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Standard Guide for Development of Specifications for Fiber Reinforced Silicon Carbide-Silicon Carbide Composite Structures for Nuclear Applications¹

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1. Scope

1.1 This document is a guide to preparing material specifications for silicon carbide fiber/silicon carbide matrix (SiC-SiC) composite structures (flat plates, rectangular bars, round rods, and tubes) manufactured specifically for structural components and for fuel cladding in nuclear reactor core applications. The SiC-SiC composites consist of silicon carbide fibers in a silicon carbide matrix produced by liquid infiltration/pyrolysis and/or by chemical vapor infiltration.

1.2 This guide provides direction and guidance for the development of a material specification for a specific SiC-SiC composite component or product for nuclear reactor applications. The guide considers composite constituents and structure, physical and chemical properties, mechanical properties, thermal properties, performance durability, methods of testing, materials and fabrication processing, and quality assurance. The SiC-SiC composite materials considered here would be suitable for nuclear reactor core applications where neutron irradiation-induced damage and dimensional changes are significant design considerations. **(1-8)**²

1.3 The component material specification is to be developed by the designer/purchaser/user. The designer/purchaser/user shall define and specify in detail any and all application-specific requirements for design, manufacturing, performance, and quality assurance of the ceramic composite component. Additional specification items for a specific component, beyond those listed in this guide, may be required based on intended use, such as geometric tolerances, permeability, bonding, sealing, attachment, and system integration.

1.4 This guide is specifically focused on SiC-SiC composite components and structures with flat plate, solid rectangular bar, solid round rod, and tubular geometries.

1.5 This guide may also be applicable to the development of specifications for SiC-SiC composites used for other structural applications, discounting the nuclear-specific chemical purity and irradiation behavior factors.

1.6 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards*:³

- C242 Terminology of Ceramic Whitewares and Related Products
- C559 Test Method for Bulk Density by Physical Measurements of Manufactured Carbon and Graphite Articles
- C577 Test Method for Permeability of Refractories
- C611 Test Method for Electrical Resistivity of Manufactured Carbon and Graphite Articles at Room Temperature
- C625 Practice for Reporting Irradiation Results on Graphite
- C714 Test Method for Thermal Diffusivity of Carbon and Graphite by Thermal Pulse Method
- C769 Test Method for Sonic Velocity in Manufactured Carbon and Graphite Materials for Use in Obtaining an Approximate Value of Young's Modulus
- C816 Test Method for Sulfur Content in Graphite by Combustion-Iodometric Titration Method
- C838 Test Method for Bulk Density of As-Manufactured Carbon and Graphite Shapes
- C1039 Test Methods for Apparent Porosity, Apparent Specific Gravity, and Bulk Density of Graphite Electrodes
- C1145 Terminology of Advanced Ceramics

¹ This guide is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.07 on Ceramic Matrix Composites.

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² The boldface numbers in parentheses refer to the list of references at the end of this standard.

³ For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

- C1179** Test Method for Oxidation Mass Loss of Manufactured Carbon and Graphite Materials in Air
- C1198** Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Sonic Resonance
- C1233** Practice for Determining Equivalent Boron Contents of Nuclear Materials
- C1239** Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics
- C1259** Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio for Advanced Ceramics by Impulse Excitation of Vibration
- C1274** Test Method for Advanced Ceramic Specific Surface Area by Physical Adsorption
- C1275** Test Method for Monotonic Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Test Specimens at Ambient Temperature
- C1291** Test Method for Elevated Temperature Tensile Creep Strain, Creep Strain Rate, and Creep Time-to-Failure for Monolithic Advanced Ceramics
- C1292** Test Method for Shear Strength of Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperatures
- C1337** Test Method for Creep and Creep Rupture of Continuous Fiber-Reinforced Advanced Ceramics Under Tensile Loading at Elevated Temperatures
- C1341** Test Method for Flexural Properties of Continuous Fiber-Reinforced Advanced Ceramic Composites
- C1358** Test Method for Monotonic Compressive Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics with Solid Rectangular Cross-Section Test Specimens at Ambient Temperatures
- C1359** Test Method for Monotonic Tensile Strength Testing of Continuous Fiber-Reinforced Advanced Ceramics With Solid Rectangular Cross-Section Test Specimens at Elevated Temperatures
- C1360** Practice for Constant-Amplitude, Axial, Tension-Tension Cyclic Fatigue of Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperatures
- C1425** Test Method Interlaminar Shear Strength of 1-D and 2-D Continuous Fiber-Reinforced Advanced Ceramics at Elevated Temperatures
- C1468** Test Method for Transthickness Tensile Strength of Continuous Fiber-Reinforced Advanced Ceramics at Ambient Temperature
- C1470** Guide for Testing the Thermal Properties of Advanced Ceramics
- C1525** Test Method for Determination of Thermal Shock Resistance for Advanced Ceramics by Water Quenching
- C1557** Test Method for Tensile Strength and Young's Modulus of Fibers
- C1683** Practice for Size Scaling of Tensile Strengths Using Weibull Statistics for Advanced Ceramics
- C1773** Test Method for Monotonic Axial Tensile Behavior of Continuous Fiber-Reinforced Advanced Ceramic Tubular Test Specimens at Ambient Temperature
- D2766** Test Method for Specific Heat of Liquids and Solids
- D3171** Test Methods for Constituent Content of Composite Materials
- D3529/D3529M** Test Method for Matrix Solids Content and Matrix Content of Composite Prepreg
- D3800** Test Method for Density of High-Modulus Fibers
- D3878** Terminology for Composite Materials
- D4018** Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows
- D4284** Test Method for Determining Pore Volume Distribution of Catalysts and Catalyst Carriers by Mercury Intrusion Porosimetry
- D4850** Terminology Relating to Fabrics and Fabric Test Methods
- D5528** Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites
- D5600** Test Method for Trace Metals in Petroleum Coke by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES)
- D5766** Test Method for Open-Hole Tensile Strength of Polymer Matrix Composite Laminates
- D5961** Test Method for Bearing Response of Polymer Matrix Composite Laminates
- D6484** Test Method for Open-Hole Compressive Strength of Polymer Matrix Composite Laminates
- D6507** Practice for Fiber Reinforcement Orientation Codes for Composite Materials
- D6671** Test Method for Mixed Mode I-Mode II Interlaminar Fracture Toughness of Unidirectional Fiber Reinforced Polymer Matrix Composites
- D7136** Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event
- D7137** Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates
- D7219** Specification for Isotropic and Near-isotropic Nuclear Graphites
- D7542** Test Method for Air Oxidation of Carbon and Graphite in the Kinetic Regime
- E6** Terminology Relating to Methods of Mechanical Testing
- E111** Test Method for Young's Modulus, Tangent Modulus, and Chord Modulus
- E132** Test Method for Poisson's Ratio at Room Temperature
- E143** Test Method for Shear Modulus at Room Temperature
- E228** Test Method for Linear Thermal Expansion of Solid Materials With a Push-Rod Dilatometer
- E261** Practice for Determining Neutron Fluence, Fluence Rate, and Spectra by Radioactivation Techniques
- E289** Test Method for Linear Thermal Expansion of Rigid Solids with Interferometry
- E408** Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques
- E423** Test Method for Normal Spectral Emittance at Elevated Temperatures of Nonconducting Specimens
- E1269** Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry

E1309 Guide for Identification of Fiber-Reinforced Polymer-Matrix Composite Materials in Databases (Withdrawn 2015)⁴

E1461 Test Method for Thermal Diffusivity by the Flash Method

E1922 Test Method for Translaminar Fracture Toughness of Laminated and Pultruded Polymer Matrix Composite Materials

E2586 Practice for Calculating and Using Basic Statistics

2.2 Non-ASTM Standards:

CMH-17, Volume 5 Composite Materials Handbook (CMC Handbook)

ASME B46.1-2009 Surface Texture (Surface Roughness, Waviness, and Lay)⁵

3. Terminology

3.1 Definitions:

3.1.1 *General*—Many of the terms in this guide for specifications are defined in the terminology standards for ceramic whitewares (**C242**), advanced ceramics (**C1145**), composite materials (**D3878**), fabrics and test methods (**D4850**), and mechanical testing (**E6**).

3.1.2 *apparent porosity, n*—the volume fraction of all pores, voids, and channels within a solid mass that are interconnected with each other and communicate with the external surface, and thus are measurable by gas or liquid penetration. (Synonym – open porosity) **C242**

3.1.3 *braided fabric, n*—a woven structure produced by interlacing three or more ends of yarns in a manner such that the paths of the yarns are diagonal to the vertical axis of the fabric. **D4850**

3.1.3.1 *Discussion*—Braided structures can have 2D or 3D architectures.

3.1.4 *bulk density, n*—the mass of a unit volume of material including both permeable and impermeable voids. **D7219**

3.1.5 *ceramic matrix composite, n*—a material consisting of two or more materials (insoluble in one another), in which the major, continuous component (matrix component) is a ceramic, while the secondary component(s) (reinforcing component) may be ceramic, glass-ceramic, glass, metal or organic in nature. These components are combined on a macroscale to form a useful engineering material possessing certain properties or behavior not possessed by the individual constituents. **C1145**

3.1.6 *fabric, n—in textiles*, a planar structure consisting of yarns or fibers. **D4850**

3.1.7 *fiber, n*—a fibrous form of matter with an aspect ratio >10 and an effective diameter <1 mm. (Synonym – filament) **D3878**

3.1.7.1 *Discussion*—A fiber/filament forms the basic element of fabrics and other textile structures.

3.1.8 *fiber areal weight, n*—the mass per unit area of the fibrous reinforcement of a composite material. **D3529/D3529M**

3.1.9 *fiber content/fraction (volume or weight), n*—the amount of fiber present in a composite, expressed either as a percent by weight or a percent by volume. **D3878**

3.1.10 *fiber preform, n*—a preshaped fibrous reinforcement, normally without matrix, but often containing a binder to facilitate manufacture, formed by distribution/weaving of fibers to the approximate contour and thickness of the finished part. **D3878**

3.1.11 *fill, n—in a woven fabric*, the yarn running from selvage to selvage at right angles to the warp. **D3878**

3.1.12 *hybrid, n*—(for composite materials) containing at least two distinct types of matrix or reinforcement. Each matrix or reinforcement type can be distinct because of its a) physical or mechanical properties, or both, b) material form, or c) chemical composition. **D3878**

3.1.13 *injection molding, n—in composite fabrication*, the process of forcing liquid polymer under pressure into a closed mold that contains a fiber preform.

3.1.14 *knitted fabric, n*—a fiber structure produced by interlooping one or more ends of yarn or comparable material. **D4850**

3.1.15 *laminate, n*—any fiber- or fabric-reinforced composite consisting of laminae (plies) with one or more orientations with respect to some reference direction. **D3878**

3.1.16 *lay-up, n*—a process or fabrication involving the placement of successive layers of materials in specified sequence and orientation. **E1309, D6507**

3.1.17 *matrix, n*—the continuous constituent of a composite material, which surrounds or engulfs the embedded reinforcement in the composite and acts as the load transfer mechanism between the discrete reinforcement elements. **D3878**

3.1.18 *matrix content, n*—the amount of matrix present in a composite expressed either as a percent by weight or a percent by volume. **D3878**

3.1.19 *ply, n—in 2D laminar composites*, the constituent single layer as used in fabricating, or occurring within, a composite structure. **D3878**

3.1.20 *prepreg, n*—the admixture of fibrous reinforcement and polymeric matrix used to fabricate composite materials. Its form may be sheet, tape, or tow. For thermosetting polymer, the polymer has been partially cured to a controlled viscosity called “B stage.” **D3878**

3.1.21 *selvage, n*—the woven edge portion of a fabric parallel to the warp. **D3878**

3.1.22 *tow, n—in fibrous composites*, a continuous, ordered assembly of essentially parallel, collimated continuous filaments, normally without twist. (Synonym – roving) **D3878**

3.1.23 *unidirectional composite, n*—any fiber reinforced composite with all fibers aligned in a single direction. **D3878**

3.1.24 *warp, n*—the yarn running lengthwise in a woven fabric. **D3878**

⁴The last approved version of this historical standard is referenced on www.astm.org.

⁵Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Two Park Ave., New York, NY 10016-5990, <http://www.asme.org>.

3.1.25 *woven fabric*, *n*—a fabric structure produced by the interlacing, in a specific weave pattern, of tows or yarns oriented in two or more directions.

3.1.25.1 *Discussion*—There are a large variety of 2D weave styles, e.g., plain, satin, twill, basket, crowfoot, etc.

3.1.26 *yarn*, *n*—in *fibrous composites*, a continuous, ordered assembly of essentially parallel, collimated filaments, normally with twist, and of either discontinuous or continuous filaments. Single yarn – an end in which each filament follows the same twist.

D3878

3.2 Definitions of Terms Specific to This Standard:

3.2.1 *1D, 2D, and 3D reinforcement*, *n*—a description of the orientation and distribution of the reinforcing fibers and yarns in a composite.

3.2.1.1 *Discussion*—In a 1D structure, all of the fibers are oriented in a single longitudinal (*x*) direction. In a 2D structure, all of the fibers lie in the *x-y* planes of the plate or bar or in the circumferential shells (axial and circumferential directions) of the rod or tube with no fibers aligned in the *z* or radial directions. In a 3D structure, the structure has fiber reinforcement in the *x-y-z* directions in the plate or bar and in the axial, circumferential, and radial directions in a tube or rod.

3.2.2 *axial tensile strength*, *n*—for a composite tube or solid round rod, the tensile strength along the long axis of the tube or rod. For a composite flat plate or rectangular bar, the tensile strength along the primary structural axis/direction.

3.2.3 *chemical vapor deposition or infiltration*, *n*—a chemical process in which a solid material is deposited on a substrate or in a porous preform through the decomposition or the reaction of gaseous precursors.

3.2.3.1 *Discussion*—Chemical vapor deposition is commonly done at elevated temperatures in a controlled atmosphere.

3.2.4 *durability*, *n*—the measure of the ability of a material or structure to endure and maintain its essential and distinctive chemical, physical, mechanical and other functional characteristics in a specific environment of use (temperature, atmosphere, stress, radiation, etc) for a designated period of time.

3.2.5 *fiber interface coating*, *n*—in *ceramic composites*, a coating applied to fibers to control the bonding between the fiber and the matrix.

3.2.5.1 *Discussion*—It is common practice in SiC-SiC composites to provide a thin (<3 micrometers) interface coating on the surface of the fibers/filaments to prevent strong bonding between the SiC fibers and the SiC matrix. A weak bond between the fiber and the matrix in the SiC-SiC composite permits the fibers to bridge matrix cracks and promotes mechanical toughness and damage tolerant failure; a strong bond between the matrix and the fiber produces low strain, brittle failure. Fiber interface coatings with controlled composition, thickness, phase content, and morphology/microstructure are used to control that interface strength. **(9, 10)**

3.2.6 *hot press and sinter densification*, *n*—in *SiC matrix composites*, a matrix production and densification process in

which silicon carbide particulate in the preform are consolidated and sintered together to high density in a die press at high pressures and temperatures.

3.2.6.1 *Discussion*—A sintering additive is often added to the silicon carbide powders to produce liquid phase sintering and accelerate densification.

3.2.7 *infiltration and pyrolysis densification*, *n*—in *SiC matrix composites*, a matrix production and densification process in which a liquid silicone-organic polymer precursor is infiltrated/impregnated into the porous preform or the partially porous composite and pyrolyzed to form the silicon carbide matrix.

3.2.7.1 *Discussion*—Pyrolysis of the silicone-organic precursor in an inert atmosphere converts the precursor to a silicon carbide form with the desired purity and crystal structure. The infiltration/pyrolysis process may be iteratively repeated to fill the porosity and build up the density in the composite. **(11)**

3.2.8 *melt infiltration*, *n*—in *SiC matrix composites*, the matrix production and densification process in which molten silicon is injected in a preform (containing SiC fibers and SiC and carbon particulate) and the molten silicon reacts with the free carbon to form a bonding silicon carbide matrix. (Synonyms – reaction sintering, liquid silicon infiltration) **(12)**

3.2.9 *primary structural axis*, *n*—in a composite flat plate or rectangular bar, the directional axis defined by the loading axis/direction with the highest required tensile strength.

3.2.9.1 *Discussion*—The primary structural axis is commonly the axis with the highest fiber loading. This axis may not be parallel with the longest dimension of the plate/bar/structure.

3.2.10 *pyrolysis*, *n*—in *SiC matrix composites*, the controlled thermal process in which a silicone-organic precursor is decomposed in an inert atmosphere to form the silicon carbide (SiC) matrix.

3.2.10.1 *Discussion*—Pyrolysis commonly results in weight loss and the release of hydrogen and hydrocarbon vapors.

3.2.11 *rectangular bar*, *n*—a solid straight rod with a rectangular cross-section, geometrically defined by a width, a thickness, and a long axis length.

3.2.12 *round rod*, *n*—a solid elongated straight cylinder, geometrically defined by an outer diameter and an axial length.

3.2.13 *round tube*, *n*—a hollow elongated cylinder, geometrically defined by an outer diameter, an inner diameter, and an axial length.

3.2.14 *silicon carbide – silicon carbide composite*, *n*—a ceramic matrix composite in which the reinforcing phase consists of continuous silicon carbide filaments in the form of fiber, continuous yarn, or a woven or braided fabric contained within a continuous matrix of silicon carbide. **(13-15)**

3.2.15 *silicon carbide fibers*, *n*—inorganic fibers with a primary (≥ 80 weight%) silicon carbide (stoichiometric SiC formula) composition.

3.2.15.1 *Discussion*—Silicon carbide fibers are commonly produced by two methods—the high temperature pyrolysis and sintering of silicone-organic precursor fibers in an inert atmosphere and the chemical vapor deposition of silicon carbide on a substrate filament. **(16)**

3.2.16 *surface seal coatings, n*—an inorganic protective coating applied to the outer surface of a SiC-SiC composite component to protect against high temperature oxidation and/or corrosion attack or to improve wear and abrasion resistance. Such coatings are commonly hard, impermeable ceramic/glass coatings.

4. Significance and Use

4.1 Composite materials consist by definition of a reinforcement phase in a matrix phase. In addition, ceramic matrix composites (CMCs) often contain measurable porosity which interacts with the reinforcement and matrix. And SiC-SiC composites often use a fiber interface coating which has an important mechanical function. The composition and structure of these different constituents in the CMC are commonly tailored for a specific application with detailed performance requirements. The tailoring involves the selection of the reinforcement fibers (composition, properties, morphology, etc), the matrix (composition, properties, and morphology), the composite structure (component fractions, reinforcement architecture, interface coatings, porosity structure, microstructure, etc.), and the fabrication conditions (forming, assembly, forming, densification, finishing, etc.). The final engineering properties (physical, mechanical, thermal, electrical, etc) can be tailored across a broad range with major directional anisotropy in the properties.

4.2 Specifications for specific CMC components covering materials, material processing, and fabrication procedures are developed to provide a basis for fabricating reproducible and reliable structures. Designer/users/producers have to write CMC specifications for specific applications with well-defined composition, structure, properties and processing requirements. But with the extensive breadth of selection in composition, structure, and properties in CMCs, it is virtually impossible to write a "generic" CMC specification applicable to any and all CMC applications that has the same type of structure and details of the commonly-used specifications for metal alloys. This guide is written to assist the designer/user/producer in developing a comprehensive and detailed material specification for a specific CMC application/component with a specific focus on nuclear applications.

4.3 The purpose of this guide is to provide guidance on how to specify the constituents, the structure, the desired engineering properties (physical, chemical, mechanical, durability, etc), methods of testing, manufacturing process requirements, the quality assurance requirements, and traceability for SiC-SiC composites for nuclear reactor applications. The resulting specification may be used for the design, production, evaluation, and qualification of SiC-SiC composites for structures in nuclear reactors.

4.4 The guide is applicable to SiC-SiC composites with flat plate, rectangular bar, round rod, and round tube geometries.

4.5 This guide may also be applicable to the development of specifications for SiC-SiC composites used for other structural applications, discounting the nuclear-specific chemical purity and irradiation behavior requirements.

5. Silicon Carbide-Silicon Carbide Composites for Nuclear Applications

5.1 Silicon carbide-silicon carbide (SiC-SiC) composites are candidate structural materials for use in nuclear reactors, because of their high temperature stability, oxidation resistance, radiation tolerance, and low neutron cross-section compared to metals and for their damage tolerance and tailored anisotropic mechanical and physical properties, compared to monolithic ceramics. **(1-8)**

5.2 SiC-SiC composites are composed of silicon carbide fiber reinforcement in a silicon carbide matrix. The chemical and phase composition, microstructure, and properties of the fibers and the silicon carbide matrix, the fiber architecture (the shape and morphology of the fiber preform, multidimensional fiber distribution, and volume content of the fiber reinforcement), and the composite density and porosity are engineered to give the desired performance properties for the composite. The SiC fibers generally have a fiber interface coating to control the bonding and sliding between the SiC fiber and the SiC matrix. **(13-15)**

5.3 The physical, mechanical, and thermal properties of SiC-SiC composites are determined by the complex interaction of the constituents (fiber, interface coating, matrix, porosity) in terms of the constituent chemistry, phase composition, microstructure, properties, and fractional content; the fiber architecture; the fiber-matrix bonding, and the effect of fabrication on the constituent properties, morphology, and their physical interactions. These factors can be synergistically tailored to produce a structure/component with the desired mechanical, physical, and thermal properties. The SiC-SiC composite properties can be tailored for directional properties by the anisotropic architecture of the silicon carbide fiber reinforcement. **(13-15)**

5.4 Silicon carbide fibers produced by the polymer precursor route are commonly small diameter (5-20 micrometers) continuous filaments. **(16)** The mechanical and thermal properties of the silicon carbide fibers are strongly dependent on the silicon carbide stoichiometry, oxygen and impurity levels, the phase composition and fractions, and the crystallite size and orientation in the fibers. These factors are determined by the precursor chemistry and the fabrication process conditions.

5.5 The silicon carbide fibers are commonly consolidated into high count multifilament tows which can be wound, wrapped or layed-up into 1D structures, woven/layed-up/ braided/knitted into 2D structures, or woven/braided/knitted/ stitched into 3D structures. Each of these fiber structures are fabricated with defined fiber architectures, offering a wide range of bulk fiber content. Different fiber architectures may have marked reinforcement anisotropy, depending on the relative fiber content in each orthogonal direction.

NOTE 1—Many commercially available SiC-SiC composites consist of stacked fabric plies with a two dimensional woven fabric architecture. The SiC-SiC composite is densified to produce a final structure with orthotropic or quasi-isotropic mechanical and thermal properties.

5.6 The silicon carbide matrix in SiC-SiC composites is commonly produced by four methods: (1) a chemical vapor infiltration process, (2) an iterative precursor liquid infiltration/

pyrolysis process, (3) a silicon melt infiltration process, or (4) hot pressing and sintering of SiC powders. The four matrix formation processes use different precursors and different processing conditions, which produce differences in the chemistry, phase composition and fractions, crystallinity, morphology, and microstructure (density, pores, and cracks) in the silicon carbide matrix. Two or more of these matrix densification processes may be combined for a hybrid silicon carbide matrix.

5.7 The interaction of these four variable factor sets [(1) silicon carbide fiber type and properties; (2) fiber interface coating; (3) fiber content, tow structure, and architecture; (4) matrix composition and properties, phase content, crystallinity, density, morphology, and porosity] can produce SiC-SiC composites with a wide range of mechanical and physical properties, along with tailored anisotropic properties in the major directions.

NOTE 2—For nuclear applications, SiC-SiC composites made from stoichiometric, high purity, and fully crystalline SiC fibers and matrices are preferred for their physical, chemical, and mechanical property stability in the temperature and high radiation flux conditions of light water fission reactors and high temperature fission reactors. (1-8)

6. Product Specifications—Properties, Materials and Processing

6.1 The fibers, matrix, fiber architecture, fiber interface coatings, any surface seal coatings, and the method of manufacture, when combined as a SiC-SiC composite structure, must produce a composite that consistently and reliably meets the performance requirements (chemical, physical, mechanical, and durability) specified by the designer/purchaser/user, applicable codes and standards, and the controlling regulatory agency.

6.2 The engineering properties and characteristics of a composite structure are manufactured into the structure as part of the fabrication process. Specifications for SiC-SiC composites shall be written to define requirements for end product properties (chemical constituents and phase composition, physical properties, mechanical properties, durability, etc.), and manufacturing specifications for starting materials and fabrication. The manufacturing specifications shall include sufficient information to ensure that critical factors and parameters in the starting materials and the manufacturing process are identified and controlled to produce the final structure/component to the defined specification.

6.3 The designer/purchaser/user shall define the specifications for the constituents (chemistry and properties), architecture, final properties, and quality assurance for the SiC-SiC composite.

6.4 The designer/purchaser/user and the manufacturer together shall define the specifications for the materials/processing manufacture and non-destructive testing (NDT) of the SiC-SiC composite.

7. Product Specification—Composite Constituents, Chemical Composition and Purity for Nuclear Applications

7.1 A SiC-SiC composite shall consist of silicon carbide reinforcement fibers in a silicon carbide matrix. The fibers may

have a fiber interface coating/treatment to control the bonding between the fiber and the matrix.

7.2 The composite may have a surface coating to seal the composite against gas and liquid penetration/escape and to protect the composite from oxidation or environmental degradation.

7.3 The designer/purchaser/user shall specify the required composite constituents and structures in terms of silicon carbide fibers, fiber interface coatings, silicon carbide matrix, and surface seal coatings. The specification shall list sources, chemical compositions and phase content, component fractions and morphology, reinforcement architecture, and seal coating requirements, as required by the designer/purchaser/user. Section 11 describes the manufacturing process specification requirements for fibers, interface coatings, matrix, architecture, and seal coatings.

7.4 For nuclear applications impurity levels in SiC-SiC composites (and any surface seal coatings) have to be carefully controlled to minimize parasitic neutron absorption, oxidation promoting catalysis, nuclear activation impurities, corrosion promotion impurities, and fissionable elements. The designer/purchaser/user shall specify the requirements and test methods for chemical purity based on the defined requirements for the specific nuclear application. (An example of chemical purity requirements for nuclear grade graphite (from D7219) is given in Table X1.1.)

NOTE 3—Table X1.2 (from D7219) contains a list of chemical impurities typically found in nuclear grade graphite and carbon. The impurities are categorized as neutron absorbing impurities, oxidation promoting catalysts, activation relevant impurities, metallic corrosion relevant impurities, and fissile/fissionable elements. The suggested limits represent the reactor designer's preferences for chemical purity in graphite, which may be extended to silicon carbide.

7.5 The designer/purchaser/user shall specify boron equivalent limits and test methods for the specific nuclear application. The boron equivalent shall be calculated in accordance with Practice C1233 as specified for nuclear grade graphite (referenced in Table X1.1).

7.6 Each SiC-SiC composite production lot sampled in accordance with Section 14 shall conform to the requirements for chemical purity and boron equivalency specified by the designer/purchaser/user.

8. Product Specification—Physical Properties

8.1 The designer/purchaser/user shall specify the required minimum/maximum values for the specified physical, thermal, and electrical properties of SiC-SiC composites based on the desired performance properties; the component constituents, fractions, and properties; the reinforcement architecture; and the final porosity fraction.

8.2 The physical, thermal, and electrical properties, of SiC-SiC composites that are of primary and secondary interest are listed in Table 1 with the recommended ASTM test standards. The selection of specific physical, thermal, and electrical properties for the specification will depend on the design requirements for the CMC component. Other properties (not included in this list) may be specified by the designer/purchaser/user, based on application-specific requirements.