Enclosure 4

Presentation Materials for Closed Portion of the Meeting on Westinghouse EnCore® Chromium Coated Cladding

(Non-Proprietary)

(79 pages attached)

March 2021

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Westinghouse **EnCore**® Accident Tolerant Fuel: Chromium Coated Cladding

Technical Exchange Meeting

March 2021

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Agenda

- Introduction
  - Purpose of Meeting
  - Program Overview
- [ ]d,e
- Performance Testing
- Ongoing Work and Next Steps

NRC-Westinghouse Coated Cladding Meeting History

Previous meetings with the NRC

- February 28, 2019
  - LTR-NRC-19-9: presentation materials
  - ML19058A128

- September 18-19, 2019
  - LTR-NRC-19-54: presentation materials
  - ML19259B403

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Purpose of Meeting

- Discuss Westinghouse product and licensing plans

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- Review current status of chromium coated cladding development and testing plans

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Overview of Cr Coating Development

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Overview of Cr Coating Development

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Overview of Cr Coating Development

d,e

Testing

[d

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[ ]d,e

C.4.5: Subsurface Damage

C.4.6: Residual Stress

C.4.8: Defects

Coated Cladding Key Characteristics

a,c

Chromium [ ]d

b, c

Subsurface Condition

b, c

Chromium Coating [ ]d

b, c

As-Fabricated Coating Thickness

b, c

Chromium Coating Microstructure

b, c

Surface Morphology

b, c

Surface Roughness

b, c

[ ]b,c

b, c

[ ]b,c

b, c

[ ]d,e

b, c

Achieving Coated Cladding Characteristics

a,c

Quality Assurance

d,e

Inspection Techniques

b, c

Performance in Normal Operation: Mechanical Testing

B.6: Yield Stress and Ultimate Tensile Strength

C.1.5: Fretting Wear

C.2.3: Cladding Fatigue

C.4.1: Cracking

C.4.2: Coating Delamination

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Mechanical Strength from Tensile Testing

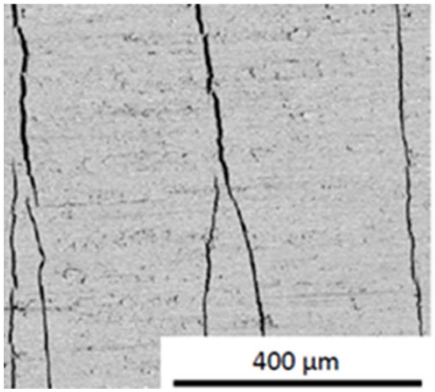
b, c

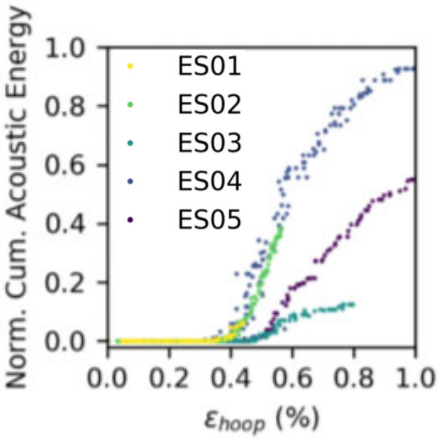
Tensile Testing to Failure
C.4.2: Coating Delamination

b, c

Expanding Plug - Hoop Strain
C.4.1: Cracking, C.4.2: Coating Delamination

[ ]a,c





D.C. Roach, A. Jarama et al, "Unveiling damage mechanisms of chromium-coated zirconium-based fuel claddings by digital image correlation and acoustic emission," Materials Science & Engineering A, A 774 (2020) 138850.

[ ]b, c

Thermal Creep Hoop Strain
C.4.1 Cracking, C.4.2 Coating Delamination

b, c

Coating Microstructure Optimization for Improved Mechanical Performance

b, c

Ball on Disk Wear Testing
C.1.5: Fretting Wear

b, c

Thermal Cycling
C.4.1: Cracking, C.4.2: Coating Delamination

b, c

Coated Cladding Key Characteristics for Mechanical Performance

a,c

Performance in Normal Operation: Corrosion and Hydrogen Pickup

B.9: Oxidation Rate

B.10: Hydrogen Pickup

Effect of Coating and Oxide on Temperature

a,c

Normal Operation Corrosion

[ ] b,c

Normal Operation Corrosion

b,c

Corrosion in Steam

b,c

Metallography after Steam Autoclave Exposure

b, c

Coated Cladding Key Characteristics for Corrosion

a,c

Performance in High Temperature Oxidation Scenarios

B.9: Oxidation Rate

B.12: High Temperature Steam Oxidation Rate

C.3.5: Cladding Embrittlement

C.4.3: Chromium-Zirconium Interdiffusion

High Temperature Oxidation Kinetics

a,c

High Temperature Oxidation Kinetics

a,c

High Temperature Oxidation Kinetics

a,c

High Temperature Oxidation Kinetics

a,c

High Temperature Oxidation: Data Analysis

a,c

Post-Quench Ductility

b,c

Post-Quench Ductility

[a,c]

High Temperature Oxidation

- Protective
  - Formation of Cr_2O_3
  - Diffusion of Cr into Zr > Zr growth into Cr
- Transition
  - Formation of intergranular ZrO_2 along Cr grain boundaries
  - Intergranular O diffusion penetrates $ZrCr_2$, forming α-Zr(O)
- Loss of Protection
  - Significant O penetration yields ZrO_2 and α-Zr(O) beneath coating

See Brachet, J.C. et Al., *Corrosion Science*, May 2020 for illustrations

Maintaining a minimum thickness ensures fully protective coating

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Coated Cladding Key Characteristics for High Temperature Oxidation

a,c

Performance in Balloon & Burst Conditions

B.11: High Temperature Ballooning

C.3.3: Bursting

C.3.8: Fuel Rod Ballooning

Initial Burst Tests

a,c

Expanded Testing

a,c

Expanded Testing

[a,c]

LOCA Burst Behavior

a,b,c

[ ]d,e

a,c

[ ] d,e

a,c

Testing for [ ]d

a,c

Coated Cladding Key Characteristics for Burst

a,c

Performance in Departure from Nucleate Boiling (DNB) Conditions

C.2.4: Cladding Oxidation, Hydriding, and Crud (Effect on DNB)

C.2.10: Boiling Crisis

C.3.1: Overheating of the Cladding

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Westinghouse Advanced Loop Tester (WALT)

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WALT Test Results: Cold Spray Coating and Crud

a,c

Preliminary WALT CHF Test Results for [ ] d,e

a,c

Coated Cladding Key Characteristics for CHF

a,c

Performance in Normal Operation: Irradiation Testing

C.4.4: Radiation Effects on Chromium

Test Reactor Irradiation Campaigns

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MITR Q3 2020 PIE Visuals

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LTRs

- Exelon Byron Unit 2:
  - 2019 Insertion: 20 cold spray Cr coated cladding LTRs (UO_2 and ADOPT pellets)
  - 2020 EOC1: ~30 GWD/MTU
  - EOC2: Exposures and outage dependent on status of Byron nuclear power plant
- Tractebel Doel Unit 4:
  - 2020 Insertion: 32 cold spray Cr coated cladding LTRs (UO_2 pellets)

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LTR programs acquire valuable operational experience for Cr coated cladding

Byron Unit 2 EOC22 Outage – ATF LTRs

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Coated Cladding Key Characteristics for Irradiation

a,c

Ongoing Work and Next Steps

Development

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Licensing

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Plans for Material Performance Enhancements

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Licensing

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Anticipated Timeline

[d,e]

Summary

[d,e]