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

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Executive Summary

■ Testing Performed at $\leq 2200^{\circ}\text{F}$ ($\leq 1204^{\circ}\text{C}$)

- As-fabricated cladding ($800\text{-}1204^{\circ}\text{C}$)
- Prehydrided cladding ($1180\text{-}1204^{\circ}\text{C}$)
- High-burnup cladding ($1100\text{-}1200^{\circ}\text{C}$)

■ Determine Ductile-to-Brittle Transition

- Calculated oxidation level at high cladding temperature ($1000\text{-}1200^{\circ}\text{C}$)
- Time at lower temperatures for breakaway oxidation ($800\text{-}1000^{\circ}\text{C}$)

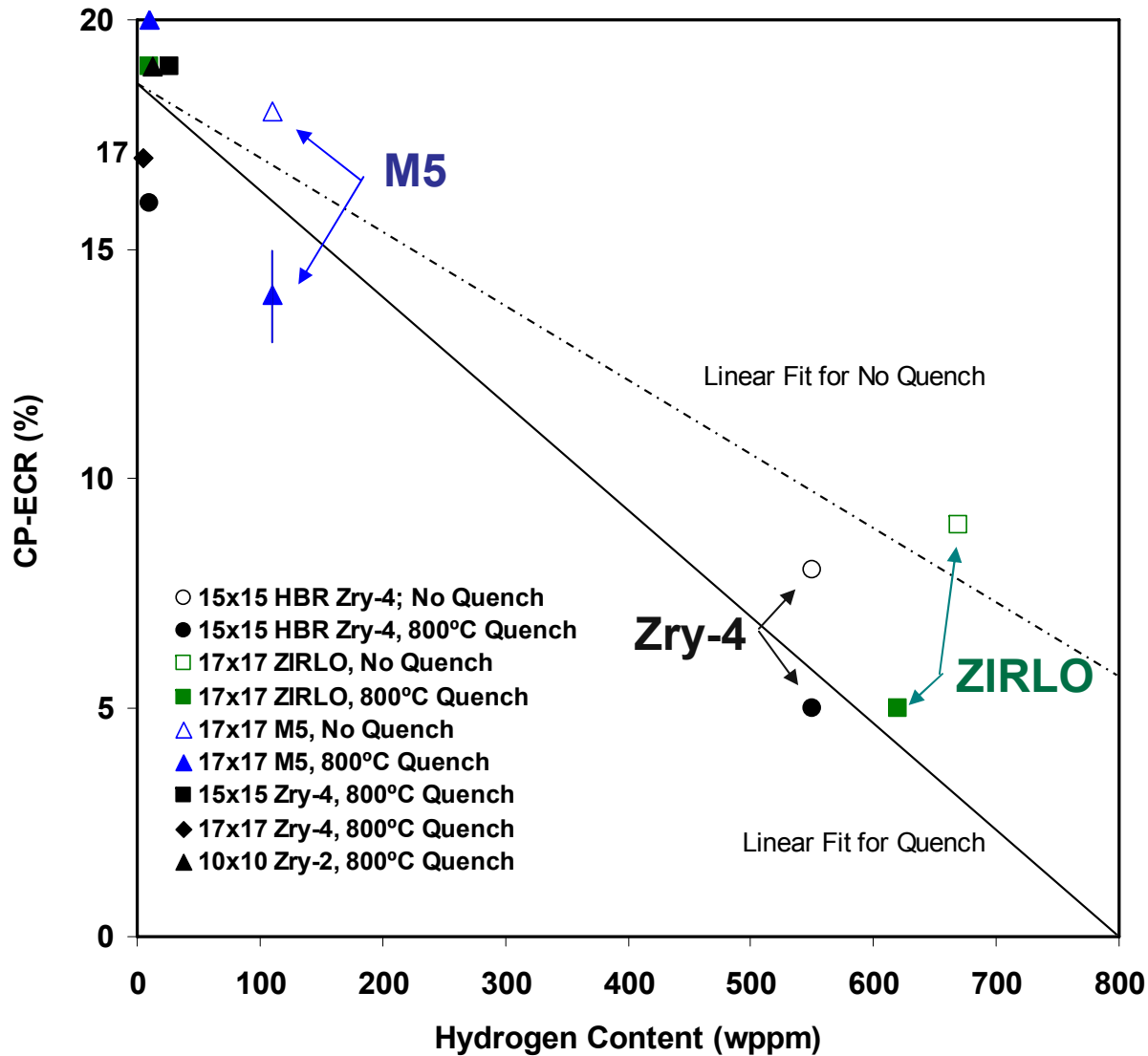
■ Quantify Decrease in Embrittlement Threshold with

- Increase in cladding temperature ($1000\text{-}1100^{\circ}\text{C}$, CP-ECR > 20%)
- Increase in hydrogen content due to in-reactor corrosion, breakaway oxidation, and secondary hydriding following burst

■ Results for Fresh and High-Burnup Cladding

- Fresh: Zry-2, Zry-4 (3 types), ZIRLO and M5
- High-burnup: Zry-4, ZIRLO and M5

Embrittlement Threshold vs. Pre-test Hydrogen Content



Notes and Additional Embrittlement Results in Section 7

■ Notes on Embrittlement Data Shown in Executive Summary

- Oxidation threshold is determined to nearest % oxidation level (CP-ECR) for which cladding retains marginal ductility; brittle behavior is observed for 1% higher oxidation level than values in figure
- Peak oxidation temperature is 1200°C for >5-8% CP-ECR
- Ductility is based on ring-compression tests conducted at 270°F (135°C)
 - *Most data points are based on a ductility limit of 1% permanent strain*
 - *Offset strain is determined for each compressed ring and used when no meaningful permanent strain can be measured (e.g., 2 cracks)*
- Pre-test hydrogen measured for corroded high-burnup ZIRLO is about 100 wppm higher than hydrogen measured after LOCA tests
- High-burnup Zry-4 and ZIRLO exhibit significant circumferential variation (± 100 wppm) in hydrogen concentration; both pre-test and post-test

■ Embrittlement Threshold vs. ZIRLO Post-Test Hydrogen (≈ 40 μm corrosion layer)

- Slow-cooled, high burnup ZIRLO: 670 ± 40 wppm \rightarrow 540 ± 100 wppm
- Quenched, high-burnup ZIRLO: 620 ± 140 wppm \rightarrow 540 ± 100 wppm

Embrittlement Threshold vs. Post-Test Hydrogen Content

