International Town Meeting on SiC/SiC Design and Material Issues for Fusion Systems

January 18-19, 2000

Oak Ridge National Laboratory

Summary

An International Town Meeting on SiC/SiC Design and Material Issues for Fusion Systems was held at Oak Ridge National Laboratory on January 18-19, 2000. The major objective of the meeting was to bring together the SiC/SiC design and material communities from Japan, the EU and the US to exchange information, identify the design-related critical issues, discuss them in light of the latest material R&D results, and provide guidelines to help focus future effort.

The list of participants and meeting agenda are shown separately at the meeting web site (http://aries.ucsd.edu/PUBLIC/SiCSiC/) along with more detailed information about the meeting and PDF copies of presentations. The agenda included presentations on the latest design concepts in the US, Japan and the EU utilizing SiC/SiC composites and the key issues influencing the performance and attractiveness of SiC/SiC for design applications. These were followed by presentations on the status of material R&D including fabrication and joining, baseline properties and properties under irradiation. A solid block of time was allocated at the end of the meeting to a discussion session aimed at better understanding the key SiC/SiC parameters and properties affecting design analysis. The discussion centered on the current status of these parameters and properties, on their desirable evolution to increase the performance and attractiveness of SiC/SiC-based fusion power plant designs, and on reasonable projections that could be used presently in long-term design studies and that would help focus the development of a SiC/SiC material R&D roadmap.

This meeting summary includes some major highlights of the presentations but focuses mostly on key points emerging from the well-informed but yet candid interchanges between the material and design experts during the discussion session. It is presented in terms of the major discussion topics:

Material

From a design point of view, we need SiC/SiC structures that cost over an order of magnitude less than present-day composites, that can be fabricated over dimensions of ≈10 m from fibers engineered to obtain adequate thermophysical and mechanical properties. The question about where we are in meeting these objectives was raised as background to the discussion.

Fiber

The trend is to go towards stoichiometric fiber, such as Tyranno-SA and Hi Nicalon-S, for improved performance. Insertion of high-conductivity carbon fibers (e.g. K1100) to increase the overall thermal conductivity has been proposed and is being assessed.

Interface

Interface materials used to promote bonding between the fibers and matrix include C, SiC and BN. C, SiC and C/SiC interfaces are being developed and evaluated for their radiation and chemical stability in fusion environments while BN does not look attractive because of the helium generation from the B.

Matrix

Stoichiometry is also desired here and β-SiC is commonly used. Chemical Vapor Infiltration (CVI) produces a stoichiometric, crystalline β-SiC matrix material. A similar matrix can be produced with the Polymer Impregnation & Pyrolysis (PIP) process but this requires that the fibers have the thermal stability to withstand the high-temperature pyrolysis process needed to convert the polymer to crystalline β-SiC. The newer fibers such as Tyranno-SA , Hi-Nicalon S and MER fiber have the needed thermal stability so SiC/SiC composites with these fibers and a PIP matrix is a possibility.

Architecture

Although a 3-D architecture is preferred for fusion application, it is not the focus of current development and experimental work mostly due to the difficulty of infiltration in a conventional architecture to provide low porosity. However, SEP's experience indicates that low porosity can be achieved (<5%) by non-orthogonal 3-D weaving for enhanced infiltration (CVI). If required for hermeticity reasons, the porosity can also be lowered by subsequent melt infiltration (having no structural function).

Fabrication

Processes

A number of processes are being considered including various forms of Chemical Vapor Infiltration (CVI), Polymer Impregnation & Pyrolysis (PIP), Chemical Vapor Reaction (CVR), Reaction Sintering (RS) and combined processing. It is not clear which is the most attractive based on performance and cost, but they should be prioritized given the limited resources.

Complex Shapes and Sizes

These are dependent on the process, the architecture and the required properties such as shear stress and through thickness tensile strength limits. These was some discussion and differences of opinion on the priority that should be given to the production of complex shapes for near-term development work.

Evaluation

In order to make the most of the testing results within the limited resources, effort should be directed towards consistency in the testing standards and methodology of the different properties, including: thermal conductivity, mechanical properties, density and microstrucutre, electrical resistivity and compatibility

Cost

A Japanese study indicates that about one order of magnitude reduction in cost could be achieved with large-scale production. Based on current cost, it seems reasonable to use $400 per kg for power plant studies looking at 20 years or more in the future. Since the cost of the fibers represents about 50% of the total cost, a lower-cost manufacturing technique is to start with a cheaper carbon fiber and to transform it into a SiC/SiC composite through chemical vapor reaction (CVR). This is being investigated by MER. Such an approach could reduce the SiC/SIC cost to about $100/kg or less. A key issue is the completeness of the conversion process and the closeness of the final product to stoichiometry since this would greatly impact the final product performance and properties.

Joining

The three major joining and repair options are: reaction bonding/sintering, polymer-based methods, stitching and mechanical joints. Some success have been achieved in developing brazes such as BRASIC, but the exact braze composition remains proprietary.

Properties

From a design point of view, SiC/SiC is particularly attractive based on its high-temperature capability as it allows for high coolant temperature and a correspondingly high power cycle efficiency (up to 55-60%) which reduces the cost of electricity. Key properties and parameters affecting the performance of SiC/SiC are: thermal conductivity, stress limits, temperature limits (including strength degradation and compatibility), and lifetime. Both baseline properties and properties under irradiation were covered in the presentations and discussion. The major points about these key SiC/SiC properties and parameters are summarized below:

Thermal Conductivity

The SiC thermal conductivity decreases markedly with temperature and irradiation although the relative effect of irradiation decreases at high temperature. Recent experiments at ORNL confirm a rapid decrease of thermal conductivity under irradiation until an apparent saturation level is reached relatively rapidly (at irradiation levels corresponding to a fraction of a dpa). Thermal conductivity measurements made on monolithic and SiC/SiC composites following irradiation are consistent with the in situ measurements.

It is reasonable to assume that the thermal conductivity of SiC/SiC would be limited to that of pure SiC in the absence of enhancement measures such as adding high conductivity carbon fibers whose integrity under irradiation is uncertain. Measurement of transverse thermal conductivity of unirradiated SiC/SiC composite tends to fall in the 10-20 W/m-K range for the earlier low-quality SiC fibers. It is expected that the thermal conductivity will be improved as better stoichiometry is achieved in SiC/SiC. Recently, measurement of the transverse thermal conductivity of MER CVR SiC/SiC samples yielded 75 W/m-K at RT and ≈35 W/m-K at 1000°C.

Consistent with the early experimental indications on the effect of irradiation on SiC/SiC conductivity, it can be assumed that the SiC/SiC conductivity degradation due to irradiation would be comparable to, or less than on a percentage basis, that observed in pure SiC. At 1000°C the reduction in thermal conductivity due to irradiation would be not less than ≈50% for standard CVD SiC. Starting with an unirradiated thermal conductivity close to the MER value, it seems reasonable to expect a transverse conductivity of about 15 and possibly up to 20 W/m-K at 1000°C and under irradiation for future generation SiC/SiC.

Stress Limits

It seems clear that conventional stress limits cannot be directly applied to ceramics. The non-isotropic behavior of SiC/SiC as well as the non-linearity arising from the unique damage mechanisms must be taken into account. CEA has initiated an effort to better understand the SiC/SiC stress limits by macroscopically accounting for the non-linear elastic behavior associated with matrix micro-cracking and matrix-fiber debonding. Initial results suggest: a maximum Von Mises tensile stress limit of ≈145 MPa corresponding roughly to the beginning of microcracks opening; a compressive stress limit of 420 MPa and a shear stress limit of 44 MPa for the CERASEP N2-1 material.

This study also indicates that the conventional primary and secondary stress limits do not apply for ceramics; instead, the imposed limit should cover the total stress (thermal + pressure +bending). At this stage, such a detailed model is not available to all designers. It is suggested that when using conventional FEM analysis to try to limit the total combined stress to ≈190 MPa although it is possible that this might be too conservative.

It is clear that consistent design codes and standards need to be formulated for ceramics operating at high temperature and under irradiation.

Temperature Limits

Major factors limiting the maximum operating temperature of SiC/SiC are strength degradation, irradiation-induced dimensional changes and compatibility with the liquid metal.

Strength degradation derives mostly from the stability of the fibers in the short-term and from chemical reaction in the long term (e.g. instigated by the presence of O at the interface). It can be alleviated by improving the fabrication procedure and material quality with an expected increase in the allowable temperature to ≈1300-1400°C.

Three distinct irradiation swelling temperature regimes can be identified:
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 few existing results, this transition temperature is ≈1000°C.

Only one data point exists in the open literature on the chemical compatibility of SiC with LiPb at high temperature. From an experiment performed at ISPRA, no compatibility problem was reported for SiC exposed over 1500 hours to static LiPb at 800°C. Unpublished results from the same experimental work indicate that the SiC degenerated after 4500 hours at 800°C. However, some questions exist regarding the quality and impurity level of the SiC used in these tests. This is certainly an area where future R&D should be directed. FZK is planning high temperature LiPb/SiC compatibility testing in the near future. Similar tests are planned within Japan for LiPb, as well as other liquid metals and salts (e.g., Flibe). 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, this limit can be revised.

The minimum temperature limit derives mostly from the need to maintain an acceptable thermal conductivity level. Although additional confirmation of the in-situ thermal conductivity data from the HFIR TRIST-TC1 experiment is needed, the results from that experiment and previous studies indicate that the thermal conductivity of SiC/SiC will be less than ≈10 W/m-K for irradiation temperatures of 200-500°C (due to phonon scattering off the radiation-induced point defect clusters). To maintain the desirable thermal conductivity levels of 15-20 W/m-K, the minimum operating temperature would be ≈600°C.

Lifetime

This is one parameter that is particularly hard to characterize based on the limited data and understanding. It is an important parameter affecting the lifetime and replacement cost of in-vessel component and needs to be characterized for power plant studies. For example, the ARIES studies have assumed a very rough estimate of 3% burnup (1.5 atom% He) based on strength degradation due to irradiation damage at this level. Certainly this is an area where future R&D should be directed. No specific value is proposed for design studies at this time.

Planned Irradiation Experiments

A number of irradiation tests have been planned for the coming year or two including those listed in the table below. They should provide key data to help better understand many of the issues described above.

SiC Irradiation Tests	**Reactor**	**Temperature (°C)**	**Irradiation Level (dpa)**
12J and 14J (monolithic and composite: thermal conductivity, bend strength, dimensional change fiber strain and creep)	HFIR	500, 800	<10
Mapping Elevated Temperature Swelling (METS) capsules (single crystals and Morton CVD)	HFIR	600-1500	1.5, 3.0
In planning stages. Will probably include composite thermal conductivity and fiber creep	HFR	600-1000	2.5
Composite thermal conductivity	ATR	300	2
Thermomechanical properties	JOYO	400-600	≤30
He effect through Boron injection followed by irradiation	JMTR	500-1000	≈1

The importance of ion beam irradiation for better control of temperature and irradiation conditions and subsequent analysis of microproperties was also pointed out.

Suggested SiC/SiC Properties and Parameters for Design Studies

Based on the above discussion, the following parameters and properties are suggested for design analysis of SiC/SiC-based power plant for the long term (20-30 years in the future, or more).

Key SiC/SiC Properties and Parameters	Suggested Value
Density	≈3000 kg/m^3
Porosity	≈5%
Young's Modulus	200 GPa
Poisson's ratio	0.16-0.18
Thermal Expansion Coefficient	4 µm/m/°C
Thermal Conductivity in Plane	≈20 W/m-K
Thermal Conductivity through Thickness	≈20 W/m-K
Maximum Allowable Combined Stress	≈190 MPa
Max. Allowable Temperature (Swelling basis)	≈1000 °C
Maximum Allowable SiC/LiPb Interface Temperature	≈1000°C
Min. Allowable Temperature (Thermal conductivity basis)	≈600 °C
Max. Allowable SiC Burnup or other Lifetime Parameter	Design dependent
Cost	≤$400/kg

Interface of the Design and Material Communities

There was strong agreement that bringing together the design and material communities is very useful and should be done on a more regular basis. It provides a unique venue for participants from the design communities to get an in-depth understanding of the current status of material property data and fabrication/joining methods and for the material community to understand the demand on material development to arrive at an attractive SiC/SiC-based fusion power plant in terms of performance, lifetime, cost and safety criteria.

It was suggested to try to organize these meetings in series with already planned meetings such as the US-Japan workshops on design and on material and the IEA-sponsored meetings of the SiC Working Group.