LOCA Integral Test Results

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Review of ANL LOCA and Dr-Cask-Storage Programs
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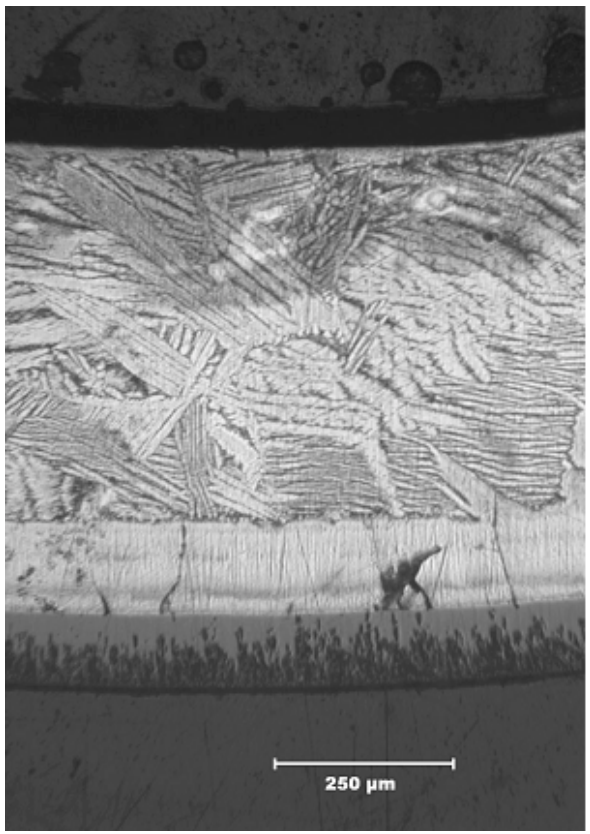
LOCA Issues for High-Burnup Fuel

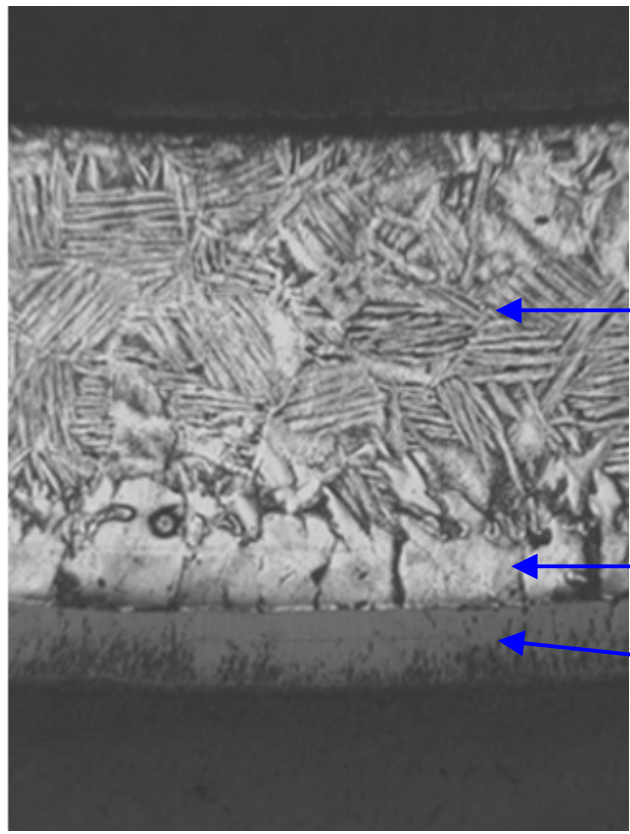
- **BWR Fuel Rods (≤57 GWd/MTU, ≈10 μm OD Oxide)**
  - Effects of fuel-cladding bond and restricted gas flow on ballooning and burst, on inner-surface **oxidation**/**hydrogen** pickup, and on subsequent **post-quench ductility**
  - Effect of irradiation on high temperature oxidation in steam
  - Effect 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 ≤ 17%, T ≤ 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**

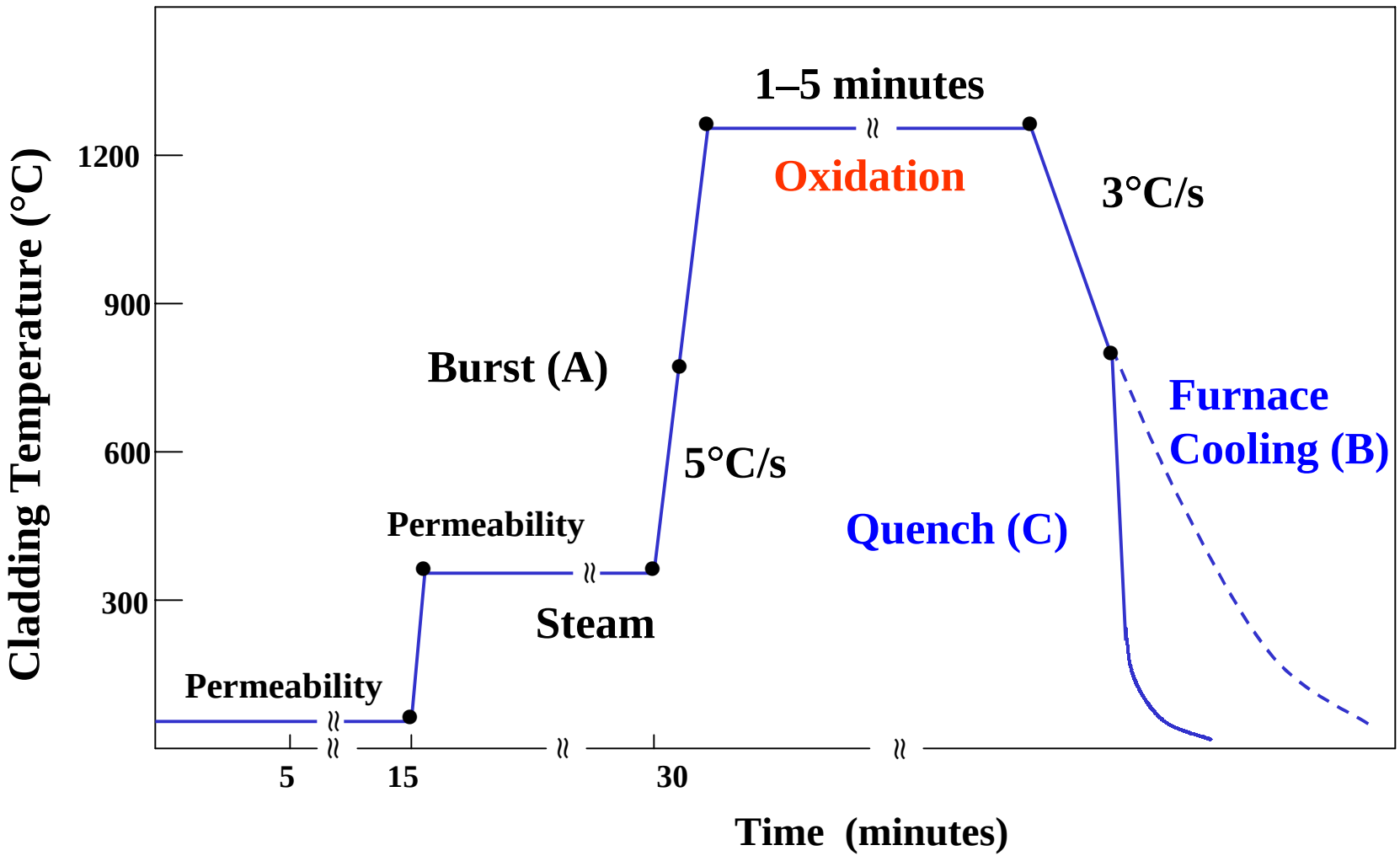
LOCA Integral Testing Scope

- **Parameters Common to BWR and PWR Tests**
  - **Fuel-cladding samples** = 305-mm long; fueled region = 270 mm
  - **Peak cladding temperature (PCT) = 1204±20°C**
  - **"Plenum" Volume ≈ 10 cm^3 (most of it outside heating zone)**
  - **Best-estimate and "measured" ECR ≈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 $\Delta P \leq 8.6$ MPa (1250 psig): gives large balloon and burst temperature <800°C (alpha phase)**
- **High Burnup PWR Rods (H. B. Robinson)**
  - Same test conditions as for BWR
  - Note: both BWR and PWR cladding thickness ≈0.7 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

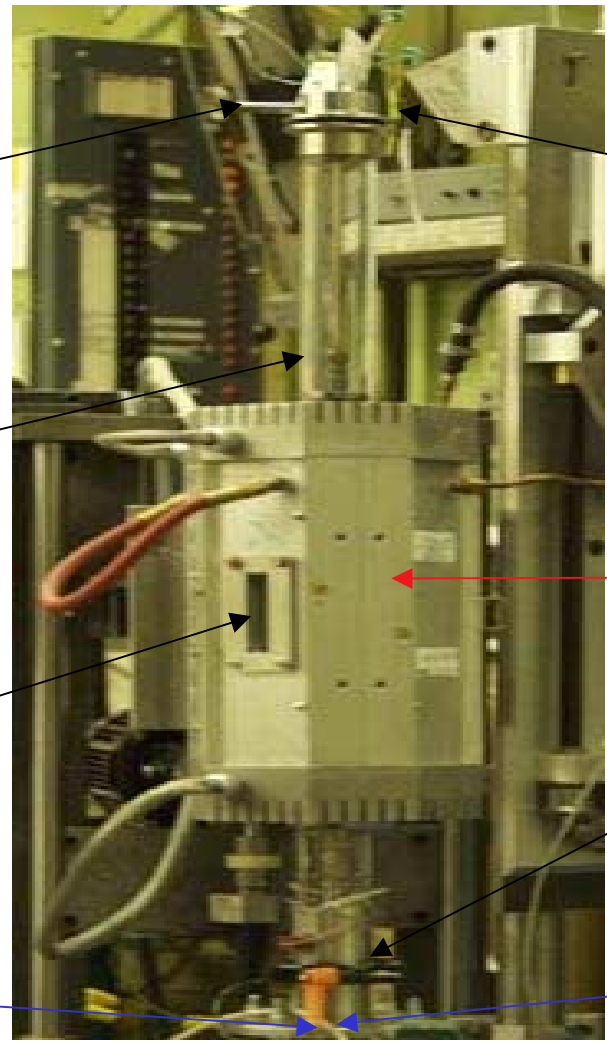


LOCA Integral Test Apparatus

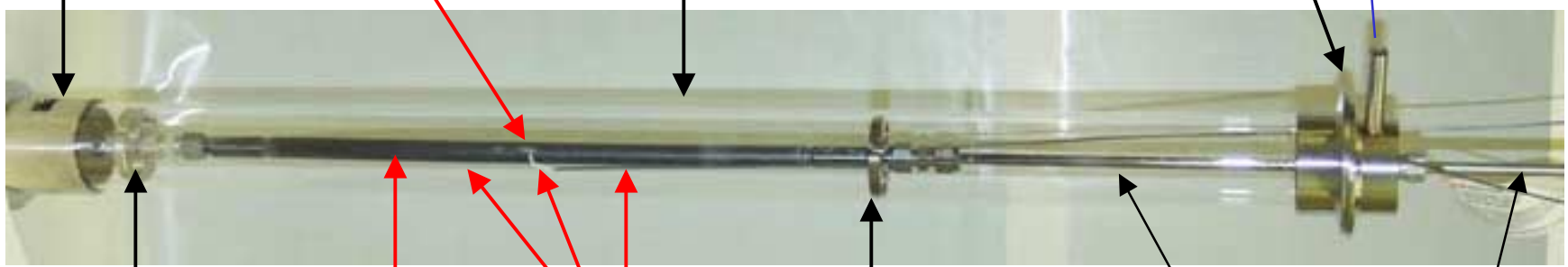
- **Out-of-Cell LOCA Integral Test Apparatus**
  - Same design as in-cell apparatus
  - Baseline data for unirradiated, archival cladding (Zry-2 completed)
  - Useful for testing modifications prior to doing them in-cell
  - Oxidation and LOCA Integral tests of cladding alloys (ongoing)
- **In-cell LOCA 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



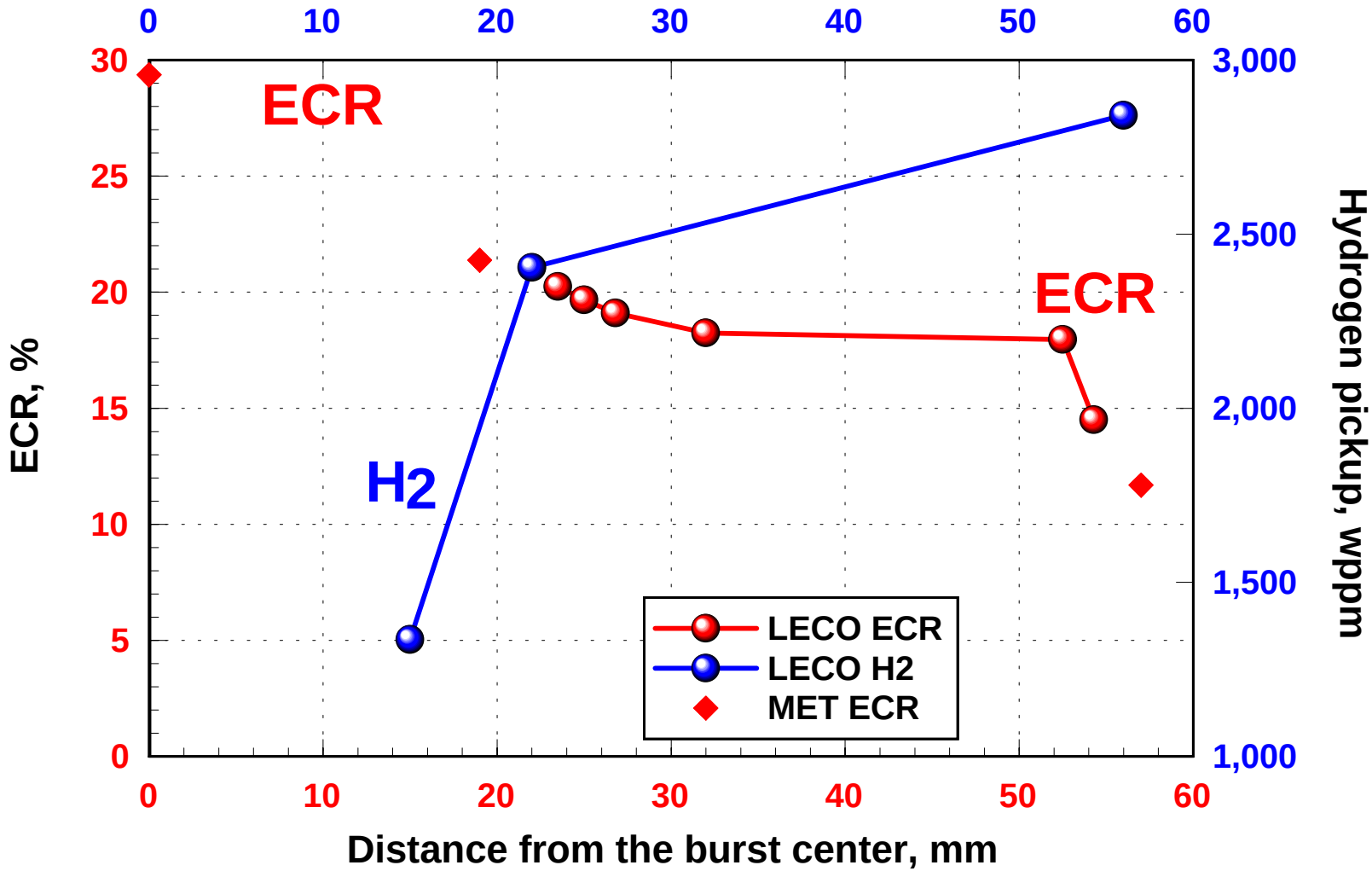
Steam Outlet
Bottom
1 TC
Quartz Tube
Top
Spacer
Test Specimen
3 TCs
Spacer
Fixed Support
Steam Flow →
Pressurized Tube

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 ΔP = 9.24 MPa, burst ΔP ≈ 8.4 MPa, **burst T ≈ 760°C**
  - "Dog-bone-shaped" burst opening; ≈13-mm long (**ECR = 29%**)
  - **Peak ΔD/Do ≈ 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 ΔP = 10.28 MPa, burst ΔP ≈ 9.42 MPa, **burst T ≈ 730°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**

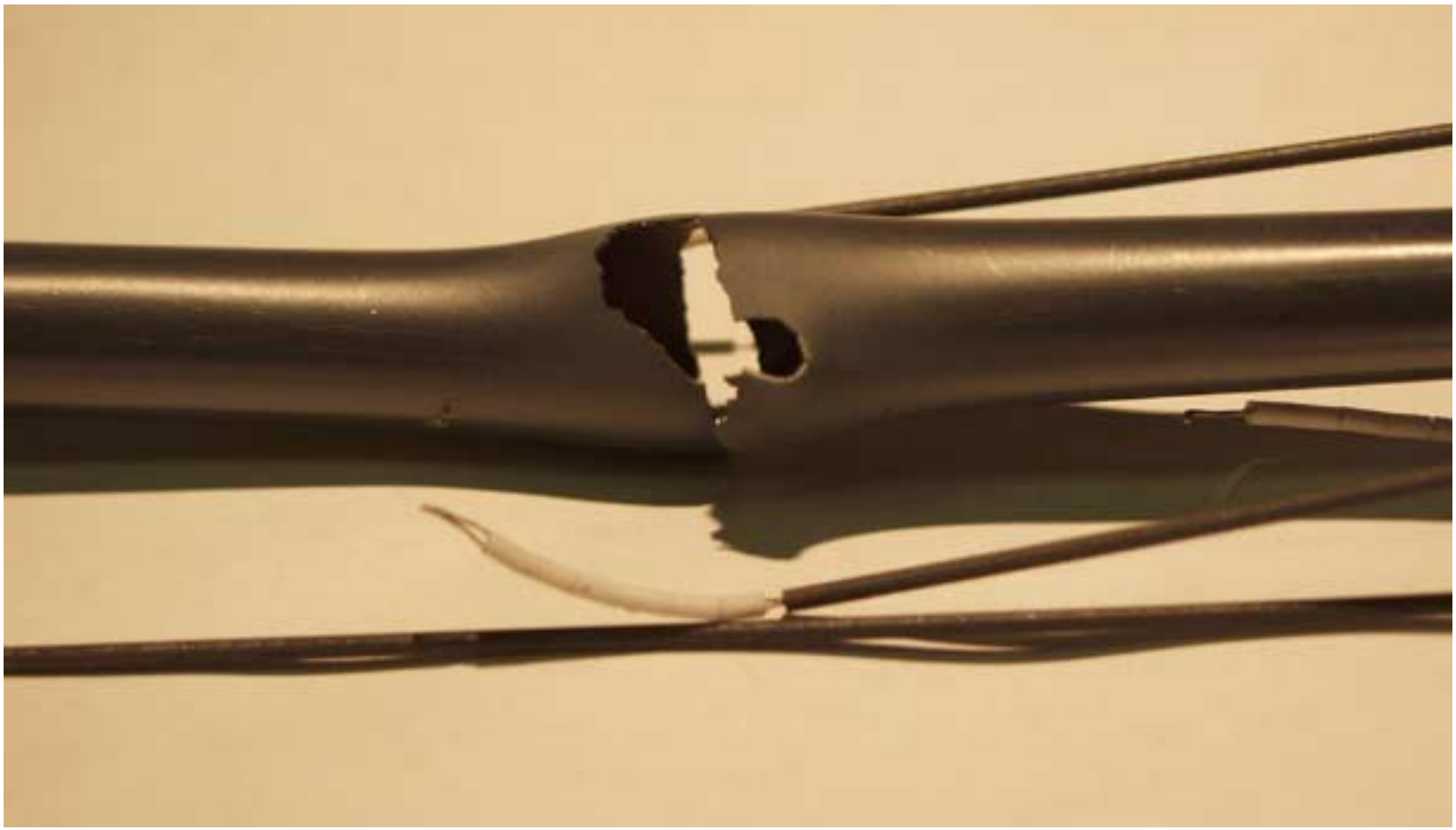
OCL#3: 10-Minute Hold Time at 1204°C

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



OCL#4: 10 min. at 1204˚C, C-P ECR ≈ 30%

Survived Quench; Failed under Dead-Weight Loads at ≈100°C

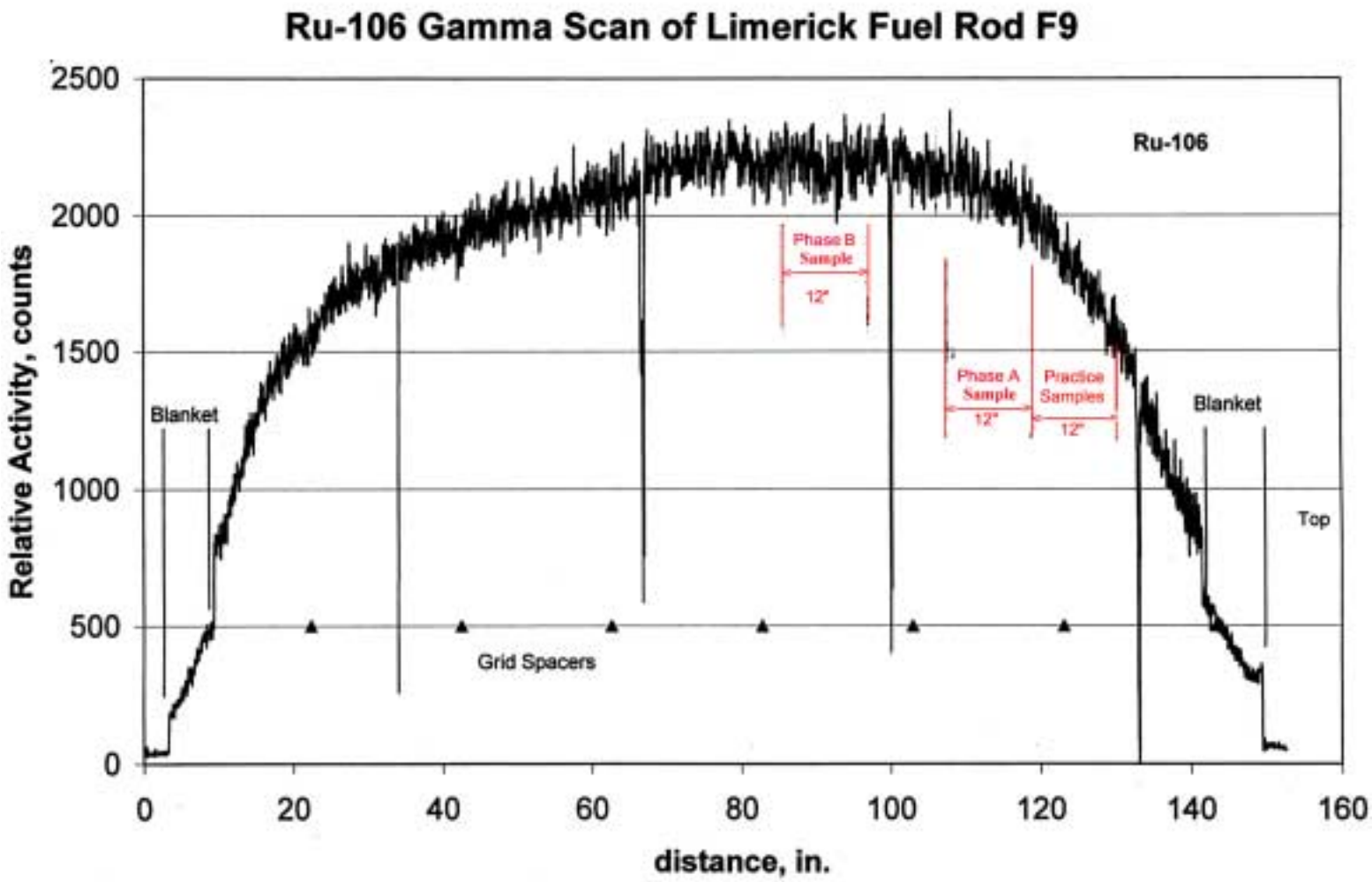


In-Cell LOCA Integral Test Results

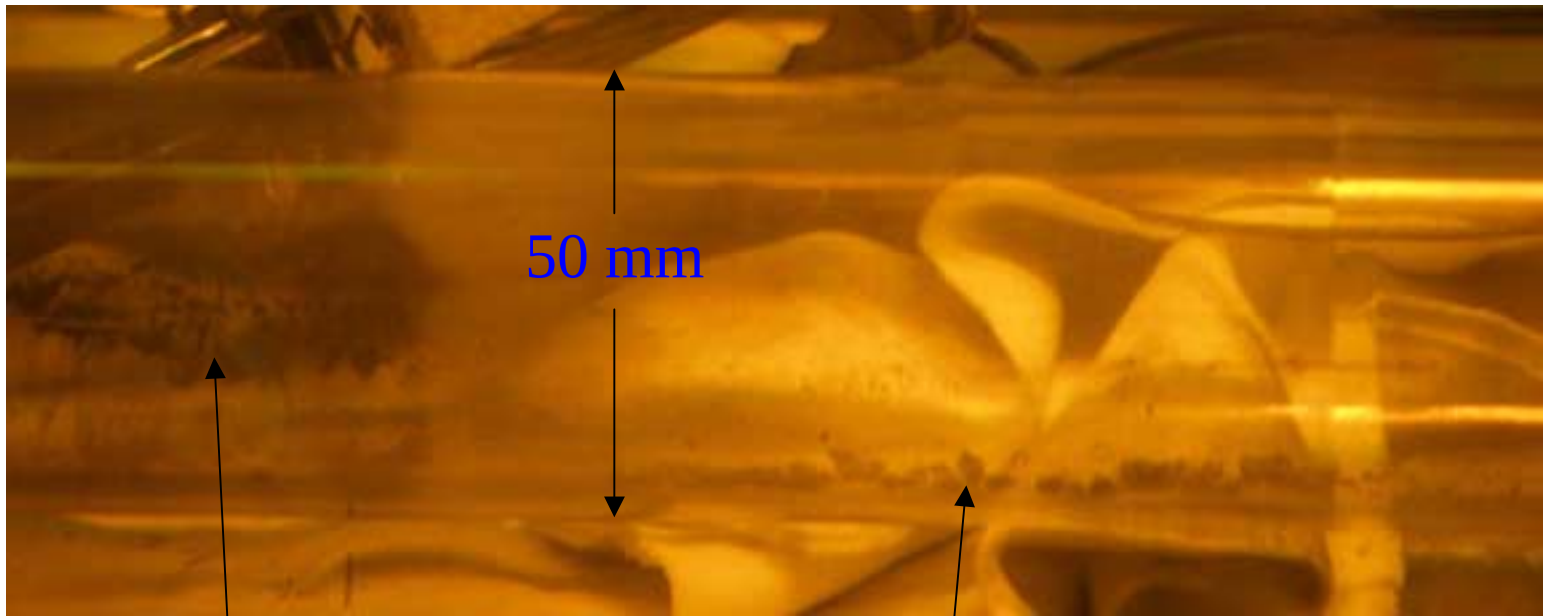
- **Limerick Specimens**
  - **Phase A: middle of Grid Span #6; 0.94-1.24 m above fuel MP**
  - Phase B: middle of Grid Span #5; 0.46-0.76 m above fuel MP
  - Phase C: to be prepared from GS #5 & 6 of Rod J4

- **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



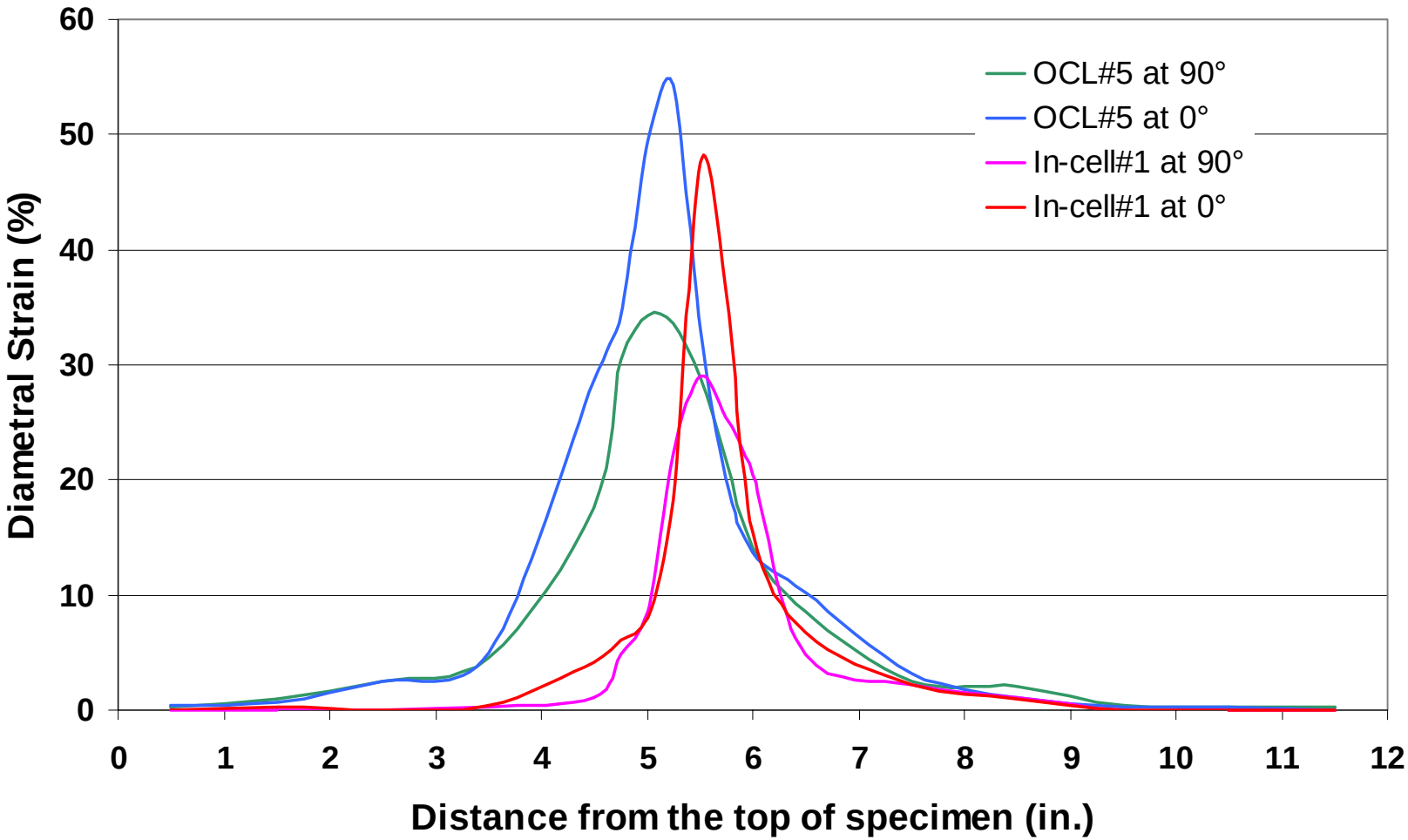
Black Deposit
Cs Compound??

Fuel Particles
< 3 mm in diameter

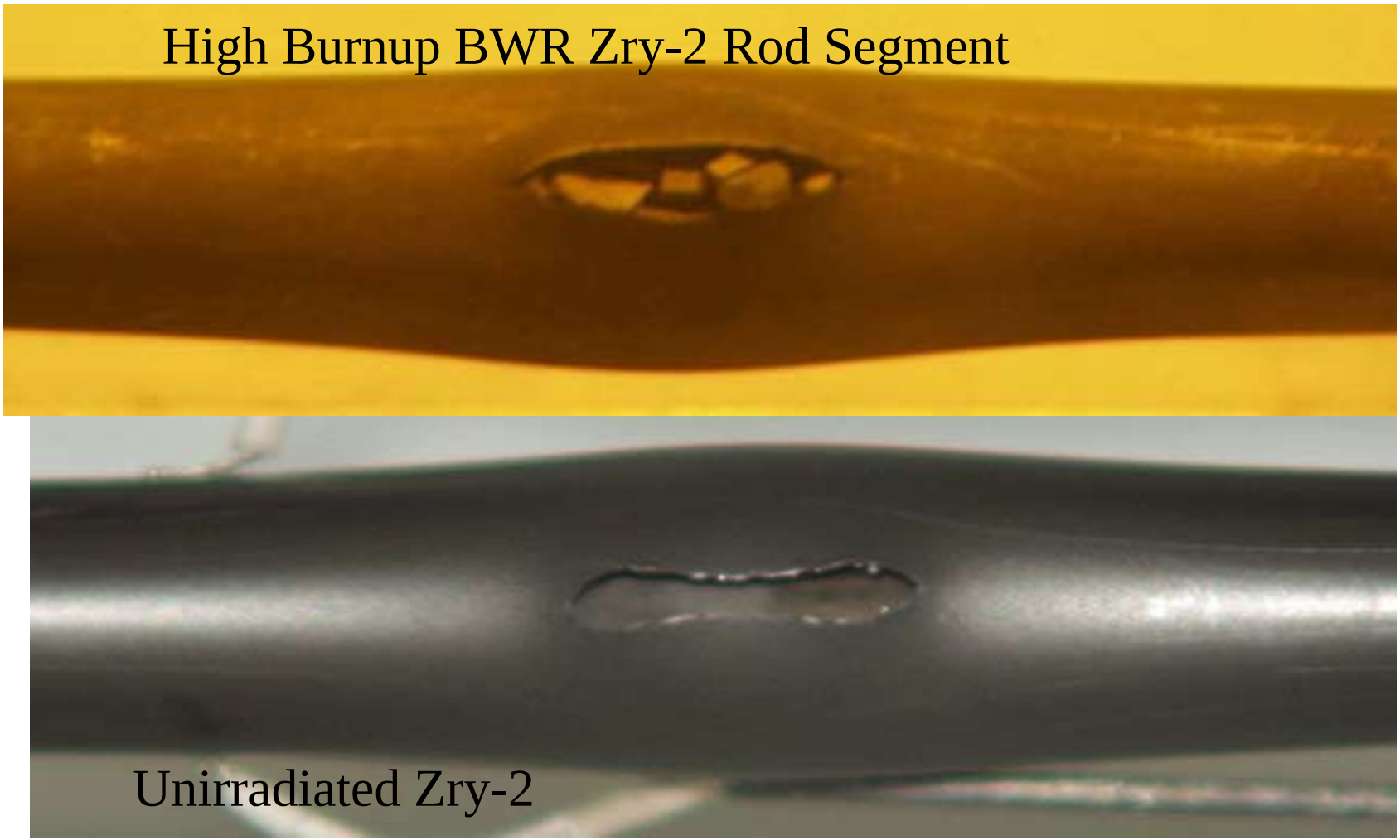
Summary of Ramp-to-Burst Tests in Argon

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±5	766±17	≈755
Burst Center, mm	+20	-10	+10
Burst Length/ Max.-Width, mm	13×2.5 (dog-bone)	17×2.5 (dog-bone)	13×3 **(oval)**
Balloon Length, mm	100	140	70
Max. Hoop Strain, %	44±10	60±10	38±9
Min. Wall for ECR, mm	0.49	0.43	≈0.51

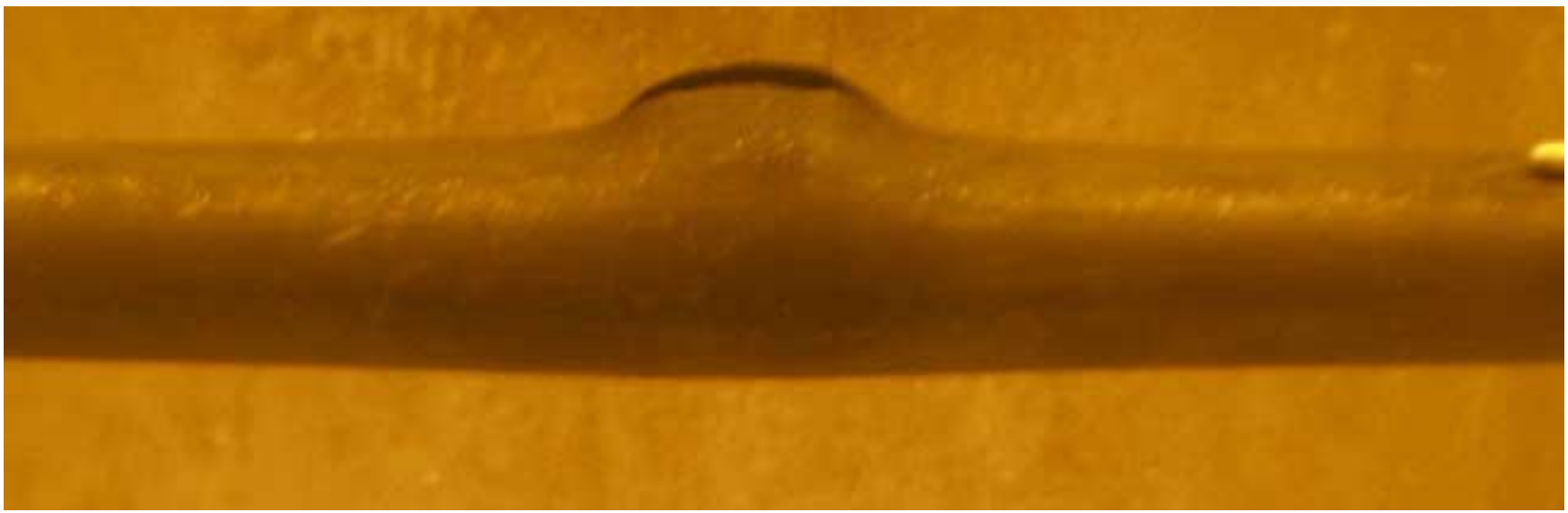
Profilometry Results for ICL#1 vs. OCL#5



Ramp-to-Burst Opening Comparison



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

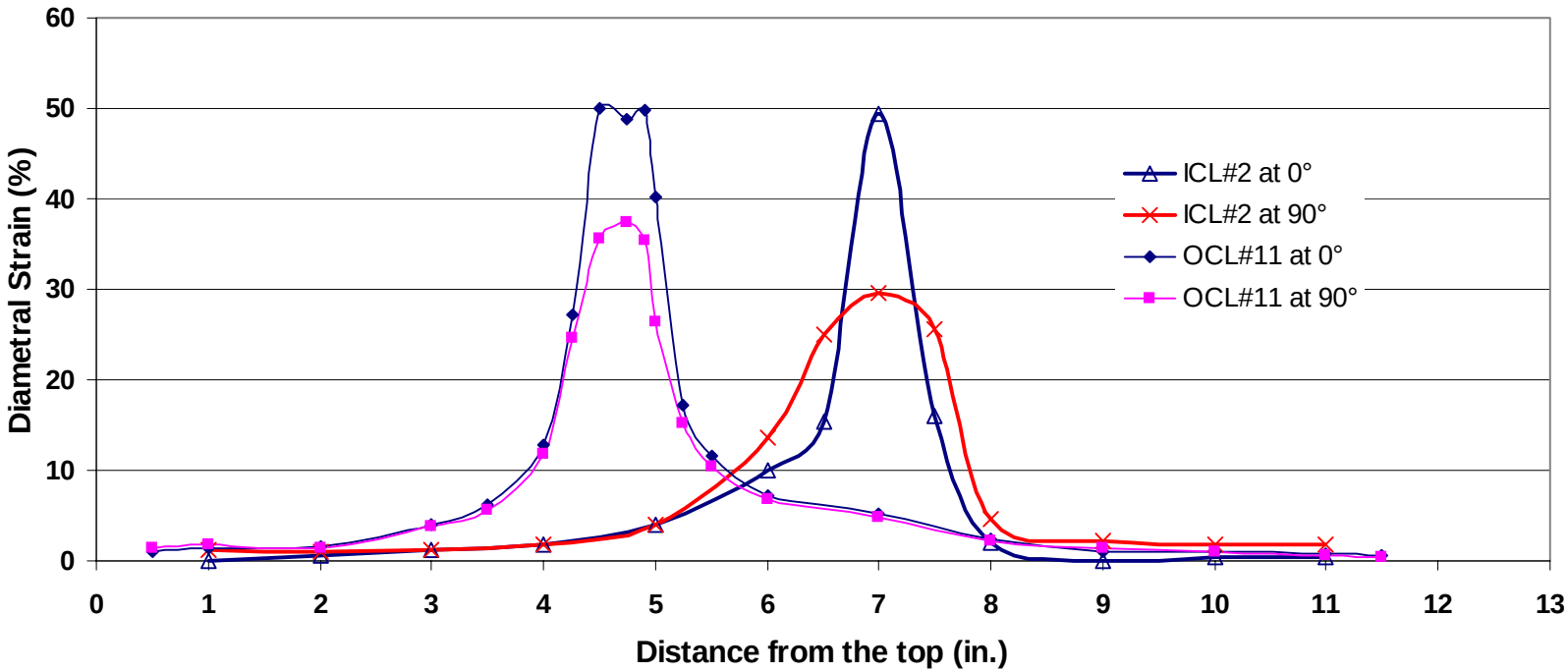
    Sample failed cleanly across burst cross-section (ductility??)
  - Live demonstration for nominal bending tension 180° from burst

    Axial crack initiated at burst tip; failure across high-H region (ductility??)

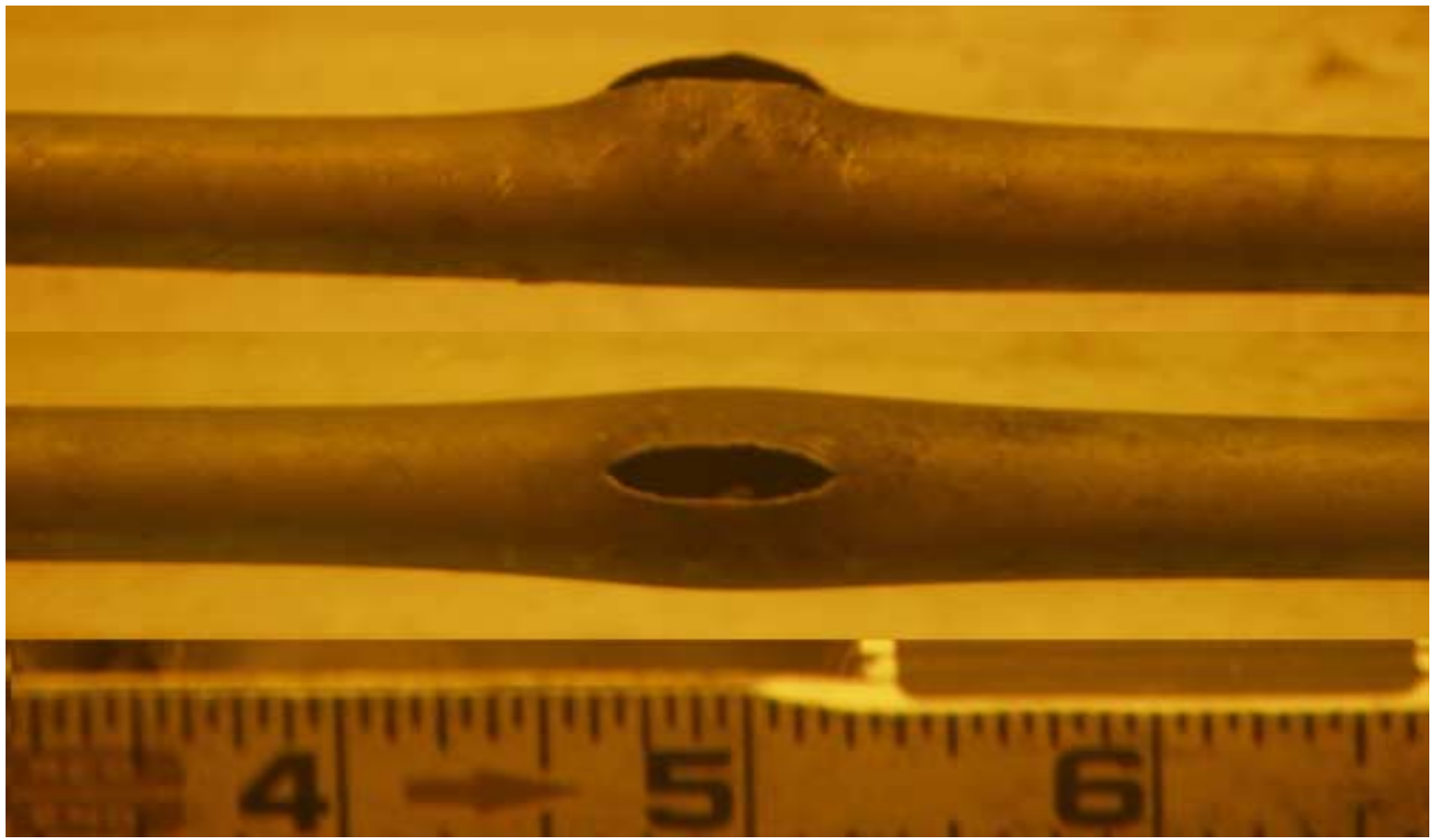
Comparison of ICL#2 and OCL#11: 5 min. at 1204°C

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

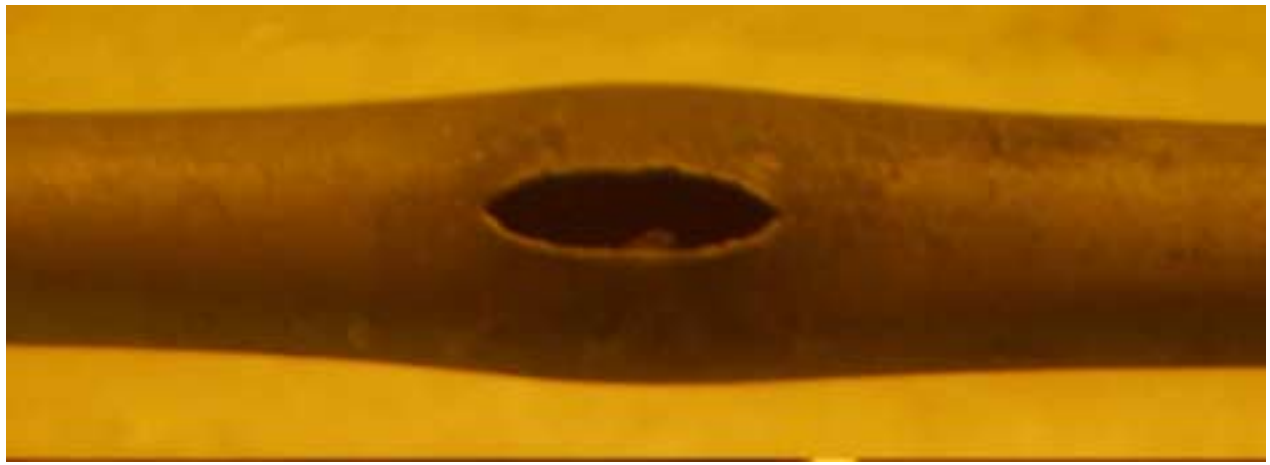
PROFILOMETRY ICL#2 and OCL#11 Specimens



High-Burnup BWR Balloon & Burst for ICL#2



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



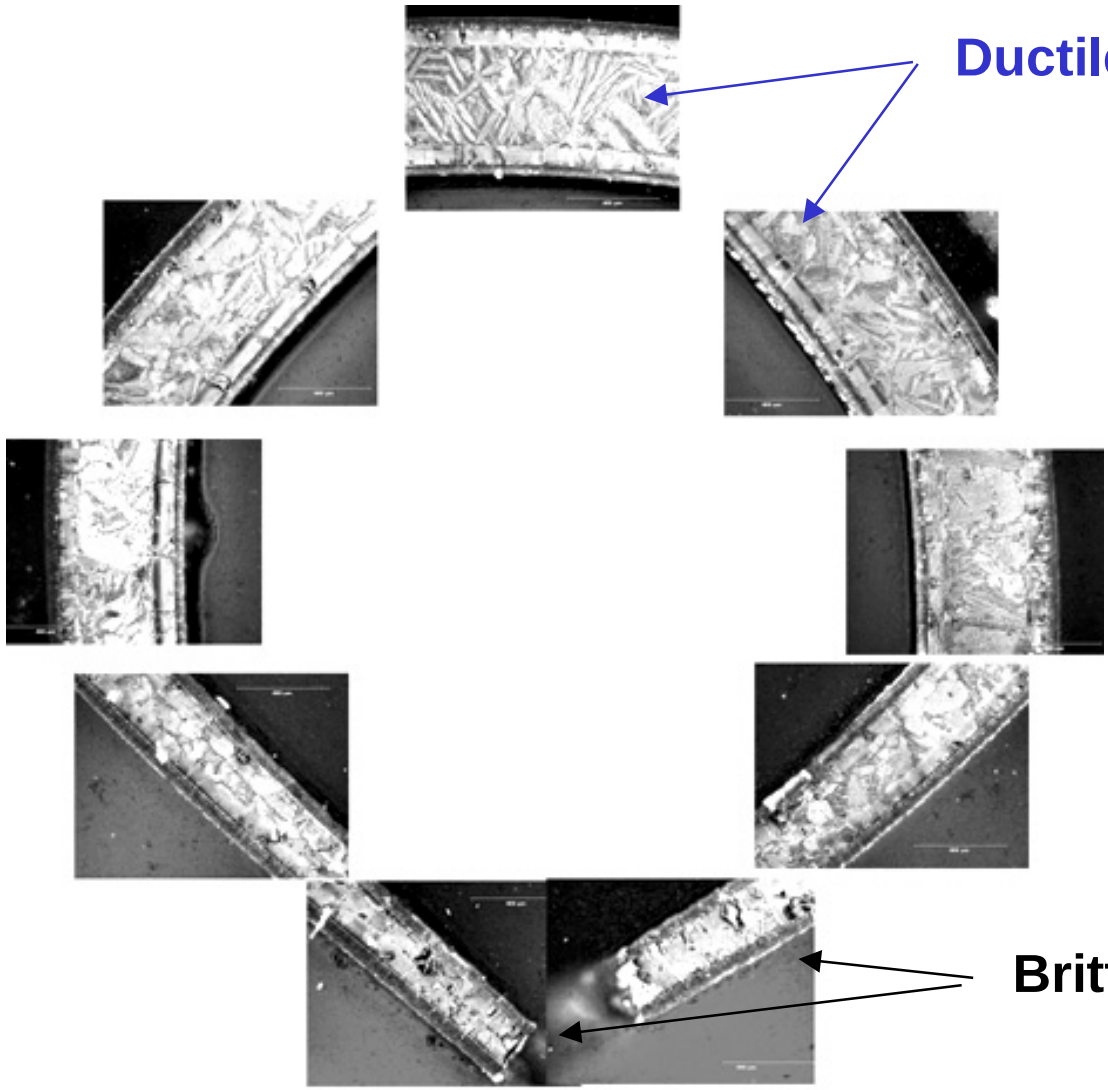
Detailed Results for ICL#2 and OCL#11

- **Metallographic Results**
  - OCL#11 at burst midplane (double-sided oxidation evident)

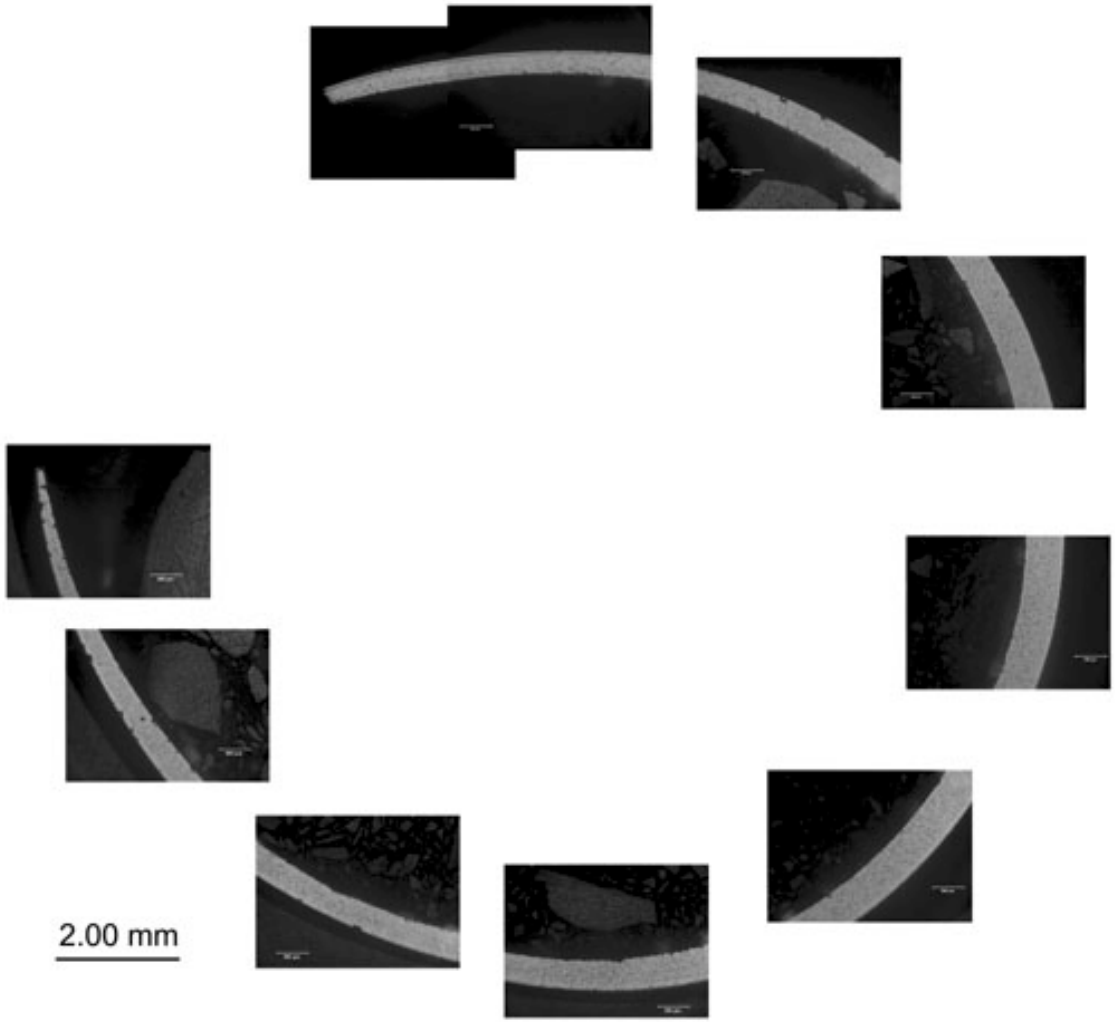
    Cross-section: brittle near burst opening to “ductile” 180° from burst
  - ICL#2 at burst midplane (double-sided oxidation evident)
  - ICL#2 at 50 mm above burst center (very little inner-surface oxidation)
- **Measured Hydrogen and Oxygen Profiles for OCL#11**
  - ECR = 2.85 $\Delta C_o \leq 17.6\%$, 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

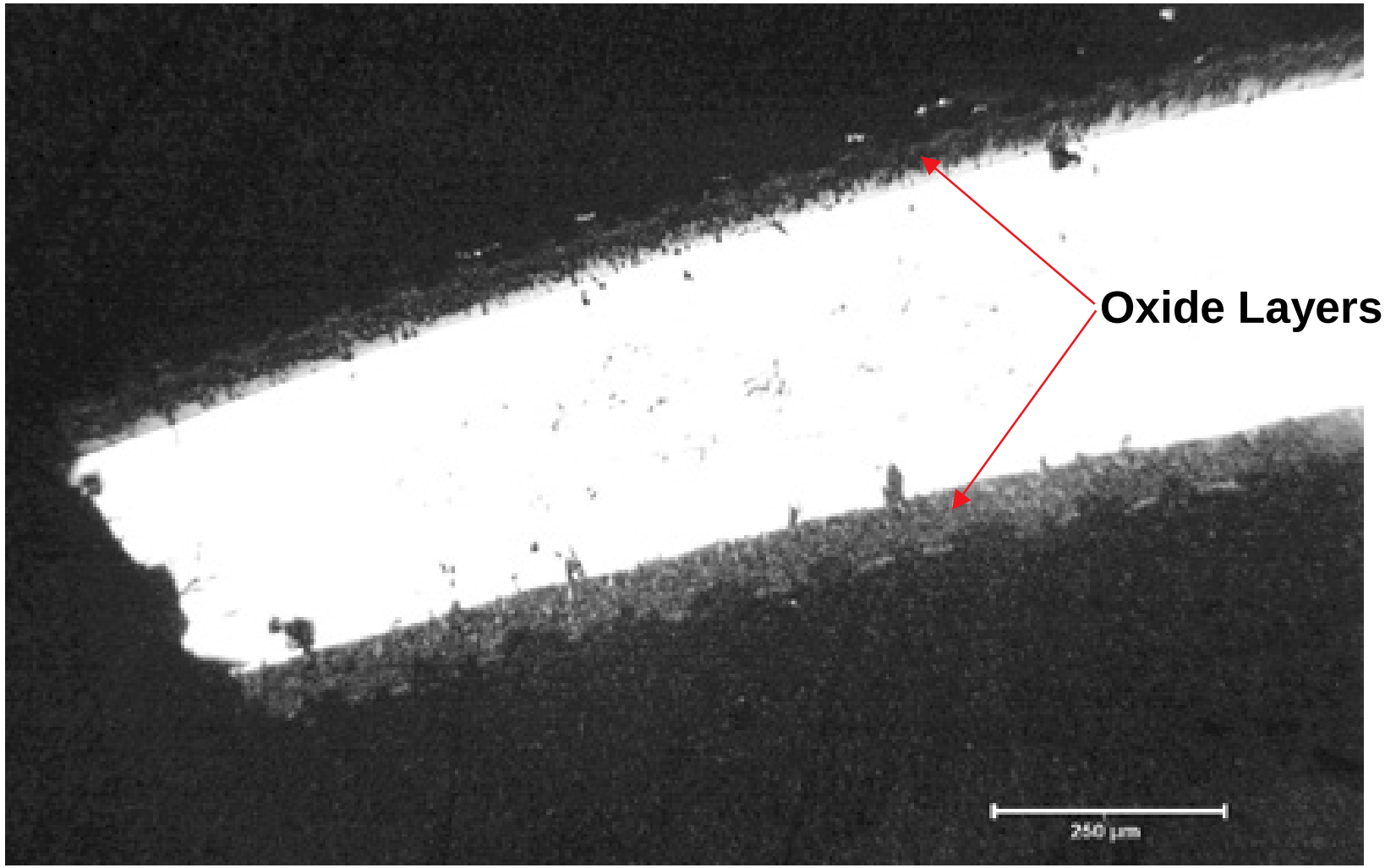
Metallography of Burst Cross-Section for OCL#11



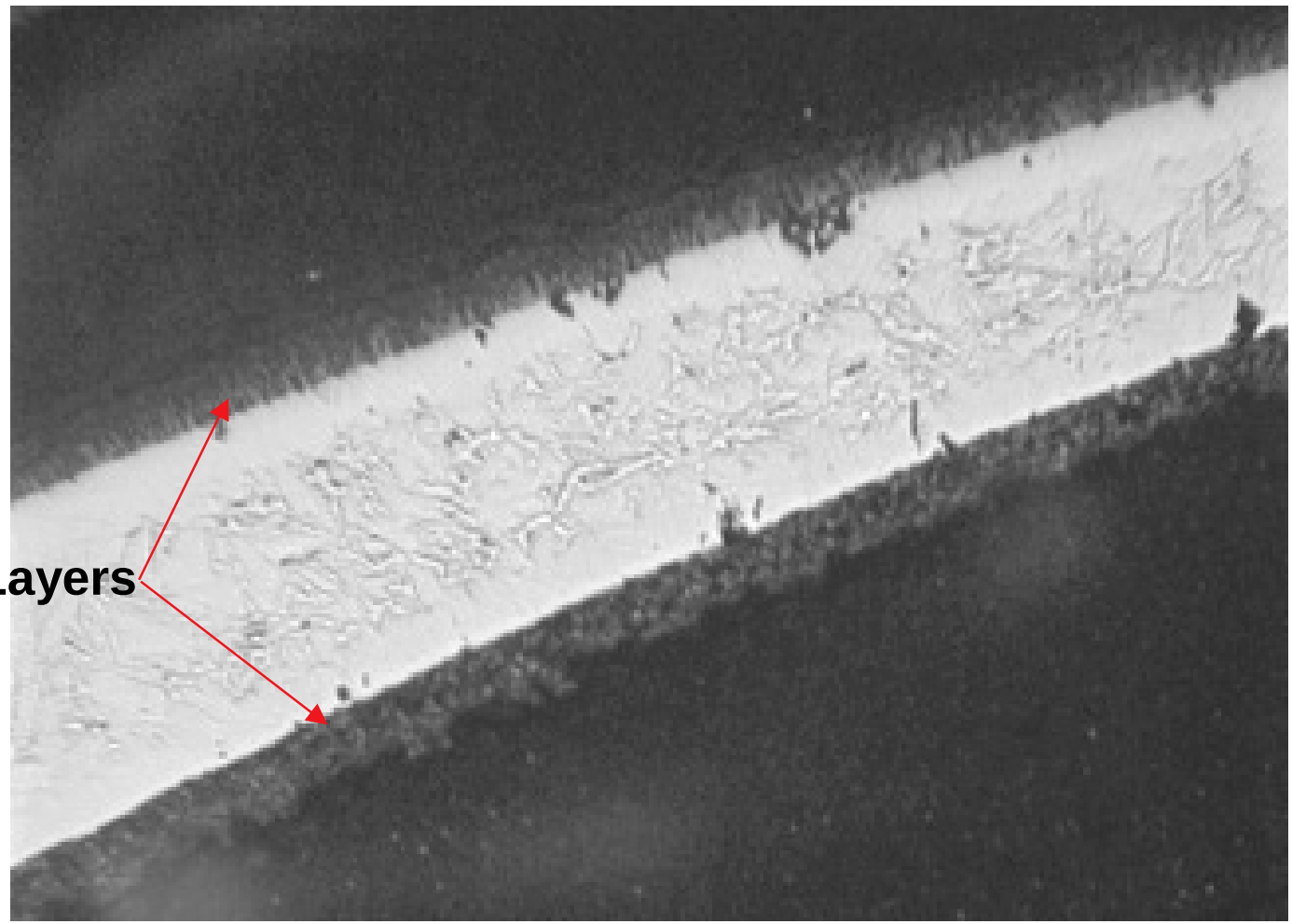
Low-Mag. Image of Burst Cross-Section for ICL#2



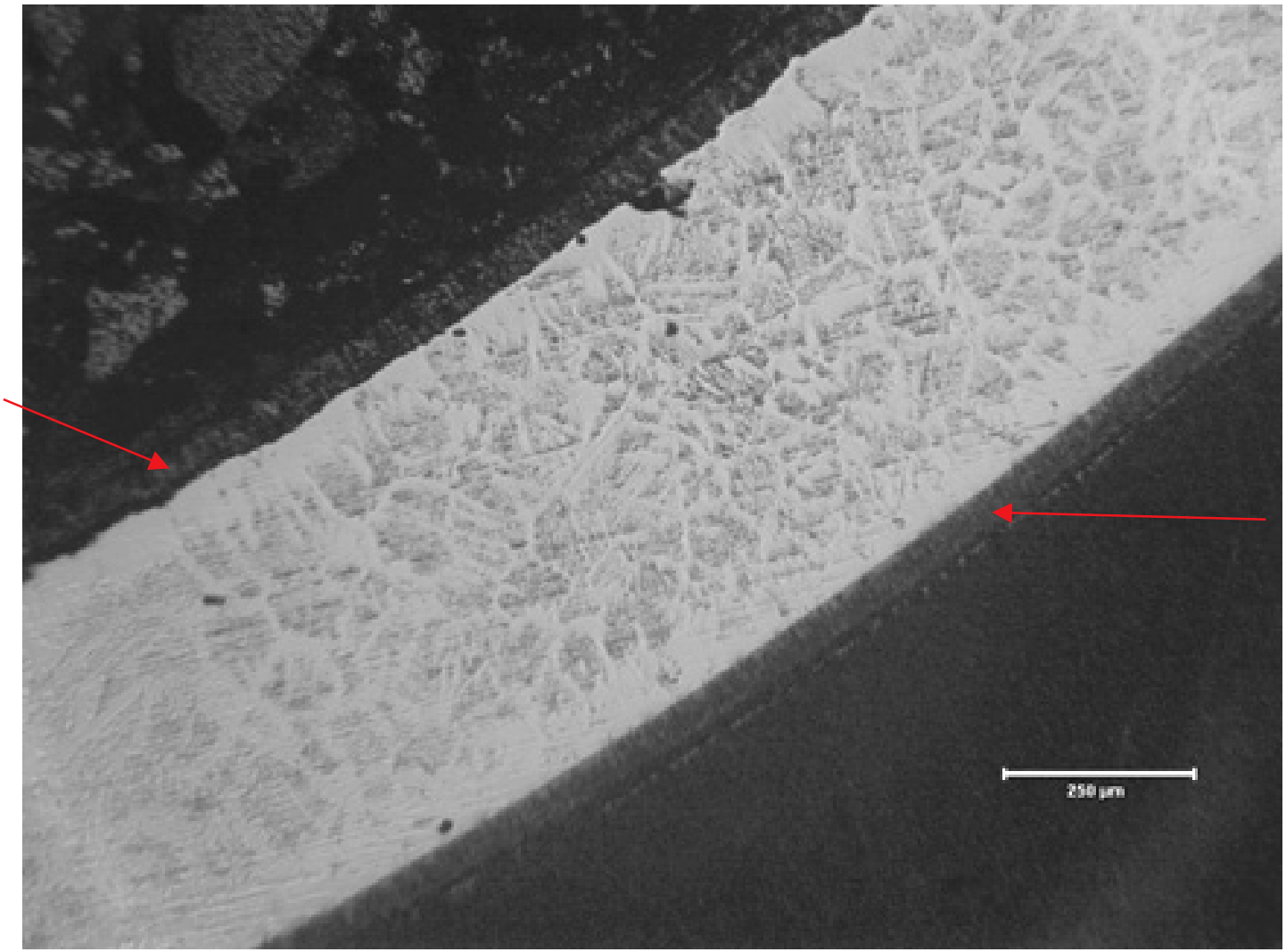
Metallography of ICL#2 Near Burst End A



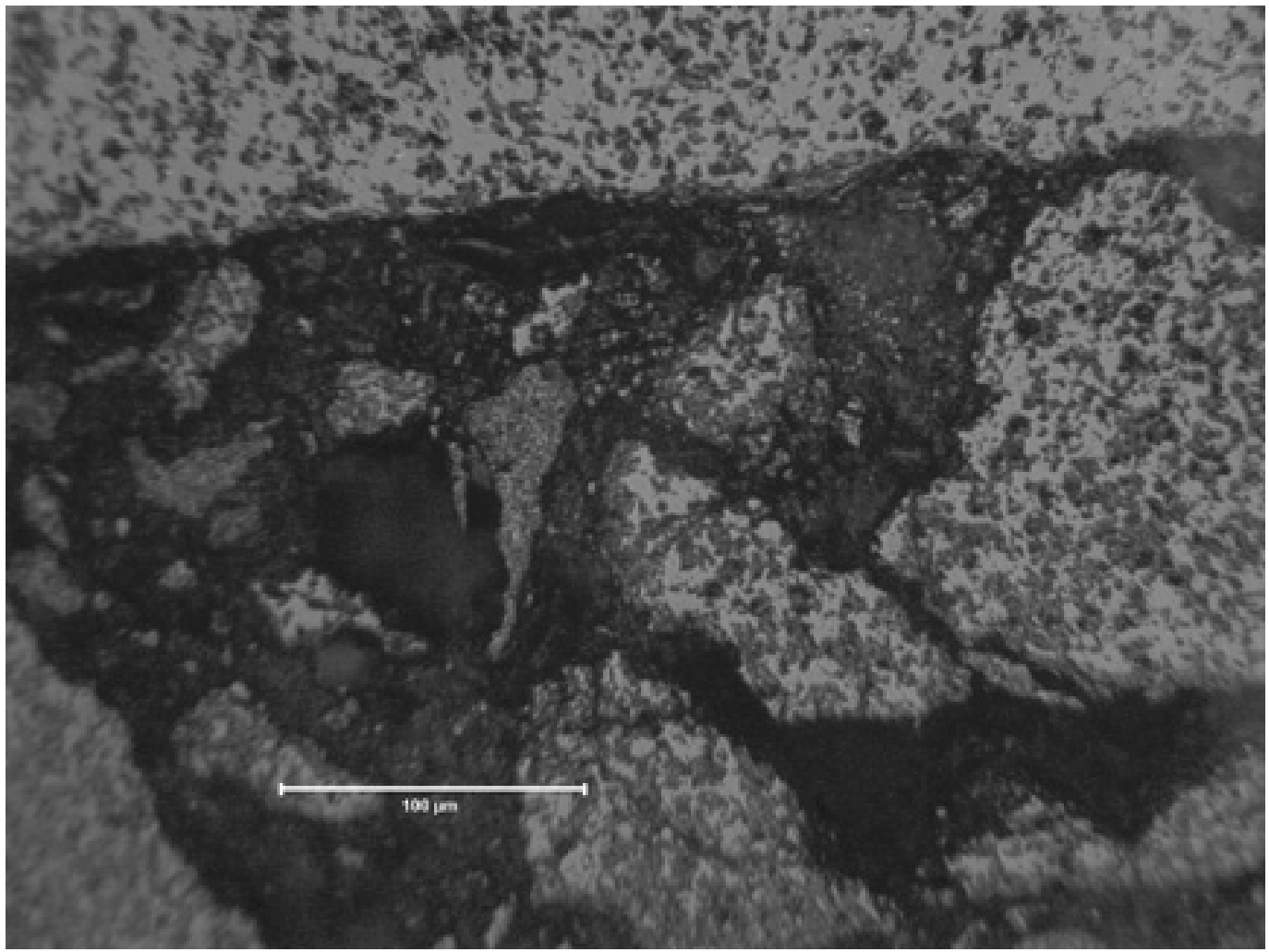
Metallography of ICL#2 Near Burst End B



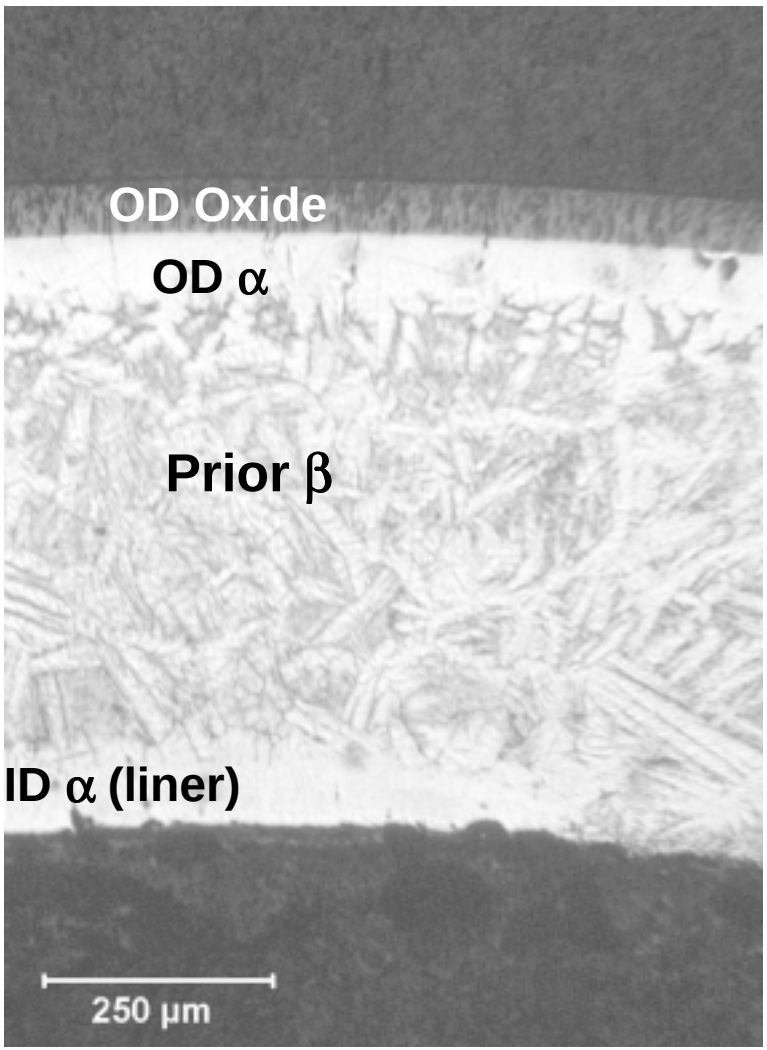
Metallography of ICL#2 180°C from Burst Opening

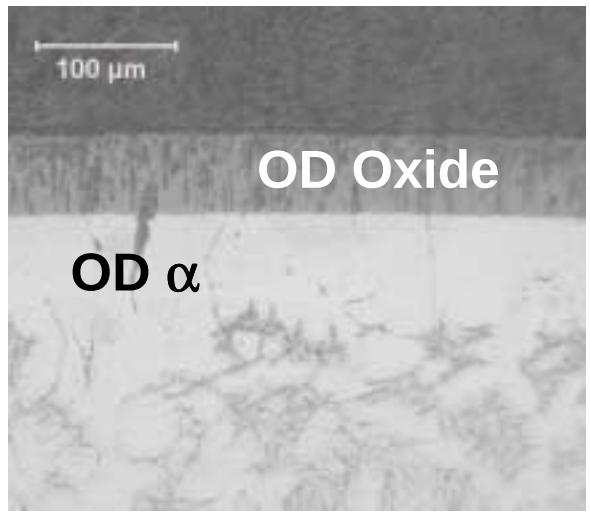


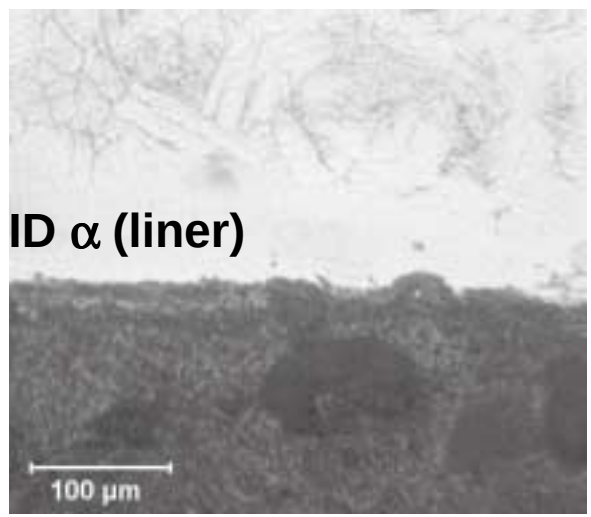
ICL#2 Fuel Particles Embedded in Epoxy at Midplane



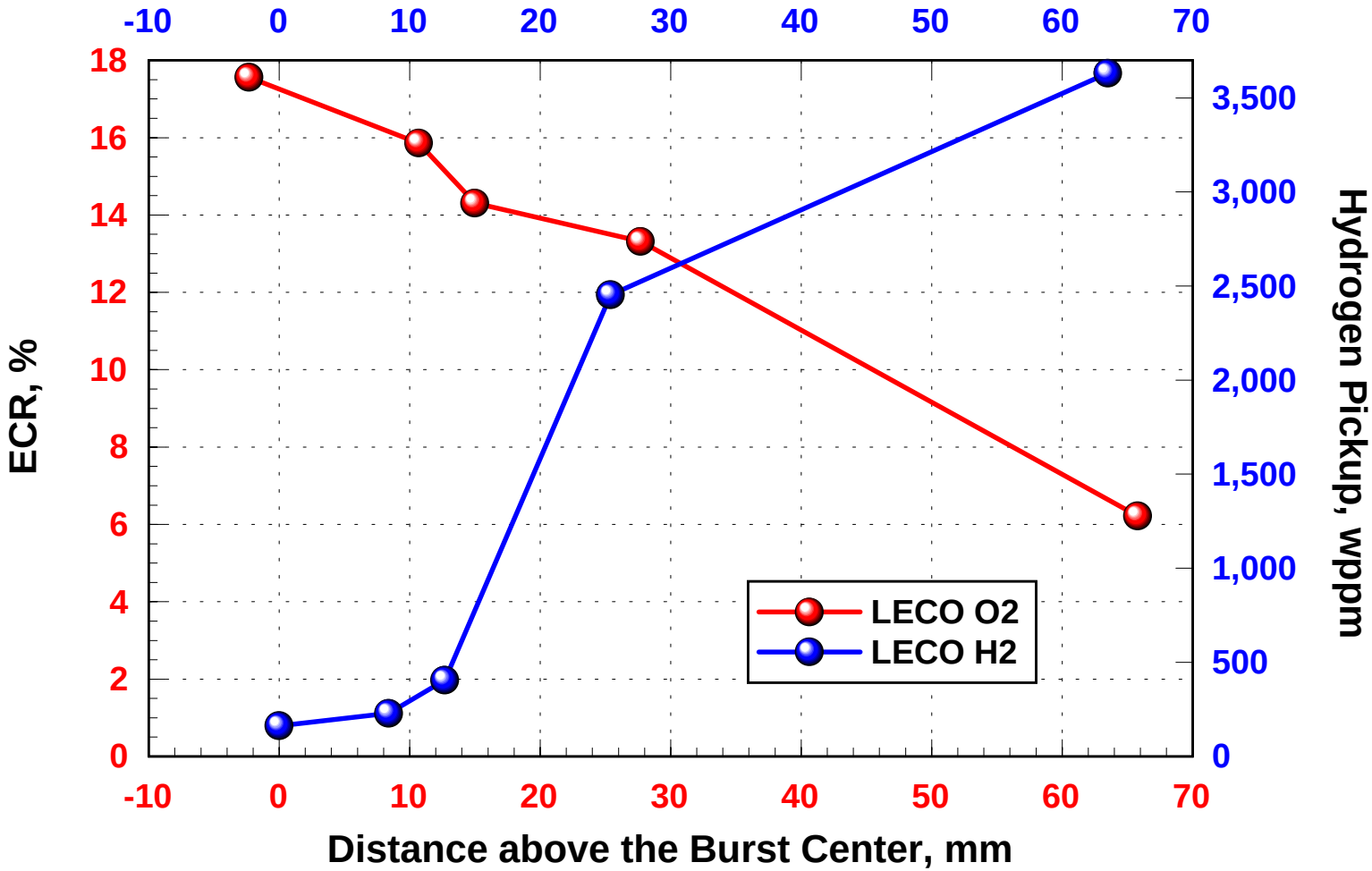
Etched ICL#2 Sample 50 mm above Burst Center







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

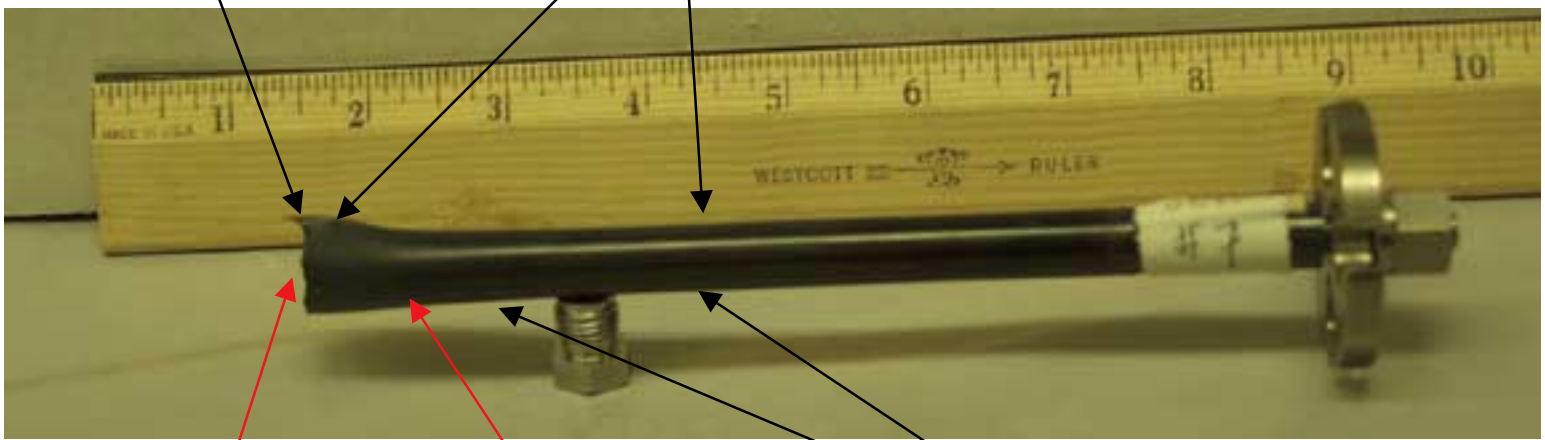
Four-Point-Bend Demonstration Results (Cont'd)

- **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

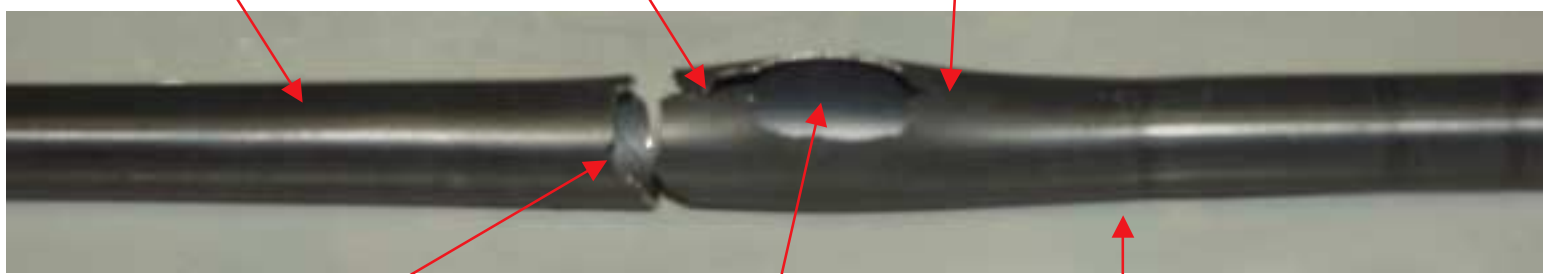
    Burst region is "flawed", partially embrittled by oxygen vs. ECR and T

    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