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

T. Forgeron, H. Palancher, JC. Brachet, C. Lorrette, E. Coulon-Picard (CEA),
N. Waeckel, A. Ambard, E. Pouillier (EDF)
C. Delafoy, J. Bischoff (AREVA-NP)

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:

[1] JC. Brachet, F. Schuster, M. Le Saux, & al. (CEA), J. Bischoff (Areva-NP) , A. Ambard (EDF) "ON-GOING STUDIES AT CEA ON CHROMIUM COATED ZIRCONIUM BASED NUCLEAR FUEL CLADDINGS FOR ENHANCED ACCIDENT TOLERANT LWRS FUE ", TopFuel 2015 Conf. proceedings, Zürich, Switzerland, Sept. 13-17, 2015

[2] C. Lorrette, C. Sauder et al. (CEA), J. Bischoff (Areva-NP) , A. Ambard (EDF) " SiC/SiC COMPOSITE BEHAVIOR IN LWR CONDITIONS AND UNDER HIGH TEMPERATURE STEAM ENVIRONMENt", TopFuel 2015 Conf. proceedings, Zürich, Switzerland, Sept. 13-17, 2015

[3] J. Bischoff (Areva-NP), K. McCoy, J. Strumpell, (Areva Inc.), JC. Brachet, C. Lorrette (CEA) - "DEVELOPMENT OF FUELS WITH ENHANCED ACCIDENT TOLERANCE", TopFuel 2015 Conf. proceedings, Zürich, Switzerland, Sept. 13-17, 2015.

CR-COATED ZR BASED CLADDINGS

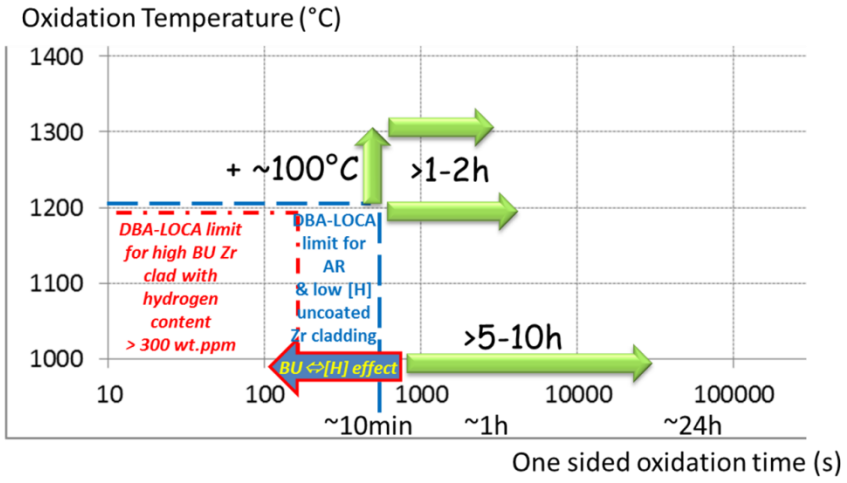
Expected Benefits :

→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



Patents

Weight gain has been decreased from ~10 mg/cm² to ~0,5 mg/cm²

[Idarraga, Lomello, Billard et al. 2012, unpublished results]

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

Cr-COATED Zr BASED CLADDINGS – MAIN ACHIEVEMENTS

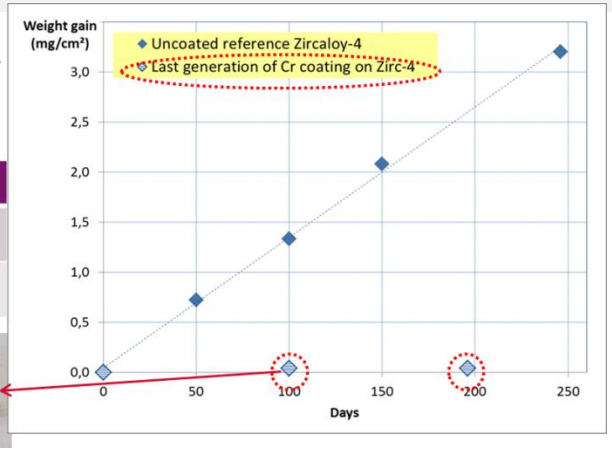
Robust and promising Performances

- **Autoclave tests performed at CEA and AREVA**

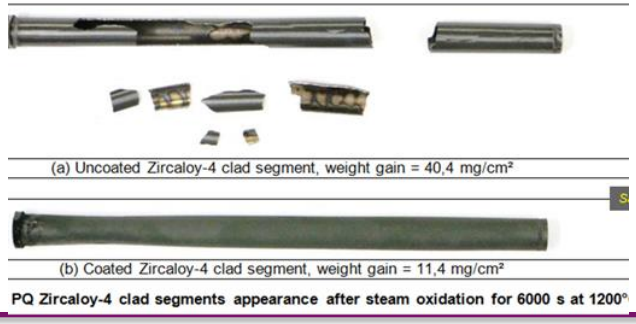
(2) Recent tests performed on the **last generation** of Cr coated samples in autoclave at **415°C in steam (100 bars) up to 200 days:**

After 200 days at 415°C/steam:

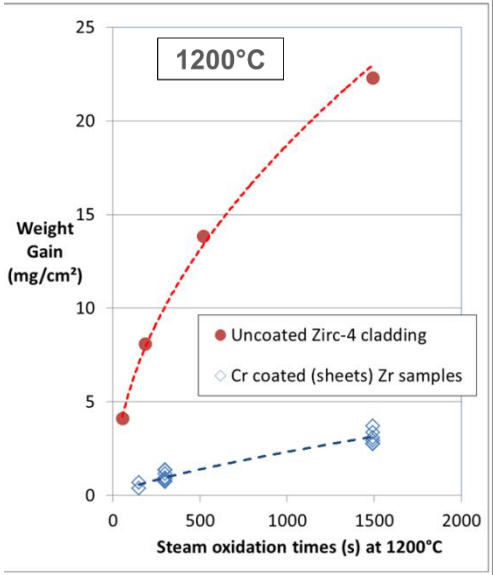
	Uncoated Zirc-4	Cr coated Zirc-4
Weight gain (mg/cm²)	~2,6	<0,05
ZrO_2 or Cr_2O_3 thickness	~17µm	<0,1µm

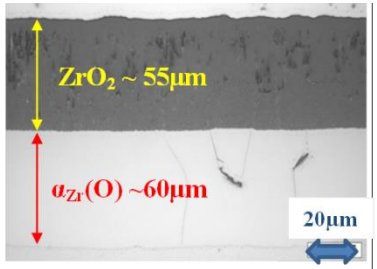


- **LOCA separate effect tests**
  - On going EDGAR tests (ballooning and burst in steam environment)
    → Protective effect maintained, no peeling
  - Oxidation and Quench DEZIROX tests

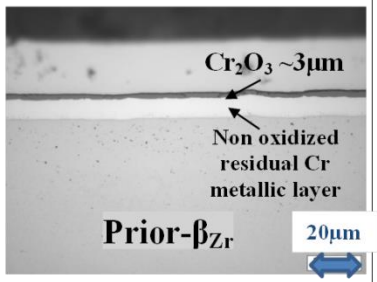


PQ Zircaloy-4 clad segments appearance after steam oxidation for 6000 s at 1200°





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



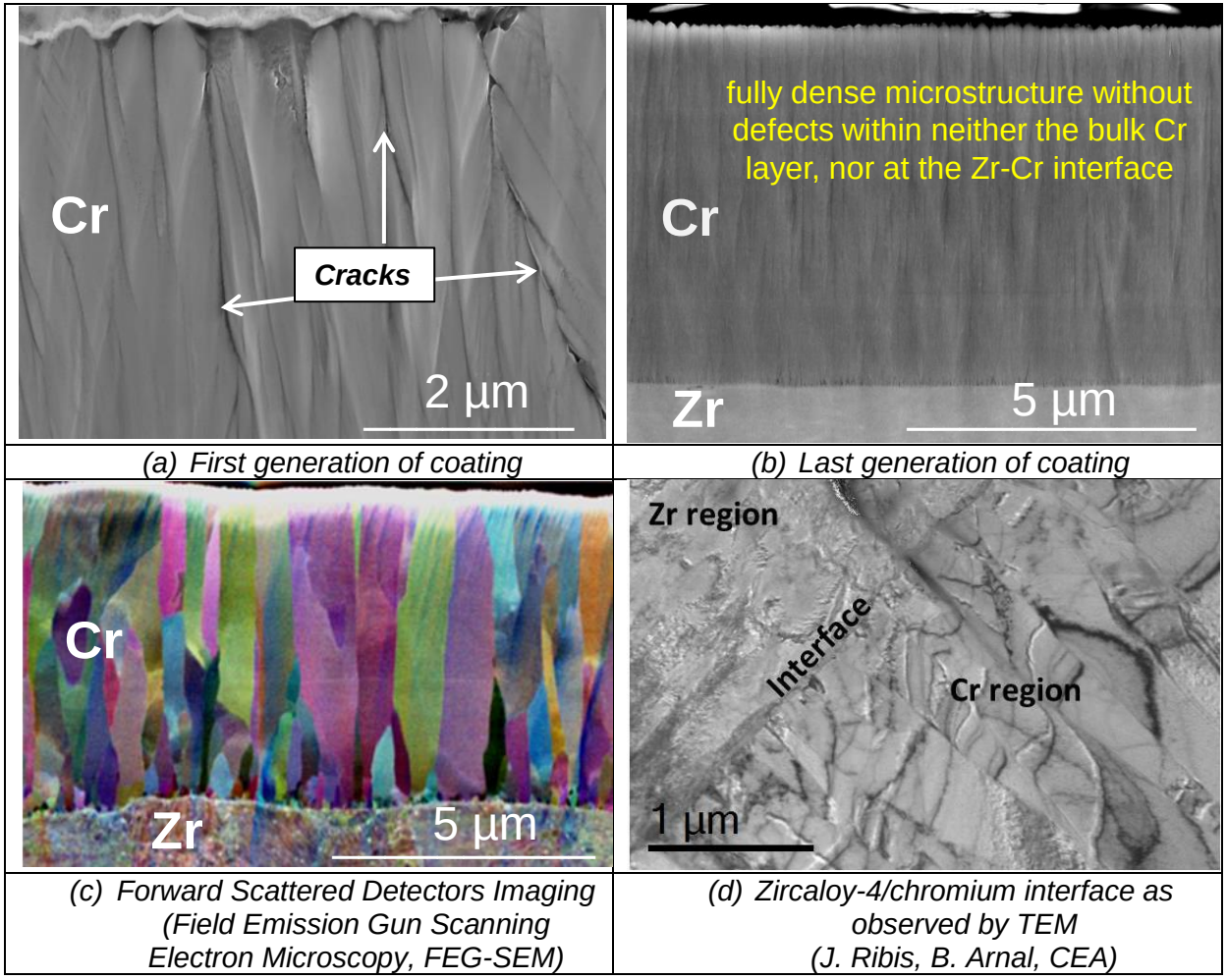
(b) Cr coated Zirc-4 after steam oxidation for 300s at 1200°C

Cr-COATED Zr BASED CLADDINGS – MAIN ACHIEVEMENTS

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…



(a) First generation of coating

(b) Last generation of coating

(c) Forward Scattered Detectors Imaging (Field Emission Gun Scanning Electron Microscopy, FEG-SEM)

(d) Zircaloy-4/chromium interface as observed by TEM (J. Ribis, B. Arnal, CEA)

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**

FUNDAMENTAL WORK TO STUDY Cr COATING BEHAVIORS UNDER (IONS) IRRADIATION

(« JANNUS » ACCELERATOR FACILITY AT CEA-SACLAY)

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

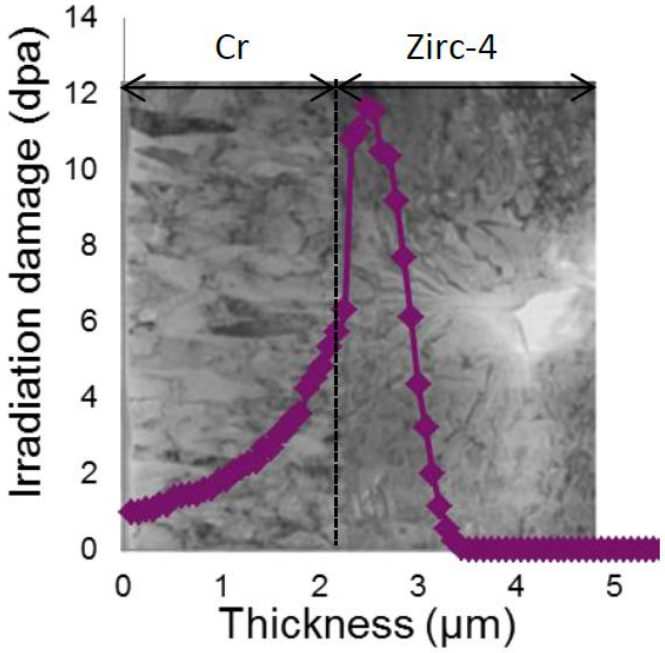


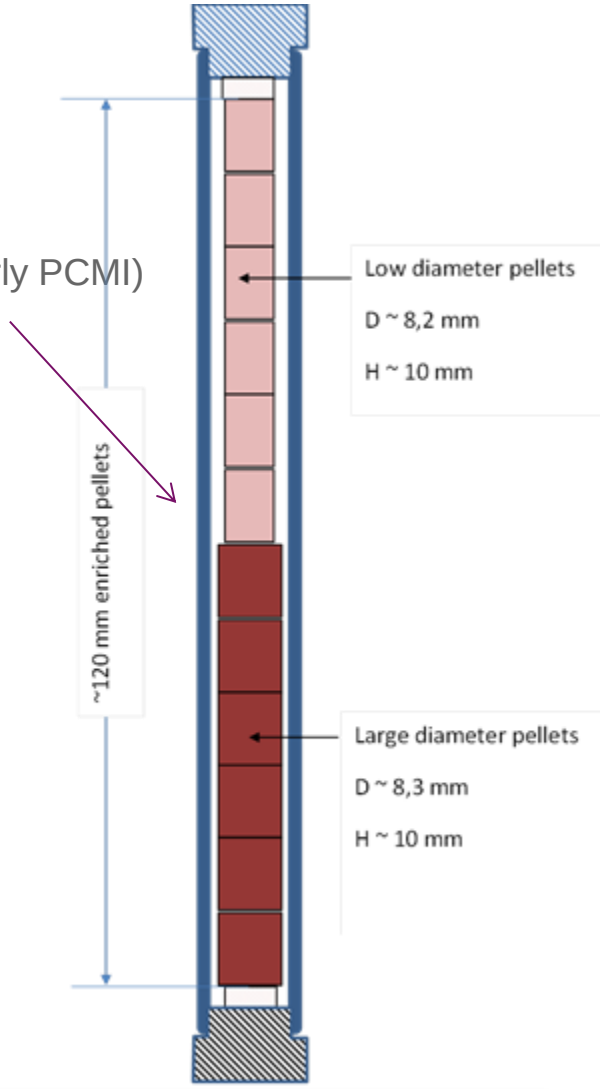
Figure 2: Simulated SRIM damage for 20 MeV Kr^{8+} ions for a fluence of 6.10^{15} ions.cm^{-2} and a flux of $2,8.10^{11}$ (Quick damage Kinchin-Pease calculation) supperimposed on TEM micrograph

PROPOSAL FOR CR-COATED ATF IRRADIATION IN OECD-NEA HALDEN REACTOR PROJECT (WGFS)

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)

Segment	CEA	KAERI	IFE	ORNL	EPRI	REF
	Rod 1	Rod 2	Rod 3	Rod 4	Rod 5	Rod 6
Top	~7 µm Cr	~80 µm Cr	CrN	FeCrAl-1	Mo-LCAC FeCrAl	Zry-4
Top-mid	~15 µm Cr	ODS	FeCrAl-2		Mo-LCAC Zry	Zry-4
Bot-mid	~7 µm Cr	~80 µm Cr	CrN		Mo-ODS FeCrAl	Zry-4
Bottom	~15 µm Cr	ODS	FeCrAl-2		Mo-ODS Zry	Zry-4



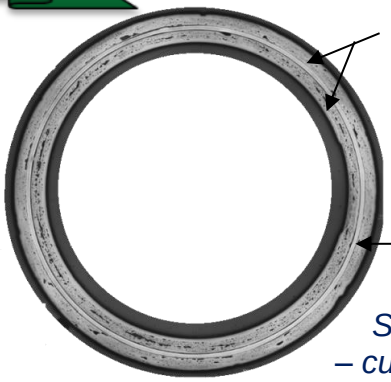
DEVELOPMENT ROADMAP FOR SiC-SiC SANDWICH CLADDINGS

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

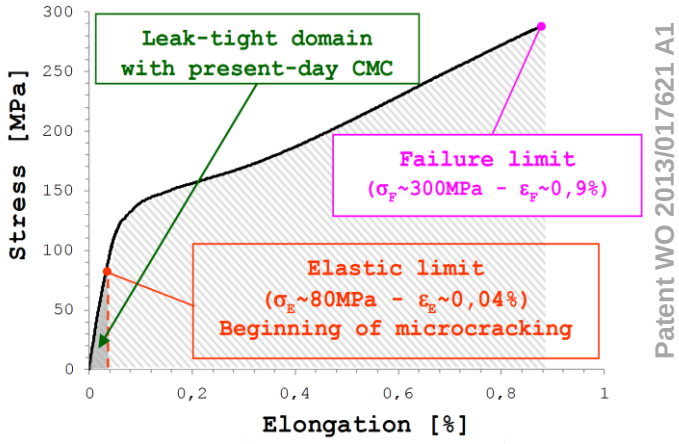
Patents



Inner and outer SiC/SiC layers

Middle thin (50-100µm) metallic liner

Selected on various criteria – current reference is Ta (GFR) –



Patent WO 2013/017621 A1

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

DEVELOPMENT ROADMAP FOR SiC-SiC SANDWICH CLADDINGS

Continue evaluation experiments dedicated to the consolidation of the viability of the concept

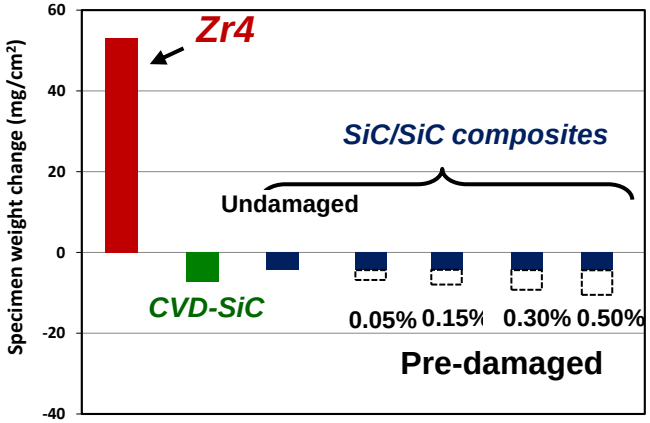
- **Autoclave testing**
- **Mechanical testing and impact on the tightness**
- **Tightness of caps ends**

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

DEVELOPMENT ROADMAP FOR SiC-SiC SANDWICH CLADDINGS

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

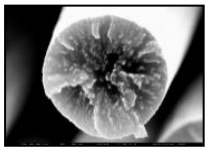
Metallic cladding → **Ceramic cladding**

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

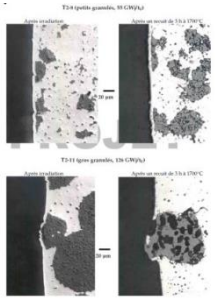
various atm.

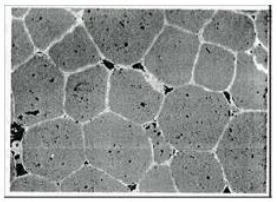
→ **Call H2020 in 2016/10**

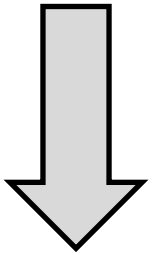
EATF: THE “PELLET” CASE

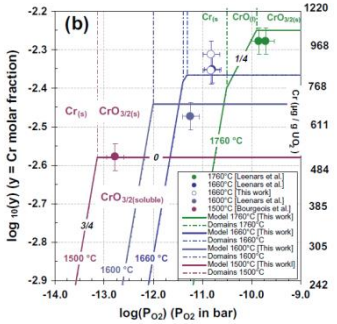
Very solid background at CEA regarding (non exhaustive):

- **Doped UO_2 fuels for LWR (Cr_2O_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)**









C. Riglet-Martial et al.,
J. Nucl. Mater (2014) 447 63-72.

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)**