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PROtect Chromium-Coated Cladding Test Plan Update

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Framatome/NRC Virtual

November 10, 2021

Meeting Objectives

- Provide an update of testing status for PROtect chromium-coated cladding
- Provide an opportunity for NRC feedback
- Inform Framatome’s plan to provide property-specific updates to NRC in 2022

Agenda

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Background

Morris Byram

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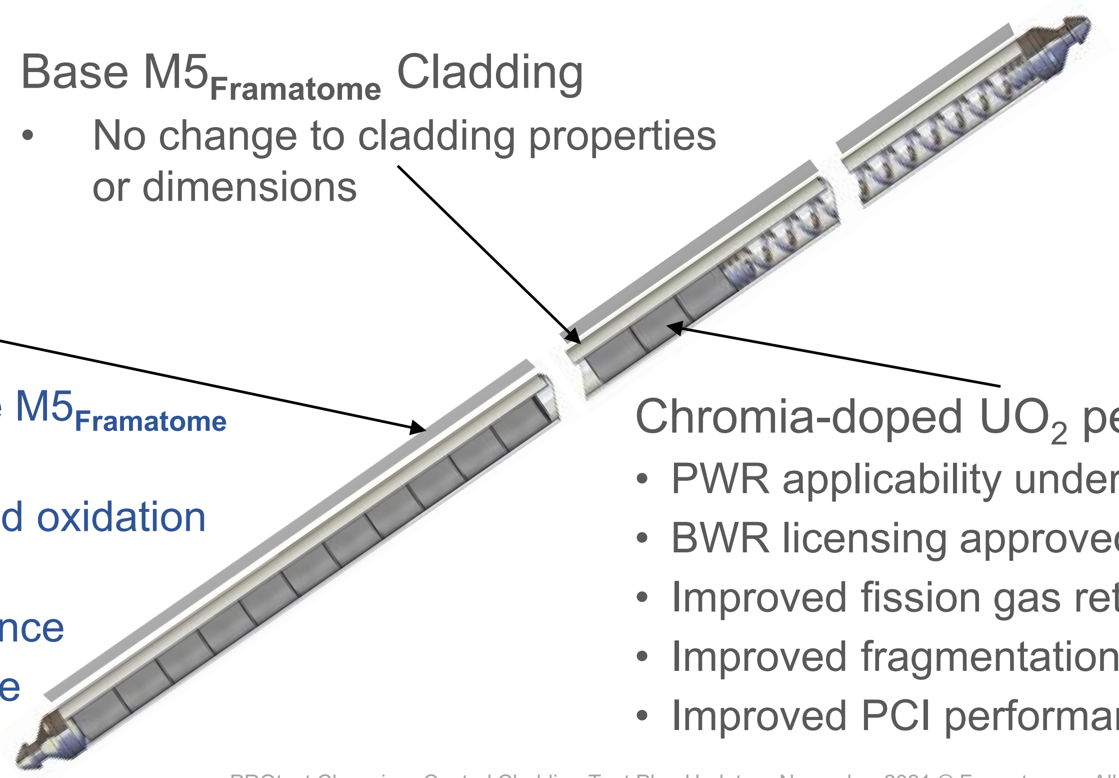
Background

- March 2017, Framatome introduced the Enhanced Accident Tolerant Fuel (EATF) Program to NRC
- In 2017 and 2018, frequent EATF program updates were provided to NRC
- January 17, 2019, presented the status of activities related to the chromium-coated (Cr-coated) cladding design features with an overview of Framatome's design process
- February 27, 2019, provided an EATF status update of Cr-coated cladding
- July 9 – 11, 2019, provided details of the Cr-coated cladding product and testing to NRC during a 2½ day audit in Lynchburg, Virginia
- November 5, 2020, Framatome provided a Cr-coated cladding test plan update
- Annual Framatome/NRC Fuel Performance Meetings include operating experience of EATF PROtect Lead Test Assemblies (LTAs) and Lead Test Rods (LTRs), most recently September 14, 2021

PROtect Solution: Chromium-Coated Cladding / Chromia-doped Pellets

Base $M5_{Framatome}$ Cladding

- No change to cladding properties or dimensions



Cr-coating

- 10-20 µm
- Does not change base $M5_{Framatome}$ cladding
- Improved corrosion and oxidation resistance
- Improved wear resistance
- Reduced LOCA rupture

Chromia-doped UO_2 pellets

- PWR applicability under NRC review
- BWR licensing approved
- Improved fission gas retention
- Improved fragmentation behavior
- Improved PCI performance

Irradiated Testing Program

Kiran Nimishakavi

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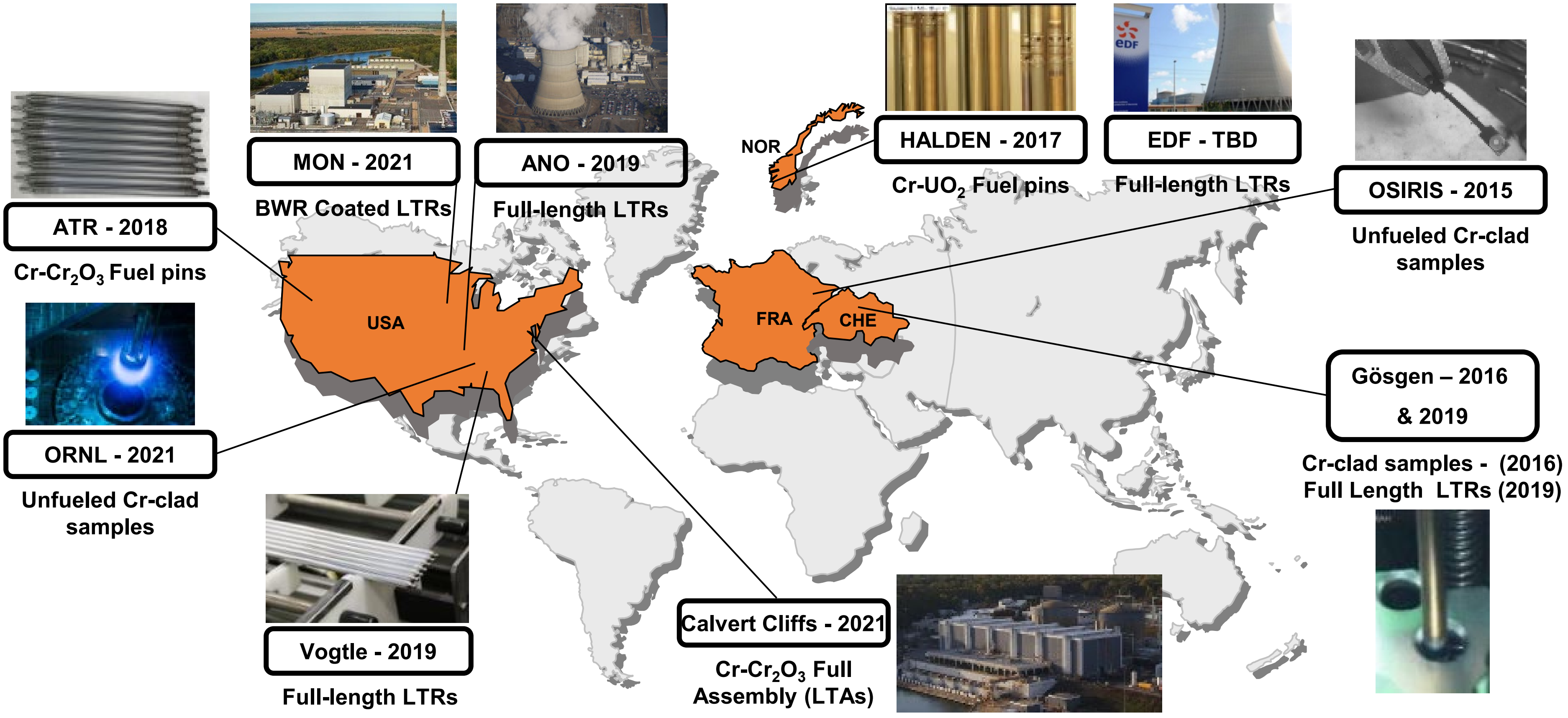
Utilizing both Commercial and Test Reactors



OSIRIS Irradiation – Coating Adhesion

Expansion Due to Compression (EDC)
21% deformation

© CEA

This confirms the behavior observed during out-of-pile testing

No delamination after 21% deformation = Excellent adherence of the coating

Cr-coated specimens were irradiated in OSIRIS reactor at CEA

- Irradiation finished in December 2015

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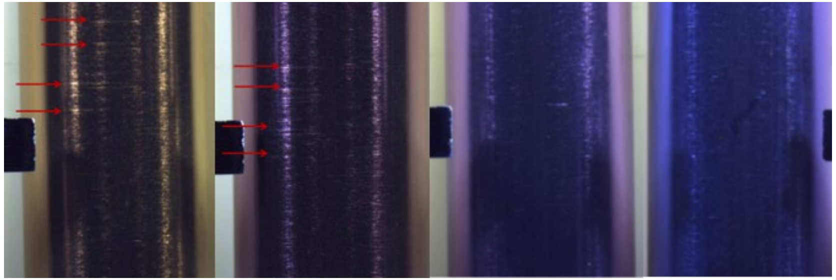
- Excellent adherence to underlying substrate

IMAGO



Pre-damaged samples show no coating delamination at the damaged region after three 1-year cycles

- First irradiation of ATF concepts in a commercial reactor
- Onsite inspection were performed up to 5th cycle in 2021
- No sign of degradation after five annual cycles of irradiation
- Coatings was dense with no observable oxide layer on the surface

Cr-coating remained adherent and showed no signs of delamination

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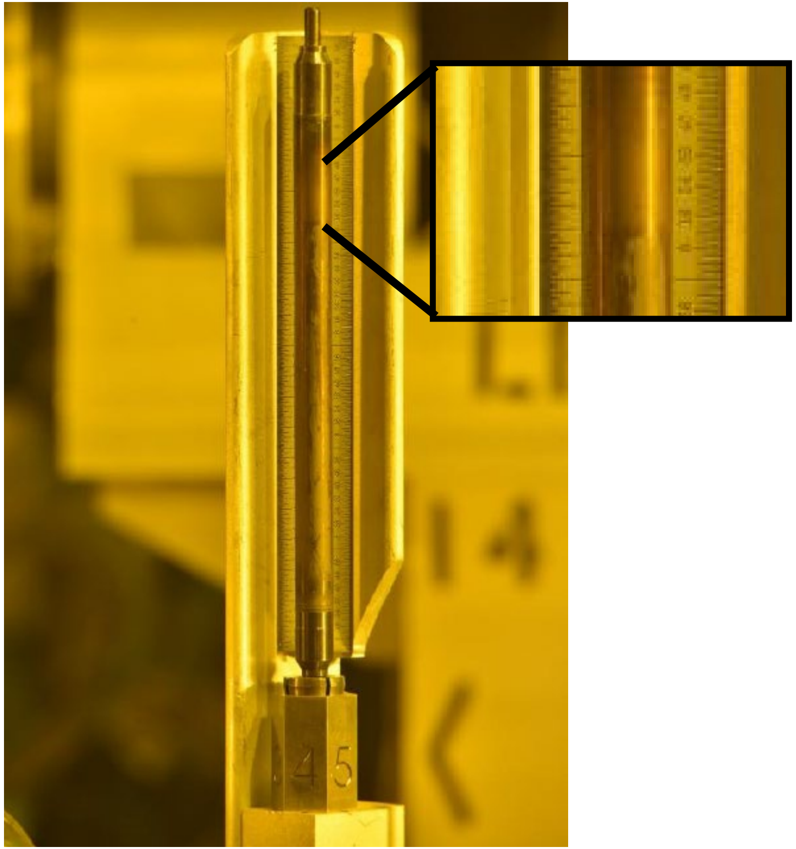
ATR PIE Scope



Cr-coated fuel rod after 15 GWd/MTU

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ATR PIE Results

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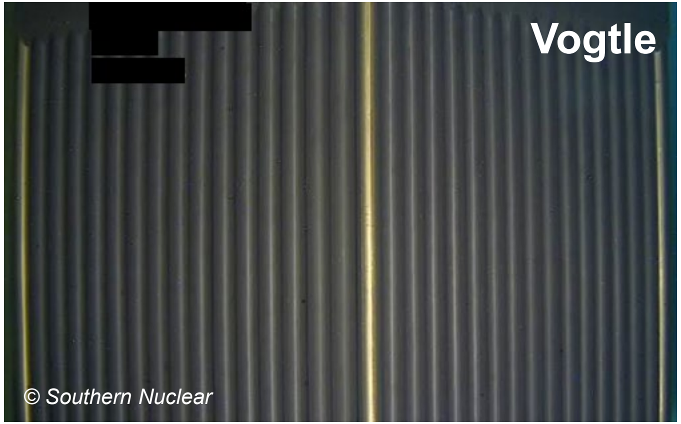
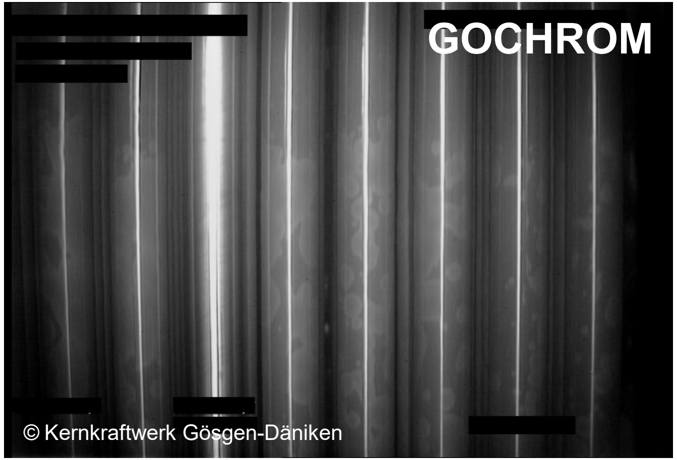
ATR Rodlets Results

- Three ATF-2 Rodlets were discharged at 30 GWd/MTU
- Surface color is driven by crud deposits
- Coating integrity is maintained
- Non-destructive and destructive examinations will be performed in GFY22

HFIR Irradiation





In-Pile LTRs

Vogtle

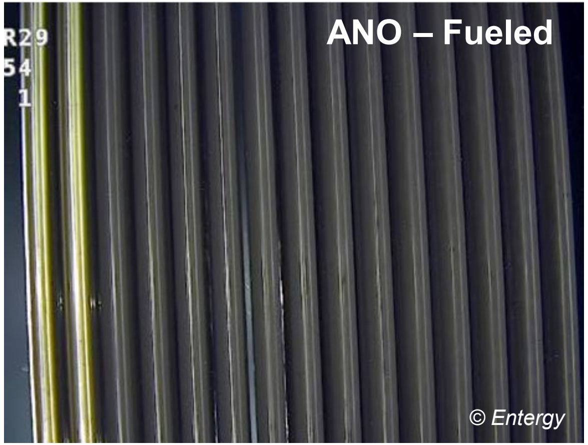
- 16 full length Cr-coated fueled rods; four in each assembly
- First cycle visuals were collected in Sep 2020
- Excellent irradiation behavior; back in for 2nd cycle

GOCHROM

- 20 full length Cr-coated fueled rods total in two assemblies
- Operation began June 2019
- Visuals, length and diameter measurement after 1- and 2-year cycles were collected

Cr-coated cladding showed bright appearance with no unusual features

GOCHROM PIE Plan



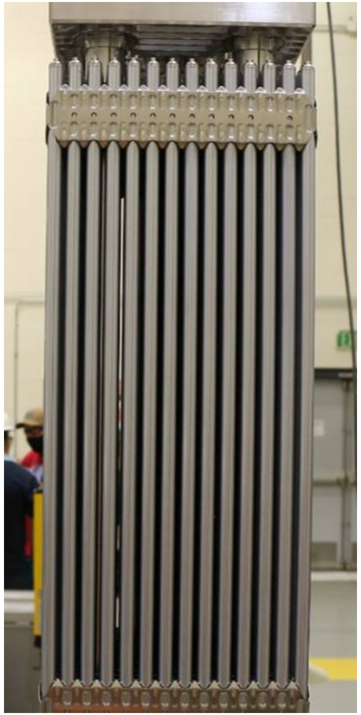
Arkansas Nuclear One (ANO) LTRs

- 32 full length Cr-coated rods provided
- 16 rods were installed in 8 irradiated fuel assemblies that will be reinserted into peripheral assembly locations which will reside in baffle locations that have exhibited past baffle/assembly interaction (leading to excessive rod wear)
- The remaining 16 rods were installed in fresh fuel
- Operation began in November 2019 and first cycle visuals were collected in April 2021

Both fueled and unfueled Cr-coated rods indicate significant reduction in corrosion

Calvert Cliffs Lead Test Assembly

- First full EATF fuel assembly of Cr-coated rods and chromia-doped fuel
- Fuel was manufactured in September 2020
- LTA was shipped to Calvert Cliffs in January 2021
- Irradiation began in March 2021
- End-of-Cycle 1 onsite inspections planned:
  - Visuals
  - Fuel Rod Length and Diameter
  - Fuel Assembly Length
  - Fuel Rod Bow



Calvert Cliffs

Will provide information on Cr-Cr_2O_3 assembly behavior

Summary

2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025

Material Properties and Testing Overview

Evrard Lacroix

Material Properties

- Eutectic
- Melting point
- Density
- Heat Capacity
- Thermal Expansion
- Thermal Diffusivity
- Emissivity
- Corrosion and Hydrogen Uptake
- Yield Strength (YS), Ultimate Tensile Strength (UTS), Elongation
- Elastic properties
- Creep
- Fatigue
- Thermal Fatigue

Confirmatory Tests

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Eutectic

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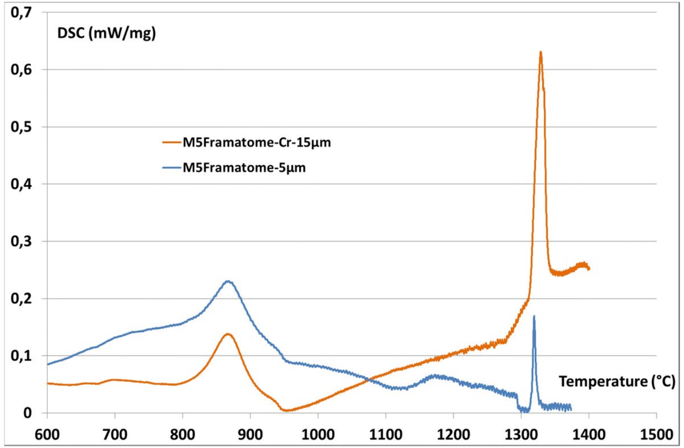
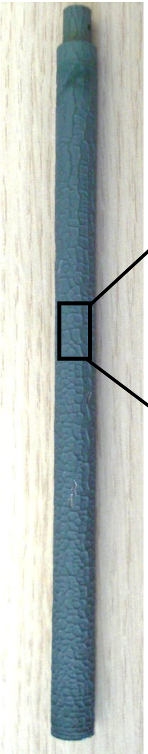


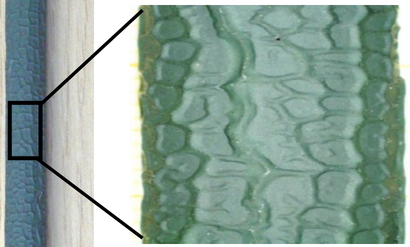
T (5µm of Cr) = 1320°C
T (15µm of Cr) = 1328°C

Eutectic point is 1330°C

Melting point



Steam oxidation at 1400°C for 100s (at 1°C/s)



Eutectic transformation:
Wrinkled crocodile-like skin

Density

Similar to $M5_{Framatome}$ cladding

Heat Capacity

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Thermal Expansion

Thermal Diffusivity

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Emissivity

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Corrosion Behavior

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Significantly reduced corrosion compared to $M5_{Framatome}$ cladding

Corrosion Behavior

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Significantly reduced corrosion compared to $M5_{Framatome}$ cladding

Corrosion Behavior (Steam)

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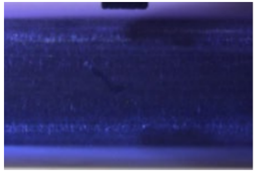
Significantly reduced corrosion compared to $M5_{Framatome}$ cladding

Corrosion Behavior (Irradiated)

5 cycles IMAGO



Significantly reduced corrosion compared to $M5_{Framatome}$ cladding

Corrosion Behavior (Pre-Damaged Coating)

No detrimental impact on underlying substrate observed

Hydrogen Uptake Behavior

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Hydrogen Uptake Behavior (Irradiated)

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Uniaxial Yield Strength, UTS, Elongation

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Uniaxial Yield Strength, UTS, Elongation (irradiated)

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Biaxial Yield Strength, UTS, Elongation

Biaxial Yield Strength, UTS, Elongation (Irradiated)

Young's Modulus, Poisson's Ratio

Low Stress Thermal Diametric Creep

Low Stress Diametric Creep (Irradiated)

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Thermal Diametric Creep (High Stress)

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High Stress Creep (Irradiated)

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Thermal Axial Creep

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Fatigue

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Fatigue (Irradiated)

Thermal Fatigue

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Thermal Fatigue (Irradiated)

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Component Behavior

Brian Painter

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Component Behaviors

- Fuel Rod Growth
- Fuel Rod Bow
- Fuel Assembly Growth
- Grid-to-Rod Fretting
- Mechanical Seismic Testing

Fuel Rod Growth

- Data is collected through PIE measurements to develop empirical models for upper and lower design limits
- The design limits in BAW-10227P Rev. 2 will be applied to the Cr-Cr fuel rods
  - A significant amount of Cr-doped fuel rod growth is available from European GAIA lead assembly programs
- The base material and applied loadings will still define the growth response

The chromium coating is not expected to alter the fuel rod growth behavior

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Fuel Rod Bow

- The mechanical evaluations for fuel rod bow assess the likelihood that a fuel assembly design will experience more fuel rod bow than the operating experience
  - Qualitative comparisons of relevant design parameters
- Testing:

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Fuel Assembly Growth

- Data is collected through PIE measurements to develop empirical models for upper and lower design limits
- The design limits in ANP-10334P-A Rev. 0 will be extended to the Cr-Cr fuel assemblies
- The Q12 assembly growth database covers many different assembly structures, combinations of spacer grid material, component loadings
- A large buffer exists between the measured growth and the upper design limit

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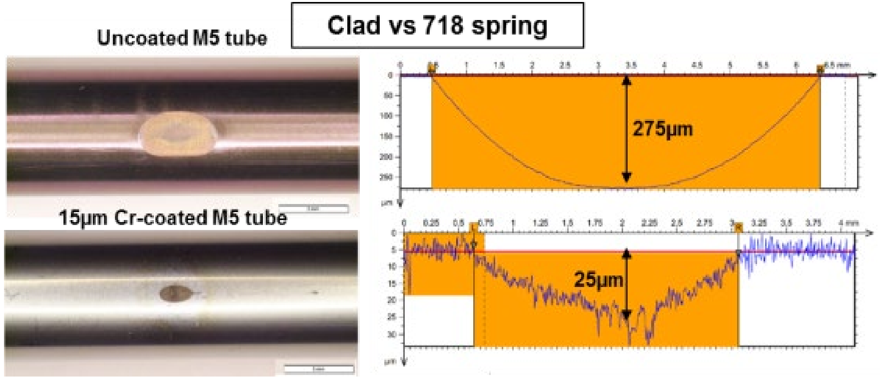
The fuel assembly growth limits remain valid for Cr-Cr fuel rods

Grid-to-Rod Fretting

Cladding-to-Grid Wear Testing (AURORE mono-excitation bench)

- Test Objective – Evaluate the material wear kinetics of the Cr-coating
- Test Scope:
  - Wear/material loss experiments of spacer grid and cladding segments at operating conditions
  - Control of displacement and contact force of cladding against grid support
  - Short duration – high demand conditions to compare coating performance

» **Clear benefit of Cr-coating on wear depth and volume**



Grid-to-Rod Fretting

Cladding-to-Grid Wear Testing (AURORE bi-excitation bench)

- Test Objective – Evaluate the material wear kinetics of the Cr-coating under representative conditions and motions (typical of Flow-Induced Vibration)
- Test Scope:
  - Wear/material loss experiments of spacer grid and cladding segments at room temperature and operating conditions
  - Control of displacement and contact force of cladding against grid support
  - Comparisons of coated/uncoated, spacer grid material, temperature effects
- Testing is planned to start by end of 2021/early 2022
- Supports reload readiness and License Amendment Requests

Grid-to-Rod Fretting

Life and Wear (Endurance) Testing

- Test Objective – Assess the fretting wear performance of the fuel assembly/cladding material under representative conditions
- Test Scope:
  - A full-size mockup assembly is subjected to axial and transverse coolant flow for 1000 hours
  - The mockup includes bounding EOL spacer grid cell sizes
  - Any significant wear scars are fully characterized for location, depth, and volume
- The fretting results for the Cr-coated fuel rods can be compared to previous results for un-coated fuel rods
- Supports reload readiness and License Amendment Requests
- Status: Test assembly has been built and delivered to the test facility

Fuel Assembly Dynamic Properties

Mechanical and Seismic Testing

- Test Objective – Measure the dynamic properties of the EATF assembly (BOL and EOL) for seismic/LOCA evaluations
- Test Scope:
  - Full-size BOL and EOL mockup assemblies with full set of Cr-coated rods
  - Free vibration, forced vibration, and baffle impact tests for lateral models
  - Axial stiffness and axial drop tests for vertical models
- The influence of the Cr-coated surface on bundle friction and cladding stiffness will be incorporated into the seismic / LOCA accident models
- Testing expected to occur Q1 2023

Critical Heat Flux

Christina Jones

Wettability

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Wettability

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Critical Heat Flux

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Reactivity Insertion Accident

Buck Barner

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Reactivity Insertion Accident

Reactivity Insertion Accident

LOCA

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LOCA: High Temperature Phenomena and Cladding Degradation Mechanisms

LOCA: Swelling and Rupture

LOCA: High Temperature Oxidation and Failure Testing

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Summary & Next Steps

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Summary

Framatome presented:

- Test plan update for chromium-coated $M5_{Framatome}$ cladding
- Material properties and testing overview
- Component behaviors
- RIA, CHF and LOCA

Next Steps

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The alloy $\mathbf{M5}_{\mathbf{Framatome}}$ is sometimes named “**M5**” in this document.

Acronyms/Nomenclature

ANO	Arkansas Nuclear One nuclear power plant
ATF	Accident Tolerant Fuel
ATR	Advanced Test Reactor
AURORE	Framatome’s test rig at Le Creusot
BOL	Beginning of Life
BWR	Boiling Water Reactor
CCL	Calvert Cliffs nuclear power plant
CEA	Commissariat à l'énergie atomique (French Alternative Energies and Atomic Energy Commission)
CHF	Critical Heat Flux
Cr	Chromium
Cr_2O_3	Chromia (chromium oxide)
$Cr\text{-}Cr_2O_3$	PROtect concept: Chromium-coated $M5_{Framatome}$ cladding with chromia-doped pellets
DOE	Department of Energy
dpa	Displacements per atom
DSE	Differential Scanning Calorimetry
EATF	Enhanced Accident Tolerant Fuel
EDC	Expansion Due to Compression
EDS	Energy Dispersive X-ray Spectroscopy
EDF	Électricité de France (Electricity of France)
EOL	End of Life
EPRI	Electric Power Research Institute
GFY	Government Fiscal Year
GWd/MTU	Gigawatt-Days per Metric Ton of Uranium
HFIR	High Flux Isotope Reactor
ISG	Interim Staff Guidance
JAERI	Japan Atomic Energy Research Institute
LOCA	Loss of Coolant Accident
LTA	Lead Test Assembly
LTR	Lead Test Rod
MON	Monticello nuclear power plant
MPa	Mega Pascal
NRC	Nuclear Regulatory Commission
ORNL	Oakridge National Laboratory
PCI	Pellet Cladding Interaction
PCMI	Pellet-Clad Mechanical Interaction
PIE	Post-Irradiation Examination
PSI	Paul Scherrer Institute
PST	Plane-Strain Tension
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System
RG	Regulatory Guide
RIA	Reactivity Insertion Accident
RT	Room Temperature
UB	Upper Bound
UO_2	Uranium oxide
YS	Yield Strength
Zr	Zirconium

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