EATF R&D IN FRANCE
STATUS AND PERSPECTIVES

CEA-EDF-AREVA Collaborative Program (I3P)

5th OECD-NEA meeting of the Expert Group on Accident Tolerant Fuels of LWRs
OECD-HQ – Boulogne Billancourt

April, 12-14, 2016

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EATF R&D STATUS IN FRANCE

Background - CEA Assets

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

→ Two candidate EATF concepts presented at previous Workshops were selected for development within the three parties collaborative program with the support of the French Industrial partners AREVA and EDF

- Coated Zr-based Cladding (↔ Materials Innovation and Fuel Innovation prgms)
- Sandwich SiC-SiC with liner (↔ Gas cooled Fast Reactor prgm)

→ In reactor evaluations on the track

Main recent publications:


CR-COATED ZR BASED CLADDINGS

Expected Benefits:

→ 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

Optimized Cr coated cladding appears as a candidate for safety improvement in current reactors in a near future → Development phase on progress

Weight gain has been decreased from ~10 mg/cm² to ~0.5 mg/cm²

[Idarraga, Lomello, Billard et al. 2012, unpublished results]
Cr-COATED Zr BASED CLADDINGS – MAIN ACHIEVEMENTS

Robust and promising Performances

- Autoclave tests performed at CEA and AREVA

- LOCA separate effect tests
  - On going EDGAR tests (ballooning and burst in steam environment)
    → Protective effect maintained, no peeling
  - Oxidation and Quench DEZIROX tests

<table>
<thead>
<tr>
<th>Weight gain (mg/cm²)</th>
<th>Uncoated Zirc-4</th>
<th>Cr coated Zirc-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZrO₂ or Cr₂O₃ thickness</td>
<td>~17μm</td>
<td>&lt;0,1μm</td>
</tr>
<tr>
<td>Weight gain (mg/cm²)</td>
<td>~2,6</td>
<td>&lt;0,05</td>
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</table>

(2) Recent tests performed on the last generation of Cr coated samples in autoclave at 415°C in steam (100 bars) up to 200 days:

After 200 days at 415°C/steam:

- Protective effect maintained, no peeling

(a) Uncoated Zirc-4 after steam oxidation for 300s at 1200°C

(b) Cr coated Zirc-4 after steam oxidation for 300s at 1200°C

ZrO₂ ~ 55μm

a_Zr(O) ~ 60μm

Cr₂O₃ ~ 3μm

Non oxidized residual Cr metallic layer

Prior-βZr

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

Weight Gain (mg/cm²)

1200°C
**Deposit process optimization**

- Cr coatings obtained by a special PVD process (in collaboration with the Technological University of Belfort-Montbéliard)
- Typical Cr coating thicknesses studied: from 2 up to 20 µm
- Multiscale microstructural / elemental analysis performed at CEA: OM, SEM-EBSD, TEM, EPMA, XRD...

**Figure 1 – Electron micrographs of some typical as-received Cr coating microstructures**
DEVELOPMENT ROADMAP FOR CR-COATED CLADDINGS

Fabrication process development

→ Strong involvement of AREVA-NP and CEA with academic and pioneer company partners

- Toward long Cr-coated tubes fabrication
  - 50 cm length tubes: Prototype process achieved
  - Full length tube on study: Feasibility seems reachable at short term
- QA control parameters definition studied in parallel

Study of Cr coated Claddings performances under irradiation

- Fundamental (PhD) work using ions irradiation (next slide)
- Participation to the ATF irradiation in the HRP (next 2nd slide)
- AREVA-NP proprietary initiatives in industrial framework

Comparative Evaluation of Performances

- EDF undertakes a “Utility oriented” evaluation of EATF concepts
Goals

- Study the microstructural evolutions of the bulk chromium coating and of the Zr-Cr interface after irradiation using charged particles, and then the irradiation consequences on hardening and residual ductility/adhesion of Cr coatings.

*Figure 2: Simulated SRIM damage for 20 MeV Kr$^{8+}$ ions for a fluence of $6 \times 10^{15}$ ions.cm$^{-2}$ and a flux of $2.8 \times 10^{11}$ (Quick damage Kinchin-Pease calculation) superimposed on TEM micrograph*
**Goals**

- Direct evaluation under representative PWR conditions
- Stability of the protective effect of irradiated Cr-coatings
  - In PWR environment
  - In PWR environment + local deformation (special design for early PCMI)

<table>
<thead>
<tr>
<th>Segment</th>
<th>CEA</th>
<th>KAERI</th>
<th>IFE</th>
<th>ORNL</th>
<th>EPRI</th>
<th>REF</th>
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</thead>
<tbody>
<tr>
<td>Top</td>
<td>~7 μm Cr</td>
<td>~80 μm Cr</td>
<td>CrN</td>
<td>Mo-LCAC FeCrAl</td>
<td>Zry-4</td>
<td></td>
</tr>
<tr>
<td>Top-mid</td>
<td>~15 μm Cr</td>
<td>ODS</td>
<td>FeCrAl-2</td>
<td>Mo-LCAC Zry</td>
<td>Zry-4</td>
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A Decade of R&D activity at CEA to develop SiC/SiC composites for cladding applications: 2005-2015

*Focus on metal/ceramic hybrid cladding: a solution to leak-tightness*

**CEA « SANDWICH » CLADDING DESIGN**

The potential benefits in terms of application temperature and dimensional stability make this concept have a very high potential for EATF

Transposition to LWR is under investigation with the current manufacturing process

**Objectives for current research (I3P)**

- Assess the SiC resistance to corrosion/interaction with coolant in normal operating conditions
- Define the overall performance under high temperature steam
Continue evaluation experiments dedicated to the consolidation of the viability of the concept

- Autoclave testing
- Mechanical testing and impact on the tightness
- Tightness of caps ends

Optimization of the concept for LWRs application

Normal conditions: Secure resistance in water environment

SiC recession needs to be mitigated by protecting surface from reaction with water

Positive mechanical/thermal behavior of SiC/SiC in LWR conditions (Out of pile)

Off-normal conditions: Oxidation of SiC/SiC under high temperature steam (up to 1400 °C)
Confirmation of the protective function by silica in these conditions
Develop integrity assessment methods

- Within the framework of NUGENIA TA5: project “TESTING“
  
  **Absolute necessity to define the adapted rules for design**

  Benefit of 6 decades of experience
  not directly exploitable

  - Metallic cladding
  - Ceramic cladding

  **Must be based on inherent mechanisms**
  (Statistical failure issues for instance…)

- Since testing is performed between various laboratories, it is imperative that common and well recognized set of testing and evaluation technologies to be established for a consistent work

SiC fibers testing at HT
- 800 to 1600°C
- various atm.

SiC/SiC tubes testing at RT
- 25°C, air

SiC/SiC tubes testing at HT
- 800 to 1600°C
- various atm.

→ Call H2020 in 2016/10
EATF: THE “PELLET” CASE

Very solid background at CEA regarding (non exhaustive):

- Doped UO$_2$ fuels for LWR (Cr$_2$O$_3$ with AREVA-NP …)
- Nuclear fuels for fast reactors ((U,Pu)N, (U,Pu)C, metal…)
- including Am and Np transmutation
- CERCER and CERMET (manufacturing studies)

Participation to the taskforce 3 of the OECD/NEA Expert Group

CEA-EDF-AREVA internal re-evaluation of the different concepts:

- Possible initiation in 2017 of a new R&D EATF program focused on the nuclear fuel itself

CONCLUDING REMARKS - PERSPECTIVES

Collaborative structured Development Program started 3 years ago progress well

Cr-coated claddings
- Out of pile separate effect tests performed up to now consolidate the behavior of Cr-coated claddings
- Fabrication route for 50cm length is achieved
- In pile test of fuel segments in HRP under preparation
- Full length rods fabrication development engaged
- Rod fabrication for LTA reachable at short term (segmented or full length)

SiC-SiC sandwich concept
- Use of SiC-SiC in PWR environment remains a challenging goal but high temperature performances make the challenge attractive
- Reasonably achievable targets
  - Remedy against recession in water environment
  - Fabrication route with a liner optimized for PWR performances
- Efforts are needed for SiC adapted integrity assessment methods
  → proposed to international collaboration (NUGENIA)