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Low-Activation structural ceramic composites for fusion power reactors: materials development & main design issues

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This paper is devoted to the development of advanced Low-Activation Materials (LAMs) with favourable short-term activation characteristics for the use as structural materials in a fusion power reactor (in order to reduce the risk associated with a major accident, in particular those related with radio-isotopes release in the environment), and to try to approach the concept of an inherently safe reactor. LA Ceramics Composites (LACCs) are the most promising LAMs because of their relatively good thermo-mechanical properties. At present, SiC/SiC composite is the only LACC considered by the fusion community, and therefore is the one having the most complete data base. The preliminary design of a breeding blanket using SiC/SiC as structural material indicated that significant improvement of its thermal conductivity is required.

1. INTRODUCTION

There are two ways for minimising the release of radioactive elements, and therefore the associated risks, in case of a major accident in a D-T Fusion Power Reactor (FPR). The first one is to minimise the total activation inventory present in the reactor, which requires the use of low short and medium-term activation materials for all reactor components and in particular for the breeding blanket. It is the solution adopted by the ARIES team with a reactor [1] whose breeding blanket uses SiC/SiC composite as structural material, a ceramic breeder (LiO_2, Li_2ZrO_3, etc.) and high-pressure Helium as coolant. The other way is to avoid the release of activated materials by minimising the energy potentially available in the vacuum vessel for breaking the confinement. In this case it is required all the activation confinement barriers remain unaltered for the worst possible accident and therefore the use of low pressure coolant and of materials with low chemical reactivity between themselves and with air. Moreover, because of the inevitable plasma erosion of the plasma facing components the later should be made by low activation materials. This solution has been adopted in a preliminary alternative concept for the ARIES blanket [2] and in the TAURO concept which is the object of the present paper. The TAURO concept is a conceptual design of a liquid metal self-cooled breeding blanket using SiC/SiC composite as structural material and Pb-17Li as coolant/breeder material. Because of the SiC/SiC is a good electrical insulator most of the problems related to MHD, typical of this type of blankets [3] are automatically avoided.

2. STRUCTURAL MATERIAL SELECTION

Non-metallic Low Activation Materials have the best performances in term of short-term (< 1 year) activation levels, which leads to a minimisation of the risks associated with accidental release to the environment and with maintenance operation, and to a very low afterheat production.. Among them the Ceramic Composites (CC) are the most promising ones because of their good thermomechanical properties [4]. After analysis of most LA elements and compounds suitable to be use in a FPR [5] the possible alternatives are the use of SiC based fibers (Nicalon or Tyranno) with a SiO_2 based matrix (high silica glasses with or without the addition of other minor elements) or the use of the composite formed by SiC-Nicalon fibers and β-SiC matrix. Major concerns are their behaviour under irradiation, tritium permeation and Pb-17Li compatibility [2].
Table 1

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Table 1
Characteristics of SEP SiC/SiC material, average value (1000°C) .[6]

Material Property	Value
Fiber content (%)	40
Specific gravity (kg m^{-3})	2500
Porosity (%)	10
Tensile strength (MPa)	285
Elongation (tensile) (%)	0.75
Young's modulus (tensile) (GPa)	200
Flexural strength (MPa)	400
Compressive strength (MPa)	
In Plane / Through the thickness	400/380
Shear strength (interlaminar) (MPa)	35
Thermal diffusivity (10^{-6} m^2 s^{-1})	
In Plane / Through the thickness	5/2
Thermal expansion coeff. (10^{-6} K^{-1})	
In Plane / Through the thickness	3/2.5
Fracture Toughness (MPa$\sqrt{m}$)	30
Specific heat (J kg^{-1} K^{-1})	1200
Poisson's ratio, taken from [1]	
ν_{12}/ν_{13}	0.05/0.18

Possible solutions envisaged for the future are the use of low-oxygen Nicalon [7] and Tyranno fibers [8] which shows better heat resistance properties but worse pyrolisis/swelling behaviour due to the higher carbon content.

For the present study it has been chosen the SiC-Nicalon/SiC-CVI composite [6] produced by the SEP (Société Européenne de Propulsion) as the CC candidate for the structural material of a FPR, because it possesses the most favourable properties and also the largest data base among the available CC materials. These properties are summarised in Table 1.

3. CONCEPT SELECTION

The preliminary blanket design has been performed using specifications defined for the SEAFP reactor [9] that is: 3 GW D-T fusion power reactor, major radius of 9.4 m, minor radius of 2.1 m, plasma current of 10.4 MA, toroidal field on axis of 7.8 T, 2 MW/m^2 neutron wall loading and 0.5 MW/m^2 peak FW surface heat load. The reactor has 16 coils with 48 outboard and 32 inboard submodules.

The TAURO blanket uses only two materials: SiC/SiC and Pb-17Li. Each outboard (and inboard) segment is toroidally divided in five containers with rounded FW (see Fig. 1). Each container is reinforced by four stiffeners some of them acting also as Pb-17Li separators. The Pb-17Li enters from the top in the front part of the segment, flows poloidally downward in a thin channel (1.25 cm thick) for FW cooling, then turns a first time at the bottom, comes up, then down, then up again in order to go out at the top of the rear part of the blanket. Because of the different channel cross sections, the Pb-17Li reduces its velocity from 1.6 m/s in the front channel to 0.06 m/s in the back channel.

4. OUTBOARD SEGMENT DESIGN

Because of the more severe operation conditions the design activities have been focused on an outboard segment. Each container is 10 m high, 0.3 m wide and 0.93 m deep. The coolant flowing route could be seen in the Figure 1 as well as the thicknesses and dimensions of the walls. The SiC/SiC CC structure will be assembled by isostatic pressure welding.

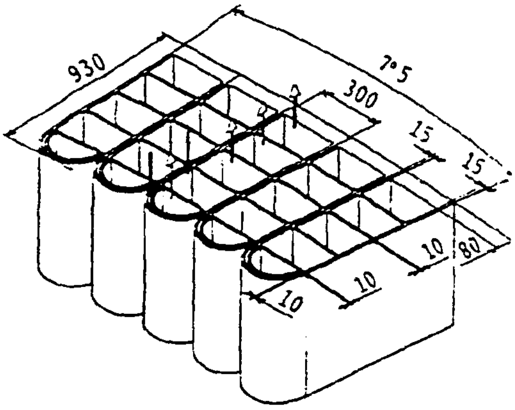

Figure 1. Outboard section of the TAURO concept (dimensions in mm)

4.1 Design criteria

Contrary to metallic structural materials for which well established design codes exist (ASME, RCCM-R), no design criteria are available for CC structure. For the present preliminary analysis the design criteria defined in the ARIES project [1] have been assumed.

In ARIES the maximum allowable primary stress has been taken as 140 MPa, following the mechanical properties code CLASS [10] and CC industry suggestions. Using the thermal shock resistance of SiC CC as a guideline, a highly conservative maximum-allowable secondary-stress limit of 190 MPa has been assumed. For the maximum allowable temperature in the composite a value from ARIES (1100 °C) is taken. This value has to be experimentally checked before it can really be accepted for a final design.

4.2. Mechanical stress calculations

In order to determine the upper limit of the stresses due to the Pb-17Li hydrostatic pressure, a pressure load of 1.5 MPa has been applied to the container cross section. Its geometrical distribution can be seen in Figure 2. The calculation has been performed with the finite-element codes CASTEM 2000 [11], using a 3-D geometry, square meshes and an orthotropic monolayer model of the SiC/SiC CC. The code is capable of dealing with anisotropic materials but property values in each direction are needed. These values are not always known so the results are only preliminary. This is also due to the fact that relevant uniaxial stress measures are not yet available for composites, so the von Mises stress is used to indicate equivalent stress levels [1].

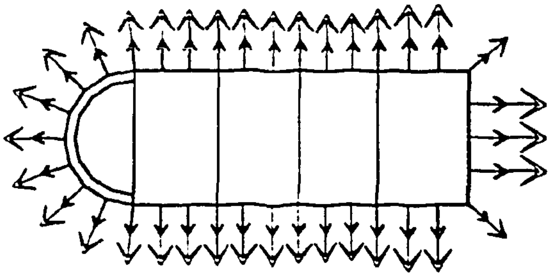

Figure 2. Pressure load of the structure

For the TAURO outboard segment the maximum pressure stress is 64 MPa, well below the maximum-allowable limit, and leading to a very small container deformation.

4.3. Neutronic calculations

As far as the TBR is concerned a 1-D comparative calculation with DEMO blankets [3] has indicated that the TAURO blanket can easily ensure the tritium breeding self-sufficiency. The radial heat deposition distribution in an outboard segment has also been determined and used as input for the thermal analysis. The nuclear heat density in the SiC/SiC FW is 11 W/cm^3, while the total heat deposited in an outboard segment has been estimated as 34 MW.

4.4. Thermal calculations

The heat deposited in the segment must be removed by the flowing Pb-17Li. The inlet coolant temperature has chosen as 275°C to keep a margin of 40°C with respect to the solidification temperature of Pb-17Li (235°C). The outlet temperature was fixed at 850°C, to keep enough margin against the maximum acceptable temperature for the SiC/SiC CC. This temperature is kept as high as possible in order to obtain maximise high thermal efficiency.

With these input data, the required Pb-17Li flow rate per container is 8.3 l/s. The temperature field in the segment has been obtained with the 2-D finite elements thermal code DELFINE [11]. The Pb-17Li flow (down and up, twice) has been modelled with iterative transient calculations.

The critical point is the FW, the most loaded part of the structure (volumic heat and surface heat flux), where are located both minimum and maximum temperature values (in the top and the bottom respectively). This is mainly due to the low thermal conductivity of the SiC/SiC CC, and also with differences following the fiber orientation. We have used an homogeneous weighted value of 15 W/mK, accounting for working temperature, fiber orientation and some irradiation effects. In the segment mid-plane the maximum reached temperature in the FW is 1005°C (526°C in the Pb-17Li) with an average of 748° (476°C). In the bottom plane the maximum temperature is 1178°C (704°C in the Pb-17Li) with and average of 897°C (622°C). In the back part of the outboard segment structure the maximum temperature is lower (~900°C) but with a higher average value (~800°C) due to the coolant outlet temperature of 850°C.

In order to know the effect of a larger thermal conductivity, we have also used a value of 20. and of 30 W/mK giving a maximum temperature in the bottom plane for the SiC/SiC CC of 1094 and 1004°C, respectively.

4.5. Thermo-mechanical analysis

To estimate the stresses due to the ΔT in the SiC/SiC wall thickness, we can use the simple isotropic formula $\sigma = E\alpha\ \Delta\ T/2(1-\nu)$ giving the result of 185 MPa just in the allowed limit.

The stresses produced in the structures by the temperature field have been estimated using the same CASTEM 2000 system. For this calculation a 3-D temperature field is needed. We extrapolated it from the 2-D distribution of the thermal calculation and its time evolution giving enough accuracy as a preliminary approach.

Using this 3-D temperature field the resulting thermal stresses show a distribution peaked in the lower part of the FW where the maximum temperature is reached. Such a value for thermal stress is 158 MPa, in all the remaining structure the thermal stresses are much lower.

The back part of the container in average is hotter: for this reason, there is a forward deformation (maximum Uz displacement: 27 mm, maximun Ux displacement: 28 mm), shown in Figure 3.

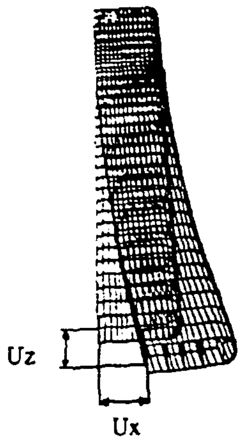

Figure 3 Thermal deformation of Outboard module

5. CONCLUSIONS

The design of a fiber reinforced structure is considerably more difficult than that of a metal structure, principally because of the anisotropy of its properties.

The preliminary analysis of the TAURO concept, where the FW is indirectly cooled by the bulk Pb-17Li, indicated that the thermal conductivity of SiC/SiC has to be improved in order to render the concept acceptable. Design alternatives could be for instance direct FW cooling by tubes, which has the drawback of more complicated manufacturing.

For both design and material development further work is still required in order to prove that CCs can be used as structural material of a FPR.

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