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THERMOMECHANICAL(PHYSICAL) PERFORMANCES OF SiC/SiC COMPOSITES FOR NUCLEAR APPLICATIONS

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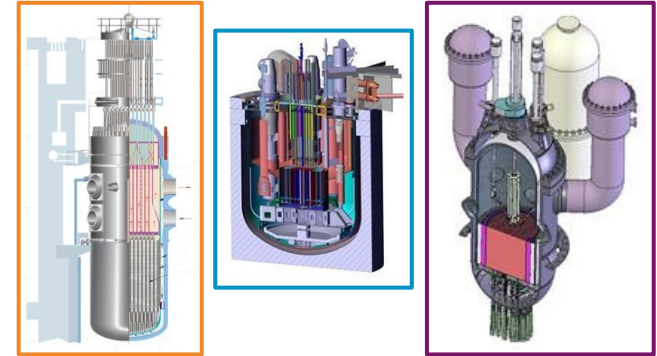
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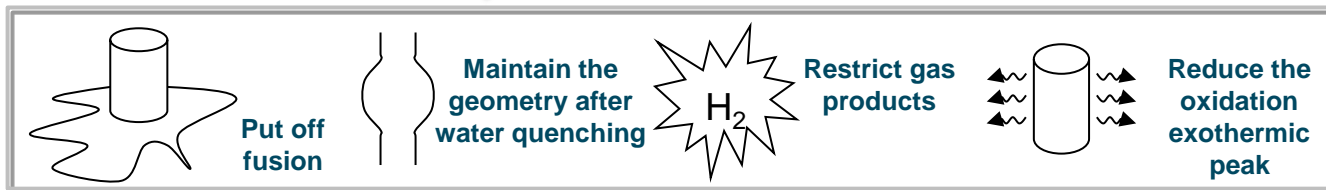
CONTEXT

Requirements to be use as material in nuclear power plant **LWR**, **SFR** and **GFR-He**

- ▶ High temperature resistance : 300/550/1000°C (nominal) & 1200-2000°C (accidental)
- ▶ Microstructure stability under fast neutron flux (75-150 dpa)
- ▶ Neutron transparency and low activation
- ▶ Corrosion resistance
- ▶ Tolerance to damage (safety requirements)



OBJECTIF → ADD ADDITIONAL MARGINS (ATF – LWR)



While preserving behavior in nominal condition



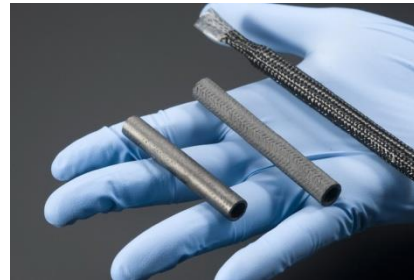
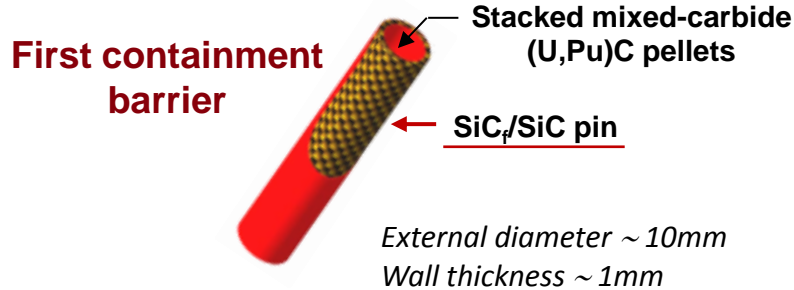
Focus on the development of SiC_f/SiC composites

R&D ISSUES

SiC/SiC composites development for actual LWR and futur GFR, SFR

→ **Two applications compatibles with ceramic composites**

Fuel cladding



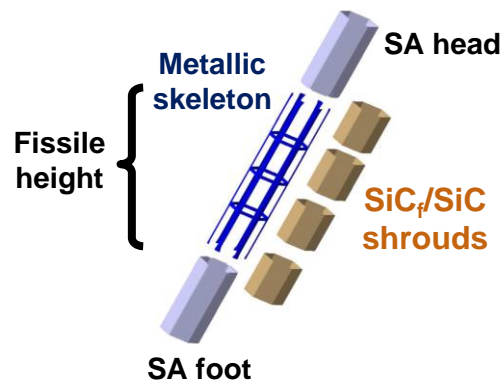
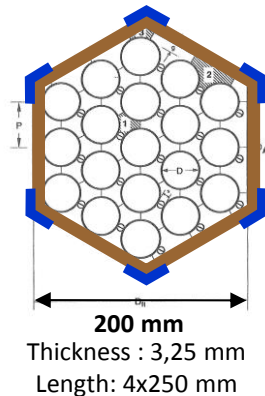
FUNCTIONAL SPECIFICATIONS

Mechanical integrity
Coolant & Fission Products tightness
Heat exchanger

Mixed CMC/Metal hexagonal SA duct

Motivations: No full-metallic solution (neutronic penalty)

Piece enclosing fuel claddings



FUNCTIONS

Axial mechanical continuity of assembly
Coolant channelling & pin-bundle protection



Patent WO 2011/042406 A1

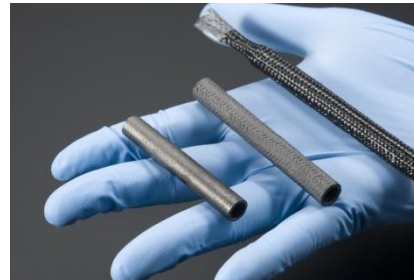
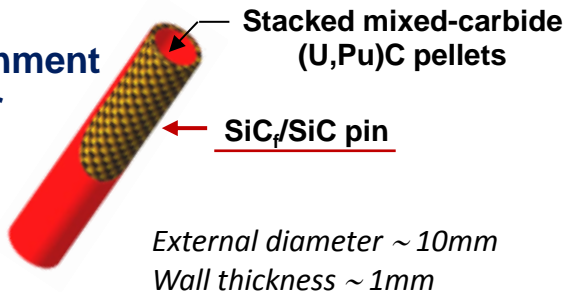
R&D ISSUES

SiC/SiC composite development for actual LWR and futur GFR, SFR

→ Two applications compatibles with ceramic composites

Fuel cladding

First containment barrier



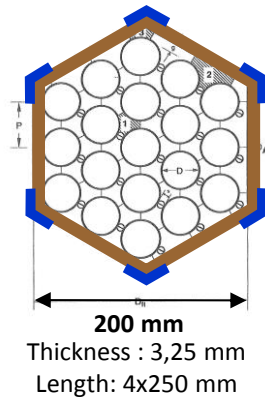
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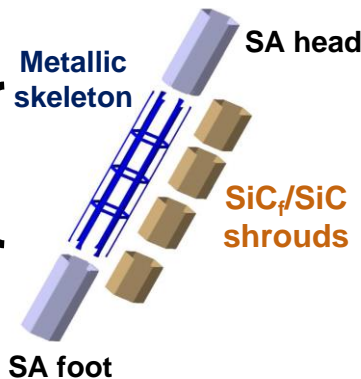
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Piece enclosing fuel claddings



Fissile height



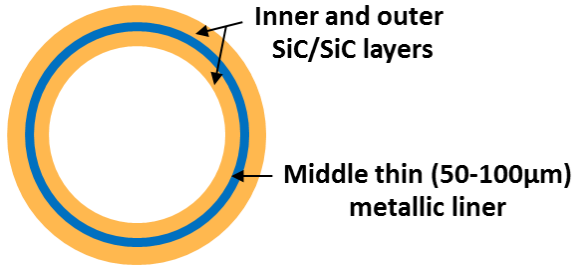
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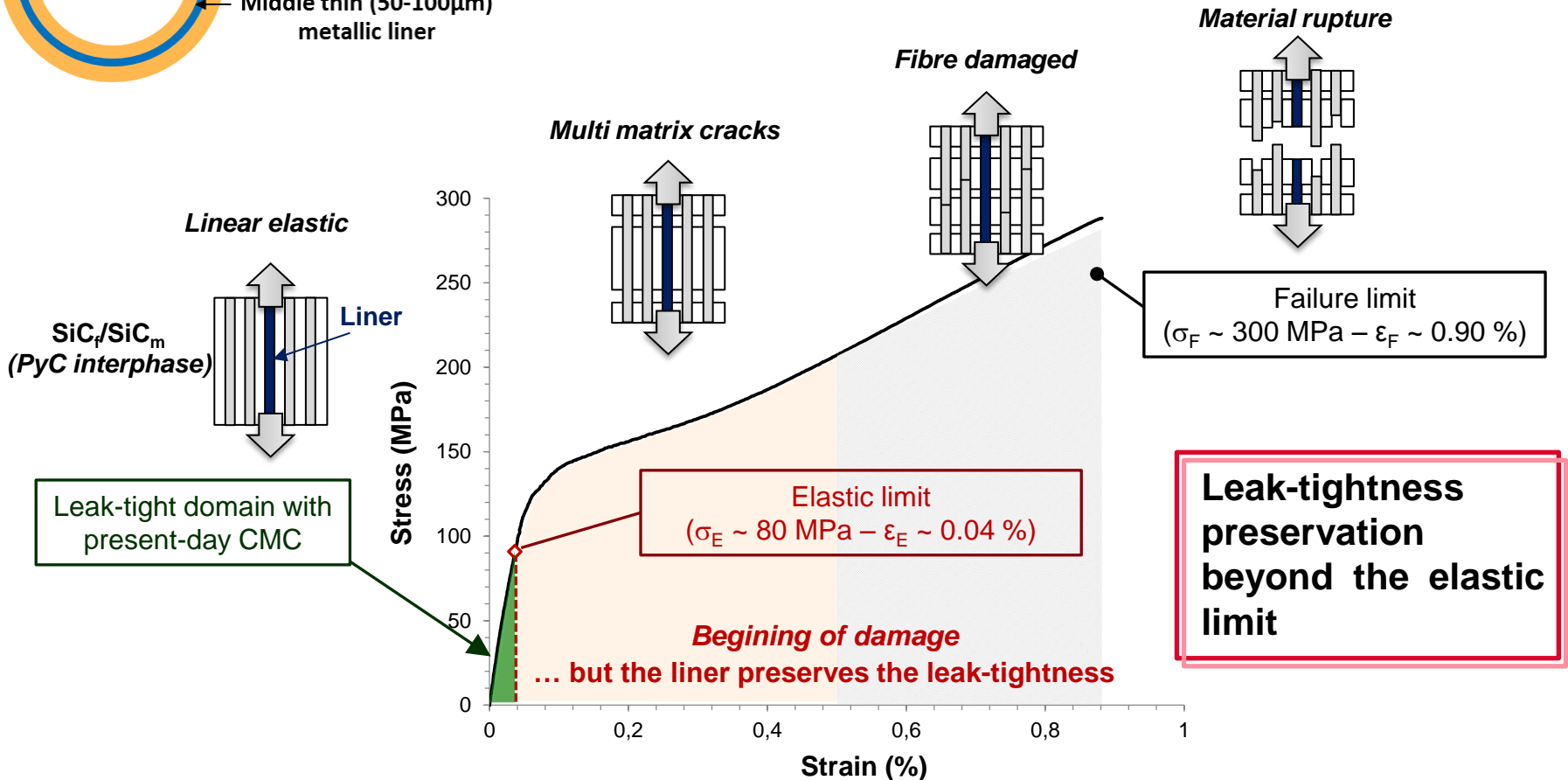


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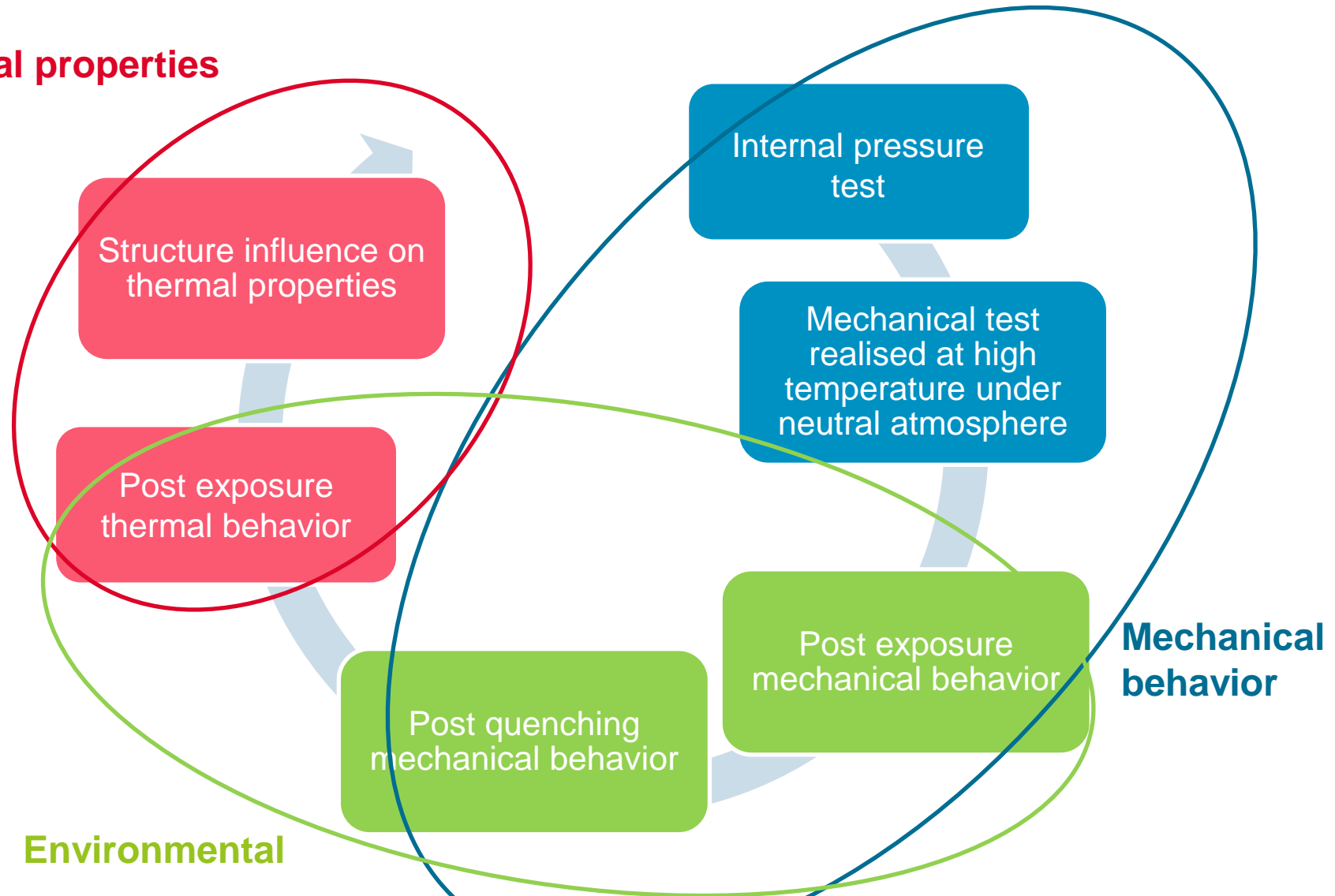
SiC CLADDING CONCEPT : « SANDWICH » DESIGN AS A SOLUTION FOR LEAK-TIGHTNESS ISSUE



- ▶ SiC/SiC cladding : refractory, pseudo-ductile behavior, resistant to irradiation and low activation
- ▶ But prone to micro-cracking beyond their elastic limit

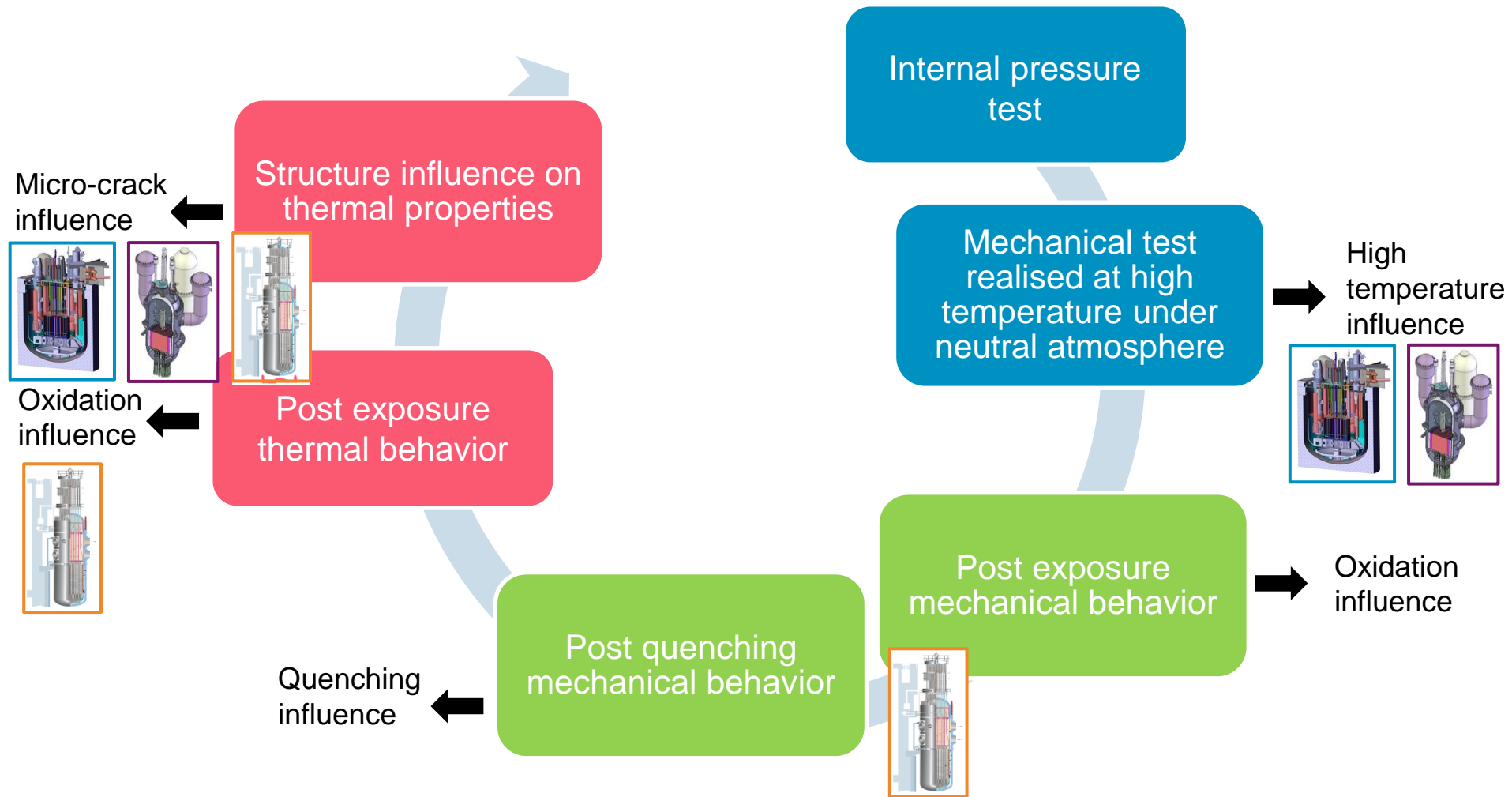


Thermal properties



Environmental

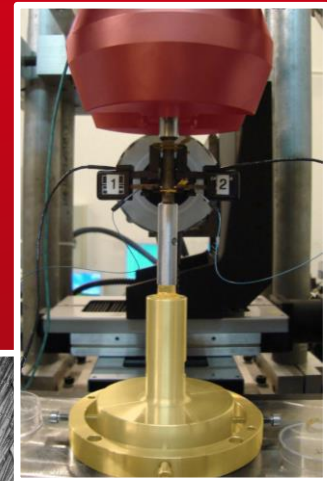
OBJECTIVES



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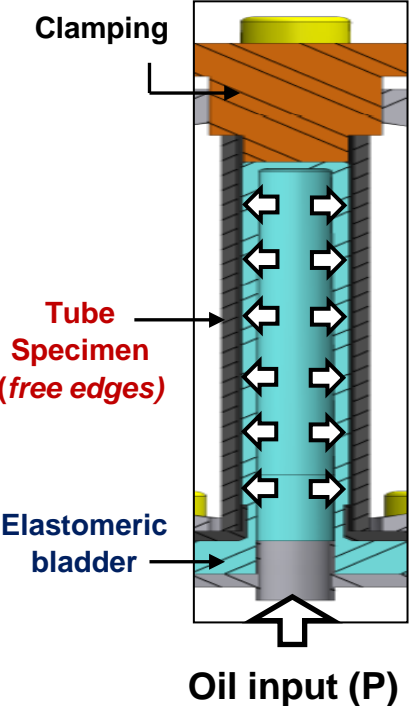
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MECHANICAL BEHAVIOR



Testing methods for mechanical behavior assessment of ceramic composites tubes

INTERNAL PRESSURE TEST



Pressurization of tubes by oil injection into an elastomeric bladder

Strains measurement by both DIC and gauges

Circumferential stress computation
(No membrane effect)

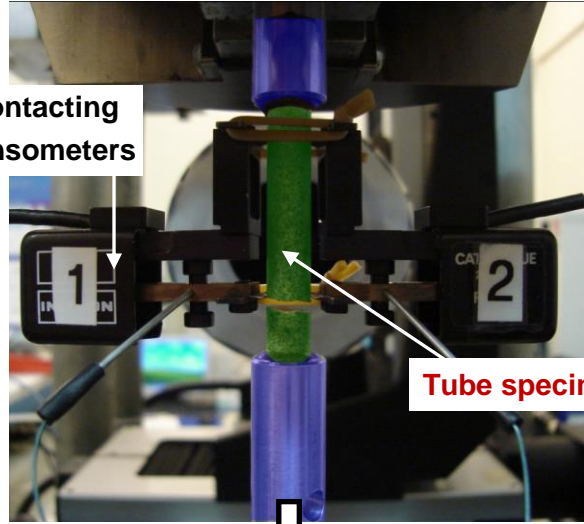
$$\sigma_{\theta\theta} = 2 \frac{P_1 R_{int}^2}{R_{ext}^2 - R_{int}^2}$$

Testing method proposed to ISO Standardization :
ISO 21971

TENSILE TEST

Constant crosshead displacement rate
(0.05mm/min)

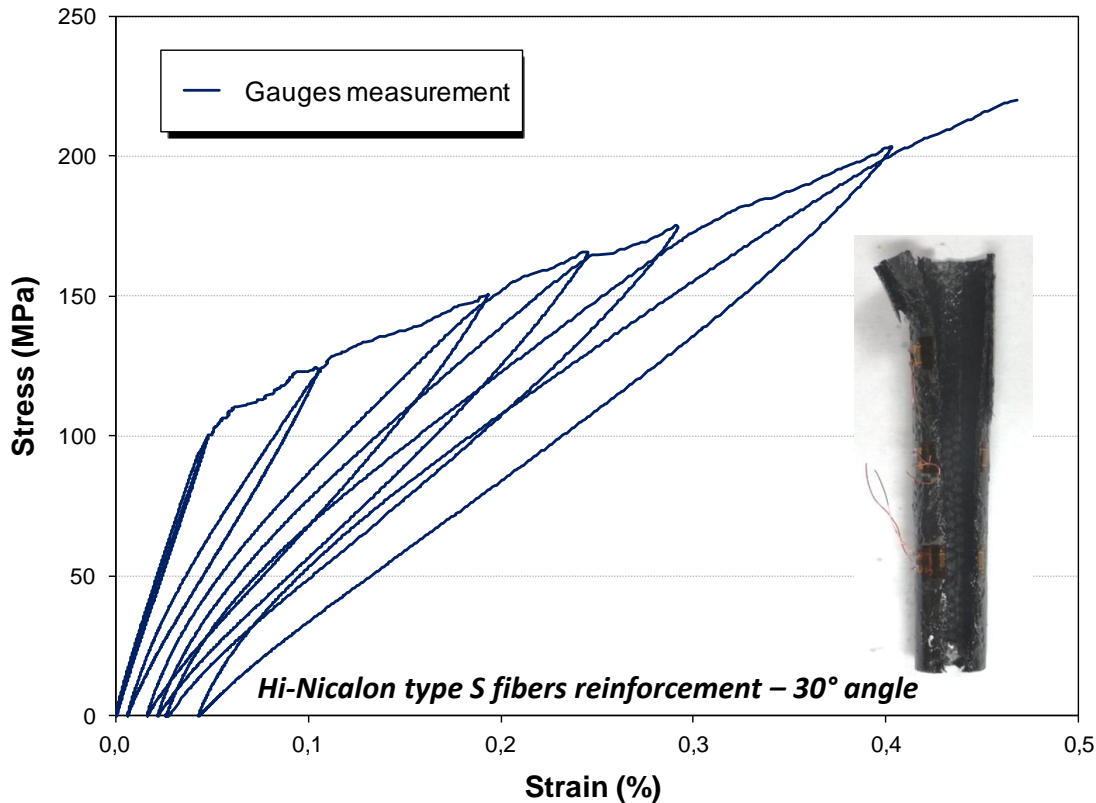
Upper active grip



Alignment of load train insured by structural bonding of specimen end

ISO 20323

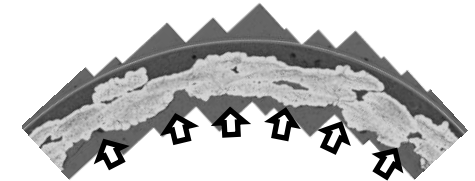
INTERNAL PRESSURE TEST (RT)



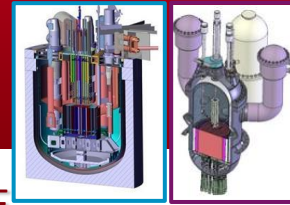
▶ **Elastic damageable mechanical behavior characteristic of most ceramic composites**

▶ **Significant residual strains**
but possibly related to structural effect

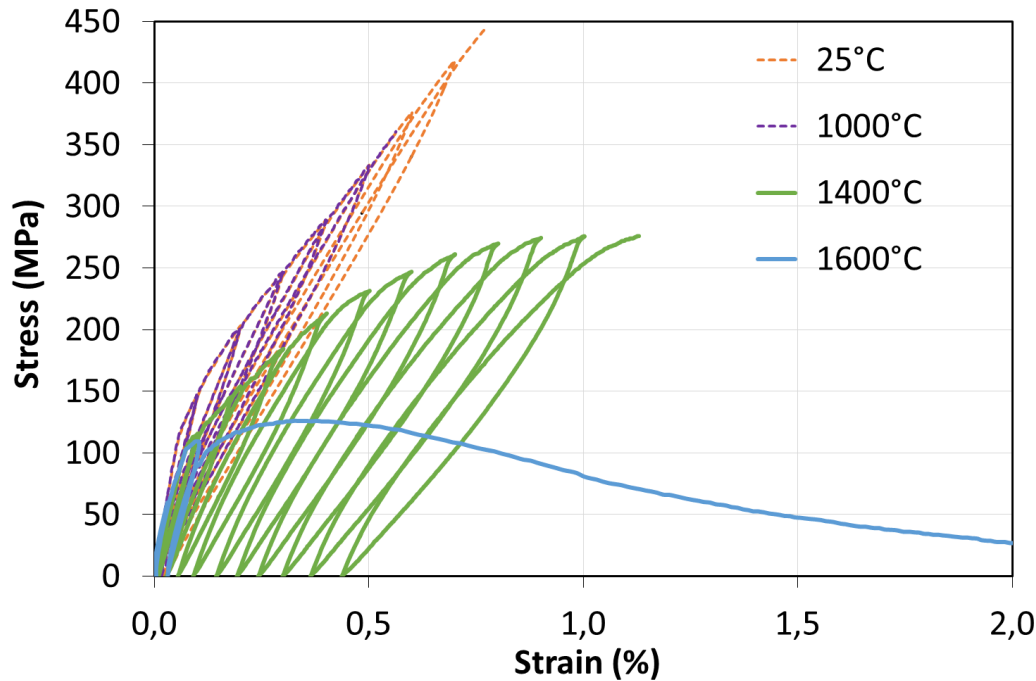
▶ **Greater density of microcracks in inner surface comparatively to the outer**
(Difference of curvature radius)



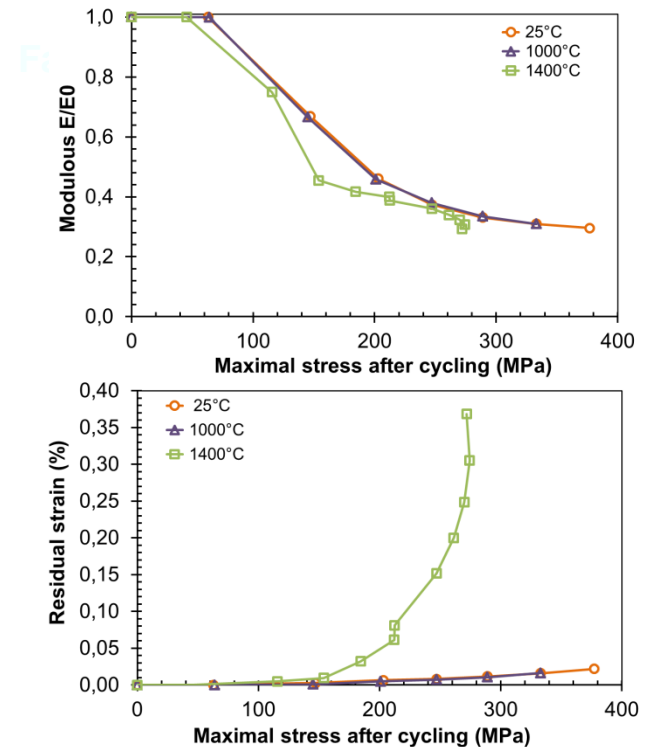
Behavior in line with longitudinal tensile tests



NEUTRAL ENVIRONMENT : MECHANICAL TEST REALISED AT HIGH TEMPERATURE

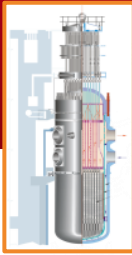


Damage indicators



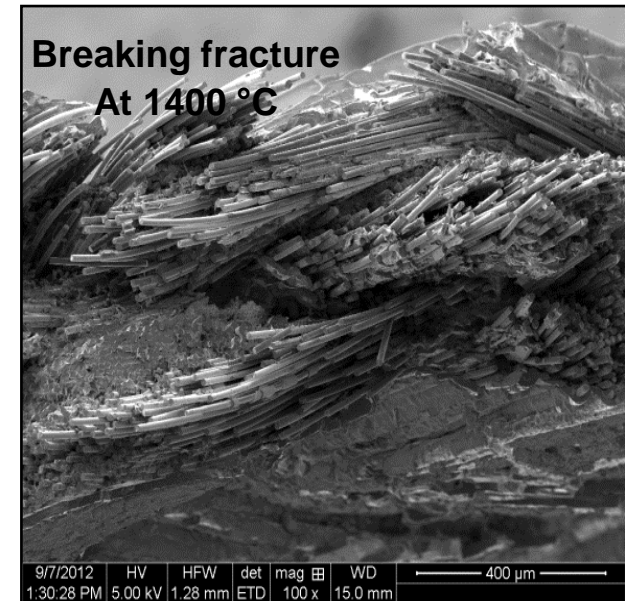
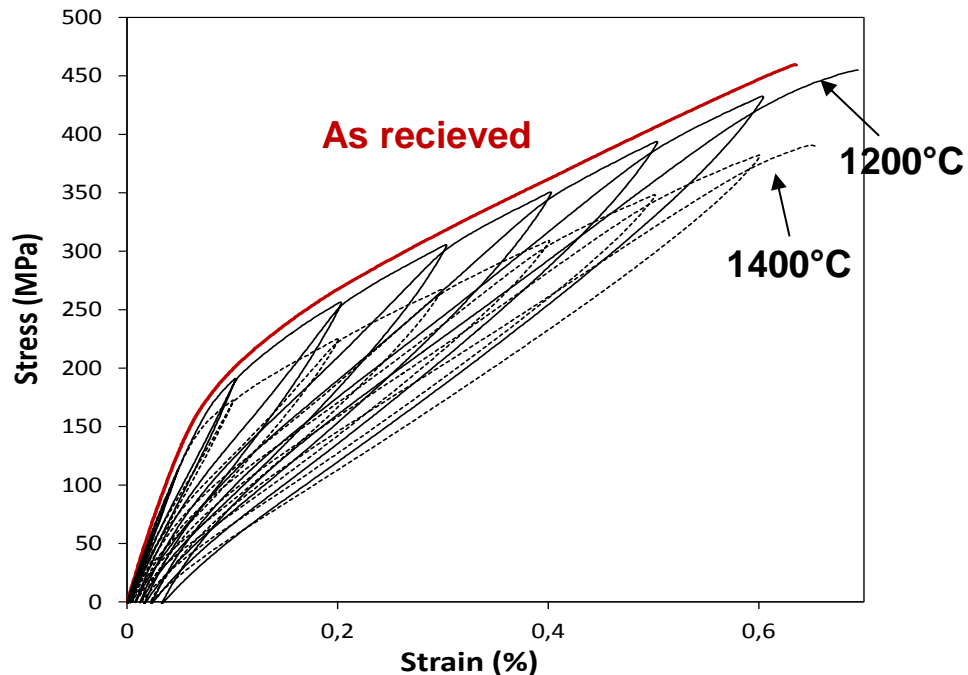
- ▶ High mechanical strength in temperature / non-zero up to 1600 ° C
- ▶ Mechanical behavior stability demonstrated up to 1000 ° C
Higher residual strain for mechanical test realised at 1400 ° C
- ▶ Weakening of mechanical properties beyond to 1000 ° C

**Limitation temperature :
1600 ° C !**



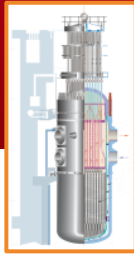
LWR - LOCA CONDITIONS : POST-EXPOSURE MECHANICAL BEHAVIOR

After 110 hours under steam at high temperature



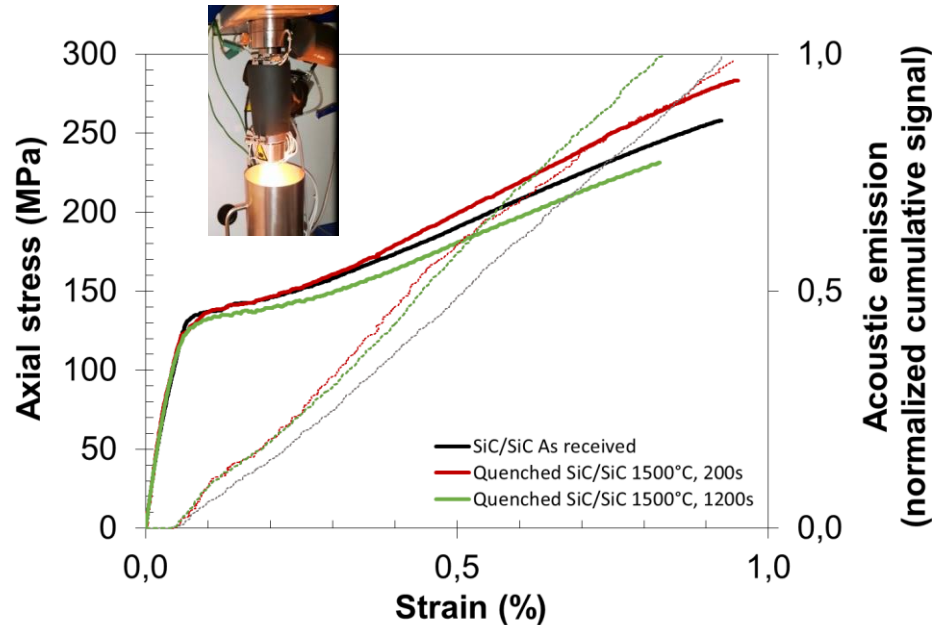
- ▶ Retention of mechanical comportment “Non-linear elastic damage” of ceramic composites
Same breaking deformation / Slight decrease of young’s modulus and breaking stress
- ▶ Protective comportment of silicon carbide matrix in these conditions :
PyC interface stay efficient to deflect craks

Interest confirmed of SiC/SiC for Accident Tolerance Fuel application



QUENCHING EFFECTS : POST-EXPOSURE MECHANICAL BEHAVIOR

After high temperature treatment and quenching

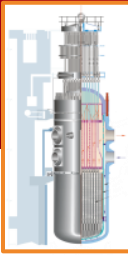


After high temperature oxidation ramp followed by water quenching
(1500°C under steam 200-1200s)

	EP (GPa)	σ_Y (MPa)	σ_m (MPa)	ϵ_m (%)
SiC/SiC As-received	285 ± 3	97 ± 6	252 ± 8	0,95 ± 0.03
Quenched SiC/SiC 1500°C, 200 s	280	104	283	0.95
Quenched SiC/SiC after 1500°C, 1200 s	280	93	233	0.83

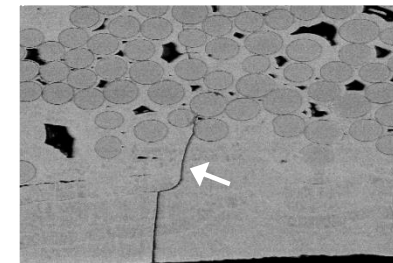
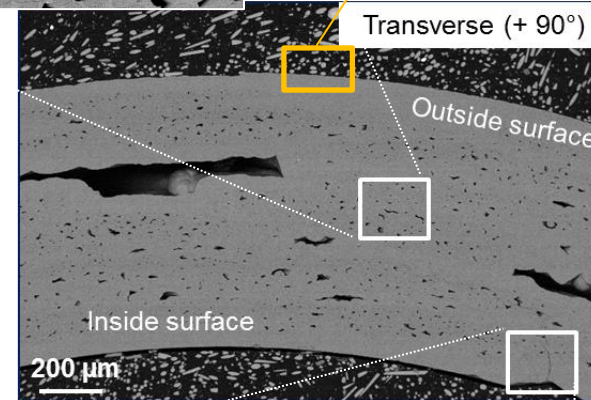
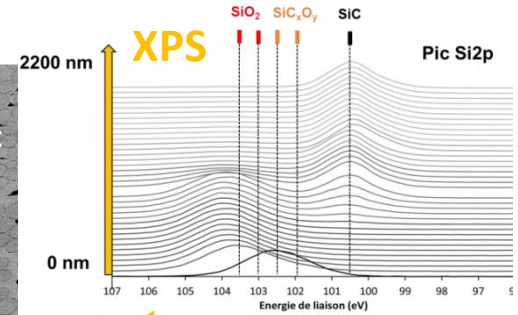
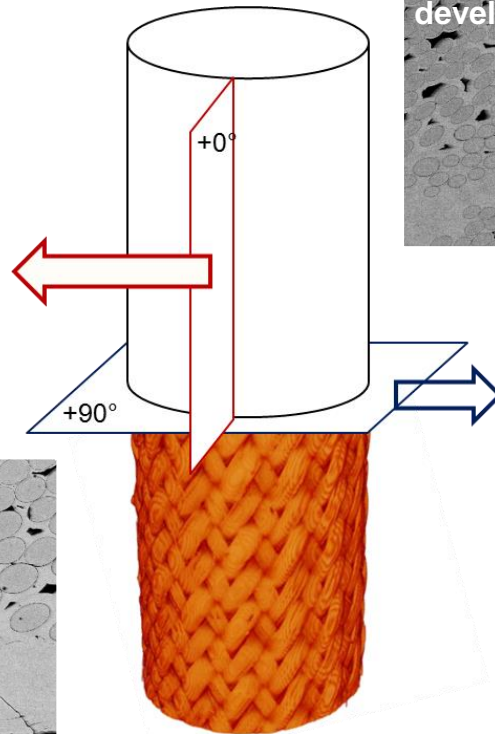
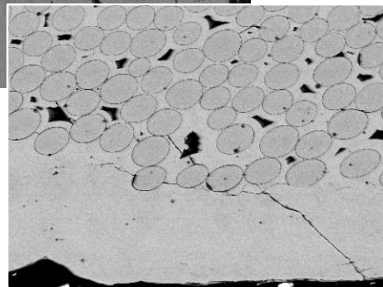
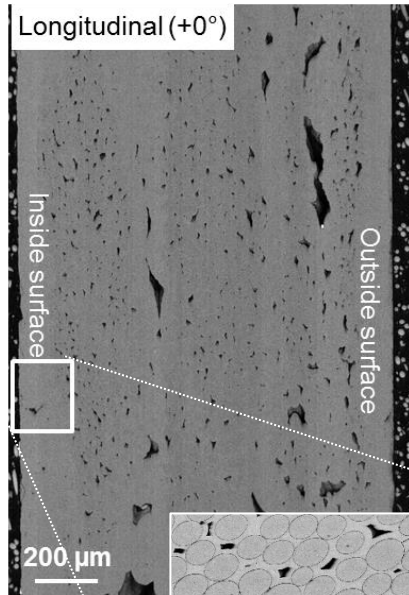
- ▶ Pyrocarbon interphase stays efficient to deviate cracks
- ▶ Matrix micro-cracking saturation did not occur before ultimate failure (singles regime of EA detected)

Preservation of the « non-linear elastic damageable » behavior characteristic of ceramic composites



QUENCHING EFFECTS : METALLOGRAPHICS OBSERVATIONS

After high temperature treatment and quenching

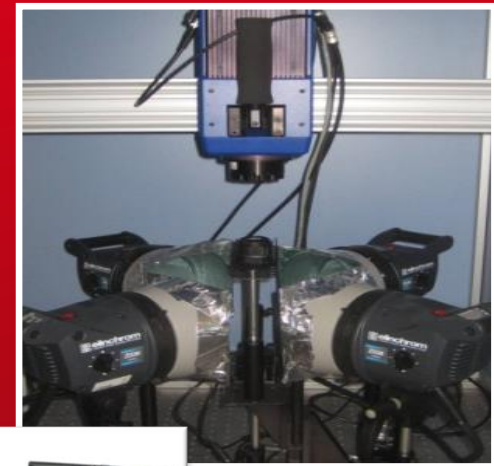
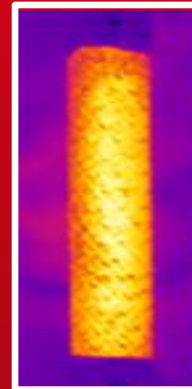


The micro-cracks observation into the matrix surface are deflected by PyC interphase

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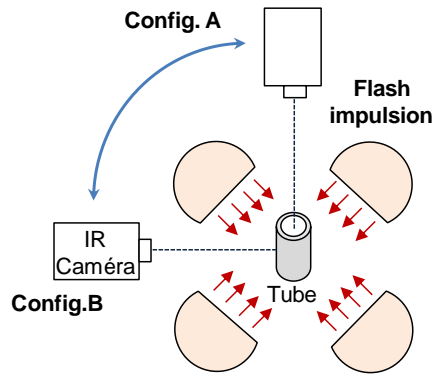
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THERMAL PROPERTIES



THERMAL CONDUCTIVITY MEASUREMENT

New testing method developed for thermal characterization of ceramic composite tubes



Originality of the measurements are based on the simultaneous treatment of both the front and rear faces of tubular specimens
(To overcome the highly anisotropic character of ceramic composites)

- ▶ Pulse « Flash method » (IR thermography, periscope)
- ▶ Acces to both transverse and in-plane diffusivities

Textures	Generation	$\alpha_f(\%)$	Density ($m^2.s^{-1}$)	Diffusivity ($m^2.s^{-1}$)	Conductivity ($W.m^{-1}.K^{-1}$)
Filament Winding 30 °		44	2,71	$5,75.10^{-6}$	10,6
2D Braiding 45 °	2009-2013	42	2,67	$7,43.10^{-6}$	13,5
Interlock 3D braiding 30 °		34	2,05	$7,40.10^{-6}$	10,3
2D Braiding 45 °	from 2014	45	2,83	$1,51.10^{-6}$	28,9

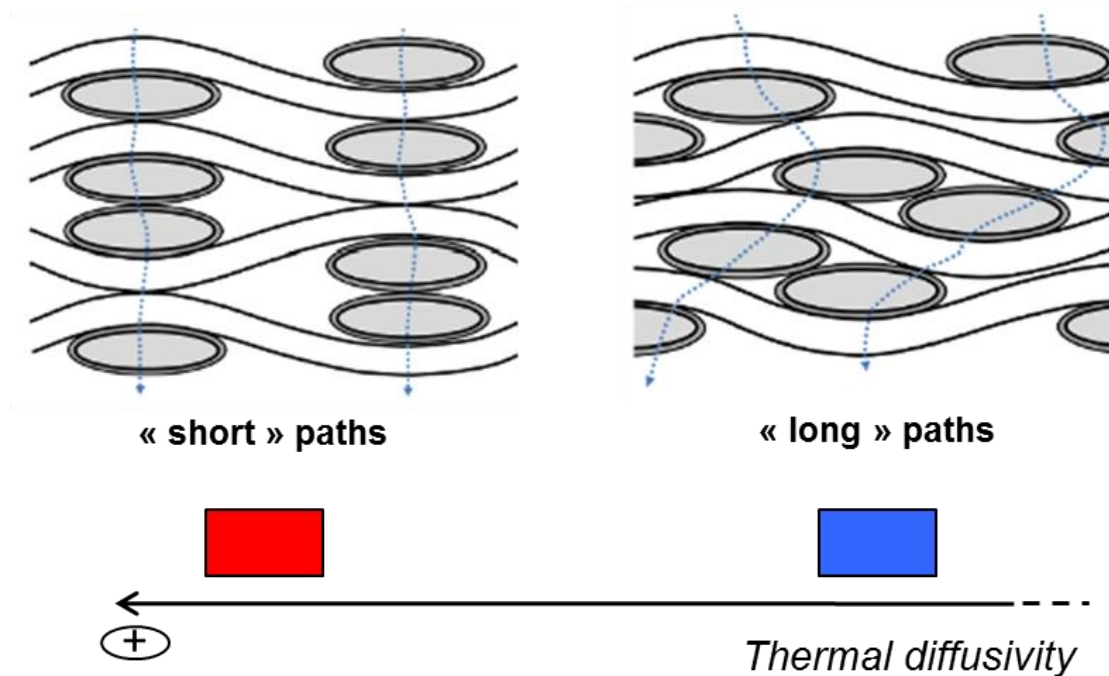
Conductivity had to be higher than $10 W.m^{-1}.K^{-1}$

Values would satisfy requirements for SiC_f/SiC-based nuclear cladding

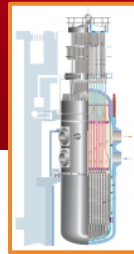
THERMAL CONDUCTIVITY MEASUREMENT

New testing method developed for thermal characterization of ceramic composite tubes

Thermal paths

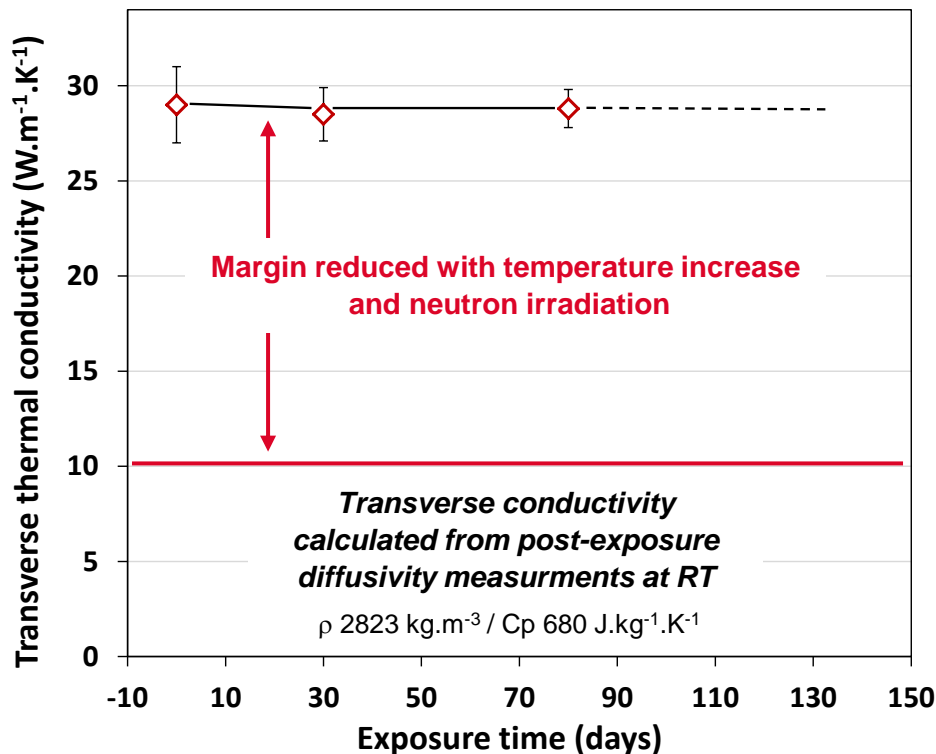


Thermal properties closely dependent on the nature of the SiC fibers (TSA_3 or $H-NS$), the processing route for densification and the fibrous architecture...



LWR CONDITIONS: POST-EXPOSURE MEASUREMENTS

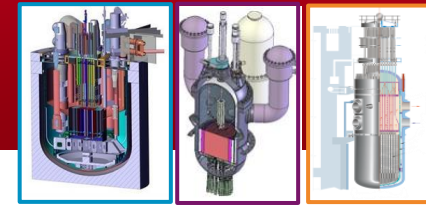
Measured at 25 °C on undamaged SiC/SiC exposed in dynamic conditions (Loop, AREVA Facility)



- ▶ No effect of oxidation on the thermal behavior after 80 days
- ▶ Conductivity stays widely higher than the required minimal value of 10 W.m⁻¹.K⁻¹
- ▶ Coherent with absence of damage and the very low sample recession

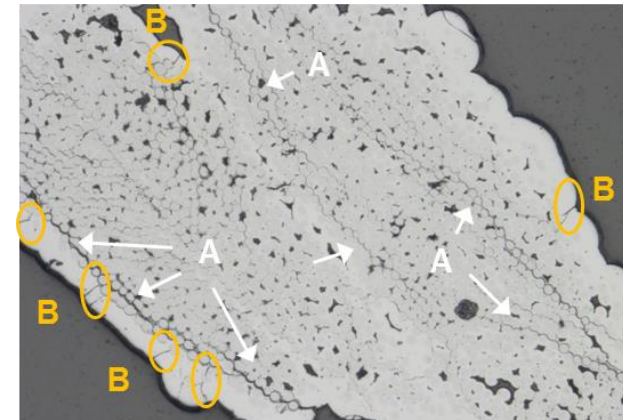
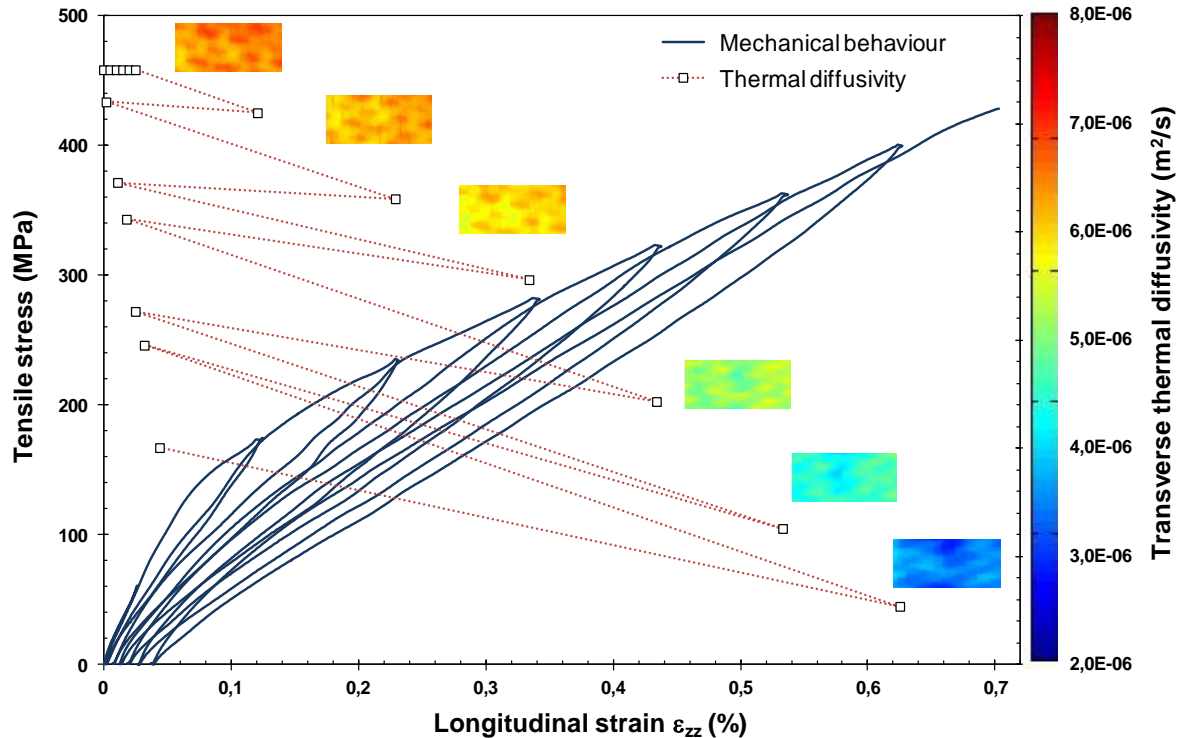
**LWR conditions (Out of pile)
do not significantly degrade
the thermal properties of SiC/SiC**

No change expected for longer times...



LIMITATION : MECHANICAL DAMAGE EFFECT ON THERMAL PROPERTIES

Evaluated on tubular composite specimen submitted to a tensile loading (in-situ testing)

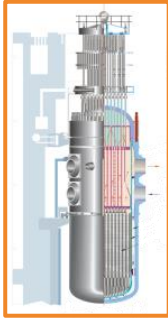


Development of matrix cracking acts as a barrier to the heat transfer in the thickness

Two populations of cracks

- ▶ Intra-bundle debonding – A
(normal to the heat flow direction)
- ▶ Intra matrix seal-coat cracks – B

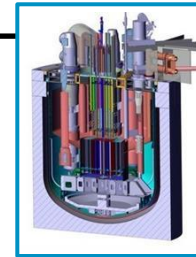
Confirmation of a close relation between thermal properties and mechanical damage



LWR

- PyC interface stays efficient to deviate micro-cracks (LOCA event)
- Low influence of steam oxidation up to 1500°C followed by water quenching on mechanical properties
- No significant influence of nominal oxidation on thermal properties

SFR



GFR



- Preservation of high mechanical behavior (strength, strain) beyond the 1000/1400°C range

Highlighted limitation

- Thermal properties degraded by mechanical damage

SiC/SiC composites are very interesting materials
 ...but there is still a long way to go before industrialization



THANK YOU FOR YOUR ATTENTION

Commissariat à l'énergie atomique et aux énergies alternatives
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Direction de l'énergie nucléaire

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