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Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, "High Temperature Reactors": Subsection HH, "Class A Nonmetallic Core Support Structures," Subpart A, "Graphite Materials"

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ACRONYMS AND ABBREVIATIONS

ADAMS	Agencywide Documents Access and Management System
AGR	Advanced Gas Reactor
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
BPV	Boiler and Pressure Vessel (Code) (ASME)
C	Celsius
CS	construction specification(s)
CTE	coefficient of thermal expansion
DDN	design data need
dpa	displacements per atom
DOE	U.S. Department of Energy
DS	design specification(s)
EDN	equivalent nickel dose
E_n	(neutron) energy
F	Fahrenheit
GCA	graphite core assembly
GCC	graphite core component
HTGR	high-temperature gas-cooled reactor
HTR	high-temperature reactor
HTTR	High-Temperature Engineering Test Reactor
JAEA	Japan Atomic Energy Agency
KTA	Kerntechnischer Ausschuss
LWR	light water reactor
m, m*	Weibull parameter values
Magnox	magnesium nonoxidizing (reactor)

MDS	material data sheet
MeV	megaelectron volt(s)
MHTGR	modular high-temperature gas-cooled reactor
MSR	molten salt reactor
MTR	material test reactor
NGNP	Next Generation Nuclear Plant
NQA	Nuclear Quality Assurance
NRC	U.S. Nuclear Regulatory Commission
NUMARK	NUMARK Associates, Inc.
OE	operating experience
PBMR	pebble bed modular reactor
PIE	post-irradiation examination
PIRT	phenomenon identification and ranking table
POF	probability of failure
QAI	Qualifications for Authorized Inspection
QSP	quality system program
R	recommended for further review by the NRC staff
RG	regulatory guide
S_c	characteristic stress of the material reliability curve
S_g	design equivalent stress
SER	specific electrical resistivity
SRC	structural reliability class
THTR	Thorium High-Temperature Reactor
U.K.	United Kingdom

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EXECUTIVE SUMMARY

This report provides an assessment of the nuclear graphite core component (GCC) design portions of the 2017 American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code, Section III, "Rules for the Construction of Nuclear Facility Components," Division 5, "High Temperature Reactors." NUMARK Associates, Inc. (NUMARK), conducted this assessment.

NUMARK followed an assessment framework that included the use of external information related to previous worldwide commercial and experimental high-temperature gas-cooled reactors and technical literature on nuclear graphite. Specifically, the study examined the 2017 ASME BPV Code, Division 5, Subpart A, "Graphite Materials," of Subsection HH, "Class A Nonmetallic Core Support Structures." The assessment included evaluation with respect to previous design practices used in the United Kingdom for the construction and operation of Advanced Gas Reactors (AGRs) and the magnesium nonoxidizing reactors (Magnox); the design practices used for the construction and operation of gas-cooled reactors at the U.S. Peach Bottom Atomic Power Station, Unit 1, and Fort St. Vrain Generating Station; the draft design code used in Germany for the design of the Thorium High-Temperature Reactor (THTR-300); the draft design code used in Japan for the construction and operation of the experimental High-Temperature Engineering Test Reactor (HTTR); the proposed design practices and codes for the construction and operation of the General Atomics modular high-temperature gas-cooled reactor (MHTGR); and the 1990 draft ASME BPV Code, Section III, Division 2, "Design and Fabrication of Pressure Vessels," Subsection CE, "Design Requirements for Graphite Core Supports." The lessons learned from German, U.K., U.S., and Japanese operating experience with the commercial and experimental reactors supported this review.

In addition to the reactor operational experience, NUMARK reviewed the publicly available technical literature on nuclear graphite manufacture, current quality assurance procedures for graphite, nuclear graphite material specification and properties requirements from ASTM International, and literature related to specific design property changes with high-temperature irradiation. The assessment framework included evaluating the code informed by numerous sources including the 2016 International Atomic Energy Agency's design safety requirements; Regulatory Guide 1.232, "Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors," Revision 0, issued April 2018, by the U.S. Nuclear Regulatory Commission (NRC); the 2008 NRC graphite phenomenon identification and ranking table exercise; the 2019 NRC graphite workshop and industry design needs published by General Atomics for the MHGTR and AREVA and Westinghouse Electric Company LLC for the construction of the Next Generation Nuclear Plant (NGNP). NUMARK also relied on potential technical basis documents from research conducted at U.S. National Laboratories and other international laboratories in its assessment.

The technical review highlighted several design code requirements that are the result of lessons learned from previous experience with high-temperature gas-cooled reactors. It is recognized that the GCCs in high-temperature reactors (HTRs) do not have any pressure-containing or retaining function, and they are not pressure boundary components. The GCCs are passive components, and their degradation during service is of concern because it may affect their intended functions. In general, GCCs perform the following safety functions: (1) moderate thermal neutrons and ensure thermal balance in the core to maintain the fuel temperature within the design limits, (2) reflect neutrons to be located within the core region, (3) maintain the overall core coolable geometry throughout reactor life, (4) maintain the geometry and structural integrity required for fuel loading and unloading, and (5) maintain the geometry and structural integrity required for restriction-free insertion and withdrawal of control rods. The graphite core also acts as a heat sink in thermal transients, significantly extending the time required for corrective action in case of accidents.

The consensus-based 2017 ASME BPV Code covers more design aspects in greater detail than any previous graphite draft codes developed and used for the construction and operation of earlier gas-cooled HTRs around the world. It includes, for example, (1) detailed quality assurance requirements to address Title 10 of the *Code of Federal Regulations* Part 50, “Domestic licensing of production and utilization facilities,” Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants”; the 2008 and 1-2009a Editions of ASME Nuclear Quality Assurance (NQA)-1a, “Quality Assurance Requirements for Nuclear Facility Applications,” and ASME QAI-1, “Qualifications for Authorized Inspection” (the latest edition), (2) specification for nuclear graphite to be used in HTRs, invoking the nuclear graphite specifications in ASTM D7219-08, “Standard Specification for Isotropic and Near-isotropic Nuclear Graphites,” and ASTM D7301-08, “Standard Specification for Nuclear Graphite Suitable for Components Subjected to Low Neutron Irradiation Dose,” (3) the specifications for nuclear graphite properties determination in ASTM C781-08, “Standard Practice for Testing Graphite and Boronated Graphite Materials for High-Temperature Gas-Cooled Nuclear Reactor Components,” (4) ASTM C625-15, “Standard Practice for Reporting Irradiation Results on Graphite,” (5) detailed requirements for developing a material data sheet used in the design, (6) stress and temperature limit requirements for the GCCs, classified in terms of safety requirements and established via structural reliability determined using probabilistic methods, (7) component classification using a structural reliability class system, (8) a list of the type of loading and loads that must be considered in estimating the stresses in the GCCs, (9) consideration of graphite degradation during service, and (10) roles and responsibilities of the graphite manufacturing organization (e.g., assembler, designer, owner, graphite inspector).

Subsection HH, Subpart A is not applicable to nongraphite materials used in HTRs, such as ceramic fuel, ceramic (fiber and fused cast refractory) insulation used for piping, and baked carbon ceramic insulation used around the graphite core to contain the temperature of the pressure vessel within limits.

Subsection HH, Subpart A contains salient articles and subarticles related to defining the classes of GCCs according to safety requirements related to the flux and temperature exposure and stresses encountered during reactor operation, loading categories for each operating condition, the category of loads to be considered in stress calculations, and the determination of the required structural integrity of GCCs using probabilistic analyses of the strength property.

The categorization of the structure, which is the graphite core assembly, and GCCs into the three different structural reliability classes is unique in that the characterization is based on probabilistic risk assessment.

CONTENTS

1. INTRODUCTION

The absence of a code of construction endorsed by the U.S. Nuclear Regulatory Commission (NRC) for nuclear reactors operating above 425 degrees Celsius (C) (800 degrees Fahrenheit (F)) is a significant obstacle for advanced nonlight-water reactor designs. Review and approval of an elevated temperature code of construction during a licensing review of a new nuclear power plant would result in substantial cost and a longer schedule.

In a letter dated June 21, 2018 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML18184A065), the American Society of Mechanical Engineers (ASME), based on letters from both industry consortia and individual companies interested in developing advanced nonlight-water-reactor designs, asked the NRC to review and endorse the 2017 Edition of the ASME Boiler and Pressure Vessel (BPV) Code, Section III, “Rules for Construction of Nuclear Facility Components,” Division 5, “High Temperature Reactors.” The NRC responded in a letter dated August 16, 2018 (ADAMS Accession No. ML18211A571), that the agency is initiating efforts to endorse (with conditions, if necessary) the 2017 Edition of ASME BPV Code, Section III, Division 5, in a new regulatory guide (RG) as one way of meeting the NRC’s regulatory requirements.

To support the review and endorsement effort, the NRC requested the technical support of NUMARK Associates, Inc. (NUMARK). This report documents NUMARK’s technical input for the NRC’s review of the 2017 Edition of the ASME BPV Code, Section III, Division 5. This report pertains only to the design rules for graphite core components (GCCs). The results of NUMARK’s review of the metallic design rules are the subject of a separate report. This report will be used as part of the NRC’s review and support the NRC’s findings in the associated RG.

2. OVERVIEW

2.1 Review Approach

The NRC wants to ensure its licensing reviews are performed commensurate with its safety and security mission and asked NUMARK to perform its technical review in accordance with the guidance in two recent NRC examples. One example is the NRC Transformation Team, which provided its findings in SECY-18-0060, “Achieving Modern Risk-Informed Regulation,” dated May 23, 2018 (ADAMS Package Accession No. ML18110A186). The other example is an NRC memorandum from Frederick Brown, Director, Office of New Reactors, titled “Expectations for New Reactor Reviews,” dated August 29, 2018 (ADAMS Accession No. ML18240A410). This memorandum is further described below.

One of the expectations stated in the NRC memorandum is to base the NRC’s regulatory findings on the principle of “reasonable assurance of adequate protection” (of public health and safety), but not on absolute certainty or risk avoidance. This is the legal standard for the NRC’s licensing decisions. The memorandum discusses considerations for the terms “reasonable” and “adequate.”

The RG that will endorse the use of ASME BPV Code, Section III, Division 5, will be based on the finding that the rules in Division 5 provide “reasonable assurance of adequate protection.” In accordance with the memorandum, new or novel designs or design features may need additional review or requirements. Furthermore, any technical areas that are not addressed by ASME BPV Code, Section III, Division 5, and that would lead to a demonstrably increased likelihood or consequence of failure should be considered.

Another area of the memorandum is the consideration of margin. If the ASME BPV Code is sufficiently conservative in a particular area and it provides a significant margin of safety, and sufficient data exist to support the ASME BPV Code values, then the review in that area should be reduced. In contrast, where the ASME BPV Code includes a smaller margin or may not provide supporting data, then the review should be increased to ensure that the staff has an adequate basis for endorsing the ASME BPV Code and any associated conditions. In any case, the review must either conclude that the ASME BPV Code provides reasonable assurance of adequate protection or recommend the NRC further review that section of the ASME BPV Code for potential acceptance, conditional acceptance, or rejection.

Similarly, the memorandum discusses making safety evaluations more succinct and including only the information necessary for the NRC staff to make its safety findings. Therefore, this report provides a concise basis for its conclusions, while also maintaining clarity and completeness. This report focuses on why and how NUMARK reached its conclusions, without including unnecessary historical or tangential information.

The NRC performed research to establish the scope of the review. This research includes a historical review of previous high-temperature design rules and NRC approvals. The final RG or another accompanying NRC document will fully identify the NRC’s specific historical findings. The specific historical findings relevant to this report are discussed in the assessment.

This report considers the adequacy of the technical basis in the ASME BPV Code, including the quality and quantity of the underlying data in the context of the selected safety margins. This report also considers the previous NRC historical findings, current operating experience (OE), and international experience, including similar design rules, as applicable.

2.2 NUMARK’s Review Approach

As indicated in the Statement of Work, NUMARK’s evaluations of the GCC design rules specifically include the following:

- Subsection HH, “Class A Nonmetallic Core Components,” Subpart A, “Graphite Materials” (HHA)
- Mandatory Appendix HHA-I, “Graphite Material Specifications”

- Mandatory Appendix HHA-II, "Requirements for Preparation of a Material Datasheet"
- Mandatory Appendix HHA-III, "Requirements Regeneration of Design Data for Graphite Grades"

ASME BPV Code, Section III, Division 5, Subpart B, "Graphite Materials," of Subsection HA, "General Requirements," contains nine articles, including the glossary. Subsection HH contains Subpart A. This subsection has eight articles (on materials, design, machining, examination and testing, installation and examination, nameplates, stamping, and reports).

NUMARK's review focused on how ASME BPV Code, Section III, Division 5, Subsection HH, Subpart A, "Graphite Materials," addresses major issues with respect to nuclear graphite, such as the type of graphite, manufacturing methods, purity requirements, and minimum property requirements. The review examined the adequacy of technical bases used for various types of loading and any calculation methods employed. Review of Subsection HH, Subpart A looked at its adequacy to address the well-known effects of neutron dose, temperature, and the three-dimensional distribution during reactor operation in changing the properties of graphite, particularly with respect to contraction and expansion over time. This has repercussions for the ability to maintain stable core geometry and to insert and withdraw control rods with no impediment, and to defuel and refuel with no impediment. Changes in thermal conductivity over time affect the required ability to cool the core by maintaining the heat transfer used in the design of the core. Among other requirements, by consideration of important properties, the overall design of the core must ensure that integrity is maintained during postulated accidents, enable the required geometry for passive removal of residual heat from the reactor core to the ultimate heat sink, and permit sufficient insertion of the neutron absorbers to provide for reactor shutdown.

The review examined how Subsection HH, Subpart A addressed potential changes in properties due to the chemical effects of the impurities in the circulating coolant on graphite, as well as the potential for erosion corrosion. It was important to ensure that Subsection HH, Subpart A sufficiently addressed the adverse effects of low impurity-induced chronic oxidation and other corrosion effects. This could form the basis for the designer or reactor operator to set temperature and controlled chemistry requirements for the helium coolant, depending on the type of graphite used for manufacturing the core.

In reviewing Subsection HH, Subpart A, NUMARK relied on information from technical basis documents; previous design review documents generated by the NRC (NRC, 2002), (NRC, 2005), (NRC, 2011); designs proposed by U.S. nuclear reactor design firms and U.S. Department of Energy (DOE) sponsored activities, (GA Technologies, 1987a, 1987b), (General Atomics, 1988b, 2002, 2009a, 2009b), (Westinghouse, 2009a, 2009b); publicly available information on graphite core designs of U.S., Japanese, German, and Chinese high-temperature gas-cooled reactors (HTGRs), (Schwartz, 1969), (Dahlberg et al., 1969), (Hirschfelder, 1982), (Saurwein, 1982), (Melese and Katz, 1984), (Alloway and Goreholt, 1986), (Schmidt, 1989), (JAEARI, 1994), (Zhensheng, 2002), (Kingrey, 2003), (Preston and Marsden, 2006), (Sterbentz, 2008), (Yu and Sun, 2010); core designs of U.K. Advanced Gas Reactors (AGRs), (Prince and Brocklehurst, 1987), (Davies, 1996), (Judge, 1996), (McLachlan, 1997), (Reed, 2005), (Martinuzzi et al., 2015), (Dihoru, 2017), (ONR, 2018), (Riley, 2018a, 2018b); the German Kerntechnischer Ausschuss (KTA) code (KTA, 1992), (NRC, 2001); the draft Japanese HTGR code (Shibata, 2010); DOE reports (Kingrey, 2003), (Windes et al., 2010), (Beck and Pincock, 2011), (Morton, 2012), (Gallego and Burchell, 2011), (Mohanty, 2011); scientific publications and conference proceedings (Morgan, 1974), (Slavbonas, 1978), (Brocklehurst and Kelly, 1979), (Bodmann, 1987), (Ishiyama et al., 1991), (Judge, 1991), (Ziermann and Günther, 1997), (Yu et al., 2003), (Ishihara, 2004), (Mitchell, 2004), (Moorman, 2008a, 2008b), (Orzáez, 2009), (Shibata, 2013), (Shi, 2014), (Black et al., 2016), (Shibata, 2017), (Marsden et al, 2019); and experience decommissioning graphite-moderated reactors (Brohovich, 1958), (Platonov, 1995), (Wahlen, 2000). Other sources of information included, for example, General Atomics' "Graphite Design Handbook," issued September 1988; the NRC graphite PIRT exercise conducted in 2008 (NRC, 2008); a graphite workshop in 2019 (NRC, 2019); RG 1.232, "Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors," Revision 0, issued April 2018; the International Atomic Energy Agency's design safety requirements (2016); and Chapter 3, "Design of Structures, Components, Equipment, and Systems," of NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition." In particular, NUREG-0800, Section 3.9.3, "ASME Code Class 1, 2, and 3 Components and Component Supports, and Core Support Structures," Revision 3, issued April 2014, was studied in greater detail to extract features potentially applicable to HTGRs and to bridge the GCC requirements in Subsection HH, Subpart A.

NUMARK consolidated available data, analyzed results, and identified areas for which additional information would be needed to confirm the adequacy of each portion of Subsection HH, Subpart A. This turned out to be a major task, mainly because of the availability of large amounts of both historical and recently generated (during the last decade) data on various graphites, which ostensibly formed the basis for the development of Subsection HH, Subpart A.

The review sought data and modeling consistency in important properties among several investigations. It explored how Subsection HH, Subpart A handled consistency in the use of underlying scientific principles, testing and analysis techniques, and potential variability in the data. The review recognized that Subpart A handles the strength data for graphite using Weibull statistics, which is a generally accepted methodology.

2.3 Historical Basis

There are no NRC-researched previous high-temperature design rules related to nuclear graphite and its application to HTGRs. There are no previous NRC-reviewed ASME BPV Code or other international (draft) codes or published Code Cases related to graphite. Thus, this review sets the precedent. NUMARK's review recognized, however, that historical bases exist in the development of various drafts of design codes for graphite, such as (1) the German KTA-3232 draft rule, (2) U.K. AGR and magnesium nonoxidizing (Magnox) reactor construction data, (3) the 1990 proposed ASME BPV Code, Section III, Division 2, “Construction of Nuclear Facility Components,” Subsection CE, “Design Requirements for Graphite Core Supports,” and (4) the Japanese draft graphite code for HTGRs. A review of publicly available information on these and their applicability to Subsection HH, Subpart A, was a part of NUMARK’s assessment.

2.4 Report Organization

This technical report uses the same nomenclature as the ASME BPV Code. The organization of Section III of the ASME BPV Code is summarized below.

Section III of the ASME BPV Code consists of divisions. Divisions are broken down into subsections. Subsections are divided into articles, subarticles, paragraphs, and, where necessary, subparagraphs and subsubparagraphs.

Articles are designated by the applicable letters indicated above for the subsections followed by Arabic numbers, such as NB-1000. Where possible, articles dealing with the same topics are given the same number in each subsection, except NCA.

Subarticles are numbered in units of 100, such as NB-1100.

Subsubarticles are numbered in units of 10, such as NB-2130, and generally have no text. When a number such as NB-1110 is followed by text, it is considered a paragraph.

Paragraphs are numbered in units of 1, such as NB-2121.

Subparagraphs, when they are major subdivisions of a paragraph, are designated by adding a decimal followed by one or more digits to the paragraph number, such as NB-1132.1. When they are minor subdivisions of a paragraph, subparagraphs may be designated by lowercase letters in parentheses, such as NB-2121(a).

Subsubparagraphs are designated by adding lowercase letters in parentheses to the major subparagraph numbers, such as NB-1132.1(a). When further subdivisions of minor subparagraphs are necessary, subsubparagraphs are designated by adding Arabic numerals in parentheses to the subparagraph designation, such as NB-2121(a)(1).

Section 3 of this report contains a synopsis of the review and assessment of the statements in Subpart A in a brief format for each category of Subsection HH, Subpart A, according to the organization described above. The recommendations are in the form of acceptance or recommendations for further review by the NRC staff (R).

Section 4 of this report highlights items for the NRC staff to consider that Subsection HH, Subpart A does not specifically address or topics NUMARK considers of particular importance for review by the NRC staff.

Section 5 of this report summarizes the assessment of Subsection HH, Subpart A.

3. TECHNICAL REVIEW SYNOPSIS OF SUBSECTION HH, CLASS A NONMETALLIC CORE SUPPORT STRUCTURES, SUBPART A, GRAPHITE MATERIALS

This section contains an assessment of Subsection HH, Subpart A for each article, subarticle, and subsubarticle, and the associated paragraphs. This section also includes recommendations for the subarticles and paragraphs to be considered for NRC approval, approval with conditions, or further review by the NRC staff to make a determination. The user will provide additional information for evaluation to sufficiently address the requirements of Subsection HH, Subpart A.

The following section of this report summarizes the recommendations for each article, subarticle, subsubarticle, paragraph, and subparagraph of this portion of Subsection HH, Subpart A.[1]

3.1.1 Article HHA-1000 Introduction

HHA-1000 Scope

HHA-1110 Aspects Covered

It is recommended that HHA-1110 be accepted because the general rule aspects consider pertinent integrity and functionality of the individual GCCs and of the graphite core assembly (GCA).

The rules consider the potential effects of degradation due to fast neutron irradiation and oxidation effects on integrity and functionality.

HHA-1120 Environmental Effects and Limits

It is recommended that HHA-1120 be accepted because the general rule aspects consider potential thermal and chemical oxidation effects on GCCs.

In modern HTGRs, little, if any, radiolytic oxidation is expected under normal operating conditions and controlled purity in the helium coolant. Also, coolant other than gas have been considered, with a requirement that coolant interaction with graphite shall be included in the design specification (DS). Thus, the Code applies to liquid-metal-coolant and molten-salt-coolant graphite-moderated HTRs.

HHA-1200 Requirements

HHA-1210 General

It is recommended that HHA-1210 be accepted because this subsubarticle is general and refers to Subsection HA, Subpart B, for specific requirements.

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[1] For the remainder of Section 3, the ASME BPV Code will refer to the ASME BPV Code as a whole, whereas references to the "Code" are specific to Section III, Division 5, Subsection HH, Subpart A, “Graphite Materials."

HHA-1220 Materials
It is recommended that HHA-1220 be accepted because this subsubarticle is general and refers to Article HHA-2000 for specific requirements. ASTM D7219-08, “Standard Specification for Isotropic and Near-isotropic Nuclear Graphites,” and ASTM D7301-08, “Standard Specification for Nuclear Graphite Suitable for Components Subjected to Low Neutron Irradiation Dose,” which are invoked by HHA-2000, currently do not have information on material property deterioration during service. As noted elsewhere in the Code, it is the designer’s responsibility to obtain such data and incorporate the data in the design of the GCCs.

HHA-1230 Design
It is recommended that HHA-1230 be accepted because this subsubarticle is general and refers to Article HHA-3000 for specific requirements.

HHA-1240 Graphite Core Component Machining
It is recommended that HHA-1240 be accepted because this subsubarticle is general and refers to Article HHA-4000 for specific requirements.

HHA-1250 Installation
It is recommended that HHA-1250 be accepted because this subsubarticle is general and refers to Article HHA-5000 for specific requirements.

HHA-1260 Responsibilities
It is recommended that HHA-1260 be accepted because this subsubarticle is general and refers to Article HAB-3000 for specific responsibilities for the designer, graphite manufacturing organization, graphite component installer, and others.

HHA-1300 Application of These Rules
It is recommended that HHA-1300 be accepted because this subarticle is general and defines the general scope of the applicability to types of nuclear reactors.

HHA-1400 Boundaries of Jurisdiction
It is recommended that HHA-1400 be accepted because this subarticle is general and defines the boundaries of jurisdiction, according to the definitions in Figures HHA-1400-1 and HHA-1400-2 of the Code.

HHA-1410 Boundary between Graphite Core Components and Core Support Structures
It is recommended that HHA-1410 be accepted. HHA-1410 defines the Code’s jurisdictional boundary between a GCC and a GCA and the metallic core support structure or the metallic/ceramic core restraints. The surfaces of GCCs are the boundary for both prismatic-type core and pebble-bed core designs. This subsubarticle also considers the load or the constraints that GCCs may impose on fuel pebbles and compacts. Mechanical fasteners, understandably, are considered as part of the fuel compacts and are outside of the jurisdiction of this subpart.

HHA-1420 Boundary between Graphite Core Components and Fuel Pebbles or Compacts
It is recommended that HHA-1420 be accepted. HHA-1420 defines the surfaces of GCCs as the jurisdictional boundary between GCCs and fuel pebbles or compacts. HHA-1420 also

requires consideration of the load or the constraints that GCCs may impose on fuel pebbles and compacts. Mechanical fasteners, understandably, are considered as part of the fuel compacts and are outside of the jurisdiction of this subpart.

Figure HHA-1400-1 Jurisdictional Boundary for Graphite Core Components and Assemblies—Circumferential Section View
It is recommended that Figure HHA-1400-1 be accepted because it provides a pictorial circumferential section view of a general representation of the jurisdictional boundary between a GCC and a GCA and the metallic core support structure or the metallic/ceramic core restraints for both prismatic-type core and pebble-bed core designs. [emphasis added] The designer will provide pictorial representations appropriate to a particular design.

Figure HHA-1400-2 Jurisdictional Boundary for Graphite Core Components and Assemblies—Longitudinal Section View
It is recommended that Figure HHA-1400-2 be accepted because it provides a pictorial longitudinal section view of a general representation of the jurisdictional boundary between a GCC and a GCA and the metallic core support structure or the metallic/ceramic core restraints for both prismatic-type core and pebble-bed core designs. [emphasis added] The designer will provide pictorial representations appropriate to a particular design.

3.1.2 Article HHA-2000 Materials

HHA-2100 General Requirements

HHA-2110 Material for Graphite Core Components

HHA-2111 Permitted Material Specifications
It is recommended that HHA-2111 be accepted because this paragraph is general and defines the ASTM material specification, further covered in Mandatory Appendix HHA-I, as required conformance for GCCs.

ASTM D7219-08 “Standard Specification for Isotropic and Near-isotropic Nuclear Graphites,” Section 7.1, states that in addition to material specification requirements, the property specifications should include the purchaser’s requirements.

ASTM D7301-08 “Standard Specification for Nuclear Graphite Suitable for Components Subjected to Low Neutron Irradiation Dose,” Section 6.1, states that the property specifications should include the additional requirements of the purchaser.

HHA-2112 Special Requirements Conflicting with Permitted Specifications
It is recommended that HHA-2112 be accepted because it clarifies the number of times an examination, inspection, test, or treatment needs to be conducted, with reference to special requirements vis-à-vis those required in the material specification.

HHA-2120 Certification of Material
It is recommended that HHA-2120 be accepted. This subsubarticle invokes paragraphs HAB-3861 and HAB-3862 and requires acceptance data, as given in certified material test reports.

HHA-2121 Application of the Rules of This Subpart

R(1). It is recommended that HHA-2121 be reviewed by the NRC staff because of the different meanings of “charge” in subparagraphs HHA-2121(a) and HHA-2121(d) and the ASTM materials specifications ASTM D7219-08 and ASTM D7301-08 invoked by the Code in HHA-I-1110.

Since the Code accepts the ASTM material specifications, where “charge” is defined, it is not necessary to include the definition here, unless it has some special meaning other than that defined in the ASTM material specifications. The ASTM material specifications define “charge” as the number of billets that is subject to a processing step, such as baking, impregnation, and graphitization (Section 3.2.1 in ASTM D7219-08 and Section 3.4 in ASTM D7301-08). This does not seem to be the case in the Code, and, thus, it is confusing.

HHA-2122 Exclusion of Small Products

It is recommended that HHA-2122 be accepted.

This applies to parts cut out or otherwise machined from already certified material. In that case, it is assumed that the certified material test report for the “mother” graphite would be sufficient; however, the user should so note.

HHA-2130 Deterioration of Materials During Service

It is recommended that HHA-2130 be accepted because it requires the design to consider deterioration factors that modify the physical and mechanical properties of the material.

HHA-2131 Design Specification

It is recommended that HHA-2131 be accepted.

This paragraph requires the designer to include the reactor operating envelope of temperature, dose, and oxidation anticipated ranges in the DS.

HHA-2132 Qualification of Materials

It is recommended that HHA-2132 be accepted.

This paragraph invokes Subsubarticle HHA-2220 on irradiated properties and the magnitude of change in irradiated properties.

HHA-2140 Material Identification

HHA-2141 Billet Marking

It is recommended that HHA-2141 be accepted.

The marking includes the axis of forming, which enables the traceability of potential variations in properties on orthogonal directions of the billet to determine potential anisotropy in properties. ASTM D7219-08, Section 8.2, “The Material Specification Requirements,” covers this in more detail, including all the process steps involved in graphite manufacture. ASTM D7301-08, Section 7.2, “Other Requirements,” covers this in more detail, including all the process steps involved in graphite manufacture.

HHA-2142 Method of Marking

It is recommended that HHA-2142 be accepted.

This paragraph requires that graphite billets be marked by any method that will not result in harmful contamination, functional degradation, or sharp discontinuities.

HHA-2143 Transfer of Marking When Materials Are Cut or Machined

It is recommended that HHA-2143 be accepted because it requires the maintenance of GCC material identification of cut or machined material with its parent billet. Such bookkeeping is necessary to trace the deviation, if any, between the properties of the components machined from the billet and the properties of the billet. Such information is also necessary to fulfil HHA-2130 requirements to assess the effects of deterioration factors that modify the physical and mechanical properties of the component.

HHA-2200 Material Properties for Design

R(2). It is recommended that HHA-2200 be reviewed by the NRC staff. This subarticle covers the general requirements and refers to subsubarticles that address design properties. HHA-3227 states that the material data sheet (MDS) (per HHA-2200) contains all of the other graphite material properties used for design. However, permeability and emissivity, for example, are not listed in either HHA-2200, ASTM D7219-08 or ASTM D7301-08.

HHA-2210 As-Manufactured Material Properties

It is recommended that HHA-2210 be accepted. This subsubarticle refers to Mandatory Appendix HHA-II for properties and subparagraph HHA-2131(b) for the temperature range required for properties.

HHA-2220 Irradiated Material Properties

R(3). It is recommended that HHA-2220 be reviewed by the NRC staff because the creep property may not be considered appropriately in HHA-2220(a)(2), which addresses the creep coefficient. Typically, there will be more than one creep coefficient (one for primary creep and one for secondary creep), including the effect of creep recovery on these. Tertiary creep may also need to be considered, depending on the design and reactor operational variables. Reliable, high-quality data are sparse. Also, the effect of creep strain on the coefficient of thermal expansion (CTE) and maybe on the modulus should be considered. Again, reliable, high-quality data are sparse. Thus, the Code should provide sufficient rationale and requirements for the use of measured properties in the design and the extent of conservatism in determined properties. Confirmation via sensitivity studies and uncertainty assessments should be required.

HHA-2230 Oxidized Material Properties

R(4). It is recommended that HHA-2230 be reviewed by the NRC staff because the Code does not adequately consider the effect of oxidation on compressive strength, preferably after irradiation. This is important for graphite core supports.

HHA-2230 requires consideration of the oxidation effect only on tensile strength, dynamic Young's modulus, and thermal conductivity. It is generally accepted that the relative change in tensile strength is in the same proportion and thus applicable to bend strength and compressive strength. However, because compressive strength varies with the geometry ratio (length/diameter) and the effect of oxidation could vary with the geometry ratio, the oxidation effect on compressive strength should be determined exclusively. It is also important to establish the compressive strength reduction data due to oxidation for irradiated graphite to assess the fidelity of the core support design.

HHA-2300 Sampling

HHA-2310 General Requirements

It is recommended that HHA-2310 be accepted because it requires sampling to be conducted in accordance with ASTM D7219-08.

HHA-2400 Material Manufacturer's Quality System Program

It is recommended that HHA-2400 be accepted.

HHA-2400 invokes HAB-3800, which has been reviewed and assessed by the NRC staff. If the NRC staff had rejected HAB-3800, then HHA-2400 would also be rejected.

HHA-2500 Examination and Repair of Graphite Core Component Material

HHA-2510 Examination

It is recommended that HHA-2510 be accepted because it states that the requirements in ASTM D7219-08 should be followed. In ASTM D7219-08, Section 12, "Finished Inspection," the specification states the following:

> 12.1 Graphite billets shall be visually inspected for external flaws. The allowable size, type, and number of flaws shall be defined in agreement between the purchaser and the manufacturer and be described in the purchase specification.
>
> 12.2 It is recommended that all graphite billets are nondestructively tested to screen for internal defects. The allowable size, type, and number of internal flaws should be defined in agreement between the purchaser and the manufacturer and be described in the purchase specification.

HHA-2520 Repair

It is recommended that HHA-2520 be accepted because regraphitization to achieve full graphitization is a demonstrated and proven graphite manufacturing method. HHA-2520 also provides a reasonable path to use graphite parts separated by cracking as long as such parts meet the material specification.

HHA-2520 invokes the material specification. Item 13.2, in ASTM D7219-08 and item 12.2 in ASTM D7301-08 allow regraphitization to repair incomplete graphitization, as measured by electrical resistivity property. The following items 13.1 and 13.2 are statements from ASTM D7219-08:

> 13.1 Graphite billets failing on chemical purity (see Section 6) may be purified/re-purified and subjected to retest.
>
> 13.2 Graphite billets failing on SER (see 5.6.3) [Specific Electrical Resistivity] may be re-graphitized and subjected to retest.

The following items in 12.1 and 12.2 are statements from ASTM D7301-08:

> 12.1 Graphite billets failing on chemical purity (see Section 5) may be purified/re-purified and subjected to retest.
>
> 12.2 Graphite billets failing on SER (4.6.3) may be regraphitized and subjected to retest.

HHA-2600 Packaging, Transportation, and Storage
It is recommended that HHA-2600 be accepted.

This subarticle requires consideration of important factors affecting graphite properties. These factors include (1) cleanliness and avoidance of the unintended contamination of graphite components during handling, (2) loading that may affect graphite structure, and (3) maintaining proper billet identification marking.

3.1.3 Article HHA-3000 Design

HHA-3100 General Design
R(5). It is recommended that HHA-3100 be reviewed by the NRC staff because of the absence of technical requirements for quantifying and assessing damage tolerance, mentioned in HHA-3100(c), and the ways in which degradation affects the structural reliability class (SRC) requirements for various GCCs.

HHA-3100(c) states, “the Probability of Failure values used as design targets may not be precisely accurate predictions of the rate of cracking of components.” Therefore, the Code recognizes the possibility of cracking of graphite components, even though the graphite components may be designed according to the Code requirements. This means that failure has occurred in the graphite component at a stress level below the design equivalent stress (S_g) and below its equivalent probability of failure (POF) value. The requirement for damage tolerance needs to be quantified and to include possible cracking of several bricks at several locations and multiple cracking within bricks. Also, the Code should incorporate the potential influence of any damaged components interacting with the GCA under reactor normal operation and design-basis accidents.

HHA-3110 Graphite Core Components

HHA-3111 Classification of Graphite Core Components
It is recommended that HHA-3111 be accepted. The SRC defines the graded level of reliability that the GCC is designed to meet and represents the quantified survival requirements in experiencing the extent of severity in duty.

HHA-3112 Enveloping Graphite Core Components

It is recommended that HHA-3112 be accepted because it provides information on grouping similar components within a GCA in a design analysis. The components can have minor variations in geometry and service loading. It is acceptable that grouping be based on similar function, geometry, and environmental conditions.

HHA-3120 Loading Criteria

HHA-3121 General

It is recommended that HHA-3121 be accepted. The paragraph contains general information on specific loading criteria.

HHA-3122 Loadings

It is recommended that HHA-3122 be accepted because it lists 14 distinctive loads that may be imposed on GCCs during service. Additionally, HHA-3122 states that the loads may not necessarily be limited to these 14 types only and thus allows other design-specific loads to be considered in the analyses of stresses imposed on GCCs.

HHA-3123 Design Loadings

It is recommended that HHA-3123 be accepted because it requires consideration of distributions of pressure, temperature, fast neutron flux or damage dose rate, and various forces applicable to GCCs.

HHA-3123.1 Design Fast Flux Distribution

It is recommended that HHA-3123.1 be accepted because it defines fast flux distribution appropriately as the enveloping fast neutron flux experienced by the GCC in all locations of the installed GCA. Furthermore, this value must be multiplied by the design life to determine the enveloping fast neutron fluence to which the GCC will be exposed.

HHA-3123.2 Design Temperature Distribution

It is recommended that HHA-3123.2 be accepted because it requires appropriate estimation of operating temperature that includes the effects of the design fast flux and nonlocal heating due to gamma and neutron interactions. Furthermore, HHA-3123.2 requires the assessment of the design life calculation using the design fast flux and design mechanical load and the temperature distribution within the GCA.

HHA-3123.3 Design Mechanical Load

It is recommended that HHA-3123.3 be accepted because it requires comprehensive considerations of dead weight loads and loads arising from design fast flux and nonlocal heating due to gamma and neutron interactions.

HHA-3123.4 Design Pressure Distribution

It is recommended that HHA-3123.4 be accepted because it requires loads on GCCs due to sustained pressure differences during normal operation to be included in the design loads.

HHA-3124 Service Loadings
It is recommended that HHA-3124 be accepted because it requires detailed service loading classifications in DS, including a complete basis for design, construction, and examination that will conform to Code requirements.

HHA-3130 Nomenclature
It is recommended that HHA-3130 be accepted because it contains the definition of all the calculated variables and properties that are used in stress calculations for establishing the design structural integrity reliability.

HHA-3140 Special Considerations
R(6). It is recommended that HHA-3140 be reviewed by the NRC staff because it cites HHA-3141 and HHA-3142, which are also recommended for NRC staff review.

HHA-3141 Oxidation
R(7). It is recommended that HHA-3141 be reviewed by the NRC staff for the reasons given below for several of the subparagraphs within HHA-3141.

It is recommended that HHA-3141(a) be accepted as oxidation effects are more pronounced and are of concern only when the weight loss is greater than about 1 percent.

R(8). It is recommended that HHA-3141(b) be reviewed by the NRC staff because it refers to Figures HHA-3141-1 and HHA-3141-2 for some of the specific ASTM nuclear graphite material specifications. However, although these data may have been generated using previous graphites, because of the inconsistency in graphite manufacture, design-relevant oxidation data must be generated for the specific graphite that will be used for the reactor. Thus, the "relationship" generated from Figures HHA-3141-1 and HHA-3141-2 cannot be considered universally applicable.

R(9). It is recommended that HHA-3141(c) be reviewed by the NRC staff because the Code seems to allow a reduction in the cross-sectional geometry of a component with oxidization up to 30 percent. Such high levels are detrimental to maintaining the structural integrity of graphite core support components.

R(10). It is recommended that HHA-3141(d) be reviewed by the NRC staff. There is no technical basis for excluding oxidation to high weight loss (greater than 1 percent) occurring simultaneously with significant irradiation (greater than 0.25 displacements per atom (dpa)) from the scope of these Code requirements.

HHA-3142 Irradiation Effects
R(11). It is recommended that HHA-3142 be reviewed by the NRC staff because of several of the subparagraphs it contains. These are discussed below.

HHA-3142.1 Irradiation Fluence Limits
R(12). It is recommended that the statement in HHA-3142.1, "Graphite components in a core are classified according to their cumulative fast ($E > 0.1$ MeV) neutron irradiation fluence," be

reviewed by the NRC staff. The value should be (neutron) energy (E_n) > 0.18 megaelectron volts (MeV) or, preferably, be stated in dpa.

Since the 1970s, either equivalent nickel dose (EDN), E_n > 0.18, or dpa has been used by the industry and academia. Presently, dpa is accepted as the most appropriate unit. EDN is a definition based on dpa.

E_n > 0.18 is similar but depends on the reactor system. Conversion factors to and from E_n > 0.18 are all approximations because they are dependent on the reactor system.

When calculating dpa, energies above 0.1 MeV are used in the damage function, but this has no relevance to E_n > 0.18, which again was an approximate unit derived by empirical observation (Morgan, 1974; Black et al., 2016).

R(13). It is recommended that the statement in HHA-3142.1(c), "Use of materials within the core shall be limited by the range of temperature and fast neutron damage dose over which the material is characterized (refer to HHA-2220)," be reviewed by the NRC staff. This implies that the designer must have the irradiated properties and use the properties in the design. Any empirical or first principle analytical models that extrapolate nonirradiated graphite properties data to estimate irradiated properties (using grain size and other microstructural features) are not allowed in the design.

Arguably, any data obtained in the material test reactor (MTR) are subject to considerable criticism because of various epistemic and aleatory uncertainties. Since properties can be determined only for a number of (fixed) fluences and temperatures, the Code should allow a technically justifiable linear or nonlinear equation to interpolate between (data-known) fluence and temperature over the allowable component lifetime. Where uncertainties are relatively large, the user should incorporate reasonable additional conservatism in bounding limiting curves.

The statement in HHA-3142.1(c) appears to contradict the following statement in HHA-II-4100(a): "Temperature and fluence intervals shall be selected so as to provide adequate confidence in the accuracy of the interpolations. Limited extrapolations are permitted, but such extrapolations shall be justified." [emphasis added]

HHA-3142.2 Stored Wigner Energy

It is recommended HHA-3142.2 be accepted because the effect of the accumulation of stored Wigner energy on thermal transients should be considered for highly irradiated graphite at temperatures below 200 degrees C (392 degrees F) (Gallego and Burchell, 2011).

HHA-3142.3 Internal Stresses Due to Irradiation

R(14). It is recommended that the statement in HHA-3142.3 regarding the use of viscoelastic modeling of material behavior be reviewed by the NRC staff because such modeling is generally used to describe elastic-plastic deformation in metals and is not suitable for graphite. Generally, the stress-strain properties become less nonlinear after irradiation, which is usually attributed to the irradiation-induced "pinning" of the graphite lattice.

In a related context, the NRC staff issued Request for Additional Information 1.2.45 in response to a presentation by Exelon on a proposed pebble bed modular reactor (PBMR) design, asking for elaboration on the basis for the viscoelastic material assumption of graphite and its related material constitutive laws (NRC, 2002).

HHA-3142.4 Graphite Cohesive Life Limit

R(15). It is recommended that HHA-3142.4 be reviewed by the NRC staff because the statement pertaining to a cohesive life limit fluence of 10-percent linear change in the with-grain direction is generally beyond the turnaround fluence for nuclear graphites.

HHA-3143 Abrasion and Erosion

It is recommended that HHA-3143 be accepted based upon the gas flow velocity and operational experience of other gas-cooled reactors.

HHA-3144 Graphite Fatigue

HHA-3144 is stated to be still under preparation. Therefore, no review was possible.

HHA-3145 Compressive Loading

It is recommended that HHA-3145(a) be accepted as it requires the graphite components loaded under compression to be analyzed for buckling failure.

HHA-3200 Design by Analysis—Graphite Core Components

HHA-3210 Design Criteria for Graphite Core Components

HHA-3211 Requirements for Acceptability

R(16). It is recommended that HHA-3211 be reviewed by the NRC staff because of technical considerations for HHA-3211(c) and HHA-3211(d), which have been recommended for review by the NRC staff as stated below.

R(17). HHA-3211(c) is recommended for NRC staff review because the Code does not address allowable strain-to-failure, based on the stress limit of HHA-3145. This consideration is necessary because of the brittle nature of graphite.

R(18). HHA-3211(d) is recommended for NRC staff review because the Code does not provide information on how the strain due to buckling must be characterized and correlated with deformation limits.

HHA-3212 General Design Requirements for the Graphite Core Components

R(19). It is recommended that HHA-3212 be reviewed by the NRC staff because HHA-3212(h) has been recommended for NRC staff review as stated below.

R(20). It is recommended that HHA-3212(h) be reviewed by the NRC staff because the Code does not provide an adequate and technically justifiable quantitative stress analysis for blended areas, using notch stress analysis. The Code should explain how the notched strength and notched strength distribution are incorporated in arriving at the S_g values in such areas. The application of Weibull statistical analysis (HHA-II-3000) for blended area strength is fraught with errors and is not appropriate; thus, the Code should provide alternate approaches to evaluate stresses and stress margins for blended areas. The Code should publish maximum allowable stress requirements that are separate and distinct from the stress requirements for nonblended areas. The qualitative requirement of fillet radius based on maximum grain size is insufficient. Notch sensitivity studies on IM1-24 graphite by Brocklehurst and Kelly (1979) indicate a minimum fillet radius of 5 times the grain size may be insufficient to prevent a significant decrease of the bending strength of graphite.

HHA-3213 Basis for Determining Stresses

It is recommended that HHA-3213 be accepted. The paragraph contains general information on the maximum deformation energy theory of failure used in the rules for combining stresses.

HHA-3214 Terms Relating to Stress Analysis

It is recommended that HHA-3214 be accepted. The paragraph contains general information on the terms used in this subpart relating to stress analysis.

HHA-3214.1 Equivalent Stress

It is recommended that HHA-3214.1 be accepted. Equivalent stress was defined earlier in HHA-3213.

HHA-3214.2 Peak Equivalent Stress

It is recommended that HHA-3214.2 be accepted, as it is consistent with the traditional and accepted definition of peak equivalent stress.

HHA-3214.3 Normal Stress

It is recommended that HHA-3214.3 be accepted, as it is consistent with the traditional and accepted definition of normal stress.

HHA-3214.4 Shear Stress

It is recommended that HHA-3214.4 be accepted, as it is consistent with the traditional and accepted definition of shear stress.

HHA-3214.5 Membrane Stress

It is recommended that HHA-3214.5 be accepted, as it is consistent with the traditional and accepted definition of membrane stress.

HHA-3214.6 Bending Stress

It is recommended that HHA-3214.6 be accepted, as it is consistent with the traditional and accepted definition of bending stress.

HHA-3214.7 Combined Stress

It is recommended that HHA-3214.7 be accepted, as it is consistent with the traditional and accepted definition of combined stress.

Note: Subparagraph HHA-3214.8 is not available in the 2017 edition of the Code.

HHA-3214.9 Peak Stress
It is recommended that HHA-3214.9 be accepted, as it is consistent with the traditional and accepted definition of peak stress.

HHA-3214.10 Load Stress
It is recommended that HHA-3214.10 be accepted, as it is consistent with the traditional and accepted definition of load stress.

HHA-3214.11 Internal Stress
It is recommended that HHA-3214.11 be accepted, as it is consistent with the traditional and accepted definition of internal stress.

HHA-3214.12 Total Stress
It is recommended that HHA-3214.12 be accepted, as it is consistent with the traditional and accepted definition of total stress.

HHA-3214.13 Operational Cycle
It is recommended that HHA-3214.13 be accepted, as it is consistent with the traditional and accepted definition of the operational cycle.

HHA-3214.14 Probability of Failure
It is recommended that HHA-3214.14 be accepted, as it is consistent with the traditional and accepted definition (and HHA-3217) of the POF.

HHA-3215 Stress Analysis
It is recommended that HHA-3215 be accepted, as it is consistent with expected loads and loading configurations and conforms to the stress analysis used in the design of previous experimental and commercial power HTRs.

HHA-3215.1 General
It is recommended that HHA-3215.1 be accepted because it specifies the types of loads to be considered, including stress concentration effects, and the type of stress analysis to be performed.

HHA-3215.2 Stress Analysis of Nonirradiated Graphite Core Components
R(21). It is recommended that HHA-3215.2 be reviewed by the NRC staff because it requires only the use of an elastic stress analysis for nonirradiated graphite. As the stress-strain behavior of graphite is inherently nonlinear, a nonlinearly elastic stress analysis should be performed for nonirradiated graphite behavior for both the nonlinearly elastic portion and the post-elastic portion of graphite deformation.

HHA-3215.3 Stress Analysis of Irradiated Graphite Core Components
R(22). It is recommended that HHA-3215.3 be reviewed by the NRC staff because of the incorrect use of viscoelastic analysis, which was earlier identified for HHA-3142.3.

The NRC phenomenon identification and ranking table (PIRT) identified the effect of creep strain on CTE as an important phenomenon, needing more experimental data and scientific understanding. The industry also identified this phenomenon in its design data needs (DDNs). More information on this phenomenon appears in PIRT ID:10 and in PIRT ID:11.

HHA-3215.4 Stress Analysis of Oxidized Graphite Core Components

It is recommended that HHA-3215.4 be accepted, as it appropriately considers dimensional changes during reactor operation.

HHA-3216 Derivation of Equivalent Stress

It is recommended that HHA-3216 be accepted because HHA-3216 describes generally accepted procedures for the calculation of the equivalent stress values that are subject to the specified limits.

HHA-3217 Calculation of Probability of Failure

It is recommended that HHA-3217 be accepted because the technical content describing the procedure for the calculation of the POF conforms to the generally accepted engineering stress calculation and analysis practice.

HHA-3220 Stress Limits for Graphite Core Component—Simplified Assessment

It is recommended that HHA-3220 be accepted because this assessment is conservative. The allowable maximum stress value relates to the target POF derived from the SRC of the GCC and the service level load.

HHA-3221 Design Limits

R(23). It is recommended that HHA-3221 be reviewed by the NRC staff because of the recommendations for NRC staff review of several subparagraphs within HHA-3221.

HHA-3221.1 Combined Membrane Stress

R(24). It is recommended that HHA-3221.1 be reviewed by the NRC staff because HHA-3221.1(b)(2) is recommended for NRC staff review. HHA-3221.1(b)(2) should be reviewed by the NRC staff because the Code has not appropriately defined “any internal stress due to irradiation at the design lifetime.” [emphasis added]

HHA-3221.2 Peak Equivalent Stress

R(25). It is recommended that HHA-3221.2 be reviewed by the NRC staff because HHA-3221.2(b)(2) is recommended for NRC staff review. HHA-3221.2(b)(2) should be reviewed by the NRC staff because the Code has not appropriately defined “any internal stress due to irradiation at the design lifetime.” [emphasis added]

HHA-3222 Level A Service Limits

R(26). It is recommended that HHA-3222 be reviewed by the NRC staff because of the suggested NRC staff review of several subparagraphs within HHA-3222. HHA-3222 defines the service stress limits for various SRCs, stated as requirements, in subsequent subsubarticles.

HHA-3222.1 Combined Membrane Stress

R(27). It is recommended that HHA-3222.1 be reviewed by the NRC staff because HHA-3222.1(b)(2) is recommended for NRC staff review. HHA-3222.1 states that the generally accepted definitions for Level A service combine membrane service stress limits for various SRCs.

It is recommended that HHA-3222.1(b)(2) be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3222.2 Peak Equivalent Stress

R(28). It is recommended that HHA-3222.2 be reviewed by the NRC staff because HHA-3222.2(b)(2) is recommended for NRC staff review. HHA-3222.2 defines the Level A service peak equivalent service stress limits for various SRCs. The Level A service peak stress is the combination of all combined and peak stresses using an accepted general stress calculation method.

It is recommended that HHA-3222.2(b)(2) be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3222.3 Deformation Limits

R(29). It is recommended that HHA-3222.3 be reviewed by the NRC staff because of its deficiency in addressing deformation limits.

As applicable, the Code should define a minimum of two deformation limits. The first limit should be related to acceptable deformation, which can be monitored and tolerated and will not compromise the free movement of control rods and fuel rods during the lifetime of the graphite component. The second deformation limit should be related to the initiation of cracking in graphite, which, theoretically, should be at a stress that exceeds S_g for the SRC component. When the second limit is reached or surpassed, the damage tolerance requirement (HHA3100(c)) is triggered.

HHA-3223 Level B Service Limits

It is recommended that HHA-3223(a) be accepted because it requires Level B service loading (HHA-3124) stress limits to be the same as Level A service loading stress limits (HHA-3222) and is conservative.

It is recommended that HHA-3223(b) be accepted because it requires the GCC to meet the Level B deformation or other limits set in in the DS.

HHA-3224 Level C Service Limits

R(30). It is recommended that HHA-3224 be reviewed by the NRC staff because several subparagraphs within HHA-3224 are recommended for NRC staff review, as discussed below.

HHA-3224.1 Combined Membrane Stress
R(31). It is recommended that HHA-3224.1 be reviewed by the NRC staff because HHA-3224.1(b) is recommended for NRC staff review. HHA-3224.1 defines the Level C service design stress limits for various SRCs.

It is recommended that HHA-3224.1(b) be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3224.2 Peak Equivalent Stress
R(32). It is recommended that HHA-3224.2 be reviewed by the NRC staff because HHA-3224.2(b) is recommended for NRC staff review. HHA-3224.2 defines the Level C service design stress limits for various SRCs.

It is recommended that HHA-3224.2(b) be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3224.3 Deformation Limits
R(33). It is recommended that HHA-3224.3 be reviewed by the NRC staff because of the deficiency in deformation limits. The following assessment made for HHA-3222.3 applies here.

As applicable, the Code should define a minimum of two deformation limits. The first limit should be related to acceptable deformation, which can be monitored and tolerated and will not compromise the free movement of control rods and fuel rods during the lifetime of the graphite component. The second deformation limit should be related to the initiation of cracking in graphite, which, theoretically, should be at a stress that exceeds S_g for the SRC component. When the second limit is reached or surpassed, the damage tolerance requirement (HHA3100(c)) is triggered.

HHA-3225 Level D Service Limits
R(34). It is recommended that HHA-3225 be reviewed by the NRC staff because several of its subparagraphs are recommended for NRC staff review, as discussed below.

HHA-3225.1 Combined Membrane Stress
R(35). It is recommended that HHA-3225.1 be reviewed by the NRC staff because HHA-3225.1(b) is recommended for NRC staff review. HHA-3225.1 defines Level D service as the combined membrane service stress limits for various SRCs, averaged over the thickness of the components, according to an accepted general stress calculation method.

It is recommended that HHA-3225.1(b) be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3225.2 Peak Equivalent Stress
R(36). It is recommended that HHA-3225.2 be reviewed by the NRC staff because HHA-3225.2(b) is recommended for NRC staff review. HHA-3225.2 defines the Level D service peak equivalent service stress limits for various SRCs. The stress limits are the combination of all combined and peak stresses, according to an accepted general stress calculation method.

It is recommended that HHA-3225.2(b) be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3225.3 Deformation Limits

R(37). It is recommended that HHA-3225.3 be reviewed by the NRC staff because of the deficiency in deformation limits. The following statements made for HHA-3222.3 apply here.

As applicable, the Code should define a minimum of two deformation limits. The first limit should be related to acceptable deformation, which can be monitored and tolerated and will not compromise the free movement of control rods and fuel rods during the lifetime of the graphite component. The second deformation limit should be related to the initiation of cracking in graphite, which, theoretically, should be at a stress that exceeds S_g for the SRC component. When the second limit is reached or surpassed, the damage tolerance requirement (HHA3100(c)) is triggered.

HHA-3226 Special Stress Limits

It is recommended that HHA-3226 be accepted because it defines deviations from the basic stress limits, which are provided to cover special design or service loadings or configurations. These are given in the following subparagraphs.

HHA-3226.1 Bearing Stresses

It is recommended that HHA-3226.1 be accepted because it defines the applicability of bearing stresses in design considerations.

HHA-3227 Design Equivalent Stress Values and Material Properties

R(38). It is recommended that HHA-3227 be reviewed by the NRC staff for the following reasons.

HHA-3227 states that the MDS (HHA-2200) contains all of the other graphite material properties used for design. [emphasis added] However, permeability and emissivity, for example, are not listed in either HHA-2200 or the ASTM D7219-08 and D7301-08 nuclear graphite material specifications.

The Code is arguably concerned with only the design aspects related to the structural integrity of graphite components and is mainly based on establishing the appropriate stress limit, S_g, for various SRC graphites. However, the design needs to use permeability properties for graphites. For graphites used in a molten salt reactor (MSR) or liquid metal reactor, permeability is an important property and needs to be as low as possible to preclude coolant intrusion and potential early graphite cracking due to the thermal expansion and contraction of trapped coolant. For an HTGR, permeability is related to porosity and is an important property for radionuclide adsorption, retention, and desorption and release.

Thus, the Code should address requirements for emissivity and permeability for various graphite grades used in the GCA, including the potential effects of irradiation and oxidation on these properties.

Emissivity data are needed to estimate the degradation of thermal conductivity and the ability for dissipative heat transfer in accident scenarios.

HHA-3230 Probability of Failure Limits for Graphite Core Components—Full Assessment

It is recommended that HHA-3230 be accepted as it relates the target POF to the design service stress limit, S_g, and compares that with the POF data obtained from strength test population according to calculations outlined in HHA-3000-II.

HHA-3231 Design Limits

It is recommended that HHA-3231 be accepted because it is general and further defines the requirements in subsequent subparagraphs.

HHA-3231.1 Probability of Failure Resulting from Combined Stress

It is recommended that HHA-3231.1 be accepted as it defines the POF for the three SRCs.

HHA-3232 Level A Service Limits

R(39). It is recommended that HHA-3232 be reviewed by the NRC staff because HHA-3232.1 has been recommended for NRC staff review due to the reasons provided below.

HHA-3232.1 Probability of Failure Resulting from Combined Stress

R(40). It is recommended that HHA-3232.1 be reviewed by the NRC staff for the following reasons.

HHA-3232.1 should require the POF calculation for a single component to be extended to all components of the same SRC to arrive at the POF for the SRC. Additionally, the Code should provide information on how such calculations will be applied to graphite components in all SRCs and how to calculate the POF of the GCA.

The Code should define the design life, namely its relationship to (1) dimensional shrinkage turnaround dose, (2) dose at which dimensional expansion starts, and (3) onset of graphite cracking and the beginning of requirements that kick in for damage tolerance.

The NRC PIRT identified dimensional change as an important phenomenon needing more reliable data (PIRT ID:6). Industry also had several DDNs in this regard.

Related to HHA-3232.1(b)(2), the Code should appropriately define "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3232.2 Deformation Limits

R(41). It is recommended that HHA-3232.2 be reviewed by the NRC staff because of the deficiency in deformation limits. The following statements made for HHA-3222.3 apply here.

As applicable, the Code should define a minimum of two deformation limits. The first limit should be related to acceptable deformation, which can be monitored and tolerated and will not compromise the free movement of control rods and fuel rods during the lifetime of the graphite component. The second deformation limit should be related to the initiation of cracking in graphite, which, theoretically, should be at a stress that exceeds S_g for the SRC component.

When the second limit is reached or surpassed, the damage tolerance requirement (HHA3100(c)) is triggered.

HHA-3233 Level B Service Limits

It is recommended that HHA-3233(a) be accepted because it requires Level B service loading (HHA-3124) stress limits to be the same as Level A service loading stress limits (HHA-3232) and is conservative.

HHA-3234 Level C Service Limits

R(42). It is recommended that HHA-3234 be reviewed by the NRC staff because several of its subparagraphs have been recommended for NRC staff review (see below). HHA-3234 defines the allowable maximum in Level C service stress for the three SRCs, based on maximum allowable POFs, which are further defined in subsequent subsubarticles.

HHA-3234.1 Probability of Failure Resulting from Combined Stress

R(43). It is recommended that HHA-3234.1 be reviewed by the NRC staff for the following reasons:

- The Code should define the design life, namely its relationship to (1) dimensional shrinkage turnaround dose, (2) dose at which dimensional expansion starts, and (3) the onset of graphite cracking and the beginning of requirements that kick in for damage tolerance.

  The NRC PIRT identified dimensional change as an important phenomenon needing more reliable data (PIRT ID:6). Industry also had several DDNs in this regard.

- Related to HHA-3234.1, the Code should require the POF calculation for a single component to extend to all components of the same SRC to arrive at the POF for the SRC. Additionally, the Code should provide requirements for how such calculations should apply to graphite components of all SRCs and how to calculate the POF of the GCA. This is similar to the assessment provided for HHA-3217.

- HHA-3234.1(b) should be reviewed by the NRC staff because the Code has not appropriately defined "internal stress due to irradiation at the design lifetime." [emphasis added]

HHA-3434.2 Deformation Limits

R(44). It is recommended that HHA-3434.2 be reviewed by the NRC staff because of the deficiency in addressing deformation limits. The following assessment statements made for HHA-3222.3 apply here.

As applicable, the Code should define a minimum of two deformation limits. The first limit should be related to acceptable deformation, which can be monitored and tolerated and will not compromise the free movement of control rods and fuel rods during the lifetime of the graphite component. The second deformation limit should be related to the initiation of cracking in graphite, which, theoretically should be at a stress that exceeds S_g for the SRC component. When the second limit is reached or surpassed, the damage tolerance requirement (HHA3100(c)) is triggered.

HHA-3235 Level D Service Limits

R(45). It is recommended that HHA-3235 be reviewed by the NRC staff because several subparagraphs within HHA-3225 are recommended for NRC staff review, as discussed below. HHA-3235 defines the allowable maximum in Level D service stress for the three SRCs, based on maximum allowable POFs, which are further defined in the following subsubarticles.

HHA-3235.1 Probability of Failure Resulting from Combined Stress

R(46). It is recommended that HHA-3225.1 be reviewed by the NRC staff because of the following deficiencies.

The Code should require the POF calculation for a single component to be extended to all components of the same SRC to arrive at the POF for the SRC. Additionally, the Code should provide information on how such calculations will be applied to graphite components of all SRCs and used to calculate the POF of the GCA.

The Code should define the design life, namely its relationship to the (1) dimensional shrinkage turnaround dose, (2) dose at which dimensional expansion starts, and (3) onset of graphite cracking and the beginning of requirements that kick in for damage tolerance.

The NRC PIRT identified dimensional change as an important phenomenon needing more reliable data (PIRT ID:6). Industry also had several DDNs in this area.

R(47). It is recommended that HHA-3235.1(b) be reviewed by the NRC staff because the Code has not appropriately defined the meaning of “internal stress due to irradiation at the design lifetime.” [emphasis added]

HHA-3235.2 Deformation Limits

R(48). It is recommended that HHA-3235.2 be reviewed by the NRC staff because of the following deficiency in addressing deformation limits.

As applicable, the Code should define a minimum of two deformation limits. The first limit should be related to acceptable deformation, which can be monitored and tolerated and will not compromise the free movement of control rods and fuel rods during the lifetime of the graphite component. The second deformation limit should be related to the initiation of cracking in graphite, which, theoretically should be at a stress that exceeds S_g for the SRC component. When the second limit is reached or surpassed, the damage tolerance requirement (HHA3100(c)) is triggered.

HHA-3236 Special Stress Limits

It is recommended that HHA-3236 be accepted as it refers to HHA-3226, which has already been recommended for acceptance. HHA-3226 defines deviations from the basic stress limits. These deviations cover special design or service loadings or configurations.

HHA-3237 Design Stress Values and Material Properties
R(49). It is recommended that HHA-3237 be reviewed by the NRC staff because it refers to HHA-2200, which has already been recommended for NRC staff review.

HHA-3240 Experimental Limits—Design-by-Test
It is recommended that HHA-3240 be approved because the technical contents of the paragraph are reasonable.

HHA-3241 General
It is recommended that HHA-3241 be accepted because the technical contents of the paragraph are reasonable.

HHA-3242 Experimental Proof of Strength and Demonstration of Probability of Failure
It is recommended that HHA-3242 be accepted because the technical contents of the paragraph are reasonable.

HHA-3242.1 Design Limits, Level A and Level B Service Limits
It is recommended that HHA-3242.1 be accepted because of the completeness in the consideration of applicable levels of service loadings.

HHA-3242.2 Level C and Level D Service Limits
It is recommended that HHA-3242.2 be accepted because of the completeness in the consideration of applicable levels of service loadings.

HHA-3243 Experimental Proof of Strength, Service Load Rating
It is recommended that HHA-3243 be accepted because the technical contents of the paragraph are reasonable.

HHA-3300 Requirements for Design of the Graphite Core Assembly
It is recommended that HHA-3300 be accepted because the technical contents of the subarticle are reasonable. HHA-3300 also includes a requirement to document functional requirements of the GCCs in the DS and to assess them as a part of the design process.

HHA-3310 General Requirements
It is recommended that HHA-3310 be accepted because it states that the GCA's structural integrity requirements must satisfy those of the GCCs, as this subsubarticle refers to the conformance of subarticles HHA-3100 and HHA-3200.

HHA-3320 Design Considerations

HHA-3321 Design and Service Loadings
It is recommended that HHA-3321 be accepted because it requires the GCA integrity to satisfy the provisions of design and service loadings of GCCs, per HHA-3120.

HHA-3322 Special Considerations
It is recommended that HHA-3322 be accepted because it requires the GCA integrity to satisfy the provisions of design and service loadings of GCCs, per HHA-3140.

The NRC PIRT has identified several items under this paragraph as phenomena of concern. The relevant PIRT are PIRT ID:32, 32(a), 32(b), and 32(c).

HHA-3323 General Design Rules

It is recommended that HHA-3323 be accepted because it provides acceptable clarity in addressing potential conflicts with the rules of this paragraph.

HHA-3330 Design of the Graphite Core Assembly

R(50). It is recommended that HHA-3330 be reviewed by the NRC staff because of technical issues related to HHA-3330(c), which does not provide adequate information and technical justification on the origin of deviations from design tolerance and on the "accumulation of tolerances." HHA-3330(g) lacks specificity on inspection for GCCs. The Code should address how the design margin for constraint would be affected by such scenarios of "accumulation of tolerances."

Related to HHA-3330(g), it appears that inspection procedures to modify current requirements in ASME BPV Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," Division 1, "Rules for Inspection and Testing of Components of Light-Water-Cooled Plants," which focus on light-water reactors and reactor vessels and piping, for HTGRs need to be developed by the designer/owner, certified by ASME, and then assessed by the regulator (NRC). At a minimum, the Code should refer to applicable ASME BPV Code, Section XI, Division 2, "Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants," for the particular GCC designed and categorized for the SRC. If such methods are currently under development or in the planning stages, then the Code should note this fact. The Code should then require the design to incorporate such developments.

The Code should provide adequate information on (1) which specific components will need to be inspected, (2) which specific areas, such as critical areas, have components subject to maximum utilization and potential degradation and would be inspected, (3) the basis for connecting inservice inspection to online monitoring, and (4) whether these inspection areas and methods used for inspection would remain the same before and after irradiation and, if not, how the design should incorporate the results of inspection and online monitoring to assess degradation.

Although HHA-3330(g) requires provision for inservice inspection or online monitoring, unless specific methods to be used are known or required, it is not entirely possible to assess the efficacy of the user's method. Thus, these aspects should be incorporated in the ASME BPV Code.

Figure HHA-3141-1 Dependence of Strength and Weight Loss and Uniformly Oxidized Graphite Classes IIHP or INHP

R(51). It is recommended that Figure HHA-3141-1 be reviewed by the NRC staff because it pertains to two ASTM nuclear graphite class materials for specific oxidation conditions that may not be relevant to the reactor operating conditions. Any relationship generated from this figure may not be universally applicable to graphite that may be used in future graphite-moderated reactors. Several grades of graphite may be used for a reactor, depending on the various SRCs in the design. Because of the inconsistency in graphite manufacture, design-relevant oxidation data must be generated for the specific graphite that will be used for the reactor.

Figure HHA-3141-2 Dependence of Strength on Weight Loss in Uniformly Oxidized Graphite of Classes EIHP, ENHP, MIHP and MNHP
R(52). It is recommended that Figure HHA-3141-2 be reviewed by the NRC staff because it pertains to two ASTM nuclear graphite class materials for specific oxidation conditions that may not be relevant to the reactor operating conditions. Any relationship generated from this figure may not be universally applicable to graphite that may be used in future graphite-moderated reactors. Several grades of graphite may be used for a reactor, depending on the various SRCs in the design. Because of the inconsistency in graphite manufacture, design-relevant oxidation data must be generated for the specific graphite that will be used for the reactor.

Table HHA-3221-1
It is recommended that Table HHA-3221-1 be accepted because it defines the design-allowable POF for Service Levels A, B, C, and D for three SRCs.

3.1.4 Article HHA-4000 Machining, Examination, and Testing

HHA-4100 General Requirements

HHA-4110 Introduction
It is recommended that HHA-4100 be accepted because it provides information on the general responsibilities of a G Certificate Holder or a G Quality System Certificate Holder, as described in Article HAB-3000.

HHA-4120 Certification of Materials and Machining by the Graphite Core Component Manufacturer

HHA-4121 Means of Certification
It is recommended that HHA-4121 be accepted because it requires the completion of the G-2 Data Report, in accordance with Article HAB-8000, as the vehicle for certification. Specifically, such certification assures that materials comply with the requirements of the materials specification and that the machining, examination, and testing of all GCCs comply with the requirements of this article, the construction specification (CS), and the shop drawings.

HHA-4122 Certification of Examinations and Tests
It is recommended that HHA-4122 be accepted because it requires completion of certified reports of examination and tests in required forms and distribution according to the requirements in Table HAB-3255-1.

HHA-4123 Identification of Materials and Machined Graphite Core Components

HHA-4123.1 Materials
It is recommended that HHA-4123.1 be accepted because it specifies the acceptance condition for marking of materials.

HHA-4123.2 Machined Graphite Core Components

It is recommended that HHA-4123.2 be accepted because, in (a) through (e), it provides the requirements for marking components. These are in addition to the requirements in the ASTM materials specification, contained in ASTM D7219-08, Section 8.2, and in ASTM D7301-08 Section 7.2.

HHA-4130 Joining

It is recommended that HHA-4130 be accepted because it requires graphite components to be joined only by mechanical means. Other means of joining, such as chemical bonding, may not be feasible for HTR applications, or such bonding could result in unacceptable chemical and radiological contamination.

HHA-4200 Machining, Examination, and Testing

HHA-4210 Procedures, Qualification, and Evaluation

HHA-4211 General Requirements

It is recommended that HHA-4211 be accepted because it requires graphite components to be examined nondestructively by qualified personnel. This requirement is beyond that in the graphite material specification and contains its own nondestructive examination, as required in Section 11, “Finished Inspection,” of ASTM D7301-08, and in Section 12, “Finished Inspection,” of ASTM D7219-08. However, the ASTM specification requirement is for the graphite manufacturer and addresses the examination required before machining the GCC.

HHA-4212 Non-destructive Examination Procedures

It is recommended that HHA-4212 be accepted. Paragraph HHA-4212 requires all nondestructive examinations be performed in accordance with detailed written procedures.

This paragraph’s requirement not to contaminate during examination is noteworthy. This requirement conforms to Section 8.1 in ASTM D7219-08 and Section 7.1 in ASTM D7301-08.

HHA-4213 Qualifications of Examination Personnel

It is recommended that HHA-4213 be accepted because it refers to the organization’s quality system program (QSP) for personnel qualification. The QSP is also tied to ASME Nuclear Quality Assurance (NQA)-1a (2008, 1a-2009), “Quality Assurance Requirements for Nuclear Facility Applications.”

HAB-3820 contains detailed requirements for the QSP. NUMARK did not review Article HAB. Therefore, if the NRC staff has accepted or rejected any aspects of Article HAB, that decision may apply here as well, and HHA-4213 may be accepted or rejected.

HHA-4220 Graphite Core Component Machining

HHA-4221 General

It is recommended that HHA-4221 be accepted because it requires suitable precautions to protect from contamination and handling damage.

HHA-4222 Machining Facilities and Tools

It is recommended that HHA-4222 be accepted because it provides detailed requirements in (a) through (h) to avoid contamination and damage. It refers to Table HHA-4222-1 for substances that should either be avoided or minimized when machining.

In this context, ASTM D7219-08 item 6.1 states: "…The chemical impurities to be measured shall be as agreed between the supplier and the purchaser…"

HHA-4223 Receiving Inspection

It is recommended that HHA-4223 be accepted because it provides general requirements for materials received.

HHA-4224 Other Processing Steps

It is recommended that HHA-4224 be accepted because it provides general requirements for materials traceability.

HHA-4230 Graphite Core Component Examination

HHA-4231 General

It is recommended that HHA-4231 be accepted because it provides general requirements for GCC examination and who should conduct these examinations. HAB-3251, HAB-3342(c) and (f), and HAB-5210(a) contain testing and documentation requirements for CS.

HAB-3820 contains detailed requirements for CS. NUMARK did not review Article HAB. Therefore, if the NRC staff has accepted or rejected any aspects of HAB, that decision may apply here as well, and HHA-4231 may be accepted or rejected.

HHA-4232 Dimensional Examination

It is recommended that HHA-4232 be accepted because it contains acceptable requirements for dispositioning GCCs with out-of-tolerance dimensions.

HHA-4233 Examination for Material Defects and Damage

HHA-4233.1 Requirements

It is recommended that HHA-4233.1 be accepted because it provides the requirements for documenting defects that may have been introduced during handling. This requirement is different than the inspection of as-manufactured graphite, which is required by the ASTM material specification (Section 12 in ASTM D7219-08 and Section 11 in ASTM D7301-08). Thus, with the baseline data from the material manufacturer, proper completion of this subparagraph's requirements will ensure that no defects were introduced as a result of handling.

HHA-4233.2 Material Defects/Flaws

This review did not assess HHA-4233.2 because this subparagraph states that the Nonmandatory Appendix HHA-D guidance on defects or flaws in graphite and their acceptability is in preparation.

HHA-4233.3 Damage
R(53). It is recommended that HHA-4233.3 be reviewed by the NRC staff because it refers to HHA-4233.4, which is recommended for NRC staff review.

HHA-4233.4 Acceptance Criteria
R(54). It is recommended that HHA-4233.4 be reviewed by the NRC staff because of the absence of assessable requirements for acceptance criteria. The Code requires the designer to establish suitable acceptance criteria in the CS in HHA-4233.4. However, such criteria need to be assessed by the regulatory authority and approved before use. Also, HHA-4233.4 itself is questionable for acceptance because of the lack of specificity in HHA-4233.4 for a reliable assessment, and Nonmandatory Appendix HHA-D, which contains guidance on defects or flaws in graphite and their acceptability, is in preparation, as stated in the Code, and thus cannot currently be assessed.

It is expected that any acceptance criteria developed would be tied to material and component SRC POF requirements and functional requirements given in the DS, as required by HHA-3300.

HHA-4233.5 Repair of Defects and Flaws
R(55). It is recommended that HHA-4233.5 be reviewed by the NRC staff because the Code is deficient in several aspects.

The Code should apply this requirement to chamfered edges, blended areas (HHA-3212(h)), and other such areas. Because of stress concentration effects, such areas could be prone to relatively easier initiation of fatigue cracks or cracks where chronic oxidation may be enhanced, leading to premature failure.

The Code should require the user to demonstrate that the 2.0-millimeter maximum depth requirement is technically adequate and conservative for the grade of graphite used for construction. The Code should also require the user to demonstrate how such flaw depth requirements scale with the component size.

HHA-4240 Graphite Core Component Testing

HHA-4241 General
It is recommended that HHA-4241 be accepted because it provides the general requirements for GCC testing, including that the test aspects be specified in the DS.

HHA-4242 Graphite Core Component Testing
R(56). It is recommended that HHA-4242 be reviewed by the NRC staff because it requires testing either individual components or a part of the subassembly. This requirement may not be sufficient because the purpose and the results achieved may be quite different for individual components and the subassembly. Seismic testing may be necessary to confirm the design assembly of the GCA under design-basis seismic events, whereas such tests may not be needed for individual components.

The paragraph should also specify whether internal pressure testing should be conducted for assessing the integrity of fuel, control rod, and coolant channels or assessing the integrity of the

GCC in the form of pressure applied to graphite in tubular form. The user should justify the chosen maximum pressure or compression load applied. The user should also provide information if the tested component would be used in the construction of the GCA and, if so, the possible effects of proof test potential damage on the expected design life of the component.

HHA-4243 Post-Test Examination of Graphite Core Components

It is recommended that HHA-4243 be accepted as it specifies responsibilities and requirements for the G Certificate Holder to examine damage after a component proof load test or an internal pressure test and determine acceptability per CS criteria.

HHA-4244 Trial Assembly

It is recommended that HHA-4244 be accepted because it provides specific requirements for trial assembly, which should be captured in the construction report.

HHA-4250 Graphite Core Component Packaging

It is recommended that HHA-4250 be accepted because it provides packaging requirements for GCCs in (a) through (e), with attention to avoiding contamination and damage during packaging.

Table HHA-4222-1

It is recommended that HHA-4222-1 be accepted because it provides specific elements that should not be introduced during machining, handling, and other operations. It also identifies elements for which potential contamination should be controlled.

3.1.5 Article HHA-5000 Installation and Examination

R(57). It is recommended that Article HHA-5000 be reviewed by the NRC staff because the Code has not provided sufficient requirements for the applicability of this article to the installation of replacement components. This article is also silent on requirements for disassembly for any replacement of GCCs.

HHA-3300(h) requires the designer to allow for repair or replacement of GCCs, if required. However, the Code does not specify requirements for how this should be done or how to inspect that such requirements have been met.

HHA-5100 General Requirements

HHA-5110 Introduction

It is recommended that HHA-5110 be accepted because it provides general information on the requirements in subsequent subsubarticles. However, HHA-5100 refers to activities carried out by the party responsible for the installation of the GCA, according to the requirements in Article HAB-3000. These would include the following requirements, for example: HAB-3220(h), HAB-1281, HAB-3251, HAB-3256, HAB-3260(b), HAB-3420(r), HAB-3454(f), HAB-3820(c), HAB-3800, HAB-3830, HAB-3842.1, HAB-3851.2(3), HAB-3855.2(c), HAB-4110(a), HAB-4134.7(e), HAB-4134.9(b), HAB-8162(a), HAB-8200, and HAB-8420.

Since NUMARK was not involved in assessing Article HAB, if the NRC staff, in reviewing related Article HHA items, has identified any items that are rejected in these subarticles, subsubarticles, paragraphs, and subparagraphs, then those could influence the acceptance of this subsubarticle.

HHA-5200 Storage, Unpacking, and Examination

HHA-5210 Storage and Unpackaging

It is recommended that HHA-5210 be accepted because it provides the minimum requirements for storage and unpacking of GCCs, which should ensure protection from adverse weather, unnecessary loading of components, and avoidance of contamination. It also allows and acknowledges additional requirements that may be contained in the CS, which the designer and the GCA installer may have agreed upon.

HAB-3820 contains the requirements for CS. NUMARK did not review Article HAB. If the NRC staff has rejected any aspects of HAB-3820, some of these decisions may also pertain to HHA-5210. In that case, HHA-5210 may be rejected.

HHA-5210(c) contains advice, and not a requirement, for grouping and storing same-type components to facilitate marshalling before installation.

HHA-5220 Examination of Graphite Core Components

HHA-5221 General Requirements

It is recommended that HHA-5221 be accepted because it requires qualified personnel to conduct an examination and refers to the evaluation of the examination results using subsequent subarticle requirements.

HHA-5222 Examination Procedures

It is recommended that HHA-5222 be accepted because it contains requirements that are reasonable for personnel qualification and the examination of records by the authorized graphite inspector upon request. It also requires avoidance of contamination during graphite examination.

HHA-5223 Qualifications of Examination Personnel

It is recommended that HHA-5223 be accepted because it requires GCC examinations be performed and the results evaluated by qualified personnel, and in conformance with the organization’s QSP.

HHA-5300 Installation

HHA-5310 Documentation

HHA-5311 Construction Procedures

It is recommended that HHA-5311 be accepted because it provides specific requirements for construction procedures in (a) through (k). HHA-5311 refers to HAB-3451. Since NUMARK was not involved in the assessment of Article HAB, if the NRC staff has identified any items related to HHA-5311 that are rejected in HAB-3451, then HHA-5311 may be rejected for dependency and consistency.

HHA-5400 Examination During Installation

It is recommended that HHA-5400 be accepted because it requires the installer to identify orientation, location, and installations of GCA components that conform to specified tolerances in construction procedures and field drawings.

HHA-5500 Examination Post-Installation

It is recommended that HHA-5500 be approved. HHA-5500 specifies the responsibilities and requirements for the G Certificate Holder (with construction scope) to (1) ensure the correct installation of GCC meeting the construction procedures, (2) visually examine GCC for specified tolerances and absence of foreign objects, (3) visually examine GCC channels for trueness and any discontinuities, among others, and (4) document the results of the examinations in the construction report. HHA-5500 also requires the authorized nuclear inspector for graphite to verify the accuracy of the construction report.

3.1.6 Article HHA-8000 Nameplates, Stamping, and Reports

HHA-8100 Requirements

It is recommended that HHA-8100 be accepted because it refers to HAB-8000, which contains specific requirements for certificates and data reports.

It is notable that HAB-8200 prohibits a nameplate for the GCA. This is important and is believed to be the result of the brittle nature of graphite and the intended use at high temperatures, as well as the nature of the many hundreds of items that compose the assembly. Instead, the G-1 Data Report contains such information, including the serial number of the vessel in which the GCA is installed (Table HAB-8100-1).

3.1.7 Mandatory Appendix HHA-I Graphite Material Specifications

R(58). It is recommended that Mandatory Appendix HHA-I be reviewed by the NRC staff because HHA-I-1110 is recommended for NRC staff review.

HHA-I-1000 Introduction

HHA-I-1100 Scope

It is recommended that HHA-I-1100 be accepted, as it defines the graphite materials used in Subpart HHA components.

HHA-I-1110 Material Specifications

R(59). It is recommended that HHA-I-1110 be reviewed by the NRC staff. It lists the acceptable ASTM nuclear graphite specifications that can be used for materials and components referenced in Subpart HHA. NRC staff review of HHA-I-1100 is recommended because there are deficiencies in ASTM D7219-08 and ASTM D7301-08, particularly the absence of specifications for graphite permeability, which is important for MSR, and graphite emissivity. Graphite emissivity is affected by its oxidation. Other deficiencies in the ASTM D7219-08 and ASTM D7301-08 are discussed in Section 3.1.8 of this report.

3.1.8 Mandatory Appendix HHA-II, Requirements for Preparation of a Material Data Sheet

R(60). It is recommended that Mandatory Appendix HHA-II be reviewed by the NRC staff because it is does not cover several technical properties, as detailed below.

HHA-II-1000 Introduction

R(61). It is recommended that HHA-II-1000 be reviewed by the NRC staff because the Code requirements in HHA-II-1000(g) may be insufficient in the following aspects.

The Code should require data and state requirements for permeability for the graphite grade used in the design of molten salt and other similar type reactors, where helium is not the coolant. This information should be included in both the material specifications and the DS. Molten salt intrusion could influence the irradiation behavior of graphite. ASTM D7219-08 and ASTM D7301-08 do not contain requirements for permeability.

R(62). It is recommended that HHA-II-2000 be reviewed by the NRC staff because it does not address the irradiated compressive strength.

For irradiated properties, the MDS does not list or require compressive strength. However, compressive strength is important for core support components. The Code should require the designer to provide compressive strength data, obtained for the designed temperature and dose ranges.

HHA-II-3000 Detailed Requirements for Derivation of the Material Data Sheet—As-Manufactured Properties

R(63). It is recommended that HHA-II-3000 be reviewed by the NRC staff because it is does not cover detailed requirements for several measured properties and the data analysis of such properties, as discussed below.

This mandatory appendix and the associated MDS are for “as-manufactured properties,” and they include only the strength and the strength distribution determined at various temperatures. This does not address the strength and the strength distribution after irradiation. Although it is generally true that (1) the strength increases after irradiation and (2) the strength distribution is tighter as compared to the nonirradiated population, these expectations should be confirmed. Thus, the Code should require data and information on irradiated strength and strength distribution.

Strength is listed as a property to be measured and recorded in MDS-1, contained in the MDS forms in Appendix HHA-II-2000. However, MDS-1 does not contain Weibull parameter values, m^*, $m_{95\%}$, and the characteristic stress of the material reliability curve, $S_{c95\%}$; the temperature range and interval for these values; and the designer-calculated S_g values. The Code should require this information.

HHA-3140 requires an assessment of GCCs composing the GCA to include a consideration of the effects of irradiation. Thus, it is important that the Weibull parameters and the S_g values envelop the reactor operation temperature influence ranges. In conducting finite element analysis for stress distributions of GCCs and GCAs, the user must apply the time-integrated temperature and dose data for determining the S_g value for the SRC under different loading conditions. If “as-manufactured properties” room temperature values are used for determining S_g, the Code should require the user to provide adequate justification, including the assumptions used to arrive at the S_g value.

HHA-II-3100 Material Reliability Curve Parameters (Two Parameter for Simple Assessment)
R(64). It is recommended that HHA-II-3100 be reviewed by the NRC staff because of the lack of mathematical relationships for the curves in Figures HHA-II-3100-1 and HHA-II-3100-2. The mathematical relationship for these curves should be clearly presented, and the figure should be resized for readability. The mathematical regression analysis relationship of the best fit of the data shown in Figures HHA-II-3100-1 and HHA-II-3100-2 should define precision for using data from these figures to determine $m_{95\%}$ and $S_{c95\%}$.

HHA-II-3200 Material Reliability Curve Parameters (Three Parameter for Full Assessment)
It is recommended that HHA-II-3200 be accepted because the contents of this subarticle are in technical agreement with ASTM D7846-16, “Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Graphites.”

HHA-II-3300 Design Allowable Stress Value
It is recommended that HHA-II-3300 be accepted because Equation (21) in this subarticle is generally accepted and used for calculating the simple stress for a given POF, using the shape parameter (Weibull modulus) and the characteristic strength, which are calculated at the 95-percent confidence level, from test data. The simple stresses are the tensile, compressive, and bending stresses, and these can be calculated using the measured tensile, compressive, and bending strengths respectively, as stated in the subarticle.

It is generally accepted that simple tensile stresses are by far the major contributor in graphite component failure, as they are the common feature in the failure of ceramic materials. Complex biaxial and shear stresses may play a secondary role in the distortion of graphite components and component failure.

HHA-3216(b) requires shear stresses to be considered in the derivation of equivalent stress; HHA-3217(a) also requires shear stresses to be included in the calculation of components’ POF. In addition, HHA-3217(b) further explains the contribution of (secondary) shear stresses to the distortion of components. The assessment makes no distinction between primary and secondary stresses. Combined stress is thus the combination of primary and secondary stresses.

HHA-II-4000 Detailed Requirements for Derivation of the Material Data Sheet—Irradiated Properties
R(65). It is recommended that HHA-II-4000 be reviewed by the NRC staff because HHA-II-4100 is recommended for NRC staff review, as discussed below.

HHA-II-4100 General

R(66). It is recommended that HHA-II-4100 be reviewed by the NRC staff because HHA-II-4100(b) and HHA-II-4100(e) are recommended for NRC staff review.

It is recommended HHA-II-4100(a) be accepted. In HHA-II-4100(a), “these properties” refer to properties covered under “Irradiated Graphite” in Article HHA-II-2000 MDS-1 and MDS-2 material data sheet forms. Requirements to determine the changes in these properties at expected design temperature and dose ranges are acceptable.

R(67). It is recommended that HHA-II-4100(b) be reviewed by the NRC staff because it does not require properties data for isotropic graphite when reporting fractional change in properties after irradiation. This is not acceptable because even though an isotropic graphite may not have profound preferred grain orientations, critical properties, such as changes in dimensions and CTE after irradiation, may still be significant.

In some instances, direction-dependent properties diverge with increasing irradiation fluence, as documented in NUMARK’s forthcoming technical letter report, “Assessment of Graphite Properties and Degradation Including Source Dependence,” expected for publication in Spring 2021. The likely small as-manufactured CTE isotropy ratio for near isotropic graphites does not necessarily imply that the irradiation behavior will be isotropic. Such an effect may be negligible for isotropic graphite subject to low fluence; however, the Code should require the designer to confirm this assumption.

This highlights the importance of obtaining data, as well as a sound scientific understanding confirming design properties determined from MTR test data and from data obtained from installed trepanned samples, which feed back into safety assessments.

It is recommended that HHA-II-4100(c) be accepted because it requires the inclusion in the MDS of creep model parameters used in the design analysis of irradiated components, as stated in HHA-3142.1(c).

It is recommended that HHA-II-4100(d) be accepted because it requires the inclusion of the effect of creep strain on CTE and elastic modulus in the MDS.

R(68). It is recommended that HHA-II-4100(e) be reviewed by the NRC staff. It is not appropriate to accept that only one curve is necessary to characterize the relative change in linear dimensions for isotropic graphite, where the difference between dimensional change curves is insignificant. This must mean that, for all temperatures and fluences, the with-grain and against-grain data overlap.

The information to be provided to the NRC in a future NUMARK technical letter report on graphite properties data compilation and analysis shows that for “near-isotropic” IG-110 grade and other directional-processing grade graphites, the with-grain and against-grain data do not overlap.

It is recommended that HHA-II-4100(e) be reviewed by the NRC staff for other reasons as well. First, this requirement does not state which data (with-grain or against-grain) must be used in the design for determining potential graphite component and channel distortions. This requirement does not state that the user must choose the most conservative data; instead, whichever indicates the larger change in dimensions with irradiation dose is required. Second, this requirement does not indicate how conservatism is ensured in using the data (namely, the type of the largest lower bound statistical estimate curve (1- σ or 2- σ, where σ is one standard deviation from the statistical curve fit of the experimental data)).

The NRC PIRT identified dimensional change as an important phenomenon needing more reliable data (PIRT ID:6). Industry also had several DDNs for this issue.

The NRC PIRT identified channel distortion due to dimensional changes as an area needing more data (PIRT ID:28(c)) for newer graphites, which is supported by industry DDNs.

3.1.9 Mandatory Appendix HHA-III Requirements for Generation of Design Data for Graphite Grades

R(69). It is recommended that HHA-III be reviewed by the NRC staff because several articles contained within it are recommended for NRC staff review, as discussed below.

HHA-III-1000 Scope

R(70). It is recommended that a portion of HHA-III-1000 be reviewed by the NRC staff for the following reasons.

It is recommended that the NRC staff review the sentence “Changes to a graphite grade (specifically the coke or processing route) will require the generation of new design data,” which appears in this article, because this statement does not differentiate between as-manufactured properties data and irradiated data. It also assumes that the knowledge base may not exist to extrapolate irradiated property trends from as-manufactured and nonirradiated properties. This is probably not a completely supportable assumption, because nuclear graphite specialists are making steady progress in understanding these correlations. If it is possible to make reasonable assumptions from nonmanufactured properties, then the Code should require confirmation of the assumptions using trepanned and surveillance coupons of graphite made with the alternate coke type.

American Society for Testing and Materials, “Standard Specification for Isotropic and Near-Isotropic Nuclear Graphites,” ASTM D7219-08, for example, does not classify nuclear-grade graphite by different coke types. Item 5.2.1.1 of ASTM D7219-08 states, for example, “The filler shall consist of a near-isotropic or isotropic coke derived from a petroleum oil or coal tar.” Item 5.2.1.2 states that “the coke shall have a coefficient of linear thermal expansion (CTE), determined in accordance with Practice C781 and measured over the temperature range 25 to 500 °C [77 degrees F to 932 degrees F] , of between 3.5×10^{-6} and 5.5×10^{-6} $°C^{-1}$ [6.3×10^{-6} (degrees F)$^{-1}$ to 9.9×10^{-6} (degrees F^{-1})].”

Rather, the ASTM graphite classification is based on the processing method used and purity.

This is likely an unnecessary and burdensome requirement. Typically, a graphite manufacturer will have several options for the type of coke to be used. However, because of specific knowledge in graphite manufacture, the graphite manufacturer may achieve the same or similar properties using a different type of coke, while keeping other manufacturing practices, such as isomolding, vibration molding, or extrusion, the same.

For the graphite manufacturer and the user, it may be impractical to project ahead of reactor construction exactly how many components will be replaced during the course of reactor operation, because of changes in local energy requirements, competing technologies, and other factors. Even if such replacement numbers are known, it may not be economical to store the inventory, given the need to ensure there is no contamination or physical and environmental damage.

HHA-III-2000 General Requirements

It is recommended that HHA-III-2000 be accepted as it relates to general requirements.

HHA-III-2000(a) refers to HAB-4000 or HAB-3800 for quality assurance requirements, including testing. NUMARK did not assess Article HAB. If the NRC staff determined that parts of HAB-4000 or HAB-3800 are not acceptable, then such nonacceptance may carry over to HHA-III-2000(a).

HHA-III-2000(b) relates to material traceability, which is consistent with Section 8.2 of the ASTM D7219-08 and with Section 7.2 of ASTM D7301-08 material specification requirements.

HHA-III-3000 Properties To Be Determined

R(71). It is recommended that HHA-III-3000 be reviewed by the NRC staff because HHA-III-3000(a) requires properties to be determined using ASTM C781-08, “Standard Practice for Testing Graphite Materials for Gas-Cooled Nuclear Reactor Components.” It does not allow the use of equivalent consensus standards, such as those of the (German) Deutsches Institut für Normung or the Japan Nuclear Energy Safety Organization. These other international standards should be permitted provided that the Code user establishes their equivalence to ASTM C781-08 and properly justifies any deviations to the regulatory authority for assessment and approval.

HHA-III-3100 As-Manufactured Graphite

It is recommended that HHA-III-3100 be accepted because it lists the important design-related physical, thermal, and mechanical properties that must be measured. The requirement includes properties determination from room temperature to at least the maximum intended use temperature.

HHA-III-3200 Oxidized Graphite

R(72). It is recommended that HHA-III-3200 be reviewed by the NRC staff because the requirement concerns only tests conducted for HHA-III-3200(a)–(c) for as-manufactured specimens and not for irradiated specimens. Such data should be required to understand the synergetic effects of irradiation and oxidation. It could be that in the helium coolant environment, minimal oxidation can be expected, with any effects enveloped by the adequate margin in S_g. Similar chemical reaction effects also pertain to the structural integrity of graphite in MSRs and liquid metal reactors and should be included in the Code.

It was recommended above that HHA-3141(d) be reviewed by the NRC staff for similar reasons. Thus, the recommendation to review HHA-III-3200 is consistent with the recommendation for review of HHA-3141(d).

HHA-III-3300 Irradiated Graphite

It is recommended that HHA-III-3300 be accepted because it lists the important design-related and irradiation-dependent physical, thermal, and mechanical properties that must be measured. Although not mentioned, density is needed to calculate thermal conductivity from thermal diffusivity measurements. The test data are required to represent and envelop the irradiation service conditions, which include appropriate reactor neutron fluence and temperature ranges. HHA-III-3000 also requires the data to be reported to conform to the specifications in ASTM C625-15, "Standard Practice for Reporting Irradiation Results on Graphite."

HHA-III-4000 Requirement for Representative Data

R(73). It is recommended that HHA-III-4000 be reviewed by the NRC staff because subarticles HHA-III-4100 and HHA-III-4200 are recommended for review by the NRC staff.

HHA-III-4100 As-Manufactured Graphite

R(74). It is recommended that HHA-III-4100 be reviewed by the NRC staff because HHA-III-4100(a)–(c) requires measurements on "two specimens" in both the with-grain and against-grain directions from both the center and periphery of a slice taken from the as-manufactured billet. Data from just "two specimens" usually do not yield any useful information.

Furthermore, the subarticle has not provided information on the difference, if any, between "as-manufactured billet" and "production billet." It is not clear if data obtained from preproduction billets made in a protype facility, for example, would or would not be acceptable and why.

HHA-III-4200 Irradiated or Oxidized Graphite

R(75). It is recommended that HHA-III-4200 be reviewed by the NRC staff because the statement in the first line is confusing. It probably means, "Design data used for irradiated and oxidized properties shall be obtained from experiments performed from representative production billets for which MDS is to be prepared."

HHA-III-4200 seems to preclude the need to obtain data after oxidation of irradiated specimens. If this exclusion is indeed true, then it may imply that the chemistry of the coolant is not to be considered, which is not acceptable. The Code should include the implications for MSR designs that use graphite.

HHA-III-5000 Use of Historical Data

R(76). It is recommended that HHA-III-5000 be reviewed by the NRC staff for the following reasons.

- The "same" graphite grade may be generically manufactured using either pitch or petroleum coke. However, for the "current production material," these raw materials may be from different suppliers when the same grade is manufactured over a period of several decades. The implications of such potential differences that would impact the use of "already generated" data are not clear.

- Because the "same" grade graphite could have either petroleum or pitch coke as the filler raw material, it violates subarticle HHA-III-1000, which has been recommended for NRC staff review.

  The NRC staff raised this issue in Request for Additional Information 1.2.3 in response to a presentation by Exelon on a proposed PBMR design (NRC, 2002).

- The properties differences between the "same" graphite grade may not necessarily be minor, and there is no assurance that their effects are already bound by the design margin (S_g values for the specific SRC POF). If the property differences are not minor, such differences could potentially impact the S_g value used for the design; thus, the use of historical data will not be acceptable.

3.1.10 Nonmandatory Appendix HHA-A Graphite as a Structural Material

It is recommended that Nonmandatory Appendix HHA-A be approved because it is nonmandatory and provides some introductory information on graphite manufacture. However, there is incorrect information that should be amended, as noted below.

HHA-A-1000 Introduction

It is recommended that HHA-A-1000 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite. However, a minor correction may be made in HHA-A-1000 to include a purification step.

HHA-A-1100 Manufacture

It is incorrect to state that the graphite industry is less than 100 years old. Acheson's original U.S. patent (568,323) was issued in 1826, and production started thereafter in Niagara Falls, NY.

Figure HHA-A-1100-1

It is recommended that Figure HHA-A-1100-1 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

HHA-A-1110 Raw Material Preparation

It is recommended that HHA-A-1110 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite. HHA-A-1110 does not offer details on “preparation,” which typically includes calcining coke grains, pulverizing, and sizing.

HHA-A-1120 Mixing and Forming

It is recommended that HHA-A-1120 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

HHA-A-1130 Baking and Impregnation

It is recommended that HHA-A-1130 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

HHA-A-1140 Graphitization

It is recommended that HHA-A-1140 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

HHA-A-1150 Finishing (Purification)

It is recommended that HHA-A-1150 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

HHA-A-1160 Grain Orientation

It is recommended that HHA-A-1160 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

Figure HHA-1160-1 Extrusion

It is recommended that Figure HHA-1160-1 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

Figure HHA-1160-2 Molding

It is recommended that Figure HHA-1160-2 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

3.1.11 Nonmandatory Appendix HHA-B Environmental Effects in Graphite

It is recommended that Nonmandatory Appendix HHA-B be accepted because it is nonmandatory and contains general information on the environmental effects in graphite.

HHA-B-1000 Introduction

It is recommended that HHA-B-1000 be accepted because it is contained in the nonmandatory appendix section as general information on structural graphite.

HHA-B-2000 Radiation Damage

It is recommended that HHA-B-2000 be accepted because it is contained in the nonmandatory appendix section as general information on the environmental effects of irradiation on graphite, which are included in the cited references.

HHA-B-3000 Gas Coolant-Graphite Interactions (Oxidation)
It is recommended that HHA-B-3000 be accepted because it is contained in the nonmandatory appendix section as general information on the environmental effects of oxidation on graphite, which are included in more detail in the cited references.

HHA-B-4000 Salt Coolant-Graphite Interactions
It is recommended that HHA-B-4000 be accepted because it provides general information, in brief, on interactions between molten salt coolant and graphite and references related literature. HHA-B-4000 has no requirements.

HHA-B-5000 References
It is recommended that HHA-B-5000 be accepted because it contains a list of references for HHA-B-2000, HHA-B-3000, and HHA-B-4000.

3.1.12 Nonmandatory Appendix HHA-D Guidance on Defects and Flaws in Graphite

No recommendation is made for HHA-D because this appendix is in preparation.

4. ITEMS FOR ADDITIONAL CONSIDERATION

During the course of the review of Subsection HH, Subpart A, NUMARK noted the following items as either absent in the design requirements or recommended for additional consideration by the NRC staff.

Design Requirement for Surveillance Coupons
Usually the designer bases the reactor design on MTR data of test coupons from as-manufactured graphite billets, representative of graphite that will be used for reactor construction. Such MTR data should be confirmed by using test samples, which have been exposed to reactor operating conditions during service or trepanned from actual components at predetermined locations. The results of post-irradiation examination (PIE) should be used to confirm design assumptions and make any necessary changes in operations to accommodate the changed condition of affected GCCs.

Therefore, provisions should be included in the design of GCCs for installing and removing coupons at designated locations for irradiation testing and PIE and for reinstallation for additional irradiation.

Design Requirement for Disassembly and Reassembly of Graphite Core Components
Subsection HH, Subpart A, contains detailed requirements in HHA-5000 for the installation of GCCs and the examination of the GCA during and after installation. HHA-3330(h) requires the ability to repair or replace GCCs, if required.

Thus, Subsection HH, Subpart A, should state the requirements for the retrieval of GCCs, if required for either repair or replacement. Such retrieval must be done without displacement or damage to adjacent GCCs during the process. After repair or when replacing with an acceptable “like” component, the repaired or new GCC needs to be installed without damaging or otherwise compromising the original configuration for which the design and operation license was granted.

When a graphite component replacement is made, this nonirradiated component will be adjacent to and in close proximity to already reactor-service-irradiated graphite components. Going forward, the replacement component will be in the early stages of its irradiation, while the adjacent component will already be in the irradiation-aged condition. Because the thermal and irradiation contraction or expansion of the “mixed” components will be different from this stage forward, Subsection HH, Subpart A, should address the implications of differential thermal and irradiation contraction or expansion and the interaction stresses between the new, nonirradiated component and the irradiated and otherwise aged component.

Like the PIE of the initial GCA presently in Subsection HH, Subpart A, such PIE requirements should be applicable after the reinstallation of the repaired GCC or the installation of the replacement GCC.

Design Requirement for Allowable Probability of Failure for Notches and Radiused Areas

Subsection HH, Subpart A, requirement is currently qualitative and relates to grain size. There appears to be discrepancies in Subsection HH, Subpart A, between the relationship of grain size to "process zone" and the relationship of grain size to fillet radius of the recessed areas. HHA-3217(g)(4), uses $1x10^3$ times the maximum graphite grain size for the volume of the process zone. This is different than the 5 times the maximum grain size requirement for allowable notch radius in HHA-3212(h). HHA-3217(g), also does not consider the potential for variation of the process zone size with irradiation and oxidation or the dependence of conservatism on these field variables.

Considerable graphite reactor OE indicates that fracture originates mostly from keyways and other areas of geometrical discontinuity. Therefore, there should be a deterministic or probabilistic requirement for an allowable maximum POF for SRCs of graphite components originating from artificial "flaws," such as notches and other discontinuities in manufactured components.

Design Requirement for Graphite Damage Tolerance

HHA-3100(c) states, "the Probability of Failure values used as design targets may not be precisely accurate predictions of the rate of cracking of components." Therefore, HHA-3100(c), recognizes the possibility of cracking of graphite components, even though the graphite components may be designed according to the requirements of HHA-3100. This means that failure has occurred in the graphite component at a stress level below S_g and below its equivalent POF value. The requirement for damage tolerance should be quantified to include possible cracking of several GCCs at several locations and multiple cracking within GCCs. Also, the design code should incorporate the potential influence of any damaged components interacting with the GCA under reactor normal operation and design-basis accidents.

The assurance of the required structural integrity of the GCA within the allowable POF depends on a number of factors. These include, but are not limited to, (1) the timely detection of graphite cracking, particularly at critical areas, (2) the evaluation of the effects of such cracking on the reduction in the originally designed safety factor, and (3) further estimation of continuing damage potentially compromising the structural integrity of the GCA. Such operational data are important for the evaluation of damage tolerance and an assessment by the NRC to permit continued reactor operation. ASME Boiler and Pressure Vessel Code, Division 5, Subpart B of Subsection HA and Subpart A of Subsection HH, should include a provision for such technical information.

5. SUMMARY

NUMARK evaluated the rules in the 2017 ASME BPV Code, Division 5, pertinent to reactor graphite components. Subsection HH, Subpart A, contains these rules.

In assessing Subsection HH, Subpart A, NUMARK examined several previous design practices used in the construction and operation of gas-cooled reactors. These included the U.K. AGR and Magnox reactors; the U.S. Peach Bottom Atomic Power Station, Unit 1, and Fort St. Vrain Generating Station gas-cooled reactors; the German Thorium High-Temperature Reactor (THTR-300); and the Japanese experimental High-Temperature Engineering Test Reactor (HTTR). The previously design practices and codes for the construction and operation of the proposed General Atomics MHTGR and the 1990 draft ASME BPV Code, Section III, Division 2, Subsection CE, design code for graphite components were also included as input for the assessment. The lessons learned from German, U.K., U.S., and Japanese OE with the commercial and experimental reactors supported the review of Subsection HH, Subpart A.

In assessing Subsection HH, Subpart A, NUMARK reviewed publicly available technical literature related to nuclear graphite manufacture, current quality assurance procedures for graphite, nuclear graphite material specification and properties requirements (ASTM D7219-08 and ASTM D7301-08), and literature related to specific design property changes with high-temperature irradiation. Reviewers considered design safety considerations and requirements published by the International Atomic Energy Agency and RG 1.232, Revision 0, published by the NRC. NUMARK augmented the assessment by reviewing literature from the NRC graphite PIRT exercise conducted in 2008; a graphite workshop in 2019; and industry DDNs published by General Atomics for the MHTGR and AREVA and Westinghouse Electric Company LLC for the construction of the Next Generation Nuclear Plant (NGNP). Potential technical basis documents from research conducted at U.S. National Laboratories and other international laboratories were also used to assess the code.

The assessment concludes that the consensus-based 2017 edition of the ASME BPV Code covers more design aspects in greater detail than any previous graphite codes developed for the construction and operation of the gas-cooled HTRs. It includes, for example, (1) detailed quality assurance requirements to address Title 10 of the *Code of Federal Regulations*, Part 50, “Domestic licensing of production and utilization facilities,” Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants”; and ASME NQA-1, (2) specifications for nuclear graphite to be used in HTRs, invoking the ASTM nuclear graphite specifications, (3) ASTM specifications for the determination of nuclear graphite properties, (4) detailed requirements for developing an MDS used in the design, (5) stress and temperature limit requirements for the GCCs, classified by safety requirements and established via structural reliability determined using probabilistic methods, (6) component classification using an SRC system, (7) a listing of the type of loading and loads that must be considered in estimating the stresses in the GCCs, (8) consideration of graphite degradation during service, and (9) roles and responsibilities of the graphite manufacturing organization, assembler, designer, owner, graphite inspector, and others.

Subsection HH, Subpart A also explicitly states that it is not applicable to nongraphite materials used in HTRs, such as ceramic fuel, ceramic (fiber and fused cast refractory) insulation used for piping, and baked carbon ceramic insulation used around the graphite core to keep the temperature of the pressure vessel within limits.

Subsection HH, Subpart A contains salient articles and subarticles related to defining the classes of GCCs according to requirements related to the flux and temperature exposure and stresses encountered during reactor operation, loading categories for each of the operating conditions, the category of loads to be considered in stress calculations, and the determination of the required structural integrity of GCCs using probabilistic analyses of the strength property. The categorization of the GCA and GCCs into three different SRCs is uniquely based on probabilistic risk assessment.

The assessment highlighted portions of Subsection HH, Subpart A that the NRC staff may consider in more detail in deciding whether to endorse the Subsection HH, Subpart A "as-is" or with provisions. NUMARK also noted the items in Subsection HH, Subpart A that were either absent in the design requirements or recommended for additional consideration by the NRC staff.

Information from the NRC graphite PIRT, NRC graphite workshop, and industry DDNs provided insights valuable for assessing the currently available nuclear graphite properties necessary to fulfill the requirements of the Code. Specifically, current data provided valuable information for the mandatory MDS, which is required in the design of GCCs for various SRCs.

6. REFERENCES

Alloway, R., and Gorholt, W., "Core Graphite Conceptual Design Criteria," Document No: HTGR-86-068/0, GA Technologies, Inc., 1986.

AREVA Inc., "NGNP Conceptual Design DDN/PIRT Reconciliation," AREVA Document No. 12-9102279-001, September 2008.

American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code*, 1990 edition, "Proposed Section III, Construction of Nuclear Facility Components, Division 2, Subsection CE, Design Requirements for Graphite Core Supports," New York, NY.

American Society of Mechanical Engineers, *Nuclear Quality Assurance (NQA)-1*, 2008, editions, "Quality Assurance Requirements for Nuclear Facility Applications," New York, NY.

American Society of Mechanical Engineers, *Nuclear Quality Assurance (NQA)-1*, a-2009 editions, "Quality Assurance Requirements for Nuclear Facility Applications," New York, NY.

American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code*, 2017 edition, Section III, "Rules for Construction of Nuclear Facility Components," Division 5, "High Temperature Reactors," New York, NY.

American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code*, 2017 edition, Section XI, "Rules for In-Service Inspection of Nuclear Power Plant Components," Division 1, "Rules for Inspection and Testing of Components of Light-Water-Cool Plants," New York, NY.

American Society of Mechanical Engineers, *Boiler and Pressure Vessel Code*, 2017 edition, Section XI, “Rules for In-Service Inspection of Nuclear Power Plant Components,” Division 2, “Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants,” New York, NY.

American Society of Mechanical Engineers, letter to Brian Thomas, U.S. Nuclear Regulatory Commission, June 21, 2018, ADAMS Accession No. ML18184A065.

American Society of Mechanical Engineers, “Qualifications for Authorized Inspection,” QAI-1, latest edition, New York, NY.

ASTM International, “Standard Practice for Reporting Irradiation Results on Graphite,” ASTM C625-15, West Conshohocken, PA.

ASTM International, “Standard Specification for Isotropic and Near-Isotropic Nuclear Graphites,” ASTM D7219-08, West Conshohocken, PA.

ASTM International, “Standard Specification for Nuclear Graphite Suitable for Components Subjected to Low Neutron Irradiation Dose,” ASTM D7301-08, West Conshohocken, PA.

Beck, J.M., and L.F. Pincock, “High Temperature Gas-Cooled Reactors Lessons Learned Applicable to the Next Generation Nuclear Plant,” INL/EXT-10-19329, Revision 1, Idaho National Laboratory, 2011.

Bodmann, E., “Mechanical Design Philosophy for the Graphite Components of the Core Structure of an HTGR”, *Proceedings of the IAEA Specialists Meeting on Graphite Component Structural Design*, JAERI, Tokyo, JAERI-M 86-192, 1987.

Black, G., B.J. Marsden, G. Wright, and A.N. Jones, “Origin and validity of graphite dosimetry units and related conversion factors,” *Annals of Nuclear Energy*, 94:241–250, 2016.

Brocklehurst, J.E., and B.T. Kelly, “Graphite Structure into Relation to Mechanical Engineering Design,” *3rd International Working Group on High Temperature Reactors*, Gif-sur-Yvette, France, 11–13 June 1979.

Brohovich, B.B., Ovichinnikov, F.I., Klimenkov, V.I., Glazkvo P.V., and Dolishnyuk, B.M., “Disassembly of an Experimental Uranium-Graphite Isotope Reactor after Four Years of Operation,” Proceedings of 2nd U.N. International Conference on Peaceful Uses of Atomic Energy, Geneva, pp. 241–249, Session E-21, Paper 2297, Vol. 7, September 1–13 1958.

Dahlberg, R. C., Turner, R.F., Goeddel, W.V., “FSV Core Design Characteristics,” *Nuclear Engineering International*, 14 (163), December 1969.

Davies, M.W., “Graphite Core Design in UK Reactors,” IAEA-TECDOC-901, International Atomic Energy Agency, 1996.

Dihoru, L., Oddbjornsson, O., Kloukinas, P., Dietz, M., Horseman, T., Voyagaki, E., Crewe, A.J., Taylor, C.A., and Steer, A.G., “The Development of a Physical Model of an Advanced Gas Cooled Reactor Core: Outline of The Feasibility Study”, *Nuclear Engineering and Design*, 323: 269–279, 2017.

Gallego, N.C., and T.D. Burchell, “A Review of Stored Energy Release of Irradiated Graphite,” ORNL/TM-2011/378, Oak Ridge National Laboratory, 2011, ADAMS Accession No. ML113110373.

GA Technologies, Inc., “Design Data Needs Modular High-Temperature Gas-Cooled Reactor,” DOE-HTGR-86-025, Revision 2, 1987a.

GA Technologies, Inc., “Probabilistic Risk Assessment for the Standard Modular High Temperature Gas-Cooled Reactor,” DOE-HTGR-86-011, Revision 3, Volume 1, 1987b.

General Atomics, “Graphite Design Handbook,” DOE-HTGR-88111, Contract DE-AC03-88SF17367, September 1988a.

General Atomics, "The Licensing Experience of the Modular High-Temperature Gas-Cooled Reactor (MHTGR)," GA-A19455, Contract DE-AC03-88SF17367, September 1988b.

General Atomics, “Assessment of GT-MHR Spent Fuel Characteristics and Repository Performance,” PC-000502, Revision 0, April 2002.

General Atomics, “Final Report-NGNP Core Performance Analysis, Phase 2,” Report 911184, 2009a.

General Atomics, “Technology Development Road Mapping Report for NGNP with 750°C Reactor Outlet Helium Temperature,” GA Report PC-000586, Revision 0, 2009b.

Hirschfelder, G., “The 300 MW Thorium High-Temperature Reactor (THTR) Nuclear Power Station - Construction, Progress, Programme and Costs”. VGB Kraftwerkstechnik, 62(12), 1007-1010, 1982.

International Atomic Energy Agency, “Safety of Nuclear Power Plants: Design, Specific Safety Requirements,” IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Vienna (2016).

Ishihara, M., J. Sumita, T. Shibata, T. Iyoku, and T. Oku, “Principle design and data of graphite components,” *Nuclear Engineering and Design*, 233:251–260, 2004.

Ishiyama, S., Oku, T., and Eto, M., “Fatigue Failure and Fracture Mechanics of Graphites for High Temperature Engineering Testing Reactor,” *Journal of Nuclear Science and Technology*, 28:472–483, May 1991.

Japan Atomic Energy Research Institute, "Design of High Temperature Engineering Test Reactor,” JAERI-1332, 1994.

Judge, R.C.B. “A Method for Assessing the Effects of Graphite Property Variability on Core Structural Integrity Criteria”, in IAEA TECDOC-690, “The Status of Graphite Development for Gas-Cooled Reactors,” *Proceedings of a Specialists Meeting* held in Tokai-Mura, Japan, 9-12, pp 78-84, September 1991.

Judge, R.C.B., “Application of a Method for Assessing Probability of Graphite Core Brick Failure”, in “Graphite moderator lifecycle behavior, Proceedings of a specialists meeting, Bath, United Kingdom, 24-27 September 1995, IAEA-TECDOC-901, 1996.

Kingrey, K.I., “Fuel Summary for Peach Bottom Unit 1 High Temperature Gas-Cooled Reactor Cores 1 and 2,” Idaho National Laboratory Report INEEL/EXT-03-00103, 2003.

KTA-3232, “Keramische Einbauten in HTR-Reacktordruckbehalten,” Sicherheitstechnische Regel des KTA, 1992.

Marsden, B.J., A. Fernandez-Caballero, J. Wade, A. Jones, P. Mummery, G. Hall, and W. Windes, “Deriving property averaging equations for polycrystalline nuclear graphite with and against grain, Examples—Thermal Creep,” *19th International Nuclear Graphite Specialists Meeting*, Bruges, Belgium, September 2019~~.~~

Martinuzzi, P. Vo., T.-T.G., Tran, V.X., Steer, A., Baylis, S., and McLachlan N., “Modelling Behaviour of AGR Graphite Core using Code_Aster”, *The 16th International Nuclear Graphite Specialists Meeting*, Nottingham, United Kingdom, 13-17 September, 2015.

McLachlan, N., Reed, J., and Metcalfe, M.P., “AGR Core Safety Assessment Methodologies”, *Graphite Moderator Lifecycle Behavior*, Bath, United Kingdom, 24-27 September 1995, IAEA-TECDOC-901, 1996.

Melese, G., and Katz, R., “Thermal and Flow Design of Helium-Cooled Reactors,” Report No: DOE/NBM—5007607, American Nuclear Society, La Grange Park, Illinois USA, 1984.

Mitchell, M., “The Design of the PBMR Core Structures,” presented at the *Fifth International Nuclear Graphite Specialists Meeting*, Plas Tan-Y-Bwlch, Maentwrog, Gwynedd, United Kingdom, 12–15 September, 2004.

Mohanty, S. and Majumdar, S. “HTGR Graphite Core Component Stress Analysis Research Program – Task 1 Technical Letter Report”, Argonne National Laboratory Report, ANL-11/04 2011, ADAMS Accession No: ML11276A009.

Moorman, R. "A safety re-evaluation of the AVR pebble bed reactor operation and its consequences for future HTR concepts," Jul-4275 (ISSN 0944-2952), Forschungzentrum Jülich, Germany, 2008a.

Moorman, R., “Fission Product Transport and Source Terms in HTRs: Experience from AVR Pebble Bed Reactor. *Science and Technology of Nuclear Installations*,” Volume 2008, Article ID: 597491, 2008b.

Morgan, W.C., “Neutron Fluence and Atomic Displacement Rates for Graphite Irradiations,” *Nuclear Technology*, 21:50–56, 1974.

Morton, D.K., “ASME Code Efforts Supporting HTGRs,” INL/EXT-10-19518, Revision 2, Idaho National Laboratory, September 2012.

Office for Nuclear Regulation, “Graphite Reactor Cores”, ONR Guide, United Kingdom, November 2018.

Orzáez, J.A., “Neutronics Analysis of a Modified Pebble Bed Advanced High Temperature Reactor”, Ph.D. Thesis, The Ohio State University, 2009.

Platonov, P.A., Chugunov, O.K., Manesvsky, V.N., and Karpikum, V.I., “Radiation damage and life-time evaluation of RBMK graphite stack,” in IAEA-TECDOC-901, Proceedings of a Specialists Meeting held in Bath, United Kingdom, pp. 79–89, September 24–27, 1995.

Preston, S.D., and B.J. Marsden, “Changes in the coefficient of thermal expansion in stressed Gilsocarbon graphite,” *Carbon*, 44:1250–1257, 2006.

Prince, N and Brocklehurst, J.E., “The Integrity of CAGR Moderator Bricks”, Proceedings of the IAEA Specialists Meeting on Graphite Component Structural Design, JAERI, Tokyo, JAERI-M 86-192, 1987.

Reed, J., “An update on results from Inspection of AGRs,” in the 6th International Nuclear Graphite Specialists’ Meeting (INGSM-6), Chamonix, France, 2005.

Riley, H., “Analysis and Validation of Advanced Gas-Cooled Reactor Core Seismic Response Using Non-Linear Time-Domain Methods,” presented at the Meeting on Analysis and Validation of Advanced Gas-Cooled Reactor Core, organized by the Society for Earthquake and Civil Engineering Dynamics and held in London on February 28, 2018a.

Riley, G., “Physical Model of an AGR Nuclear Reactor Graphite Core for Shaking Table Explorations of Seismic Behavior,” South West Nuclear Hub, Bristol, UK, October 2018b.

Saurwein, J.J., “Nondestructive Examination of 54 Fuel and Reflector Elements from Fort St. Vrain Core Segment 2,” General Atomic Company Report, GA-A16829, 1982.

Schmidt, A., “Design Methods and Criteria for Graphite Components”, pp. 480 – 487, in *Proceedings of the Workshop on Structural Design Criteria for HTR*, January 31-February 1, 1989, Jülich, Germany.

Schwartz, A., “Post Irradiation Examination of Peach Bottom Fuel Elements E05-05 and CO5-05 and Related Analyses,” Gulf General Atomic Report GAMD-8743, 1969.

Shi, D., “Extension of the Reactor Dynamics Code MGT-3D for Pebble bed and Block Type High-Temperature- Reactors”, Forschungszentrum Jülich GmbH, Institut für Energie- und

Klimaforschung, Nukleare Entsorgung und Reaktorsicherheit (IEK-6), Diss. RWTH Aachen University, 2014.

Shibata, T., M. Eto, E. Kunimoto, S. Shiozawa, K. Sawa, T. Oku, and T. Maruyama, “Draft of Standard for Graphite Core Components in High-Temperature Gas Cooled Reactor,” JAEA-Research 2009-042, Japan Atomic Energy Agency, 2010.

Shibata, T., “Nuclear Graphite”, Chapter 2.5, pp 113-123, Handbook of Advanced Ceramics, Elsevier, New York, NY, 2013.

Shibata, T., “HTGR Development in Japan and Present Status,” Presented at WORKSHOP V–VINCO Technical Meeting, 9th International School on Nuclear Power, Warsaw, Poland, 2017.

Sterbentz, J. W., “Calculated Neutron and Gamma-Ray Spectra Across the Prismatic Very High Temperature Reactor Core”, 13th International Symposium on Reactor Dosimetry, Amsterdam, Netherlands, May 2008.

U.S. Code of Federal Regulations, “Domestic licensing of production and utilization facilities,” Part 50, Chapter I, Title 10, “Energy.”

U.S. Nuclear Regulatory Commission, “Safety Aspects of HTR-technology: NRC visit in Germany,” July 23–26, 2001, ADAMS Accession No. ML092250104.

U.S. Nuclear Regulatory Commission, “Request for Additional Information (RAI) on High Temperature Materials Graphite; Control of Chemical Attack; and Design Codes and Standards for the Pebble Bed Modular Reactor (PBMR),” letter from F. Eltiwala to K. Borton, Exelon Generation, May 31, 2002, ADAMS Accession No. ML021510521.

U.S. Nuclear Regulatory Commission, “PBMR Design Certification Pre-Application Planning Meeting,” September 21-22, 2005, ADAMS Package Accession No. ML052580318.

U.S. Nuclear Regulatory Commission, “Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs),” Volume 5, “Graphite PIRTs,” NUREG/CR-6944, ORNL/TM-2007/147, March 2008, ADAMS Accession No: ML081140463.

U.S. Nuclear Regulatory Commission, “Next Generation Nuclear Plant Pre-Application Activities, Department of Energy—Idaho National Laboratory, Docket No. PROJ 0748, SRP Section: NGNP G—Graphite, Application Section: Graphite,” Request for Additional Information No. 5800, Revision 0, July 20, 2011, ADAMS Accession No. ML112030291.

U.S. Nuclear Regulatory Commission, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition,” NUREG-0800, Section 3.9.3, “ASME Code Class 1, 2, and 3 Components and Component Supports, and Core Support Structures,” Revision 3, April 2014, ADAMS Accession No. ML14043A231.

U.S. Nuclear Regulatory Commission, “Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors,” Regulatory Guide 1.232, Revision 0, April 2018, ADAMS Accession

No. ML17325A611.

U.S. Nuclear Regulatory Commission, memorandum from Frederick Brown, Director, Office of New Reactors, to New Reactor Business Line, “Expectations for New Reactor Reviews,” August 29, 2018, ADAMS Accession No. ML18240A410.

U.S. Nuclear Regulatory Commission, “Achieving Modern Risk-Informed Regulation,” Commission Paper SECY-18-0060, May 23, 2018, ADAMS Package Accession No. ML18110A186.

U.S. Nuclear Regulatory Commission, letter to Richard D. Porco, “NRC Response to ASME Letter for Request for NRC Endorsement of ASME Boiler and Pressure Vessel Code Section III, Division 5,” August 16, 2018, ADAMS Accession No. ML18211A571.

U.S. Nuclear Regulatory Commission, memorandum from Makuteswara Srinivasan to Timothy R. Lupold, “Summary of the ORNL/NRC Public Workshop on Nuclear Graphite Research, March 16–18, 2019, Rockville, Maryland,” April 14, 2019, ADAMS Accession No. ML091000232.

V. Slavbonas, V., Stilwell T.C. and Zudans, Z., “Rules for Design of Nuclear Graphite Core Components – Some Considerations and Approaches,” *Nuclear Engineering and Design*, 4:313-333, 1978.

Wahlen, E., Wahl, J., and Pohl, P., “Status of the AVR Decommissioning Project with Special Regard to the Inspection of the Core Cavity for Residual Fuel,” Waste Management ‘00 Conference, Arizona, United States, February 27–March 2, 2000.

Westinghouse Electric Company LLC, “Next Generation Nuclear Plant NGNP Technology Development Roadmapping Report—Steam Production at 750°C–800°C (Combined Report),” NGNP-TDI-TDR-RPT-G-00024, Revision 1, 2009a.

Westinghouse Electric Company LLC, “Next Generation Nuclear Plant, Conceptual Design Study, Design Data Needs (DDNs), Reconciliation against PIRTs,” NGNP-CDWP TI-DDN, Revision 1, 2009b.

Windes, W., T. Birch, R. Bratton, “Graphite Technology Development Plan,” INL/EXT-07-13165, Revision 1, Plan-2497, Idaho National Laboratory, October 2010.

Yu, S., Li, H., Wang, C and Zhang, Z., “Probability Finite Element Assessment Method for Nuclear Graphite Components”, Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17), Paper # M04-5, Prague, Czech Republic, August 17–22, 2003.

Yu S., and L. Sun, L., “The Design of HTR-PM Graphite Internals”, Presentation at NSEI, University of Missouri-Columbia, 2010.

Zhensheng, Z., Zhengming, Z., and Yu, S. “Structural Design of Ceramic Internals of the HTR-10”, presented at the Meeting of the Nuclear Graphite Technology Research Group, Sep 29 – Oct 5, 2002.

Ziermann, E. and Günther, I. Jül-3448, “Final Report on the Power Operation of the AVR Experimental Nuclear Power Station,” Jülrich Research Center, October 1997, ADAMS Accession No. ML082130449.