SiC/SiC Composite for an Advanced Fusion Power Plant Blanket

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Abstract- This paper describes the results of an exploratory study of blanket concepts based on SiC/SiC structure and LiPb breeder. An assessment of the performance of these concepts for advanced power plant application is presented, key issues are identified, and constraints relating to the SiC/SiC properties are discussed.

INTRODUCTION

The use of SiC/SiC composite as structural material in a fusion reactor is attractive based on its low induced radioactivity and afterheat. It has been considered several years ago in the ARIES-I[1] and ARIES-IV[2] power plant studies in the US and more recently in other international studies, such as the TAURO[3] blanket design study in France and the DREAM[4] reactor study in Japan. Several issues have been identified for the SiC/SiC material, including the cost of fabrication, the joining methods, and factors limiting the range of operation. Chief among these are the rather low thermal conductivity at high temperature and under irradiation, and the maximum allowable operating temperature.

Over the last years a certain level of R&D effort has helped address and better understand some of these issues. It seems appropriate at this stage to revisit the SiC/SiC structural option based on the latest R&D results and on reasonable future extrapolation to determine whether it can be used for an advanced blanket under higher power density and higher coolant temperature. The latter is particularly important since it dictates the thermal efficiency of the power conversion system which directly impacts the cost of electricity.

A liquid metal breeder provides the potential for developing a high performance, high temperature blanket system and is the breeding material of choice in this study. Two interesting candidates are LiPb and the recently proposed LiSn, both being significantly less reactive than pure Li. Both self-cooled and dual coolant options (with He as first wall coolant) are considered.

This paper describes the results of an exploratory study of blanket concepts based on SiC/SiC and the above liquid breeders. An assessment of the performance of these concepts for advanced power plant application is presented, key issues are identified, and constraints relating to the SiC/SiC properties are discussed. The major objective of the study is to determine the attractiveness of such a high performance blanket for an advanced fusion device and to choose the most promising concept for detailed design study as part of the ongoing ARIES-AT (Advanced Tokamak) power plant study.

SIC/SIC PARAMETERS

Some of the major parameters influencing the attractiveness of SiC/SiC as an in-vessel structural material

include: thermal conductivity; parameters limiting the temperature of operation, such as swelling under irradiation and compatibility with the liquid metal; maximum allowable stress limits; lifetime parameters; and fabrication and joining procedures.

Thermal Conductivity

The thermal conductivity of SiC/SiC decreases with temperature and irradiation. Its value depends on the fabrication procedure and on the fiber characteristics and would be limited by that of high-purity single crystal CVD(chemical vapor deposition) SiC (up to 490 W/m-K at room temperature but much lower at higher temperature) [5]. The ARIES-I study assumed an SiC/SiC in-plane thermal conductivity of 15 W/m-K and a transverse thermal conductivity of 12 W/m-K [1]. Comparable or lower conductivities have been observed with SiC/SiC based on cg-Nicalon fibers and Hi-Nicalon fibers[6]. More recently, SiC/SiC made from CVR (chemical vapor reaction of Si through a carbon fiber matrix) yielded a 75 W/m-K non-irradiated transverse thermal conductivity at RT and 30-35 W/m-K at 1000°C [7,8]. Since the relative effect of irradiation is much less pronounced at high temperature it is anticipated that the thermal conductivity at 1000°C will not be decreased below about 20-25 W/m-K. Current in-situ thermal conductivity measurements of irradiated SiC samples at ORNL would help confirm this estimate [9]. Based on this and taking into consideration foreseeable improvement in the quality of fiber, micro-configuration of SiC, and manufacturing technique, it seems reasonable to assume for this study a transverse thermal conductivity of ~20 W/m-K at 1000°C and under irradiation.

Maximum Temperature Limit

Two major factors limiting the maximum operating temperature of SiC/SiC are irradiation-induced dimensional changes and compatibility with the liquid metal. Three distinct irradiation swelling temperature regimes can be identified [7,8]:
1. An amorphous phase at low temperature (<~150°C) with high irradiation swelling;
2. A point defect swelling regime where swelling decreases with increasing irradiation temperature and reaches saturation at relatively low irradiation dose; and
3. A void swelling regime at high temperature where swelling keeps increasing with irradiation levels.

Clearly, the maximum SiC/SiC temperature limit must be set to avoid the void swelling regime. It is not clear at exactly what temperature the transition from point defect swelling to void swelling occurs but from the results summarized in Refs. [7] and [8], this transition temperature is about 1000°C.

Scarce data exist on the chemical compatibility of SiC with LiPb at high temperature. Ref. [10] reports no compatibility problem for SiC exposed over 1500 hours to

static LiPb at 800°C. It is not clear how the compatibility will be affected by flowing the LiPb at higher temperature in a fusion reactor environment. This is certainly an area where future R&D should be directed. In anticipation of such data, it seems reasonable not to prejudge the blanket limitations and to assume a maximum temperature limit in the blanket zone set by irradiation-induced dimensional changes (~1000°C). In the future, as new compatibility data become available the design can be adjusted accordingly.

Maximum Allowable Stresses

The derivation of SiC/SiC stress limits for SiC/SiC was addressed as part of the ARIES-I study [1] which recommended maximum primary and secondary stress limits of 140 MPa and 190 MPa respectively (effectively based on a fraction of the computed tensile strength of 286 MPa for SiC/SiC with 60% fiber volume fraction). For the purpose of this study, these values are adopted with the understanding that they would need to be updated as improvement in the fabrication method allows for higher quality SiC/SiC material. Another factor which would need to be considered in a more detailed study is whether traditional Von Mises stress calculations are adequate or whether a new approach should be used to account for the material orthotropy as suggested in Ref. [11].

Lifetime

Lifetime limits of the SiC/SiC under irradiation will dictate the required replacement frequency and cost of the first wall and blanket regions during the reactor lifetime. Irradiation damage (dpa) as well as helium and hydrogen productions have to be considered in determining the impact on mechanical properties and in setting the lifetime. Experimental data on this is rather limited in particular for the higher quality SiC/SiC and has been summarized in recent literature (e.g. [5] and [6]). For this study, a 3% SiC burnup is assumed as a lifetime parameter. This value is a best engineering judgement estimate based on current knowledge and is adopted with the understanding that it needs to be verified by future R&D.

Fabrication and Joining Methods

The SiC/SiC fabrication and joining methods affect the cost of the blanket, the quality and performance of the SiC/SiC and the possibility of rejoining when replacing a component at its end of life or due to failure. Progress has been made in this area such as in the brazed joint proposed in Ref. [12]. However, much remains to be done to ensure high quality fabrication and rebonding. This study assumes that a reliable bonding method will be developed enabling one or more replacements of part of the blanket during the plant lifetime.

Hermeticity

The SiC/SiC hermeticity issue can be mitigated by adding a SiC CVD coating to prevent leaks. In addition, the trend towards fabrication of higher quality denser multi-dimensional composite configuration should also help in minimizing any leakage. However, hermeticity should be considered as a factor when making the coolant choice in particular when this involves high pressure helium.

Other Properties

Table 1 summarizes the SiC/SiC properties used in this study. Note that there are other important parameters not considered within the scope of this study, such as those governing the tritium behavior, which would need to be included as part of a more detailed design study.

Table 1 SiC/SiC Properties Used in this Study

Density (kg/m^3)	3200
Density Factor	0.95
Young's Modulus (GPa)	360
Poisson's ratio	0.16
Thermal Expansion Coefficient (ppm/°C)	4.4
Thermal Conductivity in plane (W/m-K)	25
Thermal Conductivity through Thickness (W/m-K)	20
Maximum Allowable Primary Stress (MPa)	~140
Maximum Allowable Secondary Stress (MPa)	~190
Maximum Allowable Operating Temperature (°C)	1000
Max. Allowable SiC/LiPb Interface Temp. (°C)	TBD
Maximum Allowable SiC Burnup (%)	3

POWER CYCLE

The Brayton cycle offers the best near-term possibility of power conversion with high efficiency and is compatible with a high performance liquid metal blanket. For this reason, it is considered in this scoping study to evaluate the potential gain from high temperature operation with a SiC/SiC-based blanket. The Brayton cycle considered includes three-stage compression with two intercoolers and a high efficiency recuperator, as shown schematically in Figure 1. Its main parameters are set under the assumption of state of the art components and/or with modest and reasonable extrapolation [13,14] and are as follows:
- Lowest He temperature in the cycle (heat sink) = 35 °C
- Turbine efficiency = 93%
- Compressor efficiency = 90%
- Recuperator effectiveness = 96%
- He maximum temperature <~1100°C (extrapolation required here as the range of temperature of uncooled cast nickel blades is about 850°C)
- He fractional pressure drop in out-of-vessel cycle = 0.025

Other parameters are set as part of the scoping parametric studies. It is assumed that the cycle He would be used to cool the divertor and first wall if applicable and would then be heated up to its maximum temperature through a heat exchange with the LiPb exiting the blanket.
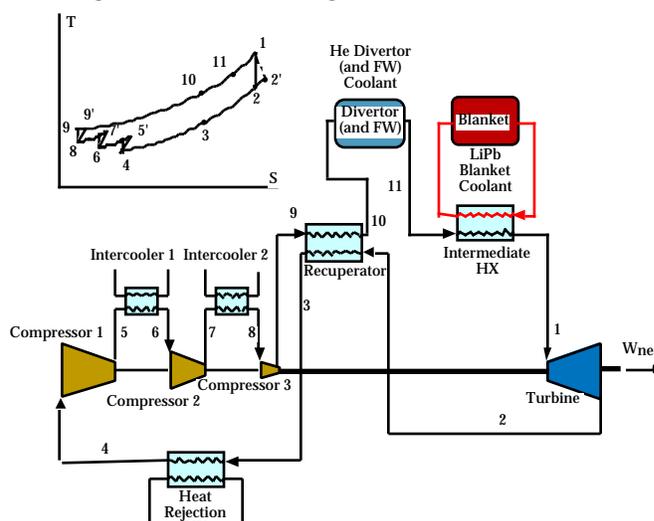

Figure 1   Schematic of the Brayton cycle including the blanket LiPb/cycle He heat exchanger

BLANKET CONCEPTUAL STUDY

In anticipation of the evolution of the next ARIES machine parameters based on advances in physics, superconducting magnet and technology, the power parameters assumed for the study are set to 50% higher than those of ARIES-RS[15] while the fusion power is kept constant implying a more compact power plant. These machine and power parameters are summarized in Table 2.

Table 2 also shows some of the 3-D neutronics parameters calculated for a preliminary SiC/SiC+liquid breeder design consisting of:
•   A 25-cm inboard and a 55-cm outboard blanket regions with 8%SiC and 92% liquid breeder
•   A 5-cm FW region on the inboard and outboard with 40% SiC and 60% liquid breeder

The resulting tritium breeding ratio was 1.1 for $Li_{17}Pb_{23}$ as breeder and only 0.95 for $Li_{25}Sn_{7}5$ as breeder, both with 90% enriched lithium. Based on this poor breeding performance, LiSn was not considered further in this study which then concentrated solely on LiPb in a purely self-cooled configuration and in a dual-coolant configuration (He for the first wall and LiPb for the blanket).

Table 2 Machine and Power Parameters Assumed for the Study (OB=Outboard, FW=first wall)

Power Parameters	
Fusion Power (MW)	2170
Neutron Power (MW)	1736
Alpha Power (MW)	434
Current Drive Power (MW)	50
Maximum Surface Heat Flux (MW/m^2)	0.71
Average Surface Heat Flux (MW/m^2)	0.6
Power to the Divertor (MW)	140
From Neutronics Analysis	
Overall Energy Multiplication	1.1
Maximum Thermal Power (MW)	2394
Outboard Maximum Neutron Wall Load (MW/m^2)	6.6
Outboard Average Neutron Wall Load (MW/m^2)	5.6
Inboard Maximum Neutron Wall Load (MW/m^2)	5.1
Inboard Average Neutron Wall Load (MW/m^2)	3.8
OB Average Heat Generation in FW SiC (MW/m^3)	28
OB Maximum Heat Generation in FW SiC (MW/m^3)	33
OB Average Heat Generation in FW LiPb (MW/m^3)	21
OB Maximum Heat Generation in FW LiPb (MW/m^3)	25
Machine Geometry	
Major Radius (m)	4.5
Minor Radius (m)	1.13
Outboard FW Location at Midplane (m)	6
Outboard FW Location at Lower/Upper End (m)	4.5
Inboard FW Location (m)	3.5

The initial effort considered a poloidal box configuration for the blanket where the LiPb would flow in large channels whose dimensions would be set to accommodate the maximum allowable pressure and thermal stresses. In one option a separate first wall region consisting of 3-cm twisted tubes was cooled by a first LiPb pass while in the other option the first wall region was cooled by a toroidal

helium flow. These two options were analyzed in some detail from which the following key points emerged for further evolving the design:
•   Separate cooling of the blanket box structure with either He or an initial pass of LiPb in order to maintain the SiC/SiC within its temperature limit. The LiPb then flows in a final pass between the cooled structure and gets heated to high temperature to maximize the cycle efficiency.
•   Radially segmenting the blanket in order to save on replacement cost. The first layer including the FW should be about 25 cm thick and would be replaced at the end of the FW region lifetime (about 2.8 FPY based on a 3% SiC burnup limit). The second layer would be about 35 cm thick and would be a lifetime component.
•   For He, a poloidally-cooled FW configuration offers advantages of a simpler layout and manifolding configuration as well as a thinner radial build and would be preferable to a toroidally-cooled configuration.

A consistent parametric comparison between He and LiPb as poloidally-flowing first wall coolant was then performed based on parallel tube configuration schematically shown in Fig. 2. For simplicity, the minimum channel wall thickness for both cases was set as one tenth of the diameter. For the He case this would correspond to a 100 MPa pressure stress for an assumed helium pressure of 20 MPa. For the LiPb, the pressure is much lower and the assumption is more conservative.
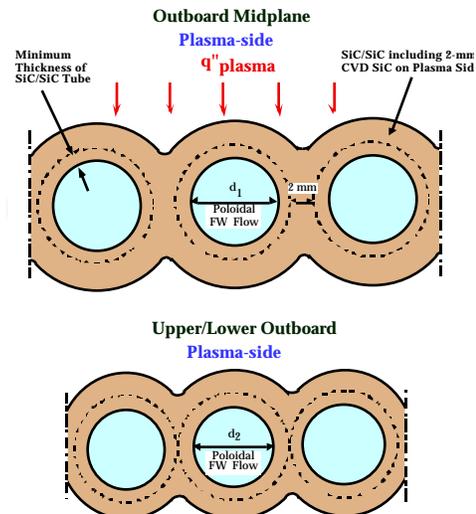

Figure 2   Poloidally-cooled first wall configuration with tapering channels

To maximize the Brayton cycle efficiency, the LiPb exits the blanket at a high temperature of ~1150°C taking full advantage of the low velocity and low heat transfer coefficient of the final high-temperature LiPb pass to maintain the SiC/LiPb interface temperature in the higher blanket irradiation zone <~1000°. The corresponding maximum Brayton cycle He temperature in the secondary side of the heat exchanger is estimated at ~1100°C (see Fig. 1). Given this temperature and the other cycle parameters listed in the previous section the cycle efficiency would be a function of the total compression ratio and, in the case of the He-cooled first wall, of the He pressure drop in the FW channels. The compression ratio also influences the cycle helium temperature at the exit of the recuperator (point 10 in Fig. 1) which affects the first wall inlet temperature in both cases and the corresponding FW maximum SiC temperature. This is illustrated in Fig. 3 for the He-cooled

first wall case. For a given flow rate, the pressure drop would vary with the channel diameter which is shown as an alternate variable in the figure.
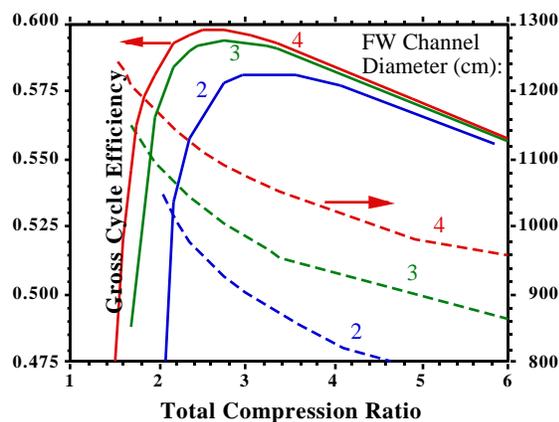

Figure 3 Cycle efficiency and maximum SiC temperature as a function of total compression ratio for different poloidal He FW channel diameters (maximum cycle helium temperature = 1100°C)

There is no fixed limit on the total compression ratio. Typically a higher ratio would require more stages which would drive the cost and possibly leakage rate. For a reasonable compression ratio of <3, the maximum FW SiC temperature can be maintained <1000°C for a channel diameter of 3 cm. The corresponding efficiency is ~59%.

A similar analysis was done for a LiPb-cooled FW. In this case MHD effects tend to laminarize the flow even with insulated walls resulting in lower heat transfer performance and higher SiC temperature [16]. To somewhat compensate for this effect, the LiPb temperature was reduced by 50°C resulting in a maximum He cycle temperature of ~1050°C. The results are shown in Fig. 4. For a compression ratio of 3, the maximum SiC temperature is ~1000°C and the cycle efficiency ~59% for a channel diameter of 2 cm. The corresponding pressure drop including MHD effects in an insulated channels [16] is relatively high, ~1.2 MPa requiring an inlet pressure of about 2 MPa.

These results are encouraging showing comparable performance for both configurations. The LiPb configuration is preferred at this stage as it helps avoid a high pressure first wall system and provides the possibility of integrating the FW and blanket without concerns about pressurizing the blanket box in case of leaks. It also provides better shielding performance in general as it also avoids any effective He "void".

CONCLUSIONS

This exploratory study has helped assess the potential of a SiC/SiC + LiPb blanket for a high performance blanket. High cycle efficiency can be achieved (close to 60% for the Brayton cycle) by superheating the LiPb in a final low velocity high temperature pass while maintaining the SiC/LiPb interface temperature in the irradiated blanket region within ~1000°C. This, in addition with the safety premium of using SiC/SiC makes such a concept quite attractive as a power plant blanket candidate. However, the results are dependent on the assumptions made which need to be verified through R&D. Particular areas of focus include improvement in the SiC/SiC quality and characterization of its properties at temperature and under irradiation, in particular its thermal conductivity and its compatibility with LiPb.
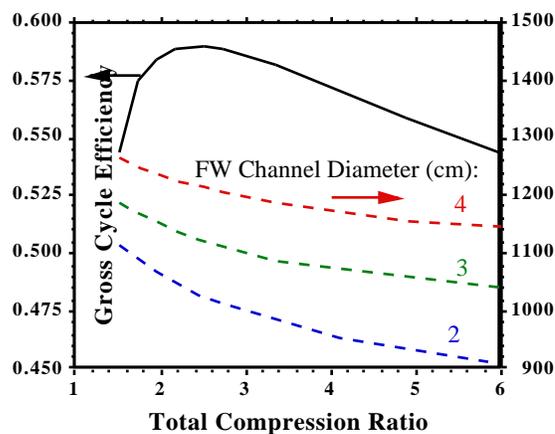

Figure 4 Cycle efficiency and maximum SiC temperature as a function of total compression ratio for different poloidal LiPb FW channel diameters (maximum cycle He temperature = 1050°C)

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