Evaluation of the behavior of Cr-coated M5^R cladding in nominal and accidental conditions

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Evaluation of the Behavior of Cr-coated M5® Cladding in Nominal and Accidental Conditions

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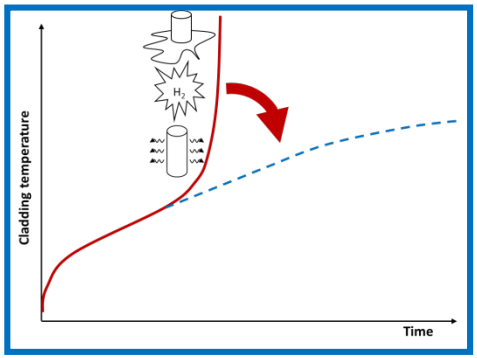
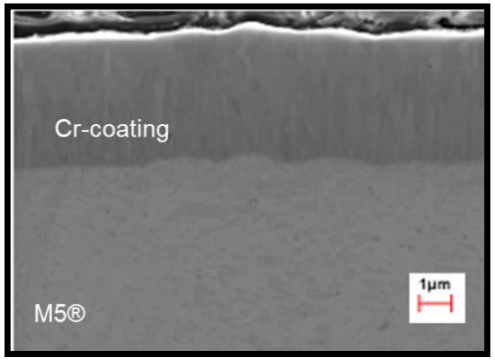
Outline



- **Enhanced Accident Tolerant Fuel (EATF) Developments at AREVA NP**



- **Behavior of Cr-Coated M5® Cladding**
  - **Description and Manufacturing**
  - **Normal Operating Conditions**
  - **Accident Conditions**

- **IMAGO: Irradiation of EATF Concepts in a Commercial PWR**

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EATF Developments at AREVA NP

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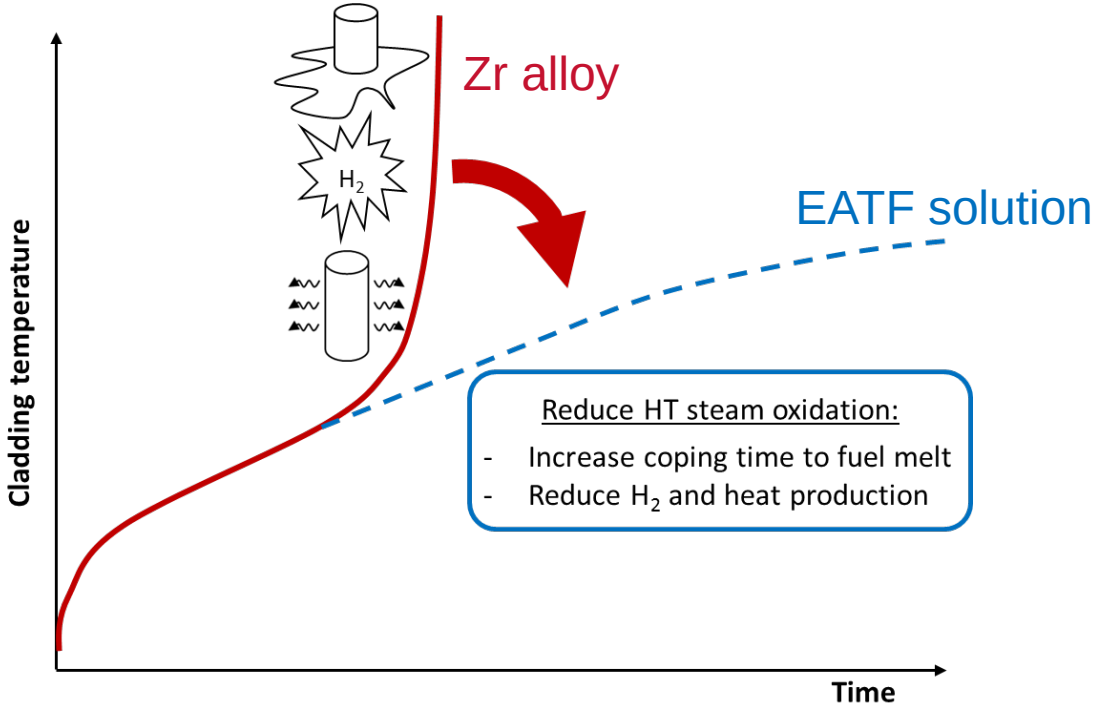
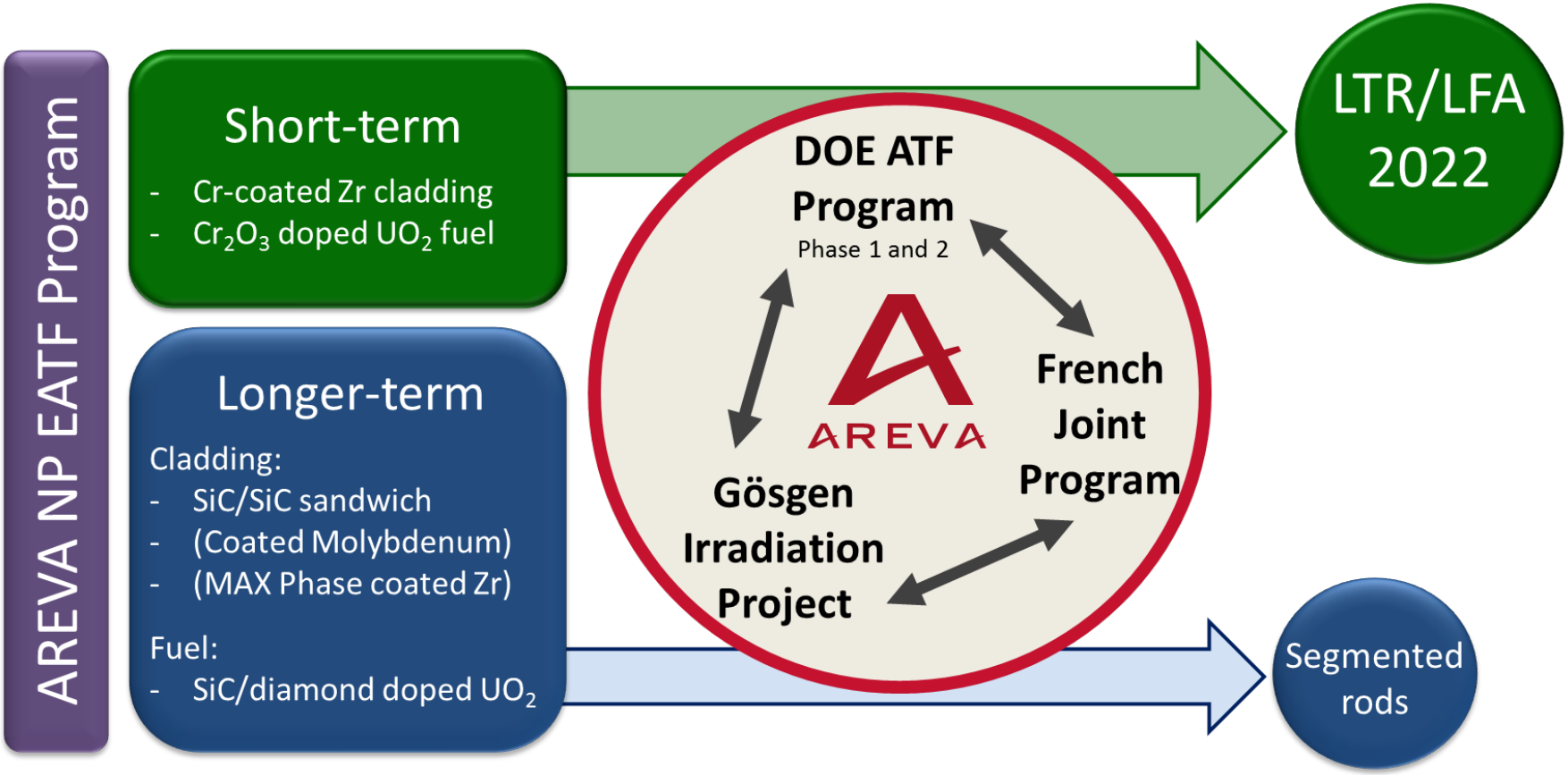
Why Develop EATF Solutions?

- **Improve fuel behavior in accident conditions to increase coping time before the core becomes unrecoverable**



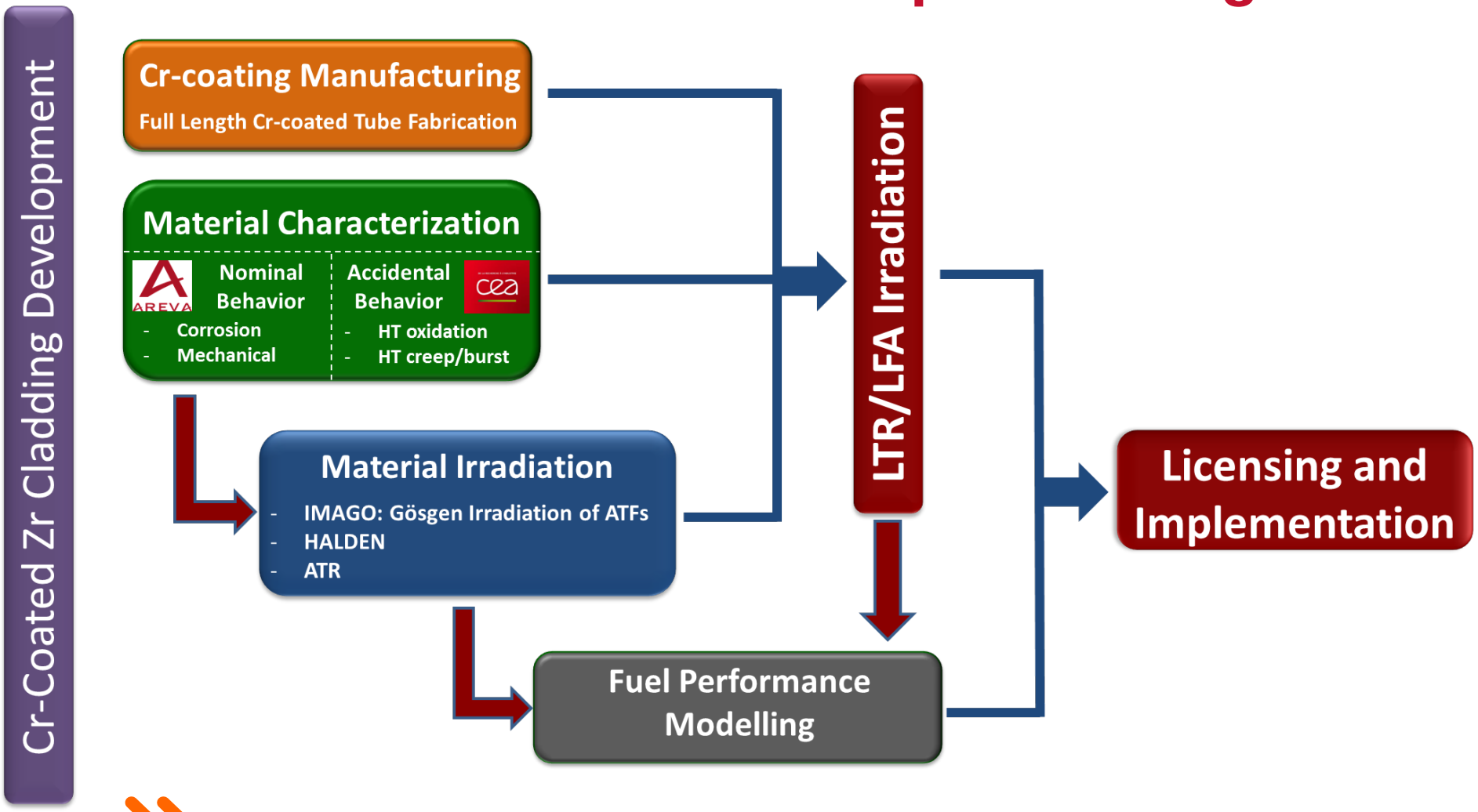
Main focus on cladding developments with emphasis on limiting the high temperature steam oxidation leading to large heat and H_2 production for zirconium alloys

AREVA NP's Worldwide Team Develops Short and Longer Term EATF Solutions



The development of Cr-coated zirconium alloy cladding with Cr_2O_3-doped UO_2 fuel is in line with the DOE's timeframe to insert LTRs or LFAs in commercial reactors by 2022

Overview of the Cr-Coated Cladding Development Program



Ease of licensing → implementation in short time frame

Behavior of Cr-Coated M5® Cladding

Description and Manufacturing

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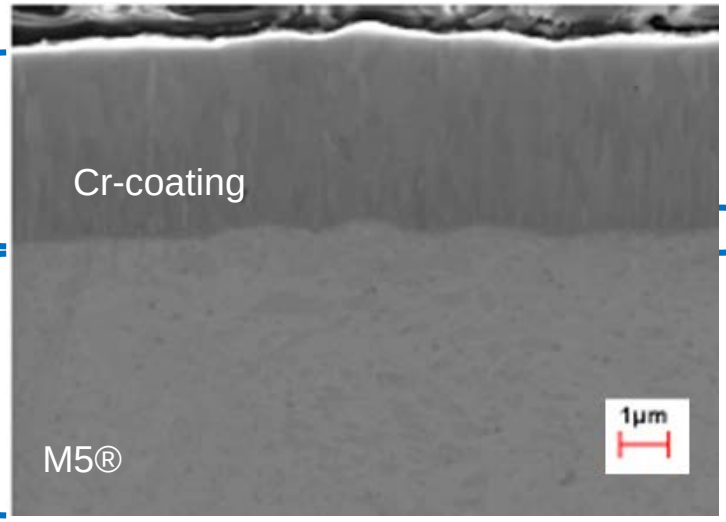
Description of the Cr-Coating

- **Cr-coating was selected for its significant reduction of HT steam oxidation**

Thin coating (5-20µm)

No modification of the underlying Zr substrate microstructure



Dense coating

+

No porosity or flaws at interface = very adherent coating

=

Very protective coating

- **Cr-coating is deposited by Physical Vapor Deposition (PVD) process**
  - **Compatible with industrial scale fabrication**

The fabrication of a prototype equipment for deposition of Cr layer on full length cladding tubes is on-going

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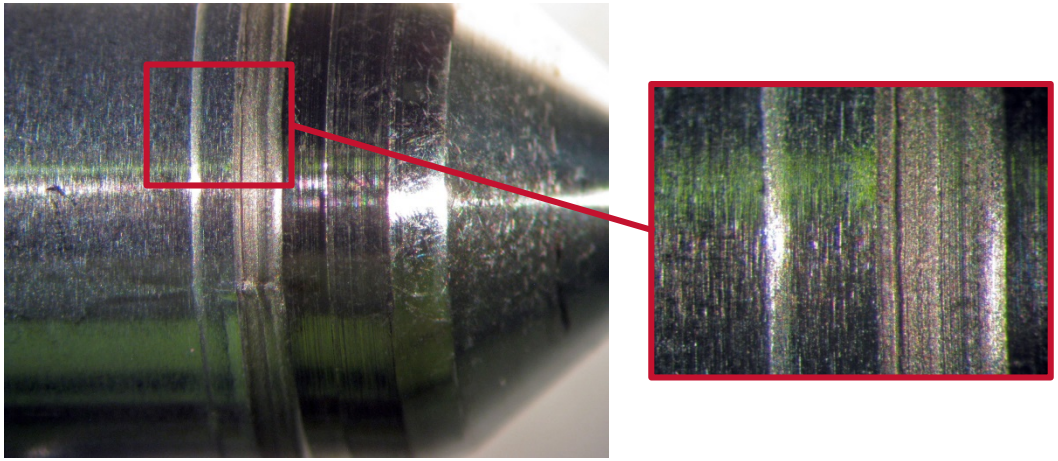
Very Good Welding Behavior of Cr-Coated M5® Tubes Using the USW Process

- **Several M5® tubes coated with Cr up to the extremity were welded with the resistance welding process (USW)**

Sound weld

Visual aspect of the weld is not affected by Cr-coating



Post weld corrosion test

Corrosion in 360°C water for 1 day (ASTM G2)

Very good behavior

Metallic Cr

Black ZrO_2

Burst tests: rupture outside weld area

The Cr-coated M5® tubes were welded successfully using the USW process → Cr-coating is fully compatible with current fuel rod manufacturing process

Behavior of Cr-Coated M5® Cladding

Normal Operating Conditions

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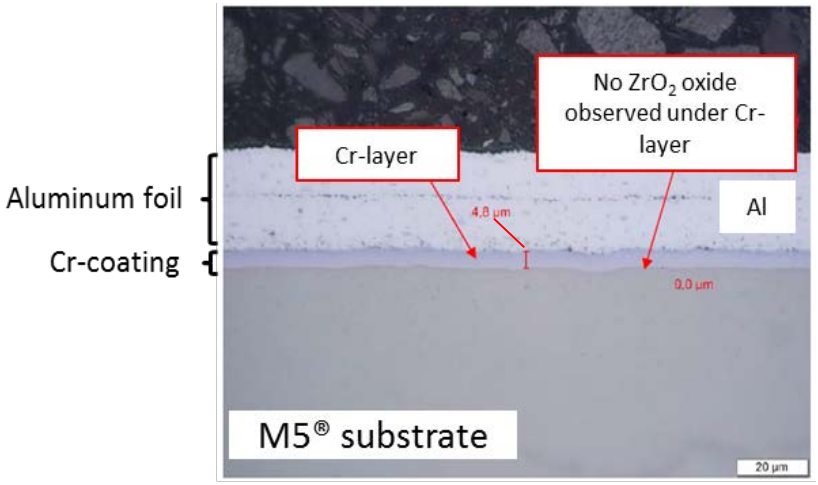
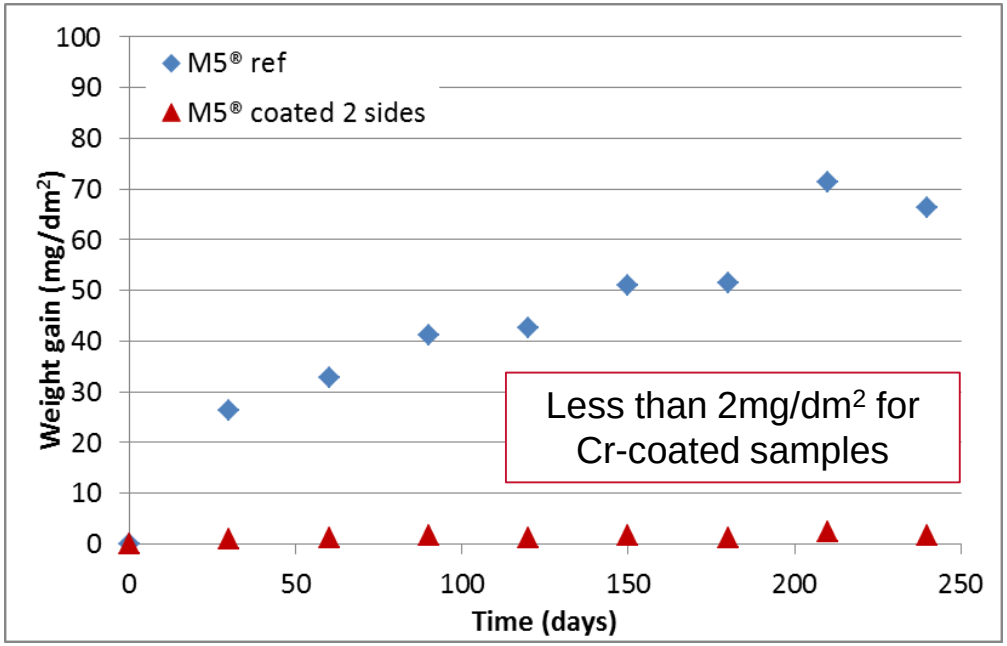
Excellent Corrosion Behavior in 360ºC PWR Conditions

- **Autoclave test in 360ºC water performed at the AREVA NP Technical Center:**
  - **Deaerated solution (<10ppb) dissolved O_2 and no added H_2**
  - **[H_3BO_3] = 650 ppm**
  - **[LiOH] = 2 ppm**





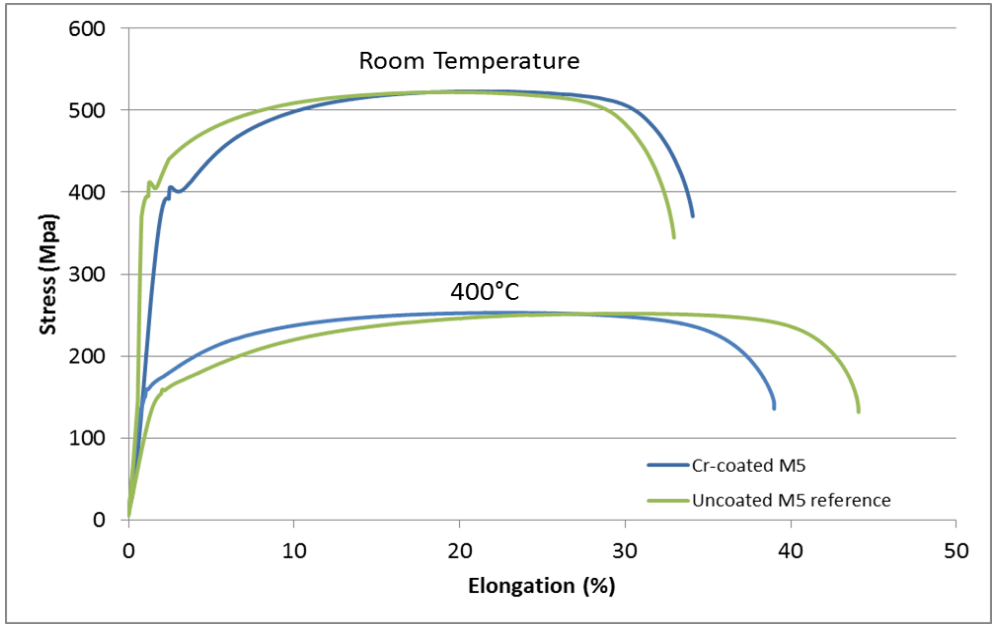
Almost no weight gain for Cr-coated samples
No delamination observed on sample surface
No dissolution of Cr in the water

Very protective coating

Similar Mechanical Behavior as Uncoated M5®

- **Tensile and radial creep tests at room temperature (RT) and 400ºC performed at the AREVA NP Research Center (CRC) in Paimboeuf**

Tensile tests



Creep tests at 400°C for 240h

Sample	Creep, ΔD/D (%) Average (Range)
Uncoated M5®	0.4 (0.1 - 0.7)
Coated M5®	0.4
Uncoated Zy-4	1.3 (0.9 – 1.8)
Coated Zy-4	1.3

Mechanical properties of coated samples fall within the range of uncoated samples → similar mechanical behavior = ease of licensing

Behavior of Cr-Coated M5® Cladding

Accident Conditions

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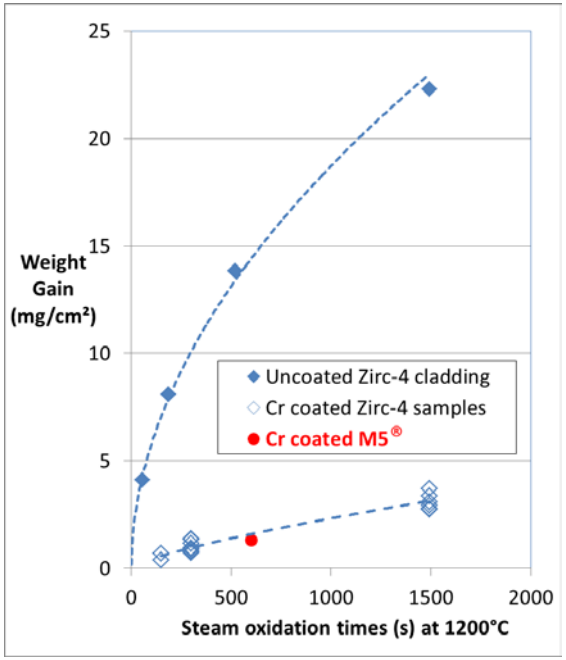
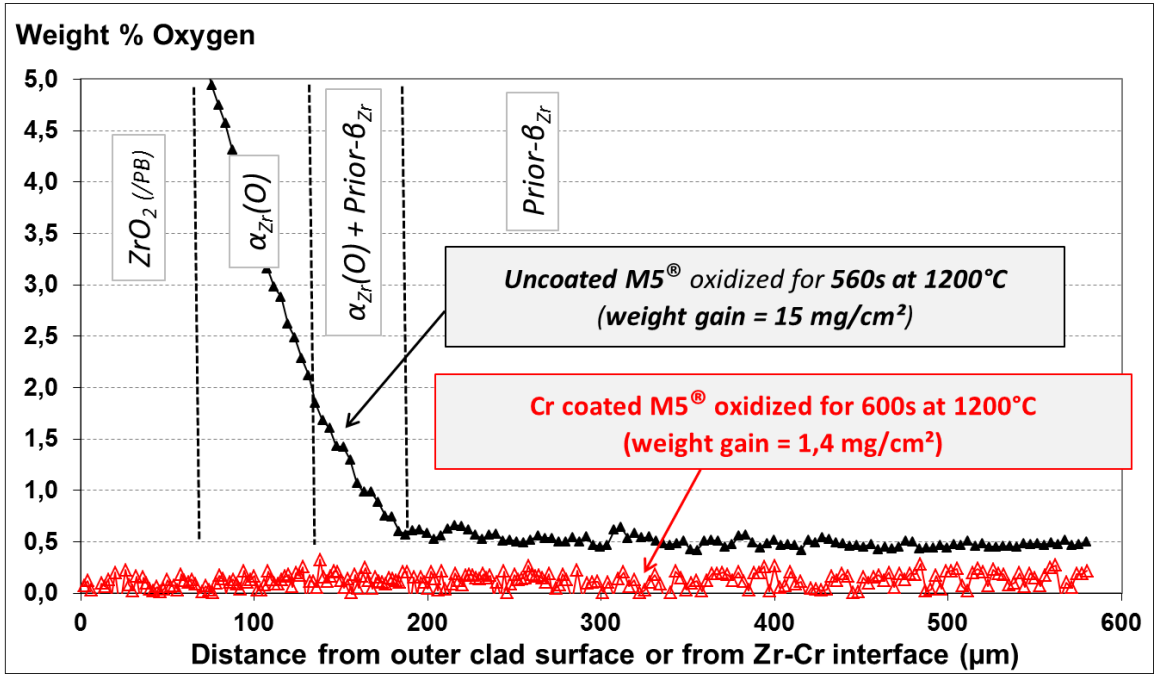
Improved High Temperature Steam Oxidation Behavior

- **HT steam oxidation tests were performed at the CEA (1200°C, 600s)**
  - **No oxygen diffusion within Zr substrate = improved post-quench ductility**
  - **Reduced heat and H_2 production**





Cr-Coated M5® cladding shows significantly reduced HT oxidation
→ significant benefits in accident conditions

Preliminary HT Ramp Tests Show Reduced Ballooning

- **Preliminary ramp tests were performed at the CEA using the EDGAR facility to evaluate the HT mechanical behavior:**
  - **Strengthening effect of Cr-coating**
  - **Significantly smaller burst opening size**
  - **Cr-coating remains adherent for high local clad deformation (burst location)**

Uncoated M5®

Cr-coated M5®

Smaller Balloon Size

1°C/s 100 bars

25°C/s 10 bars

Uncoated M5®

Cr-coated M5®

No Burst

The Cr-coating has a strengthening effect at HT which suggests improved mechanical behavior leading to significantly increased margins in Design Basis Accidents

IMAGO:
Irradiation of EATF Concepts in a Commercial PWR

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IMAGO: Irradiation of Materials for ATFs in GÖsgen Reactor

- **First irradiation of ATF concepts in a commercial PWR reactor**
- **The goals of IMAGO are:**
  - **To verify the performance of EATF concepts in representative PWR conditions**
    - Corrosion kinetics
    - Mechanical behavior
    - Evolution of the microstructure under irradiation
  - **To serve as input data for the licensing and justification of future fuel rod irradiations**
- **Irradiation of samples within Material Test Rods (MTRs) inserted within guide tubes of a fuel assembly:**
  - **Cr-coated zirconium alloys**
  - **SiC/SiC cladding tube samples**

First irradiation cycle began mid-2016

Take Away Messages

- **AREVA NP is strongly engaged in EATF developments relying on its worldwide teams with programs both in the USA and Europe**
  - **Development of both short and longer term solutions**
    - Cr_2O_3-doped UO_2 fuel with Cr-coated Zr alloy cladding
      - Technology Readiness Level (TRL) 3-4 while other ATF concepts are around TRL 2
      - Easier licensing
- **Focus on Cr-coated M5® cladding**
  - **Enhanced performance in accident conditions**
    - Reduced HT steam oxidation
    - Improved HT mechanical behavior
  - **Very good behavior in nominal conditions**
    - Very low corrosion kinetics
    - Similar mechanical properties as uncoated Zr alloy substrate = ease of licensing
- **IMAGO irradiation in the Gösgen reactor**
  - **First irradiation of EATF concepts in a commercial PWR**
  - **Input data for justification of future fuel rod irradiations**

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