ASME Code Rules and ASTM Standards Integration for Ceramic Composite Core Materials and Components

J W Geringer¹, Y Katoh¹, S Gonczy², T Burchell¹, M Mitchell³, M Jenkins⁴, and W Windes⁵

¹ Materials Science & Technology Division, Oak Ridge National Laboratory
One Bethel Valley Rd, Oak Ridge, TN 37830, USA
phone: +1-865-241-8510, geringerj@ornl.gov
² Gateway Materials, 221 S. Emerson, Mt. Prospect, IL 60056, USA
³ USNC, 2288 W Commodore Way Ste 300, Seattle, WA 98199-1465, USA
⁴ Bothell Engineering & Science Technologies, 17815-93rd Pl NE, Bothell, WA 98011, USA
⁵ Idaho National Laboratory, 775 MK Simpson Blvd, Idaho Falls, ID 83401, USA

Abstract. Fiber-reinforced ceramic matrix composites have many desirable properties for high-temperature nuclear applications, including excellent thermal and mechanical properties and reasonable to outstanding radiation resistance. Over the last 20 years, the use of ceramic composite materials has already expanded in many commercial nonnuclear industries as fabrication and application technologies mature. The new ASME design and construction rules under Section III, Subsection HH, Subpart B lay out the requirements and criteria for materials, design, machining and installation, inspection, examination, testing, and the marking procedure for ceramic composite core components, which is similar to the established graphite code under Section III, Subsection HH, Subpart A. Moreover, the general requirements listed in Section III, Subsection HA, Subpart A are also expanded to include ceramic composite materials. The code rules rely heavily on the development and publication of standards for composite specification, classification, and testing of mechanical, thermal, and other properties. These test methods are developed in the American Society for Testing and Materials Committee C28 on Advanced Ceramics with a current focus on ceramic composite tubes. Details of the composites code, design methodology, and similarities to the graphite code, as well as guidance for the development of specifications for ceramic composites for nuclear application and recent standard developments, are discussed. The next step is to “close the gap” to support licensing aspects by validating the code with benchmarking data.
1. Introduction
Continuous fiber-reinforced ceramic matrix composites (CMCs) are enabling materials for various advanced energy systems, including high-temperature reactors (HTRs). Promising material properties—such as low neutron absorption, excellent high-temperature strength, maintained mechanical properties, and, in some cases, chemical inertness—make it ideal candidate materials for core applications. The American Society for Mechanical Engineers (ASME) under Boiler and Pressure Vessel Code (BPVC) Section III, Division 5 published its first design rules for CMCs in the 2019 edition. The code addresses the construction requirements for nuclear reactor applications of silicon carbide matrix with silicon carbide fibers (SiC/SiC) and carbon-based matrix with a carbon fiber (C/C) composite material.

2. The Purpose of Codes and Standards
The US Nuclear Regulatory Commission’s (NRC) objective is to ensure public health and safety in the operation of commercial nuclear power plants as it relates to reactors, materials, and waste [1]. Besides licensing and inspection of nuclear facilities and the possession, use, and disposal of nuclear materials, it is also part of the regulator’s mission to establish regulations and requirements. From this stance, it supports the development of industry consensus codes and standards, which is valuable to both industry and the regulator [2]. Codes and standards provide guidance as to what constitutes good practice, and it enables technology for life cycle applications [3].

When applying for a license, the process requires applicants to specify the design methodology, material specifications, quality assurance, and inspection and installation requirements for NRC approval, as stipulated under 10 CFR 50 regulations. Applicants or designers can use in-house developed standards or industry consensus standards. ASME is a professional standards organization that has developed codes, specifications, and standards for metal, concrete, and graphite components. In particular, ASME Section III, “Rules for Construction of Nuclear Facility Components,” under Division 5, “HTRs,” has incorporated the general and technical requirements for CMCs under Subsection HA, Subpart B, “General Requirements for Graphite and Composite Materials” [4], and Subsection HH, Subpart B, “Composite Materials” [5]. Moreover, the code rules rely on the guidelines and test standards, which were concurrently developed by the American Society for Testing and Materials (ASTM).

3. Ceramic Matrix Composites and Potential Applications
The ASME BPVC defines CMCs as a material consisting of two or more materials, in which the first matrix component is a ceramic, while the secondary or reinforcing component, may also be a ceramic, or something else like a glass-ceramic, metal, or organic in nature. “These components are combined on a macroscale to form a useful engineering material possessing certain properties or behaviors not possessed by the individual constituents” [4].

Two types of materials systems were previously identified [6] and are currently allowed for the application of HTR core components: SiC/SiC and C/C. Guidance for the classification of SiC/SiC and C/C for structural applications is provided in ASTM C1835 [7] and ASTM C1836 [8], respectively.

Potential nuclear applications for HTRs include control rod guide tubes, tie rods, and restraint straps for core supports. Identified composite core components for HTR application are not intended to be used as pressure-retaining parts and therefore do not need to be leak-tight to maintain their function. This is different for accident-tolerant fuel cladding applications in light water reactors, which require composite tubes to be hermetically sealed. Other nuclear applications include blanket structures and flow channel inserts for fusion technologies [9].
4. ASME Section III, Division 5 Nonmetallic Rules for Ceramic Composite Components

The composite rules integrate with the graphite rules under Class SN, nonmetallic core components.

4.1. General Requirements for CMC Component and Assemblies

The general requirements for nonmetallic core components (Section III, Division 5, Subsection HH subpart A) are applicable to graphite and ceramic composites, core components, and assemblies. They provide the rules for component classification, as well as the roles and responsibilities for the owner, designer, and the material organization. They further provide the requirements for a quality assurance program and the appointment of an authorized inspector. They elaborate on how to obtain certificates and data reports from ASME and reference the applicable standards that must be applied.

The owner or owner designee is responsible for preparing the design specification, but compliance of the code remains the responsibility of the owner. The material organization is the party responsible for supplying the materials, machining the components, and installing the core components in the core assembly.

4.2. Technical Requirements for CMC Component and Assemblies

The design rules for CMCs (Section III, Division 5, Subsection HH subpart B) specifically focus on composites materials and lay out the requirements and criteria for materials, design, machining and installation, inspection, examination, testing, and the marking procedure for ceramic composite core components. They are similar to the graphite rules in that they use a probability of failure (POF) approach over the component’s lifetime. However, they are distinctly different in that they do not use the maximum deformation energy, or equivalent stress, theory that allows stresses to be combined as it is applied for graphite. Instead, they use the maximum failure mode for stress analysis, which differentiates between primary and secondary stresses.

5. Ceramic Matrix Composite Material Requirements, Specifications, and Test Standards

Composites are a “new” material system tailored for a specific component. Composites have different design rules and failure mechanisms than metals and monolithic ceramics. The rules for materials are addressed in Article-2000 [10].

CMCs have some key issues. Both SiC/SiC and C/C composites are complex in fibers, matrix, and porosity with a wide range of constituents, different properties, and many distinctly different densification techniques. The reinforcement architectures can vary widely with marked anisotropy, giving anisotropic physical and mechanical properties. The component properties can vary widely based on the constituents, architecture, and processing. Moreover, the component requirements can vary widely, depending on the design requirements and composite material architectures.

For this reason, the material must be specified in the early stages of component development. The component geometry and component primary and secondary loads must be well understood. The two ASTM standards, C1783 and C1793 [11–12], were adopted and applied in Subsection HH, subpart B. The standards provide guidance on how to specify the constituents, structure, desired engineering properties, methods of testing, manufacturing process requirements, quality assurance requirements, and traceability for composites needed for nuclear reactor applications.

The rules also require designers to obtain the necessary composite design data and provide material data sheets that must be populated, which include as-manufactured, irradiation and oxidation, or chemical attack properties, as well as material behavior being subjected to stress-time-temperature effects.

Since the initiation of code rule development for composite component nuclear application, it was realized that another important undertaking was required to develop standards to collect material properties. This effort was led by Committee C28, the Committee on Advanced Ceramic Standards—specifically subcommittee C28.07, which focuses on CMCs. A recent development includes the new standard, ASTM C1899, to perform flexure strength tests on tubes [13]. A list of standards for this application is published elsewhere [14].
6. Design Approach for Ceramic Composite Components

The design rules are structured to allow for multiple applications and the continual development of CMCs. The general design requirements are addressed in Article-3000 [15].

The design rules allow for future applications because they are not limited to the current material systems. They are also process based because they provide guidance for the permissibility of the materials and specify how to qualify the material systems.

As mentioned, the rules are probabilistic because failure is derived from the variability in the material strength and accommodates the material changes due to environment exposure, such as irradiation, chemical attack, and/or stress-time-temperature effects.

The rules provide two design approach options. Designers can either follow a design-by-analysis method or a design-by-test method. For the design-by-analysis method, two key concepts are noteworthy. First, the failure mode related to the allowable stress should be applied to determine the POF. Second, the design margin is implied from the statistical analysis of the material test data, and no specific safety factor is used in the stress assessment.

The design-allowable stress is based on the statistically determined margin from the proportional limit and ultimate limit strengths. The minimum value for both limits will be considered. The design-by-analysis method defines several steps:

- Identify the potential failure modes and loading criteria (either static or time-dependent).
- Define the component classification and acceptable POF.
- Develop models to determine the component stress and derive the maximum mode stress from the application specific failure modes.
- Statistically characterize the material reliability.
- Determine the design allowable stresses based on component POF.
- Perform the structural reliability assessment.

If the design loading or geometry is too complex to rely on analysis, it is possible to follow the design-by-test method. The design-by-test method requires multiple components and a demonstration of the requirements stipulated in the design specification.

7. Next Steps

The NRC recently completed its endorsement review of ASME Section III, Division 5 from the 2017 edition. With a few explicit exceptions and limitations, Section III, Division 5 largely passed the assessment [16].

However, the 2017 edition does not have a section on composites, which was first published in the 2019 edition. There will likely be a continuous review to include the newer sections of the code.

No HTR with composite core components has ever been constructed to serve as a basis for the safety, sustainability, or licensing case for the NRC. Because of the lack of a demonstration in previous HTRs and a need to validate the existing rules, it is necessary to develop a technical basis that supports the rules with the conditions described in the code. Working together with current HTR vendors, this can be done by producing benchmarking data.

Several activities have been undertaken. Some of these activities are also supported by efforts from the light water reactor and advanced fuels technology communities that are driving forces for the development of the SiC fuel claddings and core component applications for accident-tolerant fuel designs. Specific concerns for cladding and channel box applications include component bowing due to fluence-temperature effects.

The supply of material and qualification thereof will not be a small undertaking because of the material’s complex nature. The challenge will be to reduce the time to adopt new material for nuclear reactor use.

8. Summary and Conclusion

The ASME CMC design and construction rules were first published in the ASME BPVC Section III, Division 5 in the 2019 edition under Subsection HA, Subpart A, and Subsection HH, Subpart B. It is an
attractive material because of its low thermal expansion, superior high-temperature performance, light weight, and moderate to outstanding radiation resistance.

CMCs are complex material structures with variability in material properties, which requires probabilistic assessment methods for composite component design.

Subsection HH, Subpart B is structured to allow for multiple applications and continual development because it is process based. Most developed ASTM standards align with material testing and support the requirements of the material data sheet.

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