EATF R&D IN FRANCE UPDATED STATUS AND PERSPECTIVES

CEA-EDF-AREVA Collaborative Program (I3P)

6th OECD-NEA meeting of the Expert Group on Accident Tolerant Fuels of LWRs

Boise (Idaho, USA)

September, 15-16, 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 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 started***

Main recent publications:

[1] J.C. Brachet et al. (CEA), E. Monsifrot (UTBM), J. Bischoff (AREVA NP), E. Pouillier (EDF), TopFuel 2016 Conf. proceedings, Boise, Idaho, USA, Sept. 11-16, 2016.

[2] J.C. Brachet et al. (CEA), J. Bischoff et al.(AREVA NP), E. Pouillier (EDF), 18th International Symposium on Zirconium in the Nuclear Industry, Hilton Head, SC, USA, May 15-19 2016.

[3] C. Lorrette et al. (CEA), J. Bischoff (AREVA NP), A. Ambard (EDF), TopFuel 2015 Conf. proceedings, Zürich, Switzerland, Sept. 13-17, 2015.

*[4] J. Bischoff, C. Vauglin, C. Delafoy et al. (AREVA NP), J.C. Brachet (CEA) - "*DEVELOPMENT OF Cr-COATED Zr ALLOY CLADDING FOR EATF*", TopFuel 2016 Conf. proceedings, Boise, Idaho, USA, Sept. 11-16, 2016.*

CR-COATED ZR BASED CLADDINGS

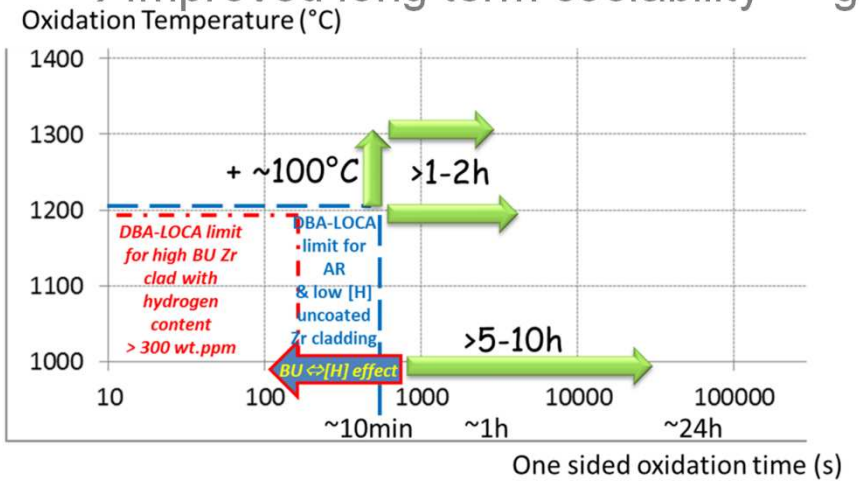
Expected Benefits :

→Reduced oxidation rate (in-reactor conditions and high temperature accidental conditions)

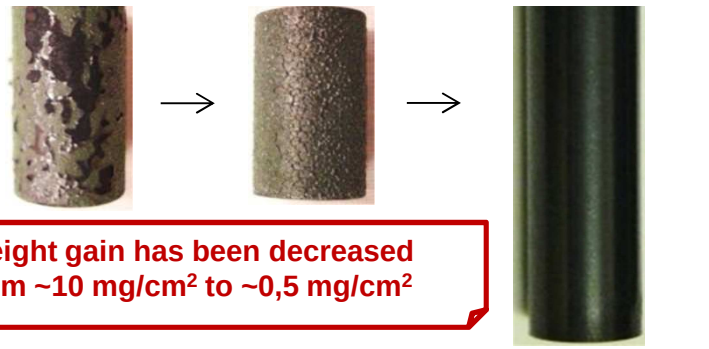
→Reduced in service hydriding and hydrogen release during accidental sequence

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

→Improved long term coolability - 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 to be a good candidate to ensure near term safety enhancements in current reactors* → **Development phase is ongoing**

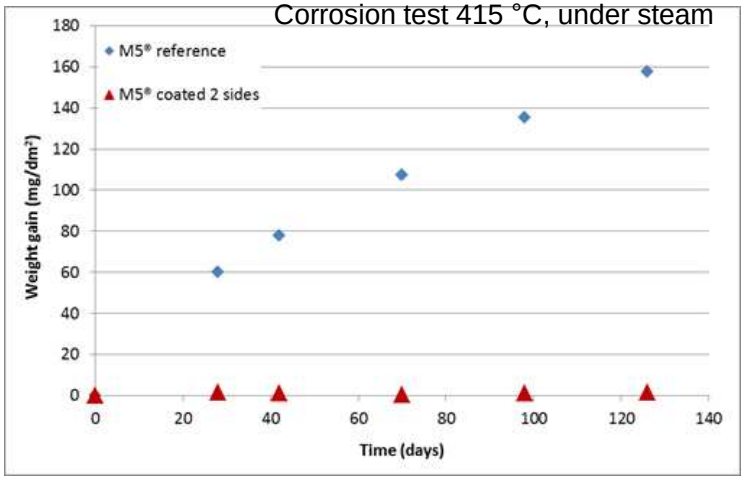
Cr-COATED Zr BASED CLADDINGS –MAIN ACHIEVEMENTS

LATEST RESULTS

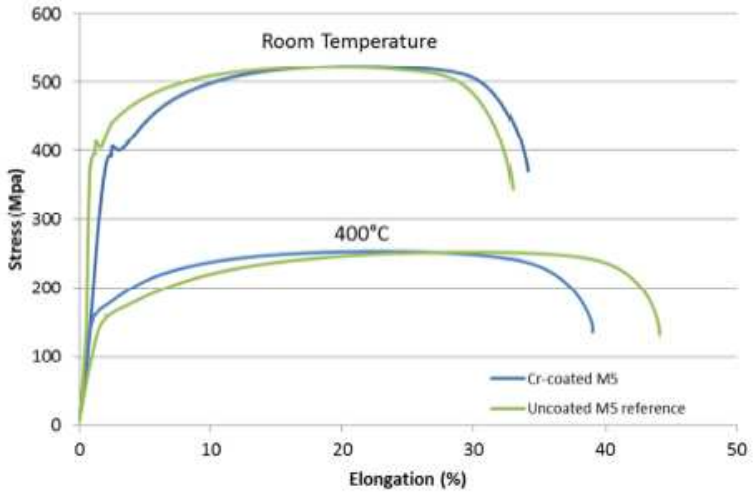
Robust and promising Performances

- **Normal conditions**
  - Similar mechanical properties as uncoated Zr alloy substrate = easier to license
  - Very low corrosion kinetics (Autoclave tests performed at CEA and AREVA NP)

Corrosion test 415 °C, under steam

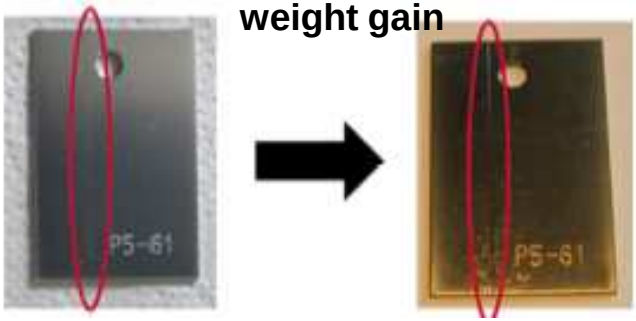


Tensile tests at RT and at 400 °C



Intentionally pre-scratched M5® Cr-coated sample before and after corrosion in 415°C steam:

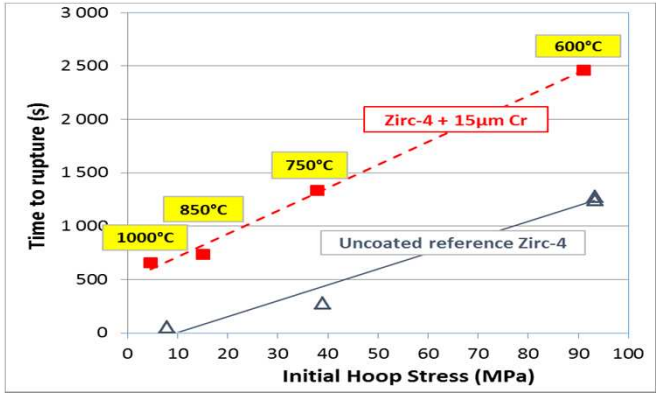
Coating remains adherent – No impact on weight gain

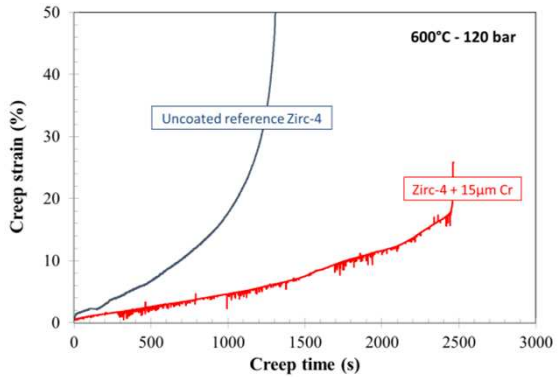


Cr-COATED Zr BASED CLADDINGS –MAIN ACHIEVEMENTS
LATEST RESULTS

Robust and promising Performances

- **LOCA separate effect tests**
  - **EDGAR tests** (ballooning and burst in steam environment)
    - → **Cr coating remains adherent** even close to the burst opening
    - → Strengthening effect of the Cr-coating on the overall creep clad behavior.
    - → Reduced balloon sizes in the 600-750℃ range (α-phase domain)
    - → Very small actual burst openings in the β-Zr phase temperature range (~1000℃)
      - → Lower probability for fuel fragments dispersal.

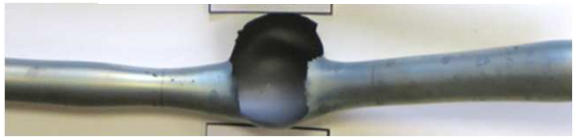




After creep tests at **750°C**

Reference uncoated Zy4:

Zy4 + 15µm thick Cr coating:



Circumferential elongations reduced of ~40% near the burst location

DEVELOPMENT ROADMAP FOR CR-COATED CLADDINGS → *ON PROGRESS*

Fabrication process development → Strong involvement of AREVA NP and CEA partners

- **Towards long Cr-coated tubes fabrication**
  - 50 cm length tubes: Prototype process achieved
  - Full length tube : launched
- **QA control parameters definition studied in parallel**

Study of Cr coated Claddings performances under irradiation

- **Basic approach using ion irradiation - PhD on progress**
- **Experimental irradiation planned within the E-ATF initiative of HRP**
- **Additional AREVA-NP proprietary initiatives (IMAGO)**

Comparative Evaluation of Performances

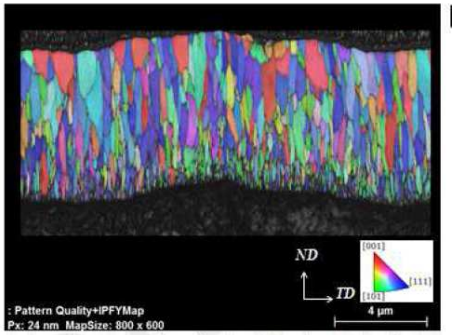
- **EDF continues its "Utility oriented" evaluation of EATF concepts**

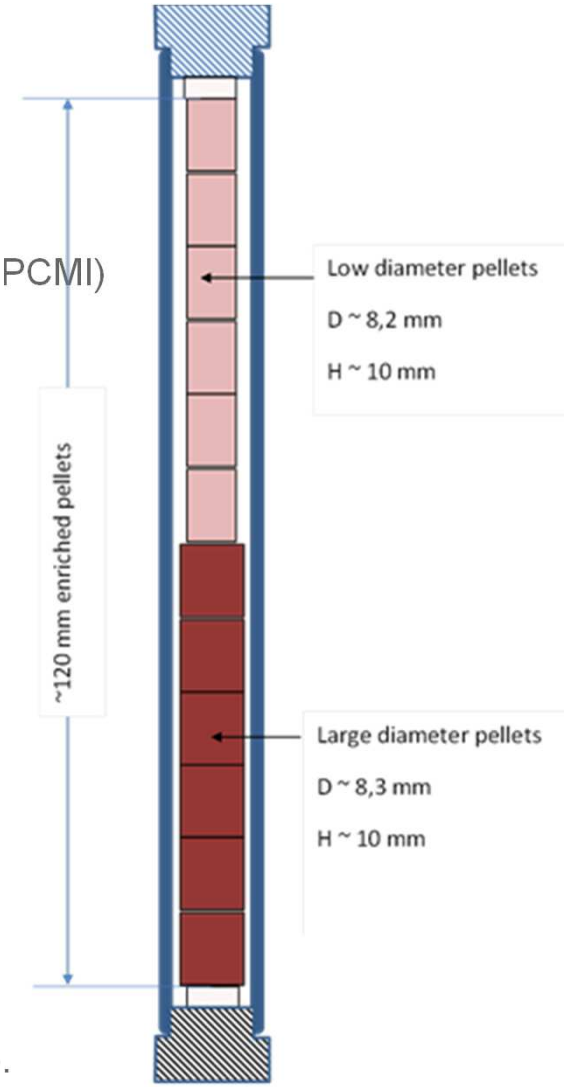
CR-COATED ATF IRRADIATION IN OECD-NEA HALDEN REACTOR PROJECT (WGFS)

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	~30 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	~30 µm Cr	CrN		Mo-ODS FeCrAl	Zry-4
Bottom	~15 µm Cr	ODS	FeCrAl-2		Mo-ODS Zry	Zry-4





Status

- Design completed
- **Quality tests at CEA and AREVA NP completed**:
  - Cr-coated Zy4 and M5® **tubes sent to Halden**
- Beginning of the irradiation test scheduled by the end of 2016.

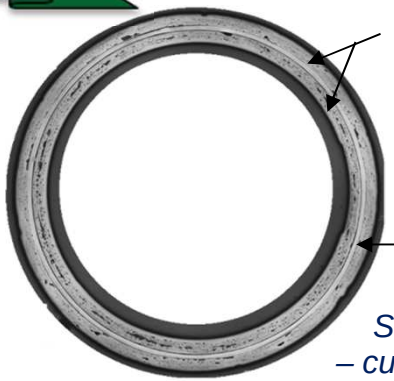
DEVELOPMENT ROADMAP FOR SiC-SiC SANDWICH CLADDINGS

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

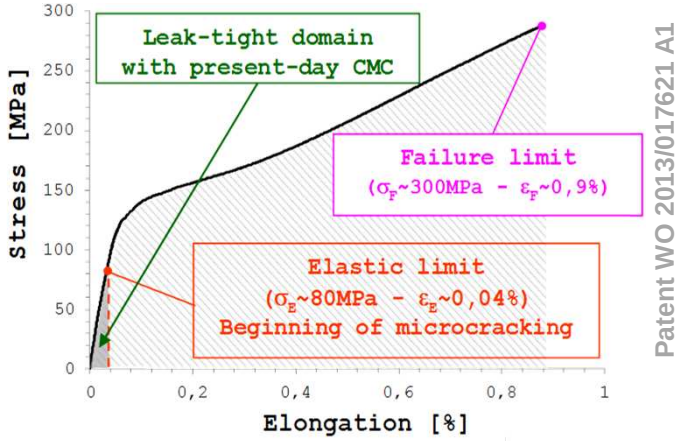
Patents



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 high temperature behavior and dimensional stability make this concept a very high potential E-ATF candidate

Transposition to LWR is under investigation based on the current manufacturing process

Objectives of current investigations (CEA-AREVA-EDF)

- 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 → *ON PROGRESS*

Confirm the viability of the concept through adequate separate effect tests

- **Autoclave testing**
- **Mechanical testing and impact on the tightness**
- **Tightness of caps ends**
- **Pellet-cladding compatibility: new studies to be published soon**

Optimization of the concept for LWRs application

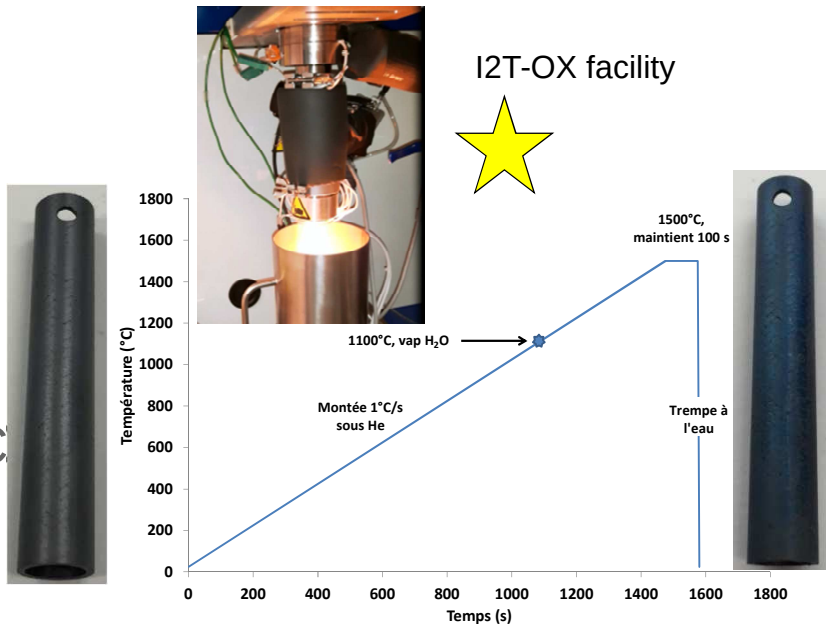
- **Normal conditions:**

Secure resistance in water environment

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

- **Off-normal conditions:**

Excellent post quench behavior of SiC claddings after heat treatment up to 1500°C



DEVELOPMENT ROADMAP FOR SiC-SiC SANDWICH CLADDINGS

Develop integrity assessment methods

- **Within the framework of NUGENIA**

Absolute necessity to define adapted design rules

Benefit of 6 decades of experience not directly exploitable

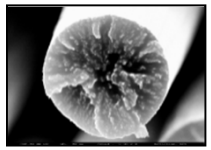
Metallic cladding → **Ceramic cladding**

Must be based on inherent mechanisms

(Statistical failure issues for instance…)

- **Since qualification tests are performed in various laboratories, common and well recognized set of testing conditions and evaluation technologies should be established to ensure overall consistency**

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

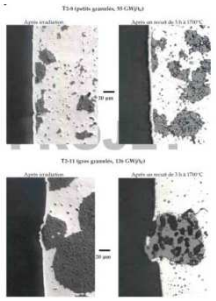
various atm.

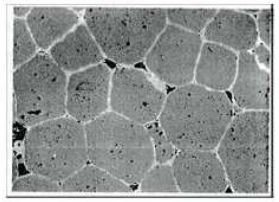
→ **Included in "IL TROVATORE" proposal (H2020 call)**

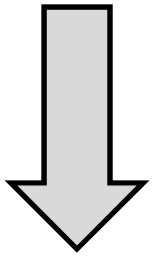
EATF: THE “PELLET” CASE

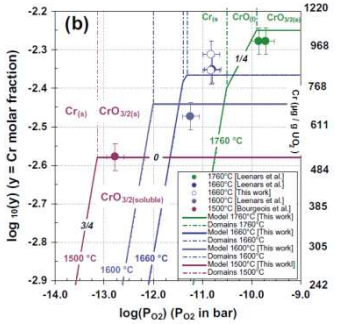
Very solid background at CEA regarding (non exhaustive):

- 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 is completing an internal re-evaluation of the different fuel concepts

- Possible initiation in 2017 of a new R&D E-ATF program focused on the nuclear fuel pellets

CONCLUDING REMARKS - PERSPECTIVES

The collaborative development program progressing well

Cr-coated claddings

- **Out of pile separate effect tests performed up to now consolidate the beneficial behavior of Cr-coated claddings**
- **Fabrication route of 50cm length tubes achieved**
- **In pile test of fuel segments in HRP scheduled 2017 – tubes shipped**
- **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 still challenging but performances at high temperatures make the challenge attractive**
- **Reasonably achievable targets**
  - Remedy against recession in water environment
  - Fabrication route optimized for PWR performances
- **Need to define and share specific SiC integrity assessment approaches → International collaboration(e.g. H2020 proposal)**

AREVA NP European EATF Developments

Jeremy BISCHOFF

AREVA

IMAGO: Irradiation of Materials for ATFs in GÖsgen Reactor

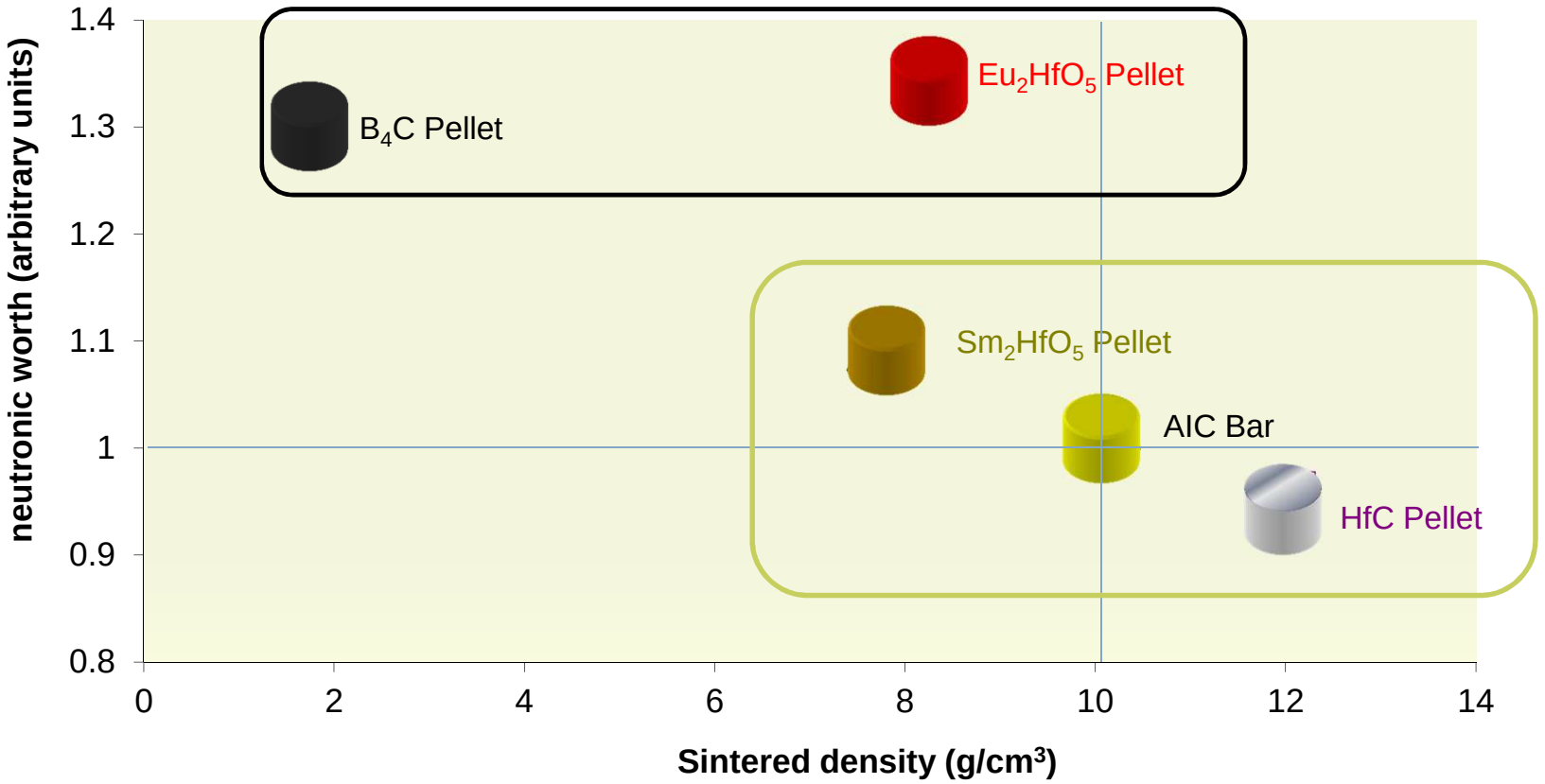
- **First irradiation of ATF concepts in a commercial PWR reactor**
- **The goals of IMAGO are:**
  - **To verify the performance of EATF concepts in representative PWR conditions**
    - Corrosion kinetics
    - Mechanical behavior
    - Evolution of the microstructure under irradiation
  - **To serve as input data for the licensing and justification of future fuel rod irradiations**
- **Irradiation of samples within Material Test Rods (MTRs) inserted within guide tubes of a fuel assembly:**
  - **Cr-coated zirconium alloys**
  - **SiC/SiC cladding tube samples**

First irradiation cycle began mid-2016

Timbre PIGA

AREVA

Development of Accident Tolerant Control Rods (ATCR)



ATCR Conclusions

- **Drop-in replacement of current absorber materials:**
  - **B_4C replaced by Eu_2HfO_5**
  - **AIC replaced by combination of HfC and Sm_2HfO_5 to maintain equivalent rod worth**
- **New absorbers show improved performance in normal and accidental conditions**
  - **Higher melting points**
  - **Improved phase stability**
  - **Lower swelling and extended life-time expected**
- **No showstoppers identified during out-of-pile testing → Performance has to be validated under irradiation**