

Enclosure 4

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

(Non-Proprietary)

(79 pages attached)

March 2021

**Westinghouse Electric Company
1000 Westinghouse Drive
Cranberry Township, PA 16066**

**© 2021 Westinghouse Electric Company LLC
All Rights Reserved**

Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

***EnCore**, **ADOPT**, and **AXIOM** are trademarks or registered trademarks of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.*



The following material is based upon work supported by the United States Department of Energy under Award Number DE-NE0008824

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.



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

Technical Exchange Meeting
March 2021

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

Purpose of Meeting

- Discuss Westinghouse product and licensing plans



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

Overview of Cr Coating Development

d,e



Overview of Cr Coating Development

d,e



Overview of Cr Coating Development

d,e



Testing



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[]^{d,e}

C.4.5: Subsurface Damage

C.4.6: Residual Stress

C.4.8: Defects

Coated Cladding Key Characteristics

a,c



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

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

Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[

]b,c

b, c



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[

]b,c

b, c



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[

]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

Mechanical Strength from Tensile Testing

b, c

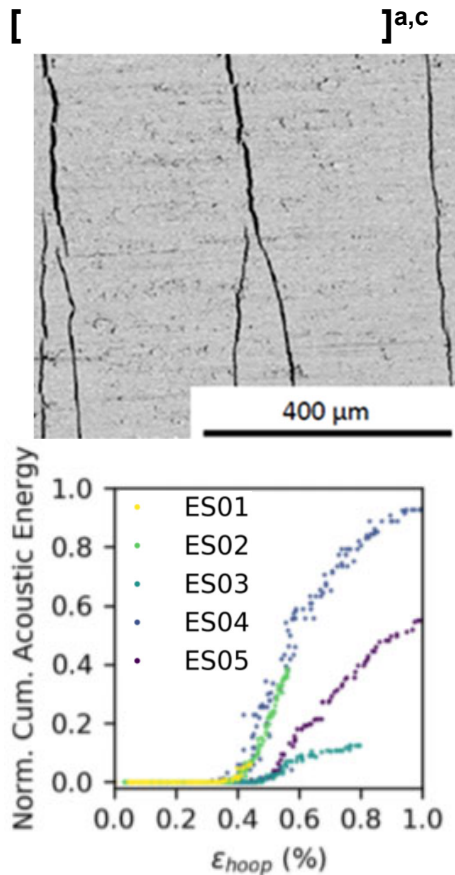
Tensile Testing to Failure

C.4.2: Coating Delamination

b, c

Expanding Plug - Hoop Strain

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



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.



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 $\alpha\text{-Zr(O)}$
- Loss of Protection
 - Significant O penetration yields ZrO_2 and $\alpha\text{-Zr(O)}$ beneath coating

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

Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[

]d,e

a,c



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

Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[

]d,e

a,c



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

[

] 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

Westinghouse Advanced Loop Tester (WALT)

a,c



WALT Test Results: Cold Spray Coating and Crud

a,c

Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

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

d,e

MITR Q3 2020 PIE Visuals

d,e



LTRs

- Exelon Byron Unit 2:
 - 2019 Insertion: 20 cold spray Cr coated cladding LTRs (UO₂ 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 (UO₂ pellets)^{d,e}



**LTR programs acquire valuable
operational experience for Cr
coated cladding**

Byron Unit 2 EOC22 Outage – ATF LTRs



Coated Cladding Key Characteristics for Irradiation

a,c



Ongoing Work and Next Steps

Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

Development

d,e



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

Licensing

d,e



Plans for Material Performance Enhancements

d,e



Westinghouse Non-Proprietary Class 3

© 2021 Westinghouse Electric Company LLC. All Rights Reserved.

Licensing



Anticipated Timeline



Summary

d,e

