

DE LA RECHERCHE À L'INDUSTRIE



French alternative energies and atomic energy commission
Saclay center | F91191 Gif-sur-Yvette Cedex
T. +33 (0)1 69 08 51 66 | F. +33 (0)1 69 08 82 52

Nuclear Energy Division
Nuclear Materials Department
Section for Applied Metallurgy Research

www.cea.fr

BEHAVIOR UNDER LOCA CONDITIONS OF ENHANCED ACCIDENT TOLERANT CHROMIUM COATED ZIRCALOY-4 CLADDINGS

*J.C. Brachet, M. Le Saux, V. Lezaud-Chaillieux, M. Dumerval, Q. Houmaire
DEN-Service de Recherches Métallurgiques Appliquées (SRMA),
CEA, Université Paris-Saclay, Gif-Sur-Yvette, France*

*F. Lomello,
DEN, Service d'Etudes Analytiques et de Réactivité des Surfaces (SEARS),
CEA, Université Paris-Saclay, Gif-Sur-Yvette, France*

*F. Schuster,
DEN-Dir, CEA, Université Paris-Saclay, Gif-sur-Yvette, France,*

*E. Monsifrot,
UTBM, Belfort, France*

*J. Bischoff,
AREVA NP, Lyon, France*

*E. Pouillier
EDF R&D, MMC, Moret-Sur-Loing, France*

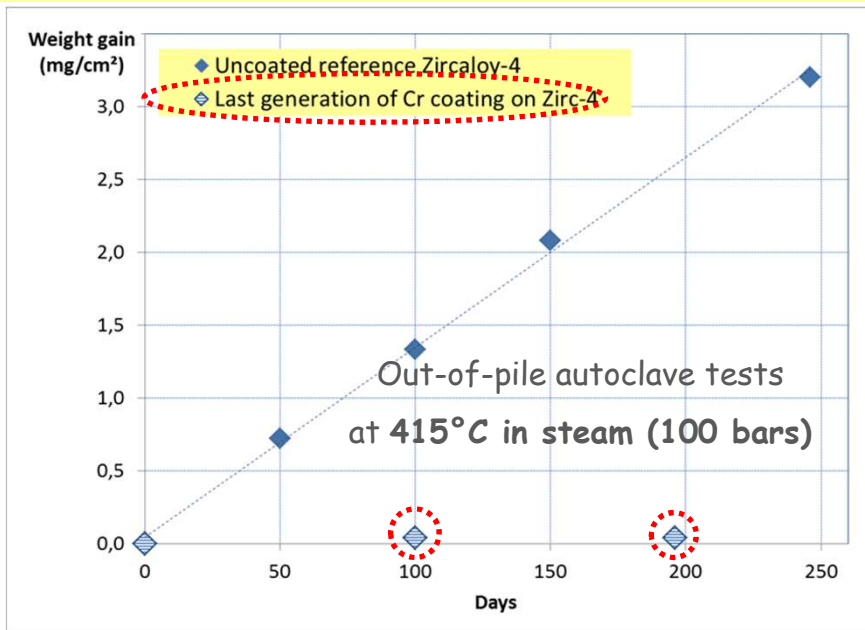
*TOPFUEL Reactor Fuel Performance 2016,
Boise, Idaho, USA, Sept. 11-15 2016*

jean-christophe.brachet@cea.fr

INTRODUCTION

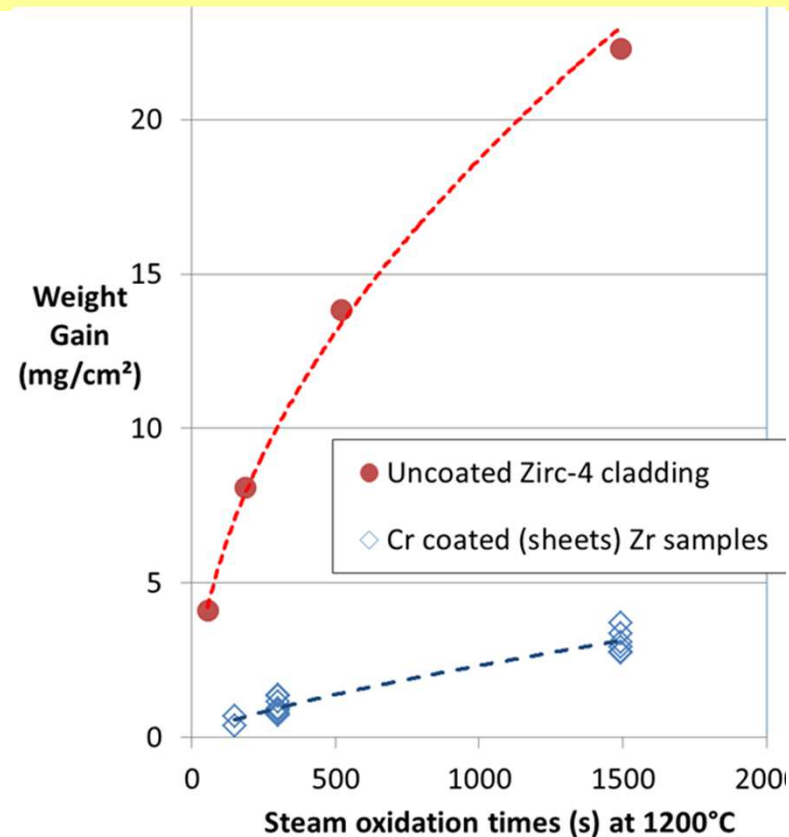
Cr-coated zirconium nuclear fuel cladding developed within CEA - Areva NP- EDF collaborative program as short-term Enhanced Accident Tolerant Fuel for LWRs (EATF): Previous studies have shown that the developed Cr-coated claddings are characterized by:

- Excellent corrosion behavior in nominal conditions - see J. Bischoff et al. - this conference;
- Significant decrease of the oxidation rate with steam at HT (LOCA).



| 200 days at 415°C (steam, 100 bars) | Uncoated Zirc-4 | Cr coated Zirc-4 |
|--|-----------------|------------------|
| ZrO ₂ or Cr ₂ O ₃ thickness | ~17µm | <0,1µm |

Brachet et al, Topfuel 2015



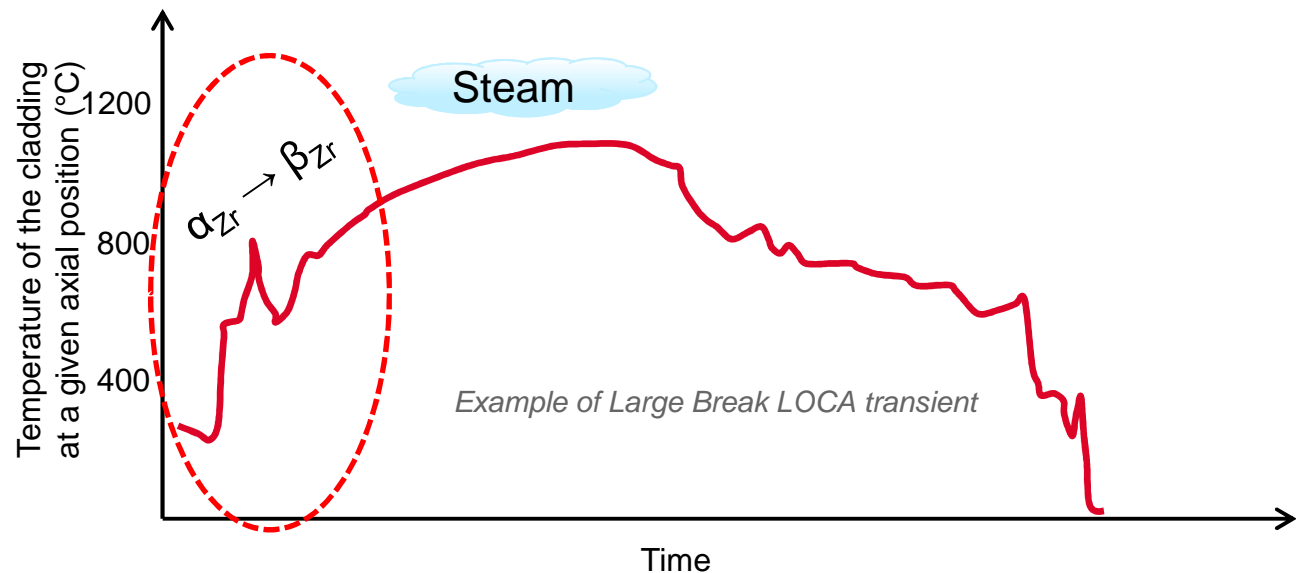
Brachet et al, Topfuel 2015

AIM OF PRESENT WORK

Present work focused on 1st step of LOCA transient, i.e., internal pressure (isothermal or ramp) tests inducing creep/ballooning and burst of the tested nuclear fuel clad segments:



Uncoated claddings appearance after ballooning and burst (« EDGAR ») testing



=> Preliminary evaluation of the influence of Cr-coating on the overall clad thermo-mechanical behavior compared to uncoated cladding by focusing on the following parameters:

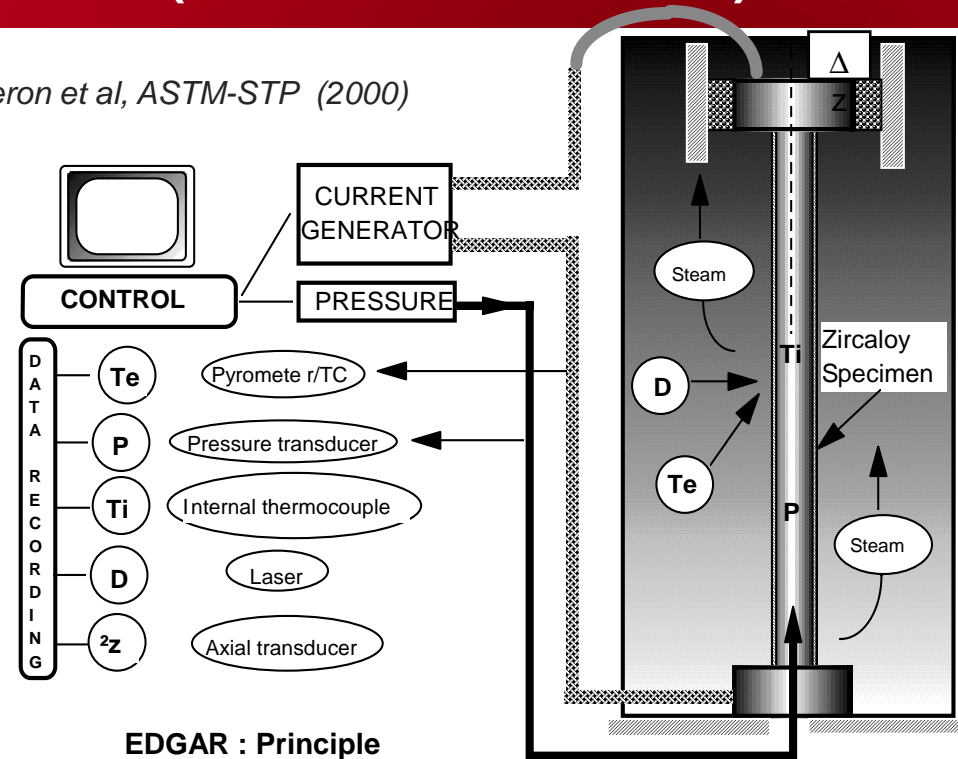
- Steady-state creep rate / time to rupture
- Size of balloon and burst opening

=> Checking also the coating adhesion capacity at HT in highly deformed (ballooned) zone

THERMAL-MECHANICAL CLAD TESTING UNDER LOCA CONDITIONS AT CEA ("EDGAR" FACILITY)

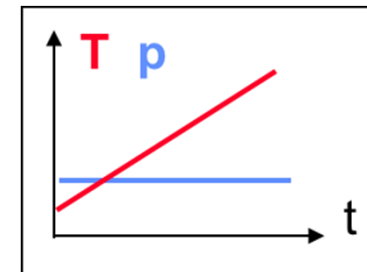
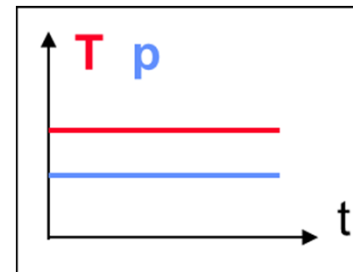
- Single(*) Rod Tests (50cm in length)
- Steam environment, Any T&P transients
- Tmax: ~1300°C, dT/dt: up to 200°C/s,
- T gradients (axial, azimuth.) < 5°C,
- Pmax: 200 Bar, dP/dt: [-10, +10] Bar/s
- * *No contact measurements:*
- *T : optical pyrometers (+ internal TC)*
- *Continuous ext. diam. measur.: laser*
- (*) *on-going multi-rod facility development*

Forgeron et al, ASTM-STP (2000)



EDGAR : Principle

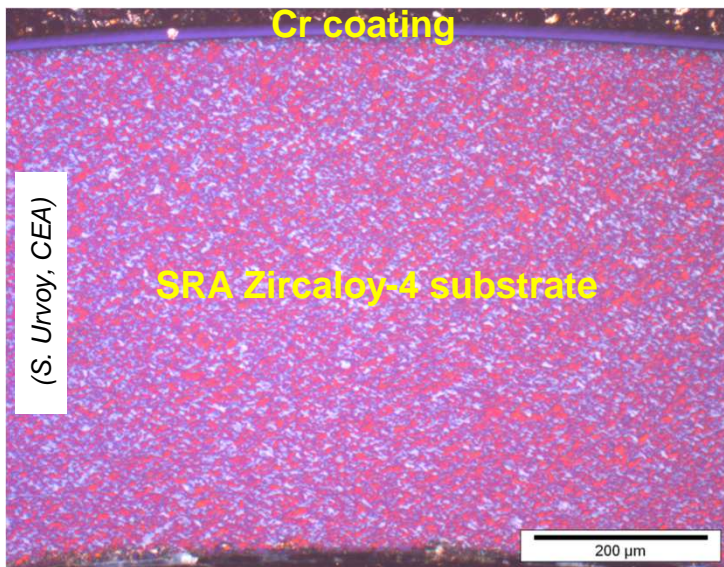
=> "EDGAR" internal pressure creep and preliminary ramp tests here performed:



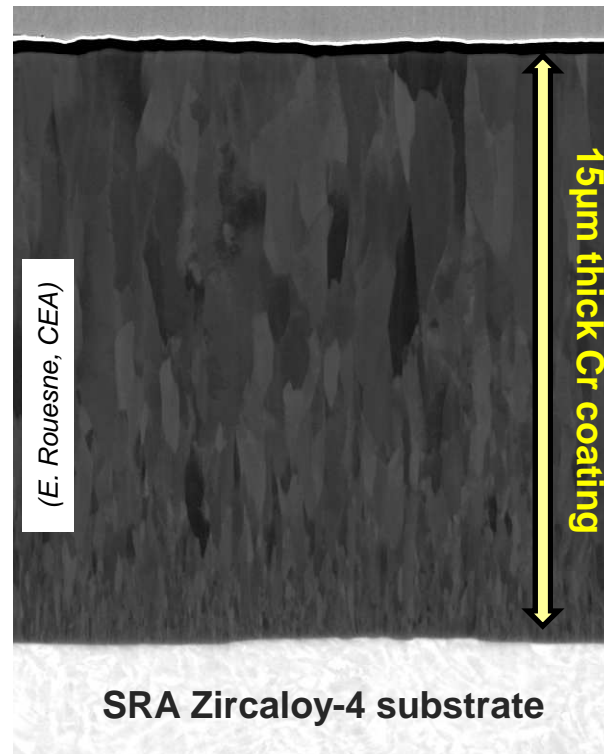
MATERIALS STUDIED AS-RECEIVED EXAMINATIONS



SRA Low-Tin Zircaloy-4 from AREVA-NP
50cm clad segments
with ~15 μ m thick Cr coating



OM (polarized light) of the wall (coated) clad thickness

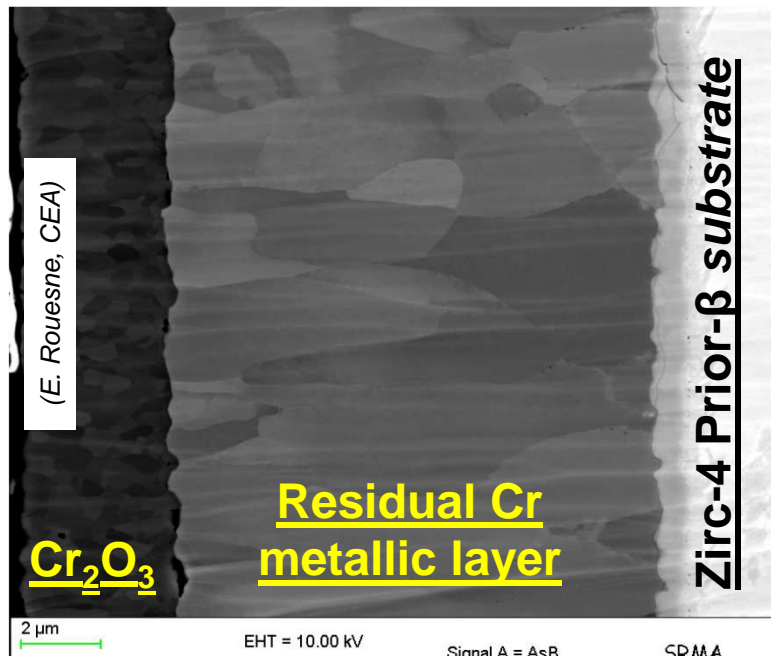


SEM micrograph (BSE mode) of the Cr coating thickness

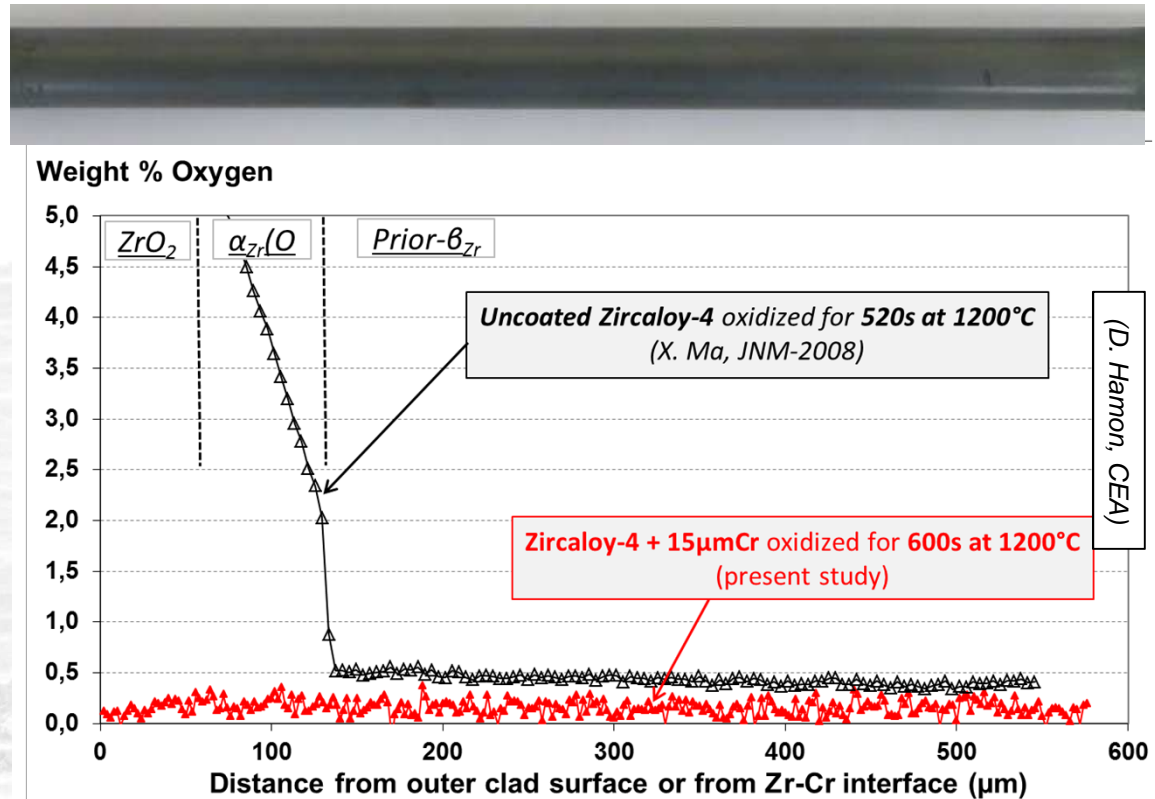
- ⇒ No modification of the SRA metallurgical conditions of the substrate after the coating process
=> *no modification of the As-Received clad mechanical properties*
- ⇒ Good homogeneity
- ⇒ Good density
(no porosities)
- ⇒ No cracks within the bulk Cr nor at the Zr-Cr interface
(good adhesion)

CHECKING OF THE HT STEAM OXIDATION 15 μm-THICK Cr COATING RESISTANCE

15 μm-thick Cr coated clad
one-sided steam oxidized
for 600s at 1200°C (ECR_{BJ}~17%)



SEM (BSE mode) micrograph
of the post-HT-oxidized
coating thickness

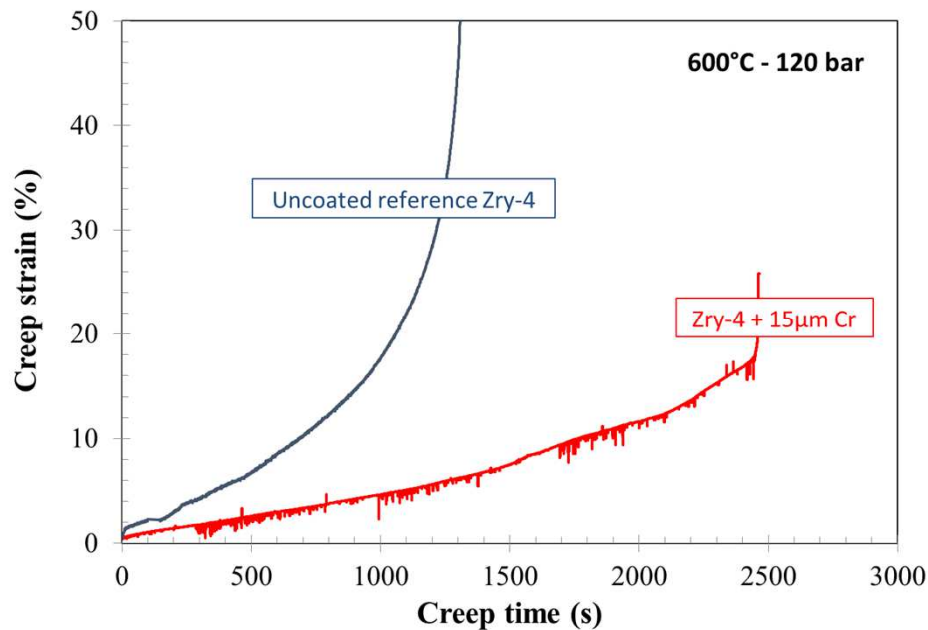


EPMA μchemical oxygen profiles throughout
the post-oxidized clad thickness

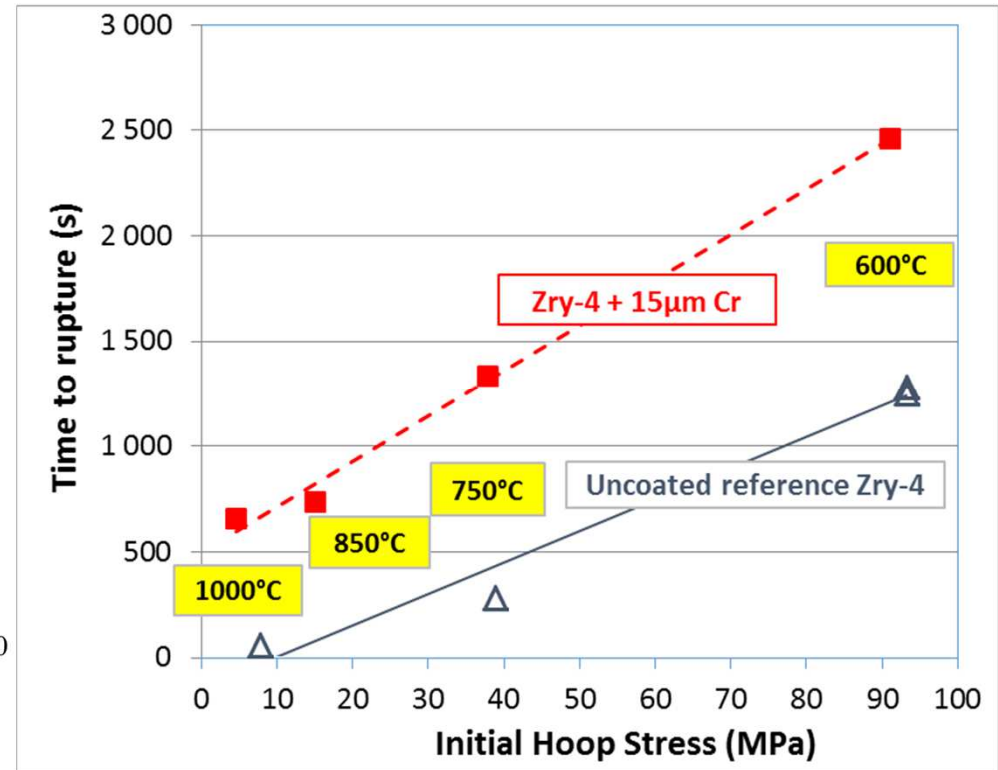
⇒ No oxygen diffusion into the metallic prior-β_{Zr}
substrate of the 15 μm thick Cr coated Zircaloy-4
after oxidation for 600s at 1200°C
⇒ High cladding PQ ductility preserved

HT CREEP TEST RESULTS (1/2)

FROM 600°C (α_{Zr} PHASE DOMAIN) UP TO 1000°C (β_{Zr} PHASE DOMAIN)



Typical creep curves obtained on uncoated & 15 μ m thick Cr-coated Zry-4 clad segments at 600°C, for an applied internal pressure of 120 bar



Time to rupture as a function of initial hoop stress for EDGAR (internal pressure) isothermal creep tests performed at different temperatures

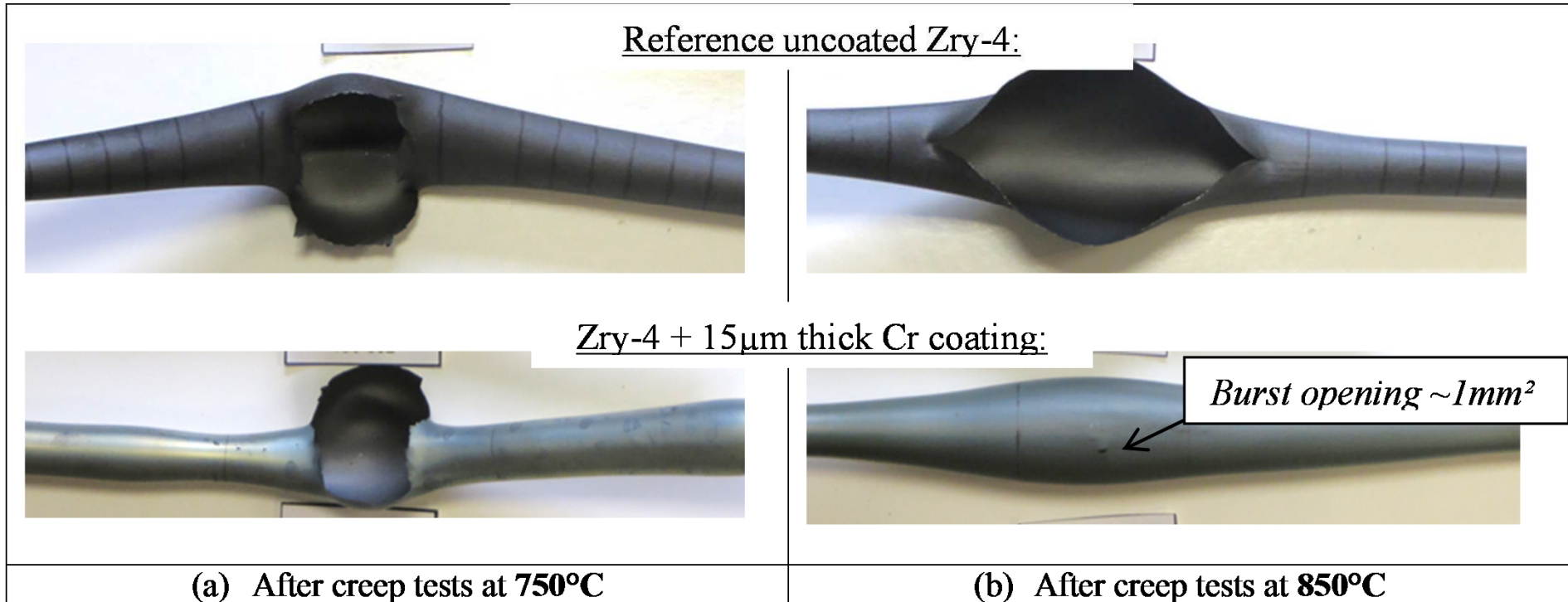
Evidence of a Cr-coating HT strengthening effect

=> compared to uncoated Zircaloy-4:

~3 times increase of the time to rupture \Leftrightarrow ~3 times decrease of the creep rate

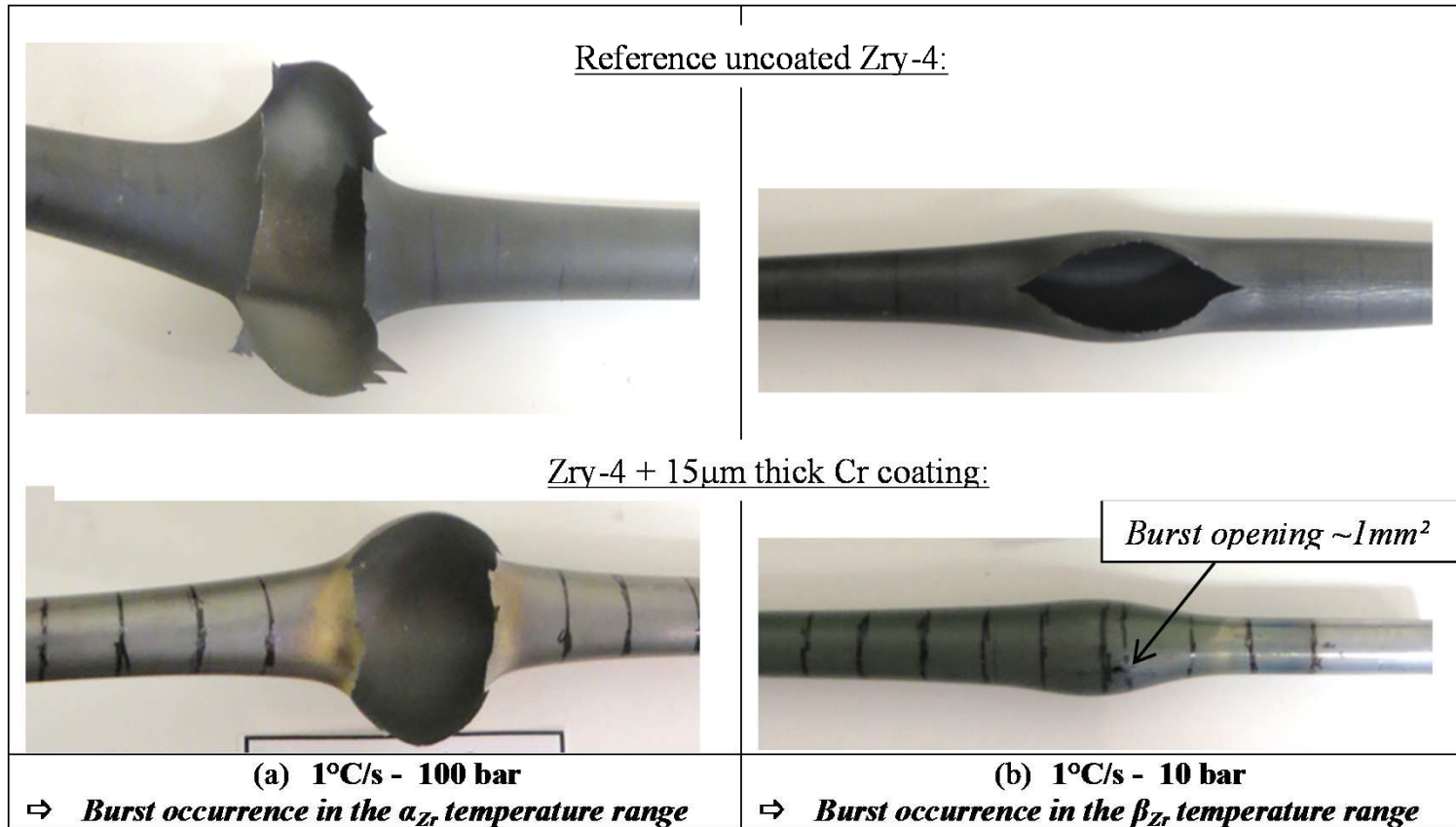
HT CREEP TEST RESULTS (2/2)

Burst appearance after EDGAR creep tests:



- Whatever applied T&P values, **Cr coating fully adherent** (including near the burst location);
- **Very limited oxidation** of Cr coated clads
(confirmation of Cr coating resistance to HT steam oxidation, including in the ballooned zone);
- For $T_{creep} < 800^{\circ}\text{C}$ (full α_{Zr} temperature range) **lower balloon size of Cr-coated clads** (i.e., up to ~40% of relative decrease of clad circumferential elongations close to the burst locations);
- For $T_{creep} > 800^{\circ}\text{C}$ ($\{\alpha_{Zr} + \beta_{Zr}\}$ and full β_{Zr} temperature ranges), **burst opening $< \sim 1\text{mm}^2$** .

PRELEMINARY RAMP TESTS (10 AND 100 BARS, 1°C/S)



Same observations as for isothermal creep tests:

=> good coating adherence, negligible oxidation, smaller balloon size when burst occurs in the α_{Zr} temperature range (high internal pressure applied), very small burst opening when burst occurs in the HT β_{Zr} temperature range (low internal pressure applied)..

CONCLUSIONS AND ON-GOING/FURTHER WORK

- 50cm long 15- μm Cr-coated Zircaloy-4 clad segments have been fabricated and then submitted to ("EDGAR") HT internal pressure creep/ramp tests;
- **No modification of the underlying Zr-4 μ structure/properties** induced by the Cr-coating process;
- **Very good adherence of Cr-coating** in both nominal & accidental conditions;
- **Significantly improved behavior in LOCA conditions:**
 - Confirmation of the HT steam oxidation resistance;
 - **Reinforcement of cladding by Cr-coating observed at HT** upon creep/ramp tests in the α_{Zr} temperature range;
 - **In the $\{\alpha_{\text{Zr}} + \beta_{\text{Zr}}\}$ and full β_{Zr} phase temperature ranges (~850-1000°C), even if some significant ballooning occurred prior to the cladding failure, **burst openings are generally very small** (\Rightarrow may have positive effect in LOCA for high BU materials, by reducing the risk of fuel fragments dispersal in the coolant.)**
- On-going and further work: **additional creep & thermal ramp tests** under internal pressure on Cr-coated materials including M5™ substrate + **further modelling**

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] 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", Avignon, France, (Sept. 14-18 2014)

[3] J.C. Brachet et al., "On-going studies at CEA on chromium coated zirconium based nuclear fuel claddings for enhanced tolerant LWRs fuel", proceedings of TopFuel 2015, Zurich, Switzerland (Sept. 13-19, 2015)

[4] J.C. Brachet et al., "Out-of-pile R&D on chromium coated nuclear fuel zirconium based claddings for enhanced accident tolerance in LWRs", proceedings of 18th Int. Symp. on Zr in Nucl. Ind.", Hilton Head, SC, USA (May 15-19, 2016)

French alternative energies and atomic energy commission
Saclay center | F91191 Gif-sur-Yvette Cedex
T. +33 (0)1 69 08 51 66 | F. +33 (0)1 69 08 82 52

Nuclear Energy Division
Nuclear Materials Department
Section for Applied Metallurgy Research