Update on Testing to Evaluate Radial Hydrides

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U.S. NWTRB Meeting on High Burnup Fuel
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Outline of Topics

- **Introduction**

- **Previous Results for High-Exposure Cladding**
  - As-irradiated cladding
  - Following cooling from 400°C peak drying-storage temp.

- **New Data for High-Exposure Cladding**
  - As-irradiated condition
  - Following cooling from 350°C peak drying-storage temp.

- **FY2016 Tests in Progress**

- **Summary and Perspectives**

Introduction

Introduction: Objectives of Argonne Program

Argonne Experimental Program

- Generate data for ductility vs. temperature following slow cooling from T ≤400°C and decreasing hoop stress (σ_θ)
- Determine ductile-to-brittle transition temperature (DBTT) for each set of peak drying-storage T and σ_θ: ductility transition temperature
- Characterize extent of radial hydrides and correlate DBTT with effective length of radial hydrides (RHCF)
- From data, extract stress-strain relationships and failure stresses and strains for PWR cladding alloys (input into codes)

Argonne Collaborations

- EPRI-ESCP Fuels Subcommittee and ORNL: relevant range for σ_θ
- PNNL and ORNL: relevant range of cladding temperatures
- SNL, PNNL, and ORNL: relevant range of NCT loads and fueled-cladding response to bending-fatigue loads (experimental)

Introduction:
Loads on Fuel Rods

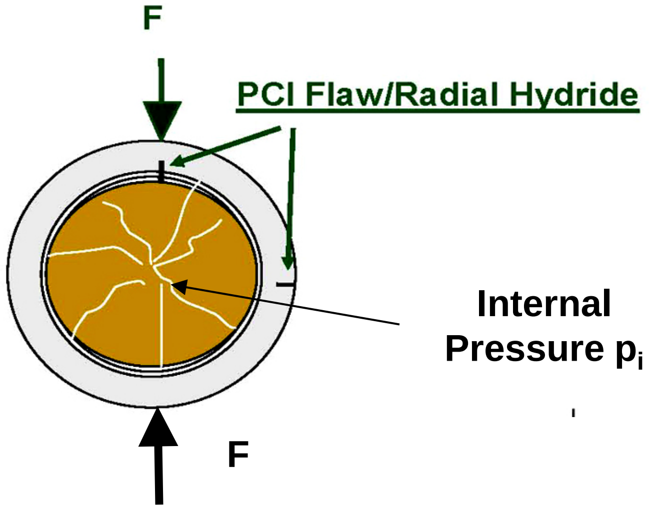
Loads on Fuel-Rod Cladding during Drying & Storage

- Primarily internal gas-pressure loading (hoop & axial stresses)

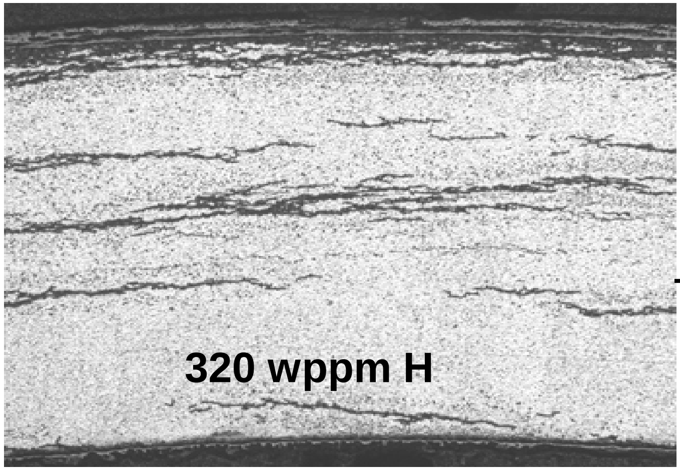
Loads on Fuel-Rod Cladding during Transport

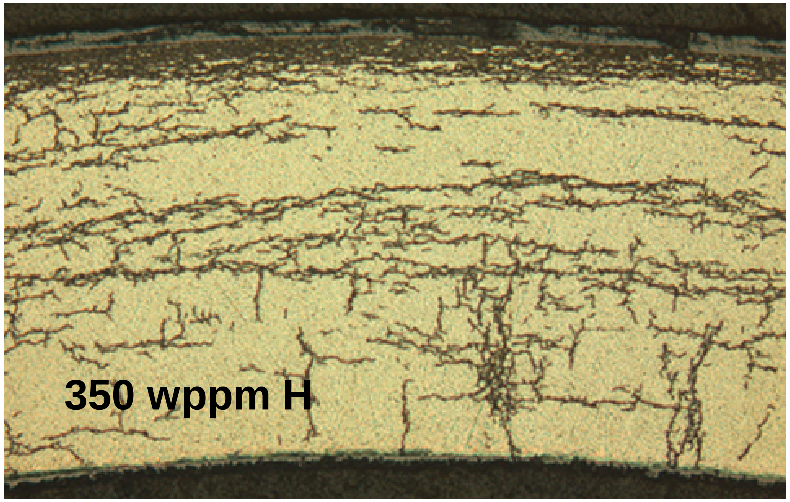
- Normal conditions of transport (NCT) include vibration and shock
  - Axial bending: axial bending stresses (other stresses at pellet-pellet interfaces)
  - “Pinch” loading at grid spacers: hoop bending stresses
- Hypothetical accident conditions include severe impact loads

Schematic of Pinch-Loading



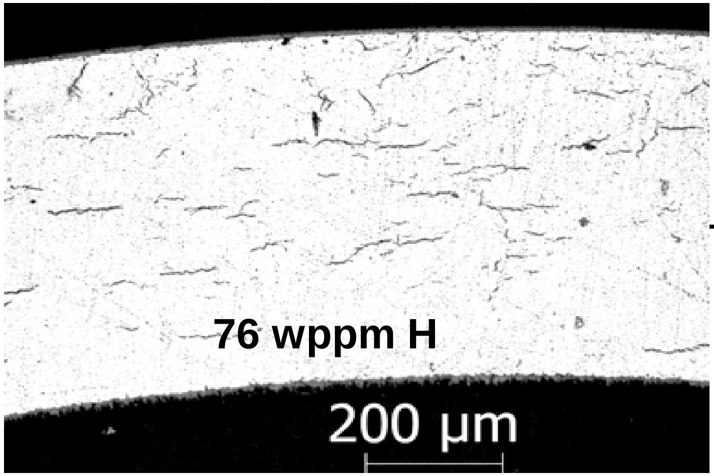
Introduction: Circumferential and Radial Hydrides in High-Exposure PWR Cladding

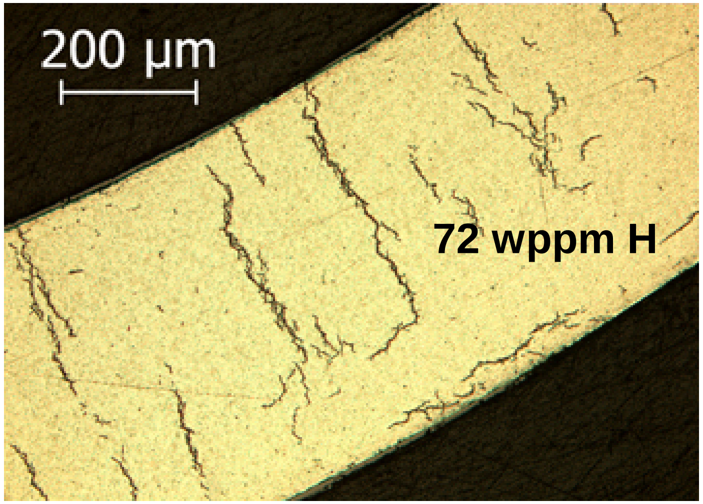




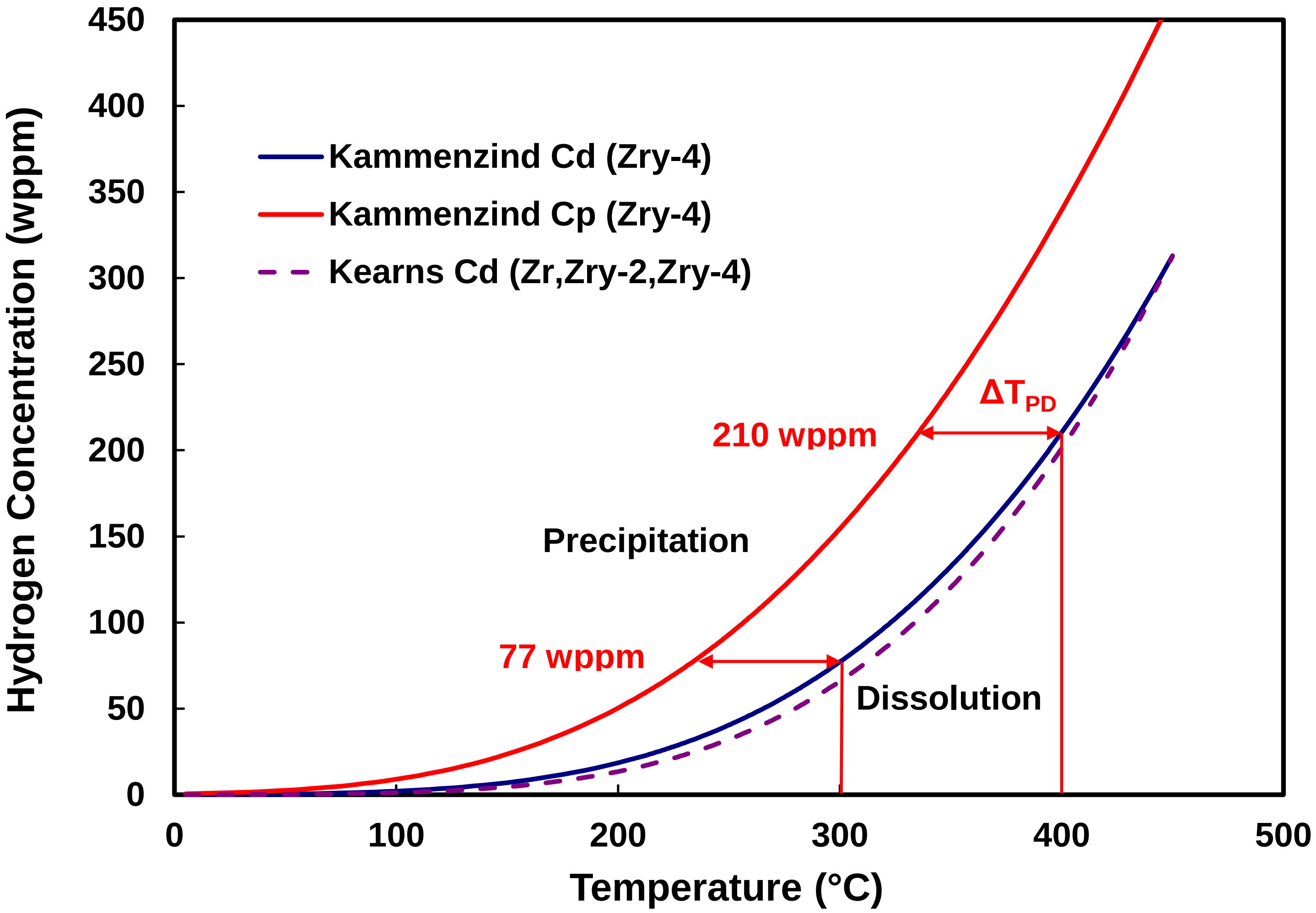
As-Irradiated

After Cooling from 400°C/110-MPa





Introduction: Dissolution (Heating) and Precipitation (Cooling) Curves



Introduction: Perspective

- **DBTT is NOT a Cladding Material Property**
  - Depends on amount and orientation of hydrides
  - Depends on orientation of loads on cladding
- **Effects of Radial Hydrides**
  - Depend on extent of radial-hydride precipitation (effective length)
  - May reduce HOOP failure stresses and strains
  - May complicate structural analysis
- **Transport of Fuel Assemblies at Temperatures <DBTT**
  - Does NOT imply failure of cladding
  - At T <DBTT, cladding is still load bearing
  - Need modeling/data to: determine loads on fuel rods,
    calculate cladding stresses and strains, and
    compare calculated values to stress and strain failure limits

Summary of Previous Results: Cooling from 400^{o}C

Response of M5® Cladding following Cooling from 400°C

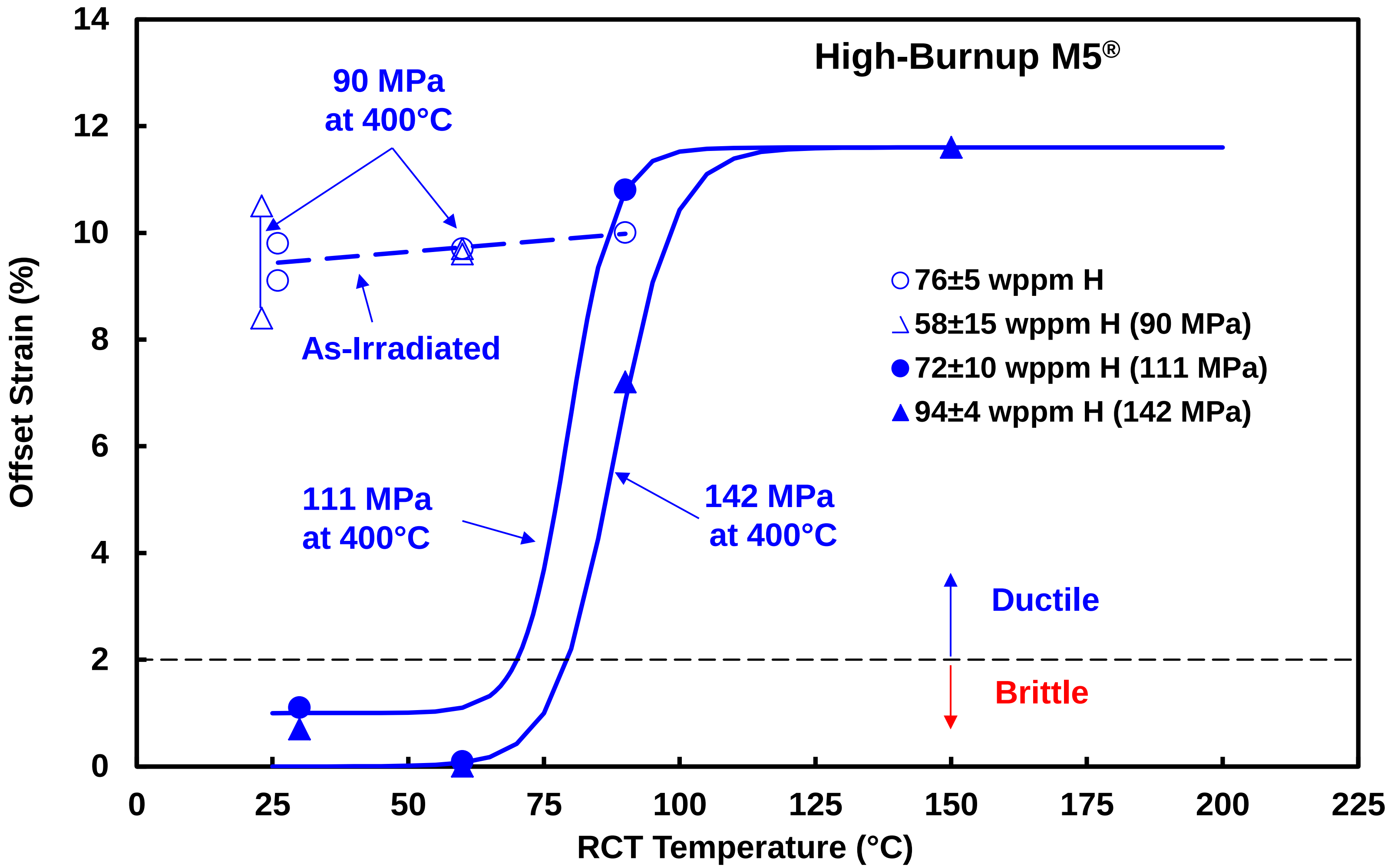
Test Matrix for High-Exposure M5® (Zr-1wt.%Nb)

- As-irradiated, 76±5 wppm hydrogen
- After cooling from 400°C/90-MPa, 58±15 wppm
- After cooling from 400°C/111-MPa, 72±10 wppm
- After cooling from 400°C/142-MPa, 94±4 wppm

Results for High-Exposure M5®

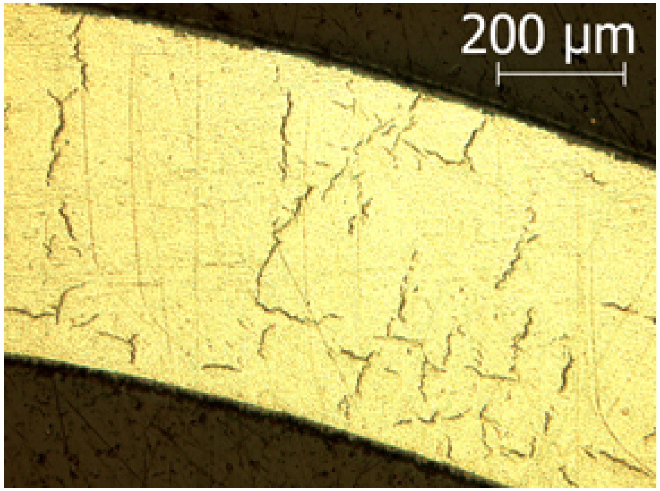
- As-irradiated:
  high ductility at T ≥20°C (no cracking up to 1.7 mm displacement)
- 90-MPa, 58±15 wppm: high ductility at T ≥20°C, 37±17% RHCF
- 111-MPa, 72±10 wppm: high ductility at T ≥90°C, 54±20% RHCF
- 142-MPa, 94±4 wppm:
  mod.-to-high ductility at T ≥90°C, 61±18% RHCF

Ductility vs. Test Temperature for High-Exposure M5®

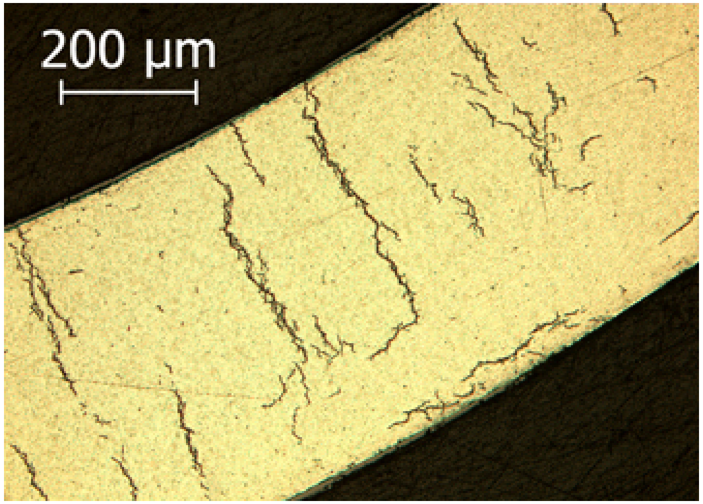


Radial Hydrides in High-Exposure M5® following Cooling from 400°C

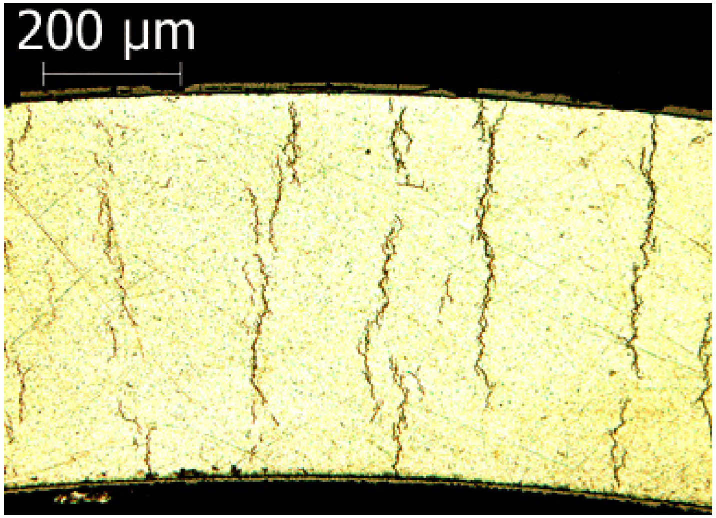
90 MPa
58±15 wppm
65 MPa at 210°C
37±17% RHCF



111 MPa
72±10 wppm
82 MPa at 228°C
54±20% RHCF



142 MPa
94±4 wppm
110 MPa at 251°C
61±18% RHCF



Assessment of M5® Database following Cooling from 400°C

- **Need Data for 90−110 MPa with 75−95 wppm Hydrogen**
  - Ductility improved with decrease in both hydrogen and hoop stress
  - Need to determine DBTT vs. hoop stress at higher hydrogen levels
- **Need Repeat Tests to better Determine DBTT**
  - Only 3 data points for 400°C/111-MPa test: 1 ductile point
  - Some data scatter is expected
  - Recommend two more rodlets cooled from 400°C/100-MPa
    - 8 RCT data points in narrow temperature range (70−90°C)
- **Need Tests at <400°C**
  - Unlikely that actual peak cladding temperatures will reach 400°C
  - Less annealing would occur at lower peak temperatures
  - Need to confirm previous results at T ≤350°C
  - Number of tests needed will depend on results of first test

Response of Zry-4 Cladding following Cooling from 400°C

Test Matrix for High-Exposure Zircaloy-4

- As-Irradiated, 300±15, 616±78, 640±140 wppm hydrogen
- After cooling from 400°C/113-MPa, 520±90 wppm hydrogen
- After cooling from 400°C/145-MPa, 615±82 wppm hydrogen

Results for High-Exposure Zircaloy-4

- As-irradiated, 530±70 wppm: mod.-to-high ductility at T ≥20°C
  - 300±15 wppm: high ductility at 20°C (no cracking to 1.7 mm displace.)
  - 640±140 wppm (>850 wppm local): no-to-low ductility at ≤90°C (brittle?)
  - 616±78 wppm: ***refined*** test method, ductility = 2.6±0.7% vs. 1% limit

- 113 MPa, 520±90 wppm: low ductility at 20°C, 9±5% RHCF
  - Recommended test at 400°C/110-MPa (4 RCT data points at 20°C)
  - Recommended test at 350°C/110-MPa (4 RCT data points at 20°C)
- 145 MPa, 615±82 wppm: low ductility at 90°C, 16±4% RHCF

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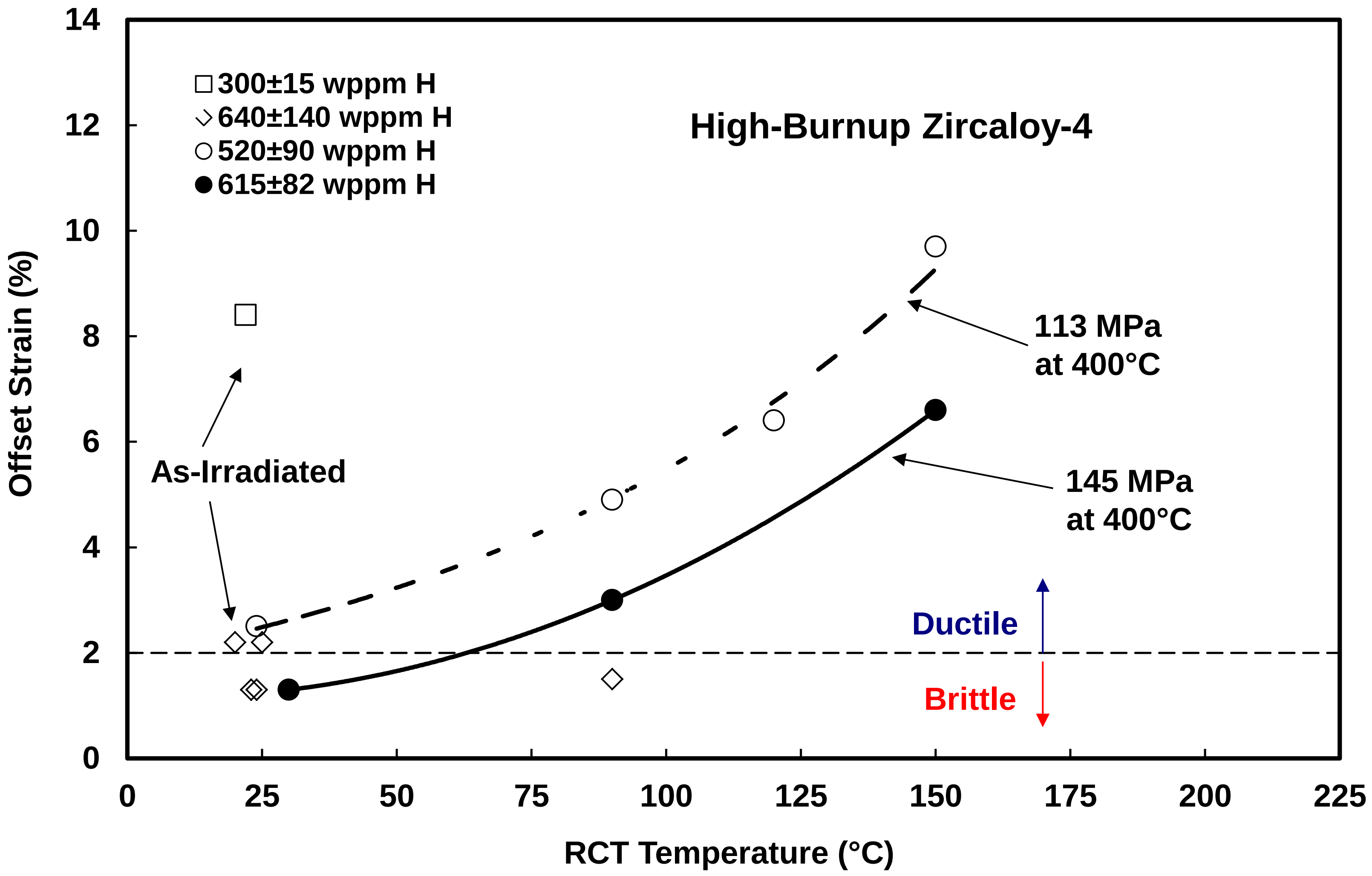
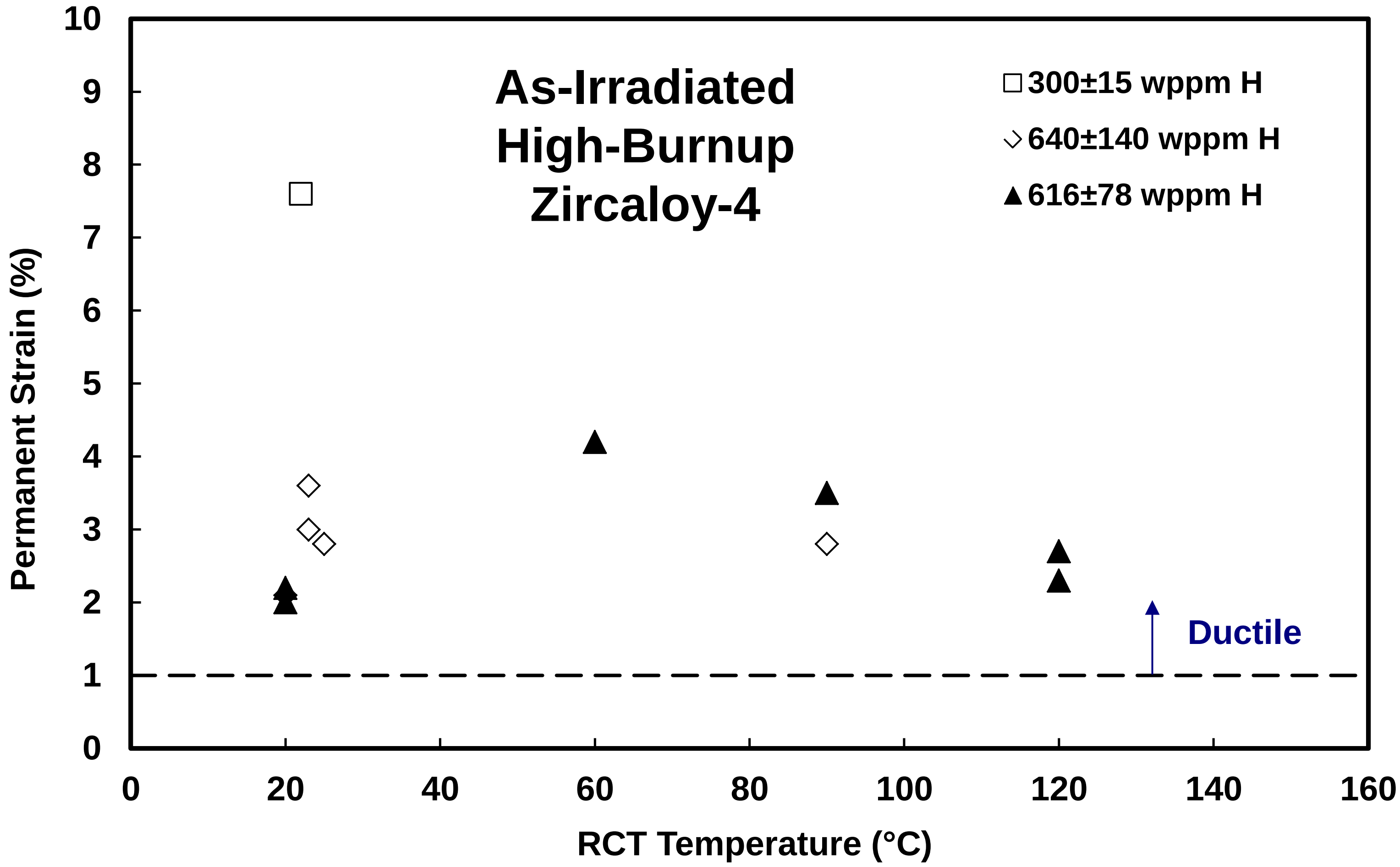
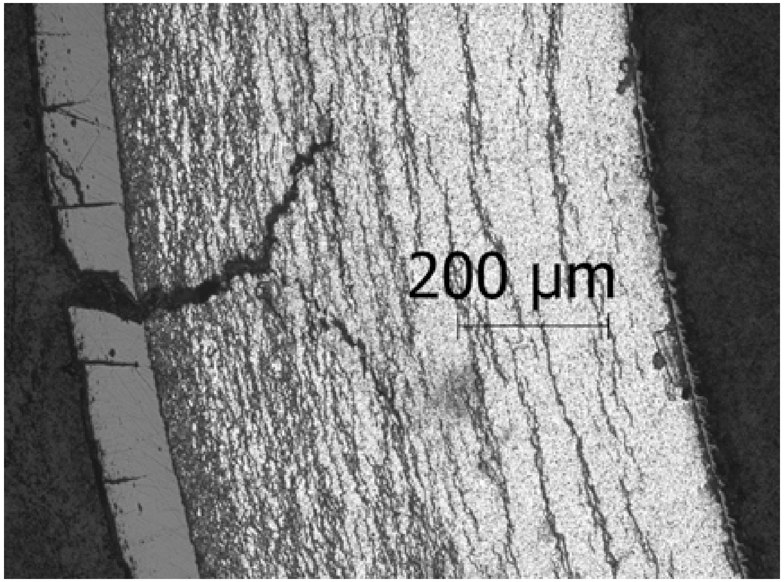
Ductility vs. Test Temperature for High-Exposure Zircaloy-4



Ductility vs. Test Temperature for As-Irradiated, High-Exposure Zry-4

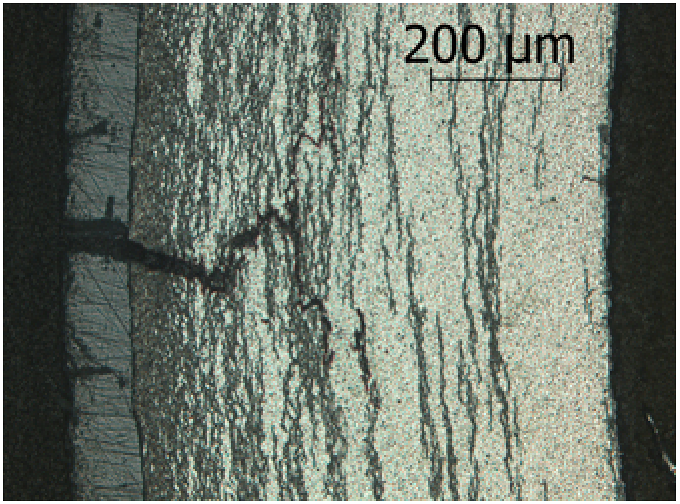


Crack Depth vs. Load Drop for As-Irradiated Zry-4: Load-Interrupt Tests

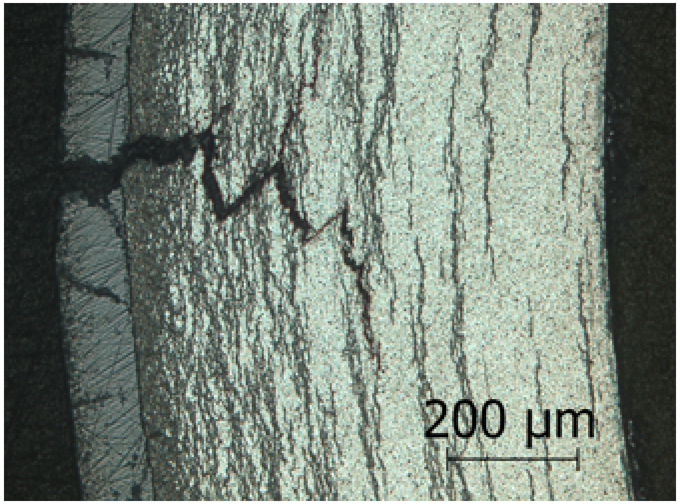


44% Wall Crack
27% Load Drop
2.1% Ductility

41% Wall Crack
22% Load Drop
2.2% Ductility



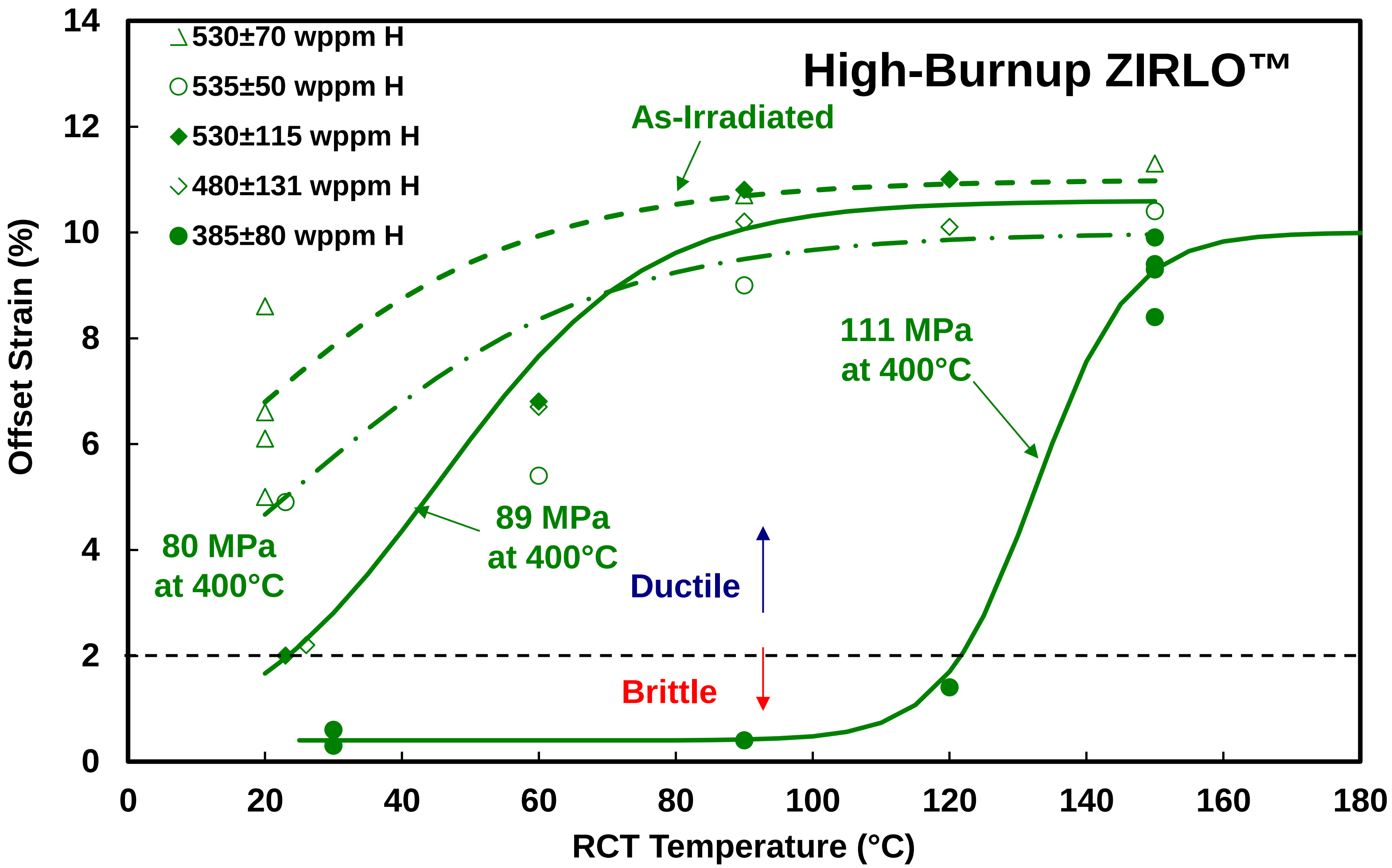
39% Wall Crack
24% Load Drop
2.7% Ductility



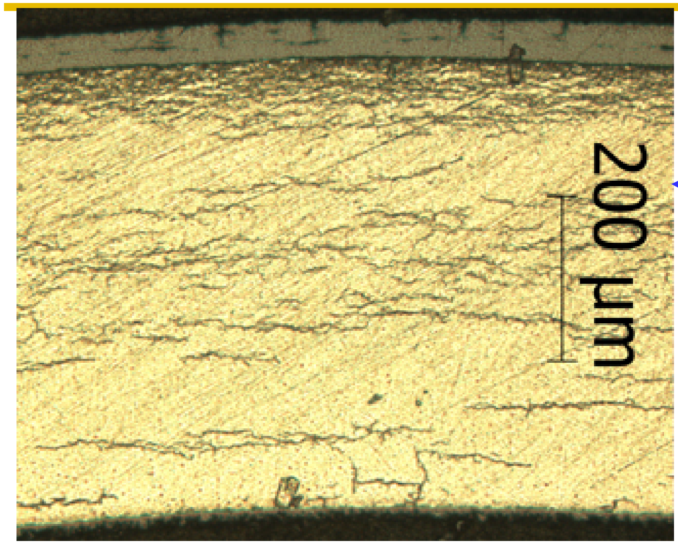
Response of ZIRLO™ Cladding following Cooling from 400°C

- **Test Matrix for High-Exposure ZIRLO™ (Zr-1wt.%Nb-1wt.%Sn)**
  - As-Irradiated, 530±70 wppm hydrogen
  - After cooling from 400°C/80-MPa, 535±50 wppm hydrogen
  - After cooling from 400°C/89-MPa, 530±115 wppm hydrogen
  - After 3-cycle cooling from 400°C/88-MPa, 480±131 wppm hydrogen
  - After cooling from 400°C/111-MPa, 385±80 wppm hydrogen (2 tests)
  - After cooling from 400°C/141-MPa, 650±190 wppm hydrogen
- **Results for High-Exposure ZIRLO™**
  - As-irradiated, 530±70 wppm: mod.-to-high ductility at T ≥20°C
  - 80 MPa, 535±50 wppm: mod-to-high ductility at T ≥20°C, 9±3% RHCF
  - 89 MPa, 530±115 wppm: low ductility at 23°C, 19±9% RHCF
  - 88 MPa, 480±131 wppm: low ductility at 23°C, 20±9% RHCF (3-cycle cool.)
  - 111 MPa, 350±80 wppm: high ductility at 150°C, 32±13% RHCF
  - 141 MPa, 650±190 wppm: brittle at 150°C, mod. ductility at 195°C

Ductility vs. Test Temperature for High-Exposure ZIRLO™

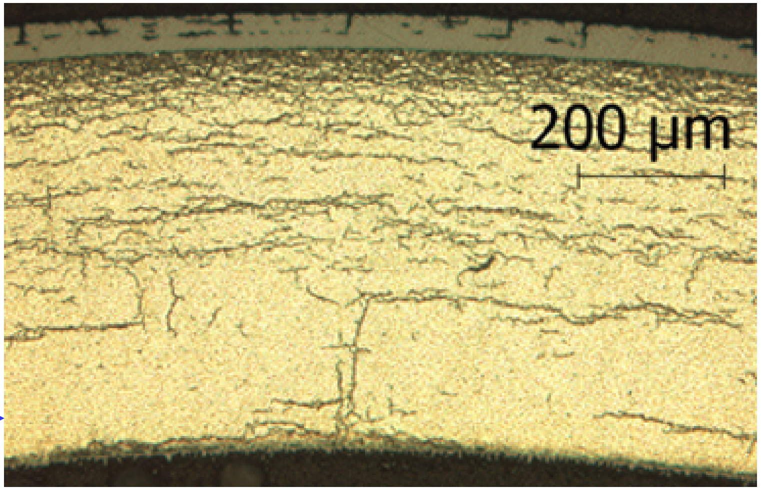


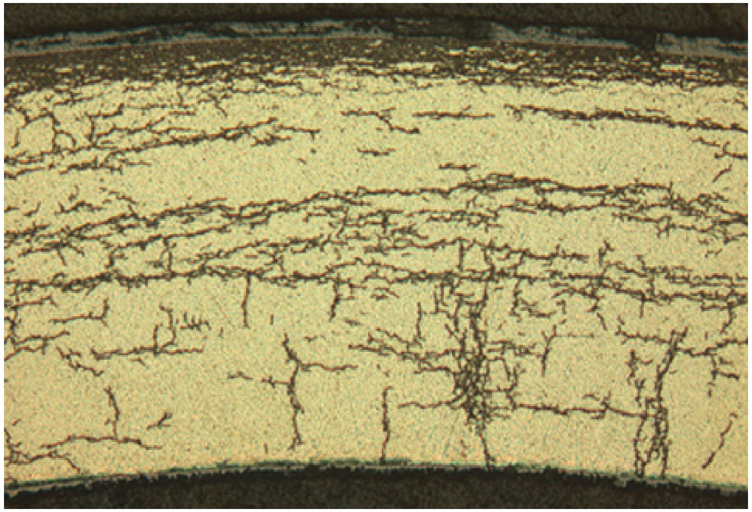
Radial Hydrides in High-Exposure ZIRLO™ following Cooling from 400°C



80 MPa
(72 MPa @ T_p)
535 wppm

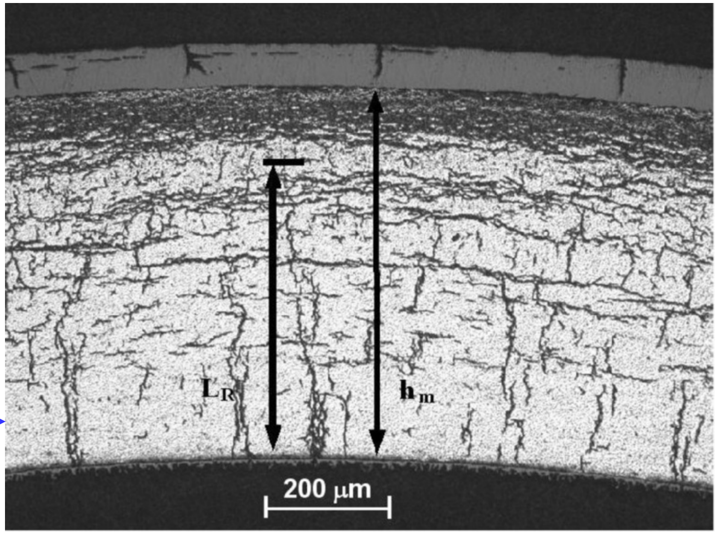
89 MPa
(80 MPa @ T_p)
530 wppm





111 MPa
(101 MPa @ T_p)
350 wppm

141 MPa
(128 MPa @ T_p)
650 wppm



Response of ZIRLO™ Cladding following Cooling from 400°C

- **Assessment of Database for High-Exposure ZIRLO™**
  - Need data in peak stress range of 90−110 MPa prior to cooling
    - DBTT increased by 100°C within this stress range

  - Need repeat tests to determine DBTT with more precision
    - Standard-fuel ZIRLO™ rods: 60−80 MPa relevant peak stress range
    - ZIRLO™-clad fuel pellets with ZrB_2 (enriched in B-10) coating
Integral Fuel Burnable Absorber (IFBA) rods
Relevant stress ranges: 80−120 MPa and 110-150 MPa for 2 designs

  - Need tests at <400°C to determine net effects on DBTT of reduction in annealing (possible DBTT increase) and reduction in dissolved hydrogen available for precipitation (possible DBTT decrease)

New Data for 350°C Peak Drying-Storage Temperature

High-Exposure ZIRLO™ and M5® following Cooling from 350^{o}C

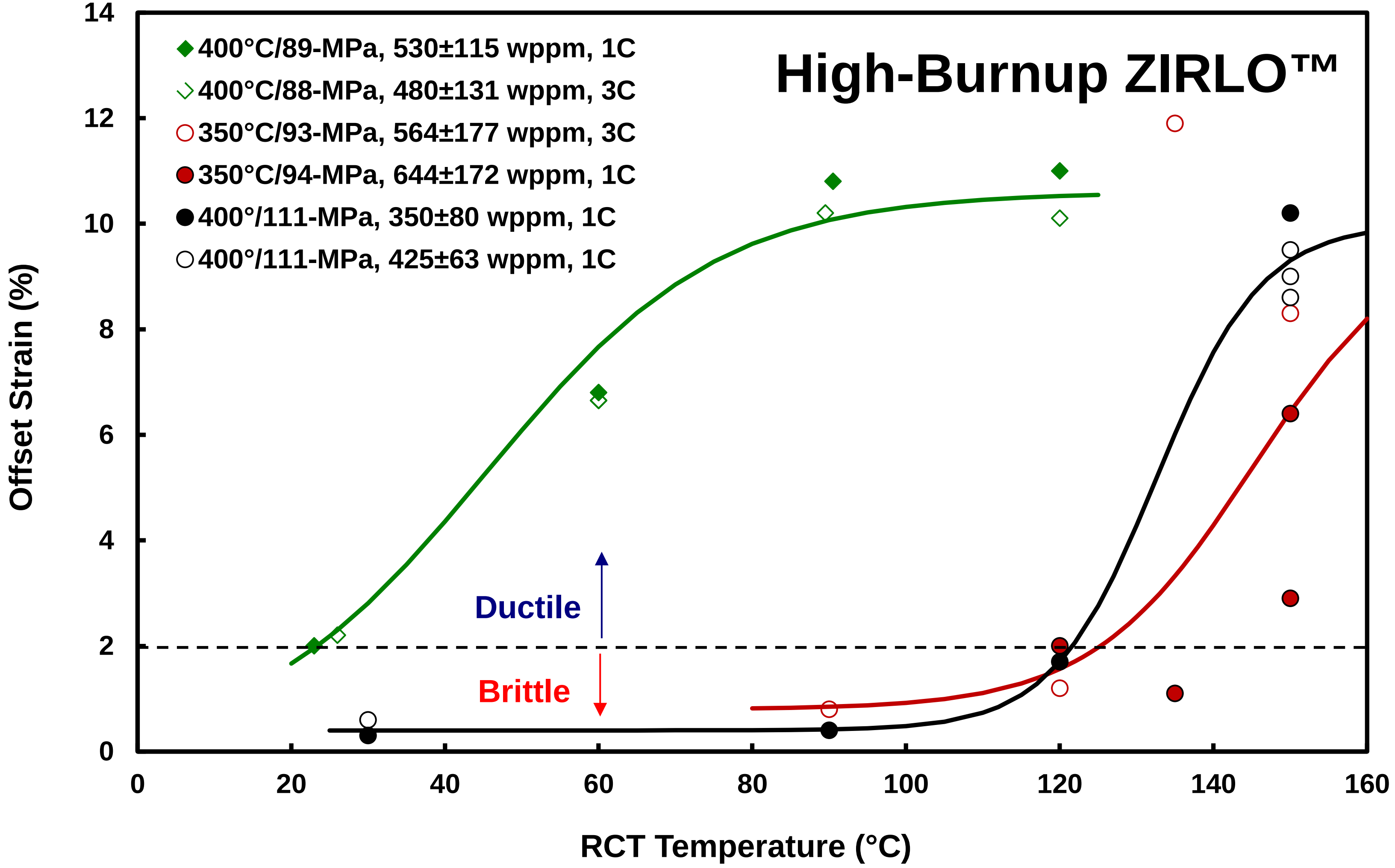
Expectations

- ZIRLO™
  - Decrease (80 wppm) in dissolved hydrogen and in precipitation temperature
  - Decrease in internal pressure and hoop stress at precipitation initiation
  - Possible decrease in annealing of irradiation hardening (lower ductility matrix)
  - Anticipated net effect: decrease in DBTT
- M5®
  - No change in dissolved hydrogen, precipitation temperature, precipitation stress
  - Possible decrease in annealing of irradiation hardening (lower ductility matrix)
  - Anticipated net effect: no change in DBTT

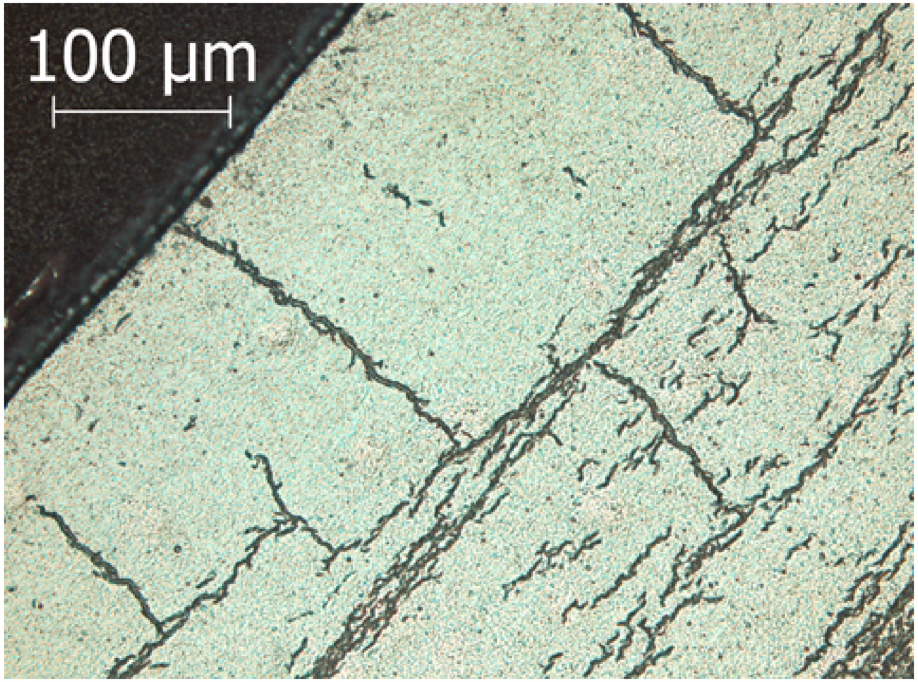
ZIRLO™ Tests at 350°C

- 94 MPa (84 MPa @ T_p), 644±172 wppm, 1-cycle cooling
  - Long radial hydrides (37±11%), low ductility @ ≤135°C, mod. ductility @ 150°C
- 93 MPa (83 MPa @ T_p), 564±177 wppm, 3-cycle cooling
  - Long radial hydrides (30±11%), low ductility @ ≤120°C, high ductility @ ≥135°C
- No effects of cycling, but DBTT comparable to DBTT for 400°C/111-MPa

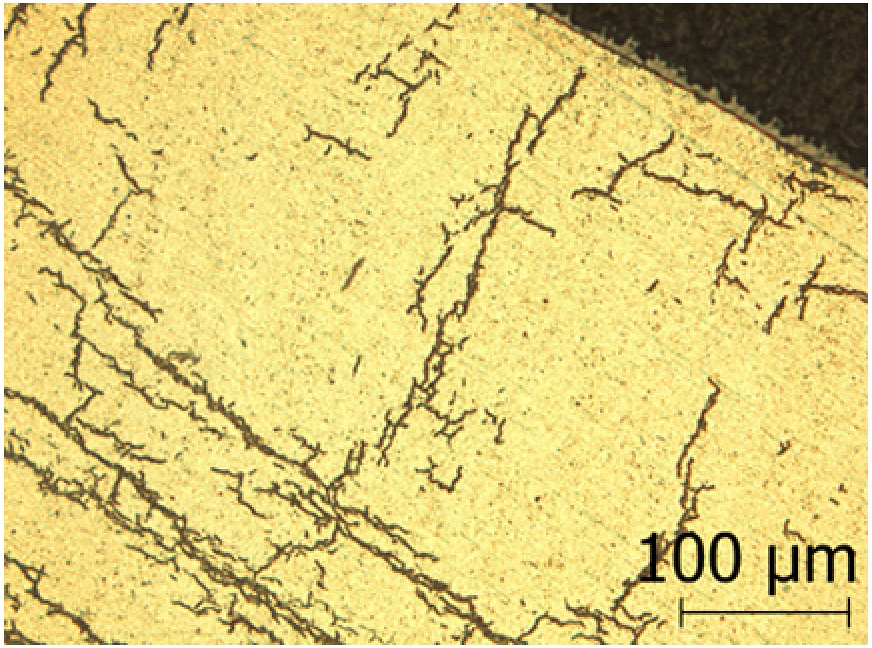
Ductility Data for High-Exposure ZIRLO™ following Cooling from 350°C



Radial Hydrides in ZIRLO™ for 1- and 3-Cycle Drying Tests following cooling from 350^{o}C



1-Cycle-350^{o}C Test
94 MPa → 84 MPa
37±11% RHCF
≥50% Max. RHCF



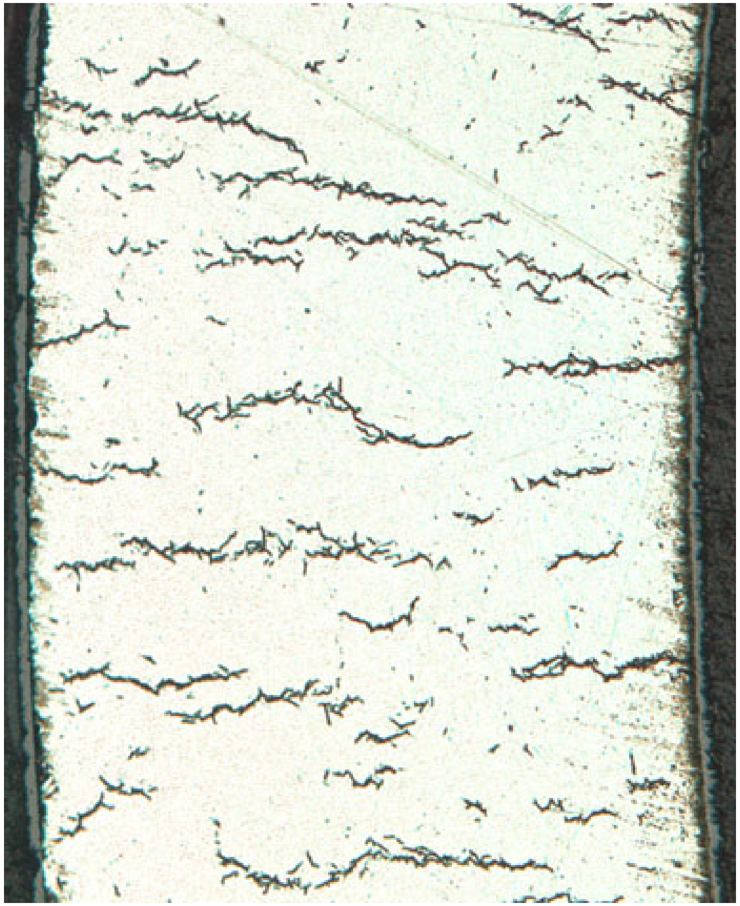
3-Cycle-350^{o}C Test
93 MPa → 83 MPa
30±11% RHCF
≥50% Max. RHCF

FY2016 Tests in Progress

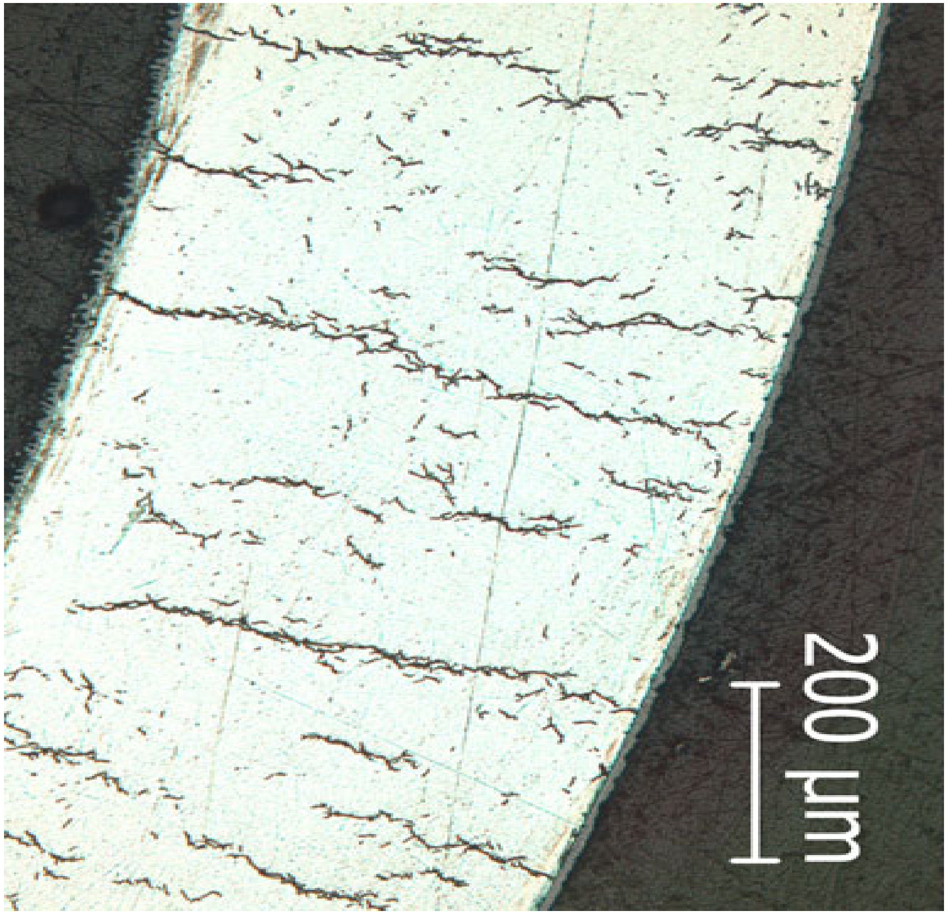
- **ZIRLO™ following Cooling from 350°C**
  - Repeat 94-MPa (1-cycle) test with lower-H (350 wppm) sample
    - High-hydrogen content (644±172 wppm) may have degraded cladding
    - 350 wppm is closer to expected hydrogen content for rods at ≤55 GWd/MTU
    - Use load-interrupt method to improve data analysis and reduce scatter
    - If ductility values are still low, investigate effects of annealing

- **M5® following Cooling from 350°C**
  - 92-MPa target hoop stress, 75−95 wppm target H-content
    - Metallography: oxide and metal wall thicknesses, 50±14% RHCF
    - 87-MPa actual hoop stress
    - Hydrogen content: 80±7 wppm (based on data for 3 rings)
    - Ring compression tests in progress

Radial Hydrides in High-Exposure M5® following Cooling from 350°C/87-MPa



Typical – 40±10% RHCF



Maximum – 95% RHCF

ANL (Billone) Perspective

- **DBTT or Ductility Transition Temperature**
  - Not a material property like Young’s modulus
  - Depends on orientation/length of hydrides and orientation of loads
  - Transport at T <DBTT does not imply failure
  - ANL data may be used to determine hoop failure stresses/strains
- **Relevant Hoop Stresses during Drying and Storage**
  - Depend on end-of-life internal gas pressures
    - Standard rods have lower gas pressures (He-fill + fission gas)
    - IFBA rods have higher gas pressures (He-fill + He from B-10 + fission gas)
  - Depend on average gas temperature during drying/storage
    - Horizontal/He < vertical/vacuum < vertical/He < vertical/convective-He
  - “Reasonable” upper-bound hoop stresses (topic for next meeting)
    - Standard PWR rods: 60−80 MPa
    - ZIRLO™-clad IFBA rods with annular blanket pellets: 80−120 MPa
    - ZIRLO™-clad IFBA rods with solid blanket pellets: 110−150 MPa

Acknowledgment

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