ATF R&D STATUS AND PERSPECTIVES

*(I3P- **T**HREE **P**ARTIES **I**NSTITUTE CEA-EDF-AREVA)*

OECD-NEA Start-up meeting of the Expert Group on Accident Tolerant Fuels of LWRs

OECD-HQ – Issy les Moulineaux

April, 28-29, 2014

T. Forgeron, Ph Guédeney, JC. Brachet, A. Michaux & al. (CEA),

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ATF R&D STATUS IN FRANCE

(no major new technical result since last Oct. 2013 Workshop detailed presentation)

Background - CEA Assets

More than 30 years of experience on the analytical experimental approach of cladding behavior in LOCA and post-LOCA conditions (EDGAR, DEZIROX, CINOG, ..)

Outcomes of domestic program for innovative fuel claddings and gas cooled reactors

→ ***Two attractive candidate ATF concepts presented at previous Workshops***

- *Coated Zr-based Cladding → In service, DBA and Post DBA benefits evaluation*
- *Sandwich SiC-SiC with liner (GFR) → Evaluation of LWR applicability and benefits*

Clad characterizations and evaluation programs are now undertaken with the support of the French Industrial partners AREVA and EDF

Main 2013 References - Publications:

[1] J.-C. Brachet, M. Le Flem, C. Sauder, & al., P. Blanpain (Areva-NP) "Satus of CEA studies on nuclear fuel claddings for LWRs enhanced accident tolerant fuel: recent results, pending issues and prospects ", proceeding of OECD-NEA ATF Workshop, Oct. 28th, 2013, Issy-les-Moulineaux, France

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

[3] C. Sauder et al., '"Assessment of SiC/SiC cladding for LWRs", proceeding of 2013 LWR Fuel Performance Meeting/TopFuel, Charlotte, USA, Sept. 15-19, 2013

COATED ZR BASED CLADINGS

targets :

→Decrease oxidation rate in service and with steam water at high temperature

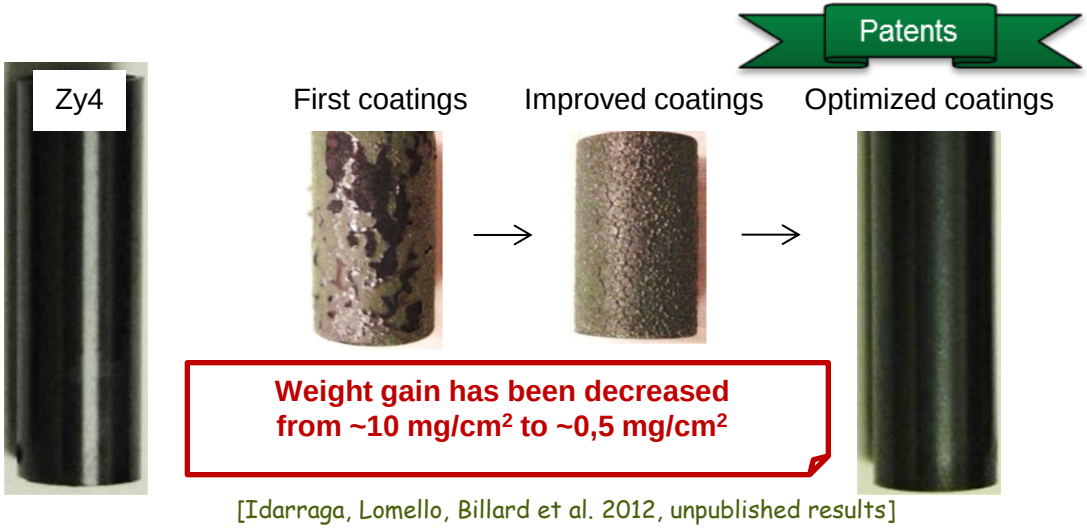
→Reduce in service hydriding and hydrogen release during accidental sequence

→Improve LOCA behavior (Peak clad T ↘, post quench ductility ↗)

→Improve long term coolability - procure grace time in the early stage of SA

COATED Zr Alloy

- Experiments made on the most promising coatings
- 1100°C 850 s., **1200°C 300 s.** in steam water + quench
- Weight gain, microstructure observations, Post-quench flexural/tensile tests



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

→ **Optimized Cr coated claddings appears as a candidate for safety improvement in current reactors in a near future**

RECENT RESULTS FOR COATED ZR "SLIGHTLY BEYOND LOCA" CONDITIONS ("BREAKAWAY"… ~4 HOURS AT 1000°C) [1]

	un-coated Zry-4	Non optimized coating	Optimized coating
Weight gain (mg/cm²)	37-40	11.2	**2.5**
Zirconia thickness (µm)	~250	0	**0**
$\alpha_{Zr}(O)$	~100µm	<100µm + $\alpha_{Zr}(O)$ incursions	**0µm + very few $\alpha_{Zr}(O)$ incursions**
Hydrogen content (wt.ppm)	**~2000-3000**	**~1000**	**≤80**

For the uncoated Zry-4, the weight gain and the associated hydrogen pick-up are fully consistent with the previous results obtained on low-tin Zry-4 cladding tubes

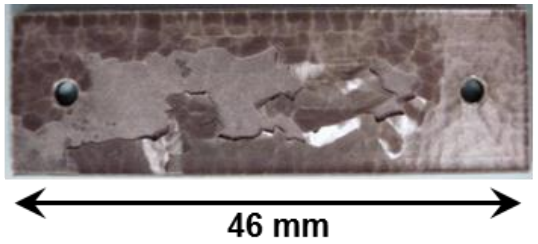
The non-optimized coating induces an intermediate behavior with no significant oxide formation but with some evidence of $\alpha_{Zr}(O)$ incursions into the Zry-4 metallic (prior-β_{Zr}) substrate and an associated significant hydrogen pick-up

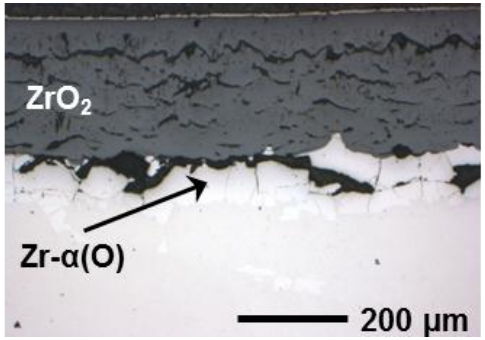
The optimized coating exhibits a very good resistance to both oxidation and hydrogen up-take:

(i) absence of significant zirconia formation nor oxygen diffusion into the metallic prior-β_{Zr} substrate

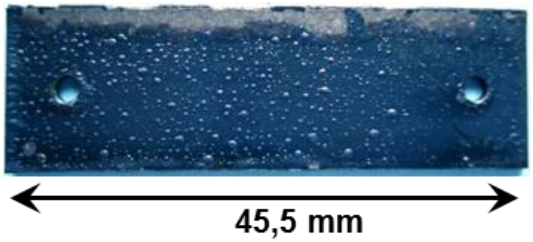
(ii) no significant hydrogen pick-up (<80 wt.ppm).

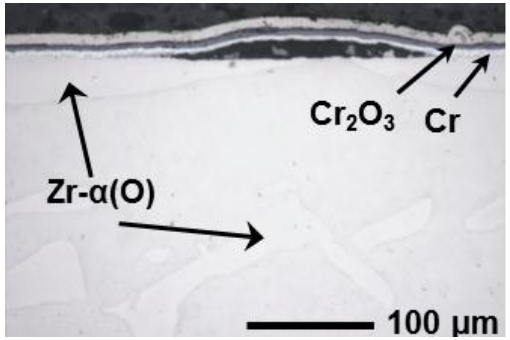
OPTICAL MACRO/MICROGRAPHS OF UNCOATED/COATED Zry-4 AFTER STEAM OXIDATION FOR 15000 S / 1000°C



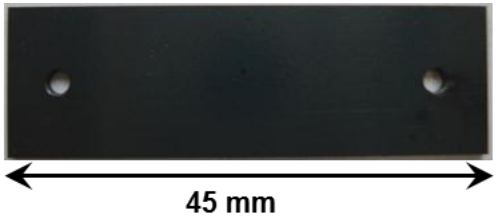


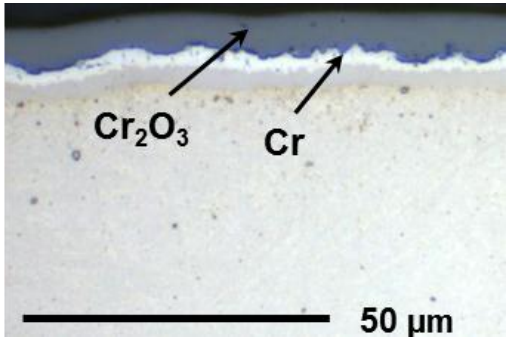
Uncoated Zy-4





Non optimized coating





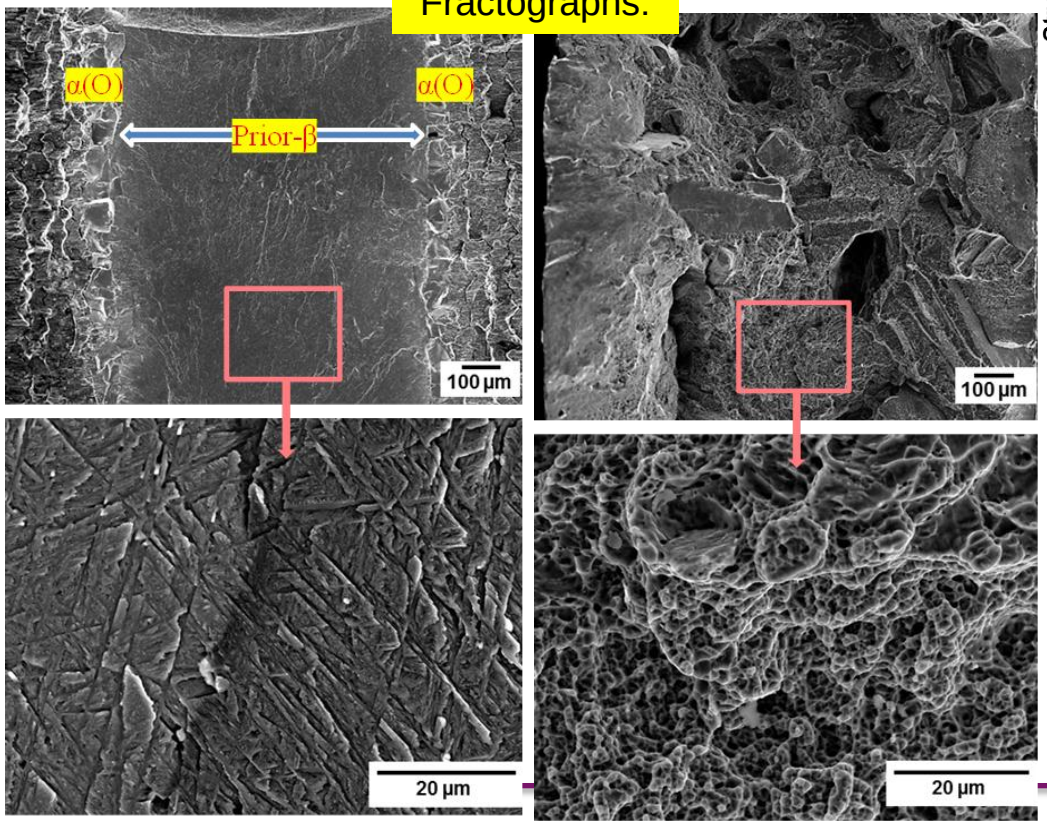
Optimized coating

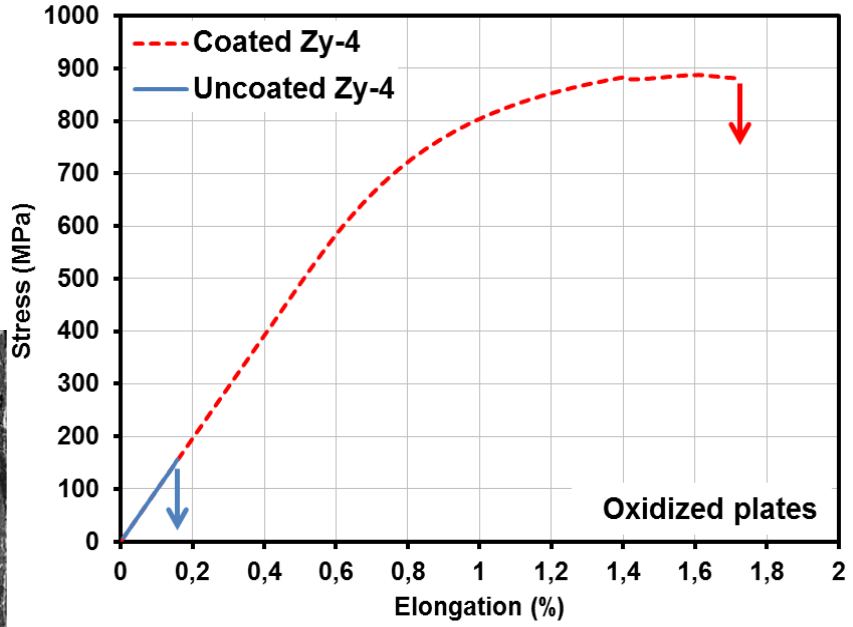
POST-OXIDATION (15000 s AT 1000°C) MECHANICAL TENSILE PROPERTIES

Engineering tensile stress-strain curves obtained at RT on uncoated and optimized coated Zry-4 (after two-side steam oxidation for 15000 s at 1000°C)

Uncoated: Coated:

Fractographs:





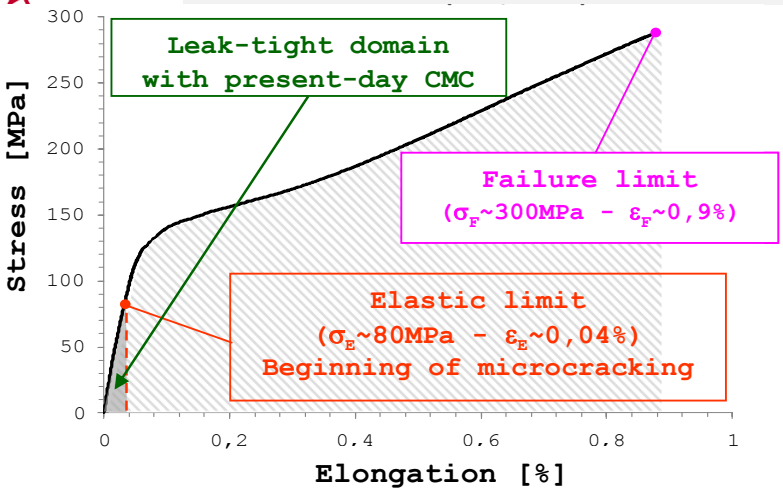
Uncoated Zry-4:
- no significant necking,
- full brittle failure mode

Mainly due to the post-breakaway high H content

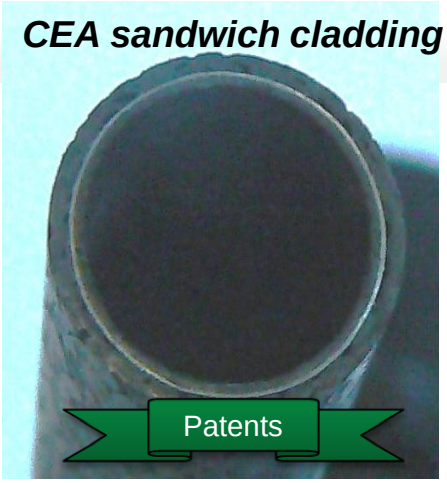
Optimized coated Zry-4:
- significant necking,
- ductile failure mode (mid-clad-thickness)

Due to the low oxidation level & [H] <100ppm

SiC/SiC SANDWICH CONCEPT MECHANICAL BEHAVIOUR [3]



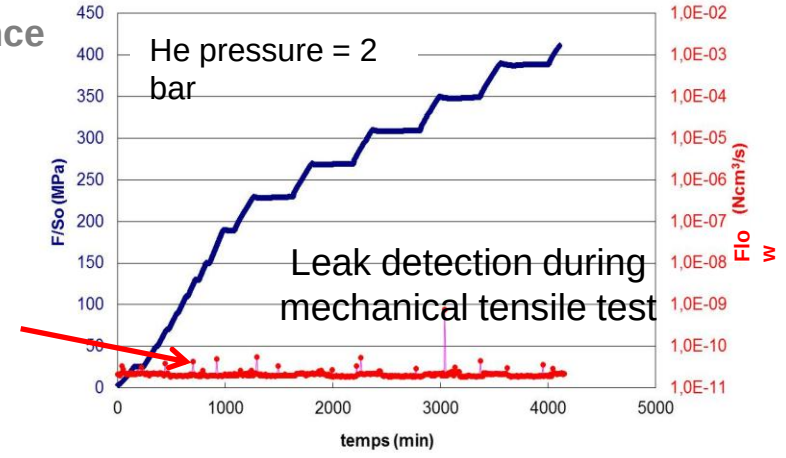
All stages of process are done in CEA



Internal tube SiC/SiC:	*e~0.3mm*
liner Ta :	*e<0.1mm*
External tube SiC/SiC:	*e~0.6mm*

- Metallic layer ensures tightness up to failure limit
- Composite SiC ensures mechanical resistance
- Process is simple and reproducible
- End-plugging solutions (welding)

Leak detection limit



SiC/SiC RESULTS UPDATE AND PROSPECTS [3]

Patents

Oxidation testing (SiC/SiC samples in nominal conditions)

- First oxidation tests of SiC/SiC in LWR nominal conditions for 3500h are promising even if oxidation mechanism must be clearly understood
- Pyrocarbon interphase is not affected : no reduction of mechanical strength
- SiC recession is estimated to be 0,5µm after 3500h of LWR nominal oxidation conditions

→ Sandwich SiC/SiC cladding must be suitable for LWR

Short/mid term Prospects

- Numerical simulation of rod behavior in Normal operation (PCI, design)
- Fuel-SiC interface issues
- Corrosion /wear in nominal conditions (sandwich concept)
- High temperature oxidation
- Irradiation testing

International collaborations (benchmarking and evaluation)

- SiC-SiC sandwich with Ta liner are candidates to experimental comparisons and numerical approach evaluations

ATF R&D PERSPECTIVES IN FRANCE

Realistic approach based on 3 axes

- **Material development and innovation (CEA + U collaborations, GFR)**
  - Long length tubes (~0,5 m at pilot lab scale) (coated Zr)
  - Tight ends for sandwich SiC-SiC concept

- **Three Parties Institute (CEA-EDF-AREVA partnership)**
  - Characterization testing, experiments and numerical simulation approach of key properties for thermo-mechanical design such as corrosion, erosion, LOCA behavior, irradiation evaluation (small samples at marginal cost in domestic sample holder)
  - Specific roadmap under construction for each concept
- **Involvement in International programs**
  - Participation to OECD/AEN Workshop and Expert Group
  - Proposal of Zy-4 coated UO2 fuel rodlets for irradiation in the Halden Reactor Program
    - -Step 1 : Assessment of coating stability in service condition (PCI design possible)
    - -Step 2 : Evaluation of Benefits in LOCA Transient
  - Proposal in the framework of Nugenia WP5 (EDF « RAMAT » proposal to be discussed with other ones for unified proposal in H2020 call for tender)

PROPOSALS FOR EXPERT GROUP ACTIVITIES EXPECTATIONS / CONTRIBUTION

Expectations from EG

- **Guidelines for ATF candidate evaluation**
  - Definition of « safety benefit », how to « measure » it
  - Choice of scenarii
    - Normal operation → DBA → early stages of post DBA → Severe Accident
    - For each stage reduction of probability /consequence is a benefit

Proposals for EG activities

- **Parametric approach by variation of some key properties**
  - On the base of scenarii selected by EG
  - Using system codes (MAAP, MELCOR, ASTEC, …)
  - Change one (or a set of) property(ies) considered as Key (T melt / Thermal conductivity, oxydation kinetics , oxidation reaction enthalpy,..
  - Evaluate the « safety benefit » of this change for the selected scenarii
- **Exchange of basic properties related to ATF material candidates**
  - Cross benefit evaluations (-/- scenarii)
- **Main output of EG**
  - Safety benefit evaluation guide
  - Scenarii
  - Tools for prioritization of development Map (difficulty, expected benefit)

SYNERGIES WITH OTHER INTL PROGRAMS

OECD-NEA Halden Reactor Project (WGFS)

- **Proposal for irradiation testing of Cr-coated- Zy-4/UO2 – fuel rodlets (White paper submitted)**
- **Goals**

Step 1

- Direct evaluation of under representative PWR conditions
- Stability of the protective effect of coating
  - In environment
  - In environment + local deformation (special design for early contact)
- Conditioning irradiated rodlet(s) for LOCA test in a second step

Step 2

- LOCA test – Direct benefit evaluation

- **Timing**

15 - 20 cm length clads may be short term delivered now

50 - 60 cm clads could be fabricated end 2014 / early 2015

Discussion on detailed program and PIE expected around mid-2014

NUGENIA Technical Area 5 :

-several proposals to be coordinated around ATF cross evaluation goals and basic data acquisition (Falstaff, Forclad, Ramat, …) → Call H2020 in 2014/9

- need of harmonization with other ATF initiatives