REDUCTION OF RADIOLOGICAL ACCIDENT CONSEQUENCES

WP:	**WP «Dessimation»**
Task:	
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Commission européenne

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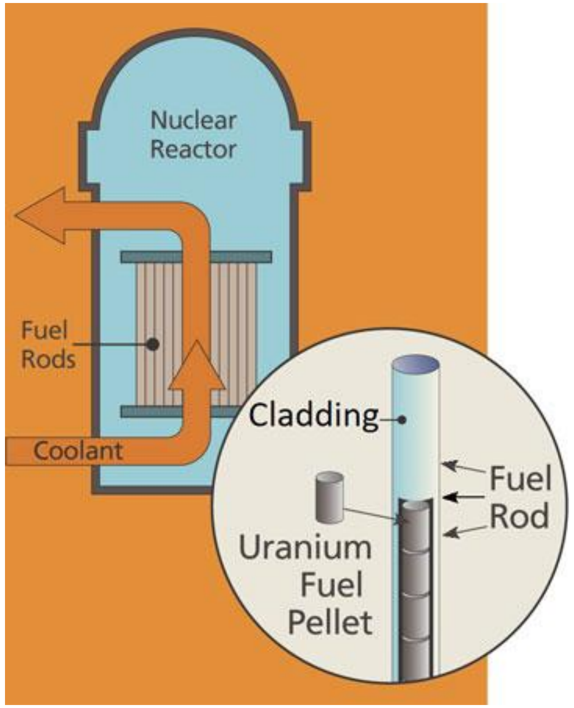
ATF or E-ATF

Historically, nuclear fuel for power reactors has consisted of zirconium alloy cladding with uranium dioxide fuel pellets. Nuclear fuel vendors are currently researching and testing new fuels. The nuclear fuel vendors claim these new fuel will provide the following advantages:

- Enhanced protection of fuel rods against debris fretting
- Oxidation resistance and superior material behavior over a range of conditions (ex : LOCA)



The CDA[1] stipulates that any reactor included in the Taxonomy must use Accident Tolerant Fuel (ATF). The term ATF or EATF (Enhanced Accident Tolerant Fuel) refers to a set of nuclear fuel concepts, and fuel assembly innovations and developments that improve performance during normal operations, transient conditions, and accident situations. ATFs and EATFs are part of the natural fuel product development process.

[1] European Commission's draft Complementary Delegated Act (CDA), which is including nuclear activities in the EU Taxonomy of green activities

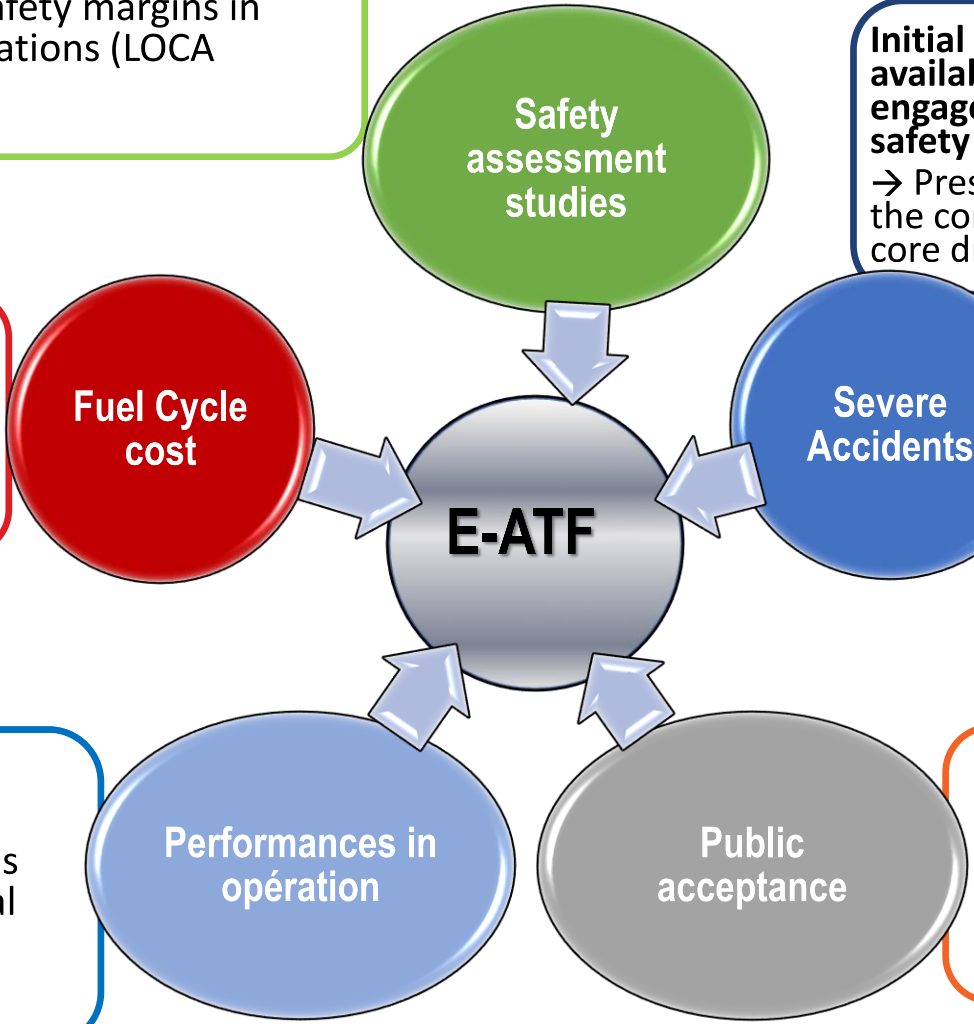
E-ATF Fuels : Multiple Issues

Increase the safety margins in accidental situations (LOCA essentially)

Initial goal : increase the available time before the engagement of the ultimate safety systems

→ Preserve as long as possible the core integrity in case of core drying up

Potential opportunity of cost savings with more robust fuels



Fuel performance and reliability at least equivalent as those or the actual products

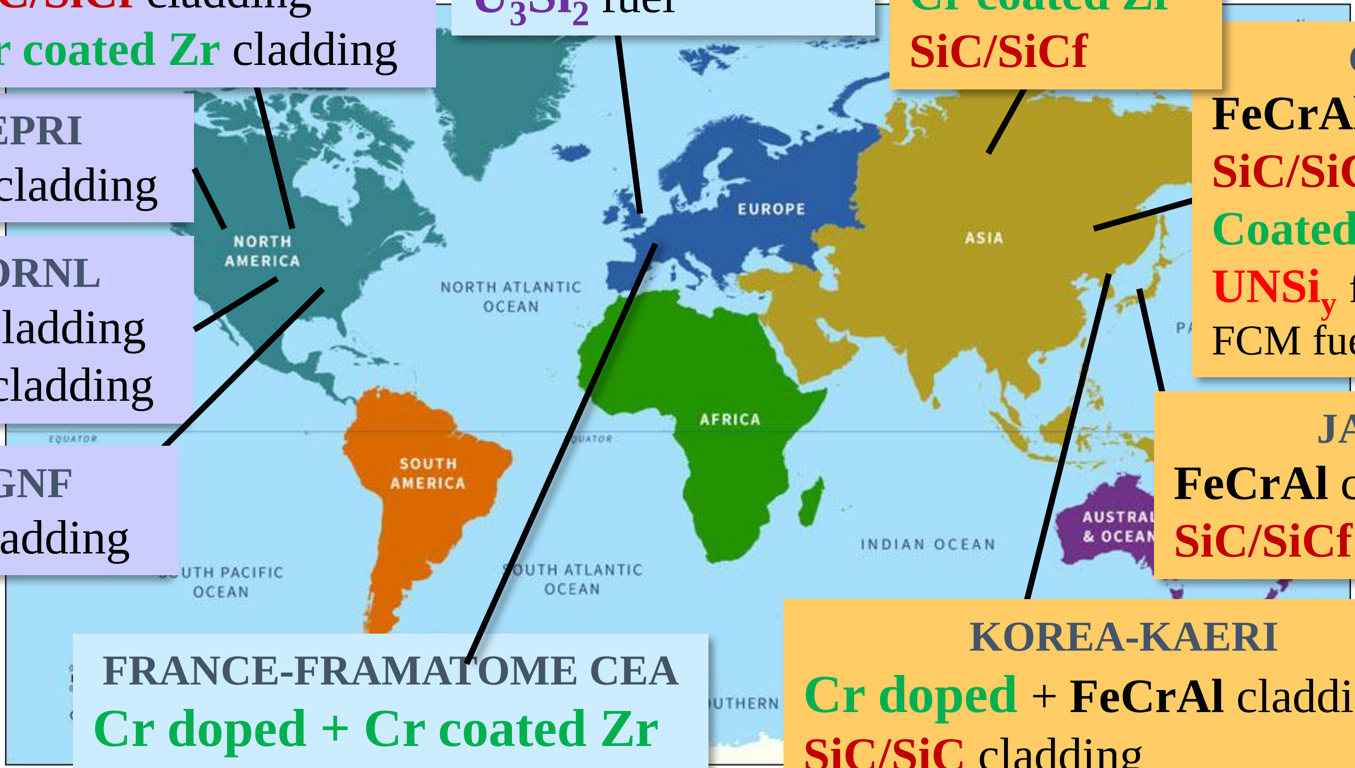
Show that the Nuclear Industry innovates to continuously improve the safety

Fukushima Event

Following loss of cooling due to station black-out, fast temperature increase leading to:

- Rapid Oxidation of the cladding due to Zr-Steam reaction
- Hydrogen Release, followed by explosion
- Fission Products release in the atmosphere
- Core Melting

E-ATF International competition is launched



USA-Westinghouse
U_3Si_2 + SiC/SiCf cladding
U_3Si_2 + Cr coated Zr cladding

GB- NNL (with W)
U_3Si_2 fuel

RUSSIA
Cr coated Zr
SiC/SiCf

USA-EPRI
Lined Mo cladding

CHINA
FeCrAl cladding
SiC/SiCf cladding
Coated Zr cladding
$UNSi_y$ fuel
FCM fuel

USA -ORNL
FeCrAL cladding
SiC/SiCf cladding

USA-GNF
FeCrAl cladding

JAPAN
FeCrAl cladding
SiC/SiCf cladding

FRANCE-FRAMATOME CEA
Cr doped + Cr coated Zr
SiC/SiC cladding

KOREA-KAERI
Cr doped + FeCrAl cladding
SiC/SiC cladding
Microcell fuel

- All the countries are engaged in the E-ATF development
- On the US market , competition between Westinghouse, GE and Framatome

E-ATF FUELS

Complex technical and economical challenges

Cladding

- Safety:
  - Reduced high temperature steam oxidation
    - Reduce exo-thermic heat production
    - Reduce production of H2
  - Stable mechanical properties at high temperature to maintain core coolability
    - High mechanical strength
    - Low embrittlement
  - High melting temperature (Zr = 1850 °C)
- Equivalent (or even improved) fuel performance during normal operations and operational transients
- Acceptable economical impact

Fuel Pellet

- **Safety**
  - Enhanced heat removal capabilities to decrease centerline temperature
    - Higher thermal conductivity
    - Lower specific heat
  - Enhanced retention of fission products, to reduce radiological impact in case of severe accident
    - Or at least to reduce the fuel rod internal pressure before the event
  - High melting temperature (UO_2= 2850 °C)
- **Acceptable economical impact**
  - Increase density of U_{235} when needed to offset the detrimental impact of ATF cladding material

> **Development of a new generation of nuclear fuel E-ATF concepts, for present NPP fleet and future reactors (e.g. EPR2, SMR)**

E-ATF development strategy

framatome
cea
EDF

Technological Challenge

SiC/SiC_f cladding

M5® Cr coated cladding

A Revolutionary long-term concept

Gainage SiC-SiC_f

- Breakthrough solution chosen for DEC capabilities
- High Challenges regarding product design, manufacturing and licensing

An evolutionary near-term solution

Cr-coated M5® + Cr2O3-doped fuel (reference Framatome product)

- Incremental easy-to-license solution, maximizing probability of success on the short-term
- LFR's irradiation from 2019

Safety benefits

Cr coated M5® cladding

Achievements

- ***Manufacturing***
  - PVD-Coating process at stat-up company for 50 cm long tubes (co-developed with CEA and Framatome)
  - Full length tube coating prototype for available since 2017 at stat-up company
- ***Normal Operation Performance***
  - Successful completion of out-of-pile tests : satisfying properties, even better than uncoated cladding for corrosion and wear
  - Promising first results after irradiation (IMAGO in KKG after 1 cycle – Halden)
- ***Promising trends regarding margins under LOCA (To be confirmed on irradiated materials)***
  - reduced ballooning; oxidation reduced up to 1300 °C; reduced post-quenching embrittlement
- ***Limited benefits under DEC (a few hours in coping time)***

➢ **An evolutionary near-term solution**

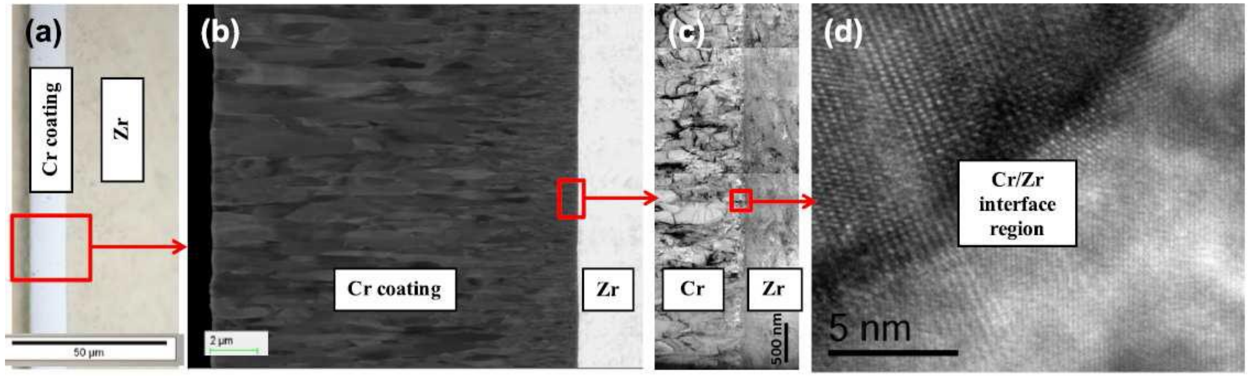
Challenges

- ***Manufacturing***
  - Fabrication of the demonstration test rods in 2018
  - Development at the industrial scale for an acceptable over cost of cladding and rods manufacturing
- ***Performance in service***
  - Robust behavior and adherence of the coating in PWR representative condition still to be demonstrated (high burn-up, PCI situations)

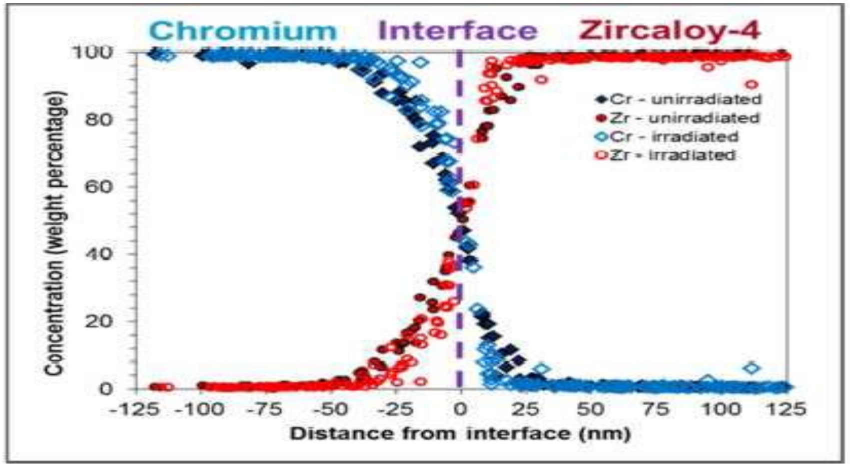
R&D Key Achievements : Cr coated M5® cladding

PVD coating:

- **Dense, homogeneous, defect free** (no crack) **and adherent**



- **Properties equivalent, even better than uncoated cladding for corrosion and wear**
- **Promising first results after irradiation**



CEA PhD work : Ion particles irradiation
=> µ-structural et µ-chemical stability if the interface Zr-Cr,
Results confirmed after neutron irradiation (2 dpa) in Osiris MTR

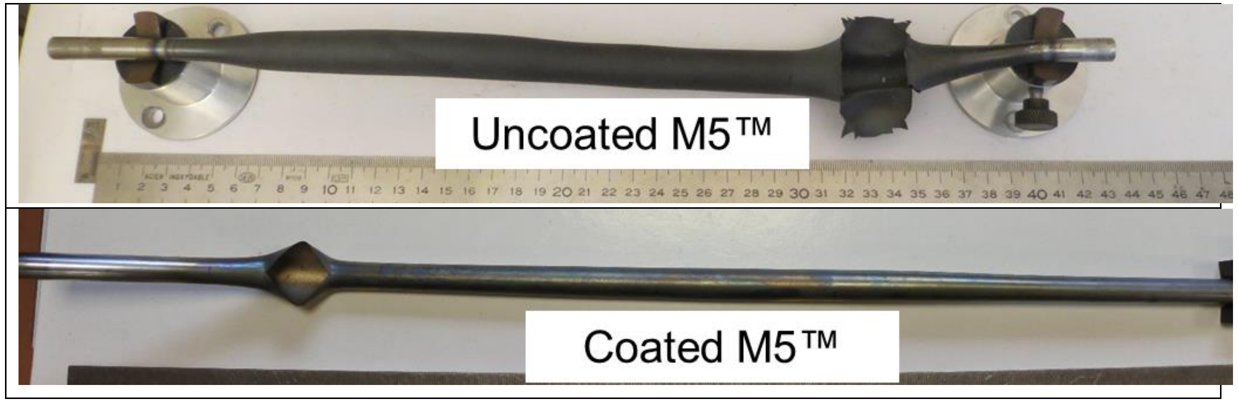
Rodlet irradiation in Halden (I3P)

R&D Key Achievements : Cr coated M5® cladding 2/3

- **Improvement of the LOCA thermomechanical behavior (ballooning and burst)** (from out-of-pile EDGAR tests):

  Creep strengthening effect → ballooning reduced in size

  ➡ **Potential benefits** *(to be confirmed on irradiated materials) :*
  - Channel blockage ratio reduced
  - Limited re-localization of the fuel fragments in the ballooned zones
  - Reduction risk of hot spots due to rod to rod contact



R&D Key Achievements : Cr coated M5® cladding 3/3

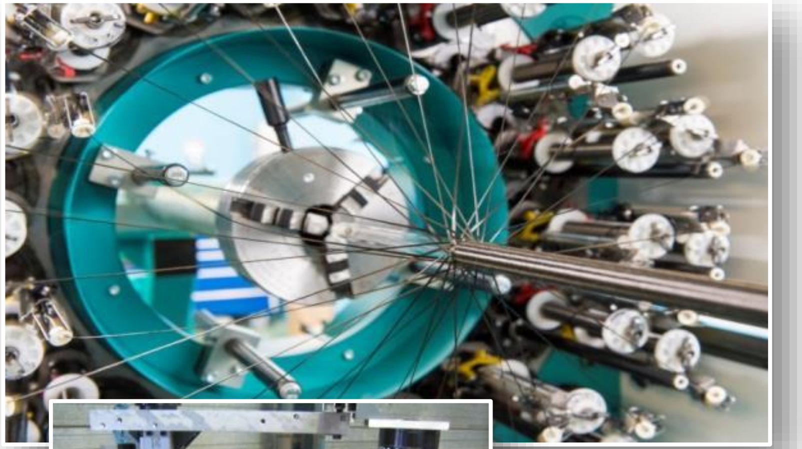
- Improvement of the corrosion resistance in steam at high temperature (**APRP**) at least up to 1300°C

  ➡**Quench Resistance and post quench ductility improved** ➔provide an additional time period before reaching the threshold of post-quench embrittlement and/or the loosing of the coolable geometry...)

(a) Uncoated Zircaloy-4 clad segment, weight gain = 40,4 mg/cm²

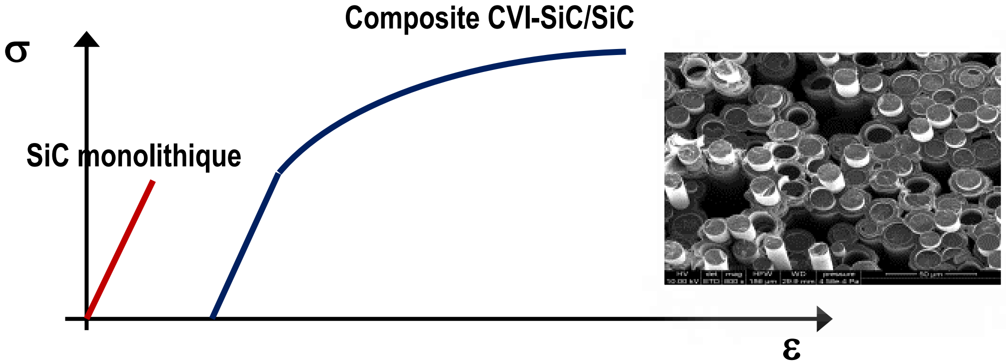
(b) Coated Zircaloy-4 clad segment, weight gain = 11,4 mg/cm²

SiC/SiC Cladding – A breakthrough solution



- **The nuclear grade of SiC-SiC composites**

  A decade of R&D activity at CEA has been dedicated to the development of SiC/SiC composites for GFR fuel cladding application



Tolerance to damages allowed thanks to the fibrous reinforcement and fiber/matrix interphase

A metallic liner was introduced in association for leak tightness

▶ **Cladding fabrication process mastered at the lab scale at CEA Saclay**

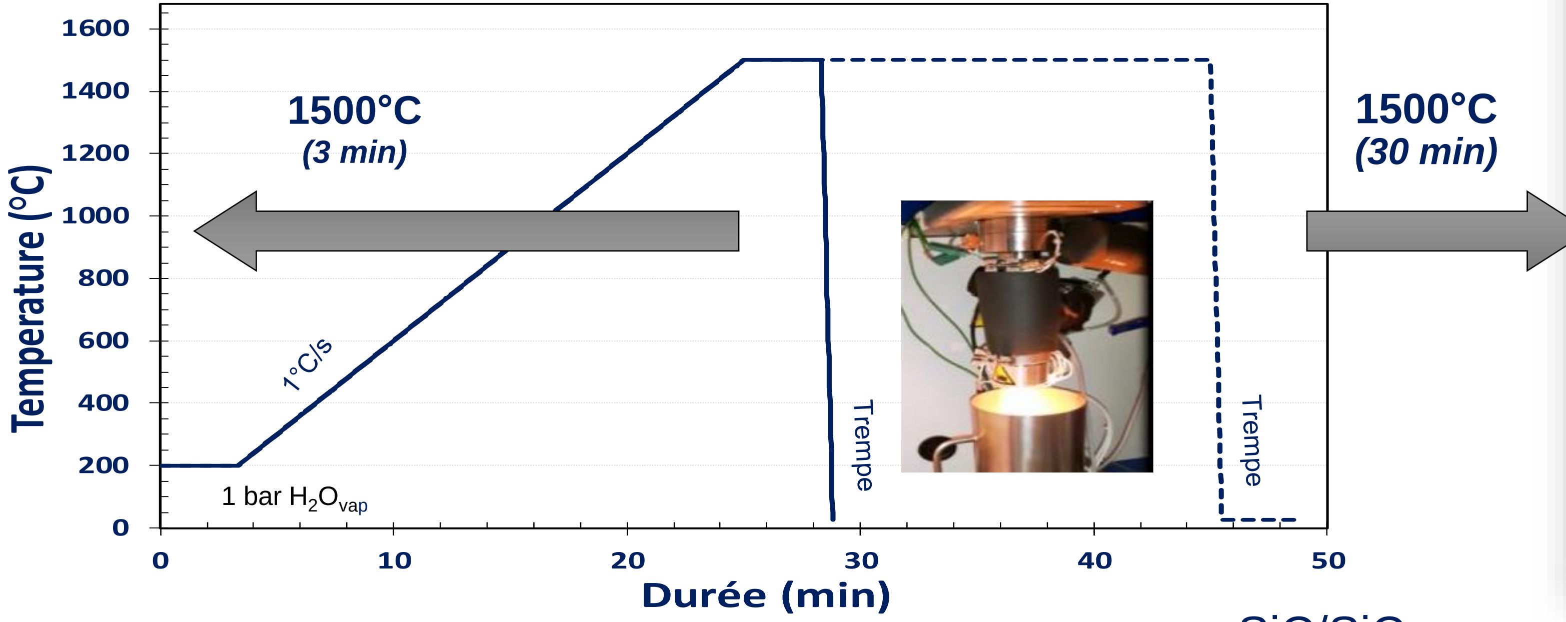
Highly-crystalline and near-stoechiometric fibers combined with a Chemical Vapor Infiltrated (CVI) matrix to ensure stability under neutron irradiation

SiC/SiC Fuel cladding - Performance accidental situations

Long time resistance to the high temperature oxidation in steam

Quench resistance not affected

Zircaloy 4



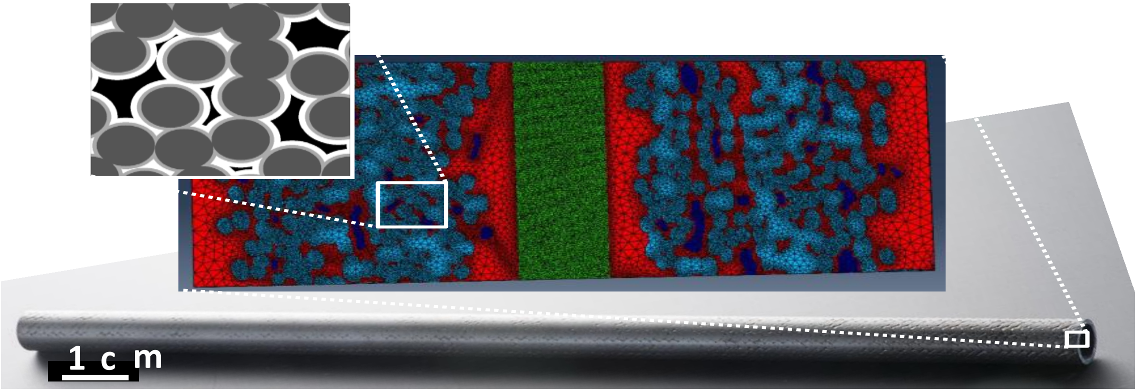
SiC/SiC composite cladding

- **Outstanding ability to preserve coolable geometry and cladding integrity during the reflooding phase**
- **Conservation of mechanical properties and capabilities to accommodate thermal shock**

➡ **Exceptional potential for accident resistance (LOCA and DEC)**

SiC/SiC Cladding - Challenges

- **Fuel rod design**
  - *Fission Product tightness (included Tritium)*
  - *Optimization of the thermal conductivity (multilayer)*
  - *Recession in water*
  - *PCI resistance*



- **Need of new adapted design rules *(safety critera) for licensing***

Metallic cladding → **Ceramic cladding**

Decades of feedback experience not directly applicable

Must be established accounting the specific properties of the product (« deterministic » vs « probabilistic » approaches)

- **Large scale manufacturing and industrial development capability**

Synthesis

- The development of E-ATF fuel represents a strong challenge for the fuel R&D. It takes place in the general innovation approach of the French nuclear industry in order to continuously improve the safety and the performances of the facilities.
- A step by step development strategy is adopted to maximize the chances of success
  - Development of evolutionary concepts, based on mature or promising achievements. A voluntary development roadmap, potentially bringing additional margins regarding the accidental situation assessment :

    Cr coated M5® cladding

    Cr_2O_3- Doped fuel

  - Development of a breakthrough concept, able to bring at a longer term, a determinant benefit for the fuel behavior under accidental scenarios, but implying to afford and unlock several challenging technological issues :

    SiC-SiC_f cladding

Thank you for your attention!

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