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Irradiation Feedback of Framatome's PROtect-Cr Cladding to a Burnup of >70 MWd/kgU

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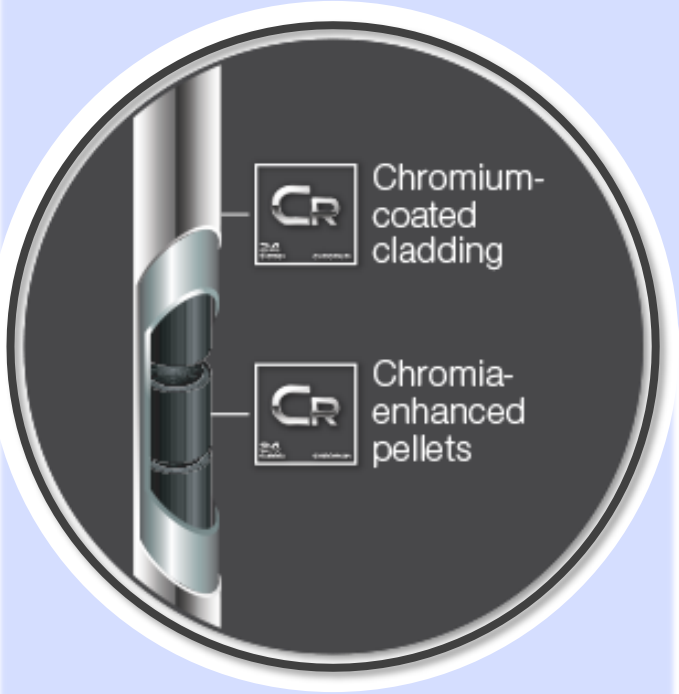
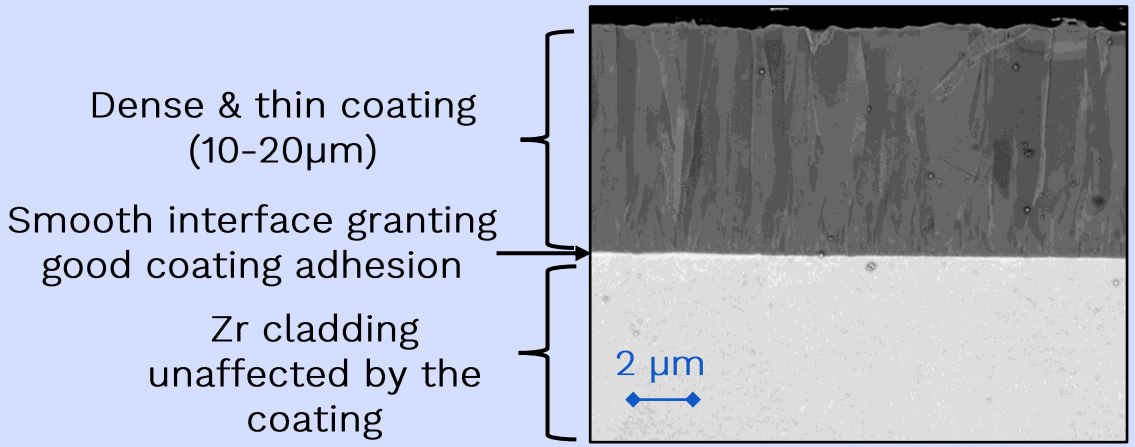
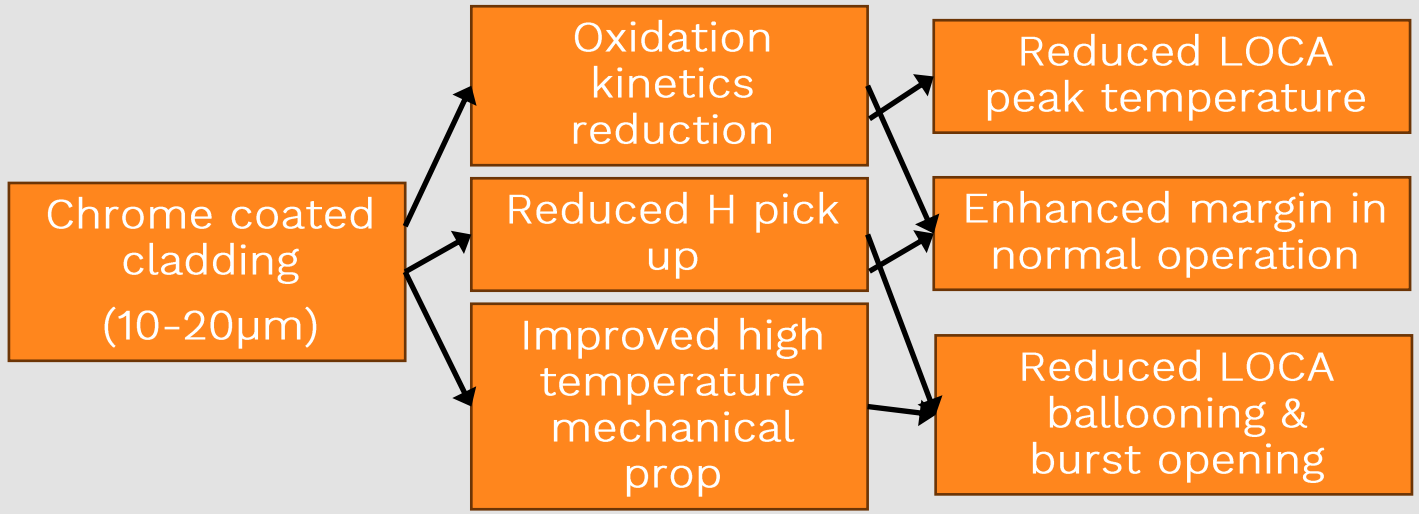
PROtect Cr: Framatome's EATF solution

In 2027, Cr-coated cladding will be licensed and in reload volume production



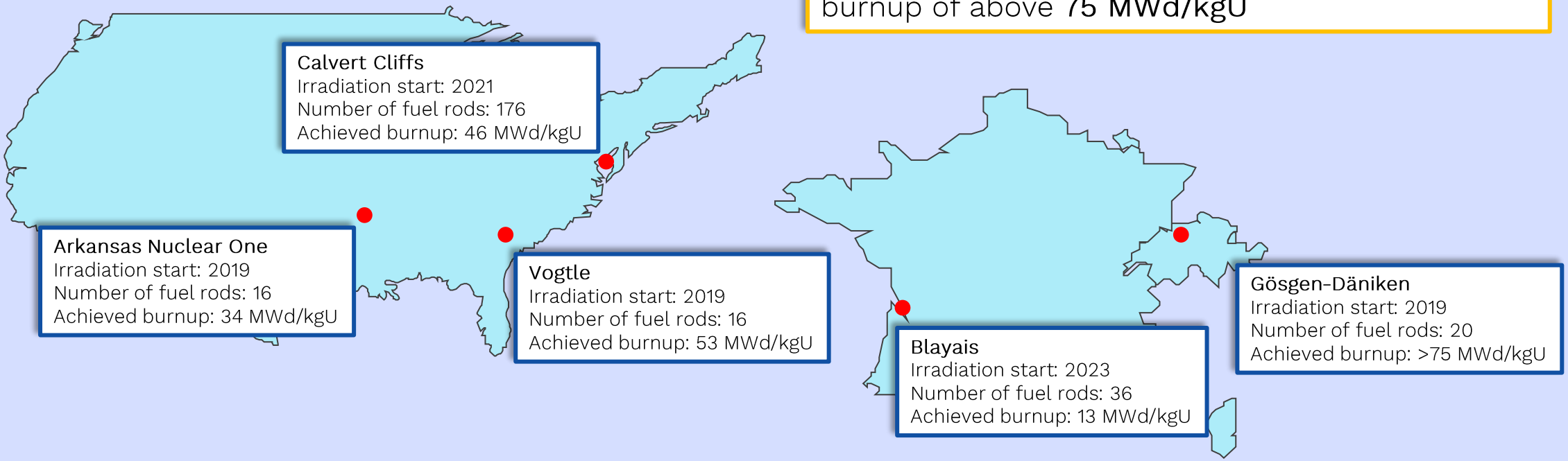
Cr-enhanced fuel pellets are already fully commercialized and in reload volume production





Worldwide irradiation experience with PROtect fuel rods

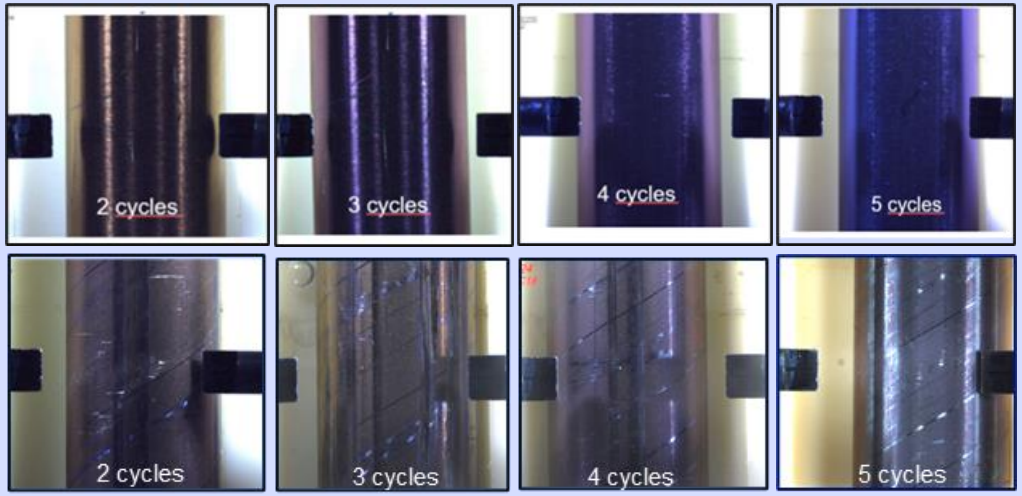
Irradiation experience with **264 Cr-coated test rods** in various types of PWRs with a maximum burnup of above **75 MWd/kgU**

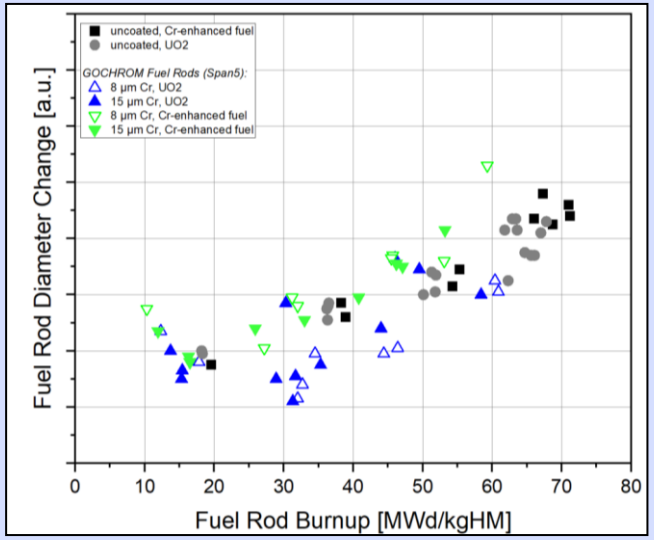


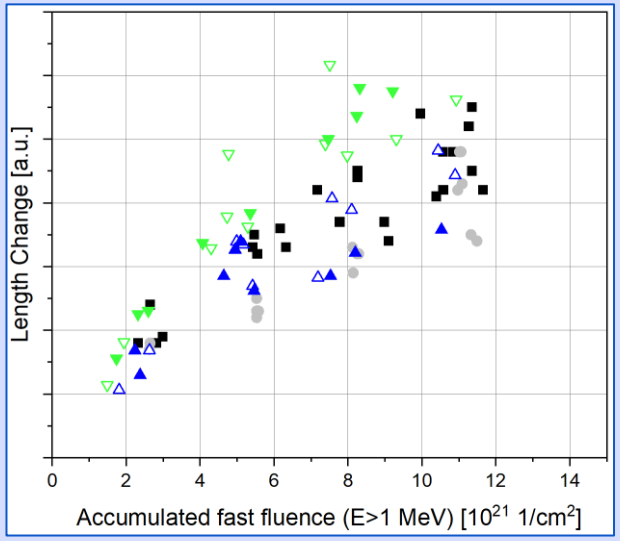
On-site PIE @ NPP Gösgen

IMAGO-Program: Material Test Rod irradiation (no fuel)

GOCHROM-Program: Lead test rod irradiation







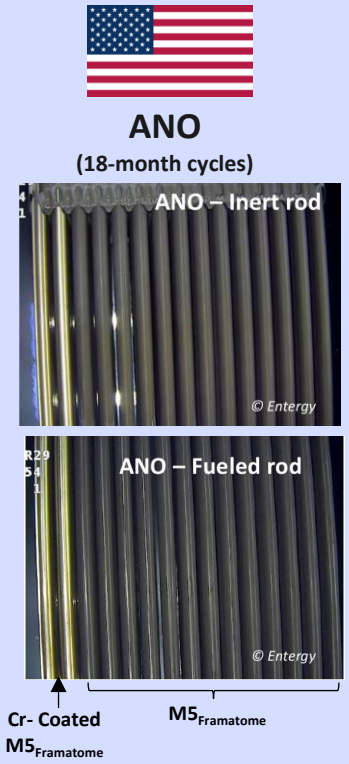
Visual appearance

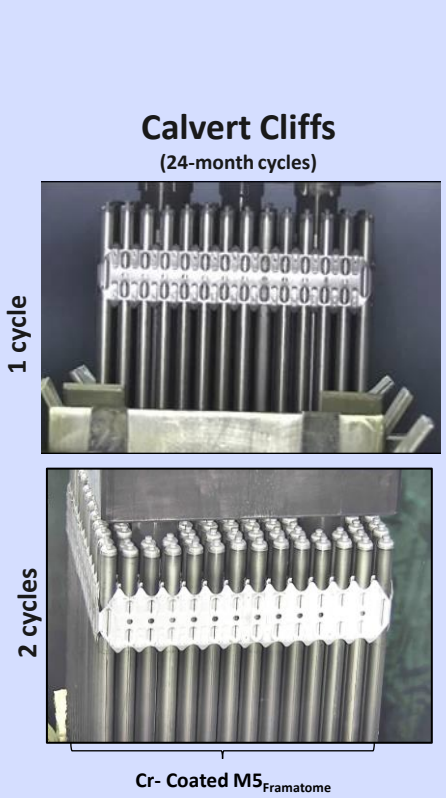
- Evolution of surface color metallic grey to gold, purple, and blue with increasing irradiation exposure ← formation of a thin chromia passivation layer
- The high quality coating did not show any sign of coating delamination, loss of coating, or other forms of visible coating degradation
- Transition between the coated cladding and the uncoated end plug was visually flawless
- Helical traces caused by the single rod inspection device are superficial influences on the passivation layer.

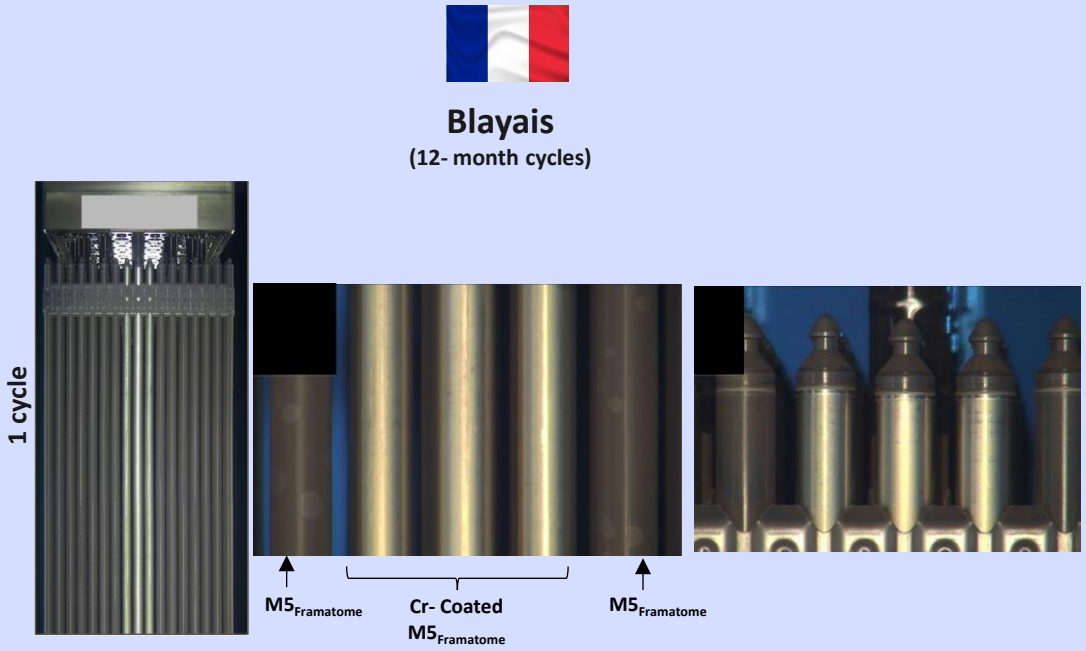
Dimensional behavior

- Initial decrease of rod diameter as expected, with similar creep down rates observed for both coating thicknesses.
- After gap closure, diameter changes for both pellet types proceed in parallel, governed by pellet swelling; overall, diameter behavior is comparable to uncoated rods.
- Rod length changes below ~$4 \times 10^{21}/cm^2$ fluence align with existing data; above, rods with Chromia-enhanced pellets show slightly higher length changes, attributed to fuel column swelling rather than cladding behavior.

Overview of on-site PIE – US & France



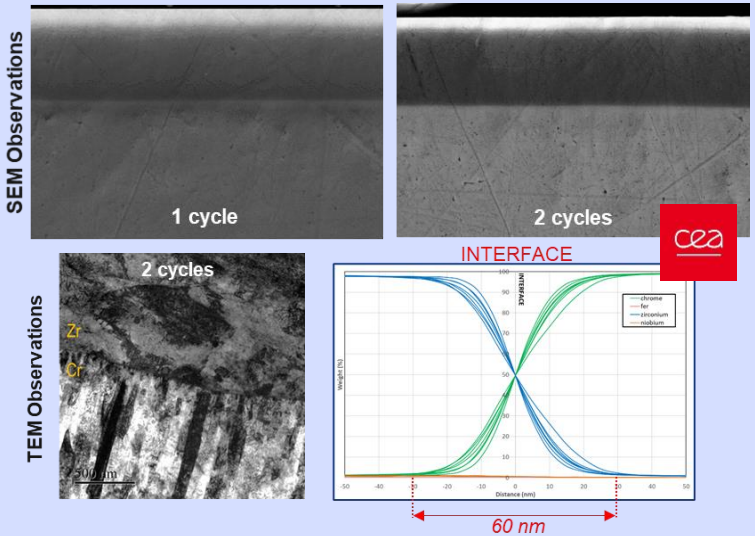


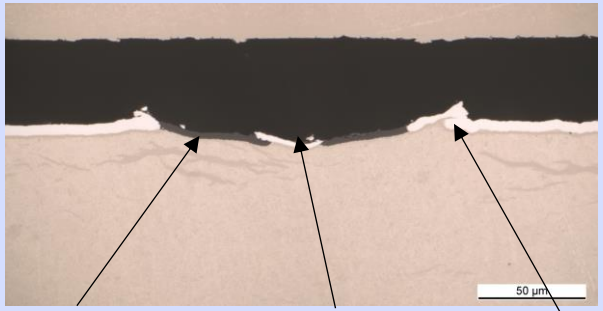


- Colored oxide appearance that slowly evolves to high burn-up
- Oxide thickness expected to be << 1µm
- Blayais LTR program features some rods with intentionally damaged coating (artificially scratched)
  → good operation feedback of scratched rods, i.e. no delamination etc.

Recent hot cell PIE feedback

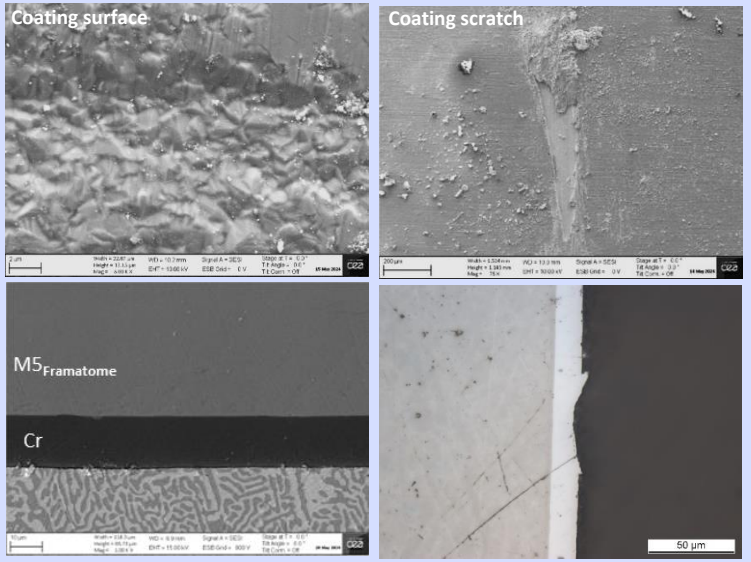
IMAGO MTR



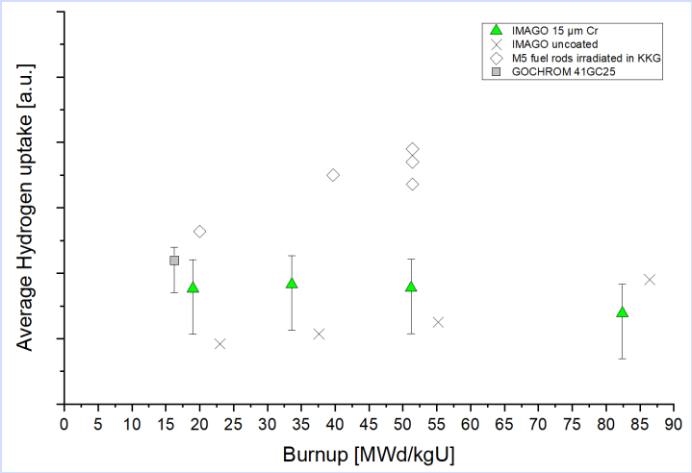


- Cr-coating remains adherent with no sign of degradation in the vicinity of existing coating damage (black ZrO2 observed at exposed regions)
- No significant evolution of the Cr/Zr interface based on observations after 2 cycles (Cr/Zr interdiffusion profiles comparable to unirradiated material)
- Minor hydrogen uptake (≤ 25 ppm) observed during 1st cycle of irradiation with no significant increase observed in subsequent cycles

GOCHROM LTRs (1 cycle)

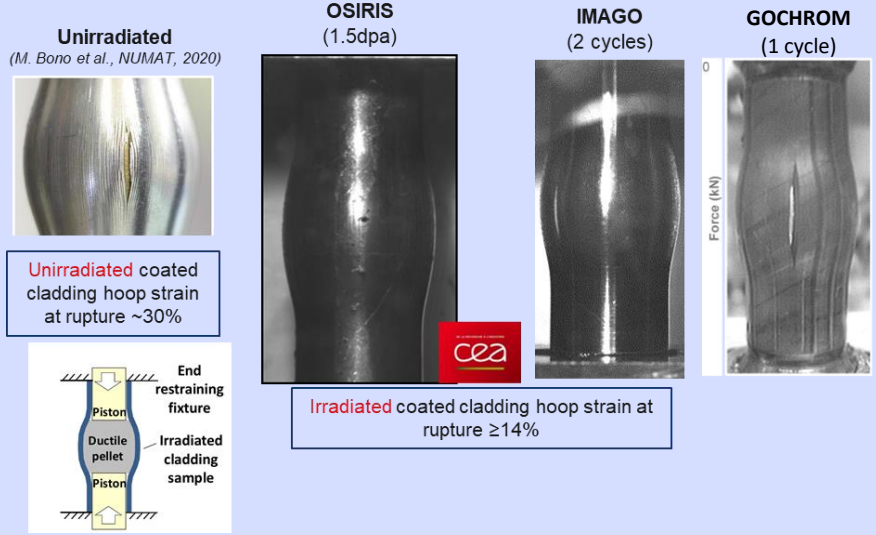


Hydrogen uptake
(IMAGO & GOCHROM)



Recent hot cell PIE feedback

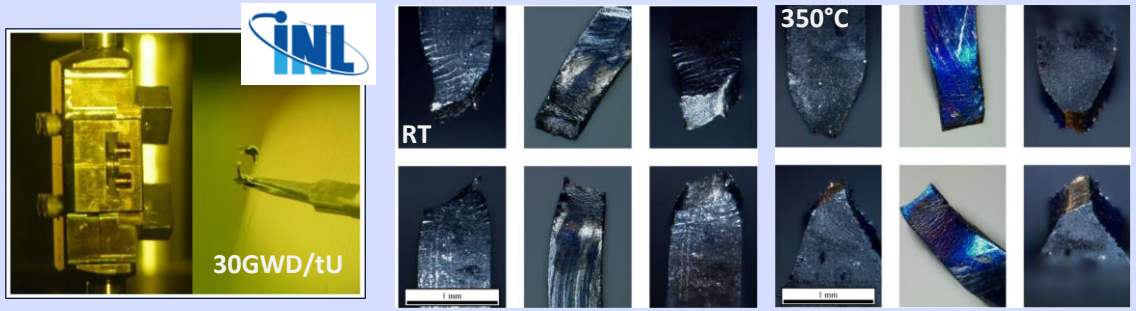
Expansion due to compression – 350°C



Burst testing – 350°C

- Mechanical properties of irradiated Cr-coated $M5_{Framatome}$ (e.g. YS, UTS and strain) similar to irradiated $M5_{Framatome}$ cladding
- No visual observation of Cr delamination after deformation
- Coating cracking observed at high strains to accommodate bulk Zr deformation (concentrated to sample's failure region)

Ring tensile testing



Conclusions

This work is supported by:
- The U.S. Department of Energy under Award Number DE-NE0009034 (and previously DE-NE0008818 and DE-NE0008220),
- The BPI France under the contract DOS0151318,
- The Electric Power Research Institute (EPRI),
- The OECD-NEA .

- The PROtect fuel rod design represents an innovative advancement over conventional nuclear fuel rods. Its operational behavior has been extensively studied through various irradiation programs.
- On-site PIE and Hot Cell investigation confirm a good operating behavior especially with respect to:
  - Corrosion Resistance: Significantly reduced oxidation rates of the cladding, especially at elevated temperatures and in steam environments.
  - Hydrogen uptake: Low H uptake (< 25 ppm) during 1st cycle and protection against further H uptake during higher cycles (passivation effect)
  - Mechanical Integrity: Good mechanical properties comparable to uncoated cladding. Cr coating stays adherent during plastic deformation
- The PROtect fuel rod design represents a significant step forward in improving the safety and efficiency of nuclear power plants. The positive outcomes from irradiation programs underscore the potential of this technology for widespread industrial application.

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Thank you