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Chromium coated nuclear fuel claddings for enhanced Accident Tolerant LWRs Fuel

(DBA-LOCA and slightly beyond DBA-LOCA conditions)

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PROSPECTIVE STUDIES AT CEA ON ENHANCED ACCIDENT TOLERANT FUEL CLADDINGS FOR LWRS

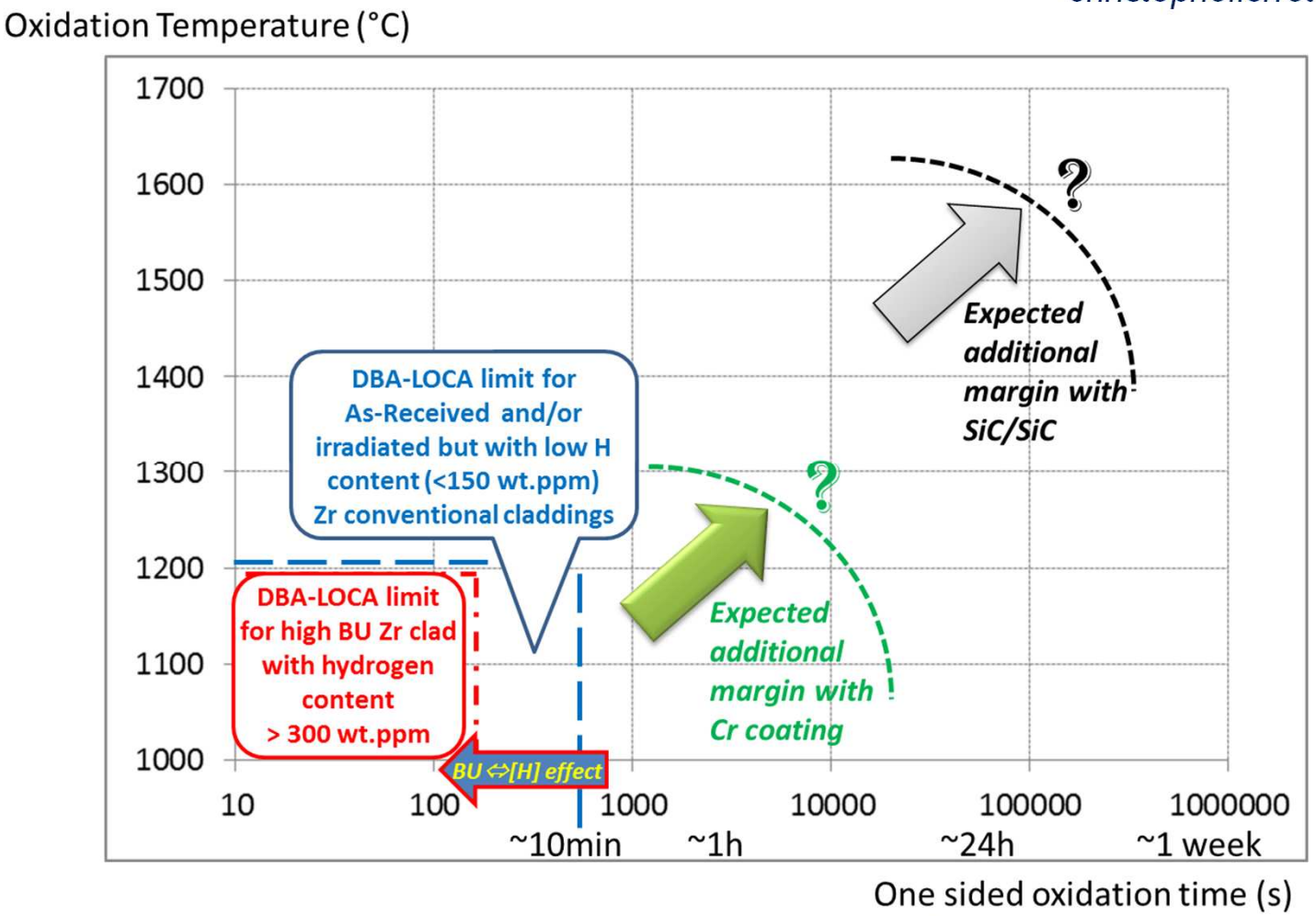
Short/mid-term R&D:

1- Optimized Cr coating on Zr clad

Break-through/long-term R&D:

2- SiC_f/SiC + liner « sandwich-design » composite

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TARGETS AND MAIN CHALLENGES…

Specific targets for optimized coating on Zr-based claddings:

Decrease the HT oxidation rate with steam water at HT:

→ **to slow down/delay the gaseous hydrogen release** (mitigation of explosion risk)

→ **to increase the HT oxidation time/temperature margin vs. quenching and post-quenching embrittlement limit** (avoid multi-fragmentation…)

→ ***potential positive effect on Peak Cladding Temperature (PCT)*** *by reducing the contribution of the (HT oxidation) exothermic reaction on the cladding temperature incursion => has to be quantified*

Points not addressed by such clad concept:

→ *Impact on HT mechanical properties => probably low, but has to be quantified*

→ *Margin to melting temperature => Eutectic formation between Zr and Cr at ~1330°C*

- Well-known Zr cladding materials and **no significant change of the fuel sub-assembly geometry nor of the mechanical/thermal properties**

Main challenges:

- Fabricate an **homogeneous and HT protective** coating with **suitable process**
- Effects of **neutron irradiation, thermal cycling, stress/strain cycles (PCI, fatigue…), more severe corrosive environment… on the coating adhesion and efficiency… ?**
- ***Fabrication issues*** *(**longer** cladding tubes, **production rate**, **non destructive** quality control, **weldability** of end plugs, etc…)*

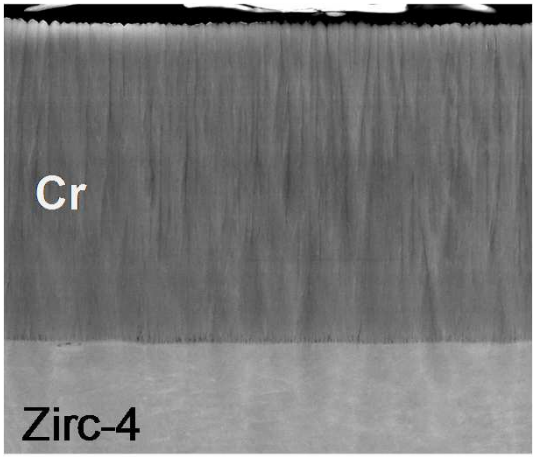
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COATING MICROSTRUCTURE FOR AS-RECEIVED CONDITIONS

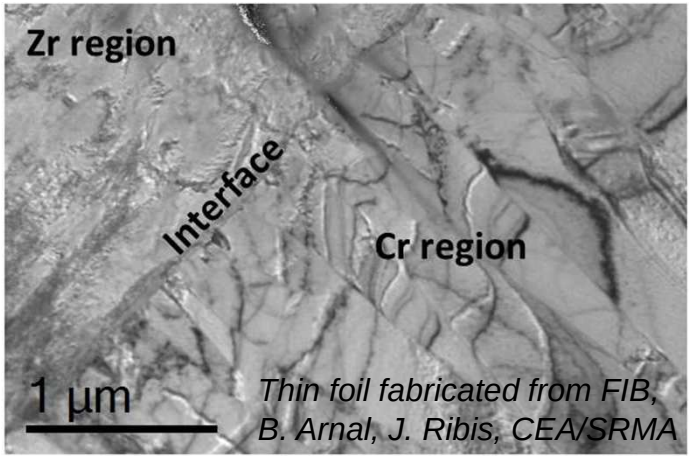
⇒ Process derived from Physical Vapor Deposition (PVD)

⇒ Typical PVD coating thickness range = **5-20µm**

CEA Patents







SEM and TEM electron micrographs of the cross-section of as-received chromium coatings on a Zirc-4 substrate

⇒ Dense and protective PVD Cr coatings have been obtained with no indication of damage, i.e., no voids/microcracks both within the bulk Cr coating and at the Zr/Cr interface

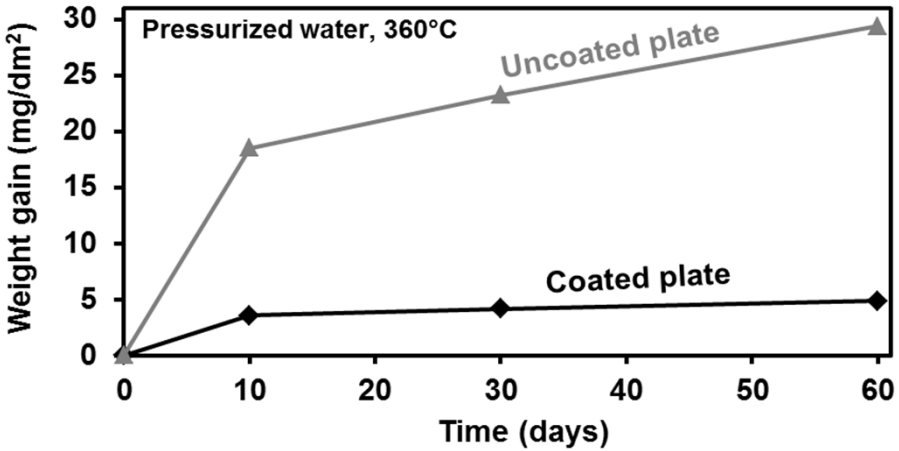
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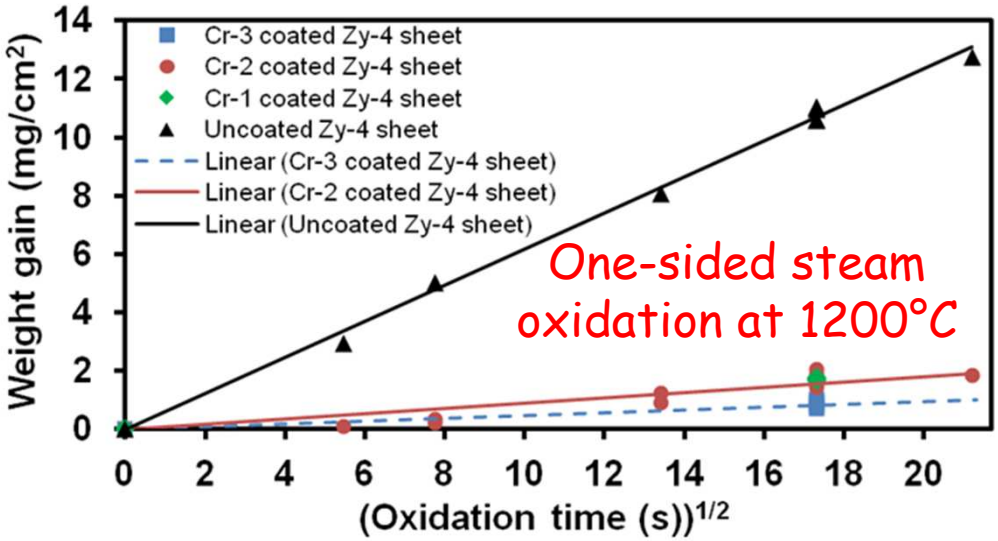
BEHAVIOR IN NOMINAL CONDITIONS

1- Coated Zr sheets

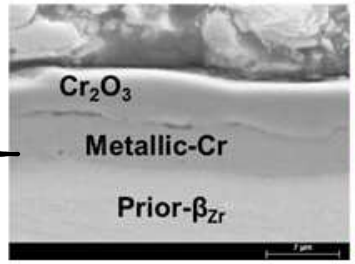
- More than 20 coatings (including ceramics, and metals) investigated at CEA on **sheets Zirc-4** base substrate => among all, **optimized Cr-based coatings are promizing**

→ **Significant decrease in the oxidation kinetics for both in-service (out-of-pile) conditions and at HT (1000-1200°C) typical of DBA-LOCA conditions**

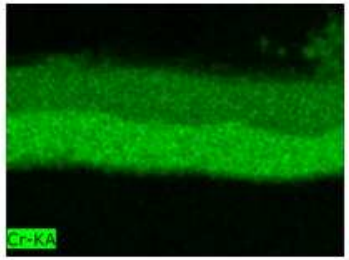




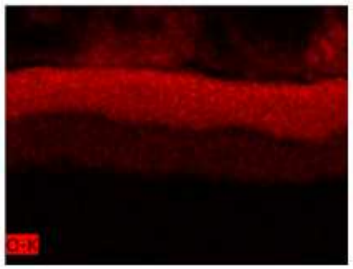
Partially oxidized Cr coating on a Zirc-4 sheet substrate after steam oxidation for **850s at 1100°C**



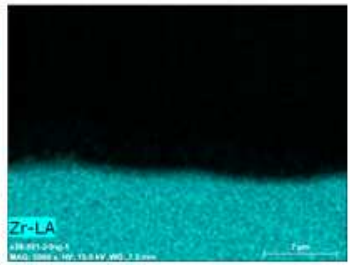
(a) SEM electron micrograph



(b) chromium map



(c) oxygen map



(d) zirconium map

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Previous work on Cr coated Zirc-4 sheets for beyond DBA-LOCA oxidation times: 1000°C, 15000s => "post-breakaway"

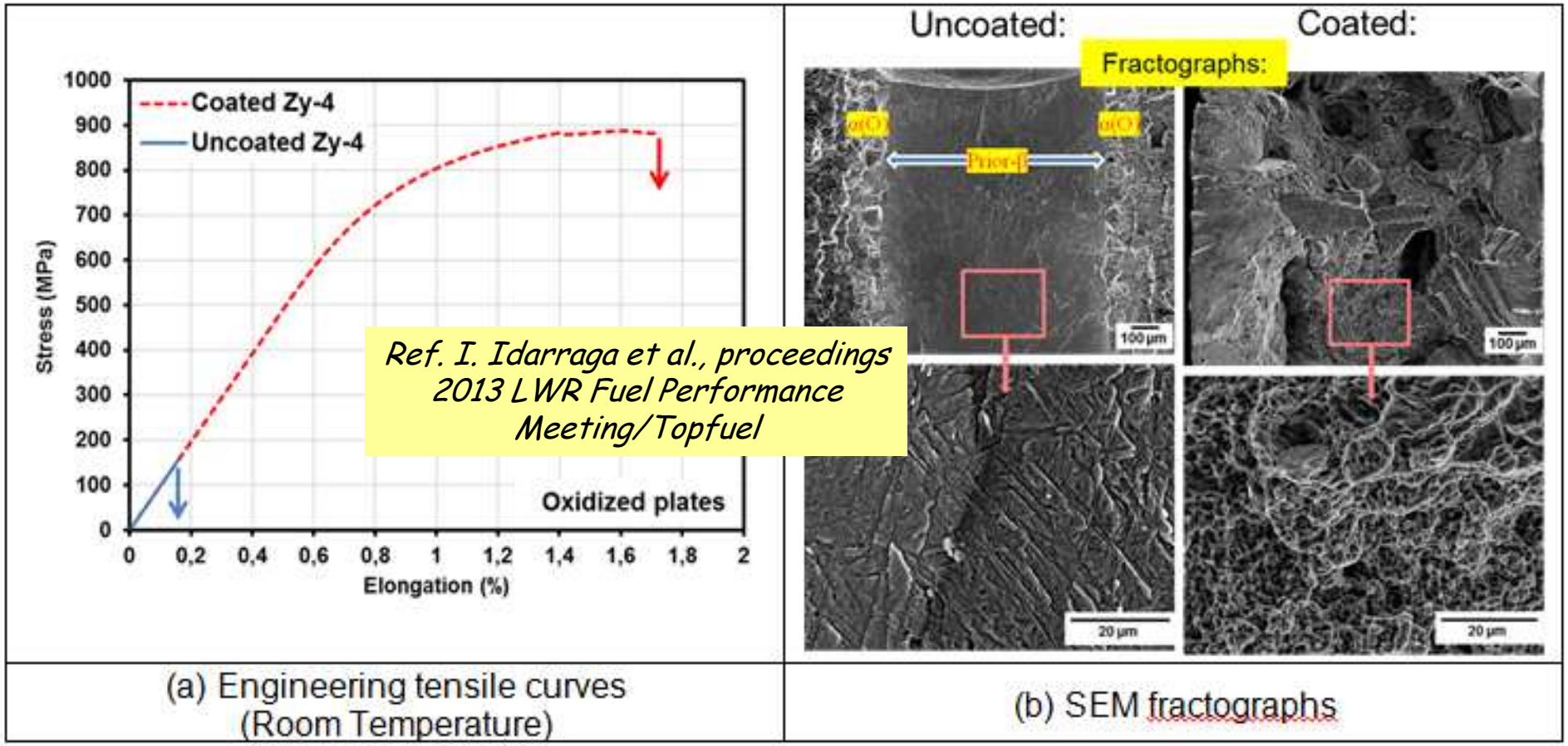


Figure 5 – PQ mechanical behavior of coated and uncoated 1 mm thick sheet (Zircaloy-4) specimen after two-side steam oxidation at 1000°C for 15000 s [1]

High embrittlement of the uncoated Zirc-4 sheet due to important hydriding:

Post-HT-oxidation: $[H_{uncoated}] \sim 2000$wt.ppm vs. $[H_{coated}] < 100$wt.ppm

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Coating applied on tubular claddings geometry and complementary tests for beyond DBA-LOCA conditions

- First tests performed on flat (sheet) Zirc-4 specimens (1 mm thick)

- Transposition of the coating process to tubular clad geometry (up to 20 cm in length):

Ex. : One-side steam oxidation
for 300s at 1200°C
+ direct water quenching from 1200°C



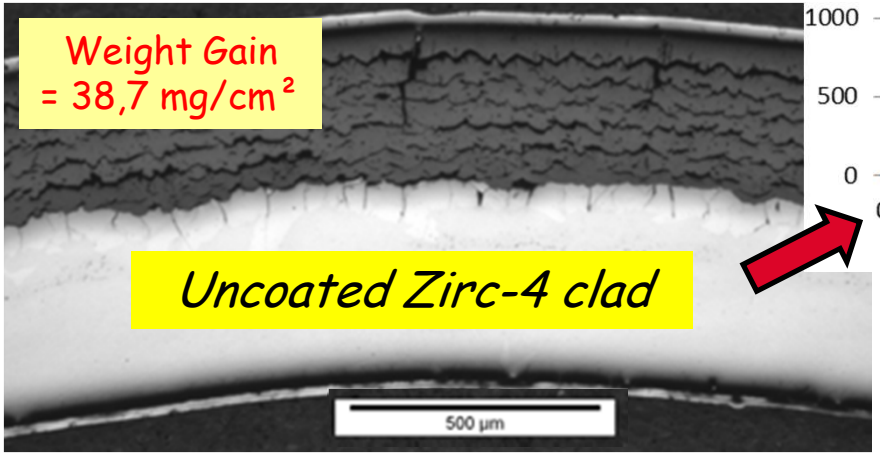
More recent results:

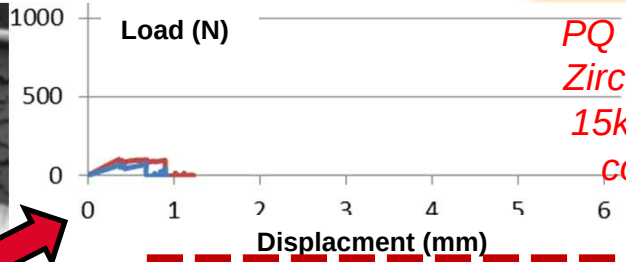
- Tests performed on optimized Cr coated **(tubular) clad** segments for **beyond DBA-LOCA oxidation times** => NEXT SLIDES…

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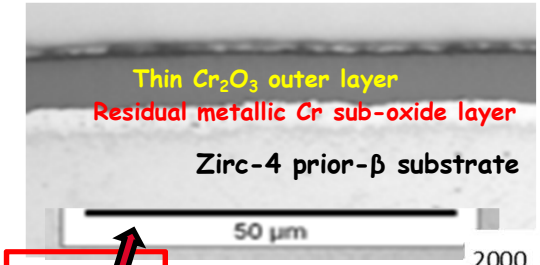
Beyond DBA-LOCA oxidation times: one-side 1000℃, 15000s => "post-breakaway"

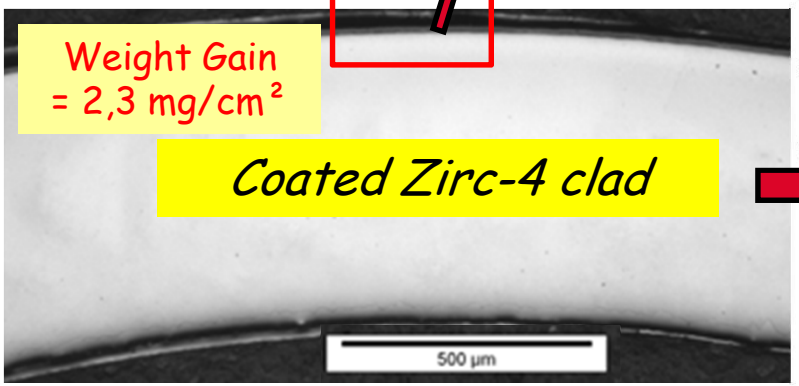
Post-Quench (PQ) Ring Compression Tests (RCT) at 20-135℃

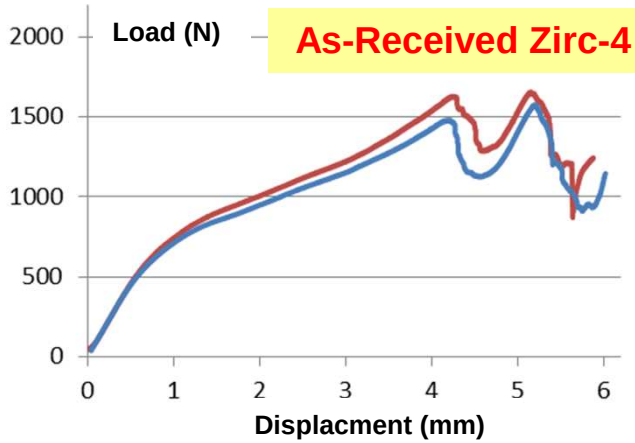


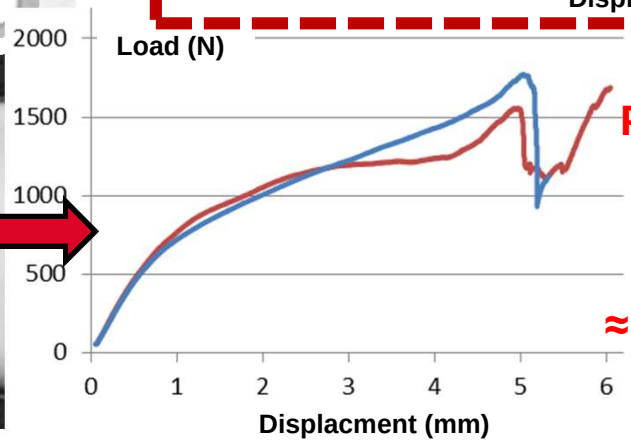


PQ strength/ductility of uncoated Zirc-4 clad ~ 0 after oxidation for 15ks at 1000℃ (due to high [H] content and advanced post-breakaway oxidation)









PQ strength/ductility of coated clad that has experienced oxidation for **15ks at 1000℃ ≈ As-received conditions (!)**

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Beyond DBA-LOCA oxidation times: one side, 1200℃, 6000s

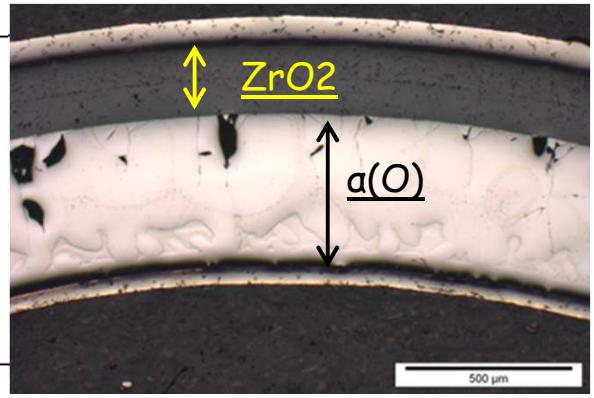


(a) Uncoated Zircaloy-4 clad segment, weight gain = 40,4 mg/cm²

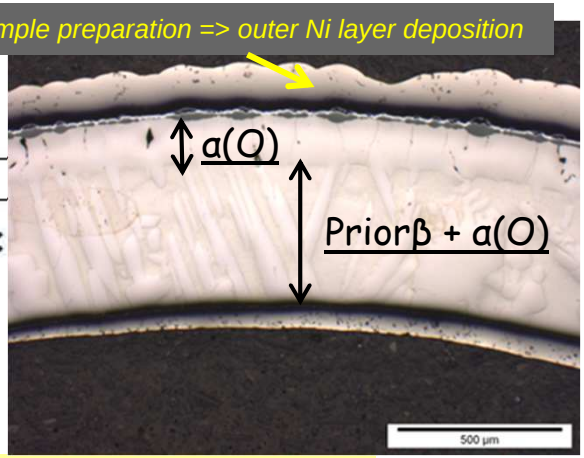


(b) Coated Zircaloy-4 clad segment, weight gain = 11,4 mg/cm²

PQ Zircaloy-4 clad segments appearance after steam oxidation for 6000 s at 1200°C



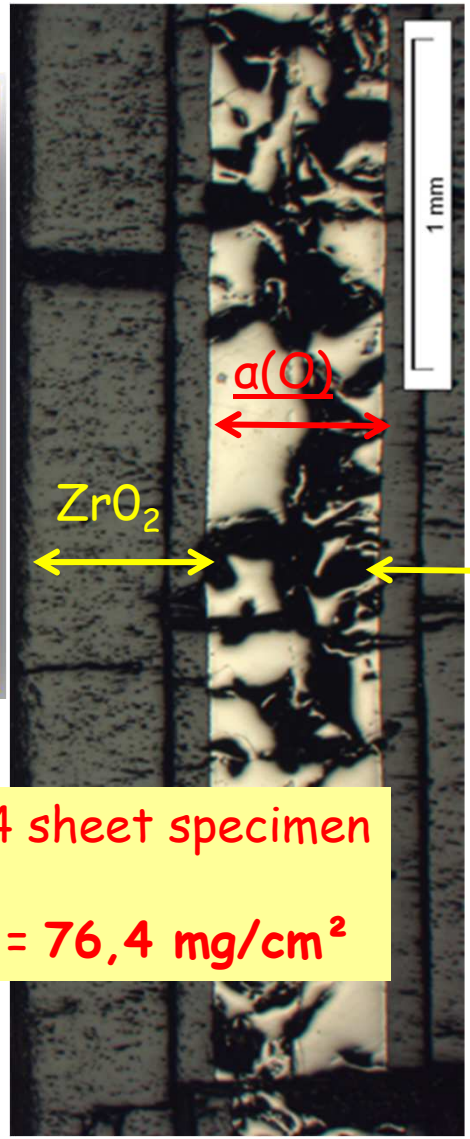
Sample preparation => outer Ni layer deposition



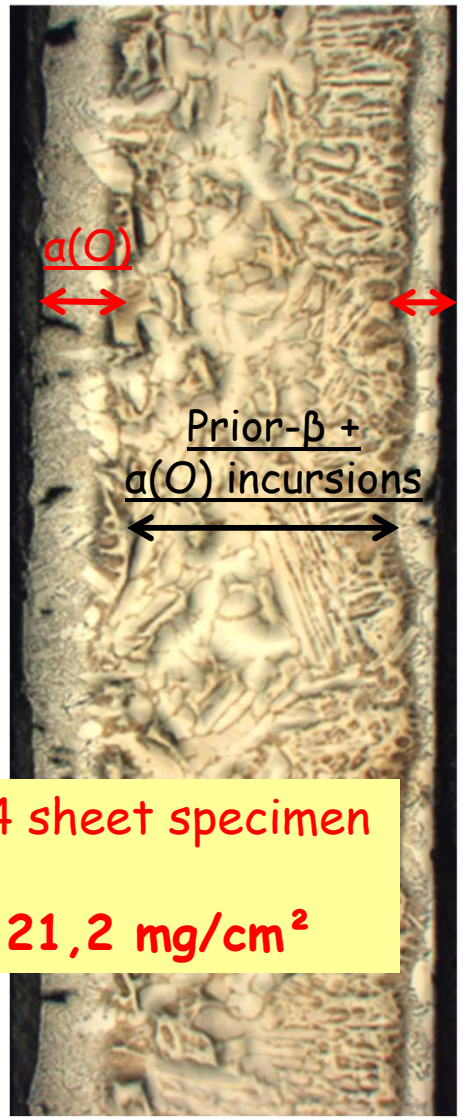
Partial conclusions: Optimized Cr coatings improve the capacity of the HT oxidized cladding to maintain some residual ductility and to survive to the final quenching for beyond DBA-LOCA HT oxidation times, thus providing significant additional "grace period"

Complementary results for beyond DBA-LOCA temperature conditions: "TGA" oxidation in oxygen+helium environment up to 1300°C – 5600 s of Zirc-4 sheets with Cr coatings initial thickness ranging from 15 to 20µm









Uncoated Zirc-4 sheet specimen

=> Weight Gain = **76,4 mg/cm²**

Cr coated Zirc-4 sheet specimen

Weight Gain = **21,2 mg/cm²**

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CONCLUSIONS AND FURTHER WORK

Status of the R&D on innovative coated Zr cladding for PWR at CEA:

- **Optimized PVD Cr-based coatings on Zirc-4** gave encouraging results so far
  - **Decrease in weight gain** in nominal, DBA-LOCA **and slightly beyond DBA-LOCA** conditions
  - **Resistance to quench and post-quench ductility are enhanced** by avoiding/limiting brittle ZrO_2 and Zr-a(O) layers formation and by reducing the oxygen content in the prior-beta layer
  - **Delay the Breakaway phenomena** (at ~1000°C) => **decreases the associated hydrogen pick up**
- Homogeneous/protective Cr coatings on Zirc-4 **clad segment** (up to ~20 cm)

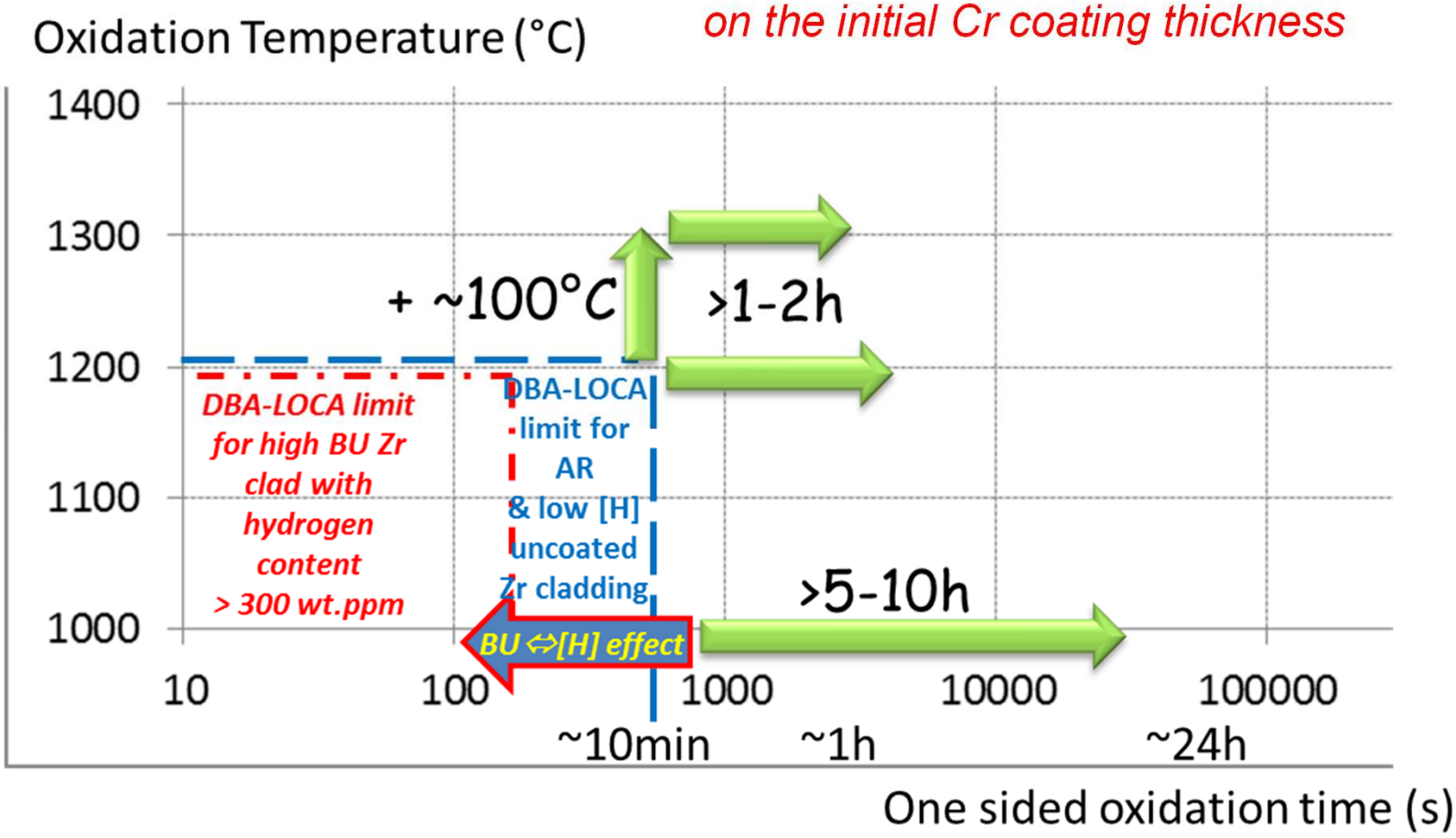
On-going and further work, pending issues:

- Assessment of Cr coatings behavior in other relevant nominal and accidental scenarii, including **under neutron irradiation, thermal/stress/strain cycles**…
- Assessment of the potential additional margins achieved by **relevant LOCA transients calculations** (adapt existing codes and methodology)
- *Fabrications issues* – ***on-going efforts to qualify the coating process for longer tubes, non destructive quality control***, *etc…*

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Expected additional HT steam oxydation time/temperature margins for ~5-20µm thick optimized Cr coated Zirc-4 claddings vs. current DBA-LOCA limits

Remark: of course, additional « grace time-temperature » which can be achieved depends on the initial Cr coating thickness



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THANK YOU FOR YOUR ATTENTION

Some CEA references:

[1] I. Idarraga et al., "Assessment at CEA of coated nuclear fuel cladding for LWRs with increased margins in LOCA and beyond LOCA conditions", in proceedings of 2013 LWR Fuel Performance Meeting/TopFuel, Charlotte, USA, (Sept. 15-19, 2013)

[2] M. Le Flem, et al., "Evaluation of potential alternative nuclear fuel cladding materials for LWRs – CEA studies", proceeding of OECD-NEA ATF Workshop, Dec. 10th, 2012, Issy-les-Moulineaux, France

[3] J.C. Brachet et al. "CEA studies on nuclear fuel claddings for LWRs enhanced accident tolerant fuel: recent results, pending issues and prospects" , Proceedings of OECD-NEA Meeting on "Increased Accident Tolerance of Fuels for LWRs", Issy-les-Moulineaux, France, (Oct. 28-29, 2013)

[4] T. Forgeron et al., "ATF R&D status and Perspectives (I3P- Three Parties Institute CEA-EDF-AREVA)", Proceeding of OECD-NEA Start-up meeting of the Expert Group on Accident Tolerant Fuels of LWRs, OECD-HQ, Issy les Moulineaux, France, (April, 28-29, 2014)

[5] J.C. Brachet, Ch. Lorrette, et al., "CEA studies on advanced nuclear fuel claddings for enhanced Accident Tolerant LWRs Fuel (LOCA and beyond LOCA conditions)", Proceedings of the 8th. Int. Symposium "Fontevraud 8" on "Contribution of Materials Investigations and Operating Experience to LWRs' Safety, Performance and Reliability", Avignon, France, (Sept. 14-18 2014)

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