SiC_f/SiC Composites for Structural Applications in Fusion Power Reactors: the TAURO Blanket

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SUMMARY: The use of a Low-Activation Ceramic-Matrix Composites as structural material for in-vessel components appears essential to achieve high safety standards in future Fusion Power Reactors (FPRs). Previous studies have identified SiC_f/SiC composites as the most attractive structural material for fusion applications because of minimal neutron activation combined with excellent mechanical properties at high temperatures. This papers presents the results of the latest design analysis of the TAURO blanket, a self-cooled blanket using Pb-17Li as coolant/breeder and SiC_f/SiC composites as structural material. At the same time, further R&D efforts are needed in order to improve the present material properties as well as to better define available joining techniques and design methodology. New materials, that appear very promising for fusion applications, are currently being developed.

KEYWORDS: SiC_f/SiC, ceramic, applications, fusion, TAURO blanket,structural materials, design methodology, FEM.

INTRODUCTION

Fusion energy is a non fossil energy source with the potential advantage over fossil and fission power of minimizing both the consequences of severe accidents and the radioactive waste burden. The development of fusion technology is a long term objective of the international community. Presently, fusion power reactors are still at the stage of conceptual design and the tokamak concept, based on the magnetic confinement of a deuterium-tritium (D-T) plasma, is the most studied one. Present experimental devices (i.e. JET in the UK or Tore Supra in France) have not reached ignition, the condition to actually produce energy. The foreseen R&D strategy includes the sequential construction of a tokamak able to demonstrate plasma ignition, then the construction of a demonstration reactor which should prove the possibility of producing significant electricity, and finally the construction of the first commercial Fusion Power Reactors (FPRs), which is expected after the year 2050.

In D-T fusion reactors the ashes of the D-T thermonuclear reactions are non radioactive. The only radioactive wastes come from the neutron-induced activation of the materials surrounding the plasma. Previous studies [1,2] have identified the SiC_f/SiC composite as the most attractive structural material for fusion applications because of minimal neutron activation and high chemical stability combined with excellent mechanical properties at high temperatures. Furthermore, the high temperature resistance improves energy handling capabilities, allowing the use of high temperature coolant with the potential of having energy conversion systems with thermal efficiency greater than 50%. In addition, the low afterheat of the material reduces the emergency cooling requirements in case of a loss of coolant accident.

Although SiC_f/SiC composites are now widely used in the aerospace industry, they are relatively new materials for FPR applications and further R&D efforts are required to optimize their properties for fusion energy systems. Some of these developments include their thermal conductivity, chemical compatibility and radiation stability, as well as the definition of appropriate joining methodologies and design criteria for FPR structural components.

THE TAURO BLANKET

SiC_f/SiC composites are more specifically envisaged to use as structural material for the blanket components. The blanket is the first structure surrounding the plasma, the most critical part in a tokamak reactor because it is exposed to both high thermal and neutron fluxes.

Functions of the blanket

In a tokamak reactor the blanket has to accomplish several functions. The first one is to collect the energy produced within the plasma into a coolant which is after sent to external heat exchangers to generate electricity. Then, it has to regenerate the tritium used by fusion reaction, as tritium does not occur in nature. This can be accomplished by means of nuclear reactions between the plasma-emitted neutrons and lithium atoms (breeding reactions). The blanket will therefore contain lithium. At the same time, the blanket has to shield the super-conducting magnets (whose temperature must be kept at few K) from the energetic plasma-emitted neutrons. It must then be capable to withstand extremely high neutron and thermal fluxes together with the primary mechanical loads.

Objectives

Two strategies can be envisaged for reaching good reactor safety standards in FPRs, one based on the minimization of the activation inventory and the other based on the minimization of the available energy [3]. The first one would allow any reasonable amount of accidental release without needing public evacuation (intrinsic safety). This requirement leads to severe compositional restrictions for the materials present in the blanket; for instance, together with pure SiC_f/SiC as structural material, the ideal choices from the safety point of view are the use of high-pressure helium as coolant and lithium oxide as tritium breeder. This is the solution proposed in the ARIES-I [4] and DREAM [5] studies.

The second strategy corresponds to the minimization of the energy available within the reactor for breaking the confinement building, so that significant accidental releases are not possible (passive safety). This requirement leads to the use of low pressure fluids with low after heat levels. Possible coolant choices are therefore limited to liquid metals. In particular, because of its low chemical reactivity with air, the eutectic Pb-17Li appears to be the best candidate, as proposed in the TAURO [6] breeding blanket design.

On the other hand, this strategy would permit comparatively higher impurity levels in the SiC_f/SiC structural material, which, for instance, would open a broader material choice for improving the composite's characteristics and joining process.

Blanket design and manufacturing sequence

Looking for a passively safe reactor, the TAURO blanket has been developed by CEA in collaboration with other European laboratories and with the support of SEP, division of

SNECMA, as SiC_f/SiC manufacturing industry. It is a self cooled liquid metal breeder blanket using SiC_f/SiC as structural material and Pb-17Li as coolant and breeder. The main goals of the TAURO blanket study are: i) to find an alternative to other existing blanket designs using Helium as coolant which present severe shortcomings; ii) to determine the main material issues concerning this type of blankets; iii) to evaluate the limits for fusion application of existing industrial SiC_f/SiC composites in order to give guidelines for further R&D.

The blanket design is based on the FPR specifications defined by the SEAFP study [7]. The fusion power of 3000 MW leads to an average neutron wall load of 2 MWm^{-2} and a peak surface heat load on the First Wall of 0.5 MWm^{-2}. The reactor has 16 toroidal field coils, 48 outboard and 32 inboard segments. Each segment is divided in the poloidal direction in four straight 2.5 m-high modules (Fig. 1), attached on a common backplate. In order to increase its exit temperature, the coolant flows through two modules before exiting the blanket. One module is further divided in the toroidal direction in five sub-modules essentially formed by a SiC_f/SiC box which acts as a container for the Pb-17Li. Toroidal plates (stiffeners) are required for reinforcing the sub-module box in order to enable it to withstand the Pb-17Li hydrostatic pressure and to serve as flow separators.

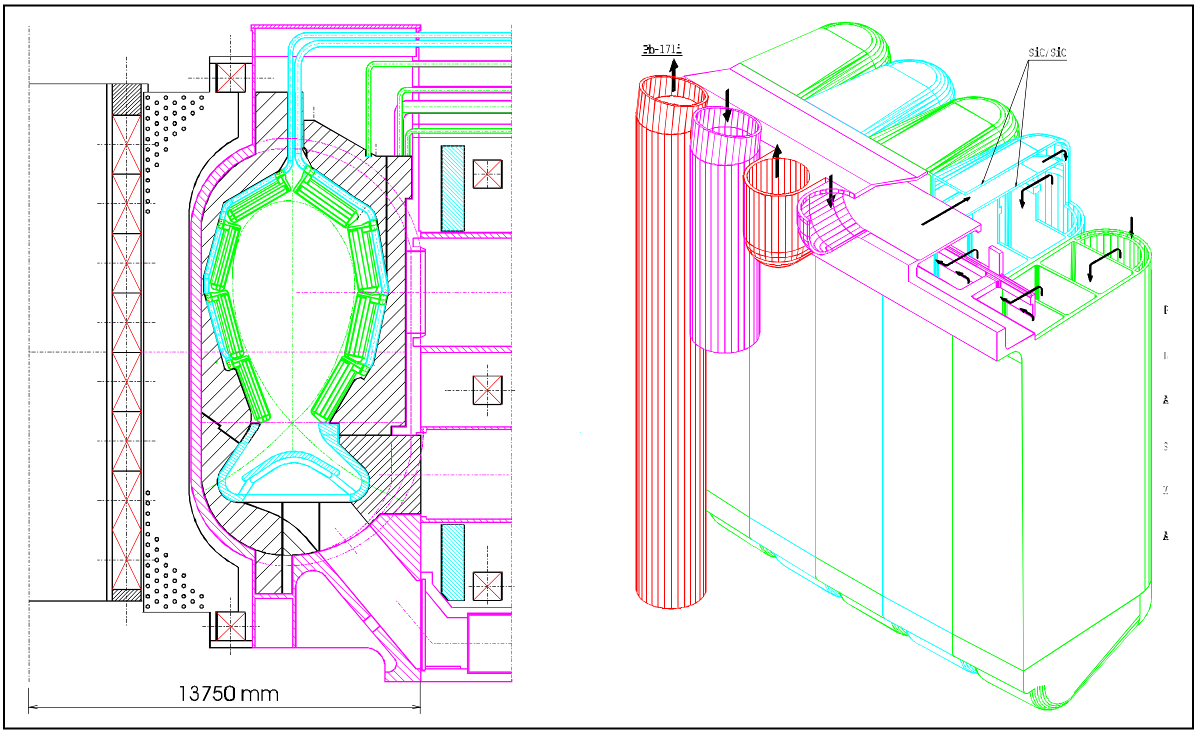

Fig. 1: Vertical section of the TAURO blanket and 3D view of a module.

The design and the preliminary manufacturing sequence (Fig. 2) are based on the use of a 3D SiC_f/SiC composite, the Cerasep® N3-1 produced by SEP [8] by Chemical Vapor Infiltration (CVI). Envisaged joining techniques (i.e., assembling during manufacturing at a textile or intermediate densification stage and/or brazing between finished components) require, in order to be efficient, a relatively large-surface support. Therefore all the components to be joined are manufactured with a T-shape or an L-shape surface at the end.

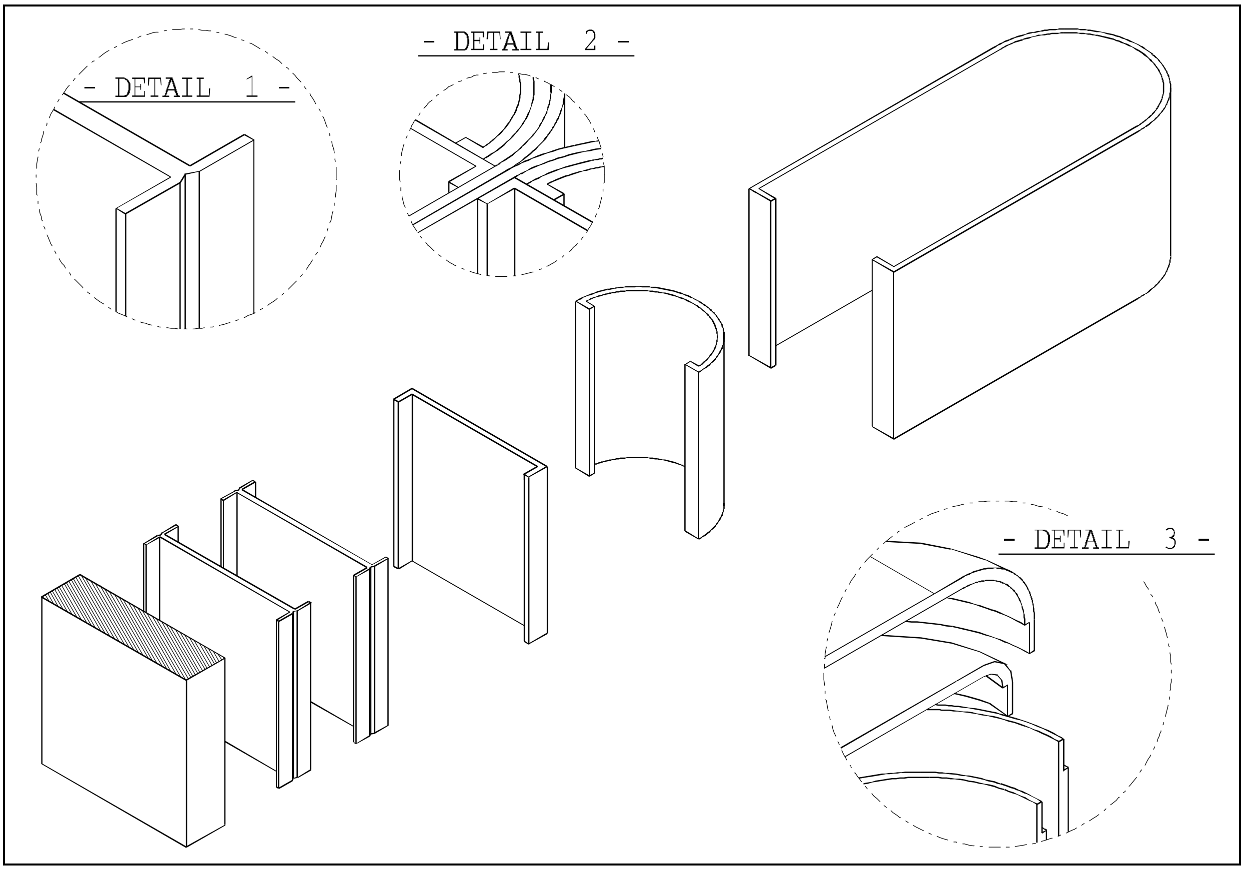

Fig 2: Manufacturing sequence of a sub-module.

ANALYSES: MODELS AND RESULTS

Different type of analyses (thermo-mechanical, thermo-hydraulic, neutronic) take part in the final design of a FPR component, in particular the blanket. Several iterations are often necessary to find the best overall solution that satisfies all the blanket requirements. A first set of analyses allowed for a global definition of the TAURO design and a first estimation of the main design issues [9]. A second set, in which the adopted calculation methods and design criteria have been improved, has recently been completed. Results are given in this section, with particular reference to the thermo-mechanical analyses. All the analyses have been carried out for an outboard lateral sub-module, where the thermo-mechanical loads lead to the highest stresses.

Adopted Modeling and Design Criteria

All the calculations have been performed with the CEA finite element code CASTEM 2000 using an orthotropic monolayer model for the SiC_f/SiC composite. The properties used in the analyses are reported in Table 1. When not available for the 3D composite the value of the correponding properties of the 2D composite Cerasep® N2-1 have been used. A fully 3D massive elements modeling has finally been adopted in order to obtain the detailed 3D stress distribution in the structure (Fig. 3). The mechanical behavior of the composite has been assumed as linear and elastic, i.e. no modeling of the damage mechanism has been made. This hypothesis is valid as long as the stress levels do not exceed the matrix microcrack treshold. For the previous 2D composite Cerasep® N2-1 the measured threshold value was approx. 110 MPa [10] in the case of tensile loading in the plane of the composite.

The mechanical behavior remains elastic, although no more linear, up to approx. 145 MPa. No data are currently available for the Cerasep® N3-1. Also, no data on the stress-strain relation through the thickness are available neither for the 2D nor for the 3D composite.

Table 1: SiC_f/SiC properties.

Property	**T (°C)**	**Measured Value (SEP data)**	**Assumed Value**
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.*

On the basis of the above considerations, the following resistance criteria have been adopted: starting from the 3D stress tensor, components in plane and through the thickness have been separately investigated. Components in plane have been combined to express the Von Mises stress. Stress levels up to 145 MPa have been considered acceptable, taking into account that they should decrease when the non linear behavior of the composite will be taken into account. For the shear stress through the thickness the limit of 44 MPa, corresponding to the inter-laminar shear stress (rupture limit - SEP data), has been assumed. For tensile stress through the thickness a limit of 110 MPa has been assumed.

Further improvements in the design criteria are still needed. A behavioral model capable to simulate the non linear stress strain relation and to predict the damage status of the composite is required. Also it must be noticed that the current resistance criterion does not distinguish between compressive and tensile stresses.

The maximum allowable operating temperature has been assumed to be 1100°C, mainly because of the maximum acceptable temperature for the industrial fibers presently used in SiC_f/SiC without degradation of their mechanical properties. More advanced composite could allow for higher temperatures.

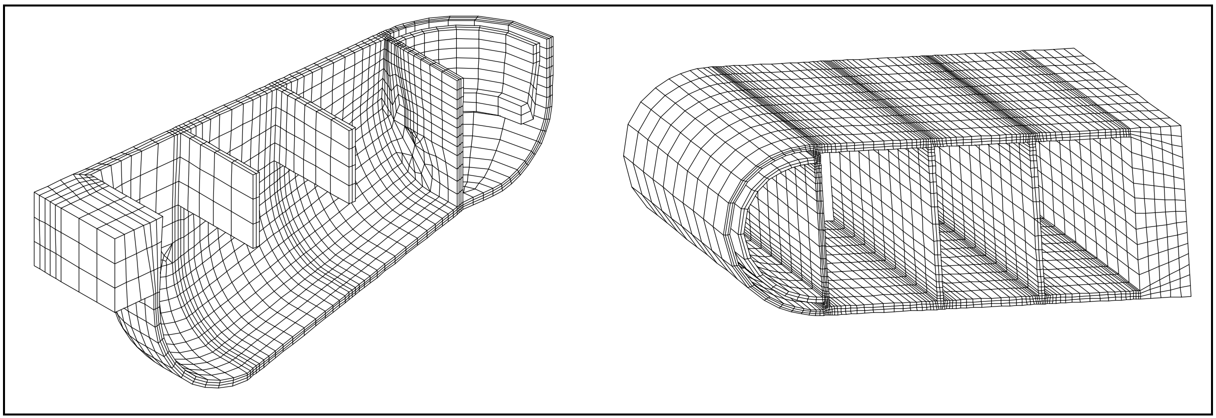

Fig. 3 : FEM models used in the analyses.

Mechanical Analysis

Mechanical loads are essentially due to the Pb-17Li hydrostatic pressure (max. estimated 1.5 MPa). Preliminary analyses [11] showed that in order to resist the mechanical loads, the minimum allowable thickness of the side walls was 10 mm. The maximum composite thickness that can be achieved with present state-of-the-art manufacturing techniques is instead 6 mm. Recent analyses showed that, by increasing the number of stiffeners, stress levels become acceptable: with four stiffeners: the Von Mises stress in plane do not exceed 110 MPa and the stresses through the thickness are well below the assumed limits.

Thermal Analysis

Thermal analyses are performed on a 2D massive elements model of the structure. A transient time depending calculation is necessary to simulate the Pb-17Li flow. The temperature distribution is obtained for each of the Pb-17Li flow channels, then the thermal flux between the adjacent channels is imposed to find the global temperature distribution in the sub-module. Thermal loads come from the surface heat flux on the FW and from the volumetric heat sources due to plasma radiation. The latter are obtained by means of specific neutronic analyses. The maximum temperature is located at the bottom of the FW and is about 880°C. The estimated mean Pb-17Li temperature at the module's exit is about 660°C. These temperatures ensure enough margin against the maximum allowable operating temperature and at the same time a high thermal efficiency can be expected.

Thermo-Mechanical Analysis

Stresses due to thermal loads are one of the main issue for the TAURO blanket, mainly because of the low thermal conductivity through the thickness of the SiC_f/SiC composite. The most critical part of the structure is the FW because of the high thermal loads to which it is exposed. As it can be seen from Table 1, the present analyses already account for an improvement of the thermal conductivity through the thickness of about a factor of two. With this assumption, the maximum estimated value of the Von Mises stress in plane in the FW is about 140 MPa while the tensile and shear stresses through the thickness are about 130 MPa (above the assumed limit of 110 MPa) and 20 MPa respectively.

Also, a strong influence of the fibers' orientation on the stress distribution in the structure has been observed. Assuming a fiber inclination in the plane of the composite of 45° the new estimated value of the Von Mises stress in the FW is considerably lower (about 100 MPa). The tensile stress through the thickness decrease (max. value 120 MPa), while the shear stress raises (max. value 30 MPa).

SiC_f /SiC COMPOSITES FOR FUSION APPLICATIONS: R&D ISSUES

Ceramic matrix composites are being developed for high temperature utilization in aerospace and non fusion power generation industries. However there are a number of developments that will not be undertaken in the framework of these programs. The most important developments are radiation stability, chemical compatibility with fusion relevant environments and joining methodology.

Effects of Neutron Irradiation

Neutron irradiation negatively affects both physical and mechanical properties of SiC_f/SiC composites. Changes in the mechanical behavior are due to the simultaneous processes of matrix swelling and fiber shrinkage. With the increase of neutron doses the mechanical properties of the composite tend to that of monolithic SiC because the Nicalon fibers densify and loose contact with the matrix, while the matrix is highly microcracked. Consequences are the embrittlement of the composite and the loss of strength and toughness. Analogous deleterious effects can be observed on the composite's thermal conductivity, a key design parameter for the TAURO blanket. Because of neutron-induced defects in the atomic structure of the composite, the thermal conductivity of present days composites decreases by a factor of 3 after few months of operation.

Improvements are being made in fiber strengths and thermal stability under irradiation through production methods that result in fibers that are chemically and structurally similar to stochiometric SiC. Very promising results have been obtained using fibers with reduced oxygen content like the Hi-Nicalon fibers produced by Nippon Carbon [12].

Chemical Compatibility

Chemical compatibility with high T, high-velocity Pb-17Li has to be measured for a relevant time length. There are evidences that SiC_f/SiC composites are inert in stagnant Pb-17Li at high temperatures [1], but no data are available for current industrial composites at lower temperatures. The issue is also related to the SiC_f/SiC tightness towards Pb-17Li: a Pb-17Li slow penetration through the SiC_f/SiC thickness could have a significant impact on the composite's mechanical properties. Compatibility of Pb-17Li with the joining material (brazing) has also to be checked.

Joining methodology

Appropriate joining techniques need to be developed in order to assemble the basic parts of the blanket. At present the fabrication sequence foresees three different joining techniques:

- assembling by sewing at textile stage to join the stiffeners to the side walls;
- sticking and co-infiltration to join the second wall to the first stiffener;
- brazing of finished components to join the bottom and the top closure plates and the different sub modules.

The main difficult in brazing current SiC_f/SiC industrial composites is their high porosity (up to 15%). During joining with a common brazing technique, a large infiltration of the braze is observed in the composite body leading to an absence of braze inside the joint area. BraSiC® alloys recently developed by CEA have already shown very promising results [13,14].

SiC_f/SiC Composites Development

Two different SiC_f/SiC industrial composites are available from SEP at this time: the 2D Cerasep® N2-1 and the 3D Cerasep® N3-1. Both of them use the Nicalon NL207 fibers produced by Nippon Carbon and are densified by CVI [8].

The Cerasep® N2-1, developed in the eighties, is well known and characterized. Its main drawbacks are the delamination problems and the consequent difficulties to obtain the complex module shapes proposed for the TAURO blanket. In fact, the TAURO manufacturing sequence is based on the use of the recently developed Cerasep® N3-1. This new composite uses the same raw components of the previous 2D version, but its 3D GUIPEX® texture avoids delamination problems and confers it a higher resistance to inter-laminar shear stresses (44 MPa instead of 30 MPa).

The limits of this composite for FPR applications are mainly to find in its low thermal conductivity and resistance to irradiation damage. The use of low oxygen content fibers like the Hi-Nicalon fibers (Nippon Carbon) could solve those two problems. Actually the thermal conductivity of this new fiber is higher than the one of Nicalon NL207 (Table 2), and its properties changes due to neutron irradiation are lower [20]. Also the maximum operating temperature increases (1300°C instead of 1100°C). A new composite, the Cerasep® N4-1, which uses the Hi-Nicalon fibers is currently under development by SEP [13]. This new composite appears a significant improvements for FPR applications.

Table 2: Main properties of the SiC fibers produced by Nippon Carbon.

Property			**Nicalon NL207**	**Hi-Nicalon**
Chemical composition	wt-%	Si	56.6	62.4
		C	31.7	37.1
		O	11.7	0.5
Tensile strength	GPa	20°C	3	2.8
Young modulus	GPa	20°C	220	270
Strain	%	20°C	1.4	1.0
Thermal conductivity	W/mK	20°C	2.97	7.77
		500°C	2.20	10.1
Electrical resistivity	Ω·cm	20°C	10^3-10^4	1.4
Industrial level			standard product	standard product

CONCLUSIONS

The use of SiC_f/SiC composite as structural material for the blanket components could permit to achieve high safety standards in future fusion power reactors. The results of the analyses presented in this work confirm that the TAURO design has the potential of fulfilling all the blanket requirements.

At the same time, the necessity of further R&D on the SiC_f/SiC composites to be used for fusion applications has been pointed out. Appropriate design criteria need to be further developed in order to fully exploit the resistance limits of the material. Moreover, main R&D

requirements for current industrial SiC_f/SiC composites to be used in the TAURO blanket include: improvement of the thermal conductivity through the thickness (at least by a factor of 2), 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) and a better characterization of the material's properties under irradiated and unirradiated conditions.

REFERENCES

1. P. Fenici, H. W. Scholz, "Advanced low-activation materials. Fibre reinforced ceramic composites". *Journal of Nuclear Materials*, 212-215 (1994)

2. S. Sharafat, R.H. Jones, A. Kohyama, P. Fenici, "Status and prospects for SiC-SiC composite materials development for fusion applications", *Fus. Eng. & Des.* 29 (1995)

3. L. Giancarli, G. Aiello, A. Caso, A. Gasse, G. Le Marois, Y. Poitevin, J. F. Salavy, J. Szczepanski, "R&D issues for SiCf/SiC Composites Structural Material in Fusion Power Reactor Blankets", IAEA - TC Meeting on FPPD, Culham 24-27 March 1998, (to be published on Fus. Eng. & Des.).

4. S. Sharafat, F. Najmabadi, C.P.C. Wong and the ARIES Team, "ARIES-I Fusion-Power—Core Engineering", *Fus. Eng. & Des.* 18 (1991).

5. S. Nishio et al., "Improved tokamak concept focusing on easy maintenance", *Fus. Eng. & Des.* 41 (1998)

6. L. Giancarli, J. P. Bonal, A. Caso, G. Le Marois, N. B. Morley, J.F. Salavy, "Design requirements for SiC/SiC Composite structural material in Fusion Power Reactor Blankets", *Fus. Eng. & Des.* 41 (1998)

7. J. Reader, I. Cook, et al., "Safety and Environmental Assessment of Fusion Power - Report of the SEAFP Project", *Report EURFUBRU XII-217/95* (June 1995)

8. Caso A. et al., "A New SiCf/SiC Composite as Low-activation Structural Material", *Proc. of the SiC_f/SiC composites Workshop*, JRC/ISPRA (I), 28-29 October 1996.

9. L. Giancarli, J. P. Bonal, A. Caso, G. Le Marios, N. B. Morley, J. F. Salavy, "Design requirements for SiC/SiC composite structural material in Fusion Power Reactor Blankets", *Fus. Eng. & Des.* 41 (1998)

10. X. Aubard, J. Lamon, O. Allix, "Model of the Nonlinear Mechanical Behavior of 2D SiC-SiC Chemical Vapor Infiltration Composites", *J. Am. Ceram. Soc.* 77 [8] 2118-26 (1994).

11. G. Aiello, L. Giancarli, Y. Poitevin, J-F. Salavy, J. Szczepanski, "A new approach for evaluating stress levels in the TAURO SiC_f /SiC breeding blanket", *CEA Internal Report*, DMT/SERMA/LCA/RT/98-2351.

12. R.H. Jones, L.L. Snead, A. Kohyama, P. Fenici, "Recent advances in the development of SiC/SiC as a fusion structural material", *Fus. Eng. & Des.* 41 (1998).

13. G. Aiello, A. Caso, L. Giancarli, Y. Poitevin, J. F. Salavy, J. Szczepanski, “SiC_f/SiC ceramic composite as structural material for fusion power reactor in-vessel components”, *Comptes rendus des onzièmes Journées Nationales sur les Composites (JNC-11),* Volume I

14. A. Gasse, G. Aiello, L. Giancarli, G. Le Marois, J. F. Salavy, J. Szczepanski, “Progress on SiCf/SiC structures joining techniques and modelling for design analyses”, *Fusion Technology 1998, Proceedings of the 20th Symposium On Fusion Technology (SOFT)*, 7-11 September 1998, Marseille, France. Volume 2.