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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- μ m 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 μ m (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 ≤1200°C 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 1000°C and 1100°C
 - Fresh cladding: 16-19% oxidation for 1200°C
 - Prehydrided cladding oxidized at \leq 1200°C
 - 5-10% oxidation level for 300-600 wppm
 - >10% oxidation level for <300 wppm
 - High-burnup cladding oxidized at ≤1200°C
 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 ≤1200°C





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





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





Ductility vs. H Content for Prehydrided Zry-4 Oxidized at 1200°C 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 1000°C for 200-wppm H in Zry-4
 - Old standard-tin Zry-4 (1970s)
- Mardon et al. (2005): 5400 s at 1000°C 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±10°C: 20-40 wppm H pickup after 3800 s; 1320 wppm after 3900 s
 - Modern Zry-4
 - 985±10°C: 5000 s minimum breakaway oxidation time
 - Retested in shorter steam chamber: >5400 s breakaway time????
- ANL and Westinghouse Breakaway Oxidation Studies with ZIRLO
 - ANL: 970-985°C; 3100±300 s (scratched, smooth, pre-oxidized)
 - Westinghouse: ≈950-1020°C; >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 1200°C
- 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 1204°C; 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 1200°C and Quenched at 800°C: Results of Multiple Tests





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

Basis for 17% BJ-ECR and 2200°F (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 2200°F (1204°C)
 - Two at 17% BJ-ECR (13% (CP-ECR)
- No ring compression tests at 270°F (135°C)
 - *RT* (brittle at 17%), 93°C (ductile at 17%), 149°C (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, 1000-1200°C)
- 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, 10°C/s ramp from 1000-1200°C; hold at 1200°C
 Quench at 1200°C or at 800°C (1000 s cooling)
 or at 600°C (2300 s); or cool without quench (>9000 s)
 - ANL: 2-sided; 1-2°C/s ramp from 1000-1200°C; hold at 1200°C (Note: 5-6% ECR accumulated at <1200°C during ramp)
 Quench at 800°C (38 s cooling) or at 600°C (83 s); or cool without quench (>600 s)

Fresh Zry-4 and M5 Cladding (Comparable Embrittlement Thresholds)

- Prehydrided Zry-4 (Comparable Results for 800°C Quench and No Quench)
 - Results differ for 600-700°C 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 = 1110°C for 2.9%; 1160°C for 4.5%, 1200°C 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





CEA Ductility Data for Prehydrided Zry-4



