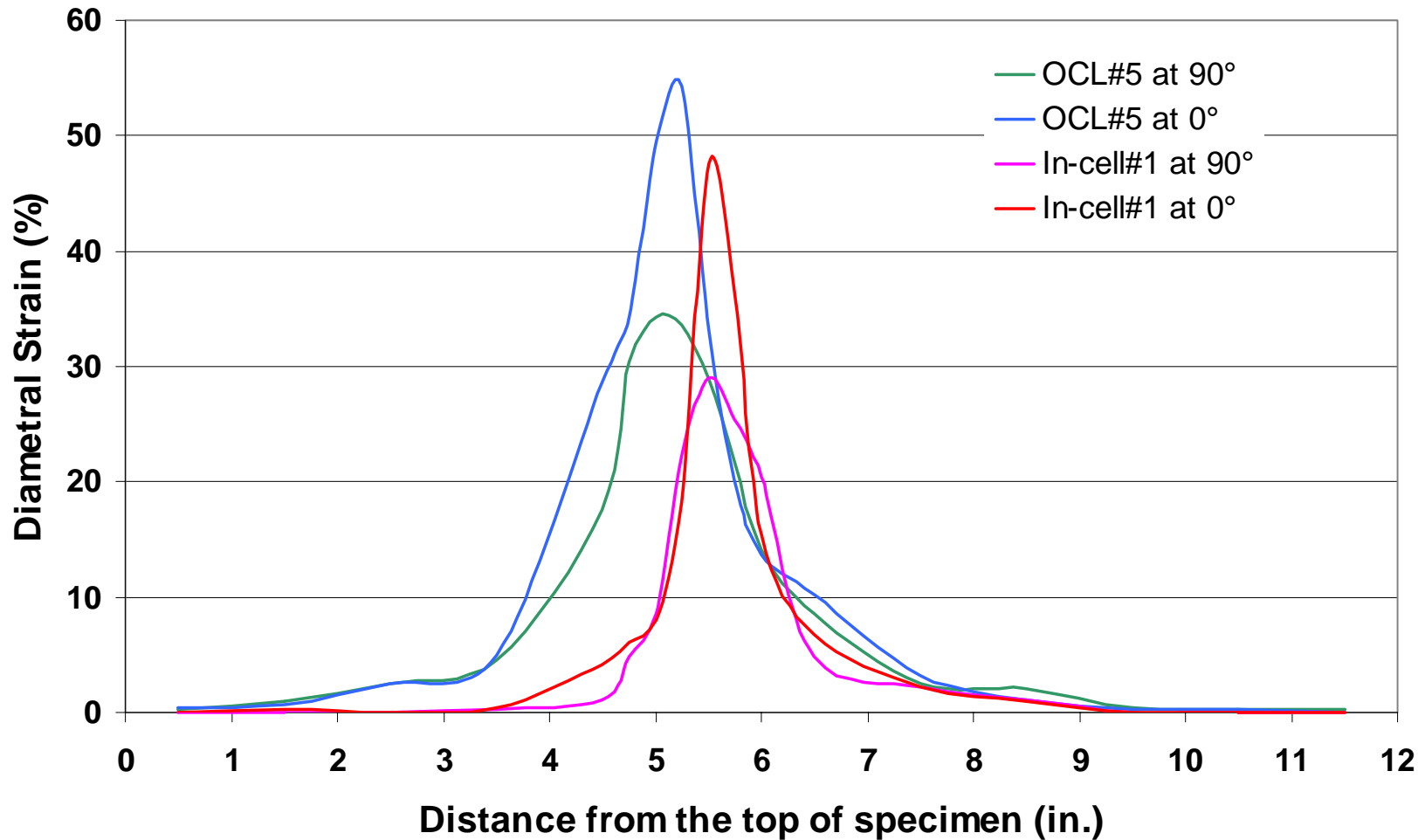
Black Deposit
Cs Compound??

Fuel Particles
< 3 mm in diameter

Summary of Ramp-to-Burst Tests in Argon

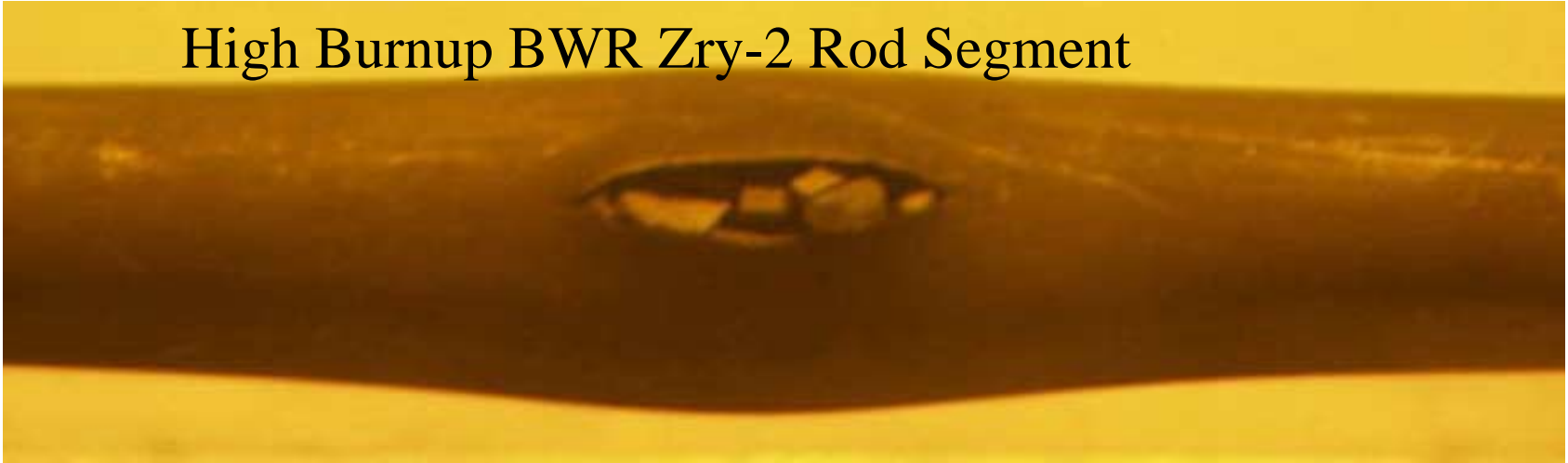
Parameter	OCL#5	OCL#8	ICL#1
Max. ΔP , MPa	8.96	8.62	8.96
Burst ΔP , MPa	8.3	7.7	8.6
Burst T, °C	733 \pm 5	766 \pm 17	\approx 755
Burst Center, mm	+20	-10	+10
Burst Length/ Max.-Width, mm	13 \times 2.5 (dog-bone)	17 \times 2.5 (dog-bone)	13 \times 3 (oval)
Balloon Length, mm	100	140	70
Max. Hoop Strain, %	44 \pm 10	60 \pm 10	38 \pm 9
Min. Wall for ECR, mm	0.49	0.43	\approx 0.51

Profilometry Results for ICL#1 vs. OCL#5



Ramp-to-Burst Opening Comparison

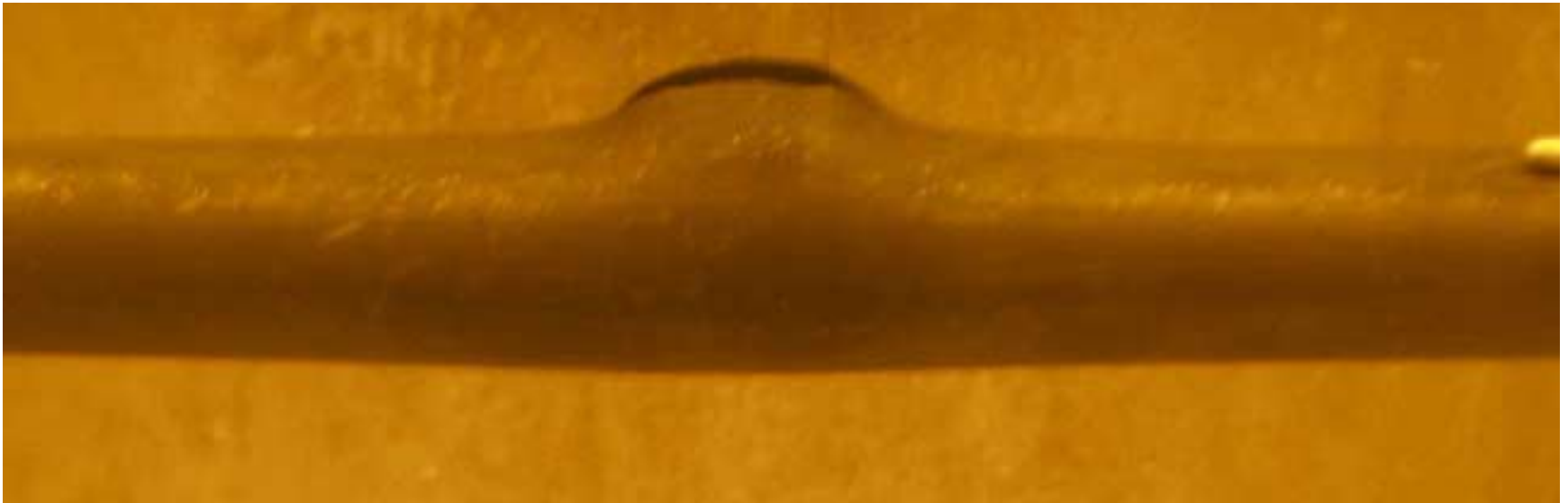
High Burnup BWR Zry-2 Rod Segment



Unirradiated Zry-2



High-Burnup BWR Rod Segment after Ramp-to-Burst Test



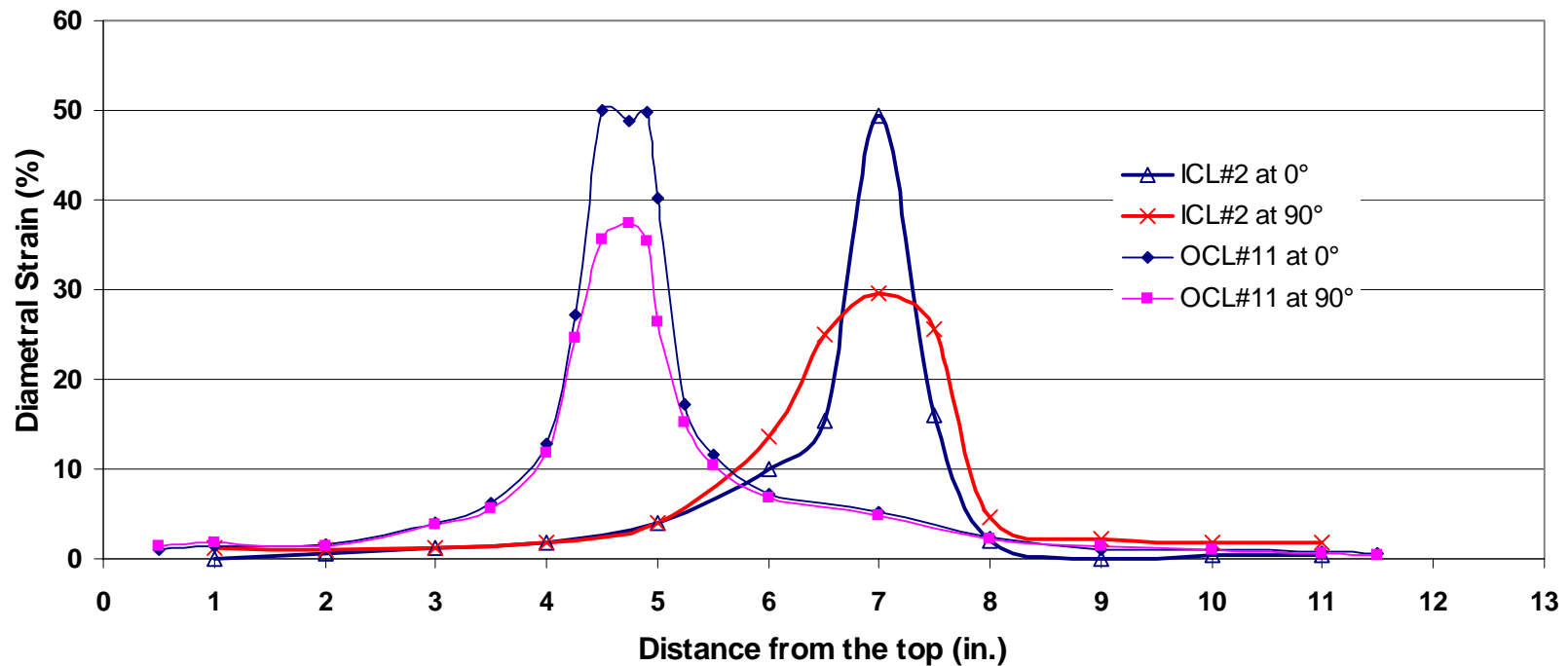
Results for 2nd LOCA Integral Test (Phase B)

- **Test ICL#2 Completed on September 23, 2002**
- **Excellent Fuel Permeability at RT and 300°C**
 - Results are consistent with fuel microstructure (macro- and micro-cracks) – see NSRC-2002 paper
- **Results Compared to Out-of-Cell Test #11 (OCL#11)**
 - See Table for comparison of non-destructive examination
 - Metallography (in progress for ICL#2)
 - H uptake and O pickup determination (in progress for ICL#2)
- **4-Point-Bend Test Demonstrations (OCL#11 Siblings)**
 - Videotape for nominal bending tension along burst side
Sample failed cleanly across burst cross-section (ductility??)
 - Live demonstration for nominal bending tension 180° from burst
Axial crack initiated at burst tip; failure across high-H region (ductility??)

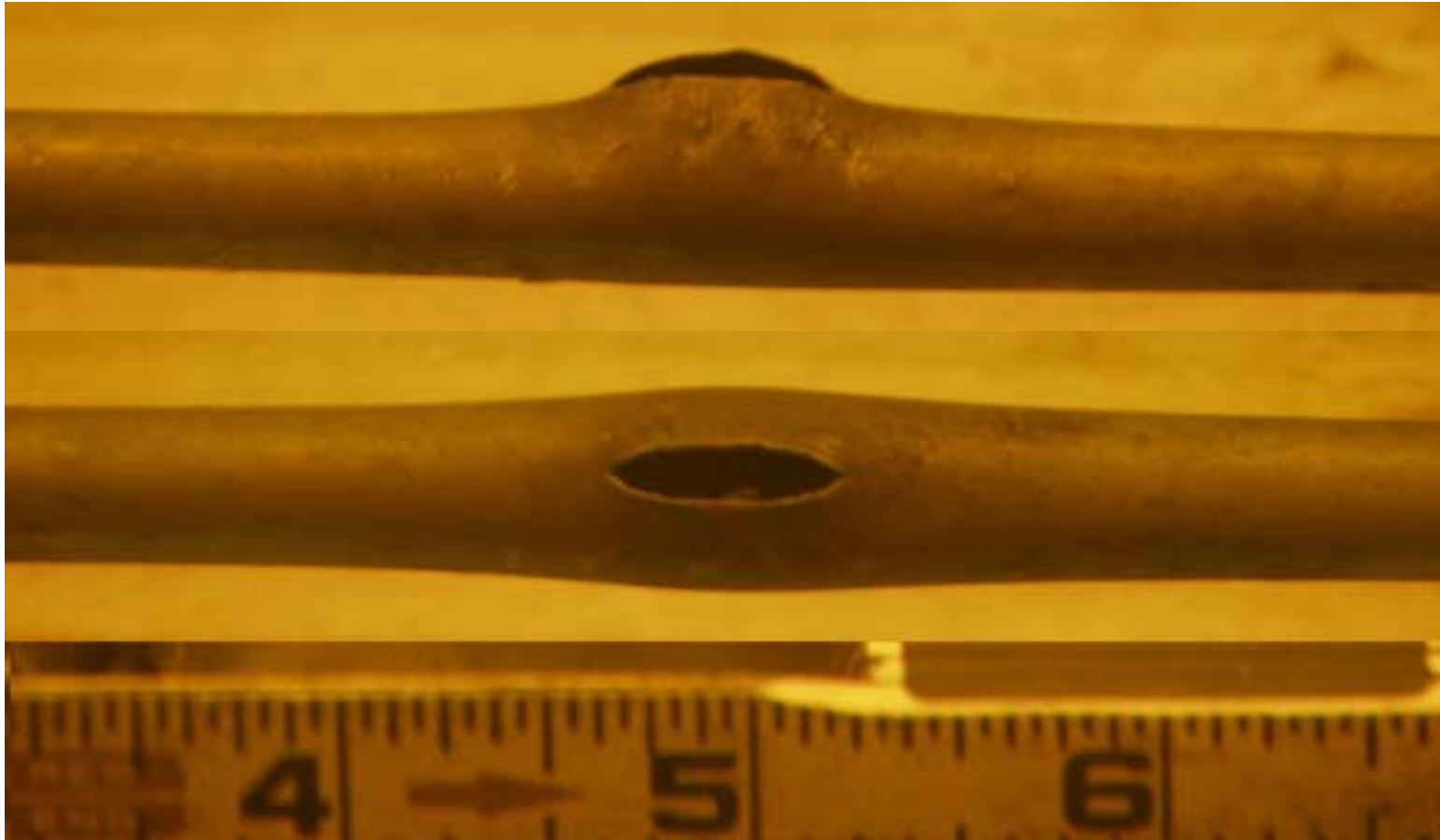
Comparison of ICL#2 and OCL#11: 5 min. at 1204°C

Parameter	OCL#11	ICL#2
Max. ΔP , MPa	8.61	8.87
Burst ΔP , MPa	7.9	8.0
Burst T, °C	753 \pm 22	\approx 750
Burst Center, mm	+35	-25
Burst Length/ Max.-Width, mm	11 \times 1 (dog-bone)	14 \times 3.5 (oval)
Balloon Length, mm	140	90
Max. Hoop Strain, %	43 \pm 6	39 \pm 10
Min. Wall for ECR, mm	0.50	0.51
Max. ECR, %	17.6	TBD

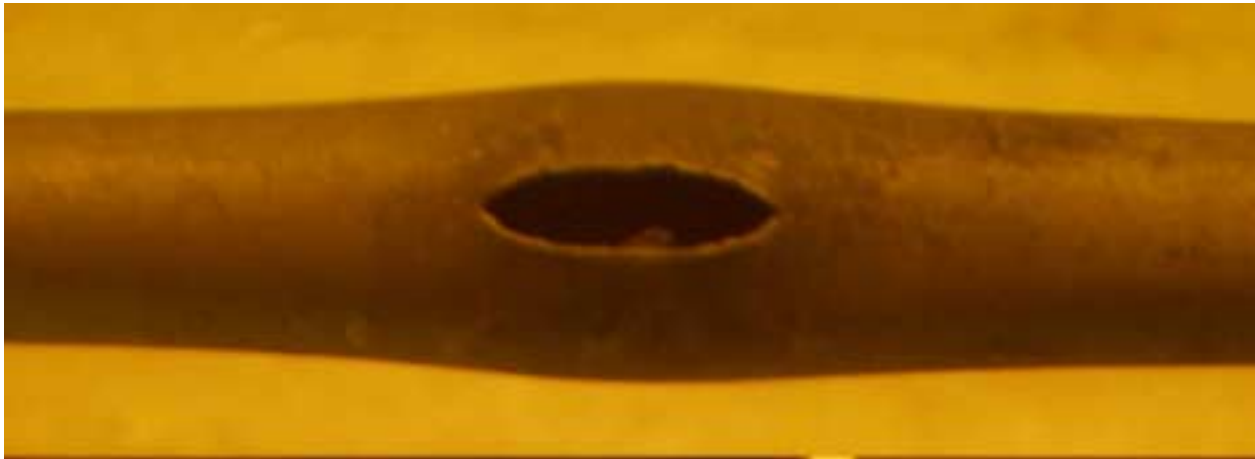
PROFILOMETRY ICL#2 and OCL#11 Specimens



High-Burnup BWR Balloon & Burst for ICL#2



Comparison of Burst Openings for ICL#2 and OCL#11



Detailed Results for ICL#2 and OCL#11

- **Metallographic Results**

- OCL#11 at burst midplane (double-sided oxidation evident)
Cross-section: brittle near burst opening to “ductile” 180° from burst
- ICL#2 at burst midplane (double-sided oxidation evident)
- ICL#2 at 50 mm above burst center (very little inner-surface oxidation)

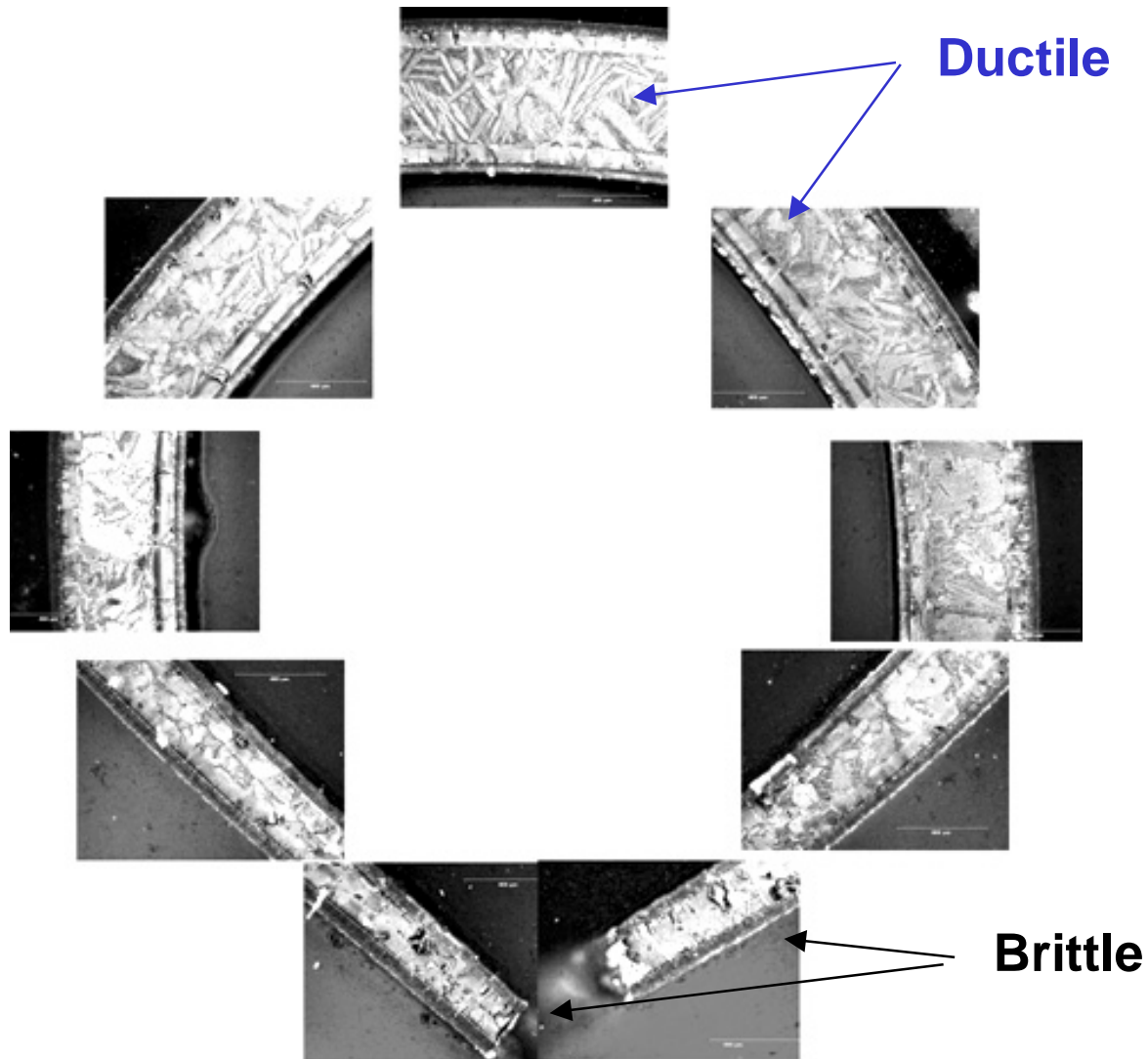
- **Measured Hydrogen and Oxygen Profiles for OCL#11**

- $ECR = 2.85 \Delta C_o \leq 17.6\%$, where ΔC_o is oxygen pickup in wt.% relative to cladding before oxidation
- ΔH_o is hydrogen pickup (wppm) relative to cladding before oxidation

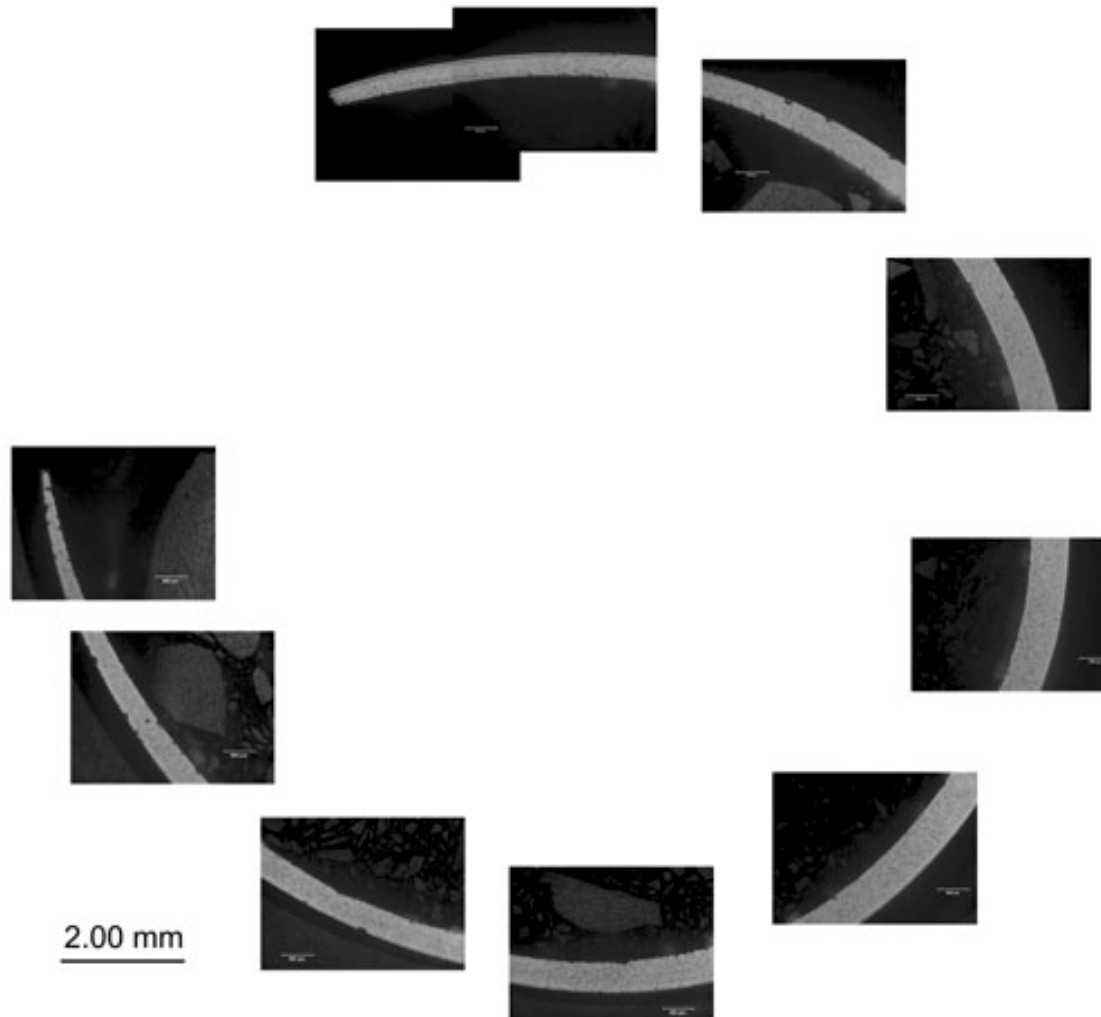
- **Hydrogen in High-Burnup LOCA Test (ICL#2) Sample**

- Epoxy (high H) was applied to seal burst opening
- Etched sample shows no evidence of hydrides at 50 mm above burst
LECO data needed to determine if there is secondary hydriding

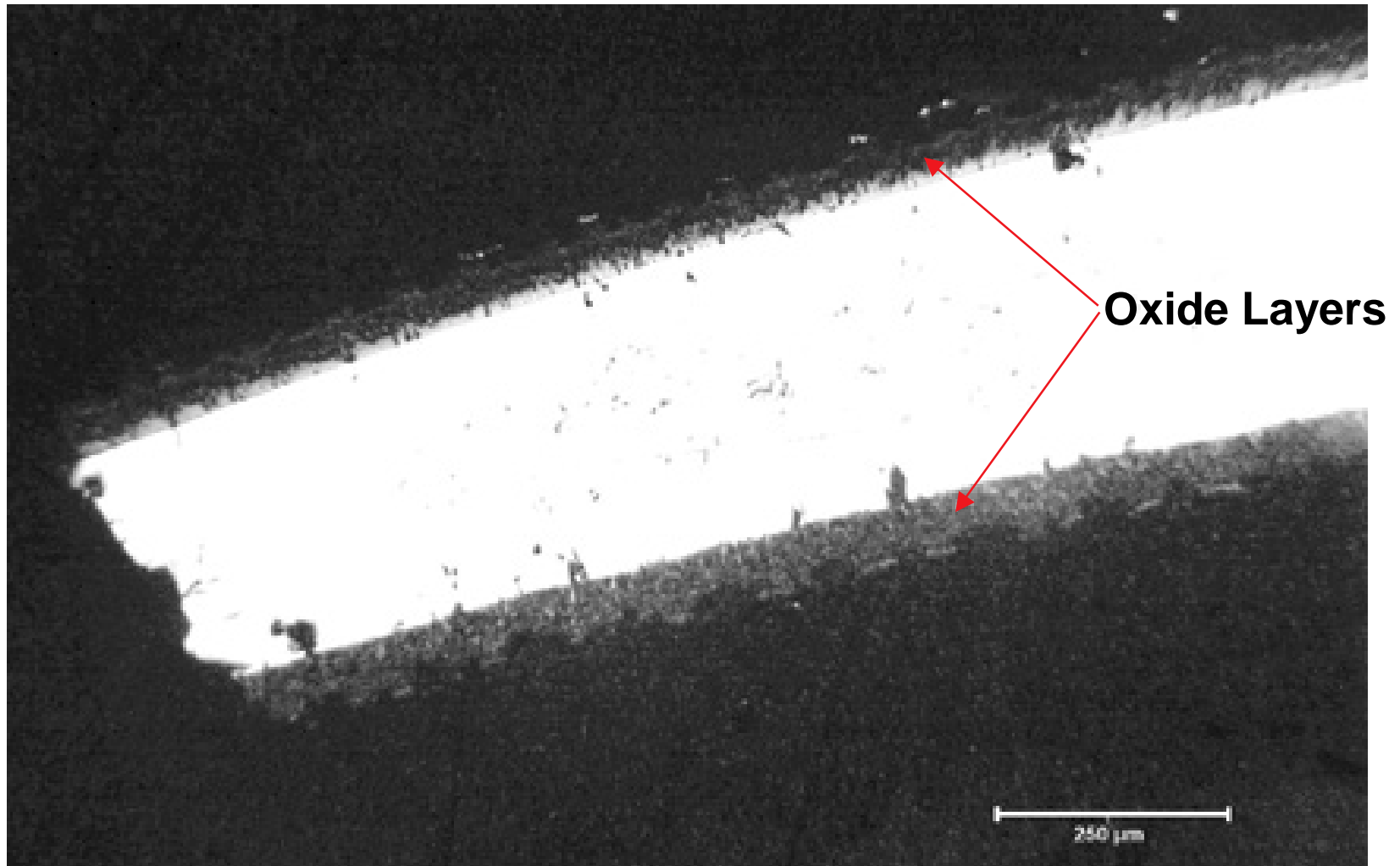
Metallography of Burst Cross-Section for OCL#11



Low-Mag. Image of Burst Cross-Section for ICL#2

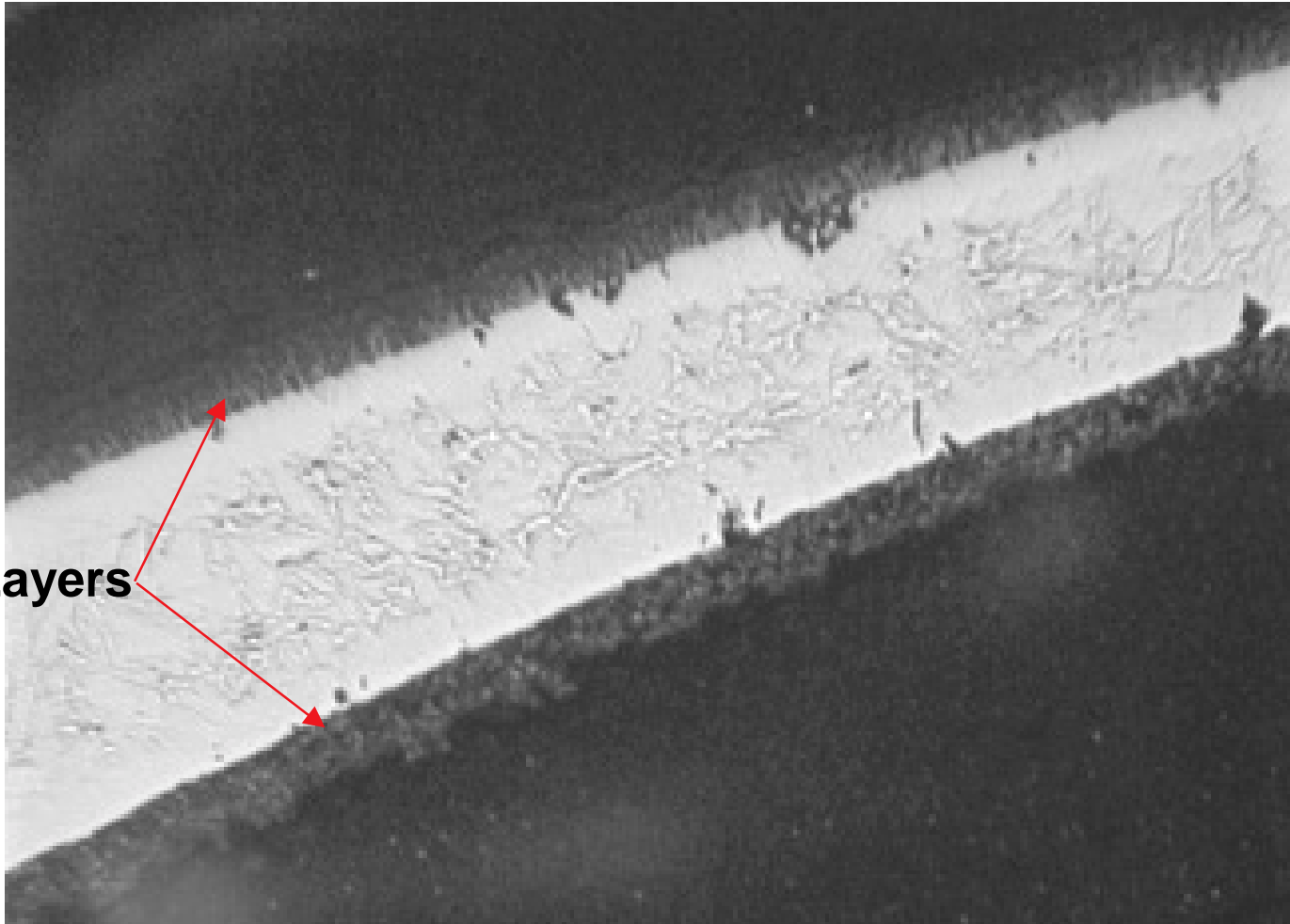


Metallography of ICL#2 Near Burst End A

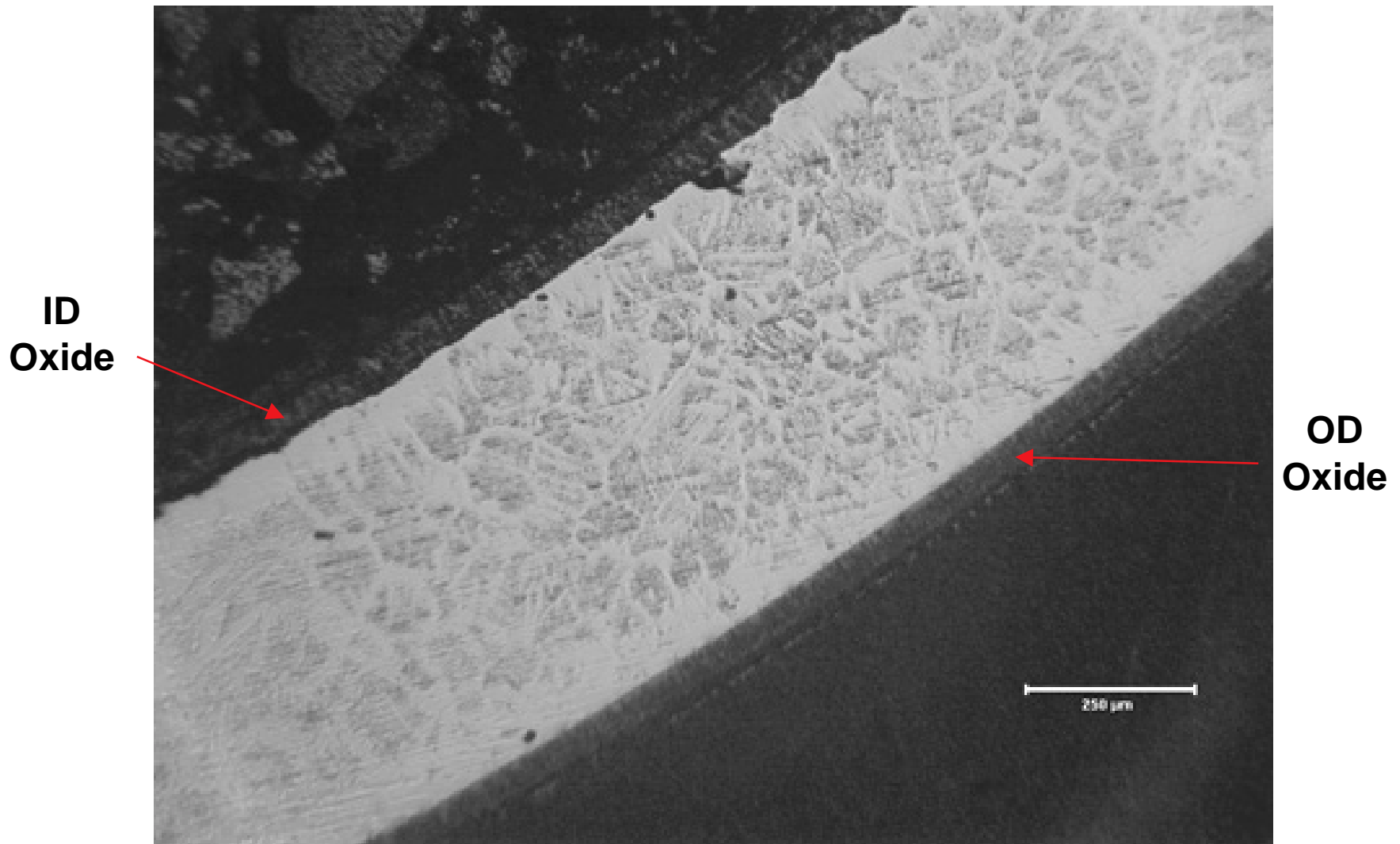


Metallography of ICL#2 Near Burst End B

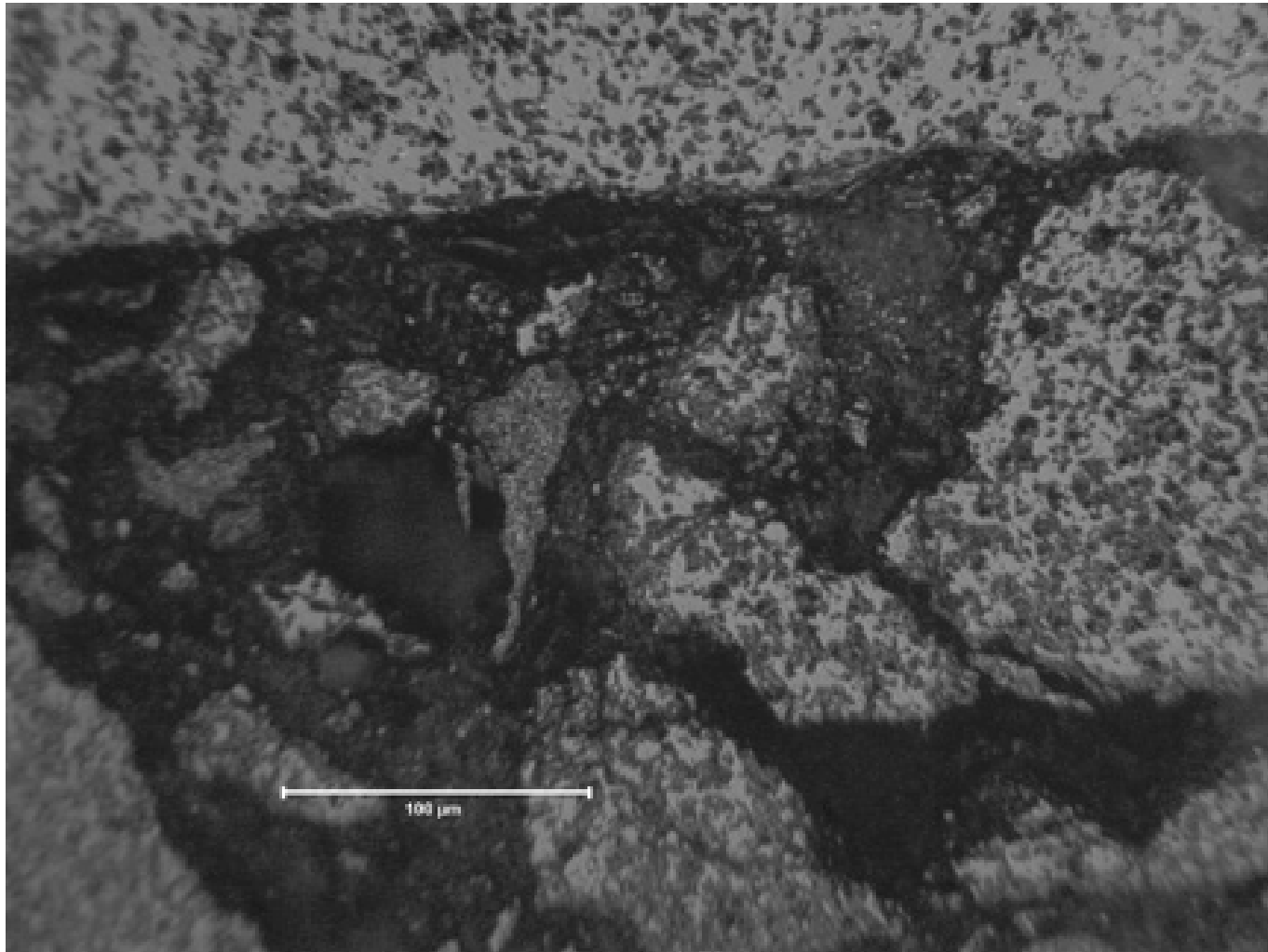
Oxide Layers



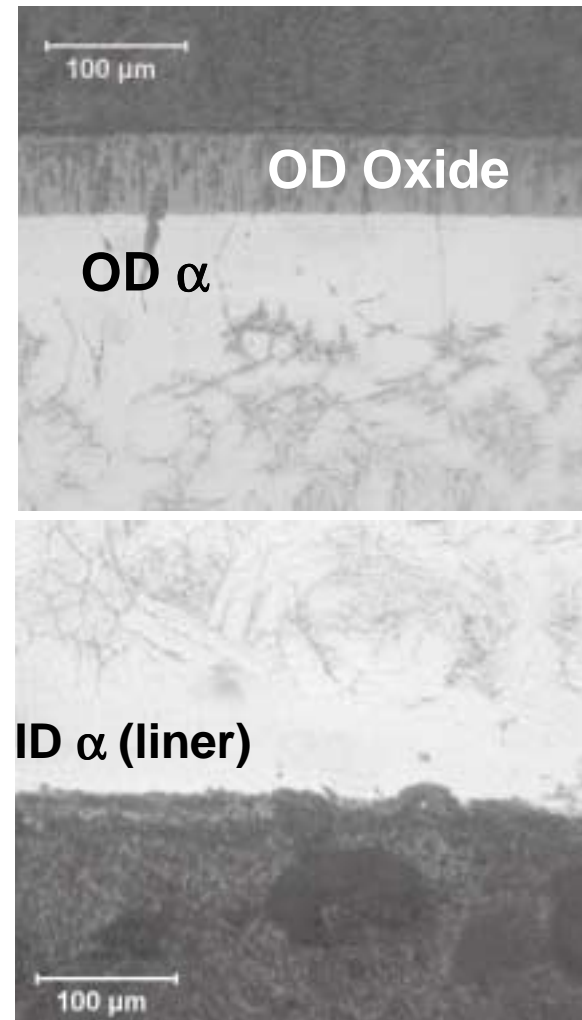
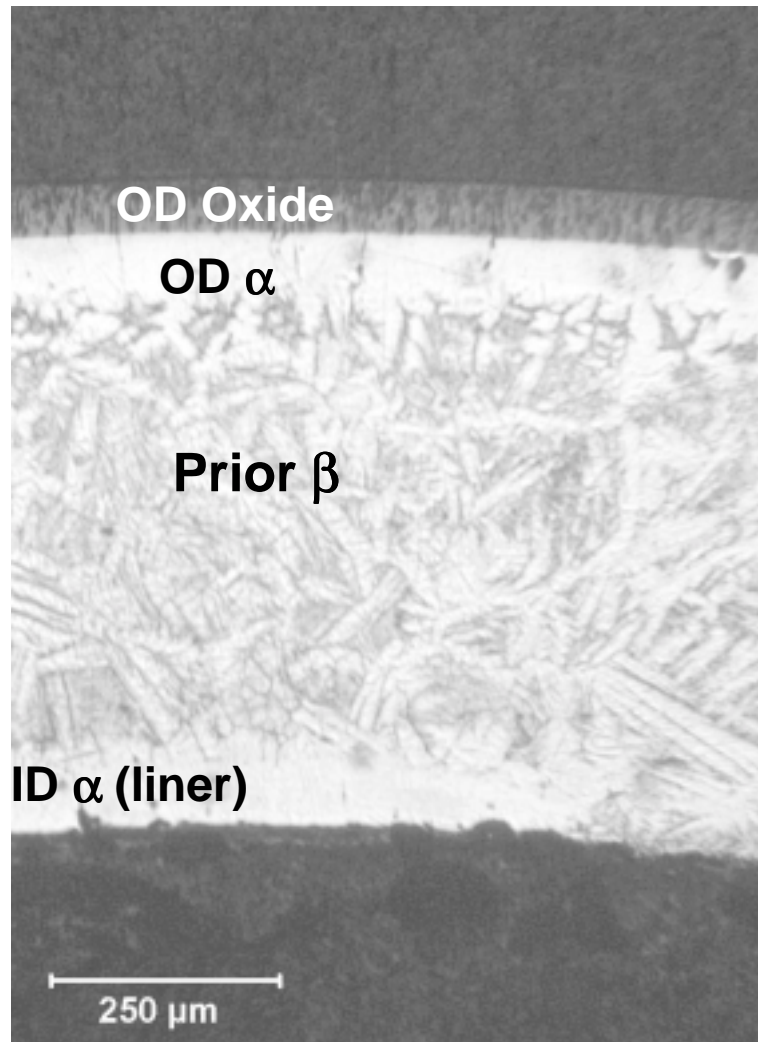
Metallography of ICL#2 180°C from Burst Opening



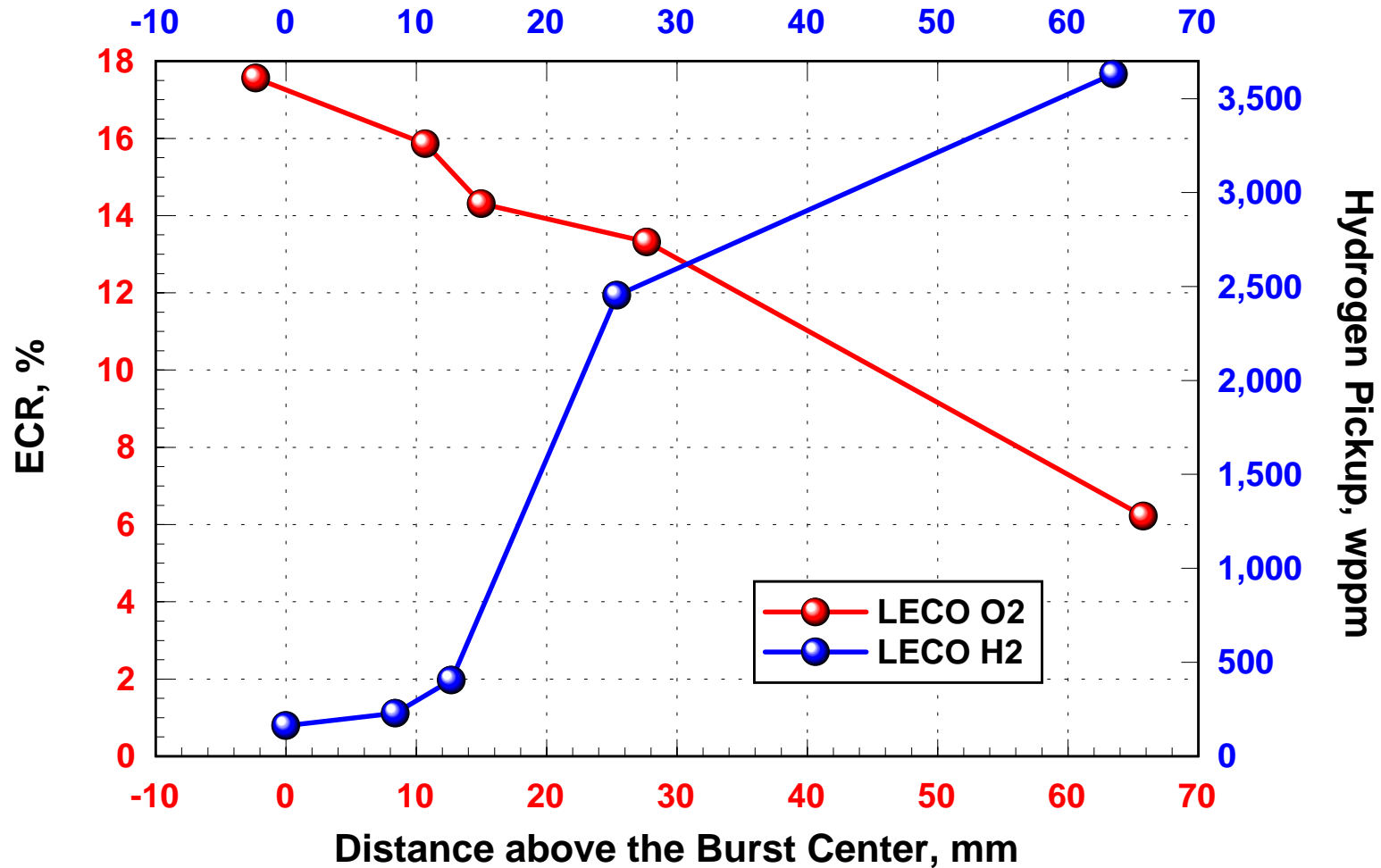
ICL#2 Fuel Particles Embedded in Epoxy at Midplane



Etched ICL#2 Sample 50 mm above Burst Center



Measured ECR and H Axial Profiles for OCL#11



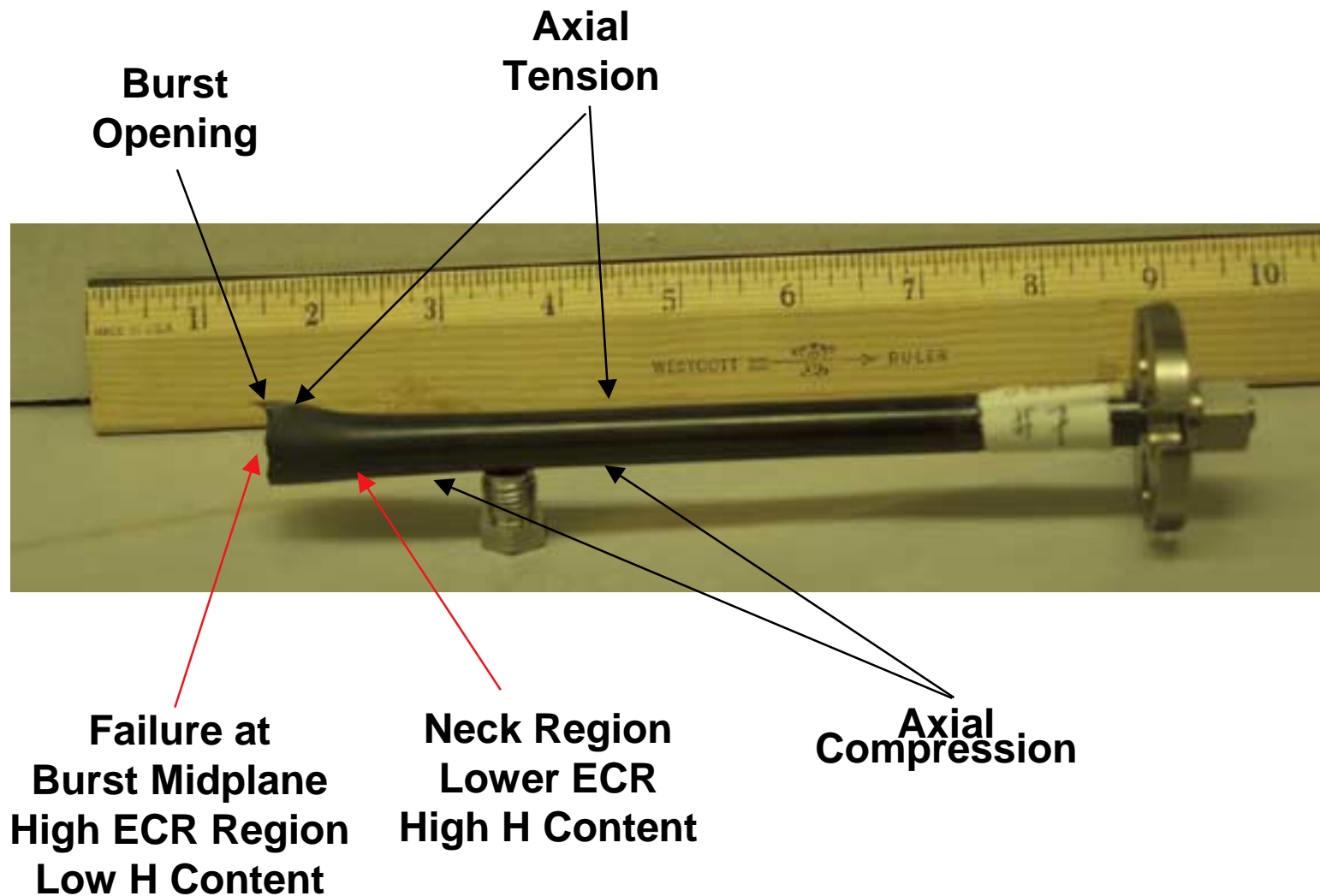
Four-Point-Bend Demonstration Results

- **OCL#11 Sibling Samples**
 - Samples were “rejects” because of T-history oscillations
 - Expected ECR and H distributions are nominally those of OCL#11
- **1st 4-Point-Bend Demonstration (June 16, 2003)**
 - Uniform bending moment applied along high ECR and H segment
 - Nominal axial tensile stress aligned with burst opening
 - Sample “snapped” cleanly across high-ECR, thin burst region
- **2nd 4-Point-Bend Demonstration (July 16, 2003)**
 - Nominal axial tensile stress aligned 180° from burst opening
 - Burst region under nominal axial compression
 - Axial crack initiated at tips of burst opening; extended to high H region
 - Sample failed cleanly across high H region

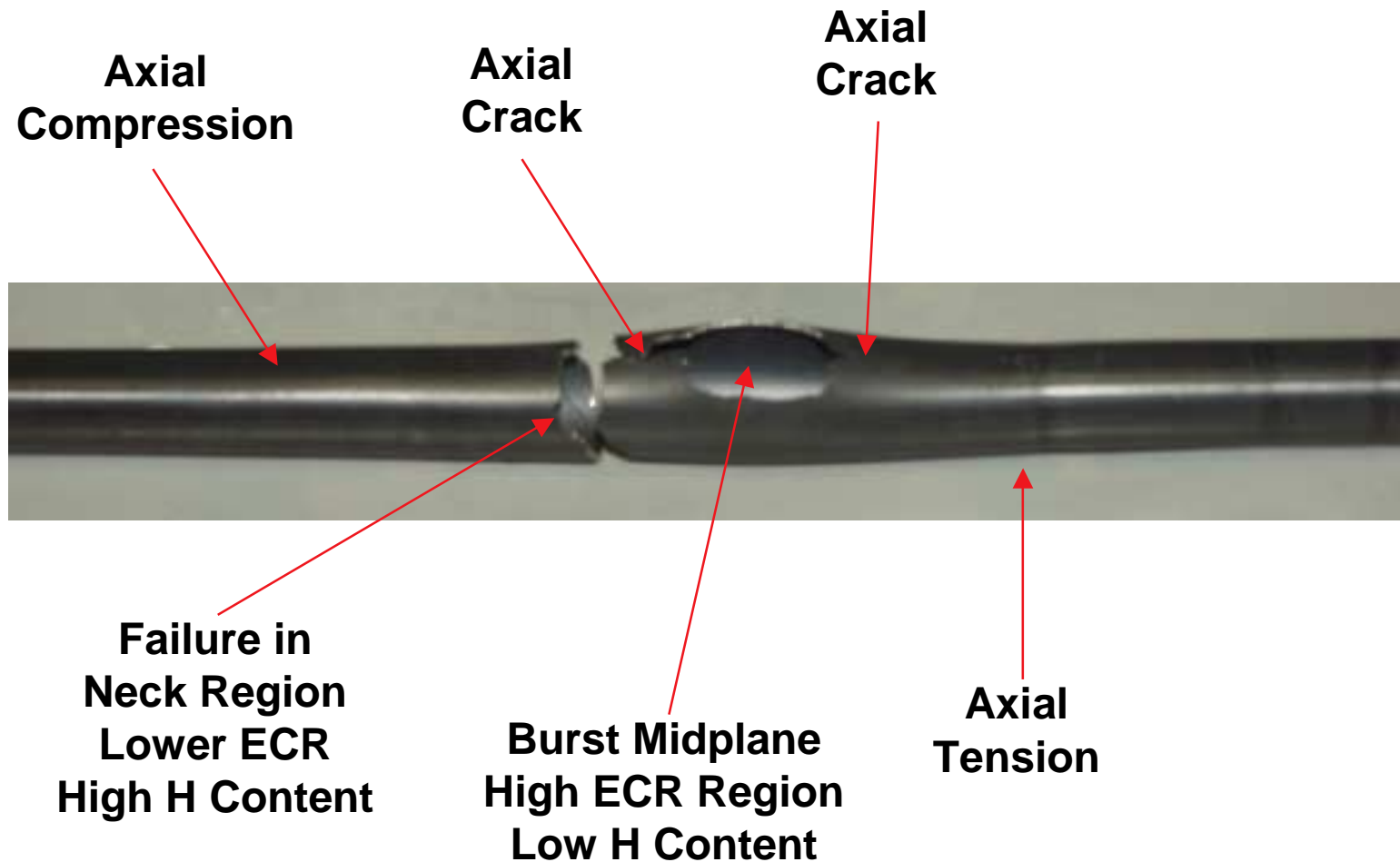
Four-Point-Bend Demonstration Results (Cont'd)

- **4-Point-Bend Test as a Post-Quench-Ductility Test**
 - Unirradiated cladding will pick up a lot of hydrogen (secondary hydriding) away from the burst opening near or beyond necks of the ballooned region
 - Where will the sample fail? Will it fail in a ductile or brittle mode
Burst region is “flawed”, partially embrittled by oxygen vs. ECR and T
Neck region has lower O and ECR, but significantly higher H
- **4-Point-Bend Failure Location Depends on How Test is conducted**
 - Subjecting burst region to axial tension initiates a brittle crack that grows rapidly across the more ductile region (90-270° from burst)
 - Subjecting the burst region to axial compression appears to initiate axial cracks extending from burst tips into the high-H neck regions, which appear to fail in a brittle manner

June 16, 2003 4-Point-Bend Demonstration Results



July 16, 2003 4-Point-Bend Demonstration Results



Summary of LOCA Integral Test Results

- **Limerick High-Burnup BWR Samples**

- Two successful tests completed
- 3rd test with quench to be run this summer
- With exception of burst-opening shape, results are more similar than dissimilar to baseline out-of-cell data for unirradiated Zry-2
- However, for unirradiated cladding, very high hydrogen uptake occurs beyond the burst zone; remains TBD for high-burnup Limerick sample

- **Robinson High-Burnup PWR Samples**

- Cladding has higher H content (≈ 700 vs. ≈ 70 wppm) and greater oxide corrosion (≈ 100 vs. ≈ 10 μm) than Limerick
- Effective cladding thickness is about the same
- Initial Robinson tests will be run at 5-min. hold at 1204°C