PROtect and Update on Additive Manufacturing

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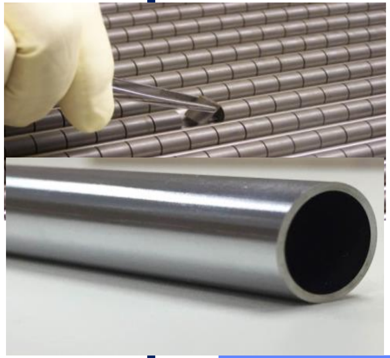
1. Framatome’s PROtect development program

Framatome's E-ATF Concepts

Technological challenge



SiC-SiC_f Cladding

A revolutionary long-term concept

- Breakthrough solution chosen for BDBA capabilities
- High challenges: product design, manufacturing licensing

PROtect SiC

PROtect Cr

Cr-coated $M5_{Framatome}$

An evolutionary near-term solution

- Incremental easy-to-license solution
- LFR's irradiation from early 2019

Benefits regarding safety

A two-phased strategy launched in 2014 balancing safety benefits with time to market

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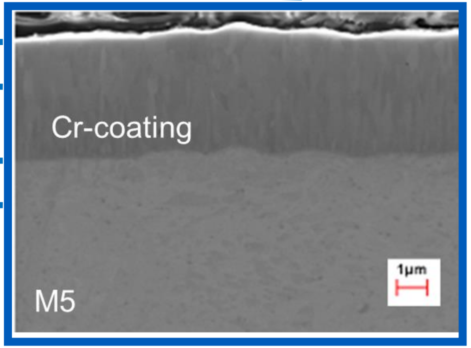
PROtect Cr
Framatome's Evolutionary E-ATF Solution

Cr-coated M5Framatome cladding

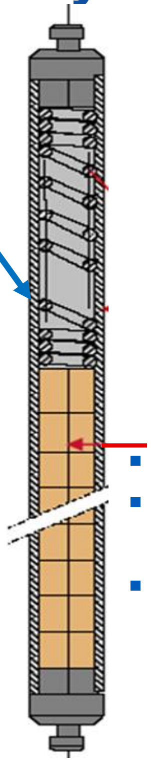
- **Improved oxidation resistance**
- **Improved wear resistance**

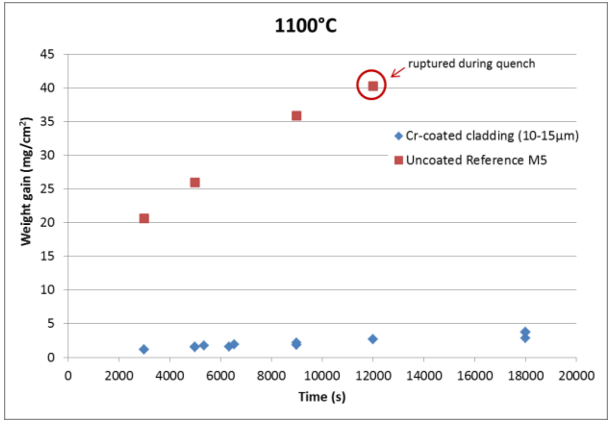
Thin coating (5-20µm)

Dense coating

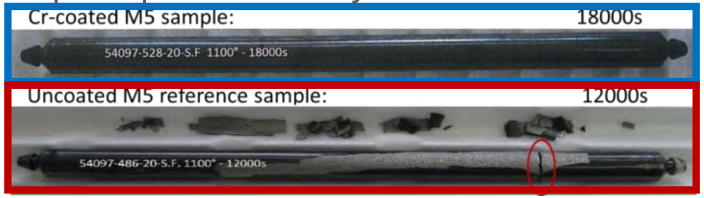


No modification of the underlying Zr substrate microstructure





- Significantly reduced oxidation kinetic
- Significantly reduced hydrogen production and hydrogen pick up
- Improved post-quench ductility



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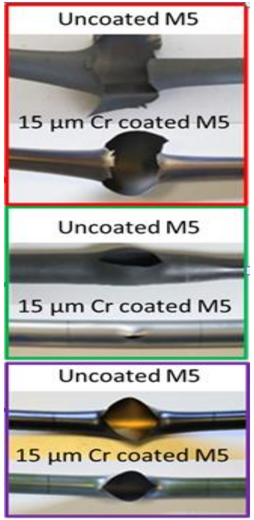
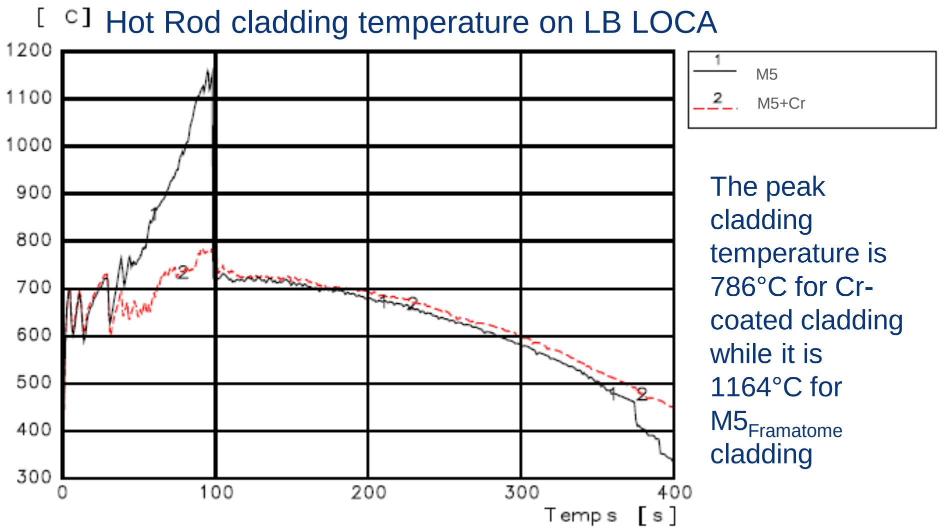
PROtect Cr benefits



Cr-coating reduces or may even prevent cladding rupture:

- Balloon in LOCA conditions significantly reduced with Cr-coating claddings
- Exothermic oxidation reaction is slowed down

➥ less penalizing effect of the exchange area reduction due to clad-to-clad contact after burst.



Thanks to PROtect product, specific technical benefits can be turned into product value adders

- Reduction of Fuel Fragmentation Relocation Dispersion => lever for increased burnup (+ higher enrichment + long cycle)
- Reduction of clad burst and temperature in LOCA => more efficient loading patterns/core design

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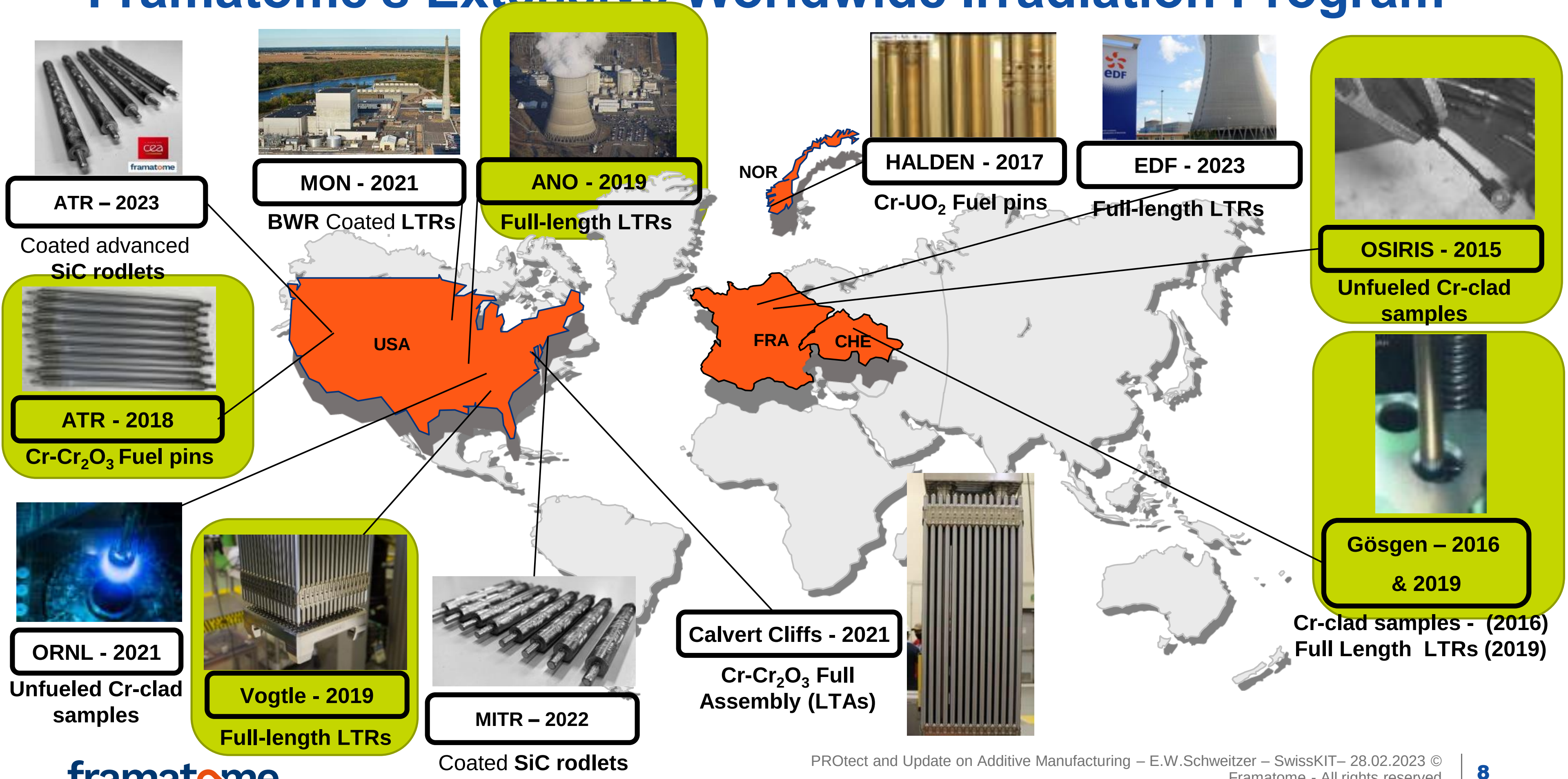
Framatome's Extensive Worldwide Irradiation Program



2. PROtect irradiation feedback

LFRs visuals after 1+ year

Fuel product

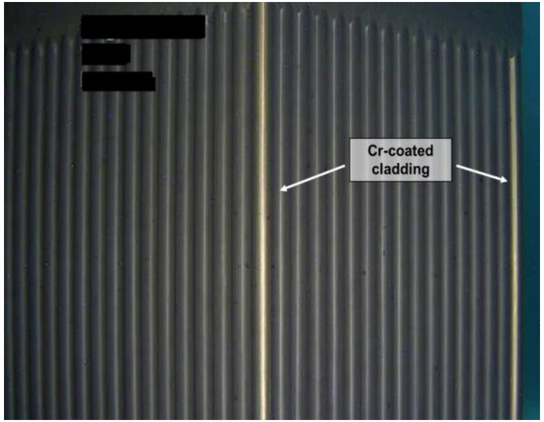
- Cladding: Cr-coated $M5_{Framatome}$
- Fuel: UO_2 and/or Cr_2O_3-doped UO_2

Results:

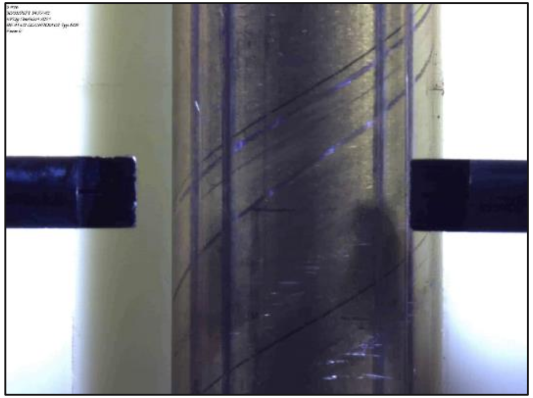
- Excellent performance, corrosion mitigated
- Cr oxide golden appearance
- No degradation of Zr, Cr or interface

Arkansas Nuclear One

Vogtle



Gösgen



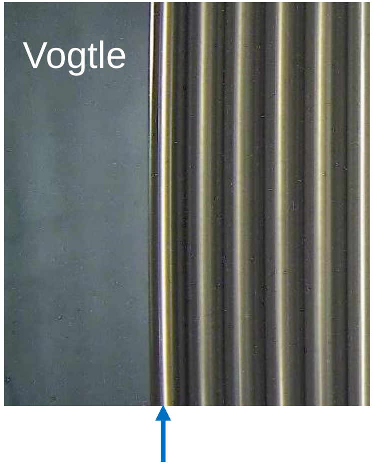
LFRs visuals after 3 years

Fuel product

- Cladding: Cr-coated $M5_{Framatome}$
- Fuel: UO_2 and/or Cr_2O_3-doped UO_2
- Uncoated Zr-alloy endcaps

Results:

- Cr-coating retains its reflective and colored appearance – indicating a thin oxide (<<1µm)
- No significant impact of coating on welded endcap - excellent coating adherence in vicinity of endcap, comparable appearance to end caps welded to $M5_{Framatome}$ rods



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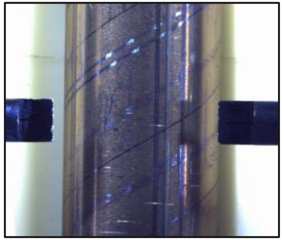
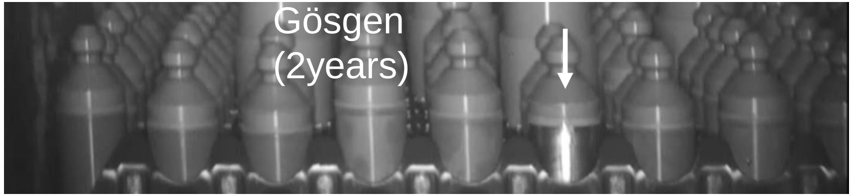
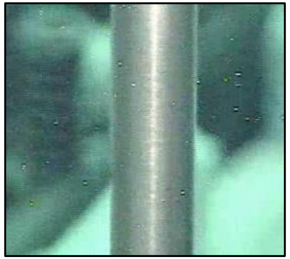
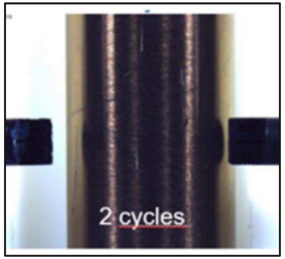
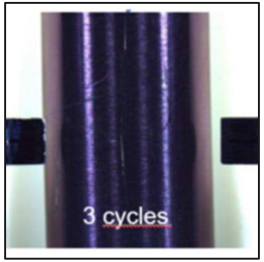


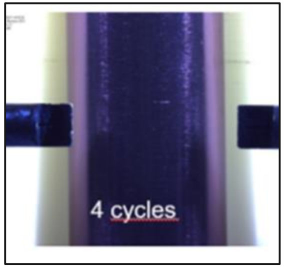


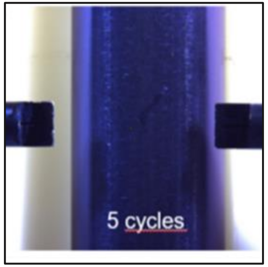
IMAGO & GOCHROM
Visual inspection after five and three cycles of irradiation in KKG

IMAGO (specimens)

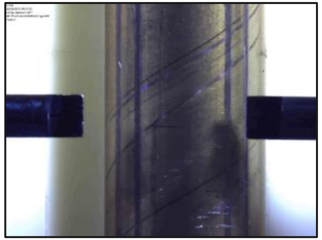



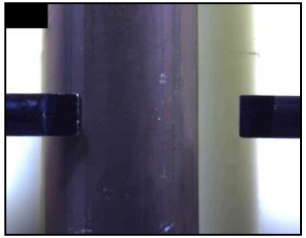


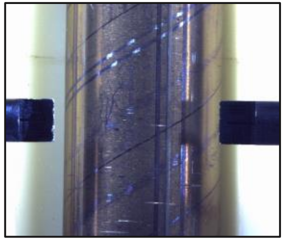




GOCHROM (LTR)


1 cycle


2 cycles


3 cycles

- Development of surface appearance in good agreement with that of IMAGO-program
- 1st cycle LTR currently being investigated at Paul-Scherrer-Institute

Kernkraftwerk Gösgen

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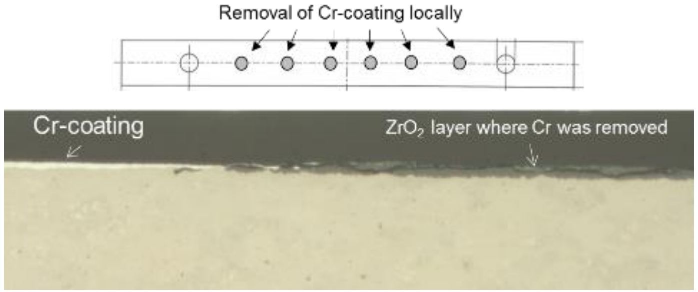
IMAGO-2016:
Pre-damaged specimens – hot cell examination

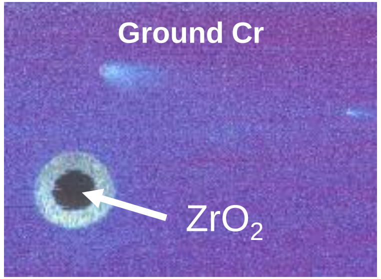
Scope:

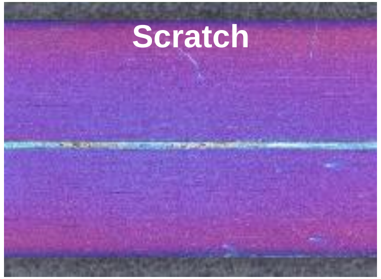
- Cr-coated $M5_{Framatome}$-cladding segment
- Coated and uncoated flat sample
- Pre-damaged coated flat samples

Cycle 1



Cycle 3



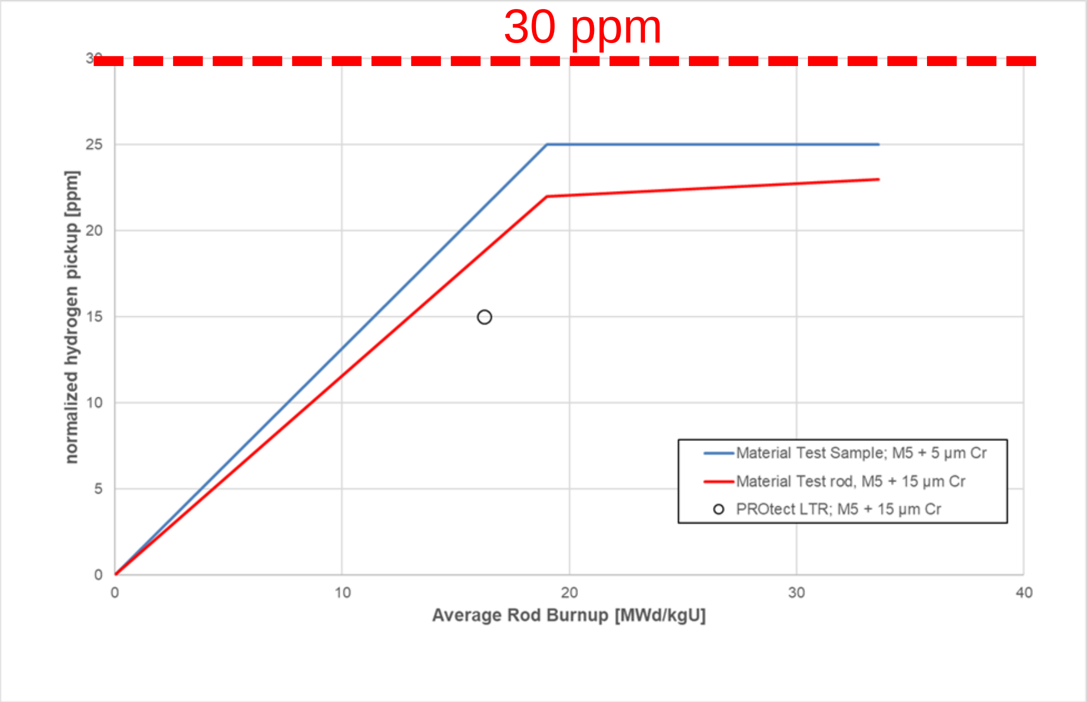


Results

- Coating and the developing passivation layer is stable → blue surface appearance after 3 cycles (characteristic of oxide thicknesses <<1µm)
- No sign of coating degradation in the vicinity of coating pre-damage.
- ZrO_2 thickness from exposed area is comparable to uncoated $M5_{Framatome}$ after 1 cycle and retains its black appearance after 3 cycles

Pre-damaged samples show no detrimental effect on the cladding

IMAGO & GOCHROM Hydrogen uptake



- No corrosion during operation → no source for corrosion hydrogen
- Hypothesis: Minor H uptake from environment at beginning of irradiation; later on reduced or even blocked by Chromia-passivation layer

Scope:

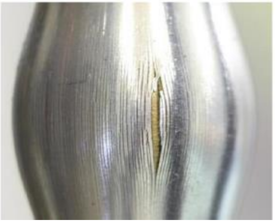
- Hydrogen content determined by Hot Vacuum Extraction
- IMAGO: 2 cycle data for test material
- GOCHROM: 1 cycle data from FR

Summary results

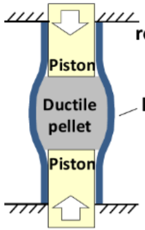
- Minor hydrogen uptake (≤ 25 ppm) observed during 1st cycle of irradiation
- No further increase of H concentration after 2nd cycle
- Hydrogen uptake of LTR after 1st cycle conservatively bound by data acquired from IMAGO program

Mechanical Testing

Unirradiated
(M. Bono et al., NUMAT, 2020)

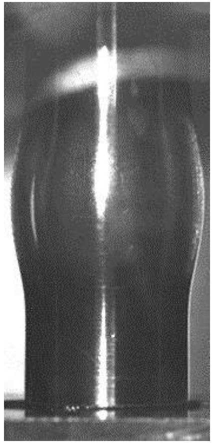


Unirradiated coated cladding hoop strain at rupture ~30%



OSIRIS
(1.5dpa)

IMAGO
(2 cycles)

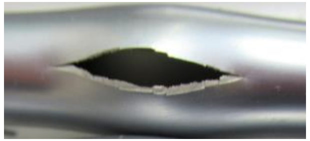


Irradiated coated cladding hoop strain at rupture ≥14%

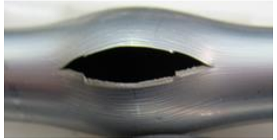
Fixed-end EDC testing at 350°C

- No visual observation of Cr delamination
  - Confirmed by SEM on OSIRIS samples
- Excellent post-irradiation cladding ductility - rupture hoop strains between 14 and 22%

Excellent coating adherence at high strains as observed in burst testing of unirradiated material



RT, >25% hoop strain



400°C, >50% hoop strain

3. Coating Industrialization

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PROtect Cr – towards industrial scale

- Early choice of the Cr-coating
  - Development of various types of coatings combined with several coating processes at CEA in the frame of the French Institute CEA-EDF-Framatome
- Cr-coating process optimization
  - Physical Vapor Deposition (PVD) Cr-coating process optimized at the lab scale to achieve the necessary coating adherence and microstructure mandatory for reactor operation
- Full-length prototype (small scale production)
  - Full-length Cr-coating qualification for the delivery of Cr-coated $M5_{Framatome}$ clad fuel rods

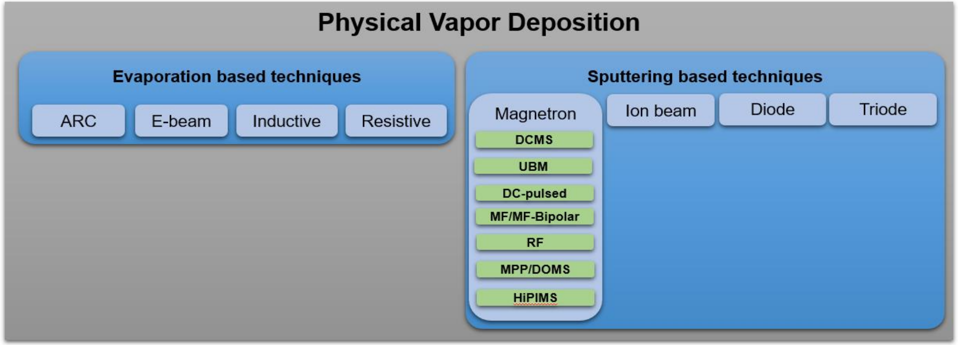
Paimboeuf facility during manufacturing of PROtect LFA

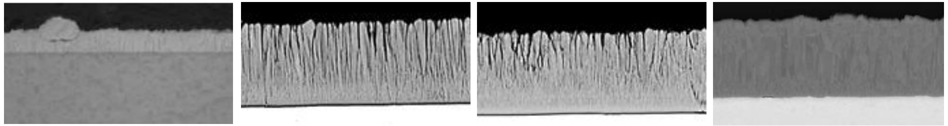
- Industrial pilot
  - Development of industrial scale pilot launched: Design of the industrial pilot almost finalized, with the target to perform coating on a tube batch representative of industrial quantities
- Industrial equipment (large capacity)
  - Scaling of the industrial pilot to meet the capacity demand

An ambitious strategy to move from laboratory scale to industrial scale

PROtect Cr – a mastered coating process

- For ATF, the coating process must
  - Produce coating thicknesses in the 10's of microns
  - Produce dense and highly adherent coatings
  - Cause essentially no modification to the substrate material's microstructure or chemical composition
  - No H2 absorption
  - Maintain a similar surface roughness to an uncoated cladding tube
- Framatome with its partners has tested a large variety of coating processes
- Some (but not all) of the Sputtering Physical Vapor Deposition (PVD) Cr-coating processes when well optimized achieve these requirements
  - Very different coating quality achievable depending on the sub-process used
  - Coating performance (adherence, HT corrosion …) depends on the process and its optimization





PVD Arc
droplets not OK

PVD Sputtering 1 and 2
density not OK

PVD Sputtering 3
porosities not OK

Framatome HiPIMS PVD: OK

HiPIMS = High Power Impulse Magnetron Sputtering

Following the choice of HiPIMS PVD process initially optimized at lab scale, for which good in pile performance has been shown, Framatome has then continuously optimized coating conditions

4. EATF for BWR

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Xcel Monticello BWR Irradiation Program

- Development work for the LTR program began in 2020
  - 8 unfueled segmented LTRs with 7 segments each
  - 3 coated segments per rod with a length of 12 in (≈ 300 mm)
  - LTR fabrication at FDL (Erlangen), assembly insertion at Richland
- Irradiation started in May 2021
- First 2-year cycle will end in April 2023

Xcel Energy
RESPONSIBLE BY NATURE

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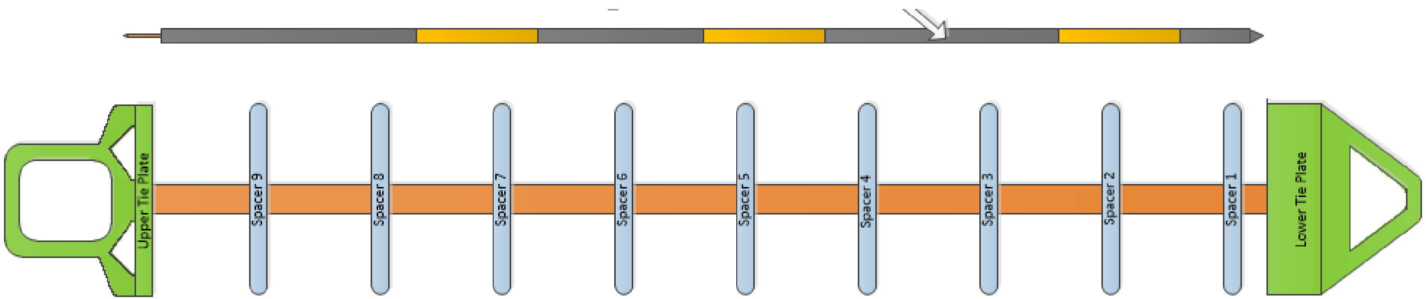
LTR design



- Challenge: pure metallic Cr-coating may have reduced stability in BWR environment depending on the actual water chemistry.
- → Modification of the PWR ATF coating design neccessary to ensure coating stability in more oxidizing conditions.
- Cladding outer surface covered with modified coating with two functions
  - Separate Zr-base material from medium in case of LOCA event
  - Protect Chromium from coolant during normal operation

- 8 x 3 = 24 unfueled segments
- First visual results after 1st bi-annual cycle expected by end of 2023

5. Additive Manufacturing

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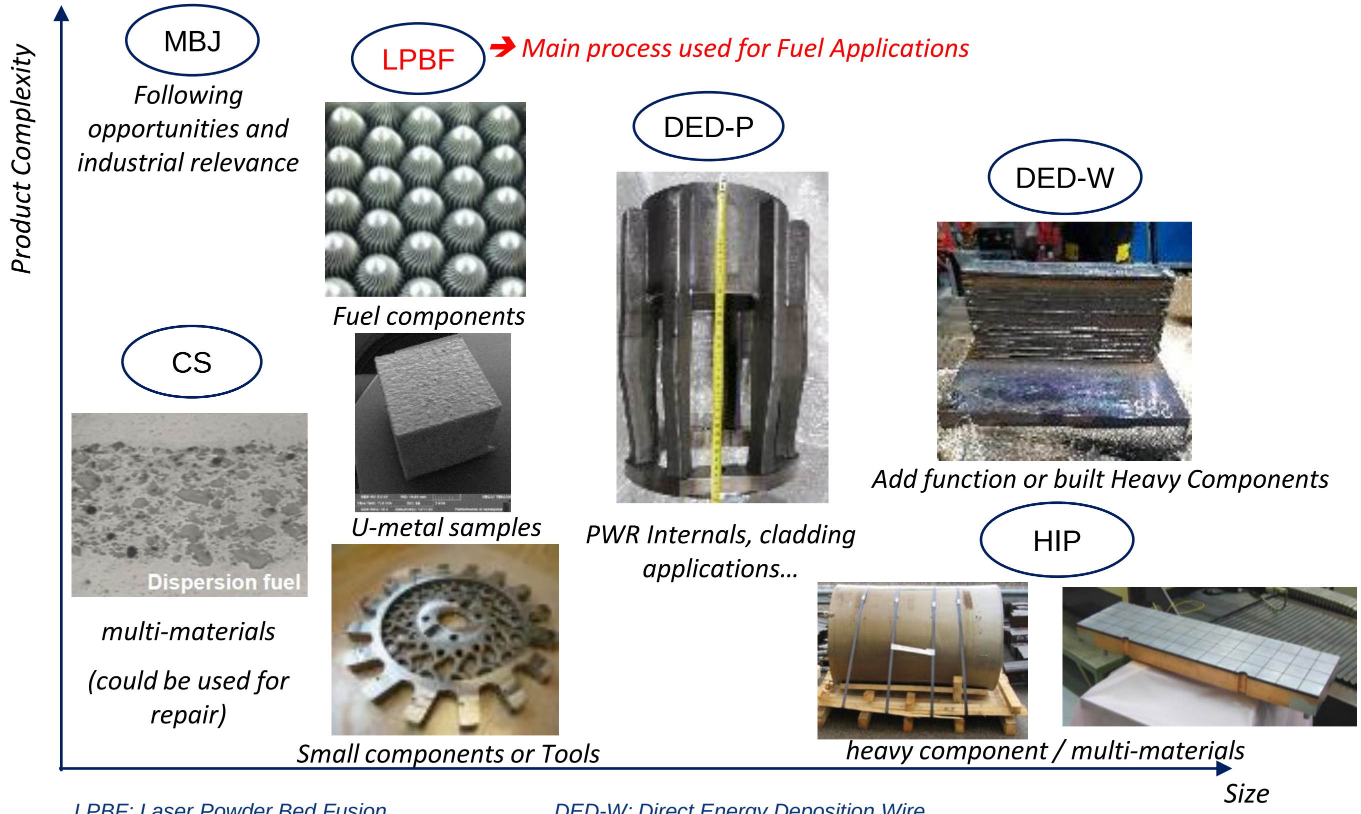
Overview of Additive Manufacturing Methods



LPBF: Laser Powder Bed Fusion
DED-P: Direct Energy Deposition- Powder
MBJ: Metal Binder Jetting

DED-W: Direct Energy Deposition Wire
CS: Cold Spray
HIP: Hot Isostatic Pressing

Framatome’s route to an industrialized process

- Additive **Design** and Manufacturing → rethinking of design paradigms
- Design for service, not design for manufacturing

Axis 1:
Development of components / Designs

Axis 3:
Material/component irradiation and testing

Axis 2:
Process optimization

Design Opportunities — ***Prototyping / parametry*** — ***Materials properties***

→ ***Material irradiation*** — ***Components in lead fuel assemblies*** → ***Industrialization of components not in the load chain***

→ ***Material irradiation*** — ***Components in lead fuel assemblies*** → ***Industrialization of components in the load chain***

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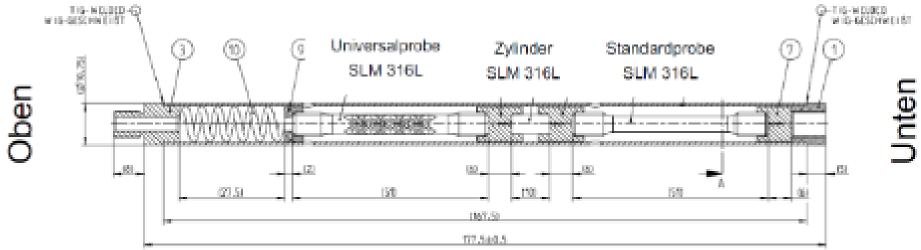
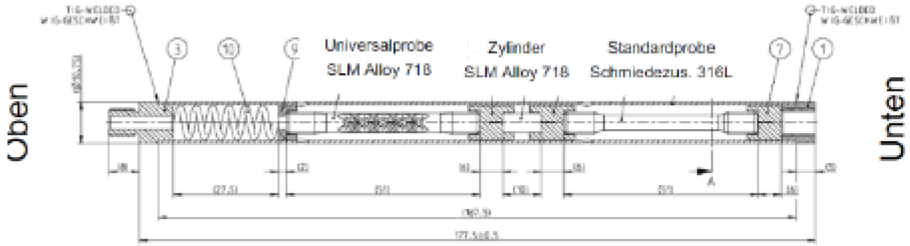
AddMAGIC Irradiation Program in coop. with KKG

- Irradiation of AM samples made of the austenitic stainless steel 316L
- Irradiation in unused guide tubes of host fuel assemblies in KKG for 1, 3 and 5 cycles
- Gather irradiation experience wrt. corrosion properties, evolution of mechanical properties, dimensional stability etc.

- 1 cycle Material test rod under investigation at Erlangen hot cell lab → stable performance in PWR conditions





Road to industrialized process

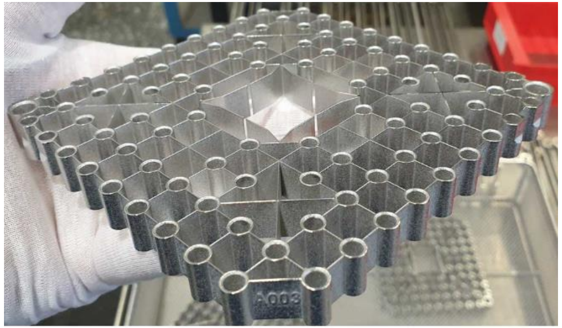
Irradiation of AM channel fasteners at Browns Ferry

- Replacement of cast part
- Start of irradiation 2021

Irradiation of AM Upper TIE plate at Forsmark

- Original component is a weld structure made of Alloy 718 straps (complex design + coeff. therm. exp. misfit with surrounding steel parts)
- Start of irradiation 2022

https://www.world-nuclear-news.org/Articles/3D-printed-components-in-service-at-TVA-reactor



https://www.framatome.com/medias/framatome-installs-first-3d-printed-stainless-steel-fuel-component-at-forsmarknuclear-power-plant/

Design Opportunities → *Prototyping / parametry* → *Materials properties* → *Material irradiation* → *Components in lead fuel assemblies* → ***Industrialization of components* not in the load chain**

Material irradiation → **AddMAGIC NUCOBAM**

Summary - PROtect

- A stepwise development strategy is pursued with a fast implementation schedule
  - PROtect Cr: A near-term product which provides substantial benefits in Design Basis Accident (lever for increased burnup with higher enrichment and longer cycle) and may increase margins in normal operation and with on-going demonstration programs in commercial reactor, rather easy to manufacture and to license
  - PROtect SiC: A revolutionary solution which provides higher benefits in beyond design basis situations but requires more development efforts to overcome key technical challenges and to reach industrial readiness

- PROtect Cr development on the way to deliver reloads industrially with on-going demonstration programs in commercial reactors (materials insertion started in 2016, full-length Lead Fuel Rods in 2019 and full Lead Fuel Assembly in 2021) and completion of the small scale production stage of manufacturing capability development and launching of the industrial pilot allowing deliveries of reload quantities

Summary – Additive Manufacturing

- Framatome is gathering irradiation experience with AM components made in BWR and PWR environments
- Irradiation programs include material test programs (e.g. AddMAGIC with KKG) as well as lead test components
- Results are promising for an industrialization of AM components outside of the load chain in mid-term with the motivation to (a) enhance performances, (b) reduce costs and/or (c) speed up market readiness
- Standardization of practices, qualification approaches ongoing for future serial production at acceptable manufacturing cost

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