The TAURO SiC/SiC breeding Blanket

G. Aiello[1], A.Gasse[2], L. Giancarli[1], H. Golfier[1],
J.F. Salavy[1+], J. Szczepanski[1#]

[1]CEA-Saclay, DRN/DMT/SERMA, F-91191 Gif-sur-Yvette
[2]CEA-Grenoble, DTA/CEREM/DEM/SHM, F-38054 Grenoble
[+]ALTEN, [#]CONCEPT 21

Why to use SiC_f/SiC structures?

Basic reason : avoid population evacuation in the case of severe accident

Two strategies:

1 - *low radioactive inventory* : SiC_f/SiC structures, He coolant (p>10MPa), lithium ceramics breeder (Li_2O), Be-multiplier

➡ ARIES (US), DREAM (Japan), HCPB (EU)

Intrinsic difficulty: all materials used in the reactor vessel must have low activation properties (low inventory)

2 - *low energy inventory* : liquid metal cooling (low pressure), low reactivity with air and water (except for Li), low afterheat and electrically insulating structures (ex.: SiC_f/SiC)

➡ TAURO (EU): self-cooled Pb-17Li blanket

Intrinsic difficulty: all the in-vessel components have to be cooled with an appropriate liquid metal;Pb-17Li potential good candidate

➡ ***Design studies with the main objective of identifying the need in term of R&D and industrial contribution***

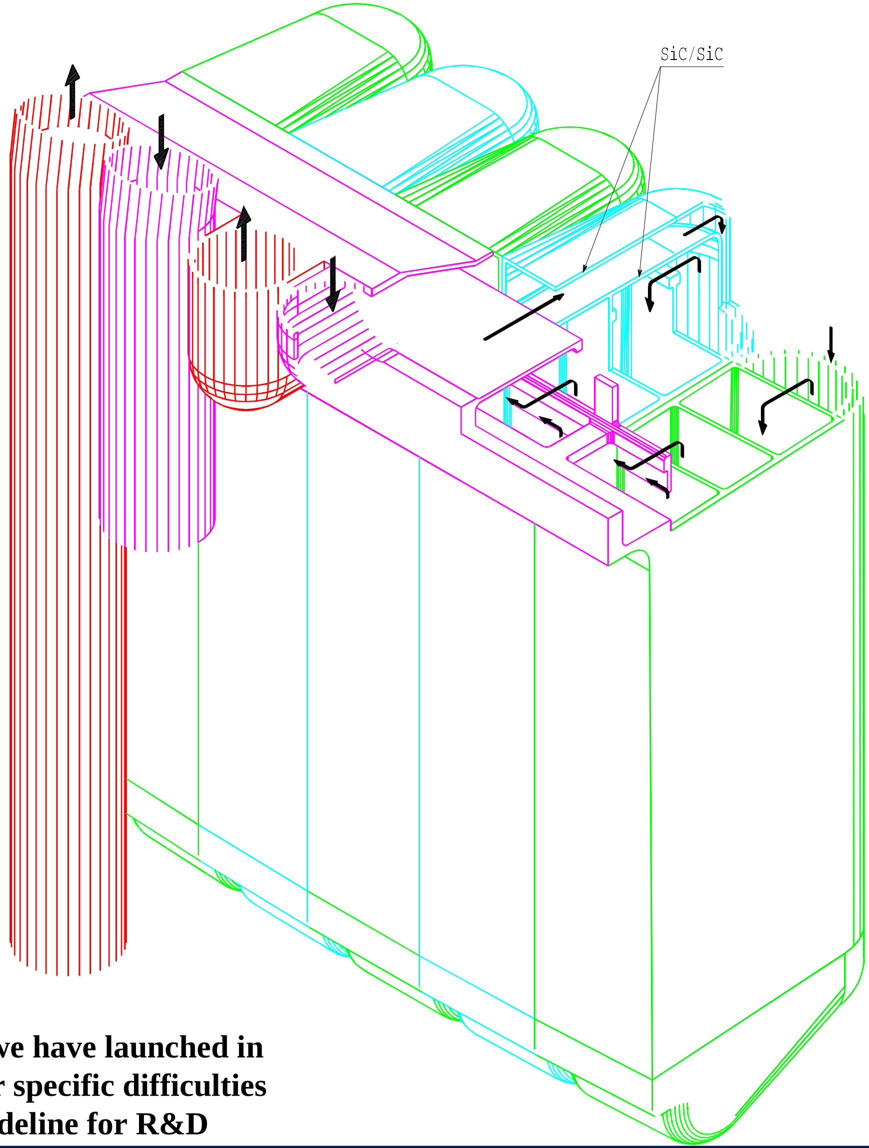
Main advantages of SiC_f/SiC

- Low radioactive inventory after shutdown
  - minimizes radioactive wastes, simplifies maintenance schemes
- Low after (decay) heat
  - potentially no emergency cooling requirements
- Low reactivity (water, air), excellent chemical stability
  - the use of high temperature coolants
  - (high thermal efficiency)
- Electric insulation

Main required improvements of SiC_f/SiC

- Thermal conductivity ⟷ Electric insulation
- Radiation resistance of physical and mechanical properties
- Compatibility in flowing Pb-17Li at high temperature

Structure self cooled Pb-17Li blanket



- **The design studies that we have launched in Europe allow to discover specific difficulties and to suply a useful guideline for R&D**

SiC_f/SiC characteristics assumed in calculations Cerasep® N3-1

Property	T (°C)	Measured Value (SEP data)	Value assumed for the analyses
Density	20	>2.4 g/cm^3	2.5 g/cm^3
Porosity	20	(10±2)%	10%
Fiber Content	20	40%	40 %
Thickness	-	0.8 - 6 mm	6 - 10 mm
Tensile Stress (in plane)	20	(300±20) MPa	-
Tensile Strain	20	(0.80±0.25)%	-
Trans-Laminar Shear Stress	20	(200±20) MPa	-
Inter-Laminar Shear Stress	20	44 MPa	44 MPa
Young's modulus (in plane)	20	(200±20) GPa	200 Gpa
Young's modulus (through the thickness)	20	-	200 GPa [1]
Shear modulus (in plane)	20	-	80 GPa [#]
Shear modulus (through the thickness)	20	-	50 GPa [#]
Poisson's ratio (in plane)	20	-	0.18 [#]
Poisson's ratio (through the thickness)	20	-	0.18 [#1]
Thermal Conductivity (in plane)	1000	15 W/m*K	15 W/m*K
Thermal Conductivity (through the thickness)	20 800 1000	(13±2) W/m*K 7.6 W/m*K 7.5 W/m*K	15 W/m*K 15 W/m*K 15 W/m*K
Thermal expansion coefficient (in plane)	20	$4*10^{-6}$ /K	$4*10^{-6}$ /K
Thermal expansion coefficient (through the thickness)	20	-	$2.5*10^{-6}$ /K [#]

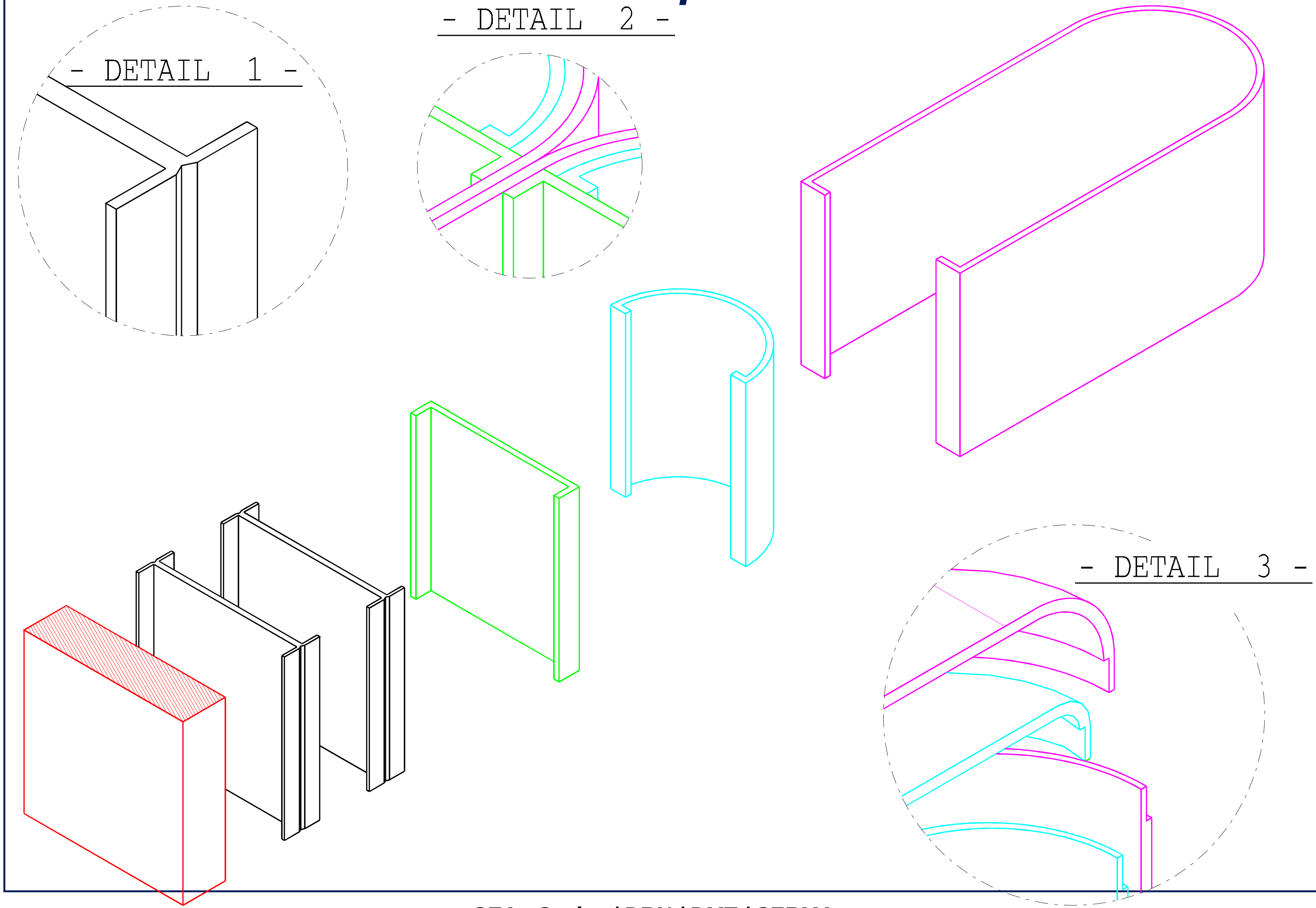
[1] value not available, the same value have been assumed through the thickness and in plane.
[#] corresponding value for the 2D composite.

- Tauro manufacturing based on the use of the recently developed Cerasep® N3-1.

    •Its 3D GUIPEX® texture avoids delamination problems
    •higher resistance to inter-laminar shear stresses (44 MPa instead of 30 MPa)

- Thermal conductivity
- Properties changes due to neutron irradiation

TAURO Basic Components Breakdown



Task : TAURO SiC/SiC blanket

CEA - Saclay / DRN / DMT / SERMA

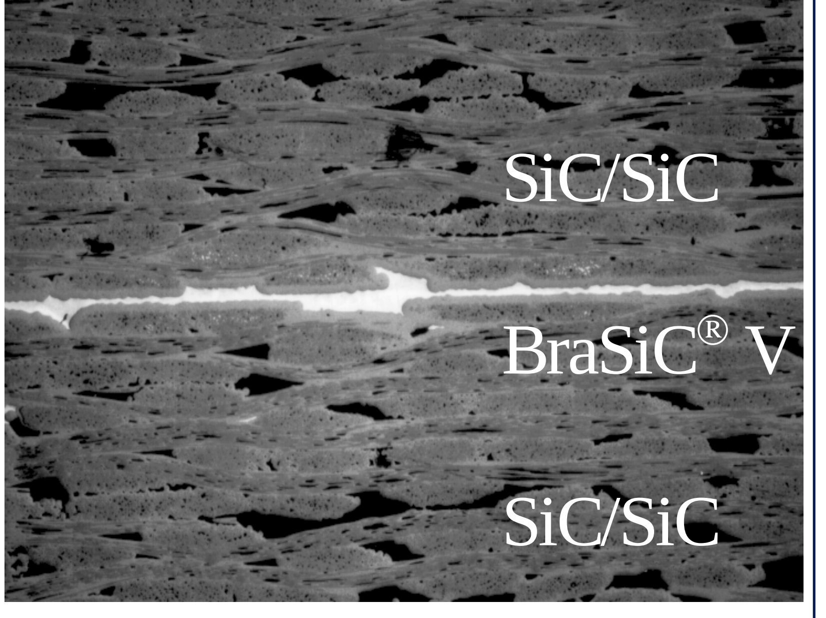
Brazing development - achievements

- ✓ **Main advantages :** high temperature resistance, LAM, no reaction to SiC/SiC, good wetting, strong bond to the substrate

- ✓ **Feasibility** of the brazing of SiC/SiC composites using the BraSiC® process has been positively assessed.

- ✓ **Process conditions** : BraSiC® H, RE and V grades are suitable atmosphere (high vacuum or inert argon), brazing range (1200-1400 °C).

- ✓ **Results** : good control of infiltration with porous composites, mechanical shear strength as high as 80-100 MPa up to 800°C, good chemical compatibility with Pb-17li at 300°C.



Resistance and Design Criteria

CMCs present different strengths depending on the loading direction.
Also tensile and compression strengths strongly differ.

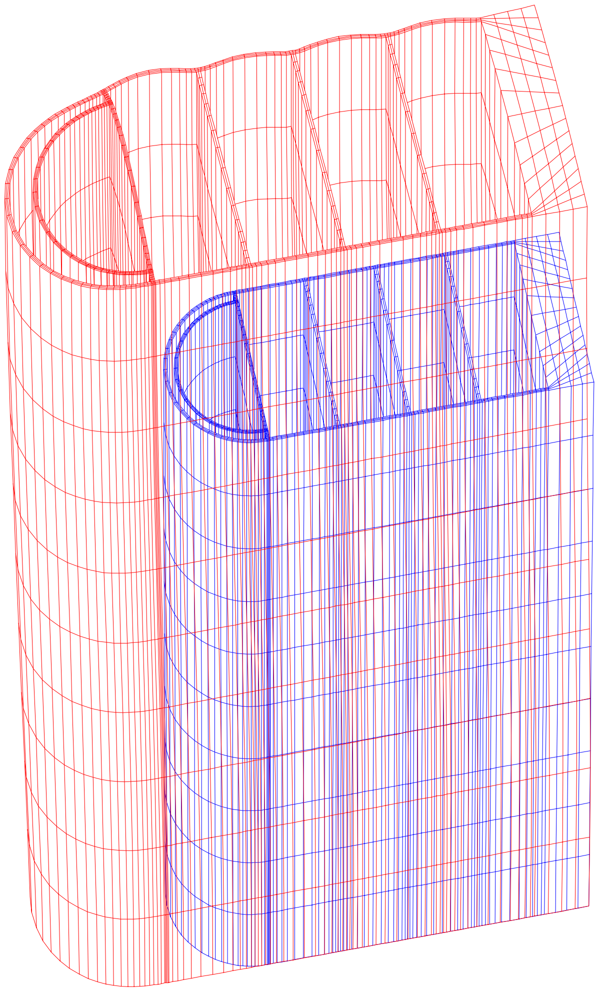
Current criteria have been inferred on the basis of the mechanical behavior of the 3D composite Cerasep® N3-1: *linear* elastic behavior extends up to 110 MPa (beginning of matrix microcraking); mechanical behavior remains elastic up to 145 MPa (opening of microcracks).

- SiC_f/SiC maximum operating temperature:
  - Limit: 1100°C (1300°C expected)
- Stresses in plane evaluated using the Von Mises criterion:
  - Limit: 145 MPa for tensile stresses (correspondingly roughly to the beginning of microcracks opening, elastic limit is 110 MPa)
    580 MPa for compressive stresses (rupture limit - CERASEP N2-1).
- Stresses through the thickness have been separately investigated:
  - Normal stress limit: 110 MPa for tensile stresses (no data available).
    420 MPa for compressive stresses (rupt. -CERASEP N2-1)
  - Shear stress limit: 44 MPa
- High efficiency coolant cycle (>43%) ➡ High temperature coolant ($T_{in/out}$=450/860°C)
- Advanced properties (not available at present):
  - Thermal conductivity through thickness: 15 $W.m^{-1}.K^{-1}$

Deformation of the sub-module

Case: Pb-17Li=1.5MPa, V_o=1.3m/s, T_{in}=650°C

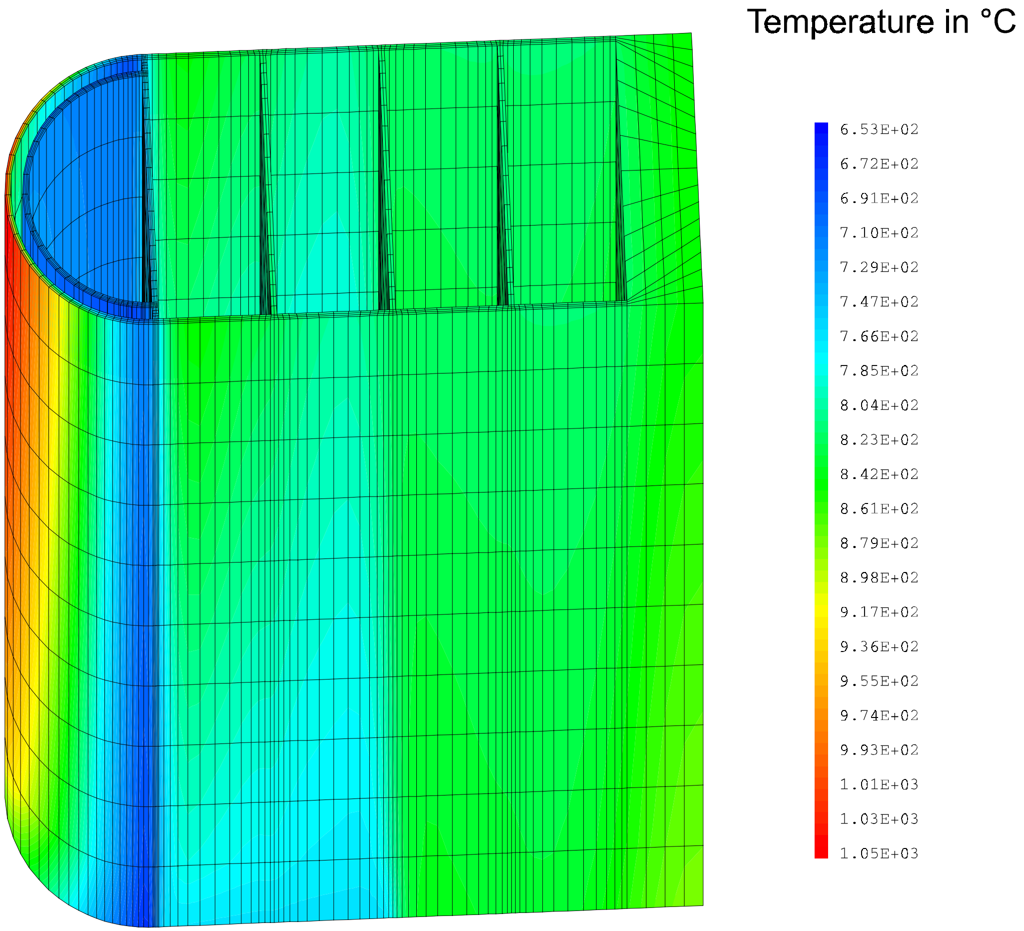
thk_{fwsw}=6mm, wdth=30cm, H_{mod}=2m



Temperature distribution in the sub-module

Case: Pb-17Li=1.5MPa, V_o=1.3m/s, T_{in}=650°C

thk_{fwsw}=6mm, wdth=30cm, H_{mod}=2m



Maximum Temperature SiC_f/SiC= 1052°C , $T_{in/out}$= 650 °C/840 °C

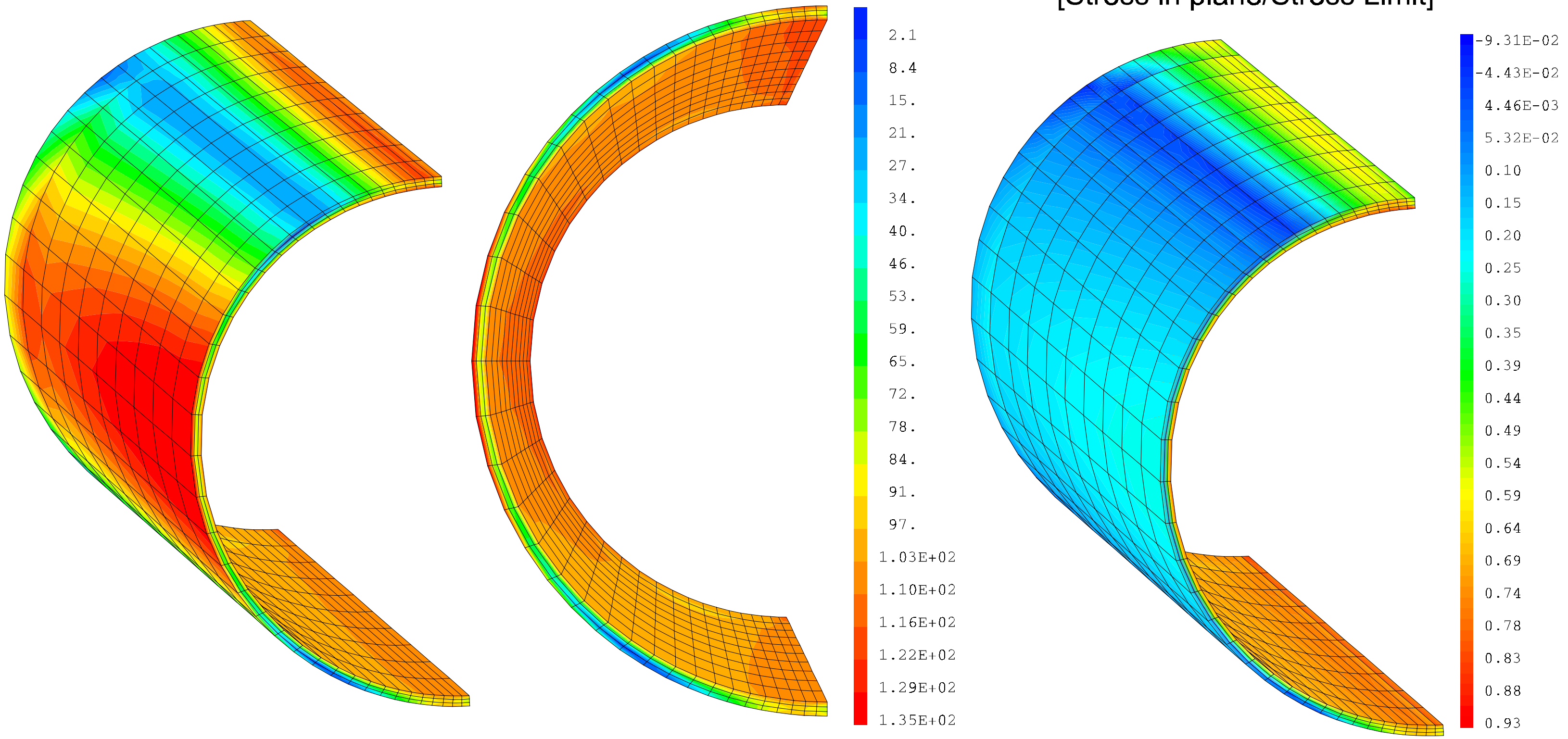
Von Mises stress in plane in the First Wall

Case: Pb-17Li=1.5MPa, V_o=1.3m/s, T_{in}=650°C
thk_{fwsw}=6mm, wdth=30cm, H_{mod}=2m

Von Mises Stress in plane

Stress in MPa

Factor of Stress :
[Stress in plane/Stress Limit]



Max. tensile stress = 123 MPa
Max. compressive stress = 149 MPa

Tensile stress limit in plane = 145 MPa
Compressive stress limit in plane=580 MPa

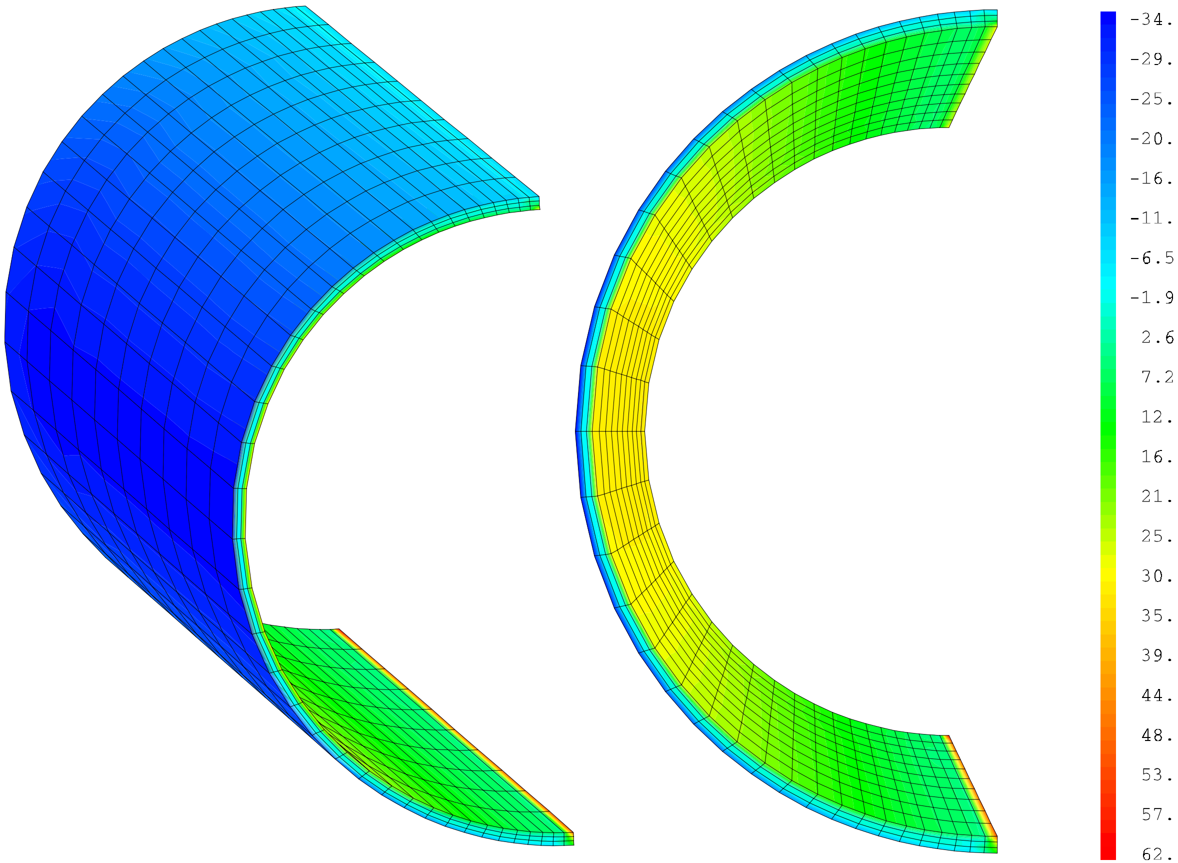
Normal stress through the thickness in the First Wall

Case: Pb-17Li=1.5MPa, V_o=1.3m/s, T_{in}=650°C

thk_{fwsw}=6mm, wdth=30cm, H_{mod}=2m

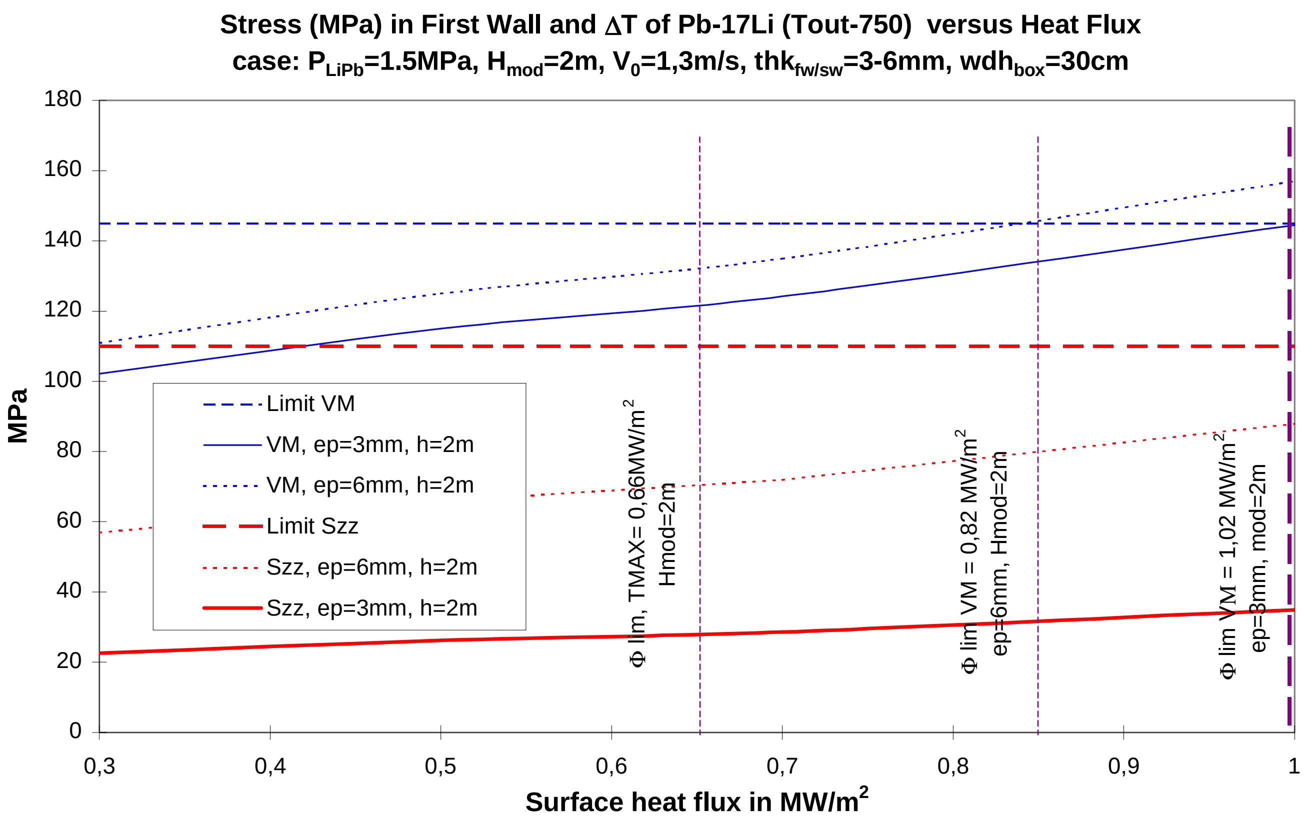
Normal stress through the thickness

Stress in MPa

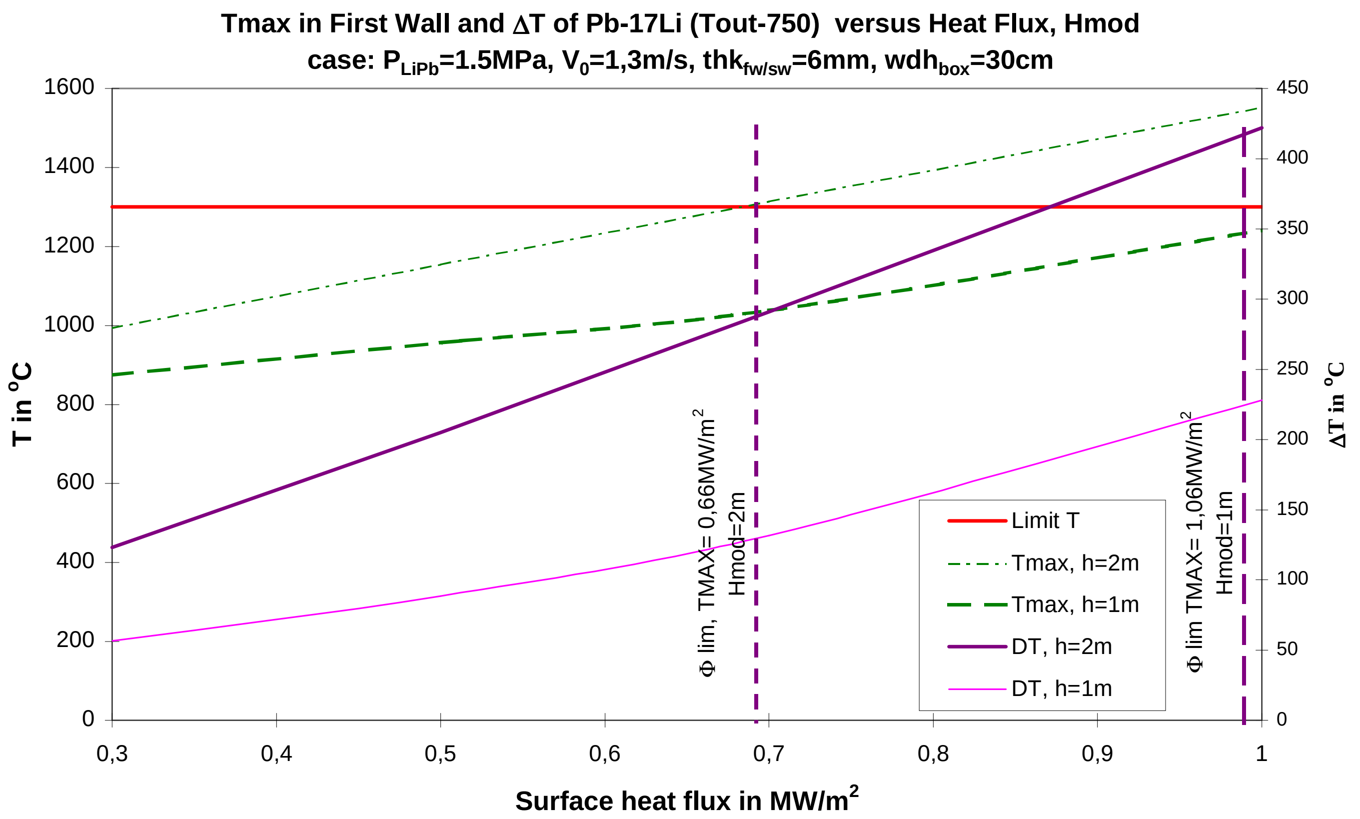


Max. stress = 62 MPa

Impact of the Surface heat flux on the stresses in FW



Impact of the Surface heat flux on the Max. Temp. in FW



Case: Pb-17Li=1.5MPa, Vo=1.3m/s, Tin=750°C		Hmod=2m	Hmod=2m	Hmod=1m	Hmod=1m
		ep=6mm	ep=3mm	ep=6mm	ep=1mm
Surface Heat Flux->VM	MW/m²	0,82	1,02	0,91	1,01
Surface Heat Flux->Tmax	MW/m²	0,66	0,91	0,78	1
Neutron Wall Load	**MW/m²**	**3,9**	**5,4**	**4,6**	**5,9**

Main results

- The limits of this concept are mainly due to the stress in FW
  - the first stiffener and the box are able to withstand the Pb-17Li hydrostatic pressure
- In order to decrease the stress,

  ΔT could be reduced

  - by reducing the height of the module that decreases ΔT between the top and the bottom on FW
  - by increasing the velocity in order to reduce the Radial and Poloidal ΔT
  - by reducing the box width

  Hydrostatic pressure of Pb-17Li must be reduced:

  - by optimizing the pipe work routing
- Case retained: Heat Flux= 0.5 MW/m^2, T_{in}= 450^{o}C, T_{out}= 860^{o}C, Hmod = 2m
  - 2x2 modules in series
- The surface heat flux limit is >0.66 MW/m^2. Investigations with the new criteria are expected to allow higher surface heat flux limits.
- TAURO-II: A solution foresees to change the Pb-17Li flow from poloidal direction to radial direction which would cover better the plasma shape, to minimize the level of stresses and to obtain higher outlet temperature.

Conclusions: TAURO blanket

- The TAURO blanket concept, because of the very low energy inventory, has in principle a great interest from the safety point of view (passive safety)

- The performances of the TAURO blanket are acceptable and significant improvements of the present-day composites are achieved. In the case of TAURO blanket, major requirements are larger thermal conductivity and improved radiation stability. The TAURO blanket offers a high capacity for heat extraction at high coolant temperatures and promises favorable conversion efficiencies. Performed thermo-mechanical analyses have shown that a surface heat flux between 0.7 to 1 MW/m^2 for the blanket could be envisaged. A surface heat flux of 0.85 MW/m^2 could be a compromise.

It is expected the need of a significant R&D effort to overcome the present shortcomings.

Conclusions: SiC/SiC Material

- The use of SiC_f/SiC matrix as structural material is promising for fusion reactor

- The advantage of SiC_f/SiC in terms of safety comes from low activation and afterheat-level

- The use of SiC_f/SiC is envisaged for the power reactor in the near future (50 years); this period could be required for the following progress:

  -improvement of the thermal conductivity through the thickness (at least by a factor of 2-3);

  -improvement of the composite's resistance to neutron irradiation;

  -assessment of the compatibility issues between flowing Pb-17Li and SiC_f/SiC (including the brazing material);

  -a better characterization of the material's properties under irradiated and unirradiated conditions: identification of parameters and validation of thermo-mechanical model

- In this respect, *the production of small mock-up* aimed at reproducing the main features of the blanket design will be necessary: validation of the models used, establishment of design criteria.