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Cladding Embrittlement During Postulated Loss-of-Coolant Accidents; NUREG/CR-6967

Clarification of Database and Issues Raised

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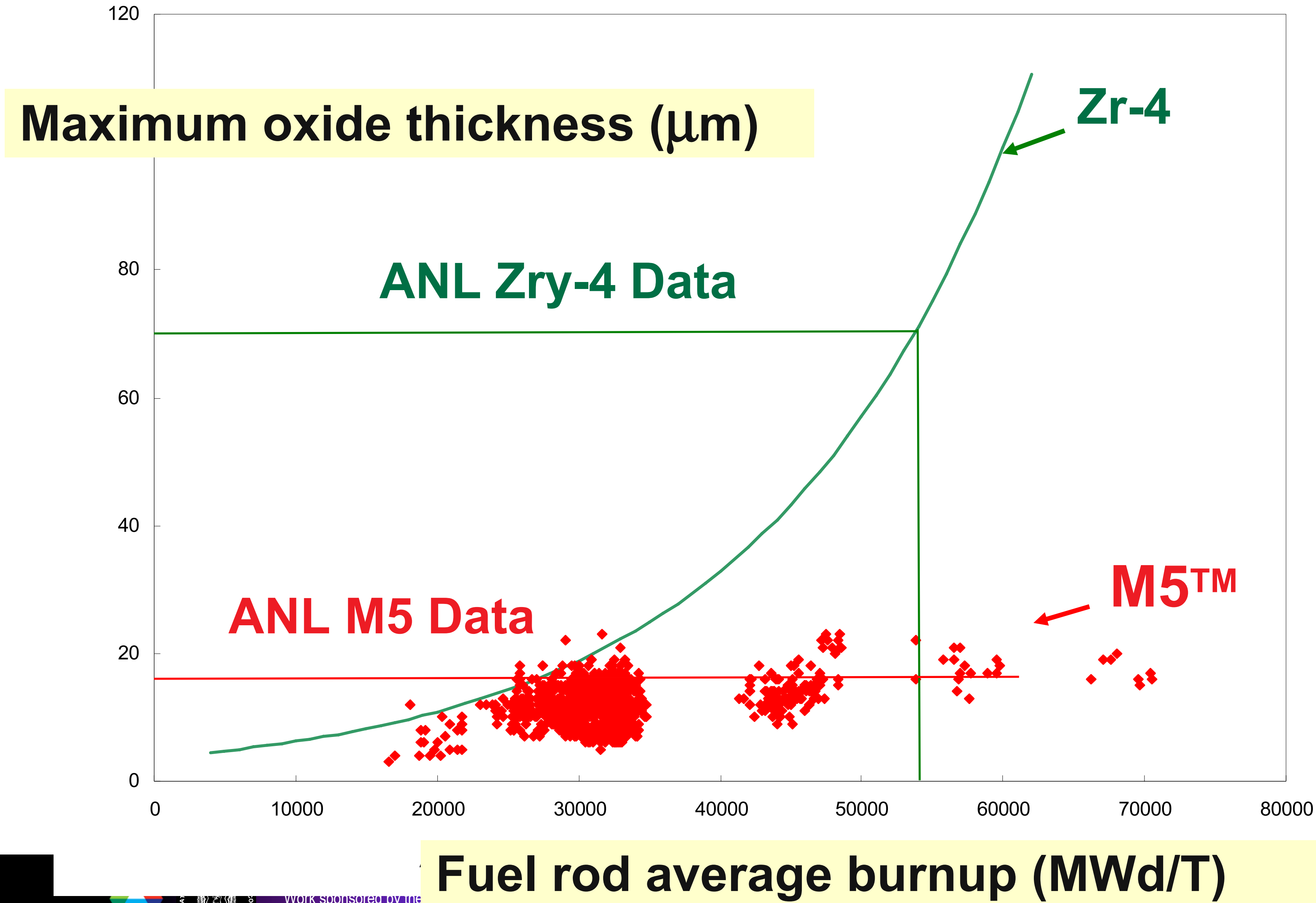
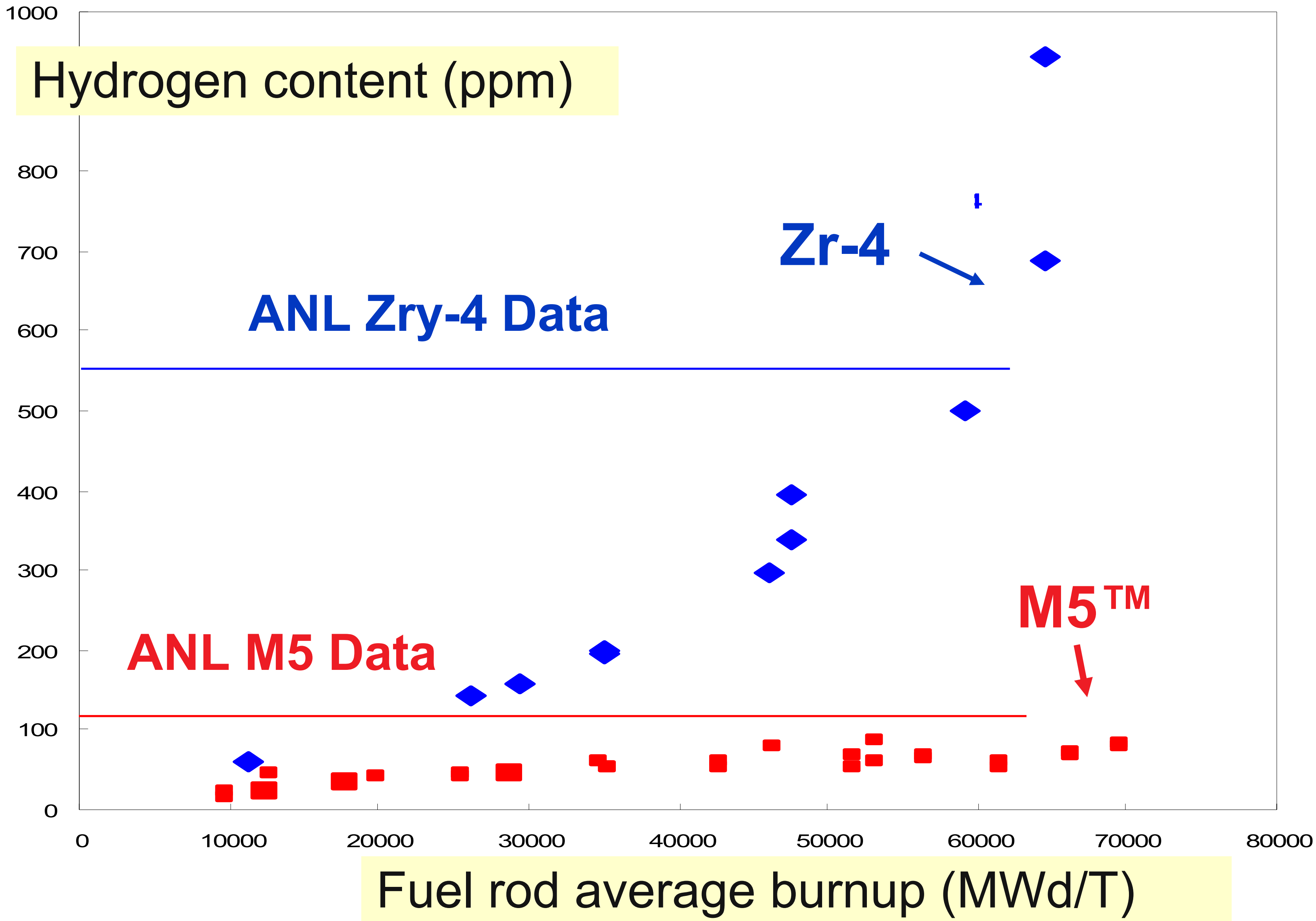
Comments on Burnup, Corrosion Layer and Hydrogen Content for Cladding from High-Burnup Fuel Rods

- **M5 (63 GWd/MTU)**
  - Corrosion layer: 13-25 μm (eddy current); 12 μm (metallography)
  - Hydrogen content: 110±15 wppm
- **ZIRLO (70 GWd/MTU)**
  - Corrosion layer: 38-48 μm (eddy current); 41-43 μm (metallography)
    - *Note: samples available with up to 70-μm corrosion layer*
  - Hydrogen content: 560-670 wppm (pre-test); 540±100 wppm (post-test)
    - *70-μm corrosion layer samples should have > 600 wppm H*
- **Zircaloy-4 (64 GWd/MTU)**
  - Corrosion layer: 71-74 μm (metallography)
    - *Note: Samples available with up to 100 μm (metallography)*
  - Hydrogen content: 540±100 wppm
    - *Note: samples available with up to 750-800 wppm hydrogen*

AREVA Data for M5™ and Zr-4 In-reactor Corrosion Layer Growth vs. Burnup



AREVA Data for M5 and Zry-4 H-Uptake vs. Burnup



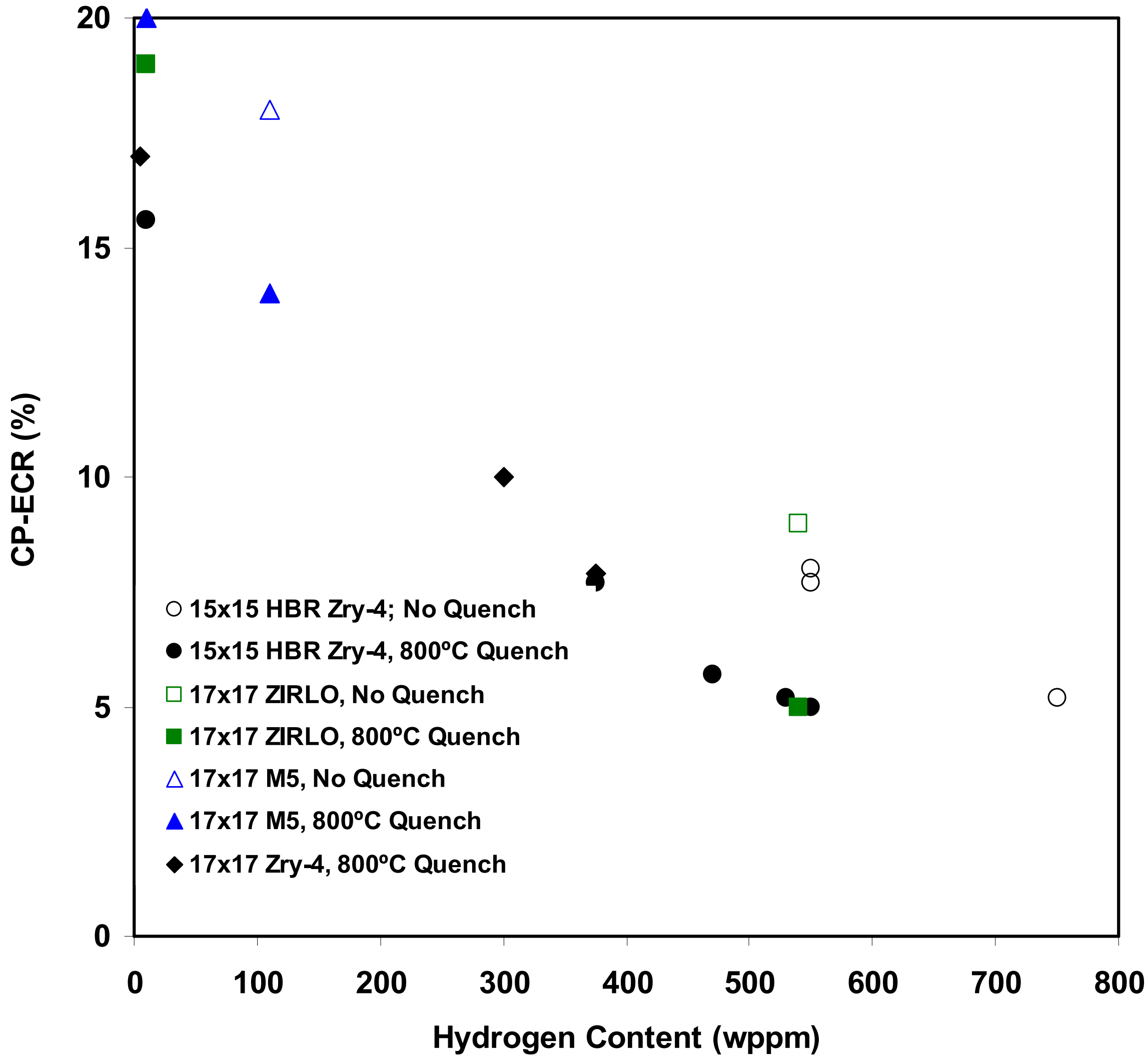
LOCA NUREG Section 7 Summary

- **Number of LOCA and Ductility Tests Used to Determine Embrittlement Threshold vs. Hydrogen Content at ≤1200ºC for Zry-4 (3 Types)**
  - Fresh Zry-4: 60 LOCA tests; 100 ductility tests
  - Prehydrided Zry-4: 50 LOCA tests; 80 ductility tests
  - High-burnup Zry-4: 12 LOCA tests; 13 ductility tests

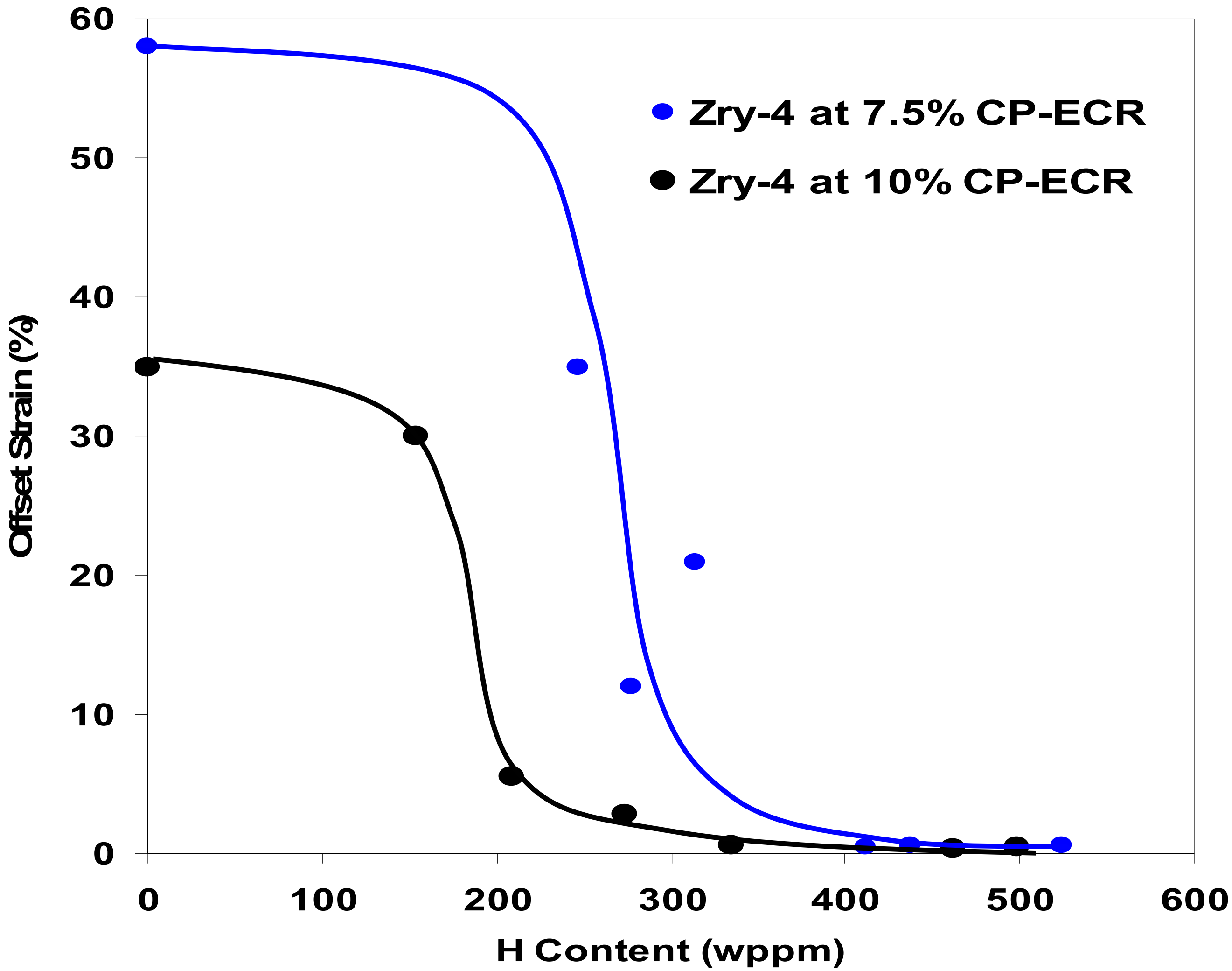
- **Embrittlement of Fresh, Prehydrided and High-Burnup Cladding vs. Hydrogen Content (5-800 wppm)**
  - Fresh cladding: >20% oxidation level for 1000ºC and 1100ºC
  - Fresh cladding: 16-19% oxidation for 1200ºC
  - Prehydrided cladding oxidized at ≤1200ºC
    - *5-10% oxidation level for 300-600 wppm*
    - *>10% oxidation level for <300 wppm*
  - High-burnup cladding oxidized at ≤1200ºC

    Note: ZIRLO hydrogen content determined from post-test data is used

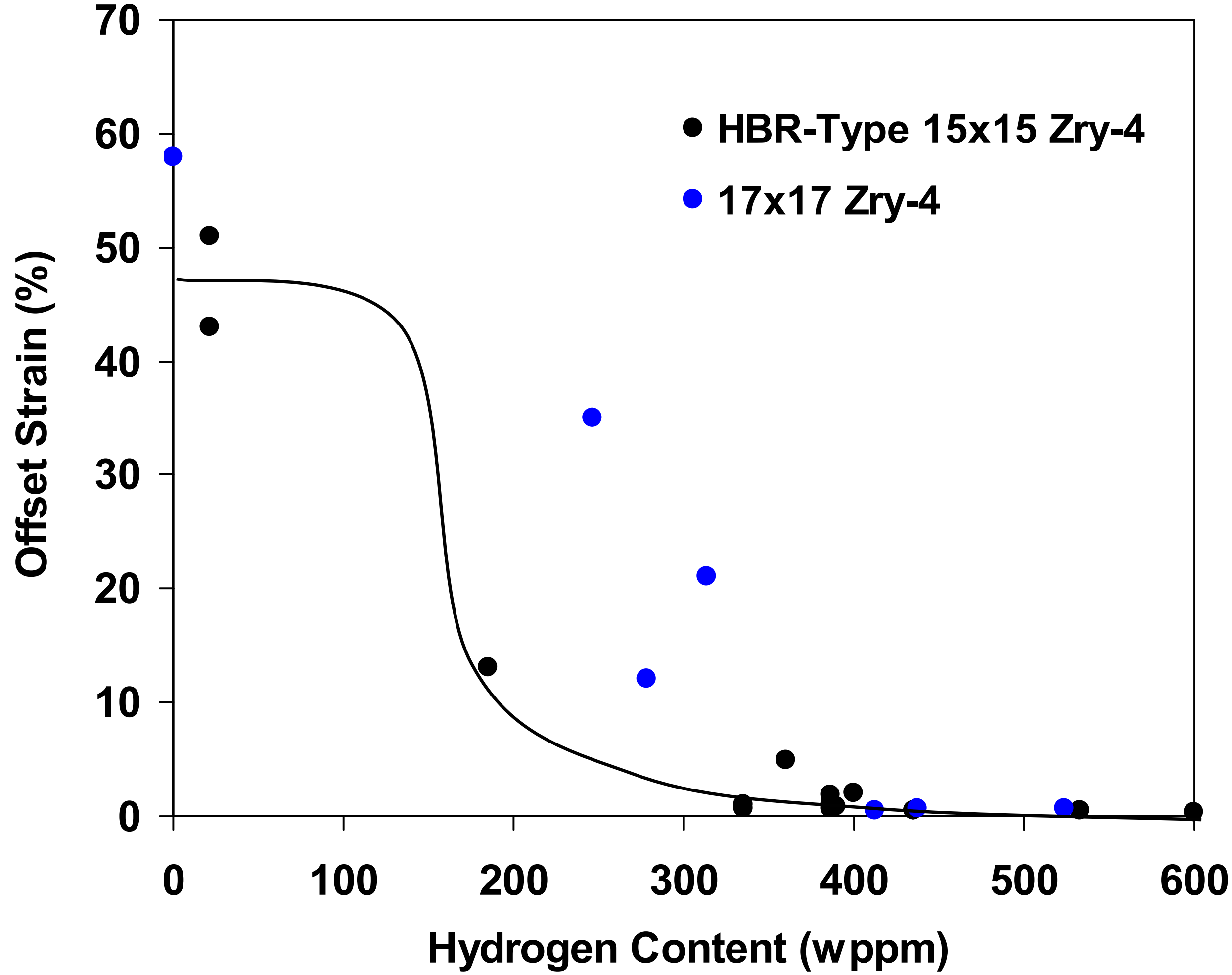
Embrittlement Thresholds for Fresh, Prehydrided (Zry-4 only), and High Burnup Cladding Oxidized at ≤1200ºC



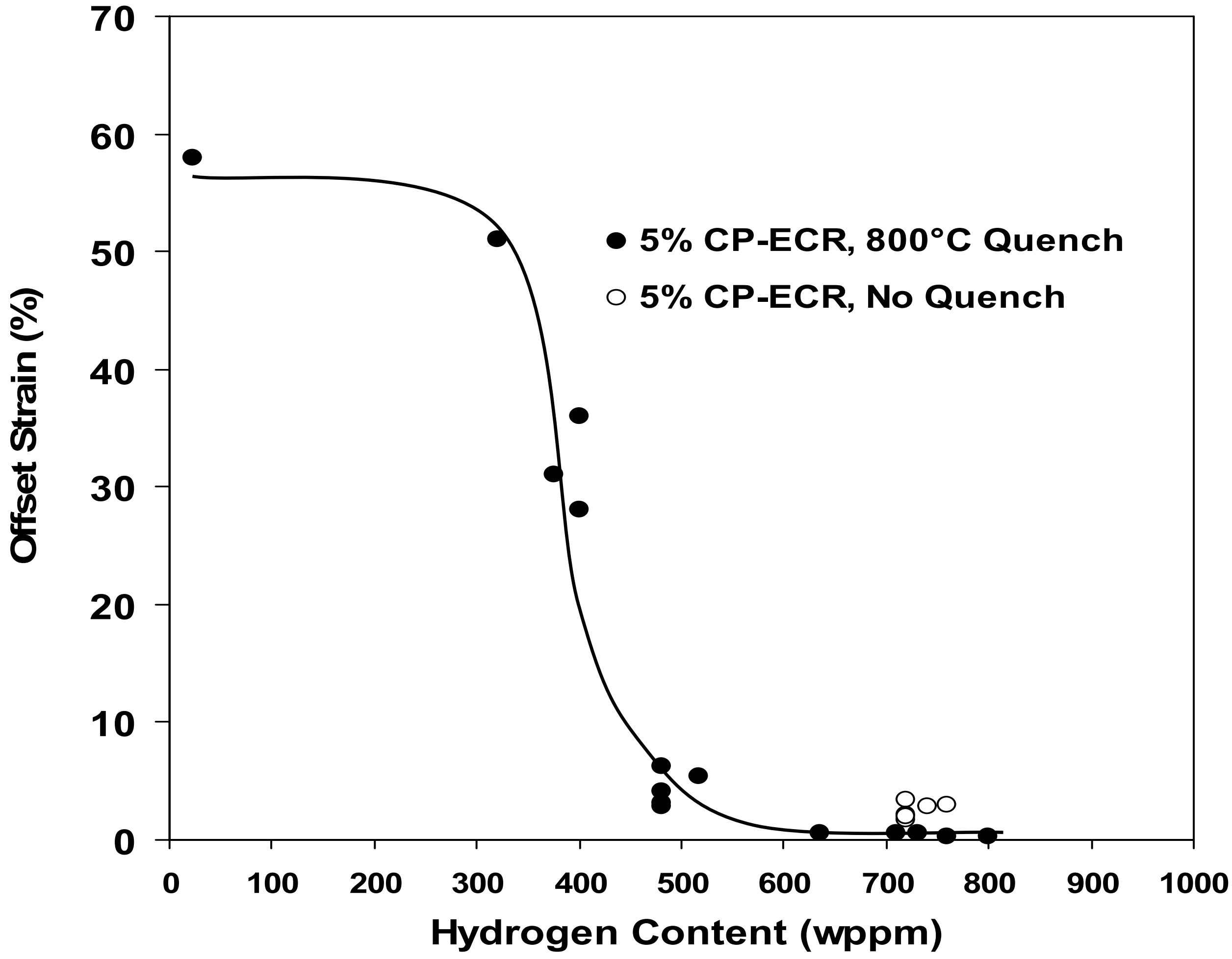
Ductility vs. H Content for Prehydrided Zry-4 Oxidized at 1200ºC to 7.5% and 10% CP-ECR and Quenched at 800ºC



Ductility vs. H Content for Prehydrided Zry-4 Oxidized at 1200ºC to about 8% CP-ECR and Quenched at 800ºC



Ductility vs. H Content for Prehydrided Zry-4 Oxidized at 1200ºC to about 5% CP-ECR



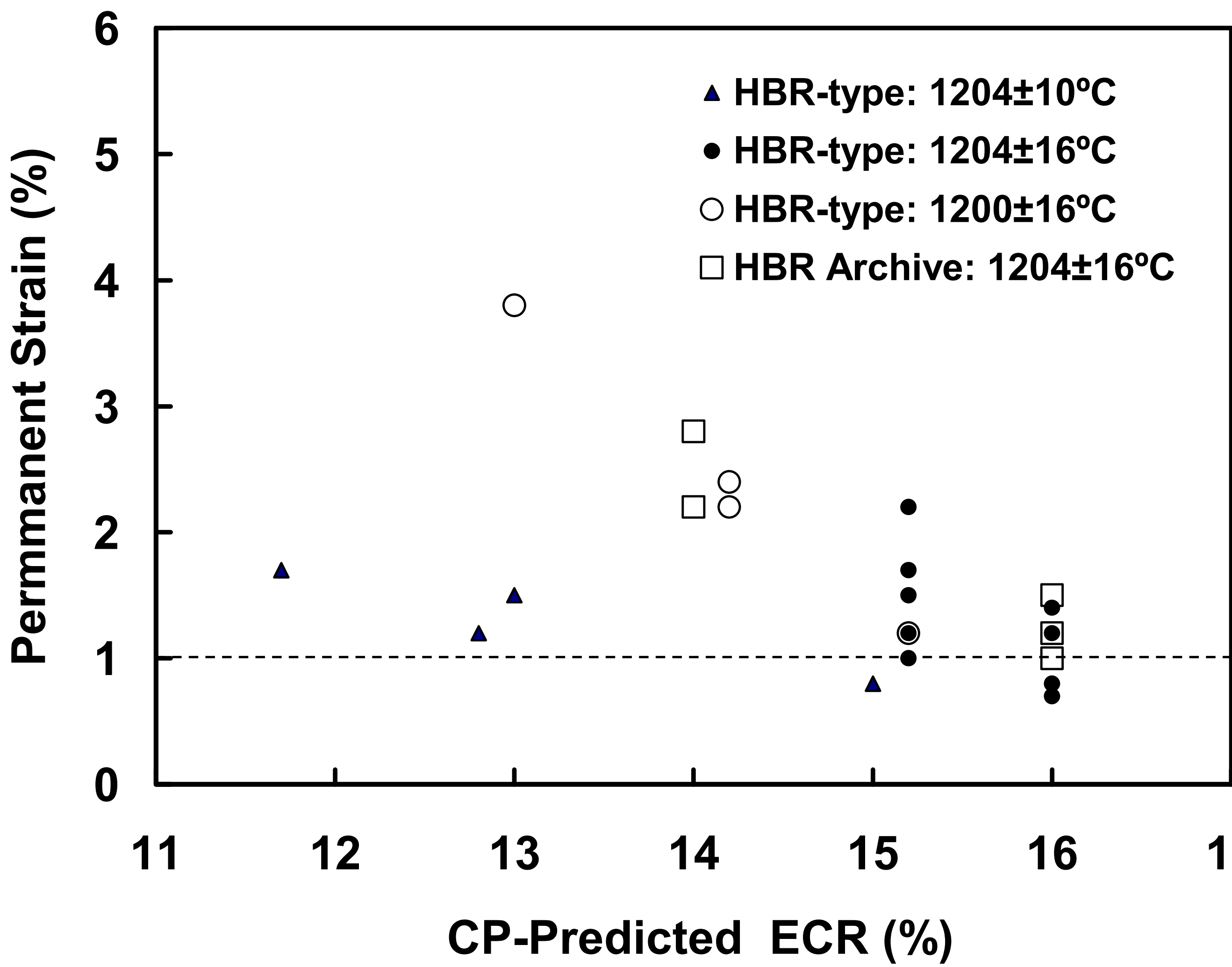
Breakaway Oxidation Data

- **Instability Phenomenon Resulting in Oxide Layer Phase Transition, Cracking, and Increased Weight Gain, as well as Hydrogen pickup**
  - Leistikow & Schantz (1985): 1800 s at 1000ºC for 200-wppm H in Zry-4
    - *Old standard-tin Zry-4 (1970s)*
  - Mardon et al. (2005): 5400 s at 1000ºC for 200-wppm H in Zry-4
    - *Modern, polished, low-tin Zry-4 more resistant to breakaway oxidation*
- **ANL Breakaway Oxidation Studies with Zry-4**
  - Old Zry-4 (1980s) with rough outer surface; pickled inner surface
    - *985±10ºC: 20-40 wppm H pickup after 3800 s; 1320 wppm after 3900 s*
  - Modern Zry-4
    - *985±10ºC: 5000 s minimum breakaway oxidation time*
    - *Retested in shorter steam chamber: >5400 s breakaway time????*
- **ANL and Westinghouse Breakaway Oxidation Studies with ZIRLO**
  - ANL: 970-985ºC; 3100±300 s (scratched, smooth, pre-oxidized)
  - Westinghouse: ≈950-1020ºC; >5400 s breakaway time
  - ANL and Westinghouse are working on resolving differences

Embrittlement Threshold Uncertainties for Fresh Cladding

- ANL Approach for As-fabricated HBR-type 15x15 Zry-4
  - Broad-brush approach: determine trend of ductility decrease with increasing oxidation level (5, 7.5, 12-13, 15% CP-ECR) for 1200ºC
  - Focused approach: multiple tests performed for narrow oxidation range (13-16% CP-ECR) to determine ductile-to-brittle transition CP-ECR
    - *9 oxidation-quench tests*
    - *18 ring-compression ductility data points*
    - *1200 and 1204ºC; HBR-type (low-tin) and true HBR archive (standard)*
- Results
  - Broad-brush results: 14.3% CP-ECR transition (interpolation from 13-15%)
  - Focused approach: 15.6% CP-ECR transition (interpolation from 15.2-16%)
  - Difference = 1.3%
  - Difference based on nearest % CP-ECR: 16%-14% = 2%

Embrittlement Threshold for HBR-Type Zry-4 oxidized at 1200ºC and Quenched at 800ºC: Results of Multiple Tests



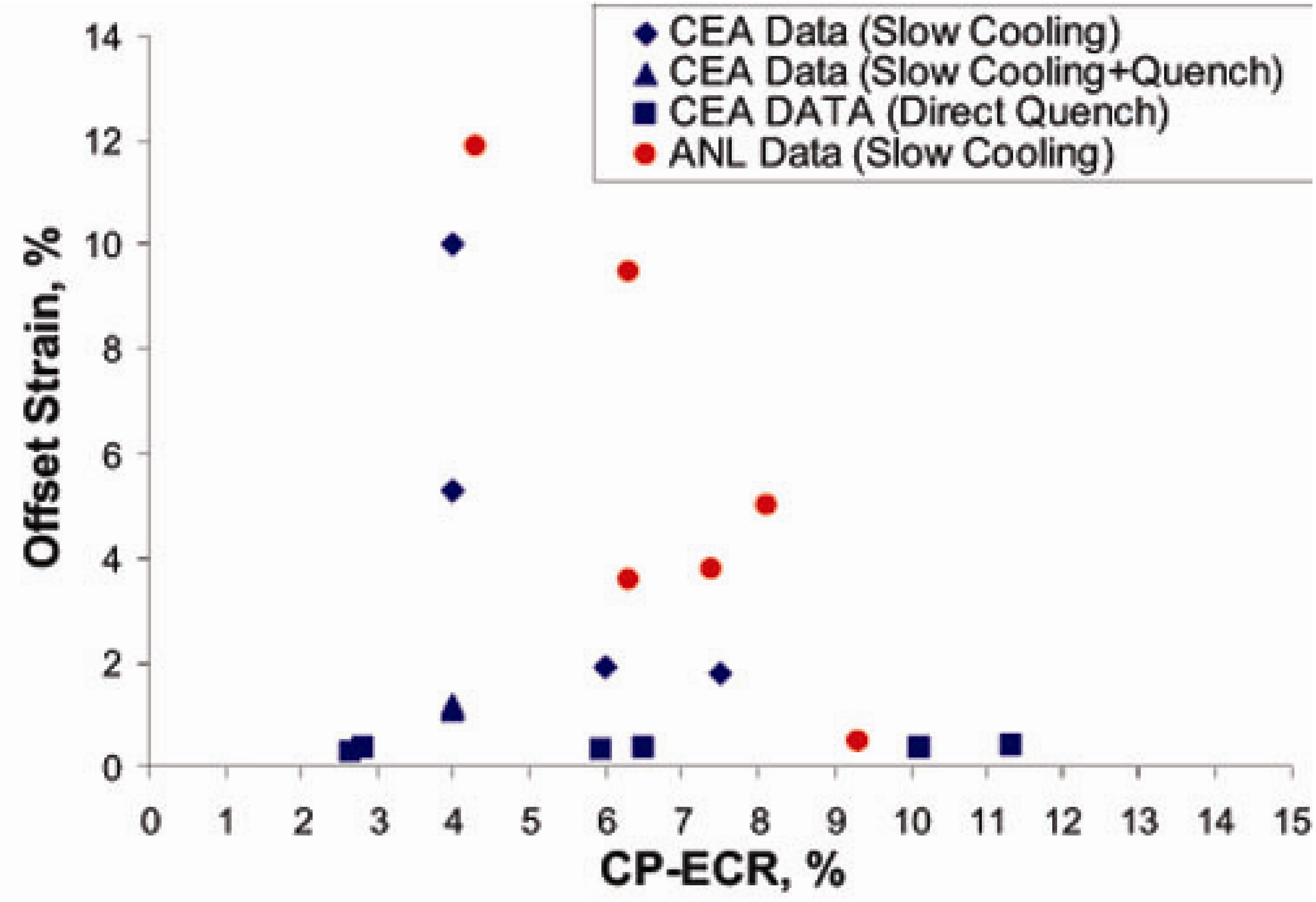
Data Inconsistencies: ANL vs. Hobson??????

- **Basis for 17% BJ-ECR and 2200ºF (Hobson Slow-strain-rate Data)**
  - Old Zry-4 cladding (ca 1970)
  - Broad-brush study over wide ranges of oxidation temperatures and times and ring-compression temperatures
  - 5 oxidation tests at 2200ºF (1204ºC)
    - *Two at 17% BJ-ECR (13% (CP-ECR)*
  - No ring compression tests at 270ºF (135ºC)
    - *RT (brittle at 17%), 93ºC (ductile at 17%), 149ºC (brittle at 25%)*
  - Crude method of determining brittle behavior
    - *Fit broken pieces (3-4) together to see if they form a circle*
- **ANL Data**
  - Modern cladding alloys
  - More focused data set (5-20% CP-ECR, 1000-1200ºC)
  - Sophisticated determination of ring-compression ductility
- **"Apples and Oranges" Comparison**

Data Inconsistencies: ANL vs. CEA??????

- Test Protocols (see NUREG/CR-6967, pp 168-171)
  - CEA: 1-sided, 10ºC/s ramp from 1000-1200ºC; hold at 1200ºC
    Quench at 1200ºC or at 800ºC (1000 s cooling)
    or at 600ºC (2300 s); or cool without quench (>9000 s)
  - ANL: 2-sided; 1-2ºC/s ramp from 1000-1200ºC; hold at 1200ºC
    (Note: 5-6% ECR accumulated at <1200ºC during ramp)
    Quench at 800ºC (38 s cooling) or at 600ºC (83 s); or cool without quench (>600 s)
- Fresh Zry-4 and M5 Cladding (Comparable Embrittlement Thresholds)
- Prehydrided Zry-4 (Comparable Results for 800ºC Quench and No Quench)
  - Results differ for 600-700ºC quench, BUT CEA cooling rates are very slow
- CEA Prehydrided vs. ANL High-Burnup Zry-4
  - Data are not comparable with respect to CP-ECR because of temperature
    - *Tmax = 1110ºC for 2.9%; 1160ºC for 4.5%, 1200ºC for ≥6% CP-ECR*
  - “Apples & Oranges” comparison
  - NEI-EPRI figure does not appear to plot ANL and CEA data correctly

NEI-EPRI Comparison of ANL and CEA Ductility Data for Zry-4 with about 600 wppm Hydrogen



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CEA Ductility Data for Prehydrided Zry-4