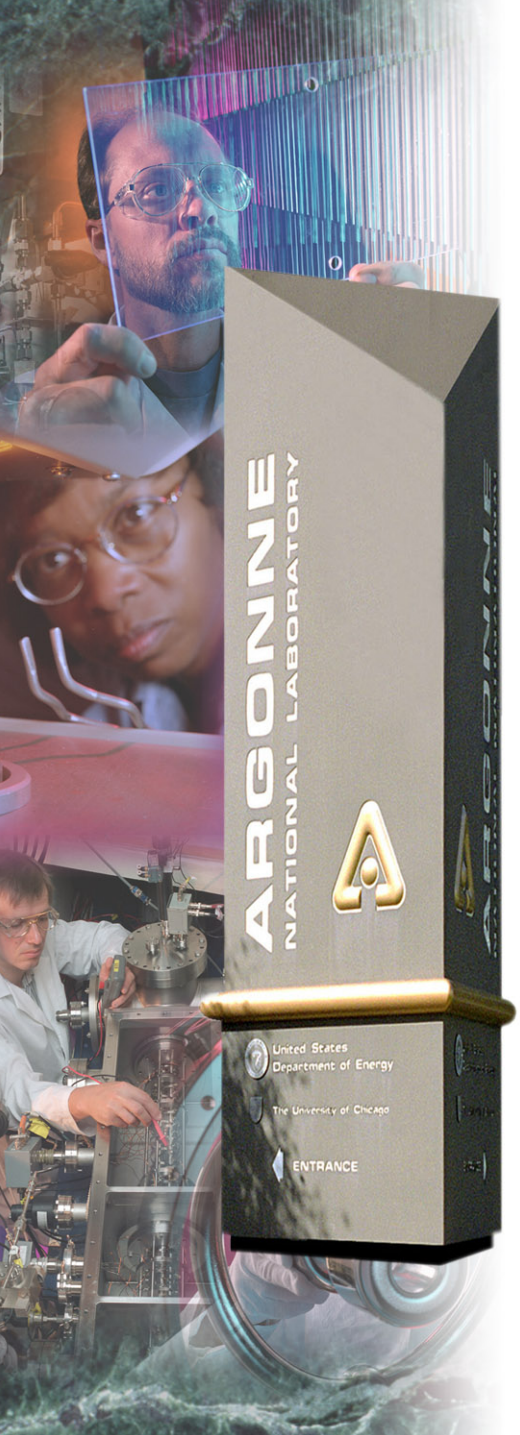

LOCA Results for Advanced-Alloy and High-Burnup Zircaloy Cladding

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Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Scope of LOCA-Relevant Research

- **Licensing Issues Addressed**
  - 10 CFR 50.46 embrittlement criteria for maintaining residual ductility in Zircaloy (Zry) cladding; temperature limit: PCT ≤ 1204ºC, oxidation limit: effective cladding reacted ECR ≤ 17%
  - Confirm embrittlement criteria for high-burnup Zry-2 and Zry-4
  - Compare post-quench ductility of ZIRLO and M5 to Zry-4 vs. ECR
- **High-Burnup Phenomena Investigated**
  - Fuel behavior and effects of fuel on cladding during a LOCA sequence
  - Effects of corrosion, hydriding and irradiation on cladding: Ballooning, burst, high-temperature steam oxidation, Quench behavior and post-quench ductility
- **Advanced-Alloy Cladding Phenomena Investigated**
  - ZIRLO and M5 oxidation kinetics (vs. Zry-4)
  - ZIRLO and M5 post-quench ductility (vs. Zry-4)

Cladding Alloys and Irradiated Fuel Rods at ANL

- **Unirradiated Cladding Alloys**
  - Zry-2: Zr-lined 8x8, 9x9 (Limerick BWR "archive"); 10x10
  - Zry-4: 15x15 (H.B. Robinson "archive"); 17x17 low-Sn
  - ZIRLO: 17x17
  - M5: 17x17
  - E110: tubing and cladding (etched/anodized or lightly oxidized)
- **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

Advanced-Alloy Post-Quench Ductility Research

- **Basic Approach**
  - **Short (25-mm), undeformed cladding segments**

    Oxidize (2-sided)-and-quench all alloys in same apparatus

    Use measured weight gain to determine oxygen pickup and ECR

    Perform RT ring-compression tests to determine ductility

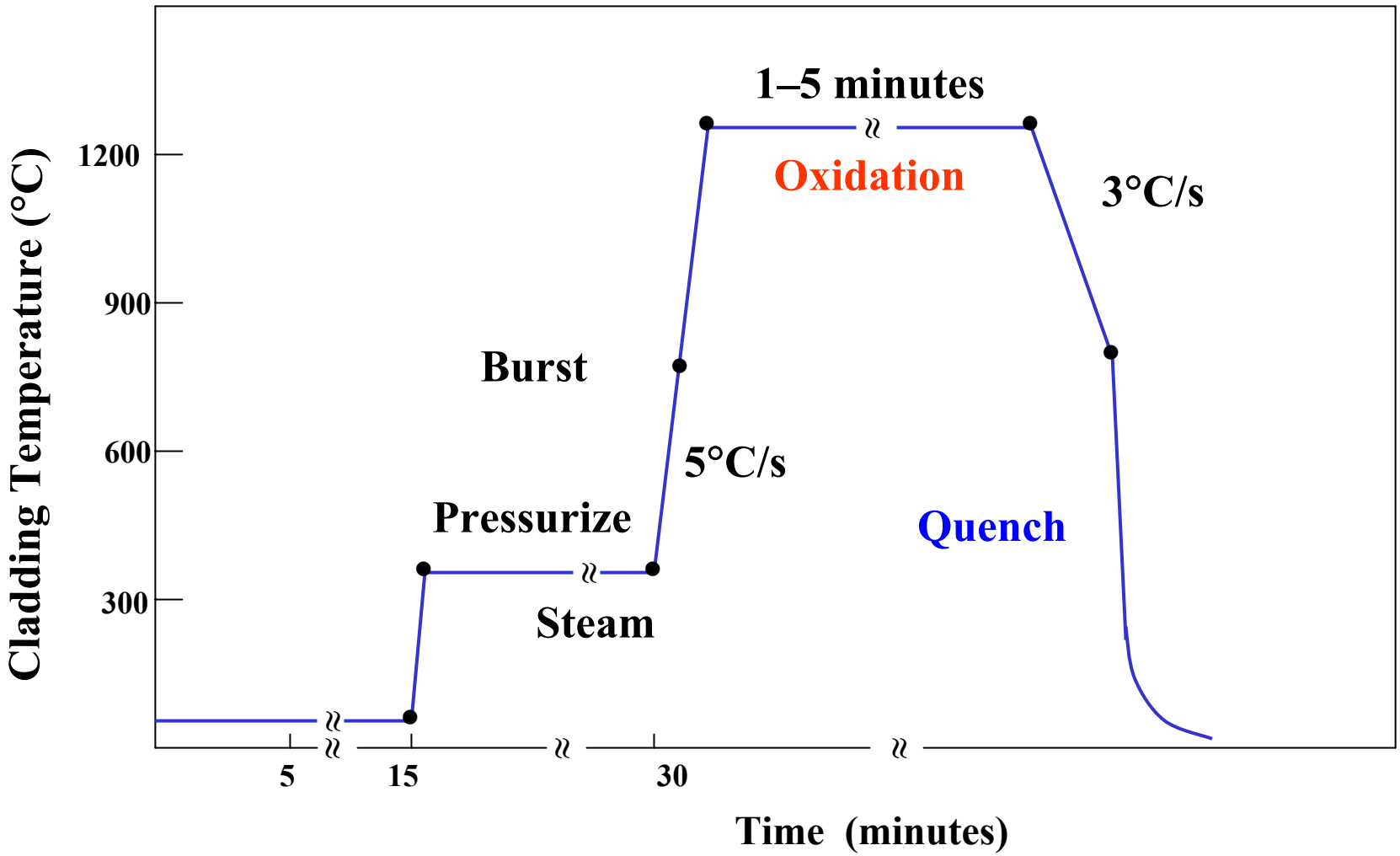
    Use metallography and LECO H-determination to confirm results
  - **Long (300-mm), pressurized cladding segments**

    Balloon, burst, oxidize and quench all alloys in same apparatus

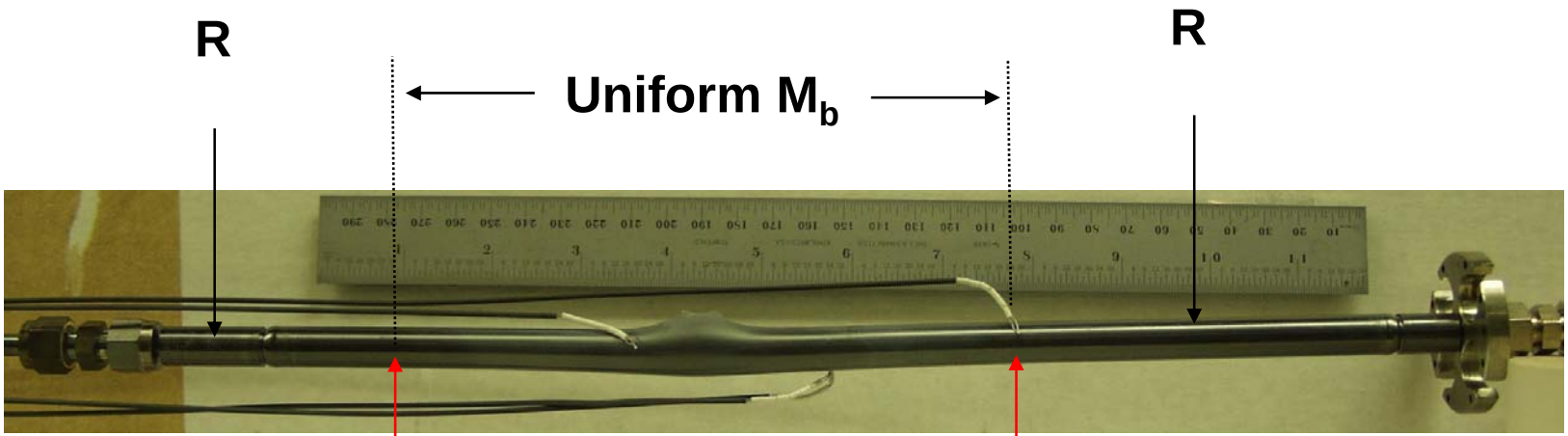
    Use 4-point-bend test to determine failure location and mode

    Perform ring-compression tests on samples from non-ballooned region
- **Oxidation Times and Temperatures for Calc. ECR ≤ 20%**
  - ≤3400 s (1000°C), ≤1100 s (1100°C), ≤400 s (1200°C), ≤230 s (1260°C)

LOCA Integral Test Sequence for Unirradiated Cladding Alloys



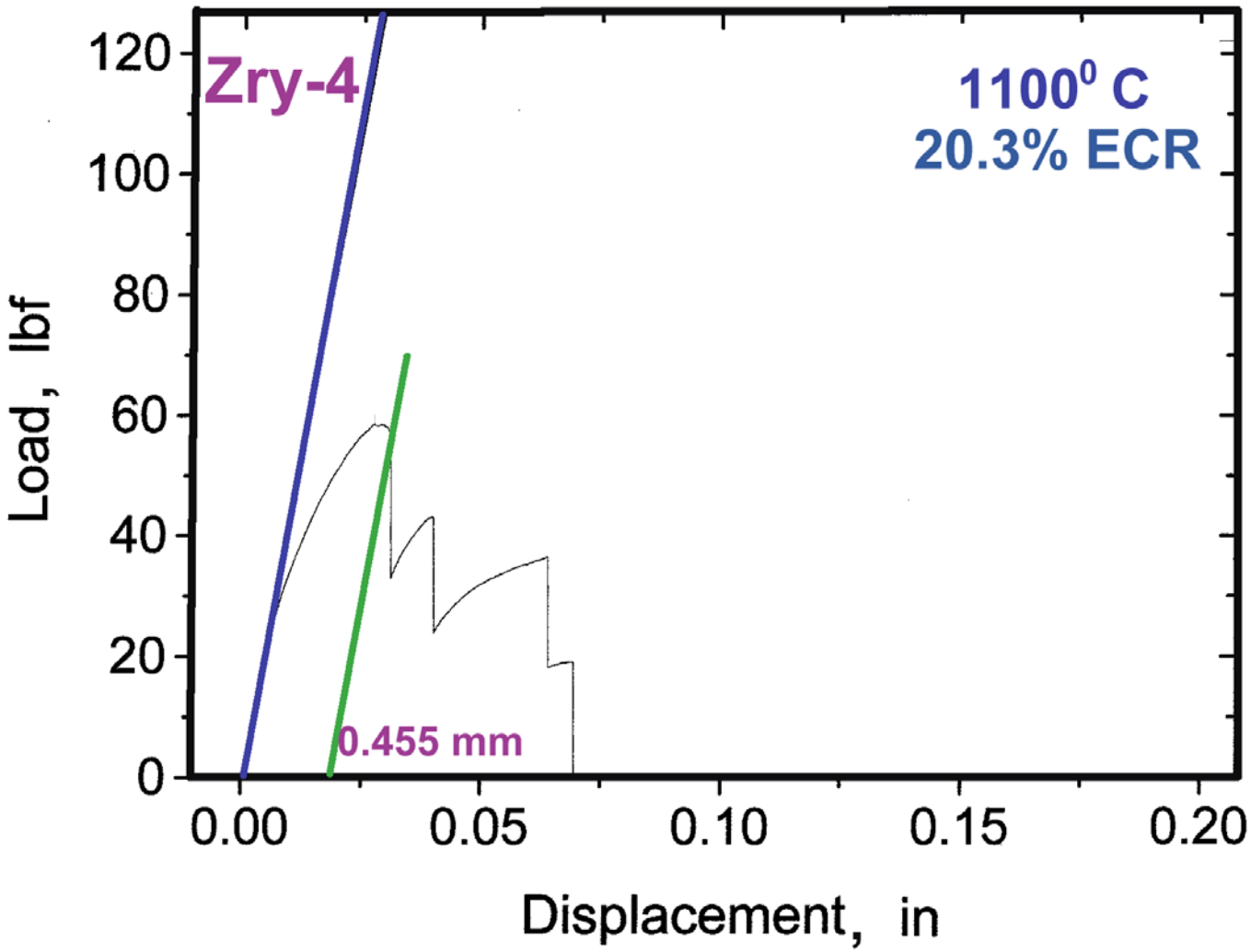
4-Point-Bend Test with Burst Area under Tension



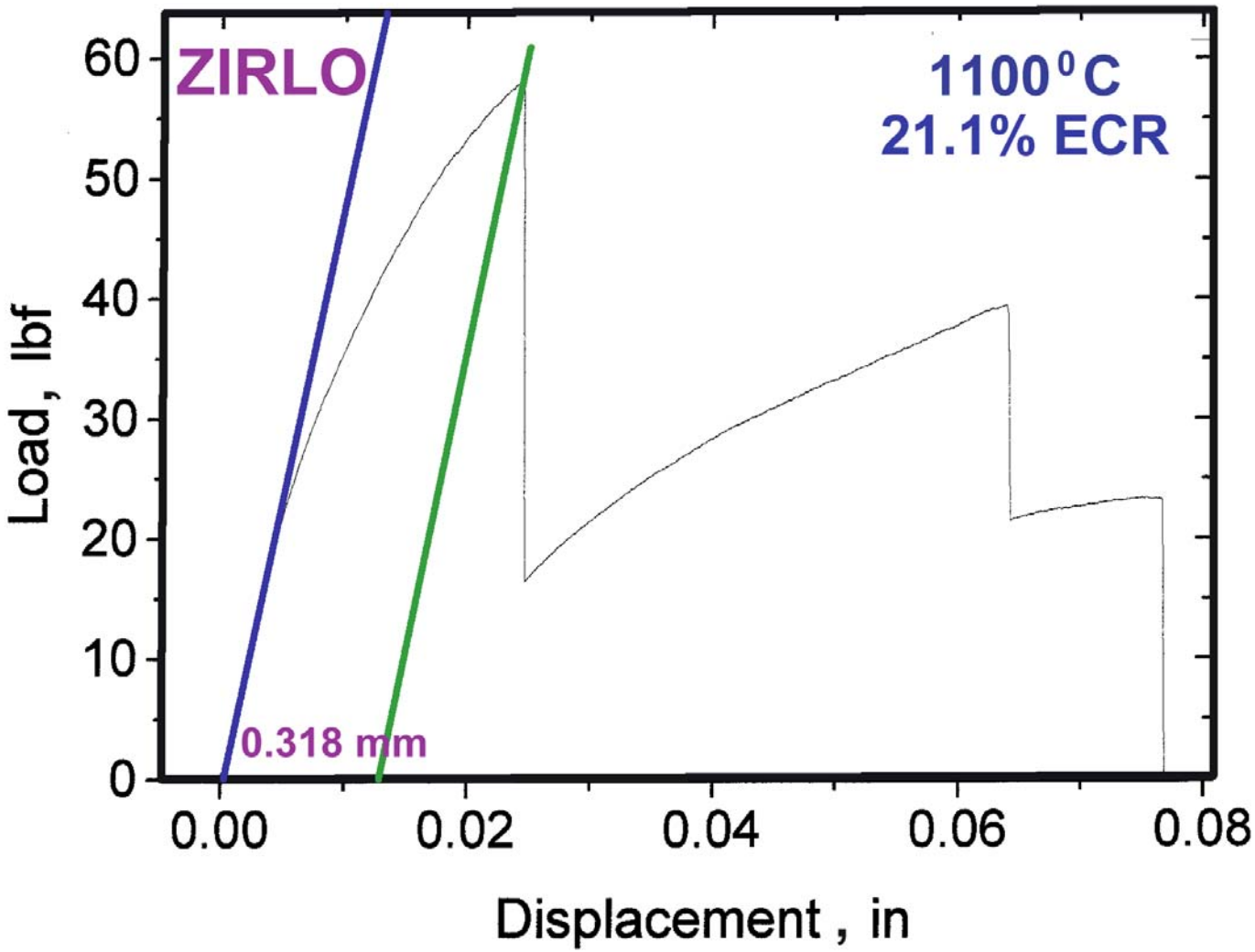
Advanced-Alloy Results

- **Weight Gain Kinetics for Short Segments**
  - At 1100ºC, Zry-4, M5 and ZIRLO data are in agreement with Cathcart-Pawel (CP) model predictions (within ≈ ±10%)
  - At 1000ºC, ZIRLO < Zry-4 and M5 << Zry-4
- **Post-Quench Ductility: Short Segments at ≤20% Calc. ECR**
  - Residual ductility measured for all alloys at 1000ºC and 1100ºC
  - Measured hydrogen pickup is low (< ≈100 wppm)
  - Metallography conducted to date supports ductility data
- **Tests at 1200°C and 1260°C are in Progress**
- **LOCA Integral Tests on Long, Pressurized Segments**
  - Conducted on 9×9 Zry-2 at 1204ºC for 5 minutes (18% ECR)
  - Highly non-uniform local ECR observed at burst cross-section
  - Significant secondary hydriding observed in balloon neck regions

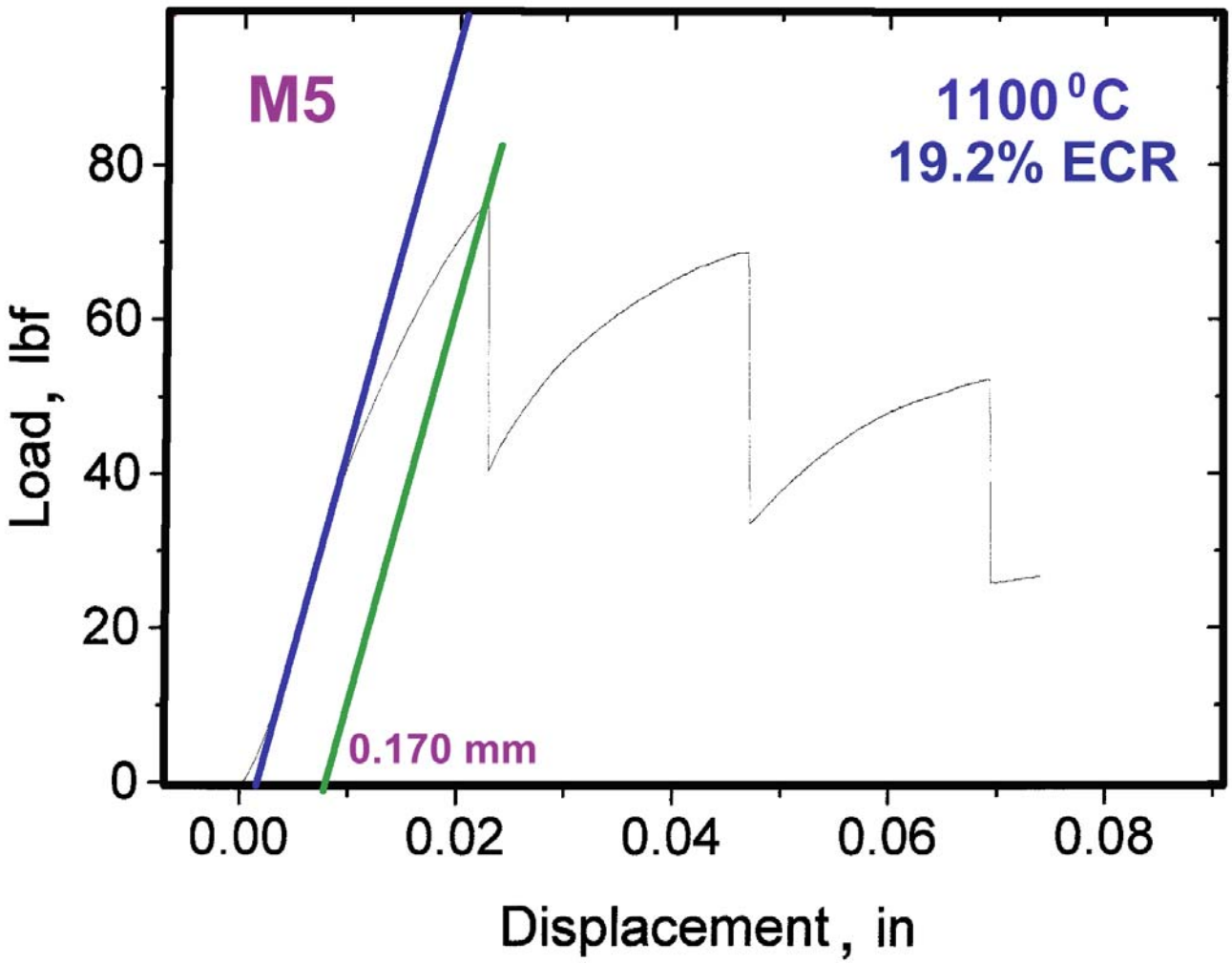
Off-set Displacement Method: Zry-4 Ductility



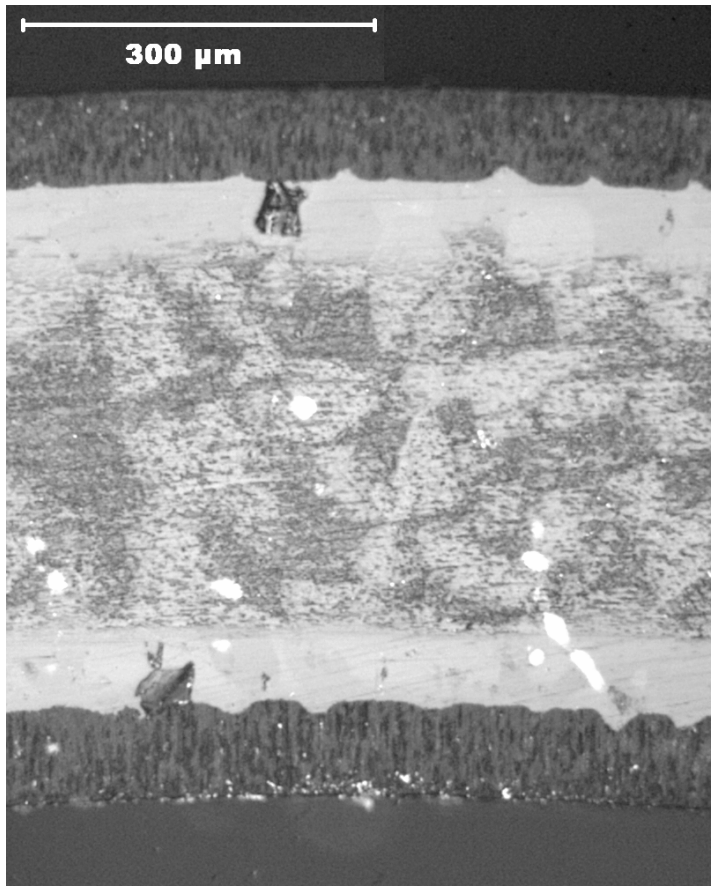
Off-set Displacement Method: ZIRLO Ductility



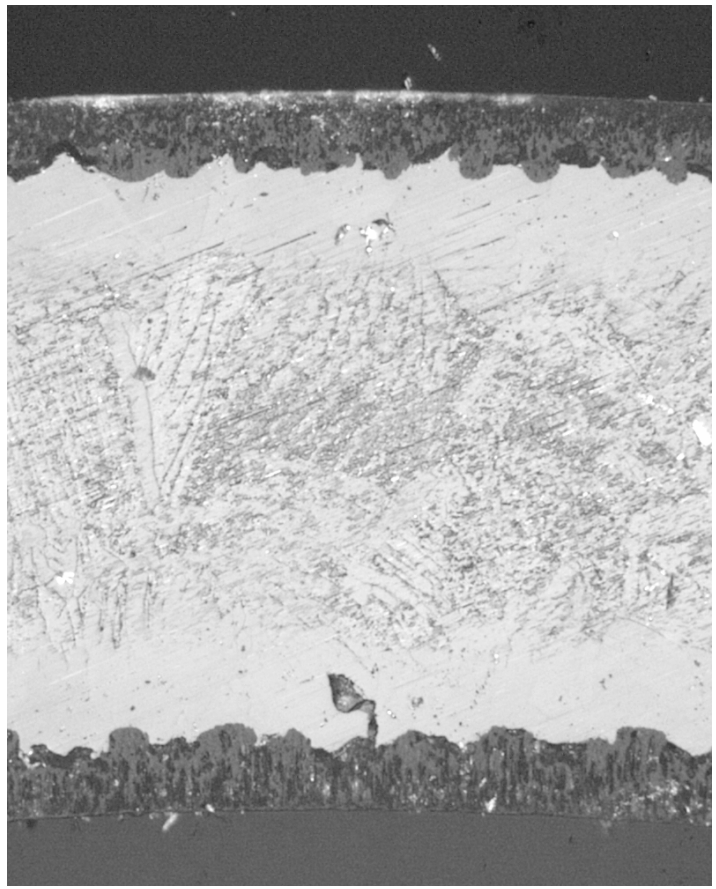
Off-set Displacement Method: M5 Ductility



Metallography of Zry-4 and ZIRLO Oxidized at 1000ºC to CP-Model-Calculated ECR = 20%

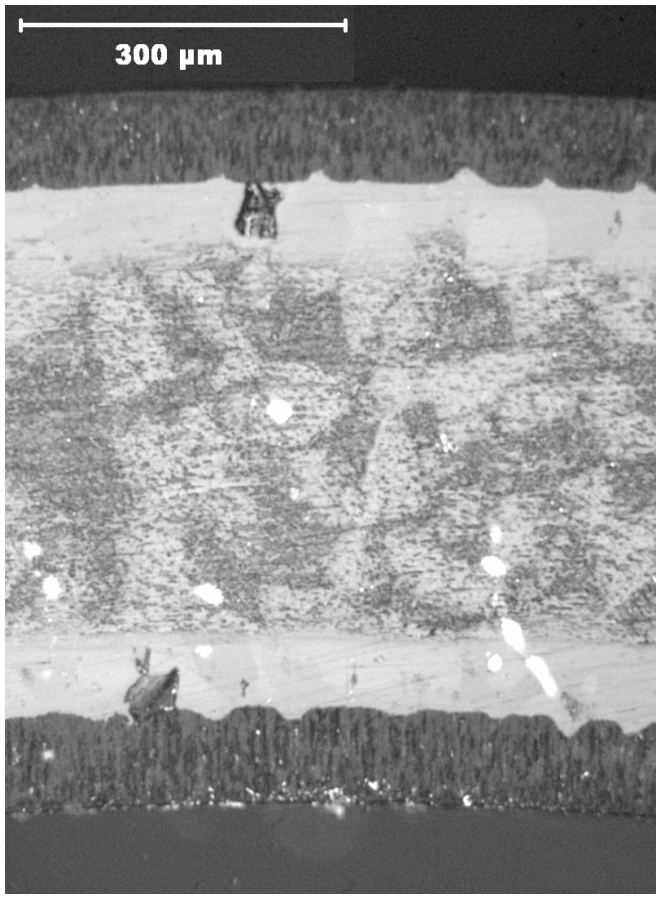


Zry-4



ZIRLO

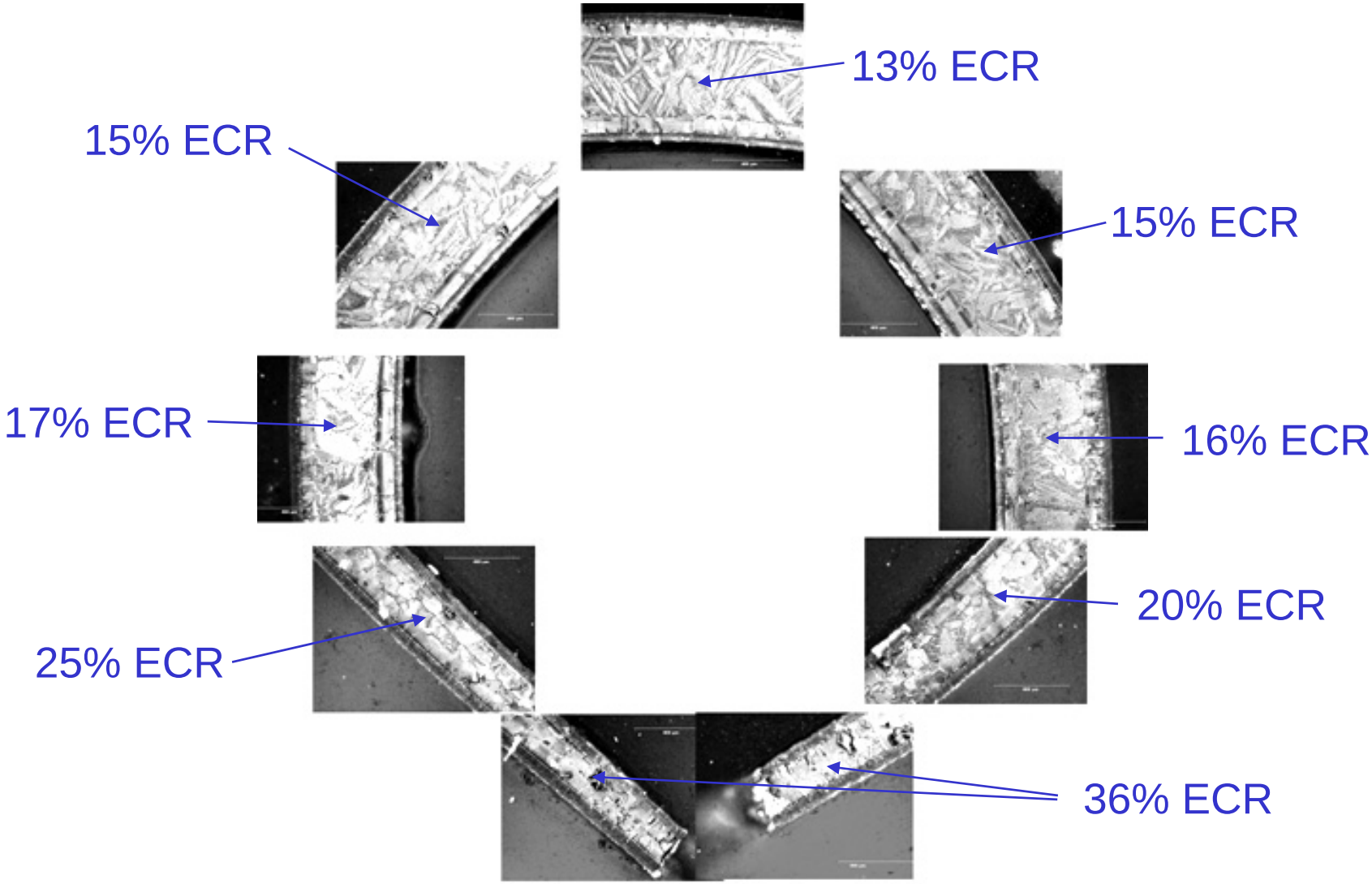
Metallography of Zry-4 and M5 Oxidized at 1000ºC to CP-Model-Calculated ECR = 20%



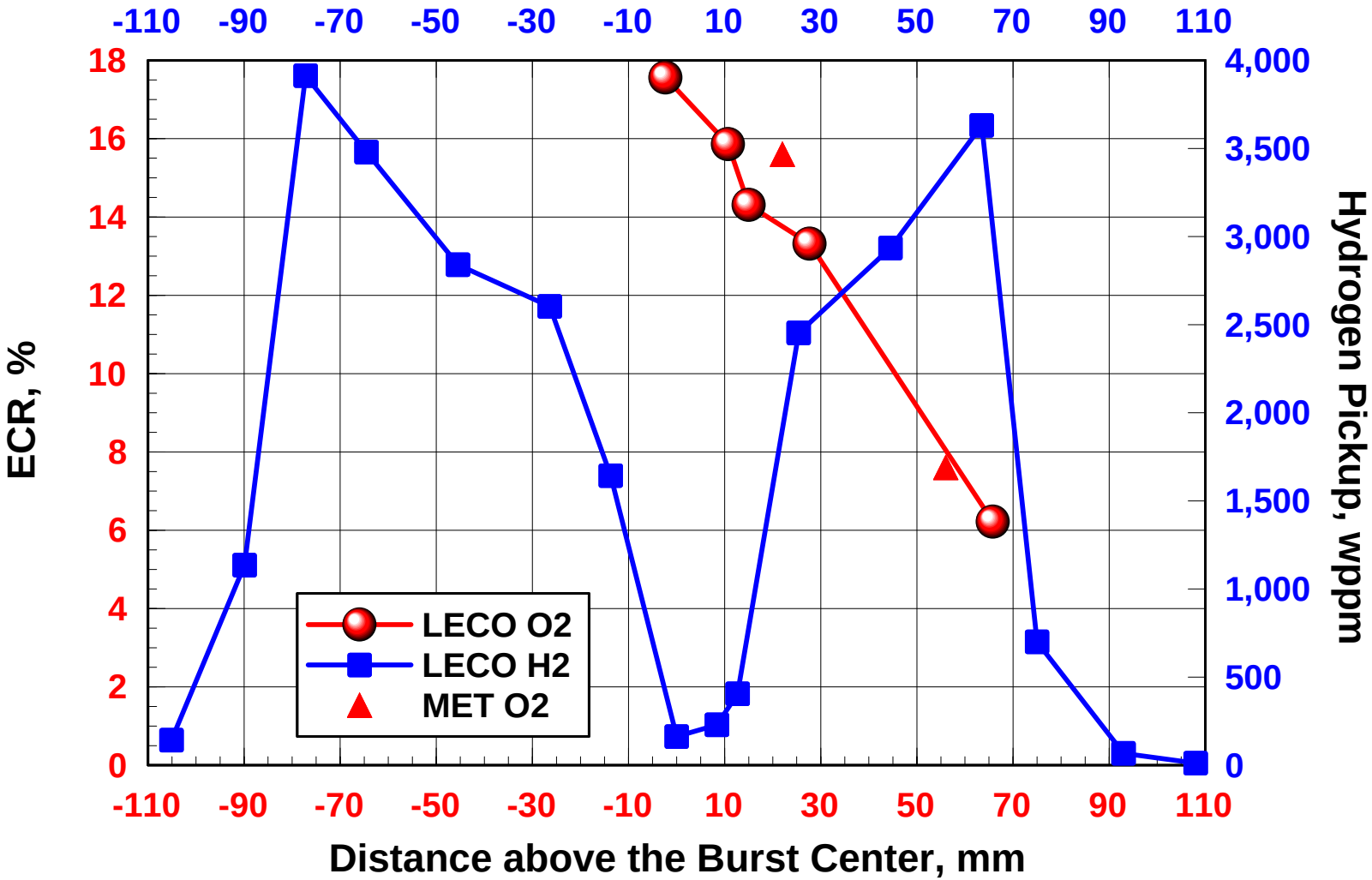
Zry-4

M5

Zry-2 Burst Cross-Section: 1204°C, 18% ECR (OCL#11)



LOCA Integral Test Results for Zry-2: 1200°C for 5 Min.

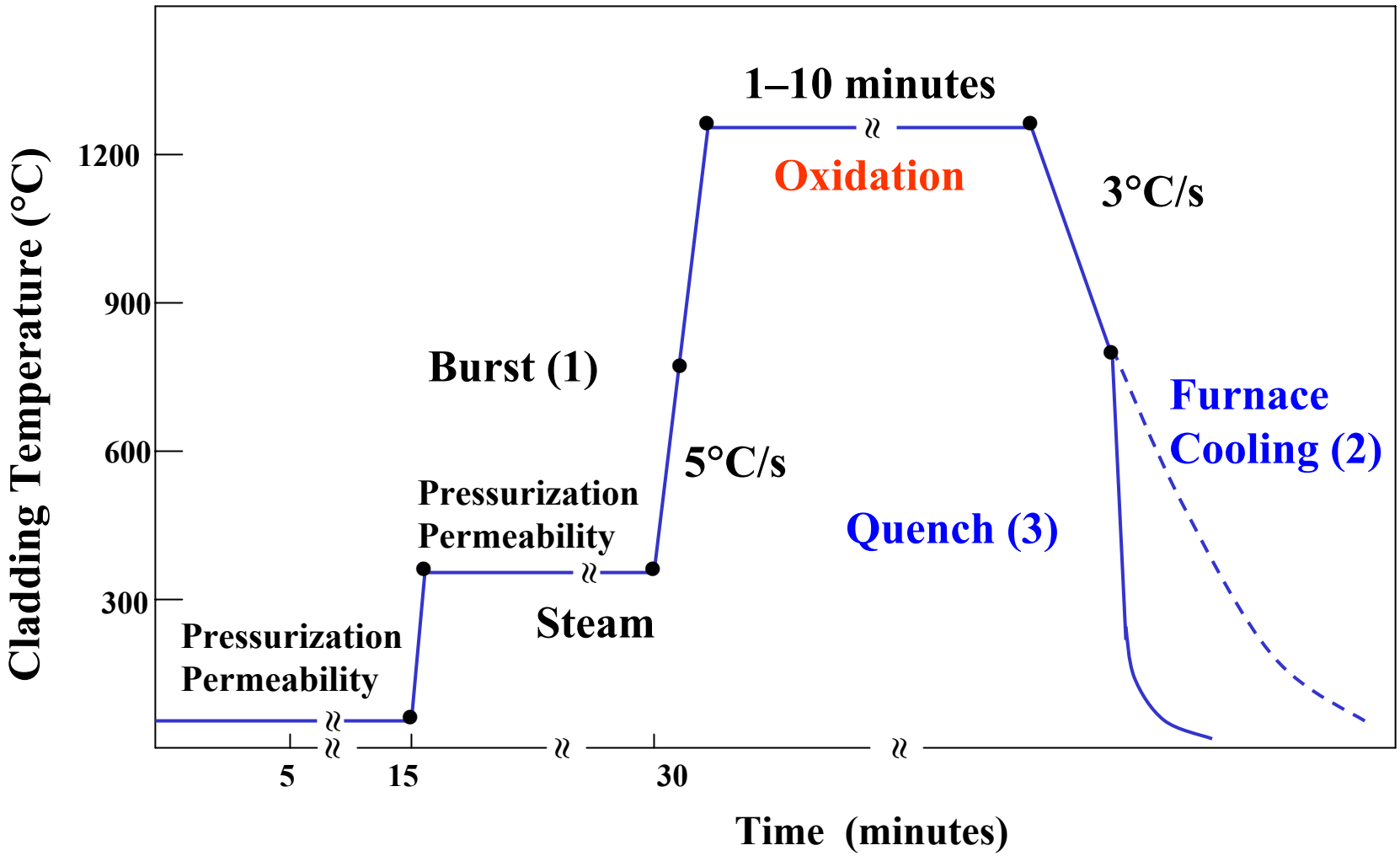


LOCA Integral Test Results for Limerick Zry-2

- **Temperature History**
  - Stabilize at 300°C and 1200 psig (8.3 MPa) internal pressure
  - Ramp at 5°C/s through ballooning & burst to 1204°C
  - Hold for 1-10 minutes, cool to 800°C at 3°C/s and quench
- **Detailed Examinations**
  - Profilometry, metallography, H & O determination (in progress)
  - 4-Point-Bend Tests & Ring-Compression Tests (to be conducted)
- **Post-Quench-Ductility Demonstration Tests with Unirradiated Zry-2 Oxidized to 15-30% ECR at ≈1200°C**
  - Brittle failure of 10-min. sample (30% measured ECR) in burst region at 100°C following quench due to dead weight loading
  - 4-point-bend-test & handling failures for 15-20% ECR specimens

    Brittle failure observed in burst (O-embrittled), balloon (O- and H-embrittled) and neck (H-embrittled) regions

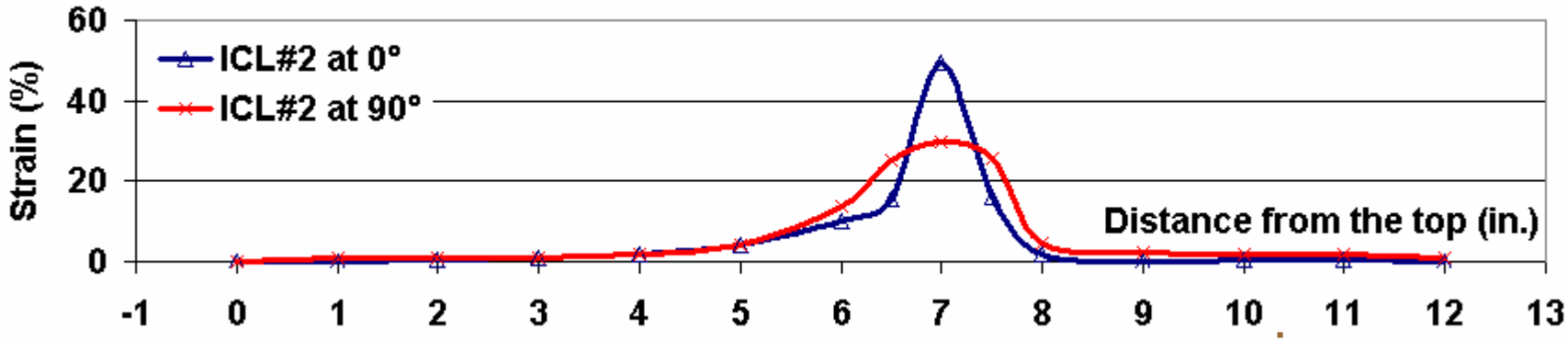
LOCA Integral Test Sequence

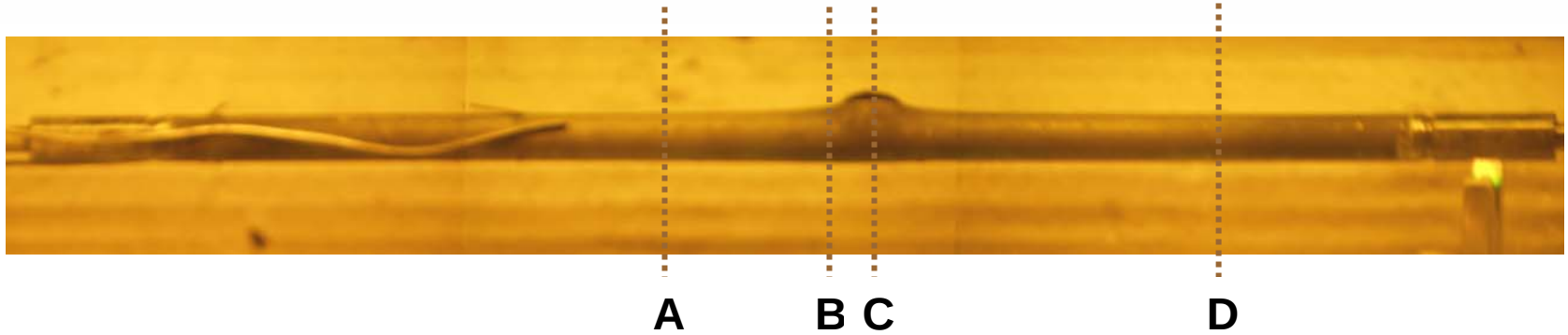


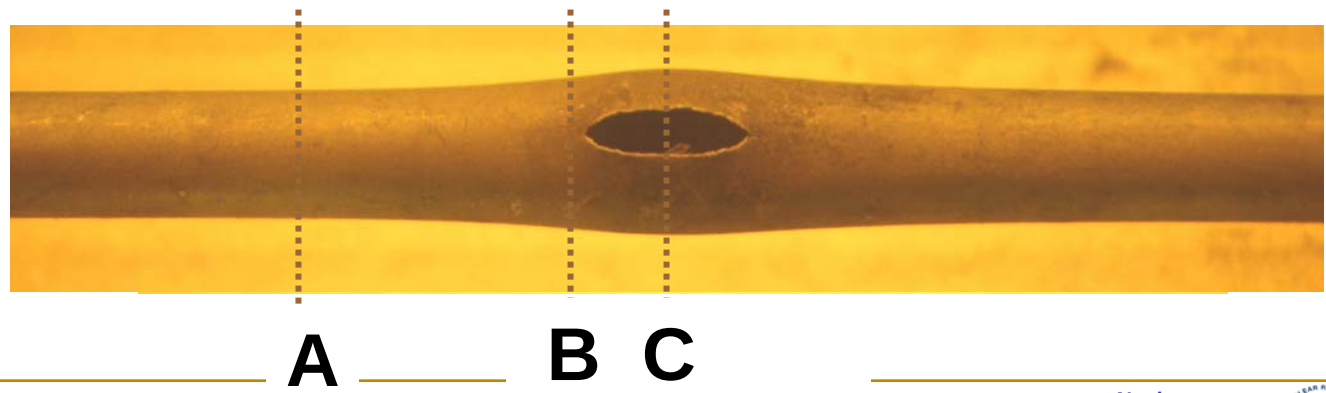
LOCA Integral Tests
High-Burnup BWR Fuel Specimens

- **Ramp-to-Burst Test Conducted in Ar (ICL#1)**
  - T- and P-histories, photos and profilometry reported at NSRC-2002
  - With exception of burst shape (oval) and axial extent of ballooning (shorter), results are similar to those for unirradiated Zry-2
- **LOCA Sequence with 5-minute Oxidation at 1204°C and Slow-Furnace Cooling (ICL#2)**
  - T- and P-histories, photos and profilometry reported at NSRC-2002
  - With exception of burst shape (oval) and axial extent of ballooning (shorter), results are similar to those for unirradiated Zry-2
  - **Additional fuel and cladding characterization has been performed**
- **LOCA Sequence with Quench (ICL#3, Nov. 2003)**
  - Specimens have been prepared
  - Quench system is being added to in-cell apparatus

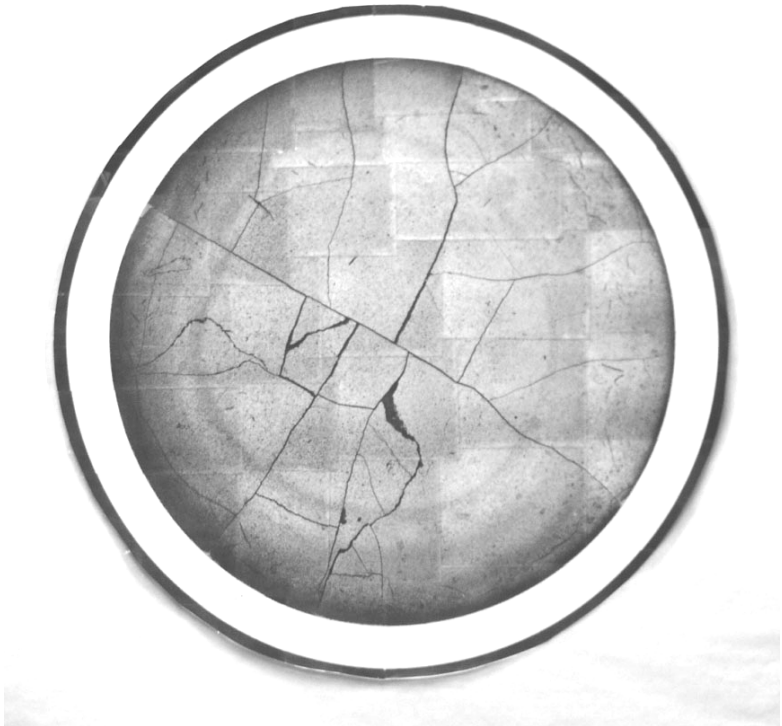
Locations of Metallographic Samples for ICL#2 Specimen



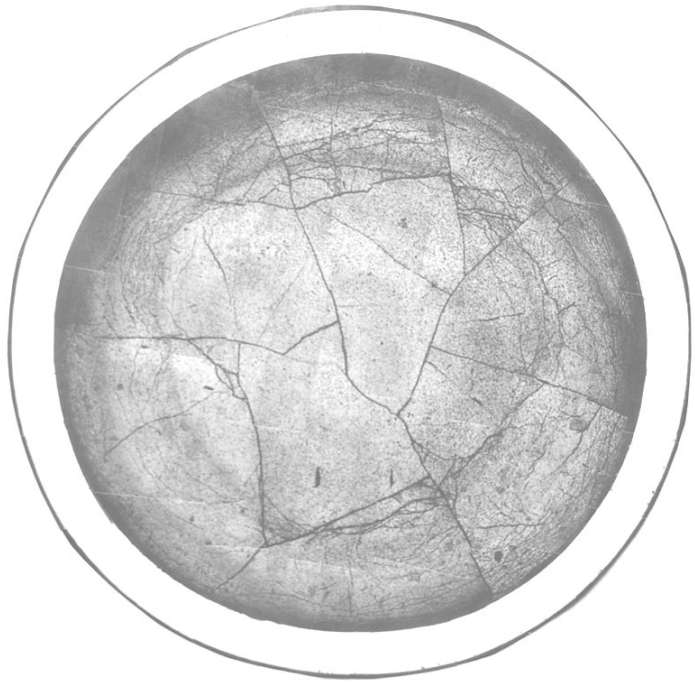




Fuel Metallographic Results for ICL#2 Specimen

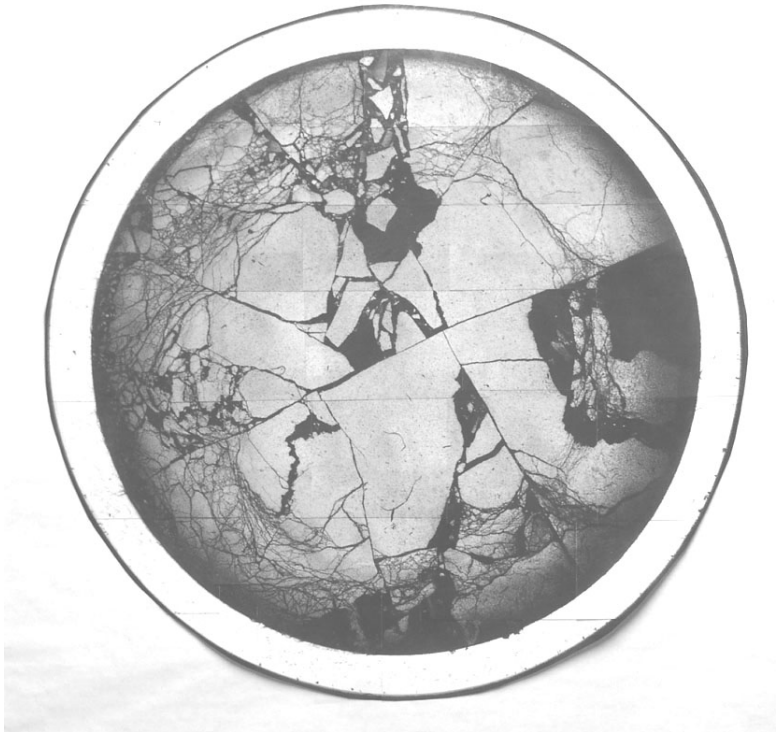


As-received Specimen:
180 mm away from the LOCA sample



Post-test Specimen D:
≈45 mm to the bottom end-cap
Strain: <1%

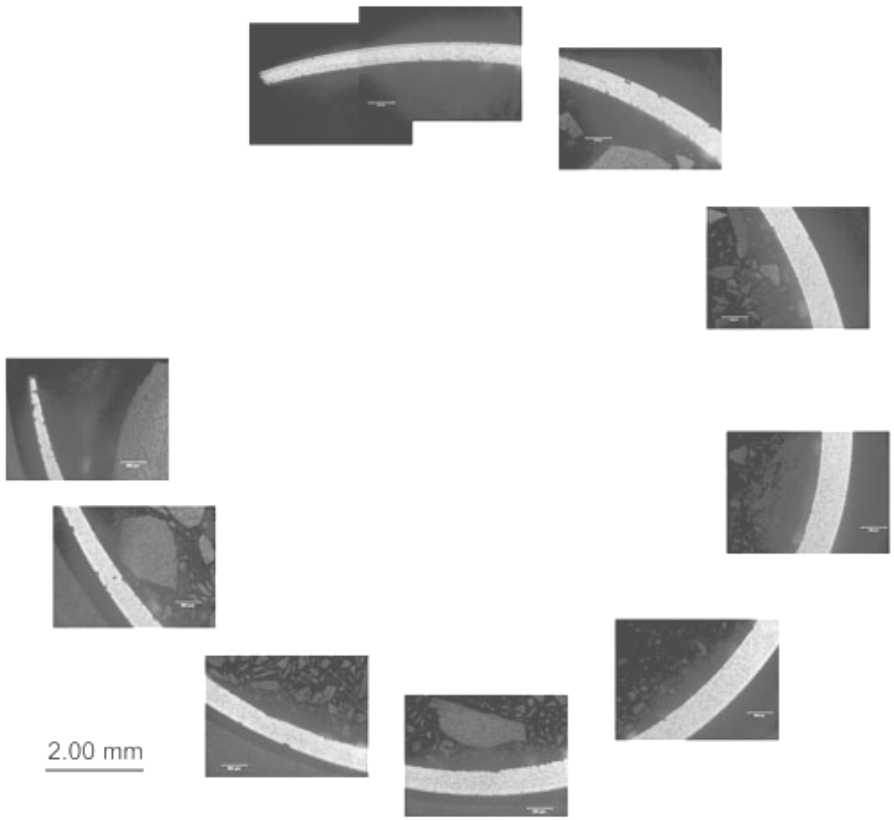
Cladding Metallographic Results for ICL#2 Specimen



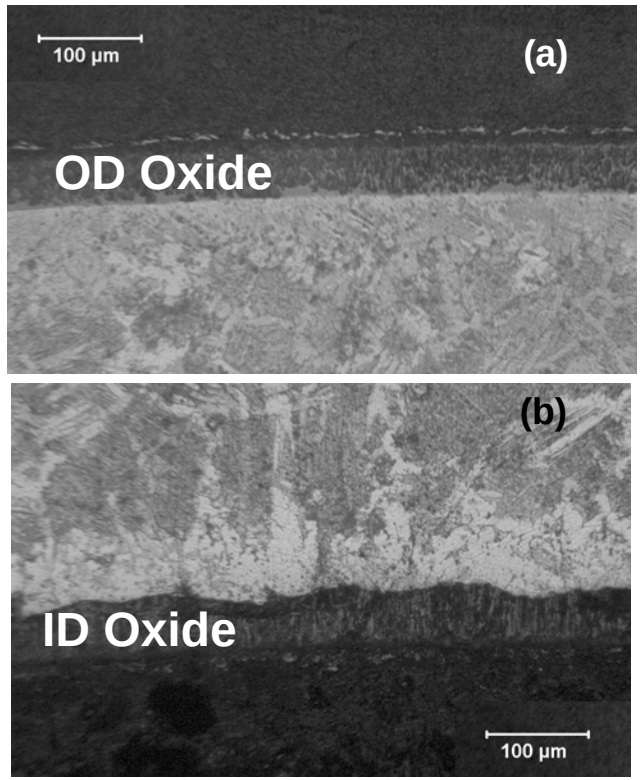
Post-test Specimen A:
≈ 50 mm above the burst mid-plane
Strain: 1% - 2%

Post-test Specimen B:
≈12 mm above the burst mid-plane
Strain: ≈14%

Burst Cross-Section for High-Burnup ICL#2 Test

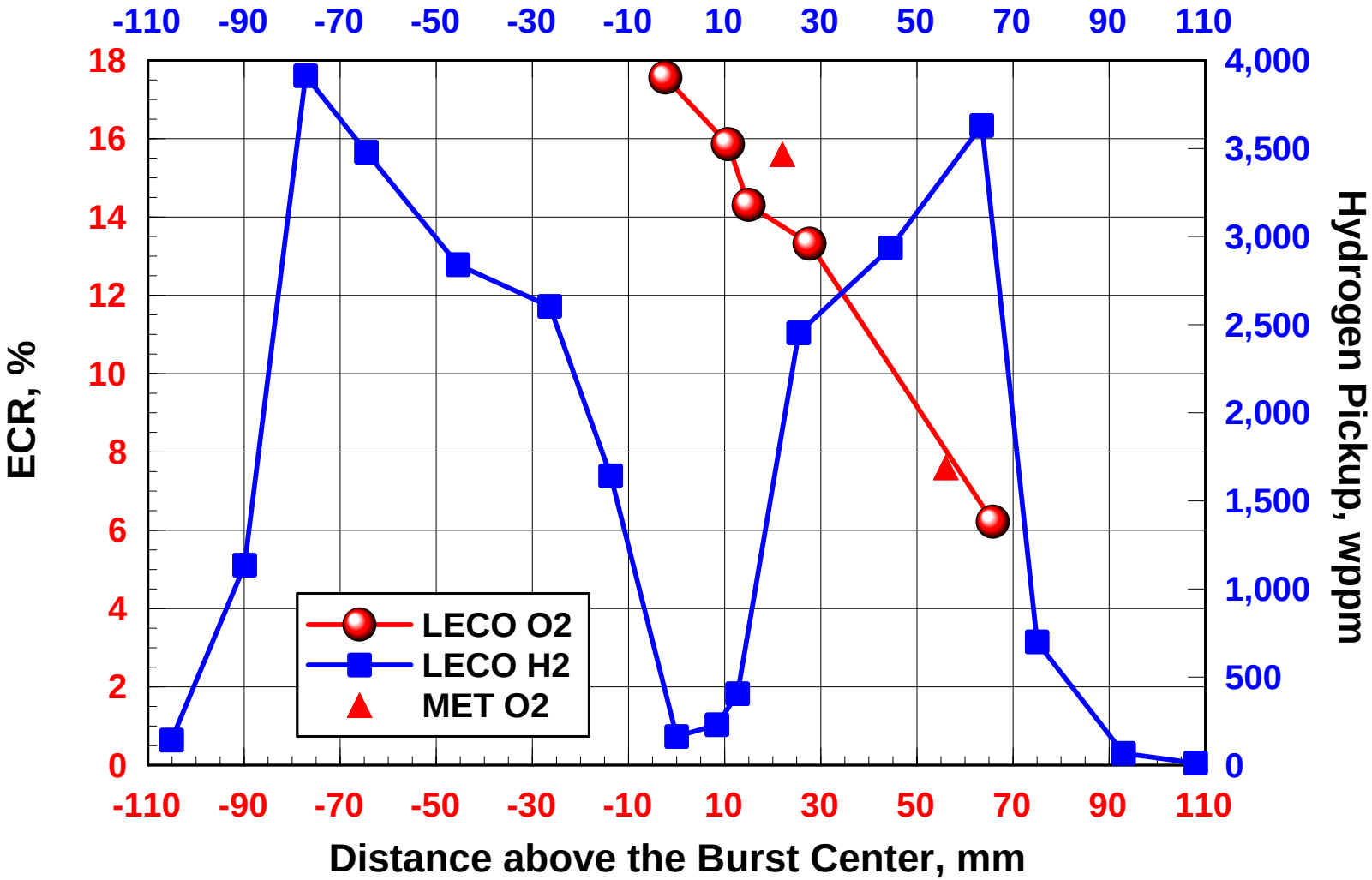


Post-test Specimen C:
Burst mid-plane
Strain: 30% - 50%



High magnification images of (a) outer and (b) inner surfaces of Specimen C.

High-Burnup (ICL#2) vs. Unirradiated (OCL#11) Zry-2



Future LOCA-Relevant Work

- **Advanced-Alloy Post-Quench Ductility**
  - Oxidize-and-quench 1200ºC and 1260ºC samples (Zry-4, ZIRLO, M5)
  - Conduct ring-compression tests; H measurements & met for 20%ECR
  - Conduct LOCA Integral Tests with advanced-alloy cladding samples
  - Perform 4-point-bend tests of post-LOCA-quench specimens
- **In-Cell LOCA Integral Tests with High-Burnup Samples**
  - Conduct Limerick BWR tests (3-5 min. at 1204ºC) with quench
  - Initiate Robinson PWR oxidation and LOCA tests
  - Develop simple in-cell 4-point-bend test benchmarked to out-of-cell Instron tests; perform bend test on fueled post-quench samples
  - Perform ring compression tests on defueled samples from beyond the ballooned region
- **Continue Companion Out-of-cell LOCA Integral Tests**