U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

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SNF Cladding Hydride Reorientation Research

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NWTRB Meeting

Albuquerque, NM

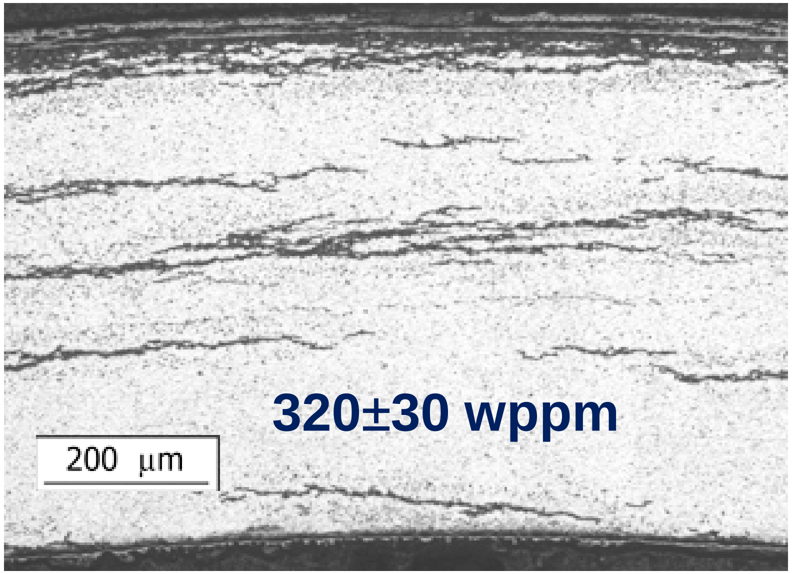
Oct. 24, 2018

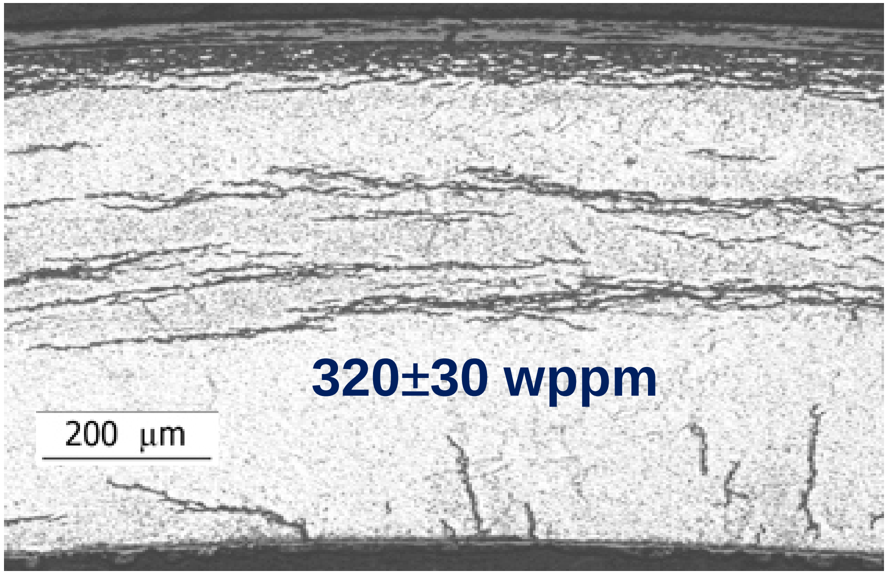
Background on Cladding and Zirconium Hydrides

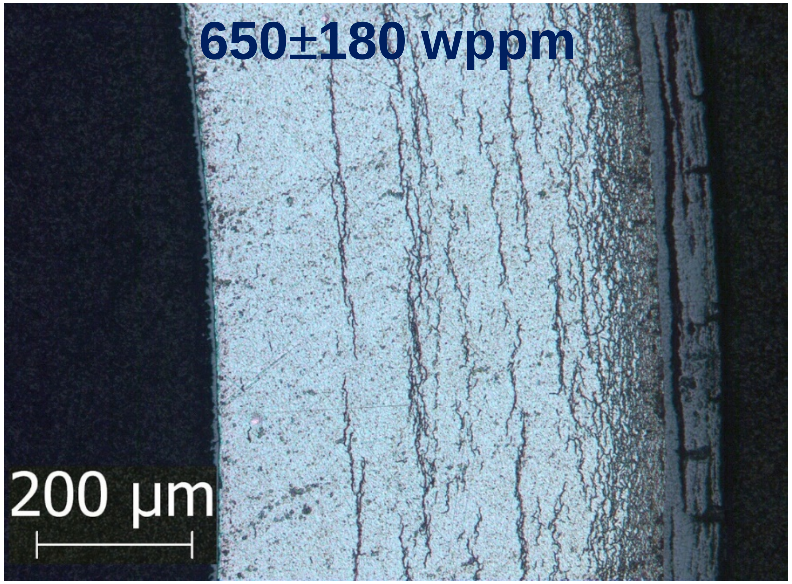
- **PWR Cladding Alloys and Thermal-Mechanical Treatment**
  - Alloys:
    - Zircaloy-4 (Zr-1.5wt.%Sn), Low-Sn Zircaloy-4 (Zr-1.3 wt.%Sn)
    - ZIRLO® (Zr-1wt.%Sn-1wt.%Nb), M5® (Zr-1wt.%Nb)
  - Thermal-mechanical treatment (final heat treatment)
    - Recrystallized-annealed microstructure (600±20°C for 1 to 2 hours)
    - Cold-worked stress-relief-annealed microstructure (e.g., 500°C for 4 hours)

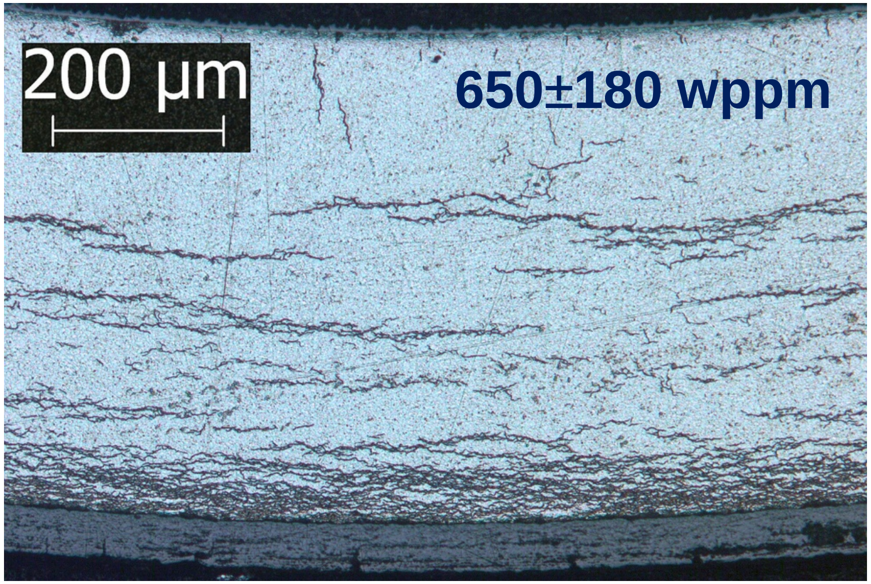
- **Hydrogen Content and Hydride Orientation in As-Irradiated Cladding (e.g., prior to drying and storage)**
  - ZIRLO® with 320 & 650 weight parts per million (wppm) hydrogen (H)
  - Zircaloy-4 with 300 & 640 wppm H
  - M5® with 76 wppm H (peak values for M5® are 100±30 wppm H)

Hydride Orientation in Irradiated ZIRLO® Cladding

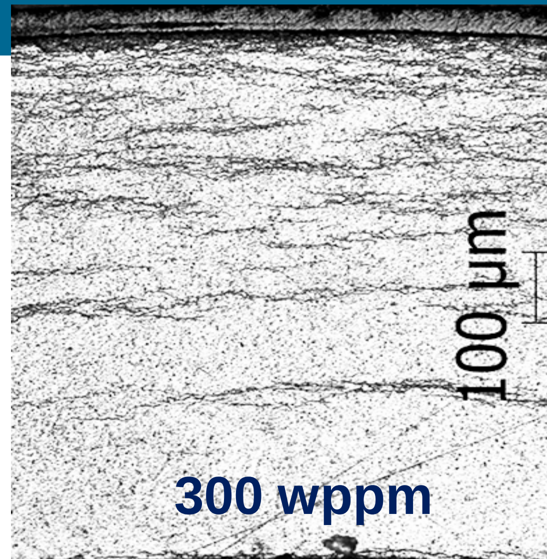


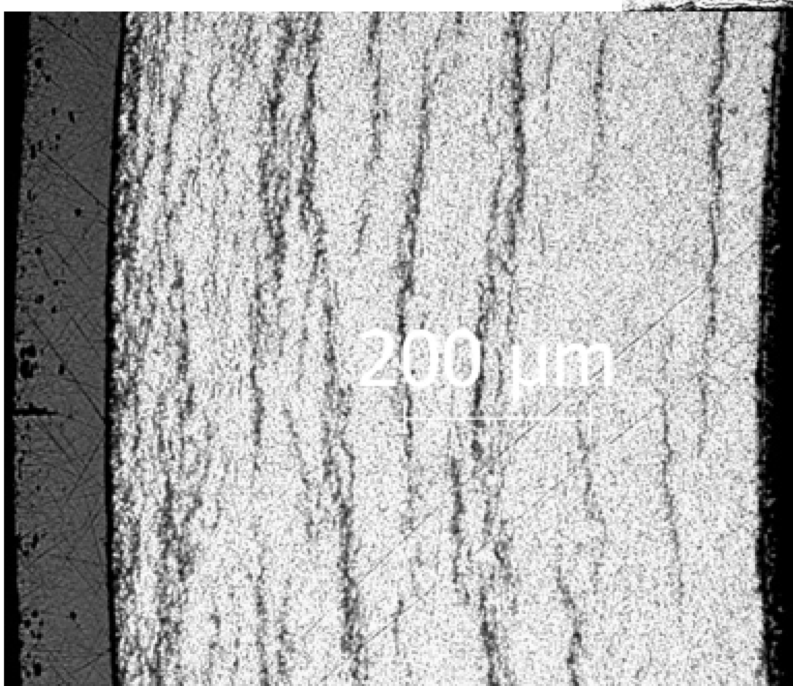




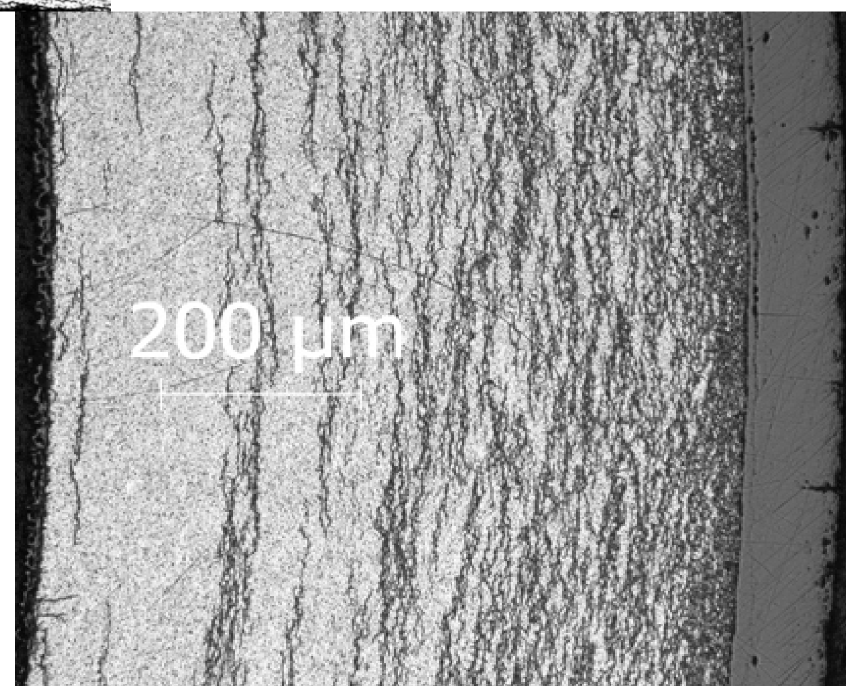


Hydride Orientation in Irradiated Zircaloy-4 Cladding

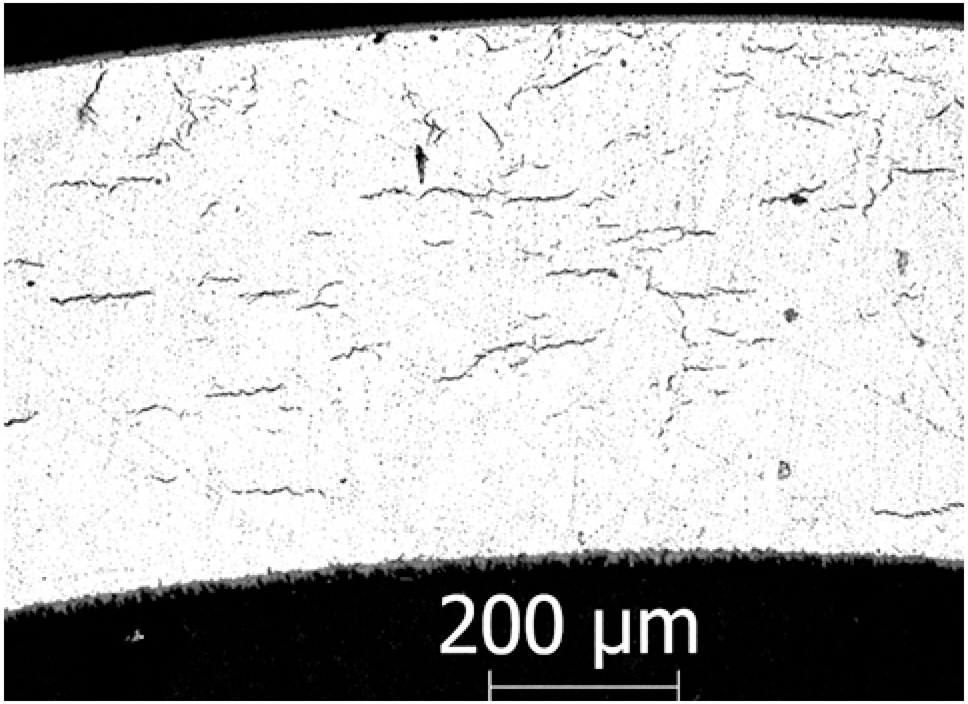


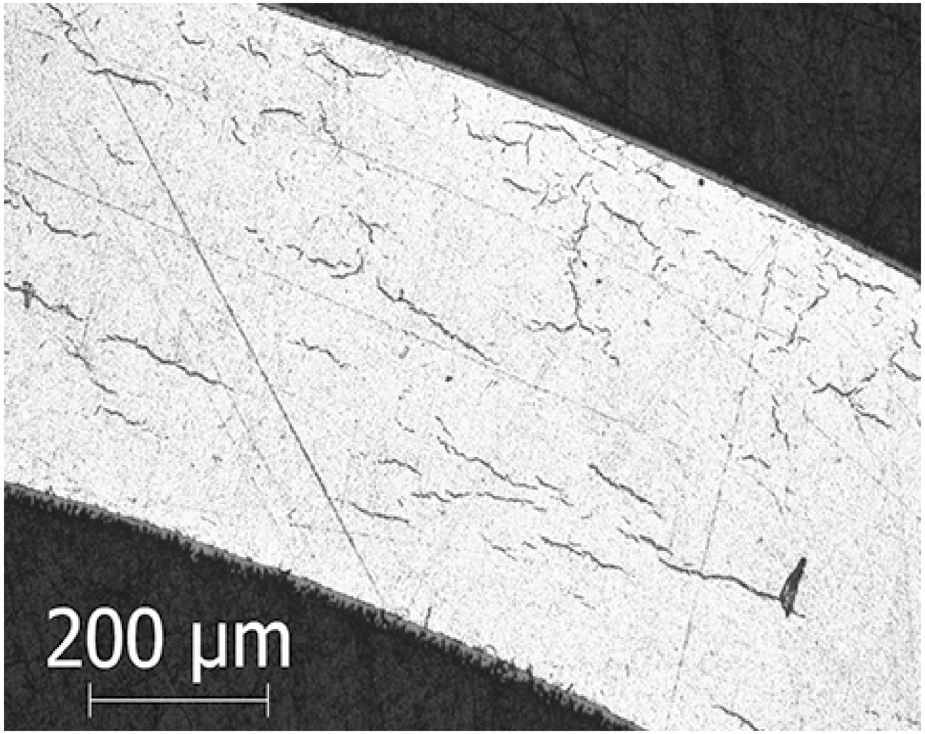


640±140 wppm



Hydride Orientation in Irradiated M5® Cladding





76±5 wppm

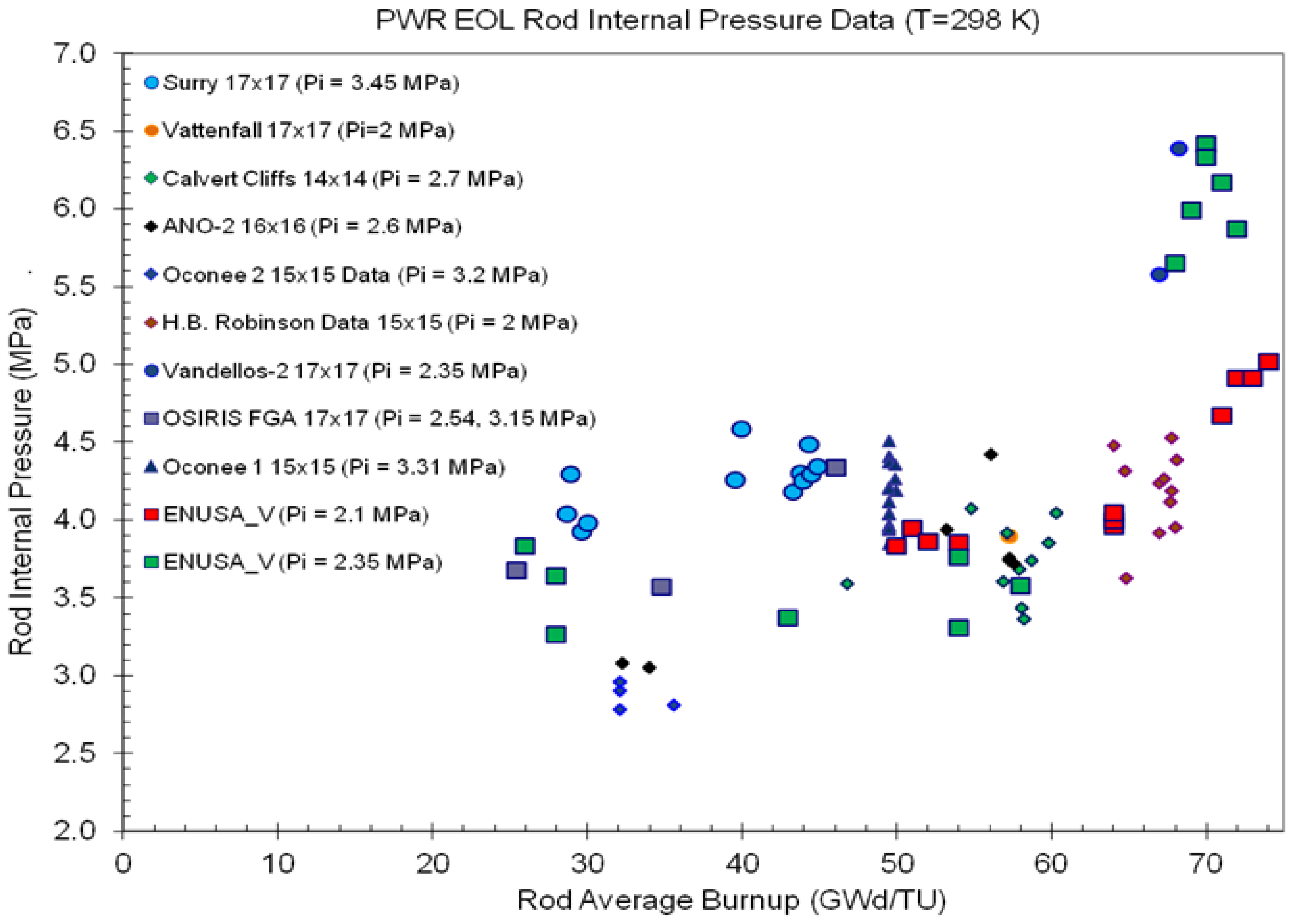
Objectives of Phase 1 Sister Rod Testing

- **Characterization and Material Properties**
  - Generate data that can be compared to 10-year stored PWR fuel rods: baseline data for as-irradiated fuel rods
  - Determine end-of-life rod internal pressures (limited public database), mechanical properties of M5® (published data are inadequate) and mechanical properties of ZIRLO® (limited public database)
- **Is Radial-Hydride-Induced Embrittlement an Issue?**
  - Use measured rod-internal pressures (P_i) at 25°C
  - Heat treat @ 400°C [≤200 wppm H in solution; $2.26 \times P_i(25^{o}C)$]
  - Peak cladding hoop stresses @ 400°C: reasonable upper bound for standard PWR stored rods (average gas temperature is <400°C)
  - Cool at ≤5°C/h with decreasing pressure/hoop-stress
  - Perform ring compression tests to determine ductility and ductility transition temperature (DTT)

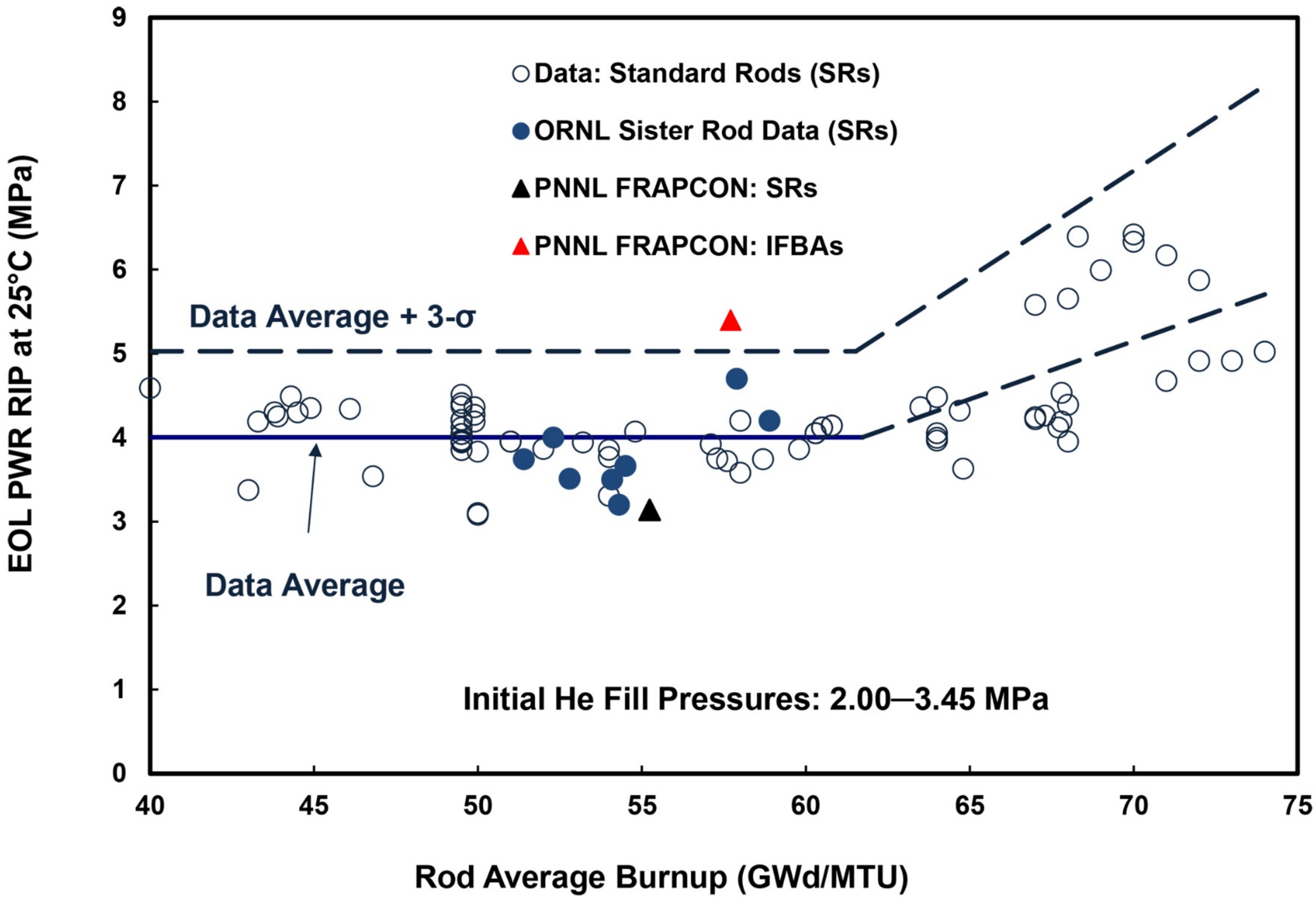
Potential for Hydride Reorientation

- **Radial-Hydride-Induced Degradation**
  - DEMO Cask fuel rods
    - Peak cladding temperature (PCT) <250^{o}C; <44 wppm H in solution
    - Internal gas pressure <9 MPa; peak hoop stress <68 MPa
    - May observe short radial hydrides, but these would not decrease ductility
  - Sister Rods
    - PCT = 400^{o}C; ≤200 wppm H; pressure <11.3 MPa; hoop stress <87 MPa
    - Expect ZIRLO® & Zry-4 radial hydrides <20% of cladding wall; DTT <50^{o}C
    - Expect longer radial hydrides in M5®; DTT <75^{o}C
- **Anticipated Range of Peak Cladding Hoop Stresses**
  - FRAPCON predictions for 400^{o}C PCT and temperature profile
    - <54 MPa for standard PWR rods; <89 MPa for IFBA rods with internal B-10
  - Predictions based on end-of-life (EOL) rod internal pressure (RIP) data

EPRI Data for EOL RIP



EOL RIP EPRI & Sister Rod Data



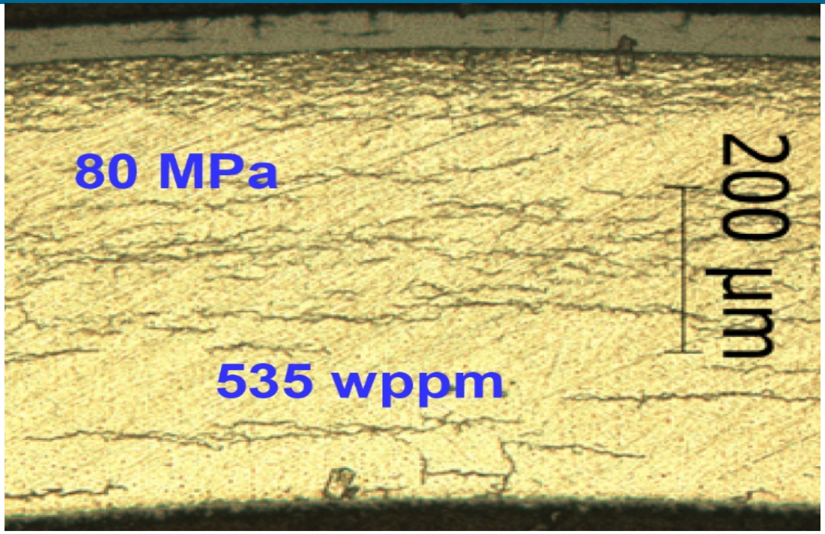
Relationship between Hoop Stress and Pressure

- **Definition of Parameters**
  - P_i = internal rod pressure, P_o = external rod pressure (0.0−0.7 MPa)
  - R_{mi} = cladding inner radius, h_{mi} = cladding wall thickness
- **Average Hoop Stress (σ_θ) Across Cladding Wall**
  - $\sigma_\theta = (R_{mi}/h_{mi})\,(P_i - P_o) - P_o$
- **Changes in Parameters with Burnup (BU)**
  - P_i increases with BU due to free volume decrease & He release (IFBA)
  - R_{mi} decreases with BU up to ≈40 GWd/MTU then increases
  - h_{mi} decreases with BU due to coolant-side oxidation
  - R_{mi}/h_{mi} = 7.3 → 7.7 (60-μm oxide layer) → 8.3 (100−μm oxide layer)
    - Initial values for 17 × 17 array: 4.18-mm inner radius, 0.57-mm wall

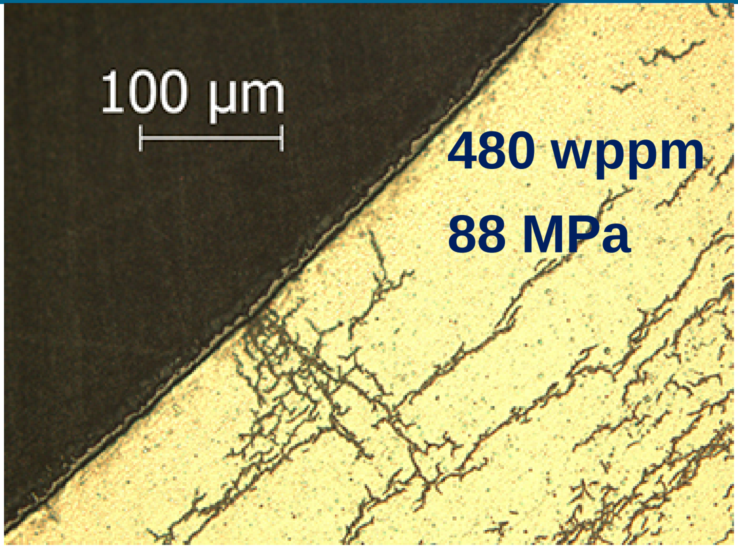
Review of Hydride-Induced Ductility Degradation

- **As-Irradiated Cladding**
  - Hydrides are primarily oriented in circumferential direction
  - Distribution of circumferential hydrides across cladding wall has a significant effect on ductility & radial-hydride precipitation
  - Short isolated radial hydrides have been observed in cladding (ZIRLO® and M5®) from PWR fuel rods irradiated to high burnup
- **Conditions for *Significant* Radial Hydride Precipitation**
  - High enough (>60 wppm) hydrogen content and peak cladding temperature (PCT >285°C)
  - High enough (>10 MPa) internal pressure at PCT
  - High enough (>80 MPa: ZIRLO® and Zry-4) hoop stress @ PCT
  - Cladding microstructure (RXA more susceptible than CW-SRA)
  - Distribution of circumferential hydrides @ PCT
- **ANL Results for 400°C & 350°C PCT**

Radial Hydrides in ZIRLO® for 400°C PCT

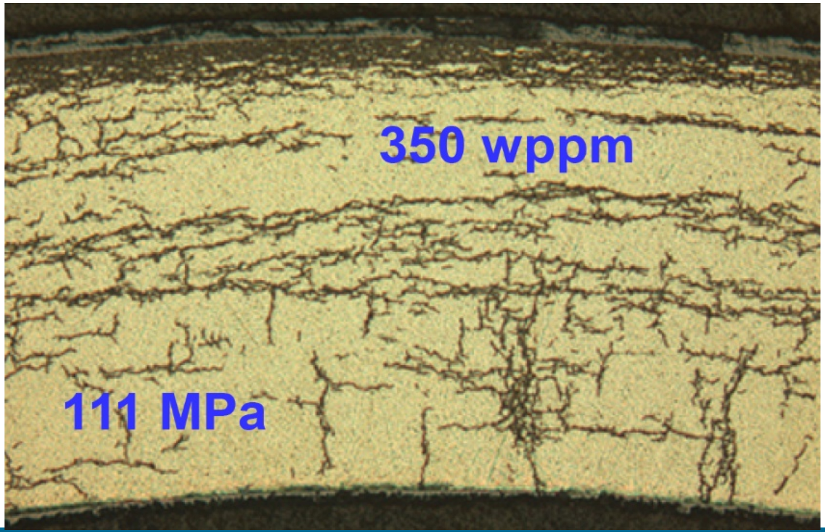


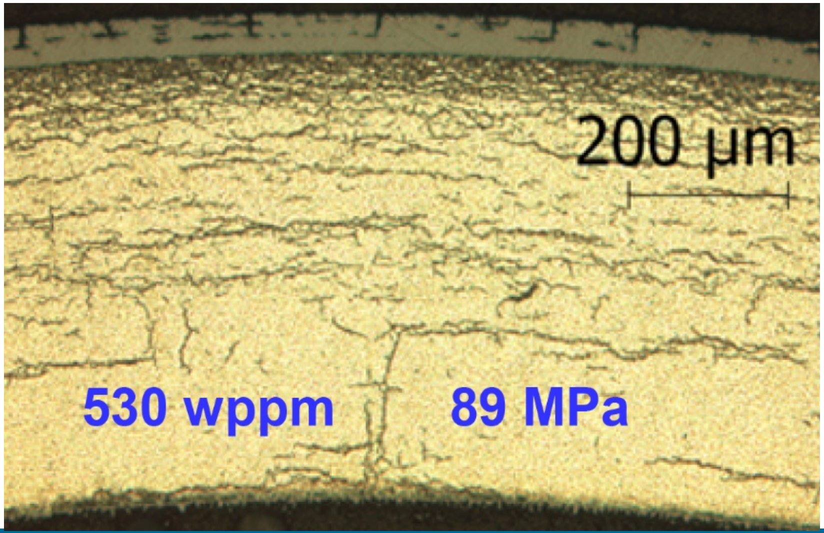
<20°C DTT **9±4% RHCF**



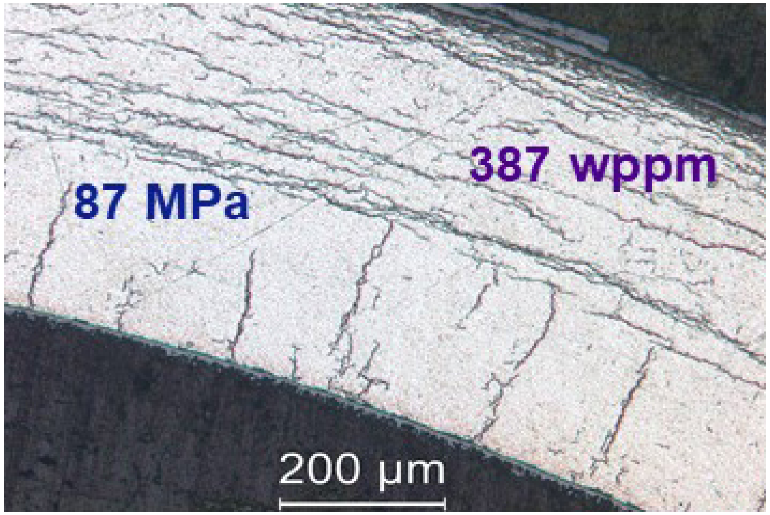
20°C DTT **20±10% RHCF**

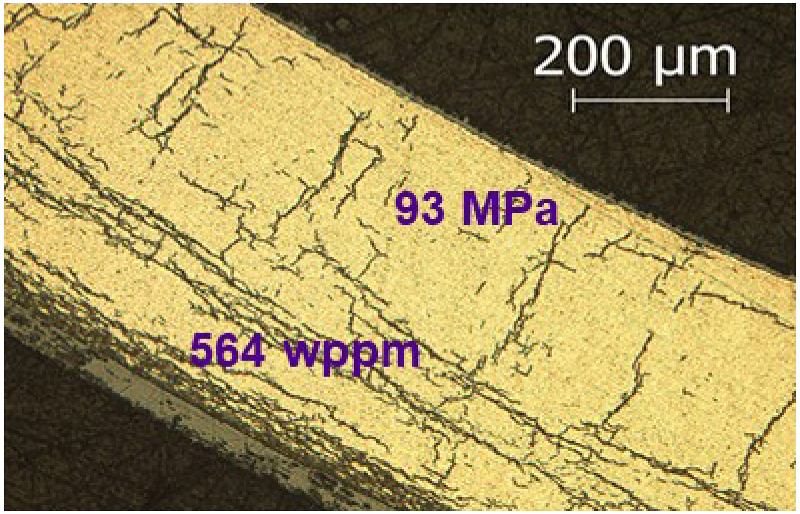
120°C DTT **32±13% RHCF**



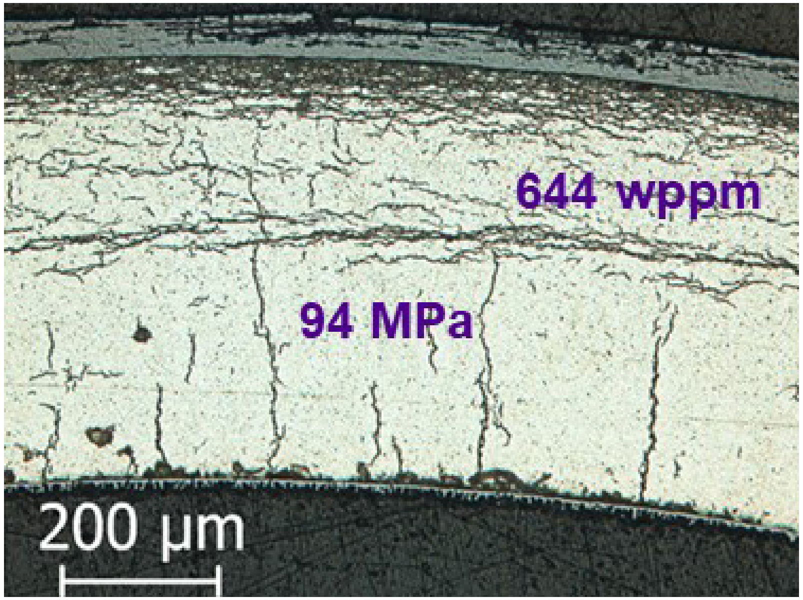


Radial Hydrides in ZIRLO® for 350°C PCT





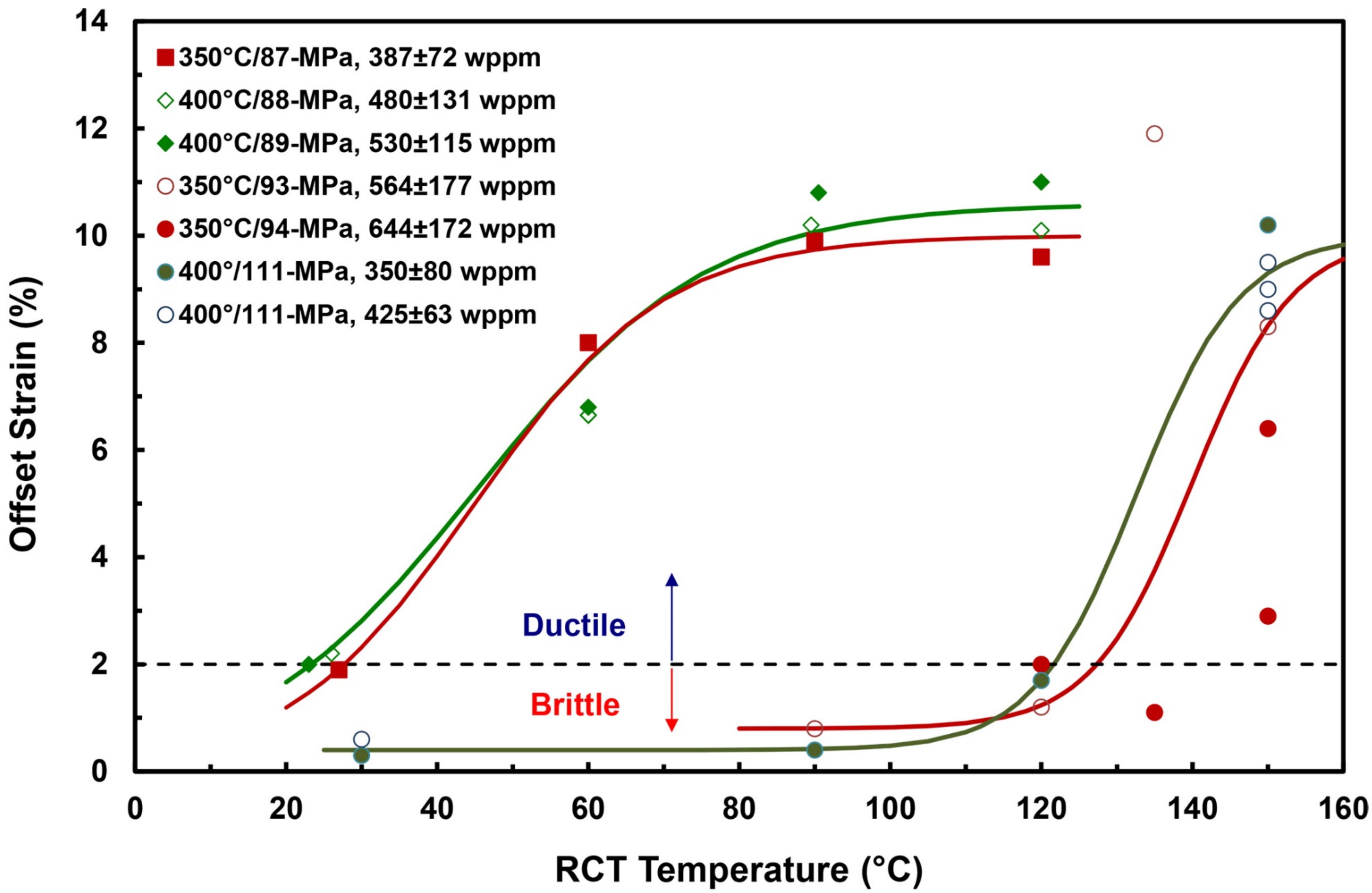
28°C DTT
20±10% RHCF



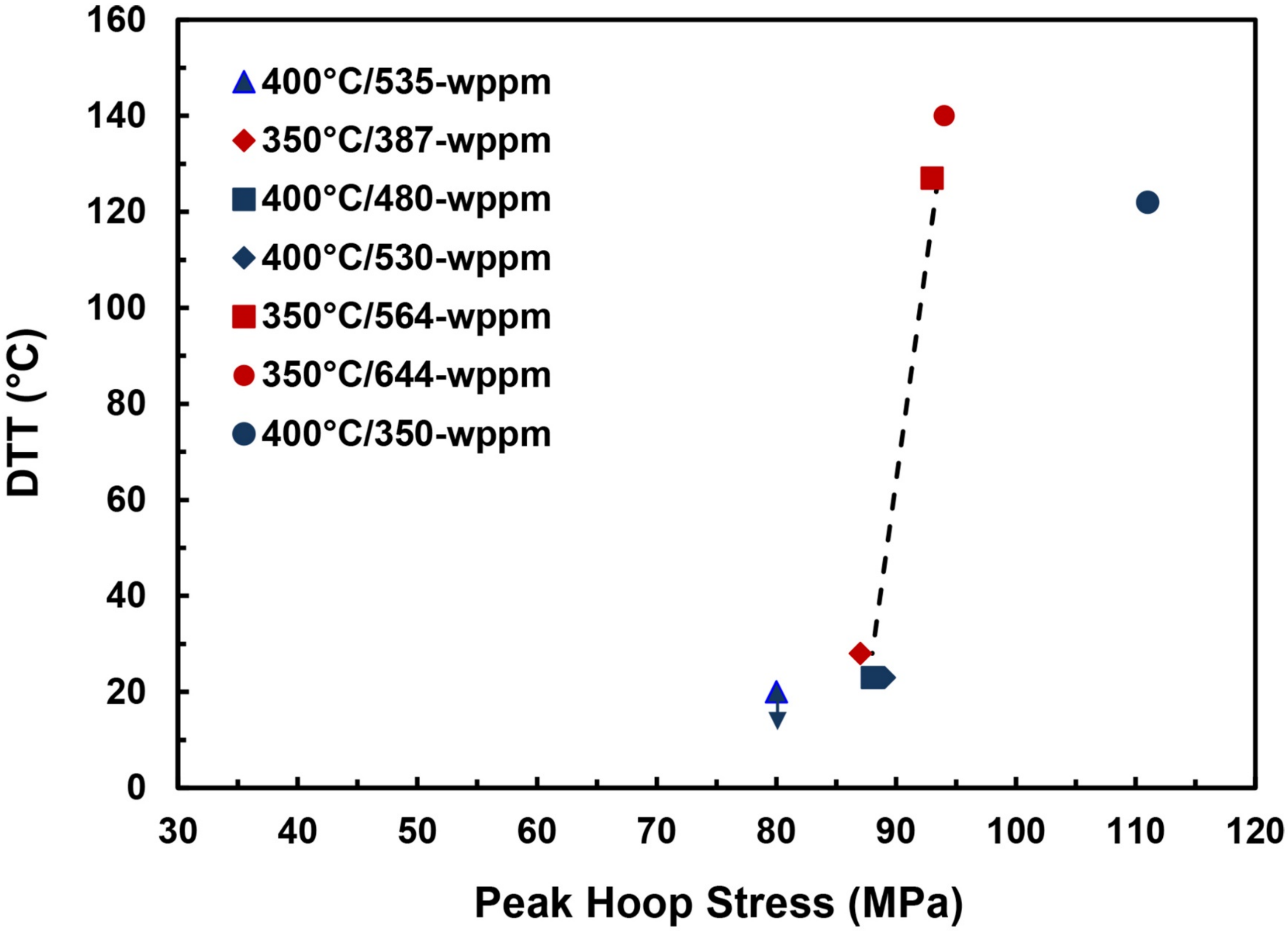
≈125°C DTT
30±11% RHCF

≈140°C DTT
37±11% RHCF

Ductility (Offset Strain) for ZIRLO® vs. Test Temperature – DTT Determination



Sensitivity of Irradiated ZIRLO® to Peak Cladding Hoop Stress



Future Hydride-Reorientation Testing

- **ANL Cladding at 350^{o}C PCT**
  - Critical stress for ZIRLO® appears to be 90±3 MPa
  - ZIRLO®: test 350-wppm-H/93-MPa, 650-wppm-H/87-MPa
  - ANL cladding is from lead-test-assembly rods at >62 GWd/MTU
- **Sister Rod Cladding at 400^{o}C PCT**
  - More prototypic linear power histories per fuel cycle (18 months)
  - Wider range of hydride distributions through cladding wall
  - More cladding samples available
    - Allows for repeat tests and intermediate-temperature tests
    - Allows for load-interrupt tests to better determine cladding ductility
    - Offers the possibility of M5® with >100 wppm hydrogen
- **M5®, Ring Compression Tests, Offset Strains, etc.**
  - Possible discussion items

Acknowledgement

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Questions?

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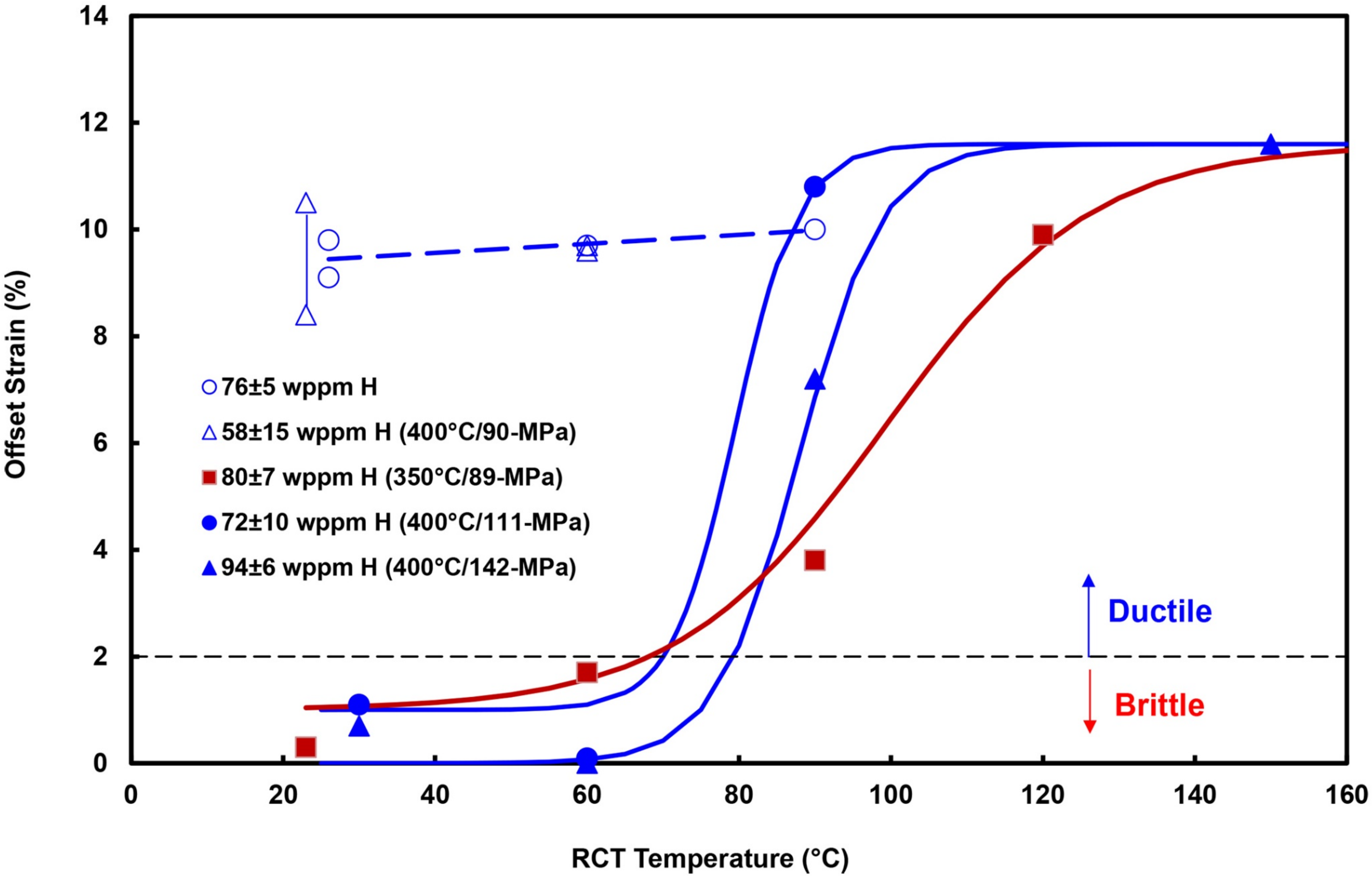
Discussion

- **Results for Irradiated M5® Cladding**
  - Conditions and results for high ductility with <20^{o}C DTT
    - As-irradiated with 76±5 wppm H
    - 58±15 wppm, 400^{o}C/90-MPa, 37±17% RHCF
  - Conditions for ductility transition at 75±5^{o}C
    - 80±7 wppm, 350^{o}C/89-MPa, 44±18% RHCF
    - 72±10 wppm, 400^{o}C/111-MPa, 54±20% RHCF
    - 94±6 wppm, 400^{o}C/142-MPa, 61±18% RHCF
- **Observations**
  - For <100-wppm H, axial continuity of radial hydrides is limited
  - No ductility degradation observed for <60 wppm H
  - Need to test M5® cladding with 100−130 wppm H

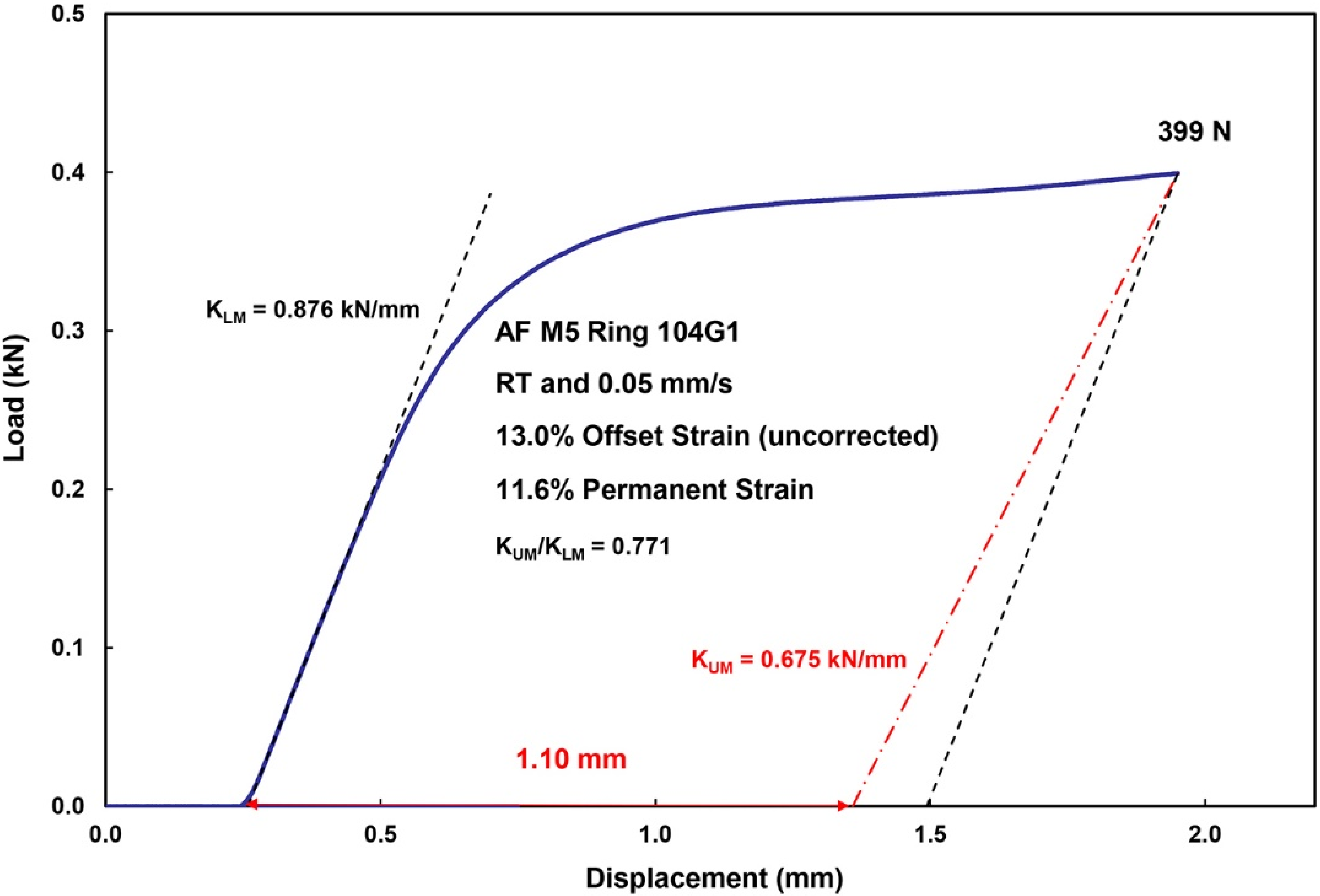
Ductility Data and DTT for Irradiated M5®



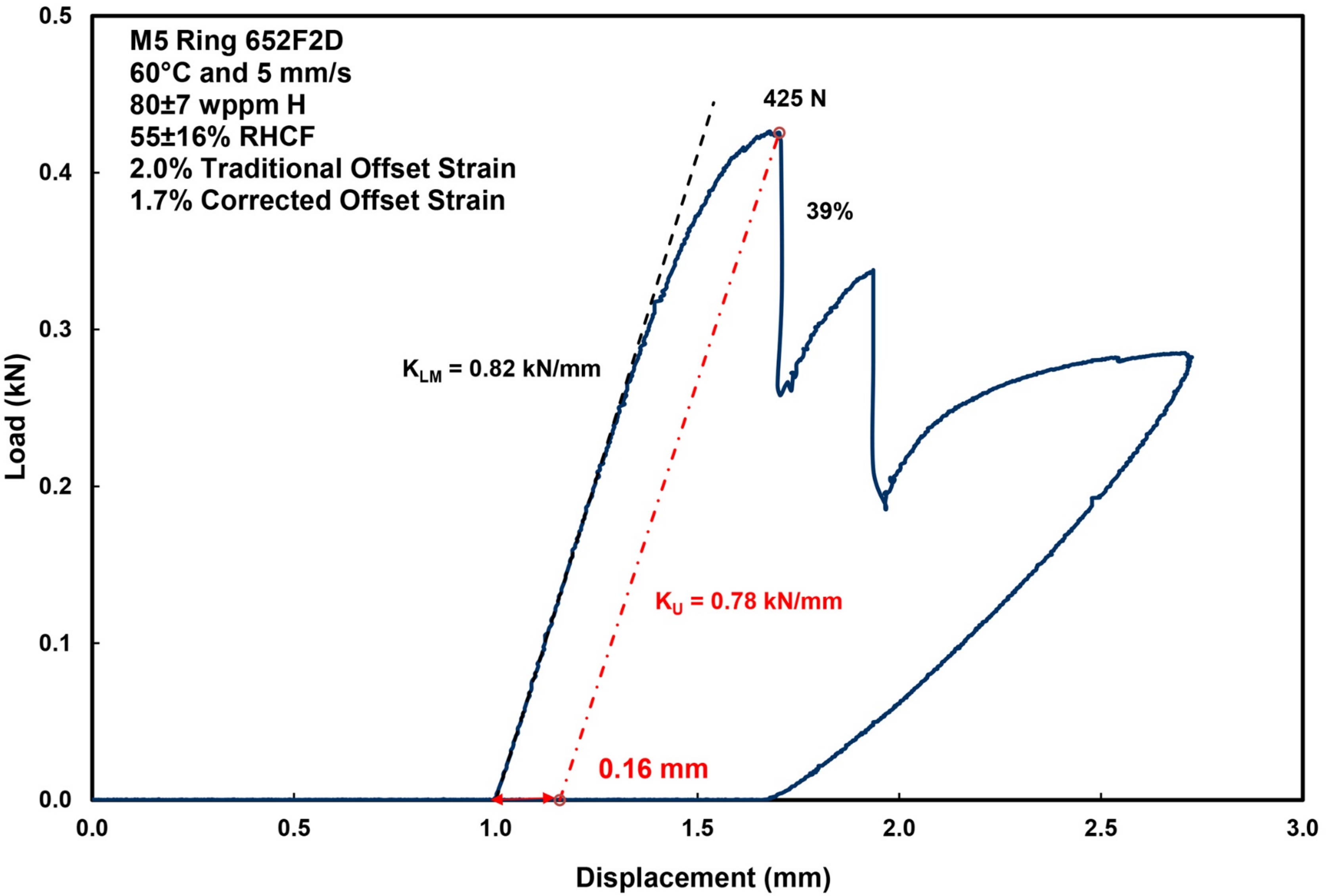
Ring Compression Tests

- **Ring Compression Tests (RCTs)**
  - Reference parameters
    - 5-mm/s displacement rate and 1.7-mm maximum displacement
    - Test temperatures: within 20^{o}C to 200^{o}C
  - Load-interrupt tests to measure permanent displacement and determine correlation between load drop and extent of cracking
    - 0.05-mm/s, stop test after significant load drop (20% to 30%)
  - Data
    - Permanent displacement: pre-test minus post-test diameter in loading direction for intact samples
    - Load-displacement curves: offset displacement, max. load, etc.
    - Normalize permanent and offset displacements to cladding outer diameter as a metric for structure “strains” (not material strain)
  - ASTM guidance document in progress

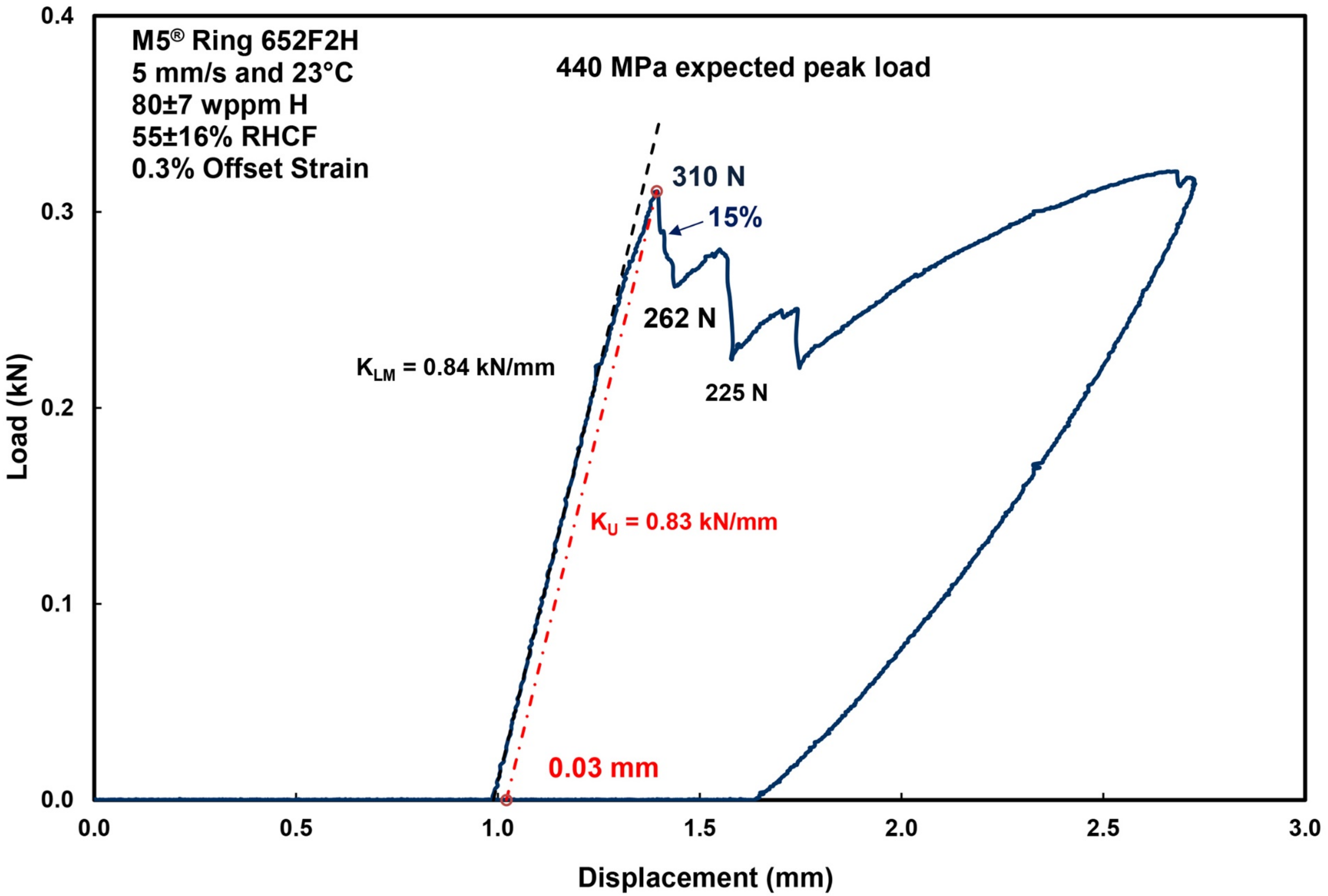
Load-Displacement Curve for As-Fabricated M5® Benchmark Test: 25°C and 0.05 mm/s



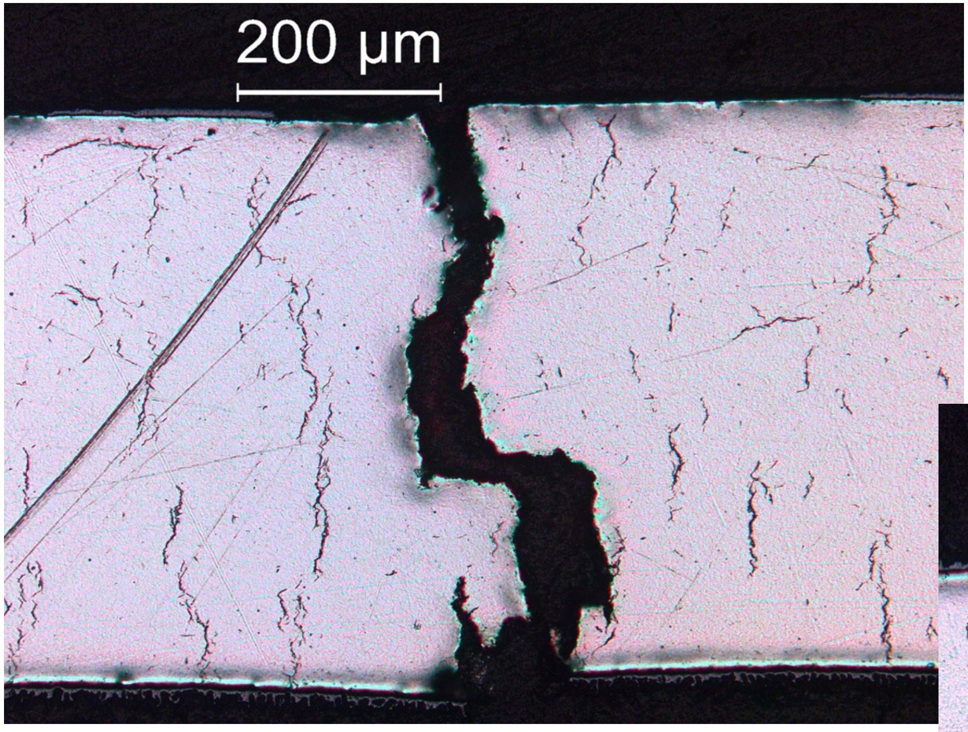
Load-Displacement Curve for Irradiated M5® Test after Cooling from 350°C/89-MPa: 60°C & 5 mm/s



Load-Displacement Curve for Irradiated M5® Test after Cooling from 350°C/89-MPa: 23°C & 5 mm/s

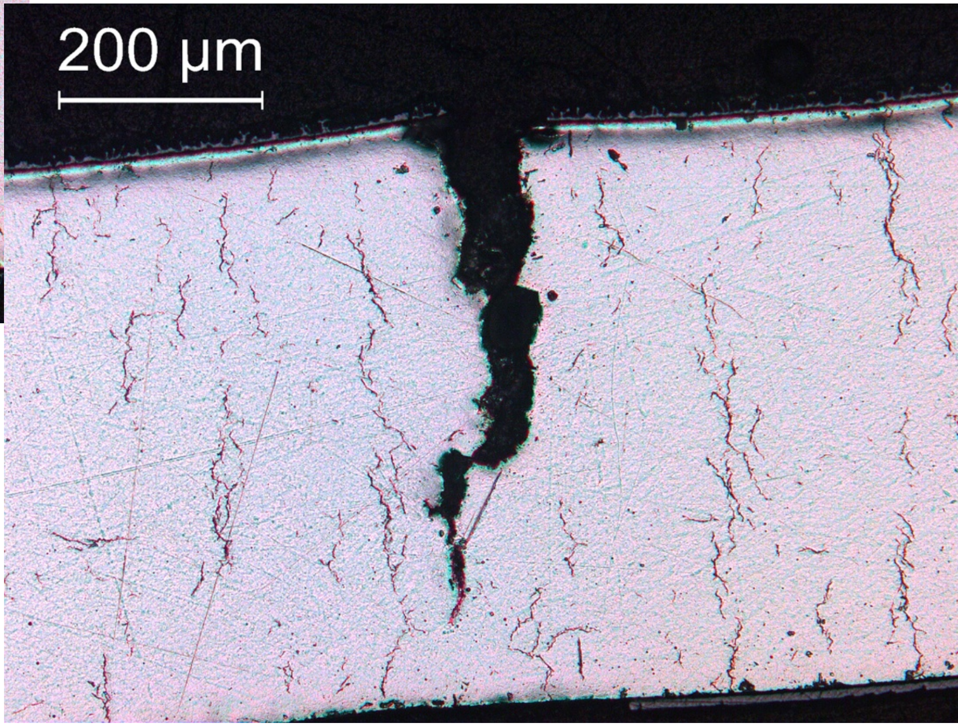


Cracks in Irradiated M5® after Ring Compression Test at 23°C & 5 mm/s to 1.7-mm Displacement



12 o'clock position

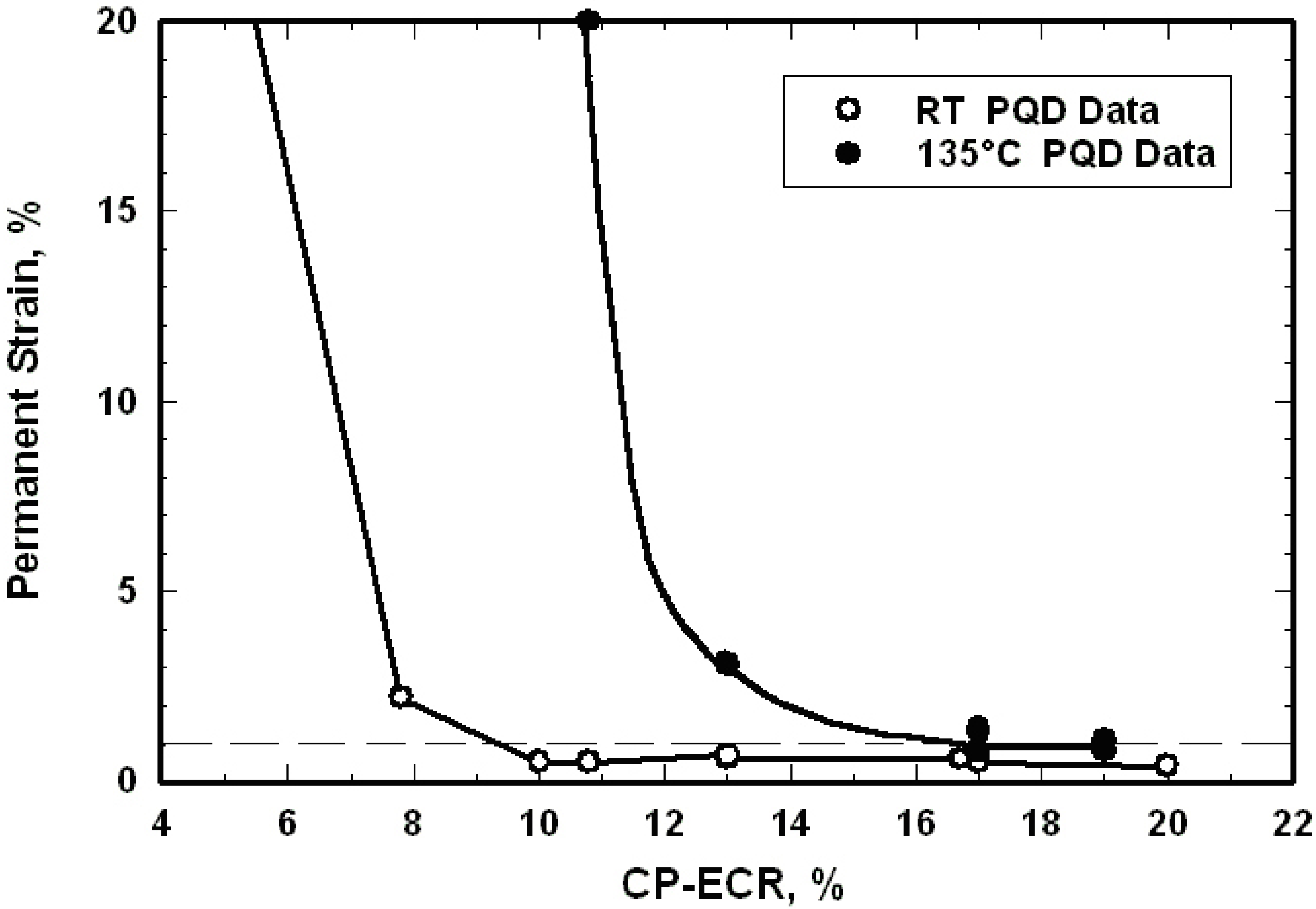
6 o'clock position



2% Offset Strain Ductility Criterion

- **Permanent Strain ≥1% Implies Ductility**
  - Observation for Loss of Coolant Accident (LOCA) studies
    - Permanent strain fluctuates in the range of $0.5 \pm 0.4\%$ as cladding becomes more and more brittle due to increased oxygen pickup
  - Many other factors considered in criterion
- **Offset Strain ≥2% Implies Ductility**
  - Observation for Loss of Coolant Accident (LOCA) studies
    - Offset strain always less than permanent strain
    - Permanent strain fluctuates in the range of $1.5 \pm 0.4\%$ as cladding becomes more and more brittle due to increased oxygen pickup
  - Many other factors considered in criterion

Permanent Strain vs. 1200°C-Steam-Oxidation Level for 17 × 17 Zircaloy-4



Offset Strain vs. 1200°C-Steam-Oxidation Level for 17 × 17 Zircaloy-4