SIC/SIC DESIGN FOR A FLOW CHANNEL INSERT—G. E. Youngblood, R. J. Kurtz, and R. H. Jones (Pacific Northwest National Laboratory)*

OBJECTIVE

The primary objective of this fusion materials research effort is to support component design and future testing of test blanket modules (TBM) for the International Thermonuclear Experimental Reactor (ITER).

SUMMARY

This report will examine the potential for using SiC fiber-reinforced composite (SiC/SiC) as the construction material for making a Flow Channel Insert (FCI) to be used in an ITER test blanket module. A SiC/SiC-FCI component is an attractive feature to enhance safe operations and power conversion efficiency in a D-T fusion reactor blanket that utilizes the dual-coolant flow concept. A SiC/SiC-FCI would act as an insulating layer to electrically and thermally decouple flowing, molten Pb-Li alloy (a combination tritium generation and heat bearing medium) from the structural, load-bearing ferritic steel channel walls of the blanket. The required properties for SiC/SiC-FCI materials are low transverse thermal and electrical conductivity, as well as Pb-Li compatibility and radiation stability. Analysis of these properties suggests that a composite architectural or "engineering" design solution will be necessary to achieve the SiC/SiC-FCI goals.

PROGRESS AND STATUS

Introduction

Over the next 30 years, the construction and operation of the International Thermonuclear Experimental Reactor (ITER) will provide the primary test-bed worldwide for integrated fusion power development. A critical issue that needs to be demonstrated in ITER is predictable and controllable power extraction from a deuterium-tritium (D-T) fusion reaction. This will involve designing and operating a high temperature heat removal and tritium breeding management system. Currently, one of the most attractive systems under consideration is based on the concept of using a Dual Coolant Blanket (DCB). The blanket surrounds the torroidal D-T reaction chamber to absorb and convert the neutron kinetic energy to thermal energy and to generate the tritium fuel. The design and testing of a DCB module in ITER is one of the key elements of the U.S. "ITER Mission" [1].

Actual electrical power will be generated in a fusion reactor for the first time in ITER. The 500 MW ITER fusion test reactor will provide a wide range of relevant material and component tests under combined 14 MeV neutron, heat and particle fluxes. Data from these tests will provide necessary information for the later development and design of a DEMO reactor (a DEMOnstration power reactor, the next step after ITER) [2]. In particular, several blanket designs that are DEMO-relevant will be tested in ITER. A particularly attractive blanket design based on the DCB concept is depicted in Fig. 1 [3].

To breed the tritium fuel, a DCB module would contain a liquid Pb-17 at % Li eutectic metal alloy (melting point ~300°C) with about 90% Li^6 isotope enrichment so that the tritium-breeding ratio is greater than one without the use of a neutron multiplier (such as beryllium). The liquid Pb-Li flows through numerous parallel, helium-cooled ferritic steel channels to carry the generated tritium and heat away. To reduce MHD-induced pressure drop in the flowing Pb-Li, an electrically insulating component called a Flow Channel Insert (FCI) is located within each steel channel. The FCIs also thermally decouple the hot Pb-Li (bulk flow temperature ~800°C max) from the He-cooled ferritic steel wall (temperature ~500°C max). A ceramic, fiber-reinforced silicon carbide composite (SiC/SiC) has been proposed as a promising material for the construction of FCIs [3].

---

*Pacific Northwest National Laboratory (PNNL) is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO-1830.

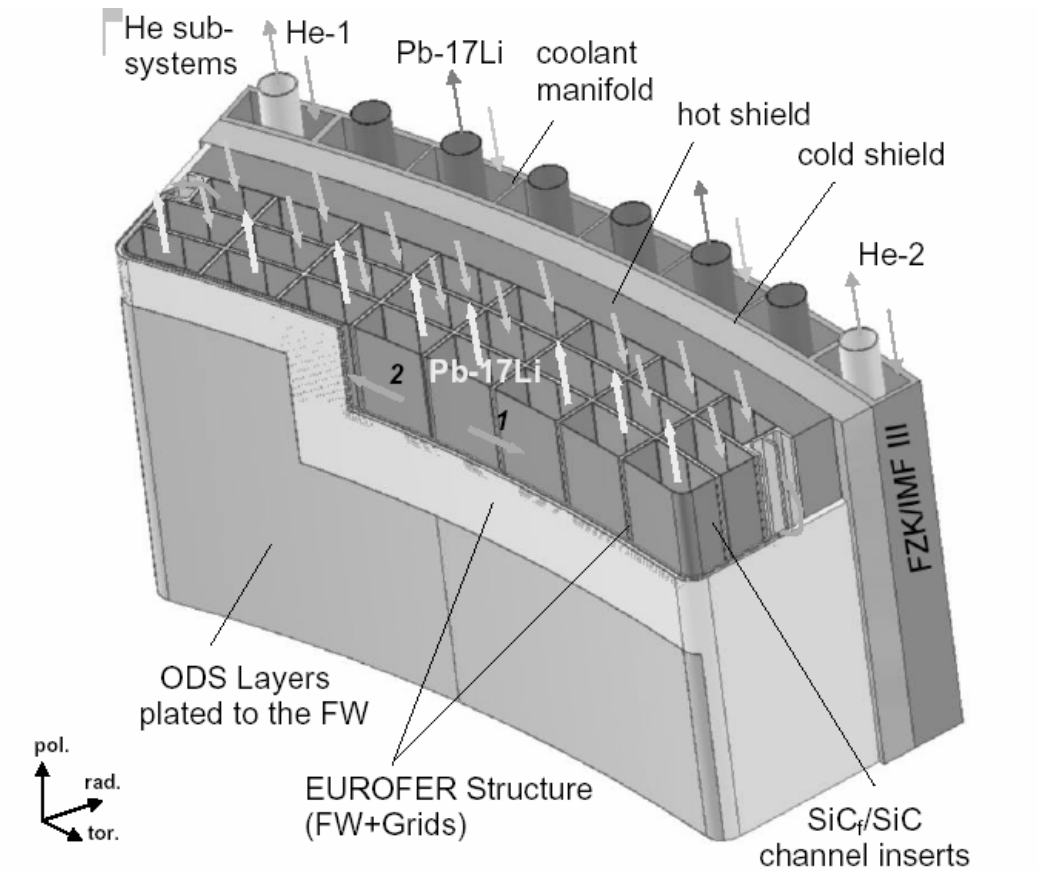

Fig. 1. Schematic of EU advanced dual coolant DEMO blanket section designed for a D-T Tokamak fusion reactor (FZKA 6780), taken from Morley et al. [3].

In Fig. 1, the first wall of the DEMO blanket, and the EUROFER ferritic steel grid structure, are helium-cooled (or heated at start-up) through embedded channels. The grid structure supports numerous (176 blanket modules x 24 FCI/module) SiC/SiC-FCIs through which the liquid metal Pb-17Li flows at low velocity (~0.1 m/s, but up to ~2 m/s in connecting piping). Each channel will have a cross-section of about 0.08 m^2 with lengths in meters. The FCIs (typical thickness ~5 mm) divide the flow channels into two regions. The larger inner region contains the slowly flowing, high temperature (460–700°C) Pb-Li. An advantage for removing heat at high temperature is the potential for obtaining high fusion power conversion efficiency, possibly >50%. The thin (~2–3 mm) outer region contains a cooler stagnant layer of Pb-Li that reduces the potential for erosion/corrosion of the steel walls. However, a torroidal magnetic field induces radial electrical currents in the flowing liquid metal, which in turn may cause a pressure drop along the long flow channels. The FCI interrupts the closed electrical conducting path in the radial (transverse) direction between the conducting steel walls and liquid metal and tends to reduce the MHD-induced pressure drops. To continue consideration of the DCBM-concept, the successful development and testing of FCIs (a key component that would utilize a large volume of SiC/SiC) obviously is necessary.

The primary goal for DCBM-testing in ITER will be the demonstration of effective tritium management, of the ability to generate high temperature heat, and of operation under integrated thermal, mechanical and electromagnetic loads. To carry out these functions in the proposed DCBM temperature operating range

of 500–800°C, according to initial modeling efforts by Morley [3], the SiC/SiC material should have the following properties (listed somewhat in order of timeliness and importance):

(1) Low transverse electrical and thermal conductivity (1–10 S/m and ~1 W/mK, respectively).
(2) Compatible with liquid Pb-17Li alloy at temperatures up to 800°C.
(3) Impermeable to the liquid Pb-Li.
(4) Good thermal shock and thermal cycling behavior (in-plane E ~100 GPa).
(5) Radiation and creep resistance.
(6) Wear resistance (hardness).
(7) Non-magnetic.

This report will examine the potential for obtaining the desired low transverse electrical and thermal conductivity properties in 2D-SiC/SiC, listed as priority (1) above.

Themal Conductivity

In Fig. 2, progress to fabricate SiC/SiC with a high effective (through the wall thickness) thermal conductivity (K_{eff}) is illustrated [4]. A K_{eff} >15 W/mK is recommended for the use of SiC/SiC as a structural fusion material during irradiation.

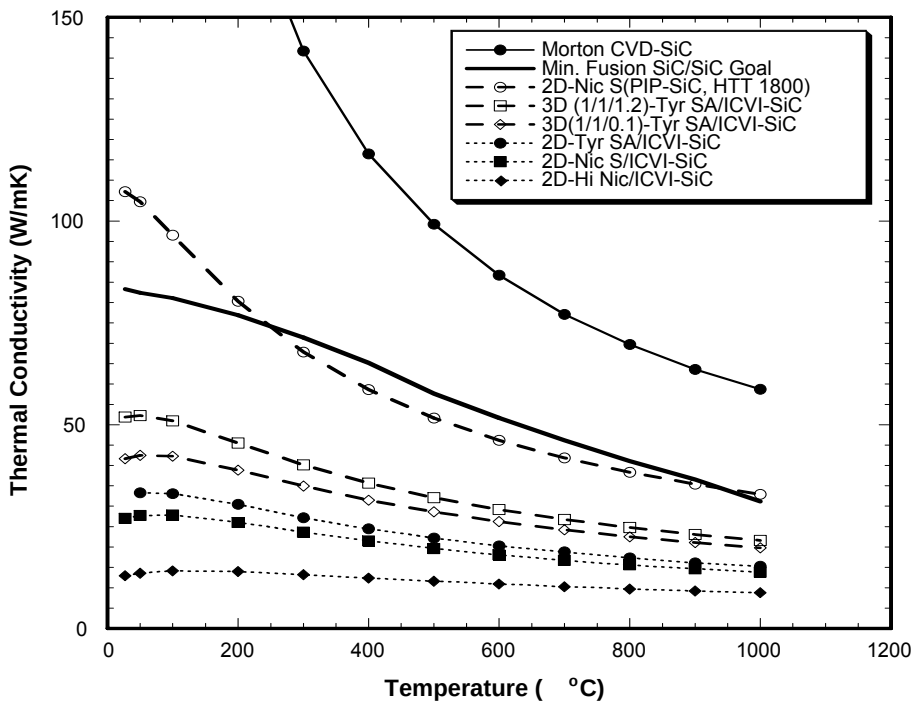

Fig. 2. Progress to attain SiC/SiC with high (K_{eff}. >15 W/mK during irradiation) transverse thermal conductivity [5]. The plotted values are for unirradiated materials.

By the use of advanced Nicalon™ type S or Tyranno™ SA fibers, the K_{eff}-values for 2D-SiC/CVI-SiC composites have more than doubled compared to values exhibited by the original fusion reference SiC/SiC made with Hi-Nicalon™ fiber (lowest curve, ~10–14 W/mK). Furthermore, by using 3D-weaves K_{eff}-values have approximately tripled over that of the 2D-Hi Nic composite. Finally, the K_{eff}-values of a 2D-SiC/SiC (made by MER Corp. with Nicalon S fibers and a polymer infiltrated and pyrolized PIP-SiC matrix given a special high temperature treatment, an HTT >1800°C) approximately match the estimated,

before-irradiation minimum fusion thermal conductivity goals for a SiC/SiC structural material (solid line). For reference, the K_{eff}-values for dense, high-purity Morton CVD-SiC also are given [9].

Although efforts to meet high thermal conductivity goals are continuing, a new goal now is to develop or design a radiation-resistant SiC/SiC-FCI with low K_{eff}. In fact, the new value desired for the FCI-application (~1 W/mK) is a factor of <1/10th of the 2D-Hi Nic reference K_{eff}-values shown in Fig. 2. To date, little research effort has been expended in reducing K_{eff}, but that circumstance has now changed with the advent of the SiC/SiC-FCI concept.

The thermal conductivity of irradiated SiC decreases due to the accumulation of point defects that effectively scatter phonons in SiC. In the 500–800°C range of interest, the degradation could be as much as a factor of 1/5 to 1/3 for SiC/SiC irradiated to saturation doses or above (~1 dpa-SiC) [6]. But for once nature is kind! Because of the decrease of K_{eff} for irradiated SiC, meeting the requirement of low K_{eff} becomes easier as the number of point defects accumulates. Therefore, as far as the SiC/SiC-FCI application is concerned, the critical time is at the beginning of life (BOL) for irradiation exposure, i.e., before SiC has been irradiated. Unfortunately, a SiC/SiC composite made with advanced SiC fibers with a crystalline SiC matrix (to preserve radiation stability) likely will have K_{eff}-values even greater than the Hi-Nic reference values of 10–14 W/mK, values well above those required for a SiC/SiC-FCI at BOL.

To provide the desired extremely low composite K_{eff}-values, it is obvious that architectural means will have to be employed. A 2D-SiC/SiC composite material will have to be specially designed and fabricated ("engineered") to meet the required very low FCI K_{eff}-values.

Electrical Conductivity

The electrical conductivity issue parallels that for thermal conductivity – low values of transverse electrical conductivity (σ_{eff}) are desired. Most measurements of electrical conductivity of 2D-SiC/SiC to date have been made in-plane rather than in the transverse direction. Because of the marked anisotropy in 2D-SiC/SiC composites made with woven fabric layers, experimental as well as modeling efforts to measure and/or to predict σ_{eff} are needed.

In Fig. 3, the electrical conductivity values for several unirradiated SiC-based materials are presented as a function of temperature.

The conductivity data by Weber [7] for high-purity (>99.999%), monolithic CVD-SiC indicate electrical conductivity values increasing with increasing temperature from 18 S/m at RT up to 210 S/m at 1000°C. A logarithmic plot of this data suggests a thermally activated process with an activation energy of ~0.12 eV, which likely corresponds to a shallow N-impurity energy band of 0.06–0.10 eV in β-SiC [8]. Nitrogen is a common trace (a few ppm) impurity even in CVD-fabricated SiC.

The data for the similar Morton CVD-SiC material exhibits somewhat higher electrical conductivity values and a different dependence on temperature [9]. The electrical conductivity of SiC, a wide band-gap (2.3 eV) semiconductor, is extremely sensitive to impurity content and types, which likely accounts for these observed differences between nominally the same materials. Although the electrical conductivity of CVD-SiC is close to the SiC/SiC-FCI goal at room temperature, in the higher 500–800°C temperature range its electrical conductivity values are ~200 S/m, much higher than the desired 1–10 S/m values.

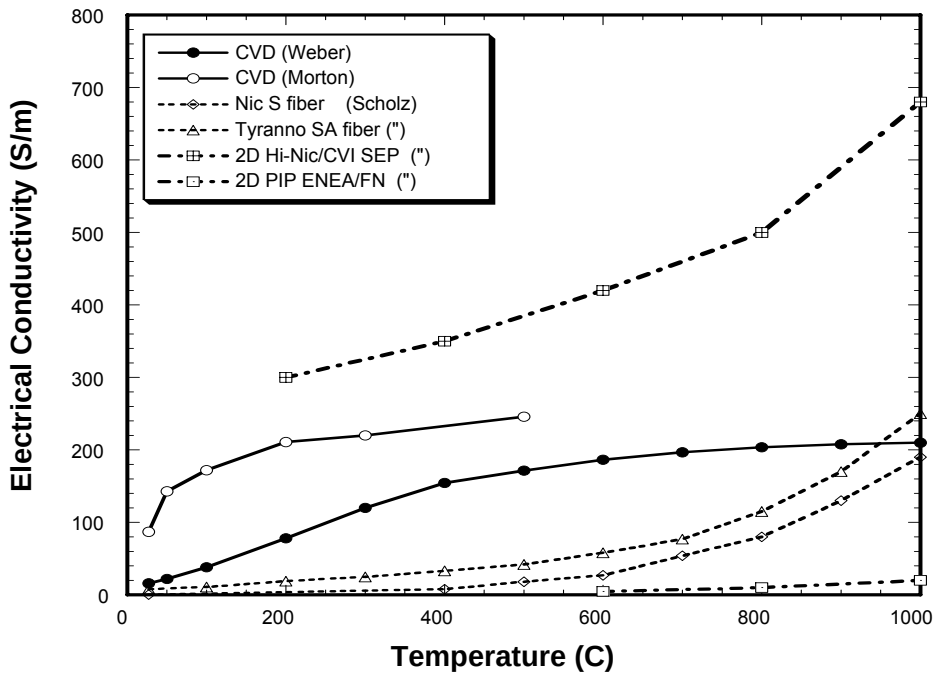

Fig. 3. Electrical conductivity of unirradiated composite, fiber and monolithic SiC-based materials [5].

The dashed lines show data for two types of high-purity, crystalline SiC fibers, Tyranno™ SA and Nicalon™ type S, reported by Scholz et al. [10]. Over the 500–800°C temperature range of interest, the electrical conductivity values increase from 20 to 80 S/m and 40 to 110 S/m for the type S and Tyranno™ SA fibers, respectively. The Tyranno fiber conductivity values are greater than for the type S fiber, but except for temperatures greater than ~1000°C, are less than the CVD-SiC values. The Tyranno fiber is sintered and has a larger grain size than the type S fiber, which may account for the small differences observed between these two fiber types. For both fibers, the electrical conductivity values increase monotonically with temperature in a similar way, but with an entirely different temperature dependence compared to that for the monolithic CVD-SiC. Unfortunately, both of these radiation stable fiber types have conductivity values that exceed the SiC/SiC-FCI goals.

Finally, the electrical conductivity data for the 2D Hi-Nic/CVI-SiC composite are extremely high (>300 S/m). In this composite, the Hi-Nicalon fibers were coated with a thin (~200 nm) pyrocarbon (PyC) layer. Microscopic examination of composite cross-sections indicated many fiber-to-fiber contacts. This is a typical composite structure with considerable electrical continuity through adjoining PyC-layers. Because carbon is an excellent electrical conductor, carbon pathways likely dominate the electrical conduction of SiC/SiC composites with PyC-coated fibers, as suggested by conductivity models. Furthermore, the electrical conductivity of the Hi-Nicalon fiber itself is about x10 that of type S fiber, which is likely due to the excess C in the Hi-Nic fiber with a C/Si ratio of 1.4. In fact, the very low electrical conductivity exhibited by the 2D PIP ENEA SiC/SiC composite (<10 S/m even up to 1000°C) partly results because its fibers were uncoated. In addition, rather than crystalline SiC the PIP-SiC matrix for this material consisted mostly of amorphous Si-C-O. Although such a matrix material exhibits a low electrical conductivity, this non-crystalline form of SiC is very irradiation unstable and not acceptable for the SiC/SiC-FCI application.

Overall, what is called for in a SiC/SiC-FCI is a composite with a nanocrystalline SiC matrix constructed with at least a few thin electrical and thermal insulating layers (perhaps silica) to first decouple the fibers one from another, and second to decouple the fiber bundles and perhaps even fabric layers from each other. The insulating layers must be thin and protected on both surfaces by CVI-SiC to hopefully

preserve radiation resistance. That is, an engineering or architectural design solution is suggested to preserve radiation stability and to provide the desired low K_{eff}- and σ_{eff}-values needed for the SiC/SiC-FCI application.

Conclusions

A composite engineering or architectural design solution is needed to provide the desired low K_{eff}- and σ_{eff}-values for the SiC/SiC-FCI application.

Future Work

A 4-probe DC-method will be used to measure the electrical conductivity as a function of temperature for candidate bar-shaped 2D-SiC/SiC-FCI materials. A 2-probe AC-method will be used to measure the transverse electrical conductivity of candidate disc-shaped 2D-SiC/SiC-FCI materials. Existing 2D-thermal conductivity models will be modified to analyze the measured transverse and parallel electrical conductivity data for the 2D-SiC/SiC materials in terms of the composite matrix, fiber and fiber coating components and the composite architecture.

Acknowledgements

The U.S. Department of Energy, Office of Fusion Energy Sciences, funded this research.

References

[1] M. Abdou and U.S. ITER-TBM Team, U.S. Plans and Strategy for ITER Blanket Testing, presented at the 16th ANS TOFE meeting, September 14, 2004, Madison, Wis.
[2] V. Barabash, Role and contribution of ITER in research of materials and reactor components, J. Nucl. Mater. 329–333 (2004) 156–160.
[3] N. B. Morley et al., Current understanding of feasibility of SiC/SiC composites for flow channel inserts in Dual Coolant Pb-17Li blankets, presented at TBM meeting, June 4, 2004, UCLA.
[4] R. H. Jones et al., Promise and challenges of SiC/SiC composites for fusion applications, J. Nucl. Mater. 307–311 (2002) 1107.
[5] G. E. Youngblood, presented at the 6th IEA SiC/SiC Workshop, Boston, June 10–11, 2004.
[6] G. E. Youngblood, D. J. Senor, and R. H. Jones, Effects of irradiation and post-irradiation annealing on the thermal conductivity/diffusivity of monolithic and f-SiC/SiC composites, J. Nucl. Mater. 329–333 (2004) 507.
[7] W. Weber (unpublished data).
[8] Y. Goldberg, M. Levinshstein, and S. Rumyantsev, In 2001 Silicon Carbide (SiC), Properties of Advanced Semiconductor Materials, John Wiley and Sons, Inc., New York (2001) 93–147.
[9] Technical Bulletin #107, Morton Advanced Materials, Woburn, Mass. (1994).
[10] R. Scholz, F. dos Santos Marques, and B. Riccardi, Electrical conductivity of silicon carbide composites, J. Nucl. Mater. 307–311 (2002) 1098.