DE LA RECHERCHE À L'INDUSTRIE

EVALUATION OF POTENTIAL ALTERNATIVE NUCLEAR FUEL CLADDING MATERIALS FOR LWRS – CEA STUDIES –

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www.cea.fr

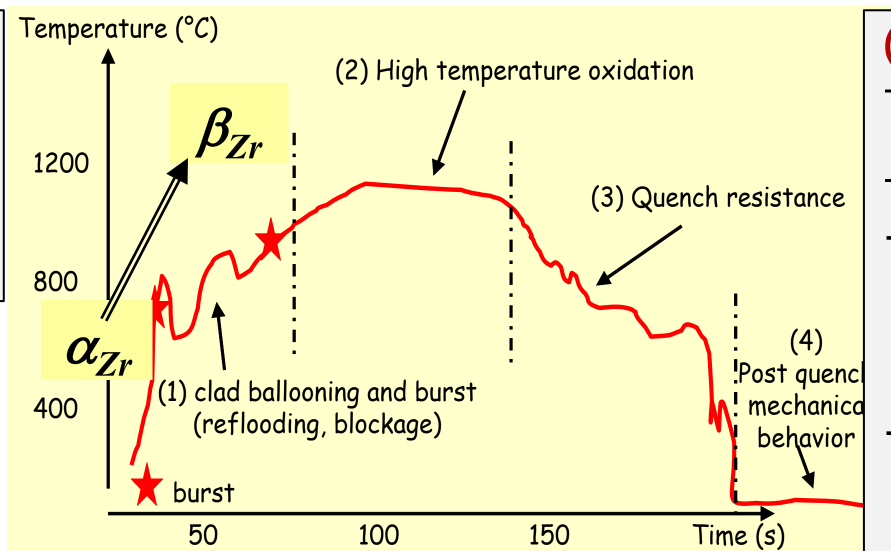
INTRODUCTION – STUDIES ON LOCA AT CEA (1/2)

Extensive LOCA tests on Zr base cladding these last 15 years

→ more than 1000 thermal-mechanical tests (including irradiated materials)
+ deep metallurgical analysis

(b) High temperature steam oxidation
- underlying metallurgical analysis
- oxygen diffusion modeling

(a) Internal pressure creep-burst tests
Link with
- α → β
- Irradiation
- hydrogen effects



(c) Quenching resistance
- Post-Quenching mechanical tests (RCT, 3-PBT, Impact)
- extensive metallurgical analysis

→ Relationship between
- phases thicknesses
- oxygen/hydrogen profiles
- and PQ properties

→ Effects of cooling scenario, of pre-hydriding, of pre-transient oxides…

INTRODUCTION – STUDIES ON LOCA AT CEA (2/2)

Motivation for a new cladding to sustain LOCA transient

→ Decrease the reaction with steam water to reduce hydrogen risk

- Lowering oxidation rate
- Creating more stable oxides

→ Improve the mechanical properties

- Lowering deformation level to keep coolability or the core
- Maintain ductility to avoid fracture/fragmentation

→ Increase the margin to melting

Accident tolerant fuel/cladding at CEA

1- Stainless Steels

2- Coated Zr clad

3- SiC/SiC composites

Assess the advantages in terms of performance towards LOCA and check the good in-sevice behaviour

1. 304 STAINLESS STEELS FUEL CLADDING

L. Portier, et al. (CEA Saclay),

Creep-rupture, steam oxidation and recovery behaviors upon dynamic transients up to 1300°C of cold-worked 304 stainless steel tubes dedicated to nuclear core fuel cladding

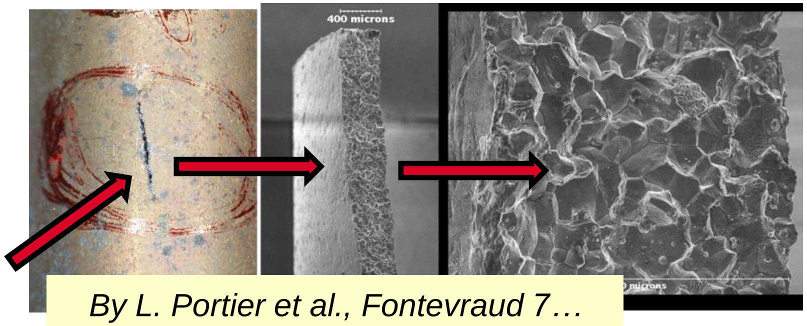
Proceeding of Fontevraud 7 - "Contribution of Materials Investigations to Improve the Safety and Performance of LWRs", 26-30 September, 2010, Avignon, FRANCE

Potential margins of stainless steel clad behavior upon LOCA conditions (vs. Zr claddings)

- Higher creep resistance at high temperature
- Lower oxidation kinetics up to 1300°C at least
- Better Post-Quenching ductility (and likely during the water quench itself) as far a significant internal metallic layer remains (no oxygen, nor hydrogen embrittlement of the remaining metallic layer)

BUT

- Important neutron penalty
- Lower melting temperature
- Potential intergranular brittle failure mode in LOCA
- Potential in-service PCI/IASCC cracking;
- In-service activation and post-service remaining radioactivity, etc…



By L. Portier et al., Fontevraud 7…

→ **CEA prospective studies on innovative nuclear fuel cladding materials/designs**

2. COATED ZR BASE CLADDING (1/5)

Purpose

- Delay or avoid oxidation of the Zr alloy in nominal conditions (higher burn-up)
- **Delay or avoid oxidation of the Zr alloy in accidental conditions**
  - In order to keep post-quenched ductility
  - and to decrease hydrogen release
- Having an iterative solution involving thin coatings on well-known Zr cladding
  - No significant change in geometry
  - No significant change in mechanical / thermal properties
  - Potential use of penalizing elements (in terms of neutron compatibility)

Main challenges

- Find the appropriate composition of the coating
- Fabricate an homogeneous coating with suitable process
- Keep the coating adherent in nominal conditions
- Avoid spalling of the (oxidized) coating at high temperature

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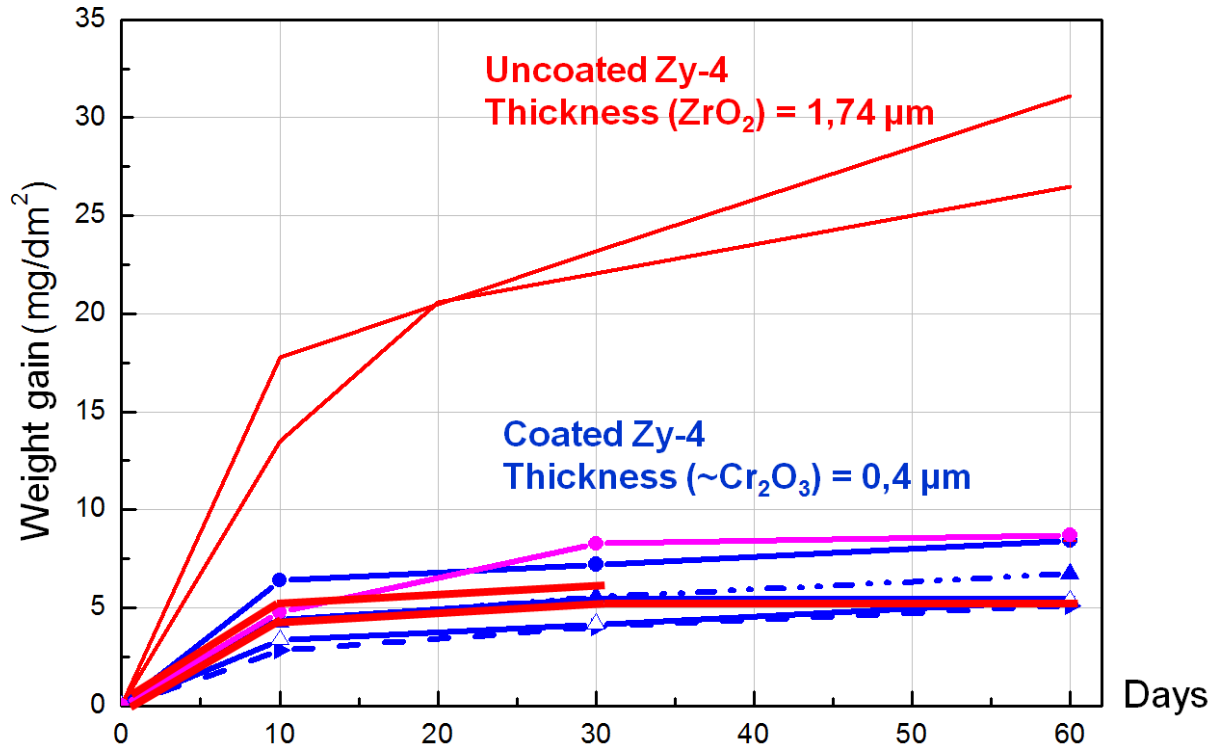
2. COATED ZR BASE CLADDING (2/5)

Behavior in nominal conditions

- More than 20 coatings investigated these last 7 years
- Ceramics (carbides/nitrides), metals, optimised microstructure
- With Cr base-coatings → **Significant decrease in the oxidation kinetics**



Oxidation at 360°C, 60 days, liquid water at 190 bar, relevant chemistry

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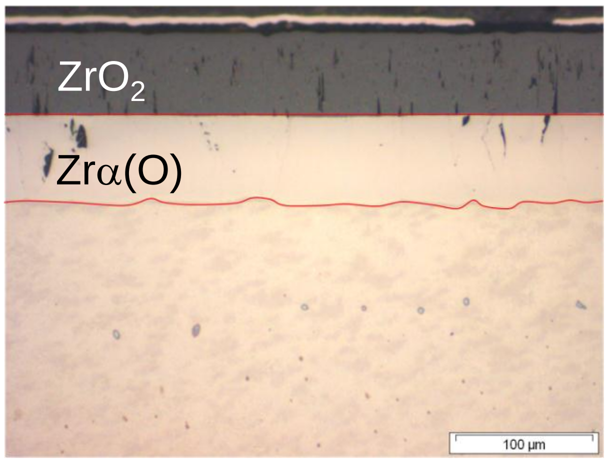
2. COATED ZR BASE CLADDING (3/5)

Behavior in LOCA conditions

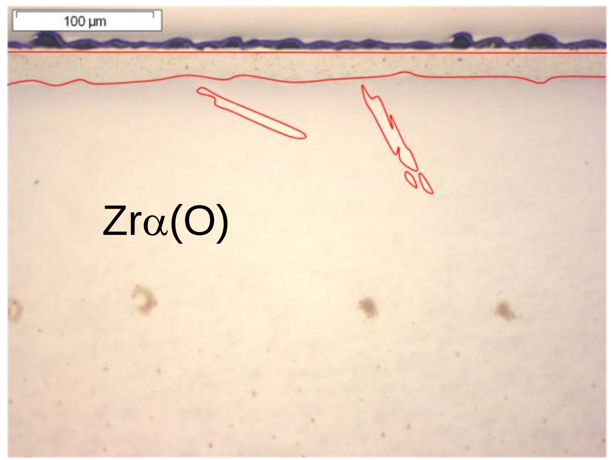
- Made on the most promising coatings (flat specimens)
- 1100°C 850 seconds, **1200°C 300 seconds** in steam water + quench
- Weight gain, microstructure observations, Post-quench flexural/tensile tests

Zy-4



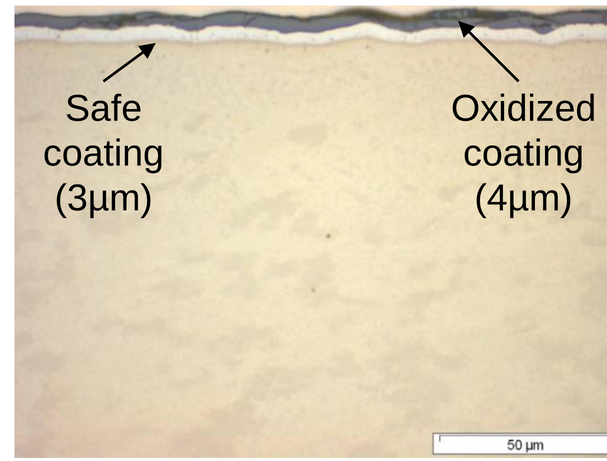
ZrO_2 60 µm
Zrα(O) 60 µm
Equivalent Zr = 100µm

Zy-4 + Cr-base coating



no ZrO_2
Zrα(O) 14 µm
Equivalent Zr = 14 µm

Zy4 + optimized Cr-base coating

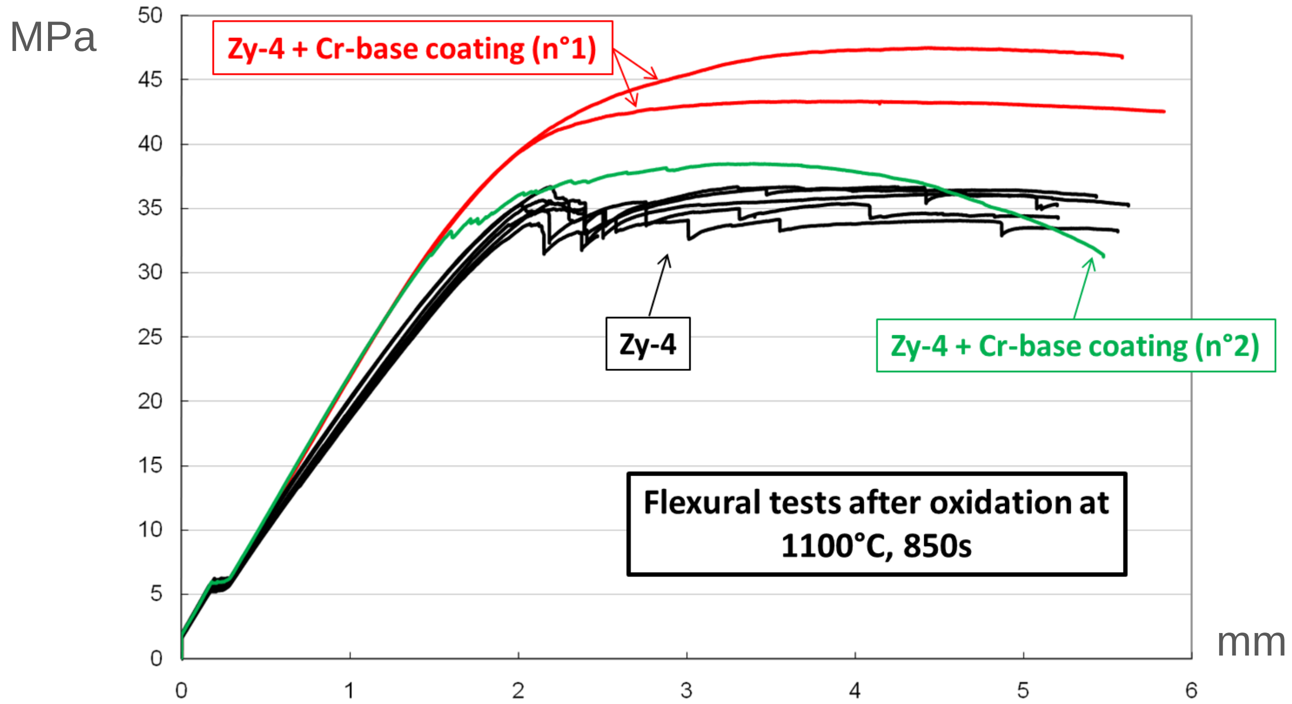


no ZrO_2
no Zrα(O)
Equivalent Zr = 0 µm

→ Significant decrease in the amount of oxidized Zr
→ Mitigation of hydrogen risk
→ Decrease in the fraction of brittle layers formed upon HT oxidation

Behavior in LOCA conditions

- Made on the most promising coatings (flat specimens)
- 1100°C 850 seconds, **1200°C 300 seconds** in steam water + quench
- Weight gain, microstructure observations, Post-quench flexural/tensile tests

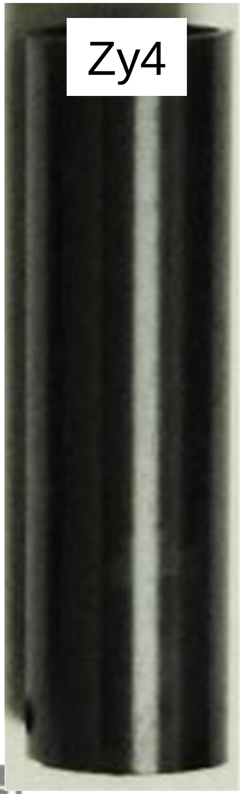


→ Significant increase in remaining ductility
→ Margins on the PQ ductility vs. ECR

2. COATED ZR BASE CLADDING (5/5)

Behavior in LOCA conditions

- Experiments performed on made on the most promising coatings (flat specimens)
- 1100°C 850 seconds, **1200°C 300 seconds** in steam water + quench
- Weight gain, microstructure observations, Post-quench flexural/tensile tests



First coatings

→

Improved coatings

→

Optimized coatings

→ Transposition to tubes has been achieved
Weight gain has been decreased
from 10 mg/cm² to 0,4 mg/cm²

[Idarraga, Lomello, Billard et al. 2012, unpublished results]

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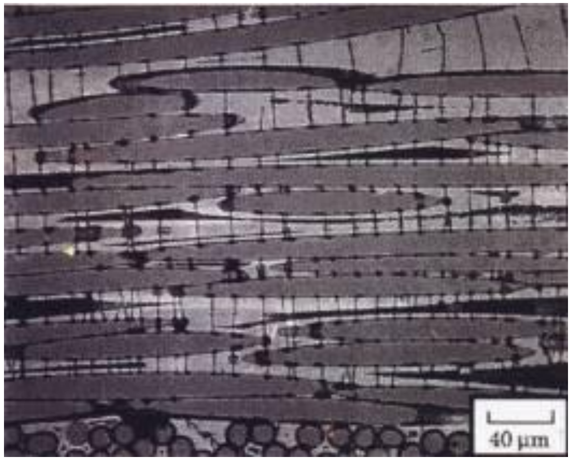
3. SIC/SIC COMPOSITE CLADDING (1/5)

Purpose

- Enhance oxidation resistance (thermodynamics, kinetics)
- Increase margin to fusion (decomposition temperature of 2700°C)
- Providing a stiff and resistant cladding
  - in order to keep a « coolable » core
  - to avoid fuel relocalization
  - and to keep the fuel confinment



Guillaumat, LCTS 1994

Main challenges of SiC/SiC for PWR cladding

- Consider an elastic/damageable material for the design (with low thermal conductivity)
- Providing gas-tightness (at the level of the cladding, or of the fuel)
- Fabrication of elongated clads
- Describe the oxidation phenomena (passive/active) and consider erosion mecanism
  - Avoid surface spoiling in nominal condition
  - Determine the gazeous species induced by LOCA

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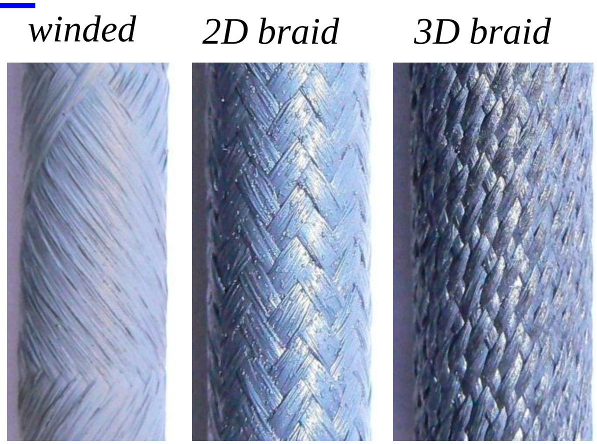
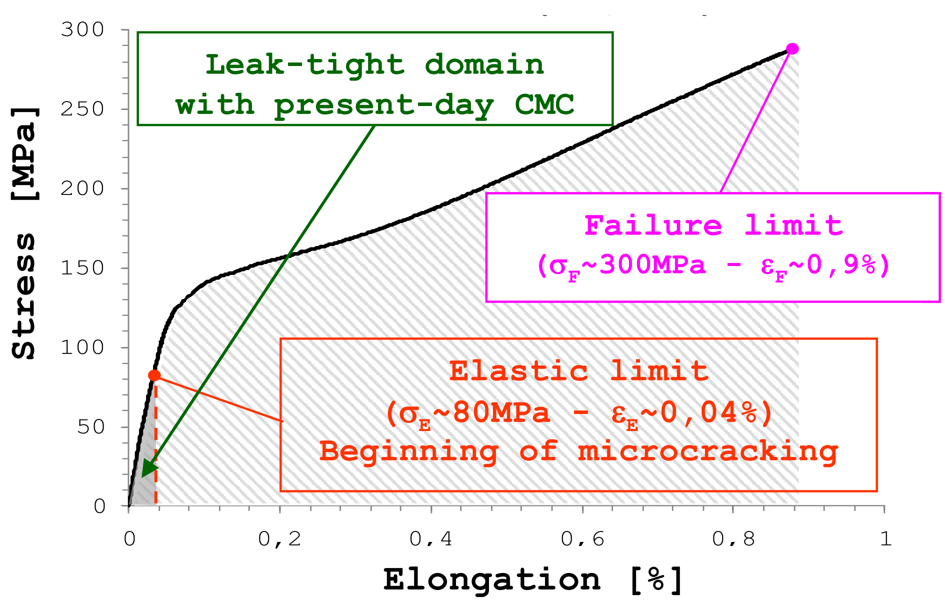
3. SIC/SIC COMPOSITE CLADDING (2/5)

SiC/SiC cladding mainly driven by GRFs applications

- Significant R&D at CEA in terms of fabrication of suitable cladding
- “Sandwich” concept with a metallic liner providing gas-tightness (demonstrated)
- Tailorable mechanical properties thanks to optimisations of interphase and braiding
- Very good dimension control and fabrication reproducibility
- End-plugging solutions



CEA sandwich cladding



Transposition to LWR is achievable

Preliminar corrosion testing of SiC/SiC for PWR


Furnace for P_{atm}


High pressure furnace

- Corrosion tests on SiC/SiC
- Mechanical tests *(tensile test at RT)*
- Characterizations *(optical / SEM / XRD)*

SiC/SiC tubes and SiC wafers (A to C)

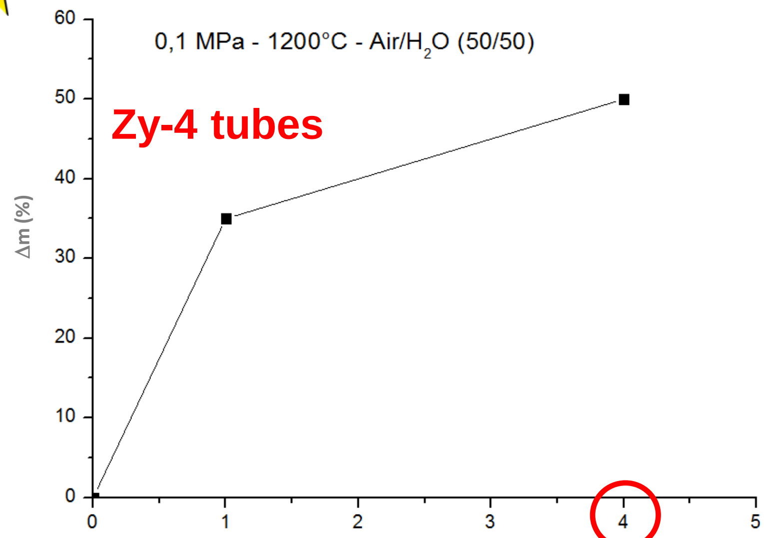
Condition A	1 MPa – 1200°C – Air/H_2O (95/5)	
Condition B	0,1 MPa – 1200°C – O_2/H_2O (50/50)	
Condition C	0,1 MPa – 1200°C – Air/H_2O (50/50)	
Condition D	0,1 MPa – 1400°C – Air/H_2O (50/50)	% O_2 ↗

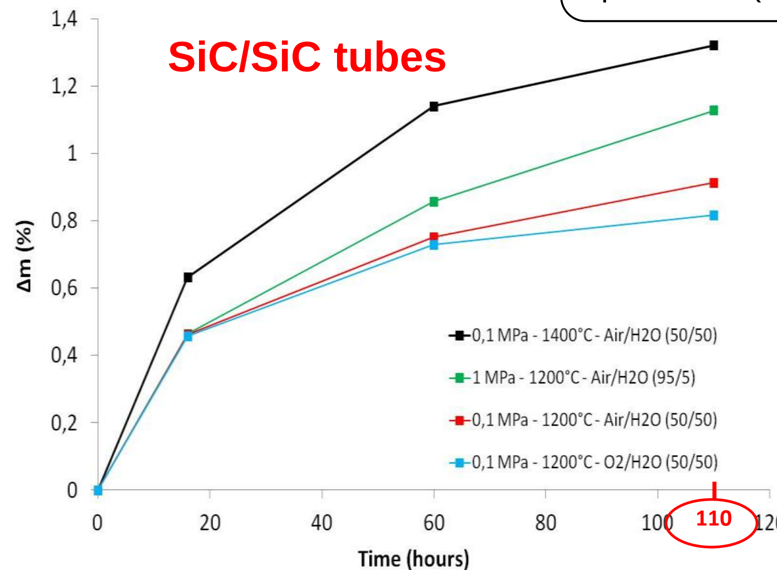
Zircaloy clad → Condition C 0,1 MPa – 1200°C – Air/H_2O (50/50)

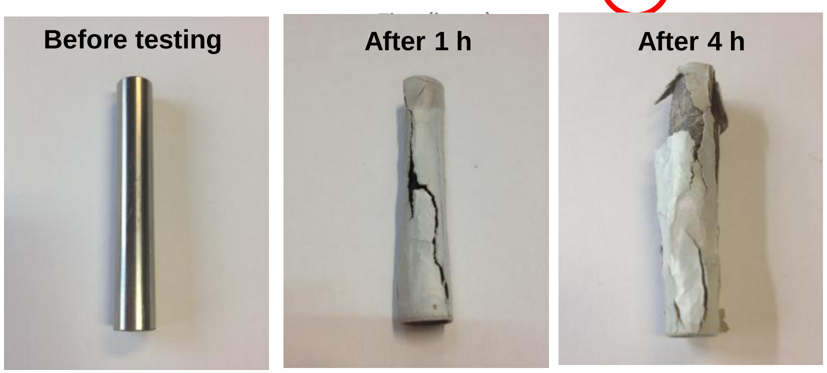
3. SIC/SIC COMPOSITE CLADDING (4/5)

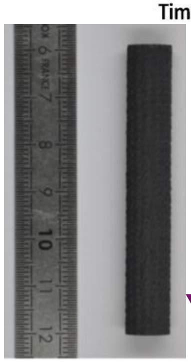
$\Delta m = SiO_2$
T ↗ Δm ↗
p ↗ Δm ↗ (1200°C)

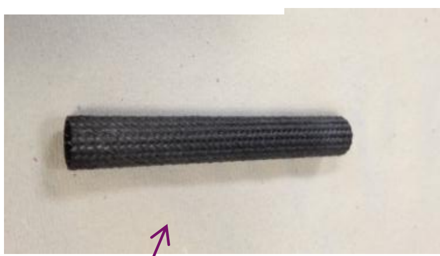
Preliminar corrosion testing of SiC/SiC for PWR











Before / After testing

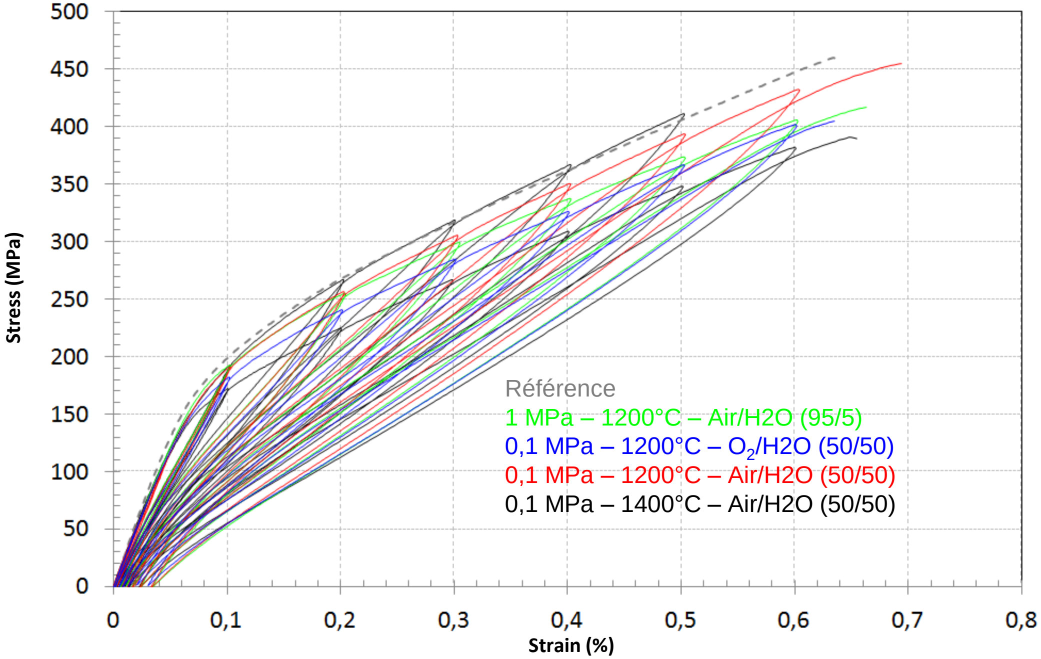
- Loss of geometry
- Cracking in the zirconia layer

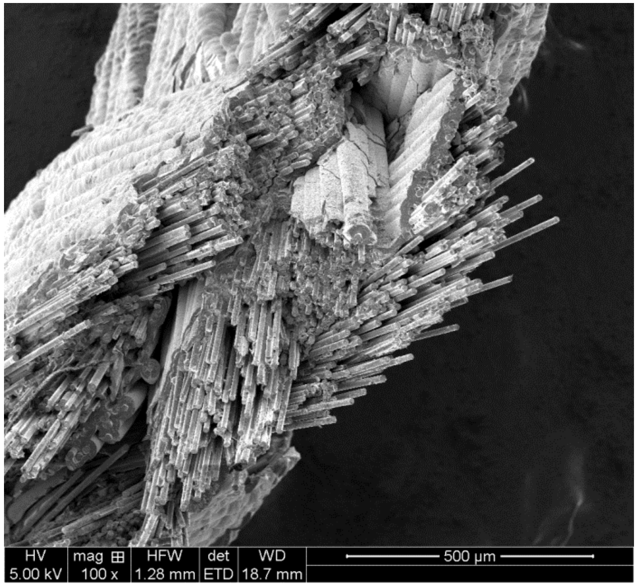
= well-known result (Steinbruck, 2011)

→ **Geometry preservation**

3. SIC/SIC COMPOSITE CLADDING (5/5)

Tensile tests after corrosion at high temperature





SEM observation of the fracture surface

- **No change in mechanical behavior**
- **No diminution of stress to rupture**
- Slight decrease in strain to rupture with :
  - total pressure increase
  - temperature increase
  - O_2 increase

CONCLUSIONS AND PROSPECTS (1/2)

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

Patents

[Le Flem at al.]
[M. Zabiégo et al.]
[C. Sauder et al.]
[Buet et al.]
etc.

- Cr base coatings on Zy-4 gave very good results
  - Decrease in weight gain in nominal and LOCA conditions
  - Post-quench ductility is enhanced by avoiding ZrO_2 and Zrα(O)
  - Promising results on hydrogen pick up (no Breakaway phenomena)
- Homogeneous coating of Zy-4 tube is achievable
- Sandwich SiC/SiC cladding must be suitable for PWR
- SiC/SiC resistance to high temperature corrosion (air/O_2) is demonstrated

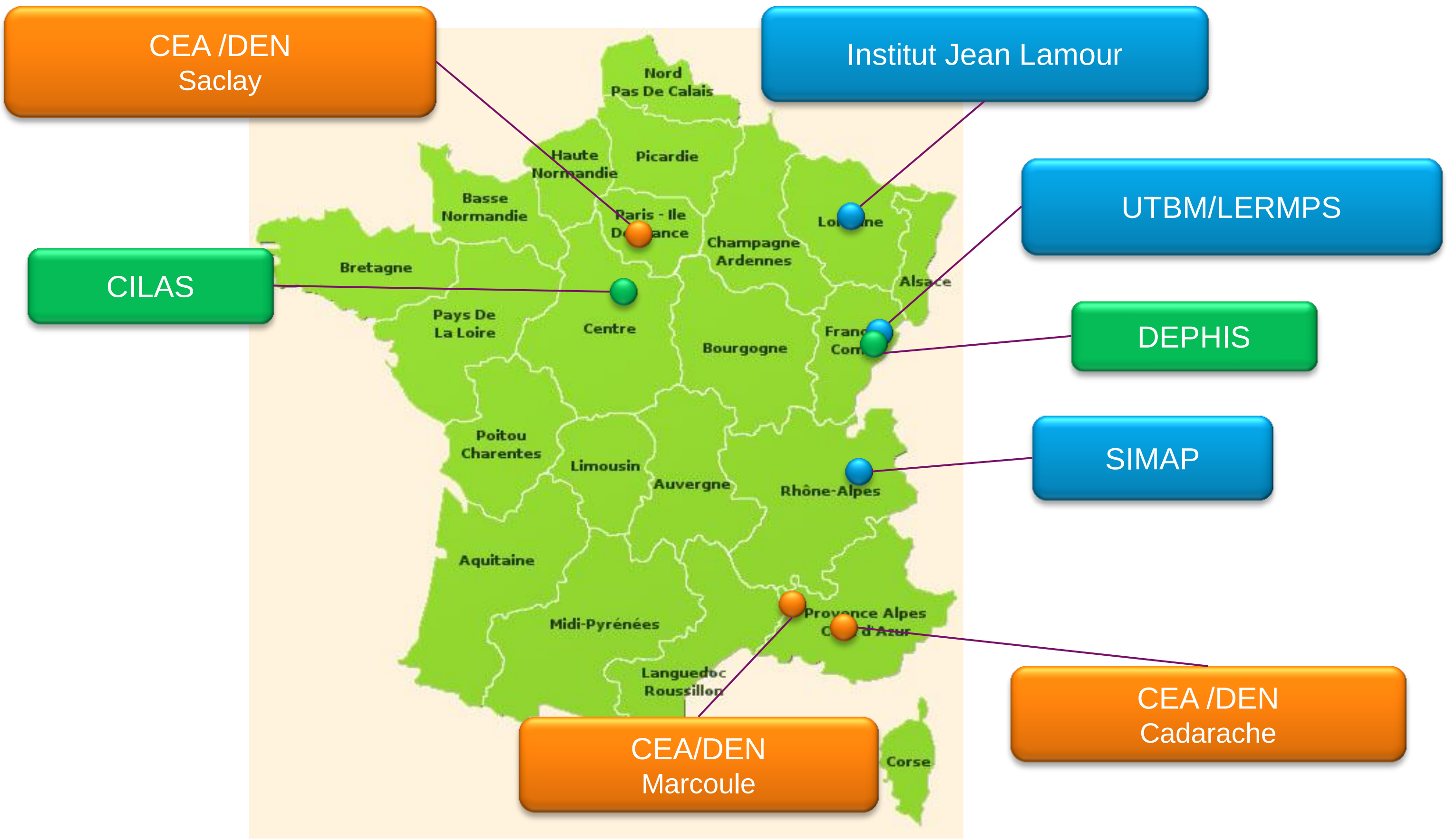
Coming next

- Optimisation of Cr-base coatings (composition, microstructure…)
- Optimisation of the sandwich tube to PWR requirements
- Assessment of corrosion resistance and **description**
  - Thermodynamics, kinetics
  - Gazeous species detection (H2 risk)
  - Integral tests with fuel up to melting
- Determination/optimisation of the mechanical properties
- Fabrication of **~1m cladding** (coatings, SiC/SiC)
- **Estimation of the costs**…

CONCLUSIONS AND PROSPECTS (2/2)

MHYRACLE **<u>M</u>elting and <u>HY</u>drogen <u>R</u>isk reduction by <u>A</u>dvanced <u>CL</u>adding Effect**

- 2013 → 2017
- lead by CEA : main investigator: A. Michaux, substitute: M. Le Flem



Special thanks to my colleagues

etc…

And thank you for your attention

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