Nuclear
TECHNICAL BRIEF

Advanced Nuclear Technology Program, P41.08.01

PROGRAM ON TECHNOLOGY INNOVATION: SiC-SiC COMPOSITES FOR NUCLEAR APPLICATIONS

This quick guide provides a brief introduction to silicon carbide-silicon carbide (SiC-SiC) composites and considerations for potential structural applications within advanced fission reactors. Owing primarily to their high temperature mechanical stability, SiC-SiC composites are being considered for applications in multiple advanced non-light water reactor concepts including molten salt reactors (MSRs), gas-cooled reactors (GCRs), and lead-cooled fast reactors (LFRs). Qualification and deployment of SiC-SiC composites requires a thorough understanding of how they are manufactured and how material performance can vary based on the manufacturing process. Within the context of this quick guide and in relation to potential advanced reactor applications, SiC-SiC composite properties of interest include those in the as-manufactured, irradiated, chemical attack/oxidation, and stress-time-temperature (STT) states. The qualification process of SiC-SiC composites through the ASME Boiler and Pressure Vessel Code (BPVC) Section III, Division 5 provides avenues for SiC-SiC composite qualification, but key technological gaps will need to be overcome to incorporate SiC-SiC composite components into advanced reactors.

SiC PRODUCT FORMS AND CONSTITUENTS

SiC can be produced in numerous ways depending on the application and desired properties. For nuclear applications, the two SiC forms of interest are: monolithic SiC and SiC-SiC composites. Interest in bulk SiC ceramics produced by chemical vapor deposition (CVD) has persisted since the 1960s due to its candidacy as a layer in TRISO fuel particles [1]. A study from Oak Ridge National Laboratory (ORNL) has found potential use for additive manufacturing of nuclear grade bulk SiC material through analysis of available advanced manufacturing processing methods and the retention of properties of the SiC through the printing process [2].

The inherent brittle nature of SiC can be overcome by combining several constituents together to form a composite capable of straining inelastically when subjected to mechanical loading. Nuclear grade SiC-SiC composites, i.e., those meeting the requirements of ASM BPVC Section III, Division 5, ASTM C1793, or similar standards, are carefully controlled in their composition to ensure no neutron absorbers, fissionable elements, or other undesirable materials are contained in the composite. A nuclear grade SiC-SiC composite consists of three components: 1) a continuous fiber SiC, 2) the SiC matrix, and 3) an interphase which is typically pyrolytic carbon (PyC, sometimes referred to as pyrocarbon). A description of each constituent including the relevant manufacturing processes used in their production are included in the following subsections.

Continuous SiC Fibers

A common approach to producing SiC fibers involves spinning and heat treating polymeric precursors. First, the green state organosilicon polymer, typically polycarbosilane (PCS) or polytitanocarbosilane (PTCS), is melt-spun and eventually cured through cross-linking at elevated temperatures either by exposure to oxygen or electron beam curing [3],

[4]. Because a polymer precursor is used, fibers can be made into continuous multifilament tows (fiber bundles) that are supplied to customers on spools. These spools allow for flexible handling such that they can be woven or braided into complex shapes [5].

Common two-dimensional woven architectures used to manufacture planar components include plain weave (PW) and satin-weave (SW). Examples of these patterns are shown in Figure 1. The PW has fibers that are interlaced in an alternating pattern over and under every other fiber to promote fiber stability and firmness. SWs, such as the eight-harness SW, are pliable and thus readily conform to complex geometry requirements. Typically, SWs are denser than PWs because more threads per inch are required to maintain adequate stability [5]. While the weaving pattern leads to differences in the ability of the pattern to conform to geometries, the properties of the composite are not significantly affected by the weave pattern when the fiber densities in the two directions are the same. Dissimilarity in the properties arises with the orientation in which the two-dimensional weaves are stacked. Choice of two-dimensional woven architecture is therefore driven by the geometry requirements and the stacking requirements of the composite. Thus, the choice of weave is made primarily on the requirements to align the layers in the desired geometry (stiffness from PW, flexibility from SW).

Orthotropic properties, i.e., properties that are different along each of the three principal directions, are achieved by stacking orthogonally woven fabrics with 0° or 90° rotations for each layer. If more isotropic in-plane properties are desired, a 0°/±30° stacking can be employed at the expense of on-axis strength. More complex three-dimensional architectures can be designed by varying x:y:z fiber ratios to tailor anisotropic properties, or by using braiding techniques to create three-dimensional tubular geometries [3]. Prototypes of nuclear components that have been successfully manufactured using SiC-SiC composites include accident tolerant fuel claddings (using braiding techniques) and boiling water reactor (BWR) channel boxes (using stacked weaves) [6].

It is important to note that the composition and microstructure of SiC fibers slated to be used in nuclear applications are distinct from typical SiC fibers that might be used in other industries. Both SiC fibers and matrices used in nuclear applications consist of polycrystalline beta-phase SiC with average grain sizes ranging from tens to hundreds of nanometers [4]. Nuclear grade SiC fibers have undergone three iterations (Generation I, Generation II, and Generation III [4]), with the first two experiencing inadequate resistance to irradiation caused by the presence of oxygen and excess carbon and impurities such as SiC nano-crystallites. To resolve these issues, additional high-temperature processes such as decarburization and sintering with alumina and boron additives were included in the fiber processing to greatly reduce the amount of excess oxygen present in Generation I fibers and to produce a near-stoichiometric composition with enhanced crystallinity compared to Generation II fibers. Commercially available examples of these Generation III SiC fibers include Hi-Nicalon Type S (HNLS), Tyranno SA3 (SA3), and Sylarmic™ [4].

SiC Matrix

Processes used to produce ceramic matrices generally involve the use of reactant fluids that infiltrate the continuous fiber structure and form a deposited matrix [3]. Specific processes include chemical vapor infiltration (CVI), melt infiltration (MI), sol-gel processing, and polymer infiltration

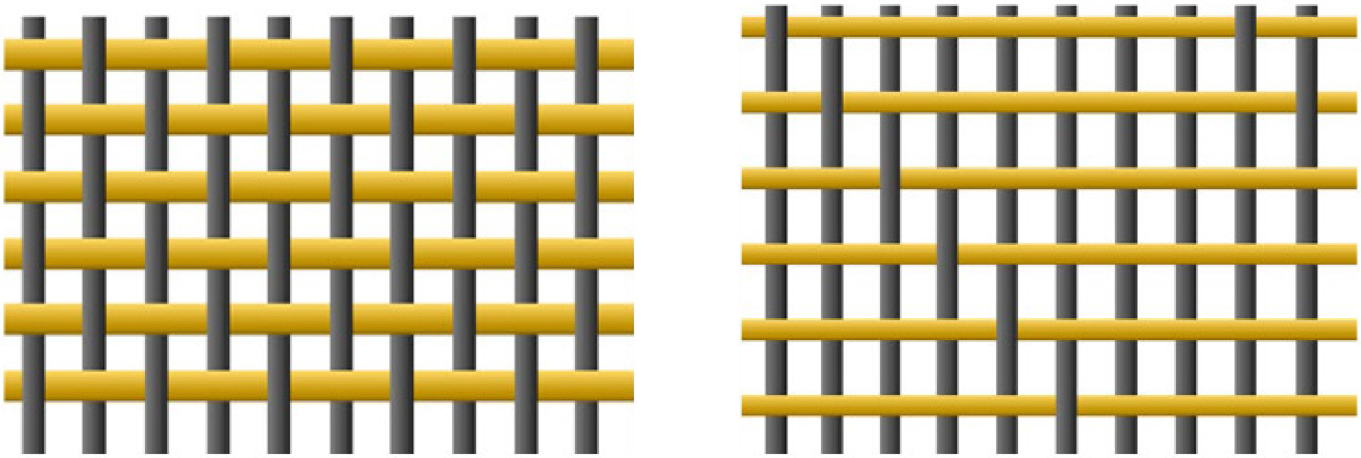

Figure 1: *Example of a PW (Left) and an Eight-Harness SW (Right)*

and pyrolysis. Like nuclear grade SiC fibers, the matrices for SiC-SiC composites require near-stochiometric composition, high crystallinity, and low amounts of impurities that could cause detrimental irradiation effects. For nuclear applications, CVI is used as the primary matrix forming method due to its ability to best satisfy the microstructural requirements of nuclear grade SiC.

SiC CVI matrices are produced by heating methyltrichlorosilane, dichlorosilane, or ethyltrichlorosilane and hydrogen to a temperature of 900-1100°C at a pressure of 10-100 kPa [3] [4]. As the SiC matrix is continually deposited onto the fibers, pores begin to form and are subsequently closed during the final stages of CVI. A representation of this process can be found in Figure 2.

If closing of additional pores is desired, then machining can be performed on the surface of the components to expose the pores to additional matrix densification through additional CVI applications. Depending on the thickness of the component, this process of pore exposure can be repeated until a desired density is achieved. Porosity values of 10-15% are typical of completed CVI processes [5]. Notable characteristics of two-dimensional SiC-SiC components produced by CVI are dense matrix regions near the fibers on which deposition nucleated and coarse pores in regions between plies or tows. An example microstructure of a completed SiC-SiC composite formed through CVI is shown in Figure 3.

PyC Interphase

The interface between the reinforcement phase and the composite matrix is where important mechanical processes occur such as load transfer, debonding, and sliding. To optimize the properties of the composite, an interphase can be added to increase the adhesion between the continuous fibers and matrix. For SiC fibers used in nuclear applications, PyC as well as multilayer PyC/SiC are commonly used as fiber coatings before matrix formation [4]. The PyC interphase coatings can be observed in the lower right-hand portion of Figure 3.

The most common method for producing PyC interphase coatings is through CVD in a methane-hydrogen atmosphere, with a thickness of 50-200 nm used in the production of Generation III SiC fibers [4]. Interphase thickness is important to control as it can influence mechanical performance. Coating thicknesses that are too thin can lead to excessive frictional

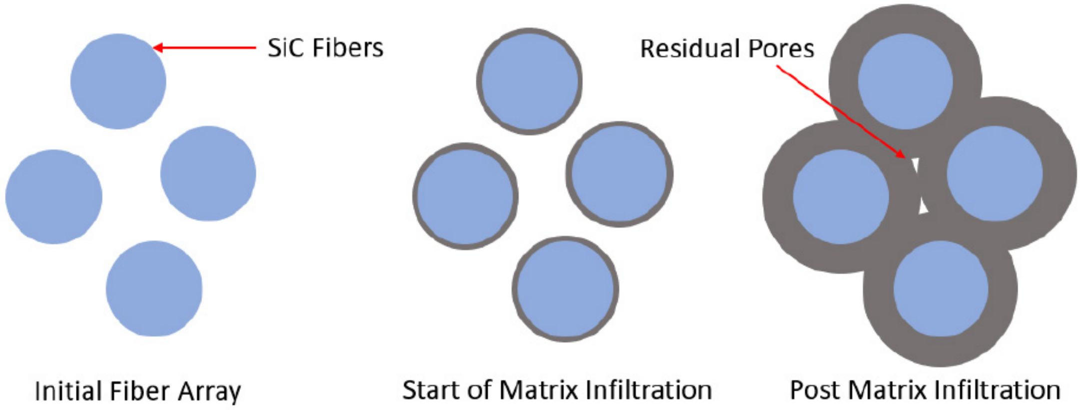

Figure 2: *CVI Growth Mechanism*

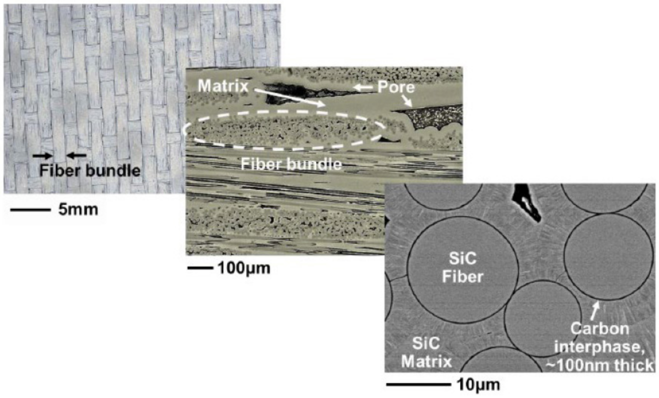

Figure 3: *Example Microstructure of SiC-SiC Composite Made Using CVI [7]*

stresses at the interfaces between fibers and the matrix, ultimately resulting in brittle fracture. Alternatively, coatings that are too thick can result in inadequate load transfer between matrix and reinforcement fibers thus reducing the overall strength of the composite.

RELEVANT MATERIAL PROPERTIES

The ASME BPVC Section III Division 5 Subsection HH Subpart B establishes rules for the design and construction of composite core components for high temperature nuclear applications, including components constructed of SiC-SiC composites [8]. The specific property categories identified as being necessary for the reactor designer to define and include in a material data sheet (MDS) are the as-manufactured properties, the irradiated properties, the chemical attack/oxidation properties, and the properties related to STT conditions. Clarification on what specific properties need to be included in each category as well as current knowledge of SiC-SiC composite properties are provided in the following subsections.

As-Manufactured Properties

Material properties of the SiC-SiC composites in the as-manufactured condition include mechanical properties such as the ultimate tensile strength, yield strength, and elastic modulus, which can be measured in tension, compression, and in a mixture of the two (flexure). Durability and reliability properties are also needed in the as-manufactured condition. These include fatigue strength, thermal shock resistance, erosion wear resistance, and fracture toughness. Other important as-manufactured properties include chemical composition, constituent volume fractions, coefficient of thermal expansion, thermal conductivity, emissivity, and density. Additionally, composite-specific descriptors such as the fiber architecture and the apparent porosity of the bulk material should be measured. It is important to note that many of the composite properties, such as the tensile strength, will need to be characterized in three directions due to the anisotropic nature of the composites.

The composite properties are significantly affected by the volume fractions and orientations of the fibers relative to the orientation of interest for specific properties. Nuclear grade SiC fibers generally have high tensile strengths upwards of >3 GPa, high Young's Modulus values of >400 GPa, and densities of 2.1 3.5 g/cm³ [4] [8]. As a result of using SiC fibers combined with the SiC matrix and PyC interphase, the bulk composites have increased fracture toughness, enhanced thermal shock resistance, the ability to undergo dynamic loading, and elongations of up to 1% before rupture.

There is currently a discrepancy between fracture toughness reported from testing and fracture toughness reported in a SiC handbook for performance properties. The values for fracture toughness versus temperature are reported to increase with increasing temperature. The highest of these measurements, reported at 1500°C, is less than half of the reported fracture toughness from a study conducted by independent researchers at the same temperature. Because many advanced reactor designers do not currently know the loading conditions of their reactors, it is unclear if this discrepancy will affect reactor designs. More testing will be necessary to understand where this discrepancy is produced and how to reconcile the accepted values of fracture toughness for SiC-SiC components [9].

Irradiated Properties

Changes in mechanical properties resulting from changes in microstructure caused by irradiation need to be rigorously quantified and understood before advanced reactors can confidently be constructed for a 60-year design lifetime. Several studies have been conducted to examine the effects of irradiation on the properties of SiC-SiC composites, with neutron irradiation doses as high as ~74 dpa at temperatures of 800°C [9]. One study examined the effects of intermediate fluence levels (~10 dpa) on the properties of nuclear grade SiC-SiC composites and found no significant changes in mechanical properties including Young's modulus, ultimate tensile strength, Poisson's ration, and damage tolerance [4].

Another notable effect of irradiation is the introduction of volumetric swelling caused by Frenkel defect production and build-up that typically saturates around a dose of ~1 dpa below 1000°C. Above 1000°C and up until 1400°C, swelling mechanisms become a mixture of defect build-up and slowly developing voids from vacancy mobilization. Beyond 1400°C, unstable growth of vacancy clusters can lead to void swelling. The swelling behavior of SiC-SiC composites has been shown to be like that of monolithic CVD SiC with low swelling values of ~2% at higher temperatures [4].

Lastly, recent irradiation studies have raised potential concerns regarding material degradation due to high doses of neutron irradiation under relatively low operating temperatures. One study using a CVI composite with Hi-Nicalon™ Type S fiber and a PyC/SiC multi-layer interphase, showed that the material exhibited an irradiation-temperature dependent degradation behavior. Significant degradation of mechanical properties occurred at temperatures below 600°C, with the composite experiencing brittle fracture following irradiation at 300°C to 92 dpa. For the EM² gas-cooled fast reactor being developed by General Atomics, the components that will consist of SiC-SiC composites will experience up to 150 dpa as reflector materials and up to 200 dpa as control rod guides. The findings from the recent irradiation studies show that this may be unsustainable for the life of the reactor and more research is needed to understand the irradiation of SiC-SiC composites. Other areas of the reactor have the potential for lower dpa values, with the fuel subassembly and fuel subassembly ducts both experiencing a total of 60 dpa. These components are designed as SiC-SiC composites [9]. In an unirradiated condition, SiC-SiC composites exhibit quasi-ductile fracture behavior. Therefore, it can be postulated that the lifetimes of current nuclear-grade SiC-SiC composites can be significantly affected by high-doses of neutron irradiation followed by loading at relatively low temperatures.

Properties Related to Oxidation and Chemical Attack

Data concerning the corrosion behavior of SiC in various environments is limited, with only a few available studies on SiC in high temperature oxygen, high temperature water, molten metal, and molten salt environments. In general, strong bases, molten metals, and oxygen at temperature exceeding 800°C react with SiC to form carbide and silicides as discussed in Nonmandatory Appendix HHB-B of ASME BPV Code Section III Division 5 [8]. For reactor designs using high temperature gas as the coolant, the reactions between oxygen and SiC will form SiO_2 and CO_2, with a passive oxidation layer of SiO_2 forming to slow down further oxidation. At low partial pressures of oxygen and temperatures above 1600°C, active oxidation of SiC forms CO, CO_2, and gaseous SiO with ensuing rapid losses of SiC [10]. Additional oxidation resistance in SiC-SiC composites can be obtained by using multilayer PyC-SiC interphases rather than the monolayer PyC interphase [4].

For advanced reactor designs using water as the primary coolant, hydrothermal corrosion of SiC will be of concern. Hydrothermal corrosion of SiC is governed by the rate of silica formation at the surface of material.
Silica will readily dissolve in water depending on the water chemistry, with higher amounts of dissolved oxygen generally causing larger corrosion rates. Results from several studies showing the weight change of SiC in simulated BWR and PWR water chemistries are shown in Figure 4.

Lastly, the effects of molten salt and liquid metal on the corrosion of SiC have been studied in a few different experiments. For liquid metal, SiC has been shown to be resistant to corrosion up to 800°C in several short-term static tests [12]. Molten salt studies were conducted by exposing SiC samples to molten FLiNaK at 700°C for 360 hours, which led to a preferential dissolution of Si from the SiC bulk material causing an increase of Si in the liquid salt from 45 µg/kg to 95 µg/kg [13]. For both of these environments, further testing has been identified as necessary for closing knowledge gaps. Liquid metal testing will require long term dynamic testing to understand the effects of wear and corrosion on SiC-SiC composites at time periods similar to reactor internals [12]. For MSR environments, further irradiation testing will be needed to understand Si dissolution. Some irradiation testing has been performed, with some indications of the promotion of Si dissolution in molten salt, but these tests were not performed in an irradiating environment, only on post irradiated SiC-SiC composites. Representative testing for MSR environments will be needed to understand the effect of irradiation on Si dissolution, as well as the effect of increased Si concentration on surrounding components [13].

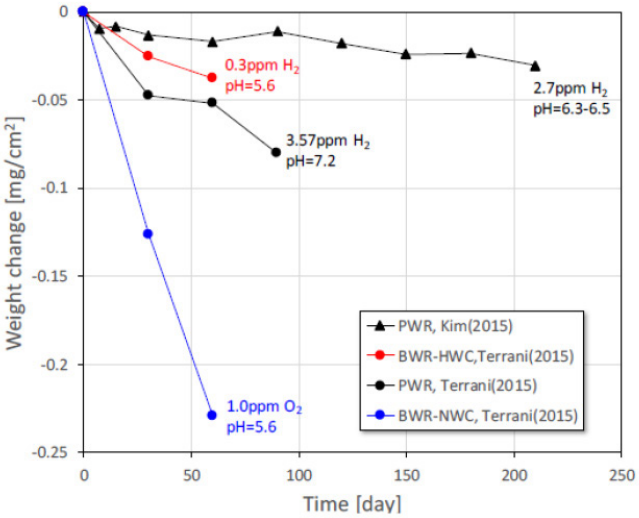

Figure 4: *Mass Change in CVD SiC After Exposure to Simulated Reactor Water Loops [11]*

Properties Related to STT Conditions

Properties related to STT conditions include effects attributable to creep, stress rupture, slow crack growth, and fatigue on the physical and mechanical properties of the SiC-SiC composite. SiC-SiC composites have an inherent stability, attributable to their robust microstructure, at temperatures up to 1400°C with some types of nuclear grade SiC-SiC composites capable of maintaining stability up to 1800°C [4]. The primary limitation of this stability is the rate at which the grains coarsen and cause reductions in fiber strength and increases in fiber surface roughness. Creep mechanisms in steady-state conditions are primarily controlled by grain boundary sliding with different limiting diffusional pathways. Previous studies have documented the creep behavior of SiC fibers [14] [15].

The abundance of STT data for SiC-SiC composites suggests that the non-irradiated stability of SiC-SiC composites is greater than the design requirements of current advanced reactor designs.

Therefore, the usable life of the composites will likely be determined by environmental effects and the relevant stress states of the components.

Further evidence of the superior performance of SiC-SiC under STT conditions can be seen in both Reference [4] and Figure 5. Reference [4] provides a detailed life prediction and time-related failure analysis of SiC-SiC composites using high temperature gas reactor (HTGR) operating conditions. Reference [4] found that a Hi-Nicalon Type S/CVI SiC composite can meet a 60-year design life at a normal reactor temperature of 950°C under low partial pressure oxidizing conditions, maximum stresses of 90 MPa, and with maximum temperature events not exceeding 1250°C. Additionally, Figure 5 presents a comparison of operating temperature windows for SiC-SiC composites and other candidates for structural components with respective lower and upper temperature uncertainty bands indicating regions where thermal creep and radiation embrittlement could become a concern.

POTENTIAL ADVANCED REACTOR APPLICATIONS

Advanced reactor designs can be categorized by their coolants, which include GCRs, MSRs, and liquid metal cooled reactors such as LFRs. A key differentiation of these new reactor designs is their elevated operating temperature relative to currently operating light water reactors (LWRs). Design outlet temperatures approaching 1000°C or more have been proposed for some advanced reactor designs.

To accommodate the high operating temperatures, several applications for SiC-SiC composite components have been identified and are tabulated by reactor design in Table 1.

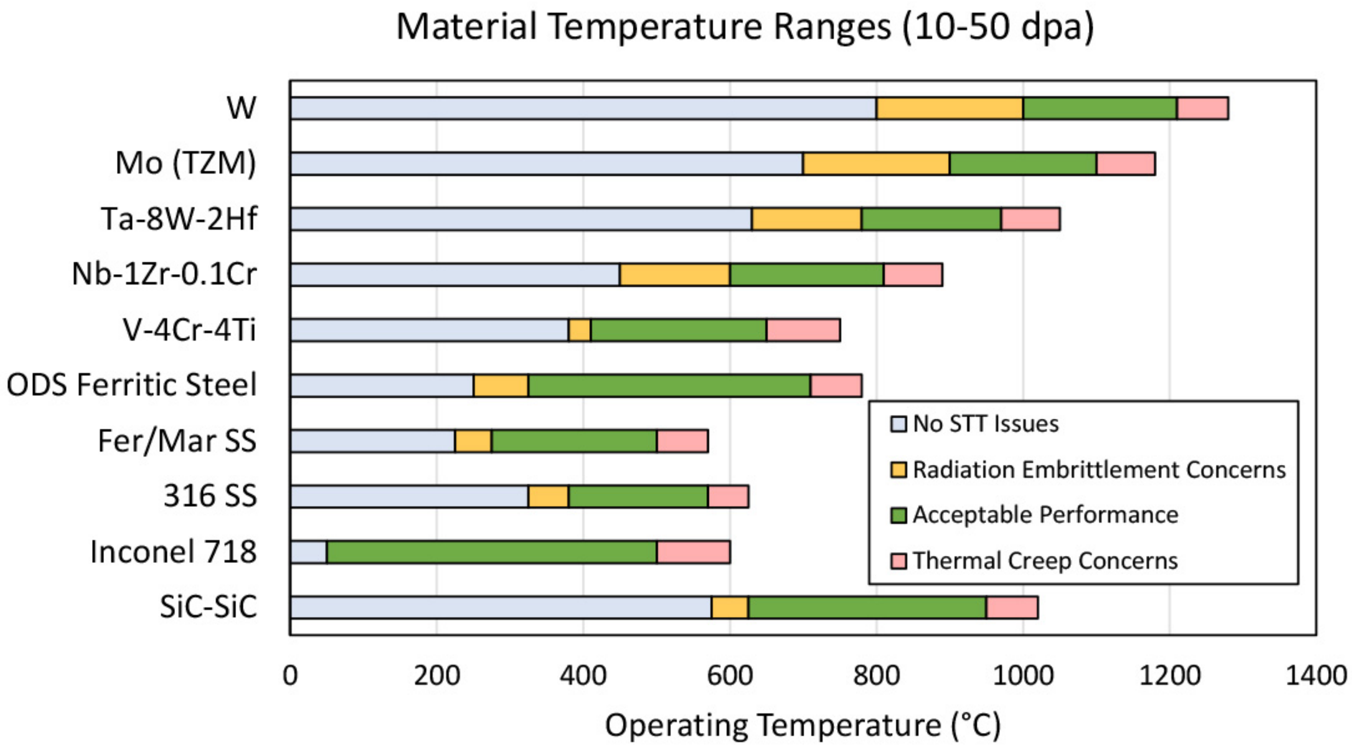

Figure 5: *Estimated Operating Temperature Windows for Structural Materials in Nuclear Energy Systems (After Reference [16])*

MSR designs have included a large amount of SiC-SiC composites. This is in part due to corrosion concerns of metals in contact with molten salt coolant, as well as the stability of SiC-SiC composites in the operating temperature range of MSR environments [7]. In general, applications where the high-temperature stability, oxidation and corrosion resistance, and radiation tolerance of high-temperature structural metals is inadequate, SiC-SiC composites could be a suitable material choice. Further research will still be needed for SiC-SiC composites in these environments. For VHTRs and GFRs, gaps related to the experience in realistic fluence environments, low oxygen concentration and rapid oxidation environments, fracture toughness requirements, and porosity in SiC composites are noted [9]. For MSR environments, the interaction of SiC composites and molten salt systems have had limited testing, with available tests showing preferential dissolution of Si into the molten salt [13]. A recent gap analysis for materials in LFR environments notes that nuclear grade SiC-SiC composite components do not have a high technology readiness level, stating that SiC-SiC composite properties are highly dependent on fabrication practices and that industrial scale SiC-SiC composite production is limited. Joining challenges have been noted, with brazing and diffusion bonding still being developed for SiC-SiC composites [12].

QUALIFICATION FOR ADVANCED REACTOR DESIGN

Qualification of SiC-SiC composites for nuclear applications is challenging due the wide range of material properties that can be achieved by varying composition, fiber architecture, and/or manufacturing process. Further, the propriety nature of SiC-SiC component fabrication makes industry-wide research efforts quite difficult. Initial efforts within the advanced reactor community have focused on design-specific component qualification to accelerate ceramic composite deployment [17].

Codification of SiC-SiC composites within ASME has recently been realized for advanced reactor core components within Section III Division 5 Subpart HHB [8]. The qualification process for SiC-SiC composite components is performed in accordance with Article HHB-2200. A material data sheet (MDS) will be generated by the reactor designer, which will contain the required material properties of the composite components in the as-manufactured, irradiated, chemical attack/oxidation, and STT states as defined in the qualification envelope of the design specification. This qualification envelope refers to the ranges of certain environmental conditions that the components will experience such as temperatures during normal and off-normal operation, irradiation conditions, long-term stress states and levels, and oxidative/chemical attack conditions. Temperature dependent properties are required to be measured over the range of temperatures defined by the qualification envelop as well as off-normal temperature conditions in increments of no more than 200°C. Additional testing details and requirements necessary to determine the as-manufactured, irradiated, chemical attack/oxidation, and STT properties are defined in ASTM C1793 [18].

As-Manufactured Properties

The MDS will first need to include the material properties of the composite in the as-manufactured condition in the temperature range as required for the application of the component. At a minimum, the following properties will need to be determined to adequately define the as-manufactured properties of the SiC-SiC composite components:

- Bulk density and porosity
- Coefficient of linear thermal expansion
- Thermal conductivity
- Tensile properties such as ultimate strength and strain and proportional limit strength and strain
- Flexure properties
- Compression properties

Table 1: *Proposed SiC-SiC Components for Advanced Reactors Grouped by Reactor Design*

ADVANCED LWR [6]	LFR [12]	MSR [13, 7]	GCR [9]
Fuel cladding	Fuel cladding and assembly structure	Reactor vessel internals	Control rods and guide tubes
BWR channel box	Heat exchanger	Primary heat exchangers	Core restraints
		Core barrel	Liners for hot ducts and insulation
		Fuel and control blade assembly supports	
		Reactor core supports	
		Instrumentation sleeves	

- Design strength and reliability curve values such as selected strength ratios and Weibull parameters
- Young's modulus

Irradiated Material Properties

The following properties, which are related to changes in microstructure caused by irradiation, will need to be determined and documented in the MDS:

- Dimensional changes
- Irradiation creep coefficient
- Coefficient of thermal expansion
- Thermal conductivity
- Tensile strength (both proportional and ultimate values)
- Young's modulus

The data are required to be representative of irradiation conditions anticipated in service, indicating that the testing shall be representative of reactor neutron fluence, damage dose, and temperature ranges.

Chemical Attack/Oxidation Effects on Material Properties

Changes in material properties directly related to oxidation/chemical attack will be characterized by conducting testing in environments representative of service conditions (reactor coolant chemistries and operating temperatures). The tensile strength, dynamic modulus, and thermal conductivity will all be measured as a function of exposure time and weight change.

STT Effects on Material Properties

The advanced reactor designer will have to specify what STT effects shall be determined for the composite materials of interest. Depending on the material's susceptibility and qualification envelop, the following properties will be measured:

- Creep data showing primary, secondary, and tertiary regimes
- Creep stress rupture life
- Slow crack growth stress rupture life
- Fatigue life

TECHNOLOGICAL GAPS

The largest technological gap in determining the feasibility of SiC-SiC composites in advanced reactors is fully understanding the environmental effects on the composites' properties and subsequent reliability for the expected life of the reactors. To address this gap requires extensive long-term testing to adequately determine whether SiC-SiC composites will be a suitable material design choice for advanced reactors.

Environmental effects encompass the combined influence of irradiation effects, corrosion/oxidation effects, and STT effects on the performance SiC-SiC composites. The environmental effects are heavily dependent on the reactor design and coolant chemistry. For GCRs, the available information on the long-term behavior of SiC-SiC composites in impure helium environments is scarce. It has therefore been identified that long-term oxidation studies in impure helium are needed for both irradiation-free and irradiation-active conditions [9]. Additionally, the extent of the potential degradation of SiC-SiC composites under low partial pressures of oxygen at high temperatures is not known. To address this gap, experimental evaluation of the stability of SiC-SiC composites at low oxygen partial pressures and high temperatures is needed.

Data for corrosion effects in other environments such as liquid metal, molten salt, and light water are also limited and will require further investigation. SiC-SiC composites have shown promising resistance to both liquid metal and molten salt in some short-term static tests, but long-term testing is needed to further validate its compatibility with these environments [12] [13]. For reactor designs using light water, hydrothermal corrosion has been identified as a critical feasibility issue. SiC-SiC composites appear to undergo an unacceptable amount of mass loss in BWR water chemistries [6]. Therefore, further systematic testing is needed to quantify the kinetics and identify the mechanism of corrosion in LWR environments to determine whether hydrothermal corrosion is a non-critical issue or resolvable through credible technical solutions such as environmental barrier coatings.

The strength at high temperatures is also not well characterized for nuclear grade SiC-SiC composites. Peak temperatures for some gas fast reactors are expected to reach upwards of 1920°C under accident conditions [9]. Therefore, the very high temperature strength and integrity of SiC-SiC composites will need to be assessed.

Lastly, more testing is required to characterize the changes in mechanical and physical properties from high doses of neutron irradiation. The effect of irradiation on SiC-SiC have been well documented for doses up to ~40 dpa, but expected doses for the lifetime of fast reactor designs are anticipated to be well above this value. As a result, more studies are needed to characterize the response of SiC-SiC composites to high doses (~100 dpa) at both high and low irradiation temperatures to provide confidence that SiC-SiC components will not fail during the design lifetime of advanced reactors.

In all of these gaps, testing time is a key issue. For deployment on practical timescales, it will not be possible to conduct sufficiently long tests before material selections must be made. Therefore, in addition to long-term testing under nominal conditions, there must also be short-term testing at accelerated conditions, whether that acceleration is caused by higher fluxes, higher temperatures, more aggressive chemistry, or greater stresses. Additionally, enough conditions must be evaluated to provide confidence that such accelerated testing is a valid predictor of long-term performance.

CONCLUSIONS

This quick guide provides a brief introduction to SiC-SiC composites and their potential uses for advanced reactor applications. SiC-SiC composites exhibit suitable thermal properties, mechanical strength, and radiation resistance, which make them an attractive candidate for use in advanced reactor applications. The current composites with nuclear-grade classifications consist of third generation SiC fibers defined by their high-crystallinity and near-stoichiometric composition, a similarly highly crystalline SiC matrix formed through CVI, and a PyC interphase material formed through CVD onto the fibers.

Although SiC-SiC composites possess inherent properties that make them ideal for high-temperature nuclear applications, there are still knowledge gaps that need to be resolved before full implementation can proceed. Such issues include a lack of knowledge surrounding the environmental effects on SiC-SiC component performance and reliability. Long-term studies in reactor-specific environments such as high-temperature helium, molten salt, liquid metal, and light water are needed to characterize the resistance of SiC-SiC composites to environmental degradation. Further investigation into the response of SiC-SiC composites to irradiation at high fluences is also needed to provide data more representative of expected fast reactor fluences. To obtain assurances needed for use of SiC-SiC composites in a useful timeframe, accelerated testing is likely to be necessary.

Once the feasibility of SiC-SiC composites is determined, specific components can be manufactured and qualified using the guidelines detailed in ASTM C1793 and Section III Division 5 of the BPVC. This process will require extensive standardized testing to meet all the material specification requirements necessary to complete the material data sheet. In general, historical qualification data can be used in this process. However, the extent to which the raw materials and manufacturing processes for new components must be similar to those for components for which historical data are available is not well defined. Efforts to change the qualification requirements to include component qualification are underway, but currently going through the ASME BPV material data sheet is the only accepted method of material qualification. Therefore, while SiC-SiC composites are a potential material candidate for nuclear core component applications, their feasibility still needs to be demonstrated through additional experimentation and the production of a component that successfully adheres to the ASME process. SiC-SiC components have been tested in different capacities depending on their desirability to advanced reactor manufacturers and their applications across different designs.

For SiC-SiC composite components such as fuel cladding, BWR channel boxes, and control rod guide tubes, all of which have been manufactured and tested, albeit not for all properties such as time-dependent properties, a Technology Readiness Level of 6 (system/subsystem model or prototype demonstration in a relevant environment [19]) would be appropriate. For other components, which are considered potential candidates and have not been tested, a Technology Readiness Level of 3 (analytical and experimental critical function and/or characteristic proof of concept [19]) would be appropriate. Overall, more research on SiC-SiC composite components will be required to begin qualification of components in earnest for advanced reactor designs.

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EXPORT PART 810 CONTROL

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Dominion Engineering, Inc.

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Advanced Nuclear Technology

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