Characterization of SiC/SiC Composites Used for Power Plant Blanket

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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.

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1. Introduction

The use of SiC/SiC composite as structural material in a fusion reactor is attractive based on its low induced radioactivity and afterheat. 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 [1]. Chief among these are the rather low thermal conductivity at high temperature and under irradiation, and the maximum allowable operating temperature [2].

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 [3].

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.

2. 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 [4].

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 [5,6]:

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. [5] and [6], this transition temperature is about 1000°C.

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. [7].

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. [8]. 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.

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.

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

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 Fig. (1). Its main parameters are set under the assumption of state of the art components and/or with modest and reasonable extrapolation [9,10] 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

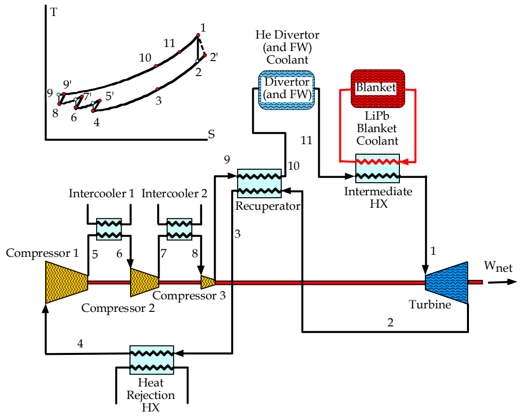

Fig. (1) Schematic of the Brayton cycle including the blanket LiPb/cycle He heat exchanger

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.

4. 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 [11] 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 3D 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.

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.

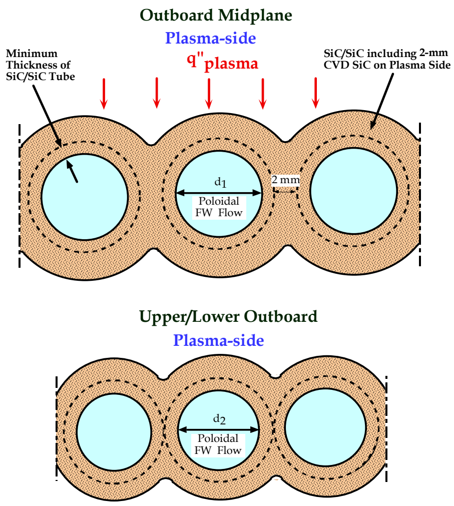

Fig. (2) Poloidally-cooled first wall configuration with tapering channels

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

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%.

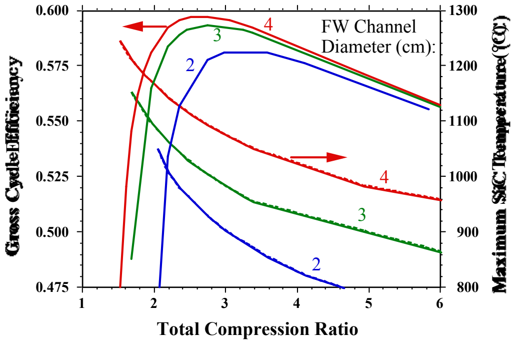

Fig. (3) Cycle efficiency and maximum SiC temperature as a function of total compression ratio for different poloidal He FW channel diameters (maximum cycle helium temperature=1100°C)

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 [12]. 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 insulated channels [12] 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".

5. 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.

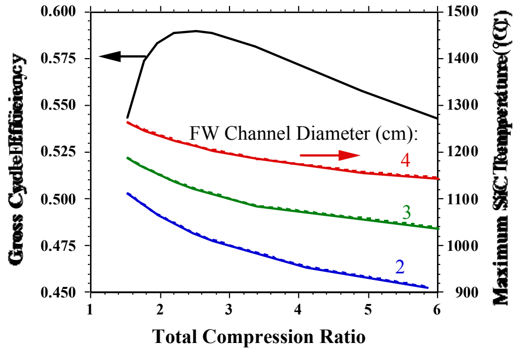

Fig. (4) Cycle efficiency and maximum SiC temperature as a function of total compression ratio for different poloidal LiPb FW channel diameters (maximum cycle He temperature=1050°C)

References

[1] F. Najmabadi, R. Conn, et al., "The ARIES-I Tokamak Reactor Study," Final Report, UCLA-PPG-1323, UCLA, CA, 1991.

[2] F. Najmabadi and R.W. Conn, "The ARIES-II and ARIES-IV Second-stability Tokamak Reactors," Proceedings TMTFE-10, La Grange Park, IL, USA, June 1992.

[3] L. Giancarli, et al., *Fusion Eng. and Design*, 41, 165- 171, 1998.

[4] S. Nishio, et al., *Fusion Eng. and Design*, 41, 357-364, 1998.

[5] S.J. Zinkle and L.L. Snead, in Fusion Materials Semiann. Prog. Rep. for period ending June 30 1998, DOE/ER-0313/24, 93-100, Oak Ridge Nat. Lab, 1998.

[6] S.J. Zinkle and L.L. Snead, in 9th Cimtec-World Forum on New Materials, Symp. VII-Innovative Materials in Advanced Energy Technologies, edited by P. Vincenzini, Techna Srl, Faenza, Italy, 307-318, 1999.

[7] S. Zinkle, *private communication*, 1999.

[8] V. Coen, et al., in High Temperature Corrosion of Technical Ceramics, Editor: R. J. Fordham, Elsevier Applied Science, London, 167-179, 1990.

[9] R. Schleicher, *private communication*, 1999.

[10] S. Malang, H. Schnauder, and M. S. Tillack, *Fusion Eng. and Design*, 41, 561-567, 1998.

[11] F. Najmabadi, and the Aries Team, *Fusion Eng. and Design*, 38, 3-25, 1997.

[12] M. A. Hoffman and G. A. Carlson, Proc. of the 13th Intersociety Energy Conversion Energy Conference SAE P-75, IEEE 78-CH1372, San Diego, August 1978.

