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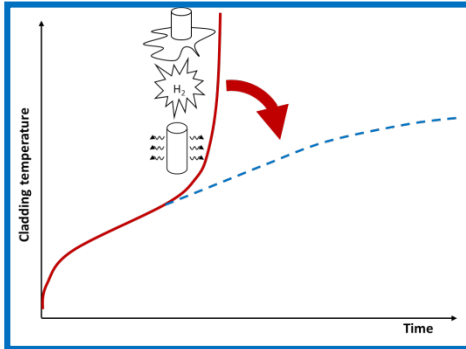
Evaluation of the Behavior of Cr-coated M5® Cladding in Nominal and Accidental Conditions

Jeremy BISCHOFF (AREVA NP)

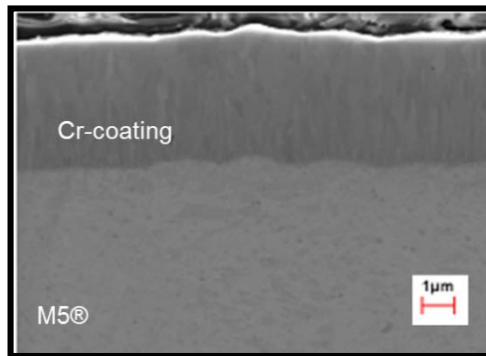
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(AREVA NP)

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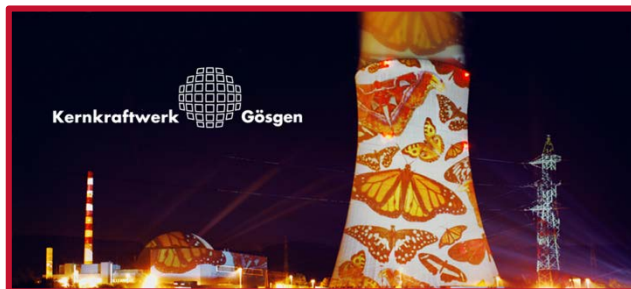


▶ Enhanced Accident Tolerant Fuel (EATF) Developments at AREVA NP



▶ Behavior of Cr-Coated M5® Cladding

- ◆ Description and Manufacturing
- ◆ Normal Operating Conditions
- ◆ Accident Conditions



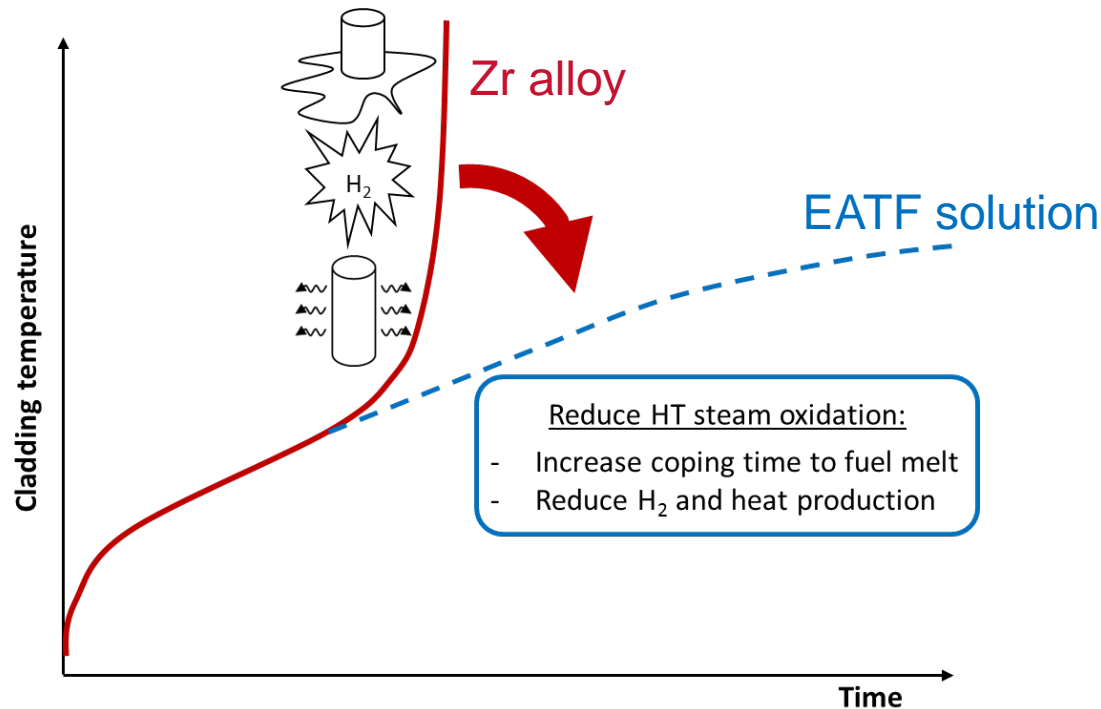
▶ IMAGO: Irradiation of EATF Concepts in a Commercial PWR

EATF Developments at AREVA NP



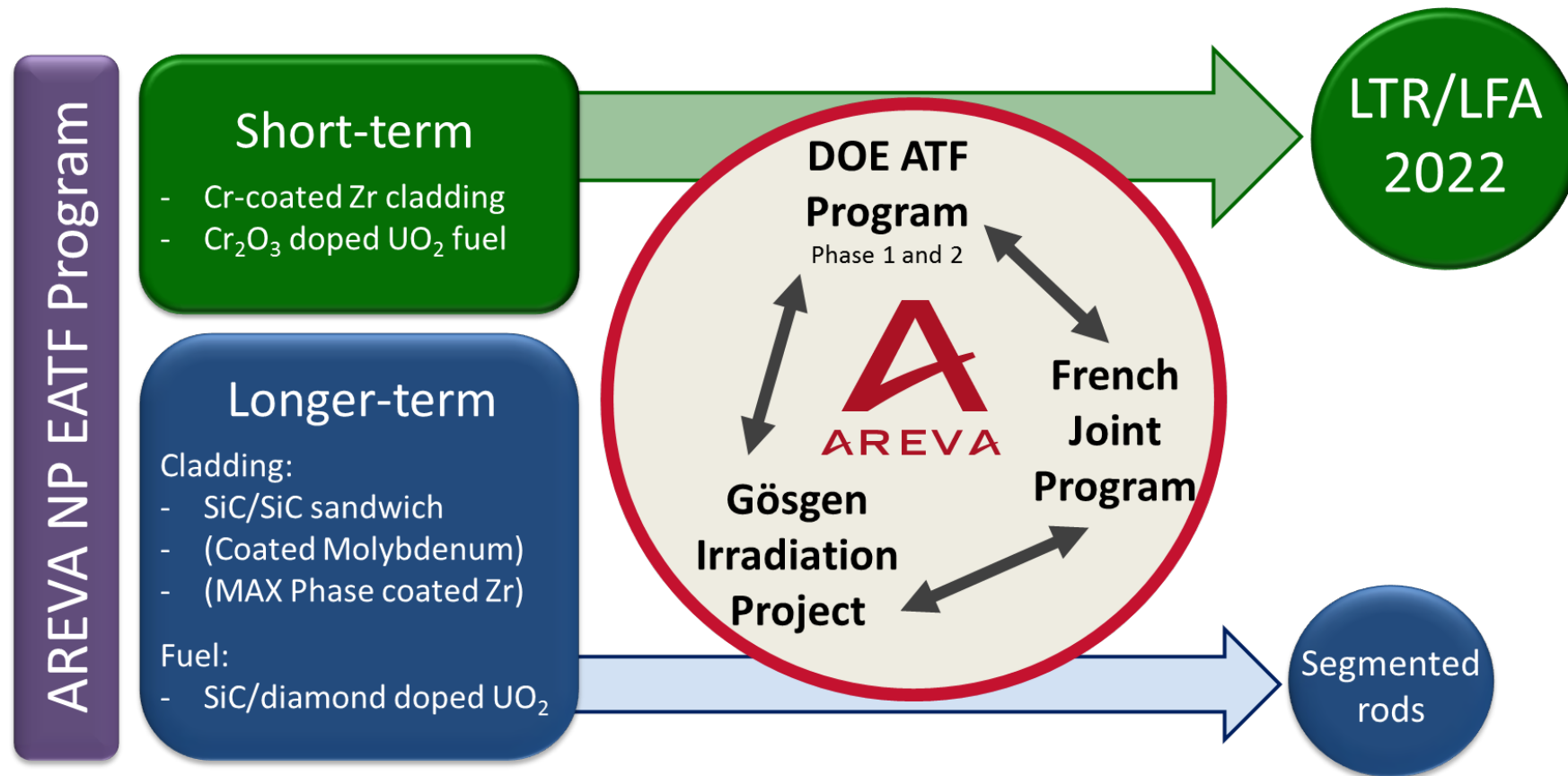
Why Develop EATF Solutions?

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



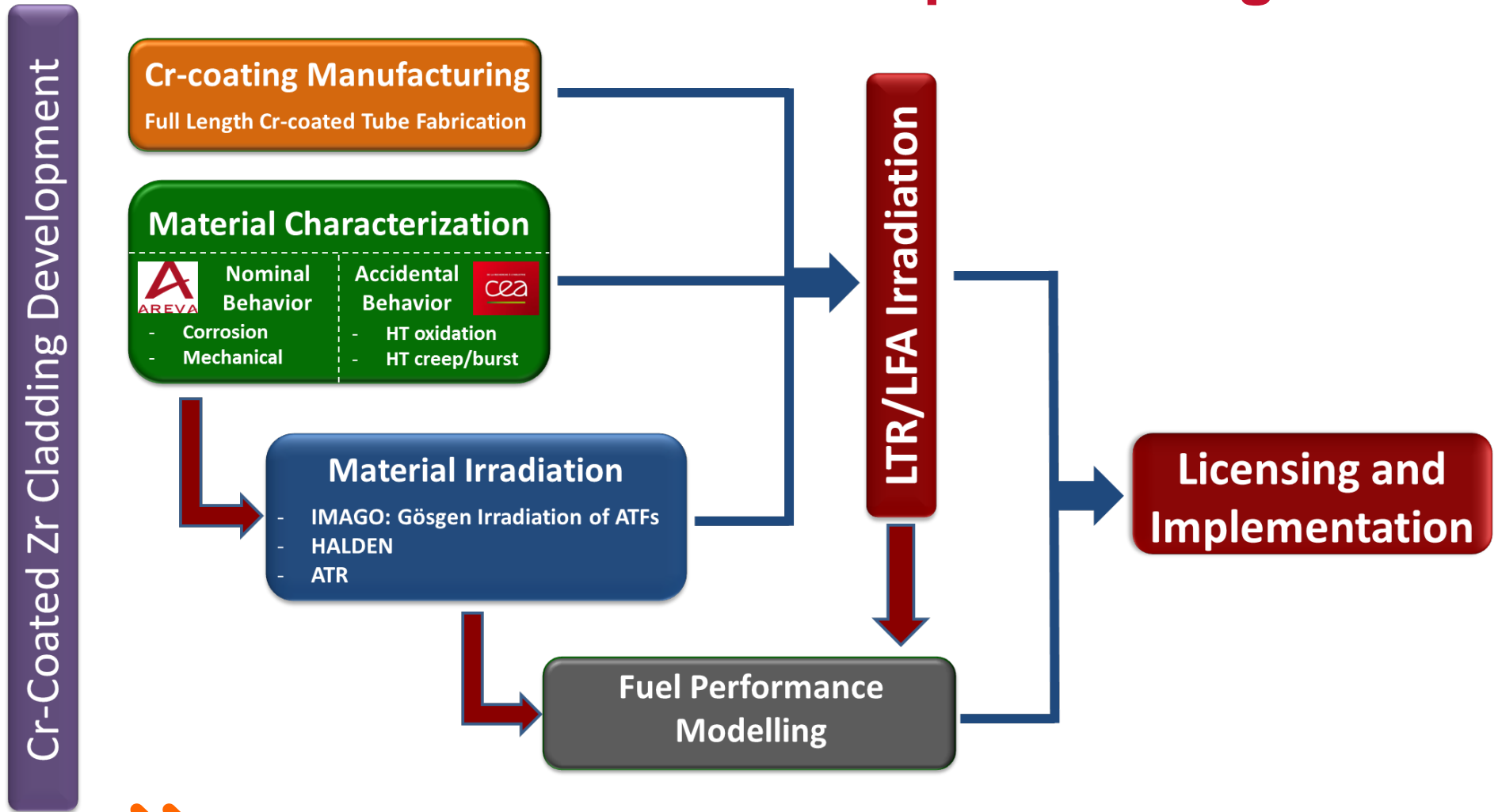
▶▶ Main focus on cladding developments with emphasis on limiting the high temperature steam oxidation leading to large heat and H₂ production for zirconium alloys

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



➤ The development of Cr-coated zirconium alloy cladding with Cr₂O₃-doped UO₂ 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



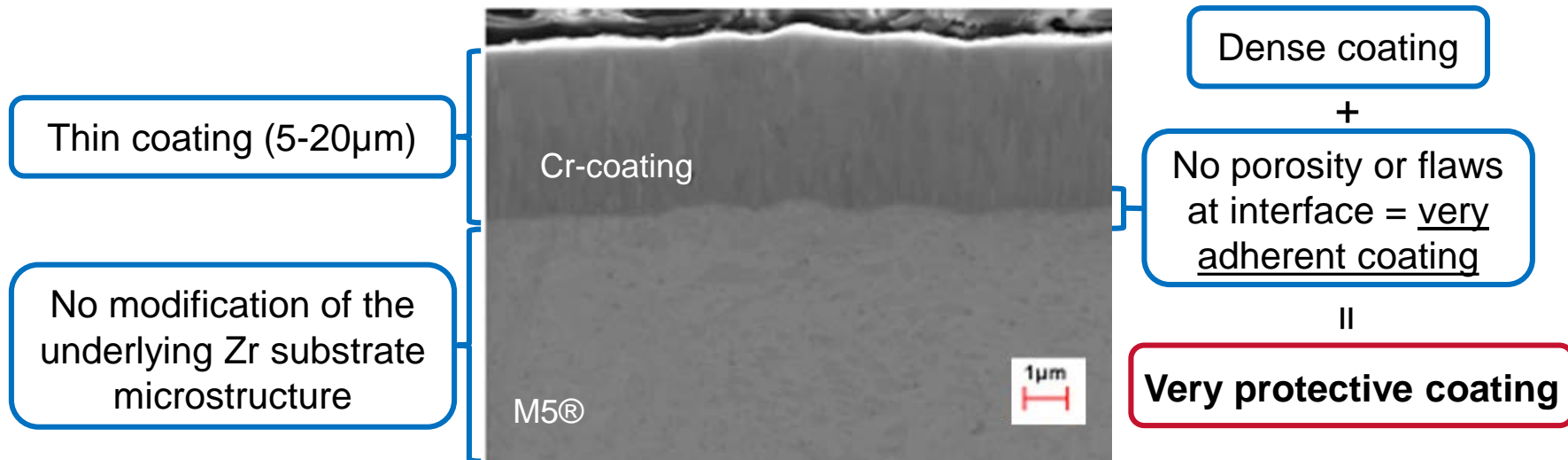
➤➤ Ease of licensing → implementation in short time frame

Behavior of Cr-Coated M5® Cladding

Description and
Manufacturing

Description of the Cr-Coating

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



- ▶ Cr-coating is deposited by Physical Vapor Deposition (PVD) process

- ◆ Compatible with industrial scale fabrication



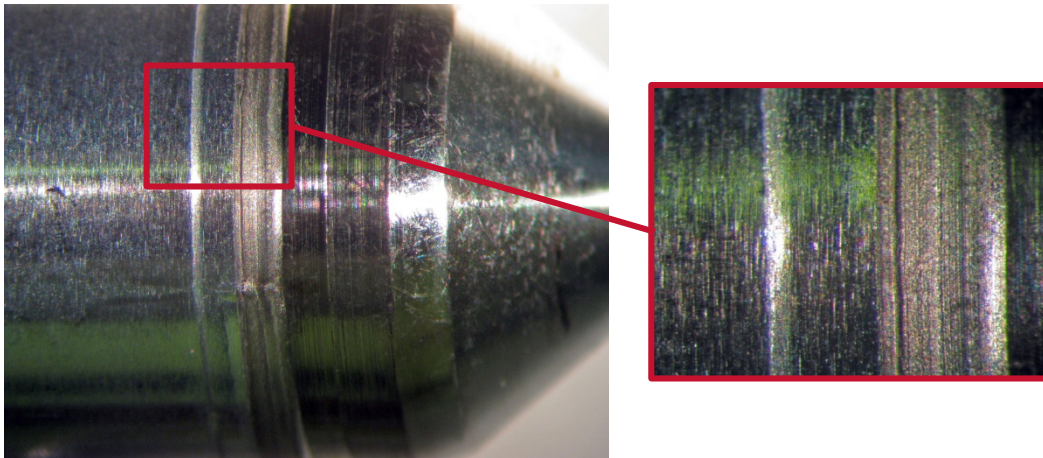
The fabrication of a prototype equipment for deposition of Cr layer on full length cladding tubes is on-going

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

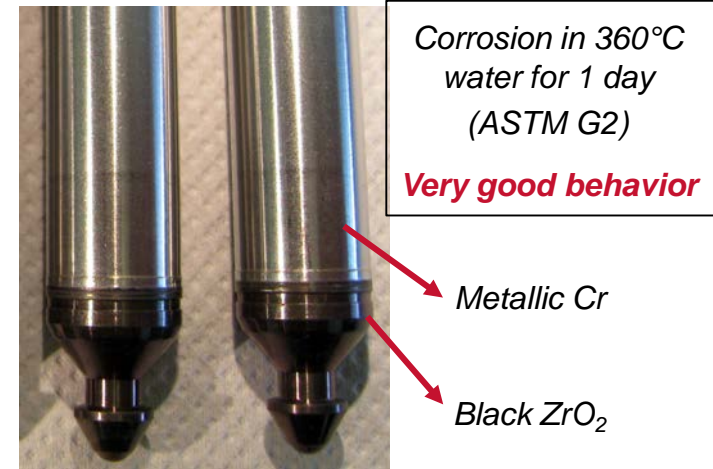
- ▶ Several M5® tubes coated with Cr up to the extremity were welded with the resistance welding process (USW)

Sound weld

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



Post weld corrosion test



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

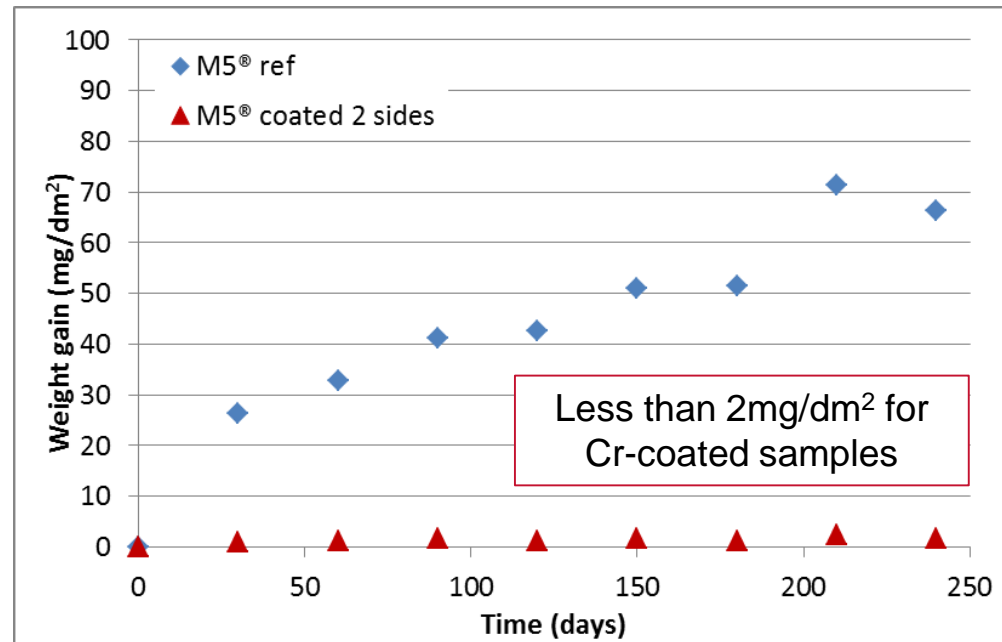
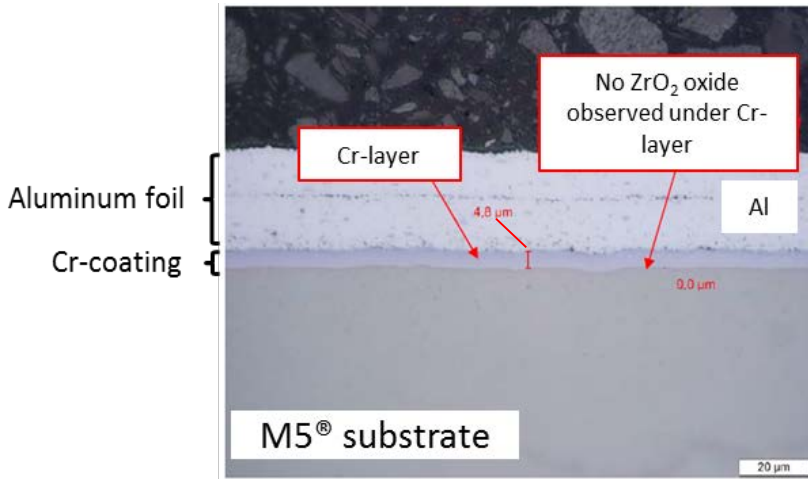
Behavior of Cr-Coated M5® Cladding

Normal Operating Conditions

Excellent Corrosion Behavior in 360°C PWR Conditions

▶ Autoclave test in 360°C water performed at the AREVA NP Technical Center:

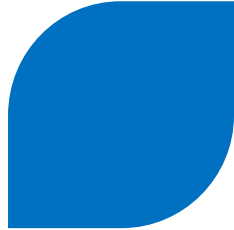
- ◆ Deaerated solution (<10ppb) dissolved O₂ and no added H₂
- ◆ [H₃BO₃] = 650 ppm
- ◆ [LiOH] = 2 ppm



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

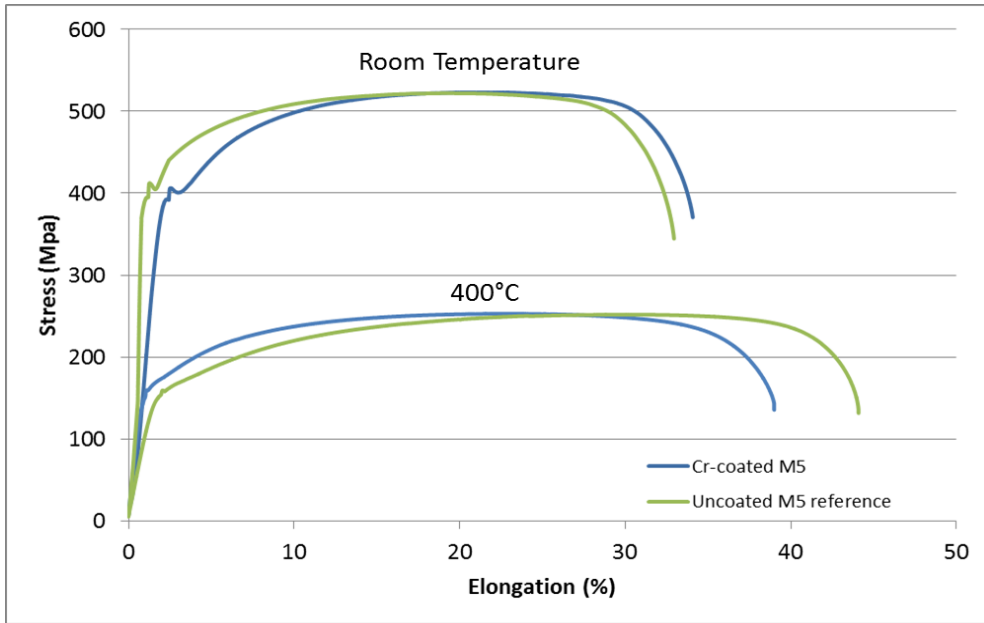
Very protective coating

Similar Mechanical Behavior as Uncoated M5®



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

Tensile tests



Creep tests at 400°C for 240h

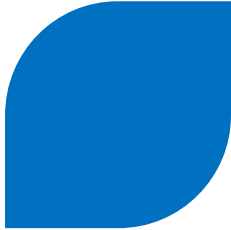
Sample	Creep, $\Delta D/D$ (%) Average (Range)
Uncoated M5®	0.4 (0.1 - 0.7)
Coated M5®	0.4
Uncoated Zy-4	1.3 (0.9 – 1.8)
Coated Zy-4	1.3


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

Behavior of Cr-Coated M5® Cladding

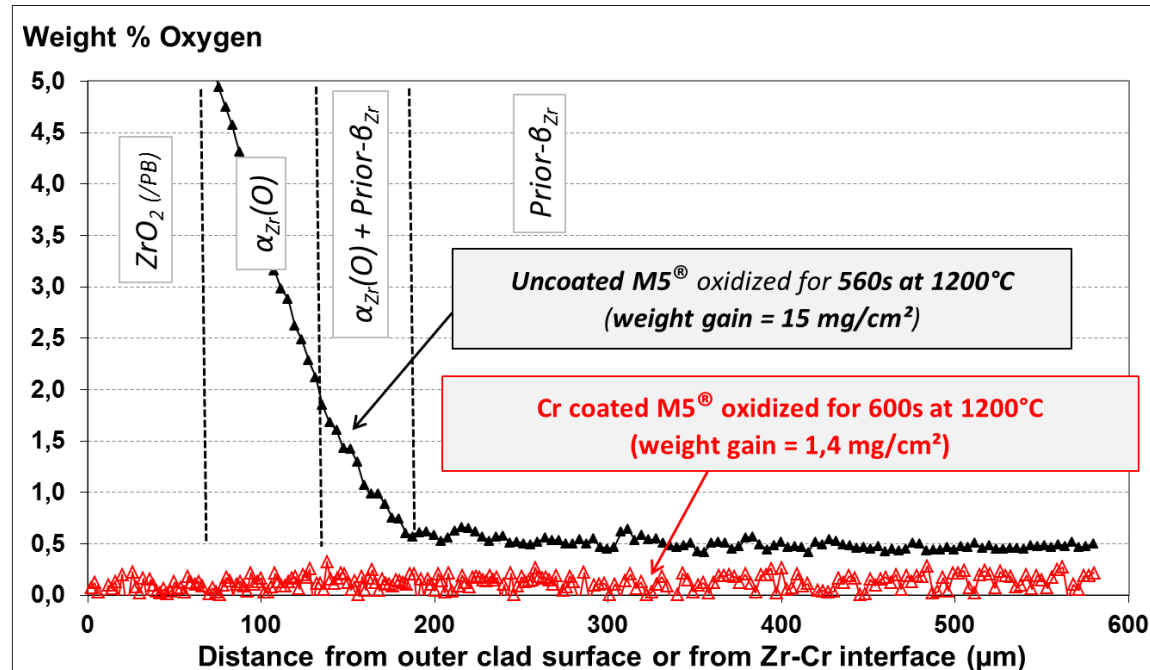
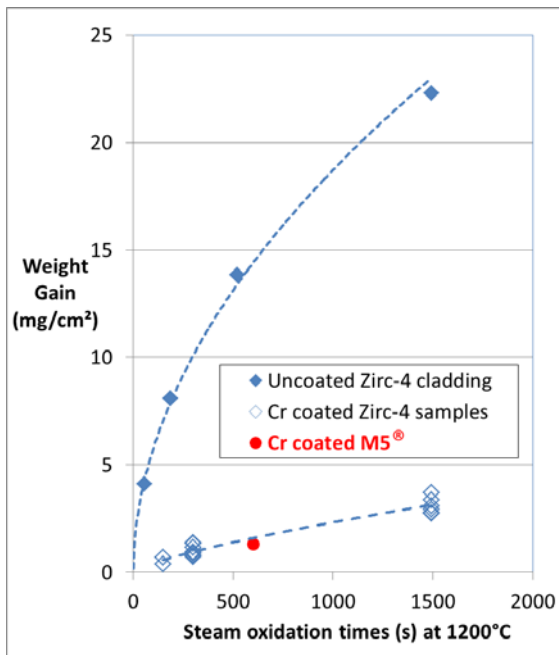
Accident Conditions

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 H₂ 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)

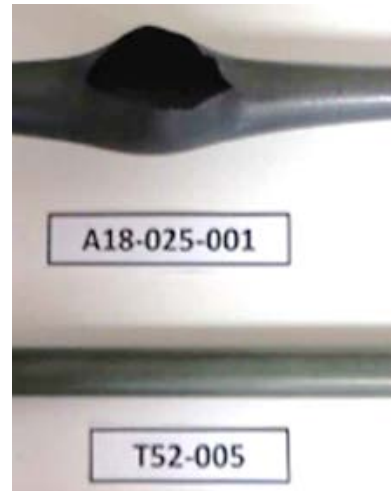
Uncoated M5®



Cr-coated M5®

Smaller Balloon Size

1°C/s 100 bars



Uncoated M5®

Cr-coated M5®

No Burst

25°C/s 10 bars

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



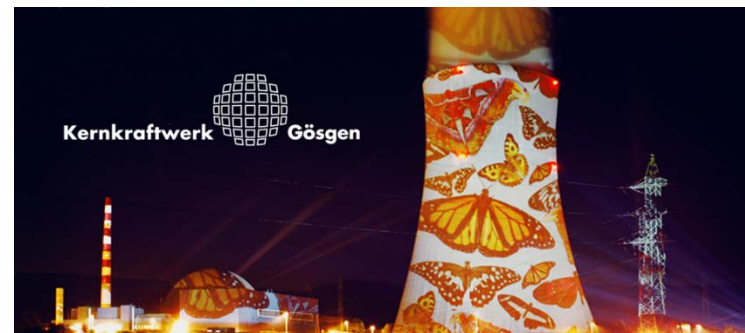
IMAGO: Irradiation of EATF Concepts in a Commercial PWR



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**
 - Cr₂O₃-doped UO₂ 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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