Overview of CEA's R&D on GFR fuel element design:

From challenges to solutions

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OVERVIEW

Decade of **GFR**-dedicated R&D at **CEA**: 2002-2012

Large effort devoted to **nuclear fuel element design**

Considerable **challenges** related to **ambitious objectives**:

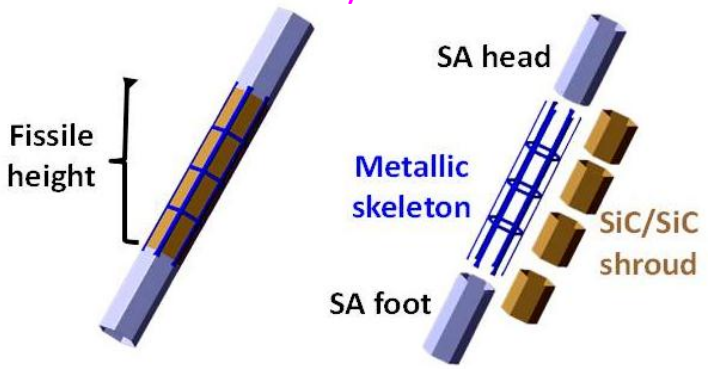
- High **temperature** (structures): 400-1000°C (nominal) & 1600-2000°C (accidental)
- High fast neutron **flux / dose**: a few 10^{19} $n.m^{-2}.s^{-1}$ / 75-150 dpa
- **Burnup**: 5-10 at% (core averaged)
- **Power density**: 100 MW/m^3 (core) – 50 W/g (fuel)

Extensive use of **SiC/SiC** CFCMCs (Continuous Fiber Ceramic Matrix Composite)

This presentation: **status on *recent* evolutions** (only published through **patents**)

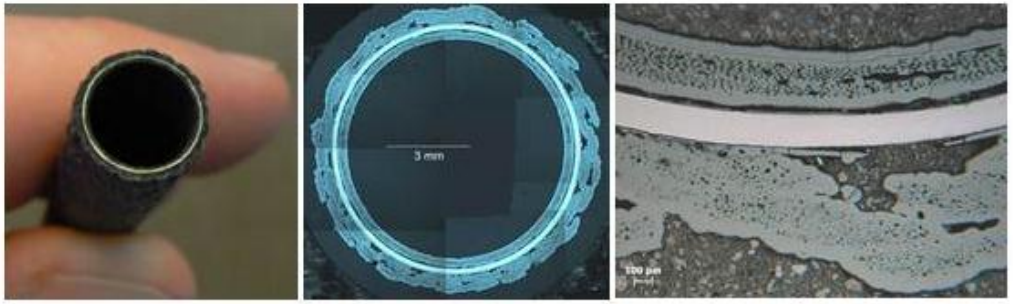
4 INNOVATIONS OVERCOMING TECHNOLOGICAL BOTTLENECKS

Mixed CFCMC/metal SA-duct



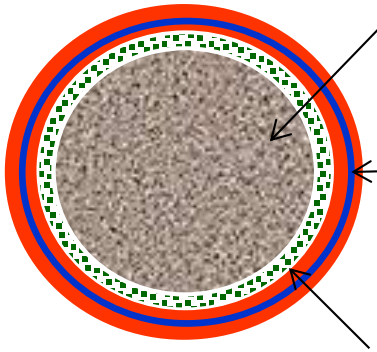
Patent WO 2011/042406 A1

"Sandwich" cladding



Patent WO 2013/017621 A1

"Buffer" bond



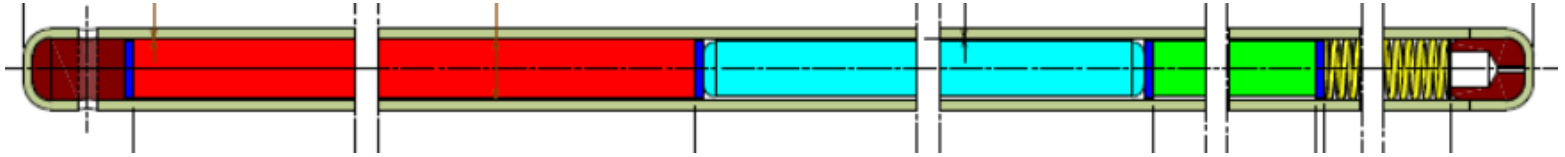
Patent WO 2011/157780 A1

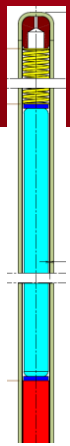
Blind-end SiC/SiC cladding

Patent WO 2011/061249 A1

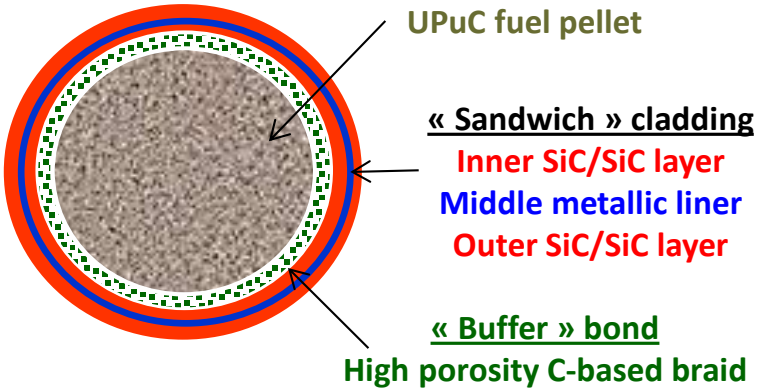
THE GFR PIN DESIGN: OVERVIEW

GFR fuel design studies conducted by CEA since 2002 (plate, then pin)



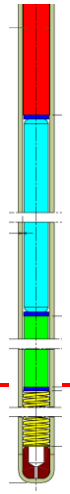


- **Pin**: two ½-pins joined end-to-end (support grid)
- **Fuel**: stacked mixed-carbide UPuC pellets
- **Cladding**: ceramic SiC/SiC-based cladding with refractory-metal liner
- **Bond**: *pressurized* (~5-10bar) He with C-based *porous* "buffer"



Specifically important issues :

- Material choices (high temperatures) ⇒ thermo-chemical interactions
- In-core integrity ⇒ thermo-mechanical behavior
  - ➢ UPuC fuel : *gaseous* swelling
  - ➢ SiC/SiC clad : pseudo-ductile behavior
- Detailed design ⇒ Core optimization
  (neutronics, thermal-aeraulics, thermal-mechanics & safety)



« SANDWICH » CLADDING: OVERVIEW

Motivation & challenges

- SiC/SiC cladding: refractory & resistant to irradiation… but prone to micro-cracking
- Leak-tighness is an issue ⇒ separate functions « resistance » / « confinement »
- US-proposed "Duplex/Triplex" design (monolithic SiC inner layer) raises questions:
  SiC failure beyond elastic limit & End-plug joining ⇒ long-term leak-tightness?
- Metallic liner: ductility & weldability… but raises compatibility issue (SiC & UPuC)

Proposed solution

- Thin (50-100µm) Ta/Nb liner
- Protected (in/out) by SiC/SiC layers

Patent WO 2013/017621 A1

Status

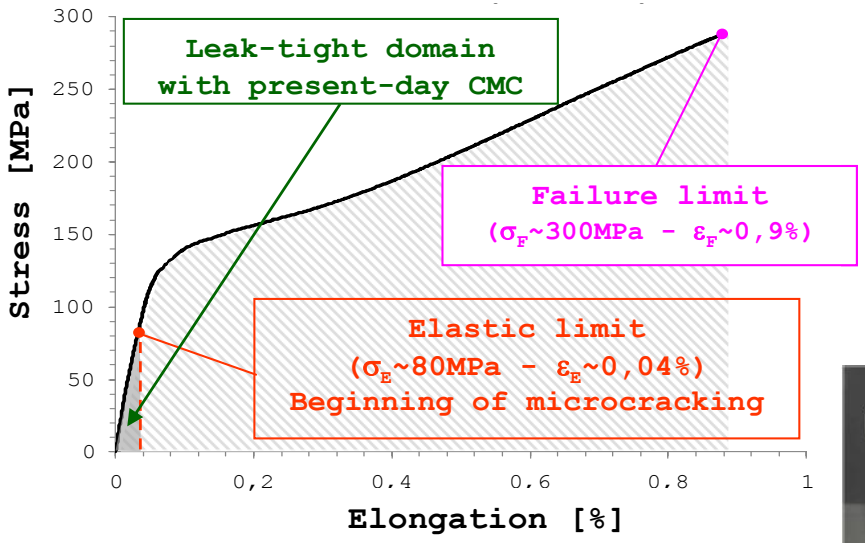
- Also considered for LWR… but not SFR
- Fully manufactured (short pin) at CEA
- Characterized: therm., mech., leak. & chem.
- End-closure *in progress*
- Irradiation program (TIRAMISU) *in progress*
- Design rules: codes & norms are required

"SANDWICH" CLADDING: A SOLUTION TO LEAK-TIGHTNESS

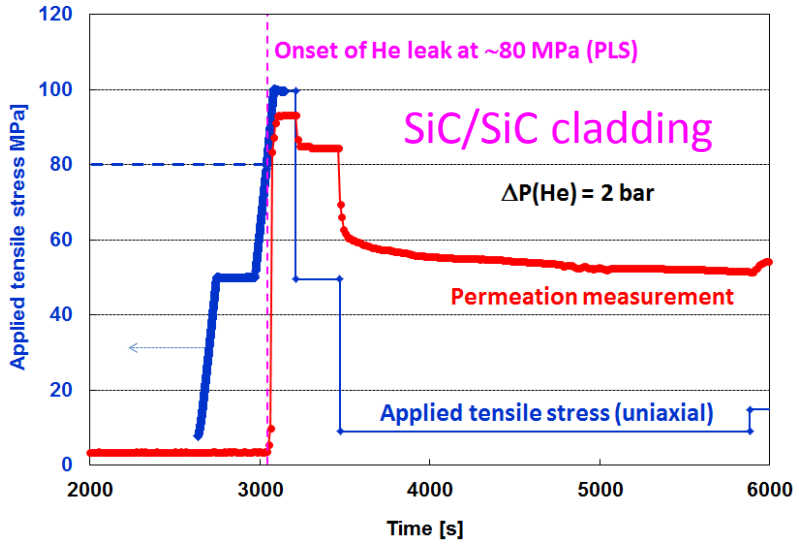
SiC/SiC leak-tightness ends for $\sigma \sim$ PLS

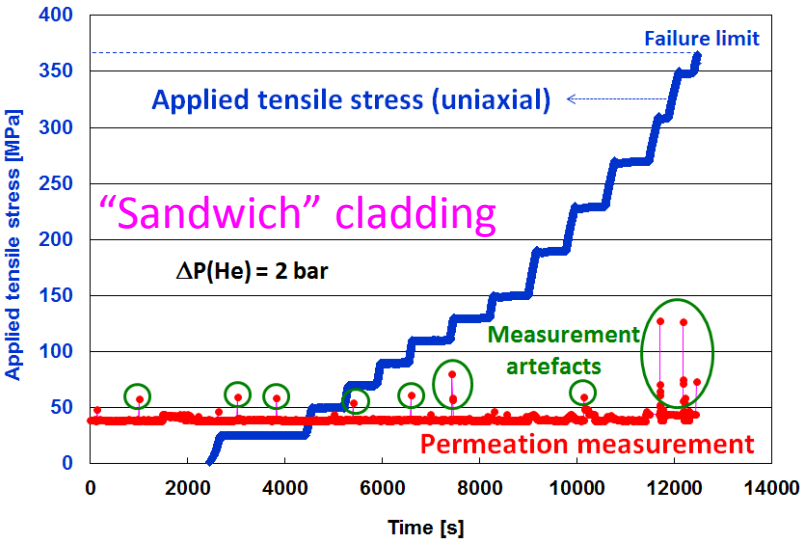
...long before failure

...particularly as regards deformation-induced failure



Permeation tests performed on both SiC/SiC & "sandwich" tubes **prove "sandwich" leak-tightness up to SiC/SiC failure limit**





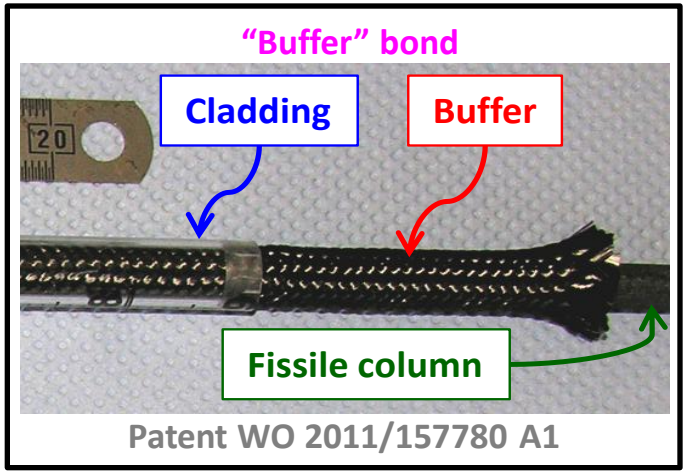
« BUFFER » BOND: OVERVIEW

Motivations & challenges

- UPuC fuel gaseous swelling favors interaction with the pseudo-ductile SiC/SiC cladding
- PCMI potentially limits performance: burnup & Pu inventory
- Increasing pellet/clad gap thickness doesn't help: thermal & relocation/puncturing issues
- He bond & UPuC fuel practical limit: BU ~ 5-6 at% (core average) & Pu_{GFR} / Pu_{SFR} ~ 1.5-2
- Thermochemical interactions: UPuC/SiC eutectic & U/Pu metal phase (C depletion)

Proposed solution

- Low-density C-based sheath



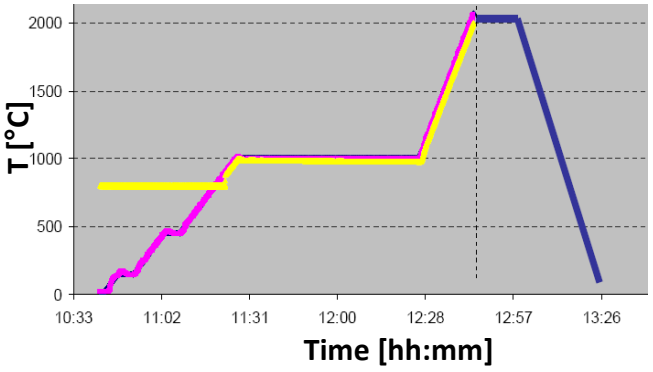
Patent WO 2011/157780 A1

Status

- Buffer = *unique* performance & safety improvement
  - BU approaching 10 at% (core average)
  - Pu_{GFR} only ~ 20% higher than Pu_{SFR}
  - Improved fuel grace time & supply pumping power
- Core optimization challenges:
  - Increased LHR: cladding thermal stress
  - Bond thinness (~300 µm): implementation
- Strong interest… but R&D is still very preliminary

"BUFFER" BOND: A SOLUTION TO MATERIAL INTERACTIONS

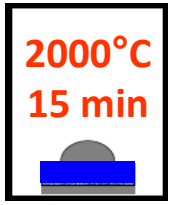
$UC_{1.04}$ – SiC/SiC

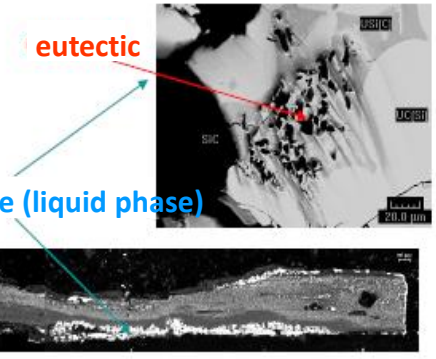


Important material interactions

Fuel largely melt

Clad severely damaged





$UC_{1.04}$ - C - SiC - Ta - SiC/SiC

Limited material interactions

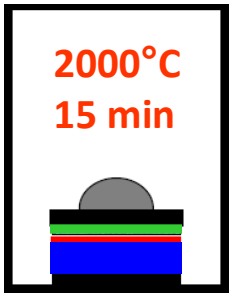
Fuel essentially preserved (buffer effect)

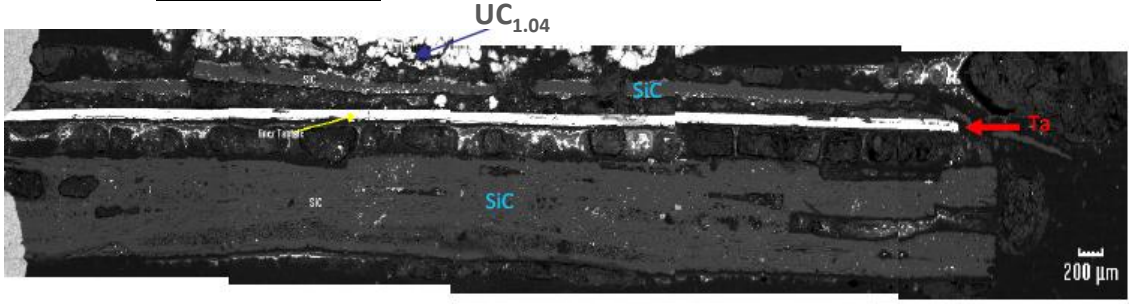
C layer disolved in UPuC

SiC layer essentially preserved

Ta liner essentially preserved

SiC/SiC layer essentially preserved





CONCLUSIONS & PERSPECTIVES

Designing **GFR fuel elements** represents a **considerable challenge**
There does seem to be little (if any) alternative to relying on **SiC/SiC-based solutions**
This resulted in CEA's R&D program facing **several technological bottlenecks**

Innovative solutions were proposed and patented in the recent years:

- **Mixed ceramic/metal SA-duct**
- **"Buffer" bond**
- **Blind-end SiC/SiC cladding**
- **"Sandwich" cladding**

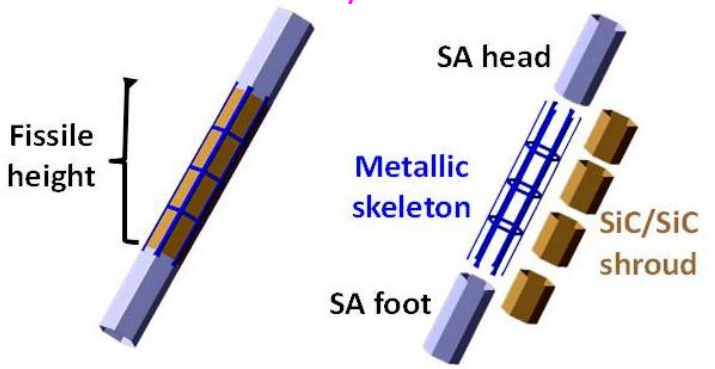
Much progress has been accomplished and **many perspectives** have been open…

…**but proof is yet to be established that the proposed concepts are truly viable**

Despite the present **slowing down of GFR-dedicated R&D**, limited studies are still conducted by CEA within the frame of LWR/SFR-dedicated programs

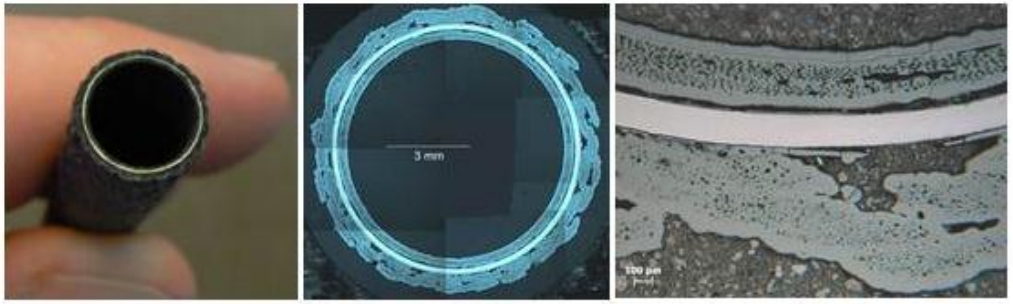
THANKS FOR YOUR ATTENTION - QUESTIONS ARE WELCOMED

Mixed CFCMC/metal SA-duct



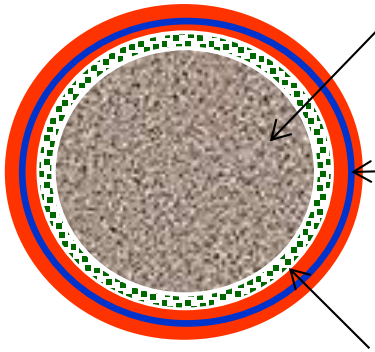
Patent WO 2011/042406 A1

"Sandwich" cladding



Patent WO 2013/017621 A1

"Buffer" bond



Patent WO 2011/157780 A1

Blind-end SiC/SiC cladding

Patent WO 2011/061249 A1

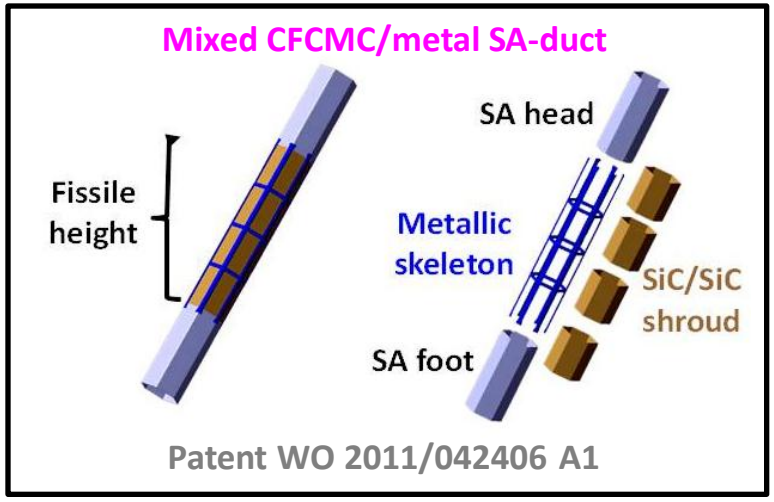
MIXED CFCMC/METAL SUB-ASSEMBLY DUCT: OVERVIEW

Motivations & challenges

- Duct material selection is an issue for GFR: refractoriness & neutron transparency
- Compatibility with differential deformations: diagrid, heterogeneities…
- No full-metallic solution: neutronic penalty
- No full-ceramic solution: joining with SA-head/foot

Proposed solution

- Light metallic skeleton: axial mechanical continuity (handling)
- SiC/SiC shroud module(s): coolant chanelling & pin-bundle protection



Status

- Also considered for SFR (advanced design)
- *Preliminary* thermomechanical design
- Shroud-module manufacturing *in progress*