ASME NTB-4-2021

Background Information for Addressing Adequacy or Optimization of ASME BPVC Section III, Division 5 Rules for Nonmetallic Core Components

ASME SETTING THE STANDARD

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BACKGROUND INFORMATION FOR ADDRESSING ADEQUACY OR OPTIMIZATION OF ASME BPVC SECTION III, DIVISION 5 RULES FOR NONMETALLIC CORE COMPONENTS

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ASME SETTING THE STANDARD

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FOREWORD

The purpose of this document is to provide background information on the scope, development, and verification of elevated-temperature design and construction rules as defined in the ASME Boiler and Pressure Vessel Code ("BPVC"), Section III *Rules for Construction of Nuclear Facility Components*, Division 5 *High Temperature Reactors* Subsection HH, *Class A Nonmetallic Core Support Structures*, Subpart A *Graphite Materials*, 2017 edition. The general requirements applicable to nonmetallic core components are discussed in BPVC Subsection HA *General Requirements*, Subpart B, *Graphite Materials*.

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ABBREVIATIONS AND ACRONYMS

AG	against grain
AGR	Advanced Gas Reactor
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BPVC	Boiler and Pressure Vessel Code
CDF	cumulative density function
dpa	displacements per atom
DOE	Department of Energy
EIHP	extruded, isotropic, high purity
ENHP	extruded, near-isotropic, high purity
FEA	finite element
IIHP	isomolded, isotropic, high purity
INHP	isomolded, near-isotropic, high purity
JAEA	Japan Atomic Energy Agency
KTA	Kerntechnischer Ausschuss (Nuclear Safety Standards Commission)
MIHP	molded, isotropic, high purity
MNHP	molded, near-isotropic, high purity
NRC	US Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PDF	probability density function
POF	probability of failure
POS	probability of survival
RSF	reserve strength factor
SF	safety factor
SRC	Structural Reliability Class
VP	verification problem
WG	with grain

1 INTRODUCTION

Before its appearance in the 2011 edition of ASME BPVC, there was no internationally recognized graphite core design code. Although the need for such a code was recognized by stakeholders such as the US Nuclear Regulatory Commission (NRC) and several reactor designer/constructers, it was not until 2002 that ASME formed a project team to initiate a graphite design code. Graphite is used extensively for reactor internal components in high-temperature gas reactor concepts, as it is needed to establish core geometries allowing coolant flow, reactivity control, and shutdown element insertion; serve as a moderator while supporting the nuclear heat generation process; and provide a passive heat removal flow path in certain licensing basis events [1].

Those functions are key to the operation and safety of the reactor system. One critical difference between graphite core components and the pressure vessel is that the graphite core assembly is a structure comprising many hundreds of components. The designers take measures to ensure that the failure of a single component does not compromise the function of the assembly.

The prior approach to graphite design was deterministic, similar to the approach applied for metallic components today. Graphite, with no strength in the plastic regime, was treated as a linear Hookean material. Any component that suffered cracking was considered a "failed component" and was removed. Additionally, only nonirradiated graphite use was addressed. This approach has been found to be inadequate for design and regulatory licensing. Graphite, because of its nature, is inherently cracked; and the absence of cracking cannot be ensured nor used as an indicator of absolute reliability, as it can be for metals.

After assessment, a new probabilistic approach was adopted. It concluded that the designer can allow for cracks in the component but must demonstrate through analysis and testing that the component can maintain the assigned safety function. Moreover, the design should account for the effects of irradiation on the thermal and mechanical properties of the graphite in the design of the graphite core and consider statistical strength variations within a billet, as well as variation from billet to billet due to different production runs. The new approach also does not follow the standard ASME practice of defining primary and secondary stresses but instead uses a combined stress approach that incorporates the largest stress contributors — irradiation-induced stresses and mechanical stress concentrations — as well as lesser stress contributors like combined membrane, bending, and peak stresses.

It was initially envisioned that the design code would be applied for helium-cooled high-temperature reactors, as that was the leading technology at the time.

The purpose of this document is to provide background information on the scope, development, and verification of elevated-temperature design and construction rules as defined in ASME BPVC Section III, Division 5 Subsection HH, Class A *Nonmetallic Core Support Structures*, Subpart A *Graphite Materials*, 2017 edition. The general requirements applicable to nonmetallic core components are discussed in BPVC Subsection HA *General Requirements*, Subpart B, *Graphite Materials*.

Similar to the rules for metallic components, BPVC Section III, Division 5, *High Temperature Reactors* is structured to provide a central location for all aspects of construction for high-temperature reactors, including nonmetallic components or, more specifically, graphite components, in the 2017 edition. For nonmetallic components, according to ASME code terminology, "construction" includes all aspects of Materials (HHA-2000), Design (HHA-3000), Machining, Examination and Testing (HHA-4000), Installation and Examination (HHA-5000), and Nameplates (HHA-8000). The rules stipulate details for material specifications (HHA-I), the requirements for preparing a material data sheet (HHA-II), and the requirements for generating design data for different graphite grades (HHA-III). It also gives reference guidance for consideration of factors such as graphite as a structural material (HHA-A) and the environmental and oxidation effects in graphite (HHA-B).

The general requirements under BPVC subsection HAB complement the technical rules, as subsection HAB details the rules for classifying graphite core components (HAB-2000), the responsibilities and duties during the design and construction process (HAB-3000), the quality assurance aspects (HAB-4000), the Authorized Inspection requirements (HAB-5000), the applicable standards (HAB-7000), and the required certificates and reports (HAB-8000). It also provides a glossary of highlighted terms (HAB-9000). It specifically states the limitations of the rules in HAB-1130 [2]:

> The rules of this Subpart and Subsection HH, Subpart A provide requirements for new construction and include consideration of mechanical and thermal stresses due to cyclic operation. They include consideration of deterioration that may occur in service as a result of radiation effects and oxidation.

At the outset, several materials issues were considered when drafting the code:

- Differences between nuclear graphite and traditional ferrous core construction metals
- The manufacture of graphite
- The effect of the reactor environment on nuclear graphite

Several important differences between the properties and behavior of graphite and steels were recognized, as listed in Table 1 (refer to Appendix A):

Table 1: Comparison of the Behavior of Steels and Nuclear Graphite

Steel (Metal)	Nuclear Graphite (Nonmetallic)
Region of linear elastic behavior	Always nonlinear elastic behavior
Yield stress can be defined	Yield stress is not definable
High tensile strength, fracture strain, and fracture toughness	Low tensile strength, fracture strain, and fracture toughness
Small scatter in strength data	Large scatter in strength data
Strength decreases with increasing temperature	Strength increases with increasing temperature
Relief of peak stress due to plasticity	Relief of peak stress due to microcracking
Local peak stresses are not critical	Local peak stresses can cause damage
Crack initiation depends upon the primary stress	Crack initiation depends upon the flaw size distribution and total stress
Material properties depend on thermal neutron flux	Material properties are independent of thermal neutron flux
Fast neutron flux influences the material properties (raises the nil ductility temperature)	Fast neutron flux changes all properties and induces dimensional change (shrinkage/swelling) and creep

Moreover, graphite is not weldable like metal.

One unique aspect of the behavior of graphite is the material's temperature response. Graphite, unlike other materials, increases in strength with increasing temperature. Tensile strength increases of ~50% are typical, with the strength increasing with temperature until the onset of plasticity at approximately 2000°C. This behavior requires the exclusion of oxidizing gases, such as air, to prevent gasification of the graphite.

Several consequences of the manufacture of graphite must be considered in formulating a design code. Although graphite has been in production for over 100 years, there are no standardized graphite grades. Polycrystalline graphite is produced from specifically sized carbonaceous fillers bonded with a carbon-rich binder; this plastic mix is formed into the desired shape and heat treated to carbonize the binder (~1000°C) and heat treated again at ~2500–3000°C to graphitize the material [3]. When this process is coupled to the desire to control the chemical purity, it can be understood why each graphite grade has a unique distribution of pore sizes and shapes. These differences lead to a unique set of properties and a somewhat unique response to reactor environmental conditions.

An extensive review of graphite materials as they relate to application, selection, and qualification; the available graphite grades and properties; and operational considerations was conducted for the Next Generation Nuclear Plant project [1], which provides details and a comprehensive background and overview.

2 CODE APPROACH

This section provides the basis for the code and a typical design sequence for a graphite core component. Because there is not a standardized graphite grade for nuclear applications, the code places the responsibility for determining the design properties of the graphite used on the core designer. The approved properties for the selected graphite grade are then determined through material testing and listed in the form of a materials data sheet [4]-[6], which is used to justify the design.

Previous studies [7], [8] determined that variations of the Weibull distribution best describe the graphite reliability curve. HHA-II-3000 [9] describes how to statistically characterize graphite material based on specimen test results so that a material reliability curve can be derived. The approach is supported by many other studies [10]-[17].

To perform a stress-based analysis, the rules derive an equivalent stress state (from a multiaxial stress analysis) to determine the peak equivalent stress for a component for a given load condition.

In general, parts are designed by comparing calculated stresses to strength limits based on specimen test results and adequate design margins. But in the case of graphite, fixed design margins do not ensure uniform reliability because of the variability in the material. The stochastic strength (large random fluctuations from the population mean) and the nonlinear stress-strain response (quasi-brittle) of graphite [18], as well as billet-to-billet variation [19], require that the material be statistically characterized. That characterization is then used to determine the design margin [20], [21].

The identified modes of failure for graphite are brittle fracture, fatigue, excessive deformation (including both elastic instability and irradiation-induced dimensional changes) and environmental effects such as irradiation and chemical attack.

The following are fundamental concepts for the code approach.

- It is possible to allocate probability-of-failure (POF) targets to the graphite parts such that if the targets are met, the overall functional integrity of the assembly is ensured.
- The effects of loads on a part can be calculated and expressed as stress states in the part. Complex stress states can be reduced to an equivalent stress, which is equivalent to uniaxial stresses applied to test specimens.
- The nature of graphite implies that a probabilistic assessment method is better suited to the design of graphite parts than is a deterministic method.
- It is possible to characterize the materials by a statistical treatment of the material specimen test results to produce a statistical distribution (referred to as the material reliability curve) and generate confidence intervals to ensure conservatism.
- To ensure margin against brittle fracture, for a simple assessment, it is possible to determine stress values — based on the POF targets and material test data — so that when the part stresses are lower than these limits, adequate reliability of the part is ensured. For a full assessment, it is possible to calculate expected POF values for a graphite part based on material test data that are directly comparable to the POF targets and ensure adequate reliability of the part.
- Environmental effects such as irradiation and oxidation can be incorporated into the method by considering the changes to the input material properties.
- To ensure the margin against fatigue fracture, the code requires protection against fatigue failure; but it does not specifically address guidance regarding failure of graphite parts due to fatigue-induced damage for the major operating cycles of the reactor (HHA-3144) [22].

- Provisions are made for the use of fracture mechanics to extend the assessment of parts should it be necessary.

The graphite code treats design, service, and test loadings consistently with the rest of the ASME BPVC. The design loadings, defined in HHA-3123.1 through HHA-3123.4 [22], include the distributions of pressure, temperature, fast neutron flux or damage dose rate, and various forces applicable to nonmetallic core components. According to HAB-2142 [23], the design specification defines the design limits (the enveloping case for the design) and service limits according to the designer's classification with regard to functional performance (Level A); the ability to withstand damage requiring repair (Level B); and the extent to which large deformations in the areas of structural discontinuity (Level C) and gross deformations with consequential loss of dimensional stability and damage requiring repair (Level D) are permitted.

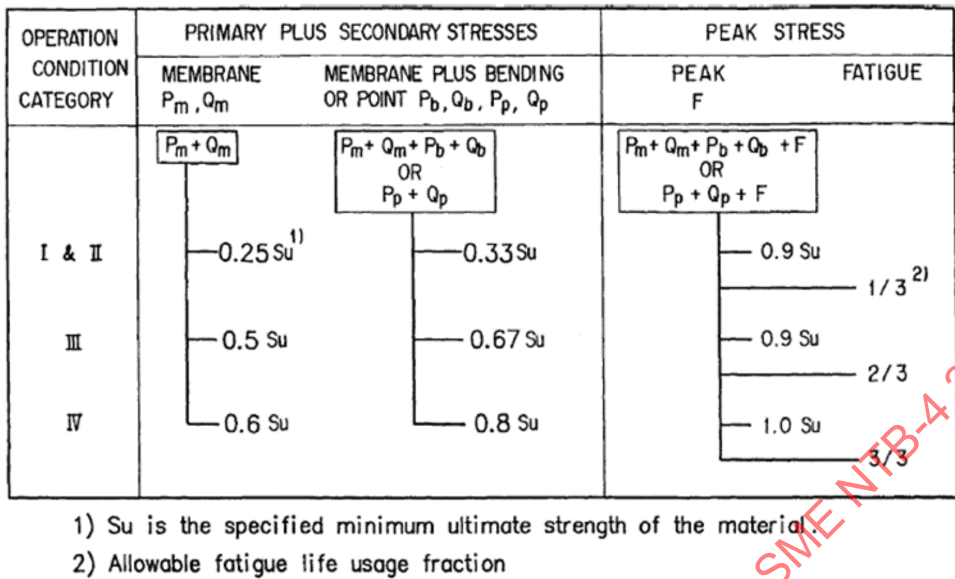
To determine stress in the ASME BPVC, it is customary to distinguish between primary stress (a normal stress or shear stress developed by an imposed loading that is necessary to satisfy the laws of equilibrium of external and internal forces and moments), secondary stress (a normal stress or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure), and peak stress (the increment of stress that is additive to the primary plus secondary stresses by reason of local discontinuities or local thermal stress). Because of the brittle nature of graphite, no distinction is made among the three types of stress; instead, a combined stress approach is used that combines them.

The theory of failure is based on the maximum deformation energy theory, in which an equivalent stress is derived from an arbitrary stress state at a point. The POF is determined by comparing the peak equivalent stress (the highest equivalent stress computed from the total stress) with the results of a uniaxial strength test as specified in HHA-3213 and HHA-3214 [22]. Reducing the risk of failure requires incorporating adequate design margin. As mentioned, fixed design margins do not ensure uniform reliability because of the strength variability in graphite. Instead an allowable POF is used.

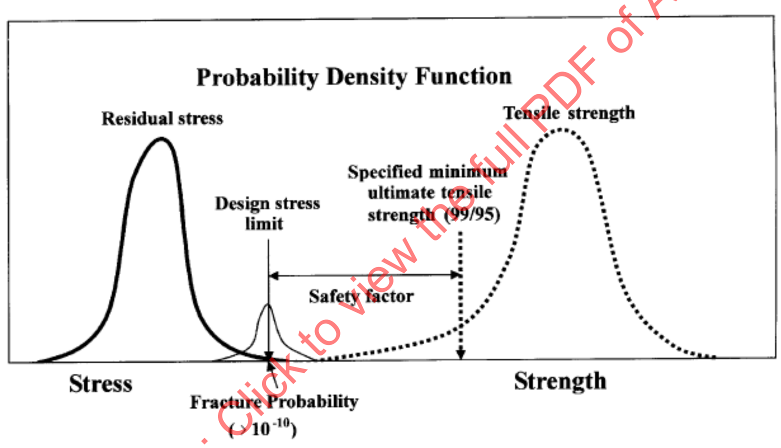
The specified design allowable POF was derived from a review of design margins from several code methodologies that included the proposed ASME CE draft methodology [24], the Japan Atomic Energy Agency (JAEA) methodology [25], [26], the Kerntechnischer Ausschuss (KTA) 3232 methodology [27] and the United Kingdom (UK) Advanced Gas-cooled Reactor methodology [28] as reported by Mitchell [20].

The JAEA methodology (and previous ASME BPVC Section III Division 2 Subsection CE draft method) used a predicted failure approach, applying the failure probability function with defined limits (or ratios), as shown in the Hopper diagrams in Figure 1a, the JAEA approach, and the Subsection CE approach (Figure 2).

The JAEA methodology defines primary, secondary, and peak stresses using the minimum ultimate strength ratio while assuming a linear cumulative damage law for fatigue evaluation with usage factors limited to 1/3, 2/3, or 1 for the different operating conditions [25]. The specified minimum ultimate strength (S_u, with a survival probability of 99% and confidence level of 95%) is applied to obtain the acceptable design stress limit, as shown in Figure 1a (reprinted from [25]). For example, the induced stress in the core support structure should be less than 0.25 of S_u, as shown in Figure 1a; but it is also shown that, by applying this ratio to a corresponding graphite with a tensile strength distribution, it is estimated that a fracture or failure probability of 10^{-10} is attained, as illustrated in Figure 1b (reprinted from [26]).



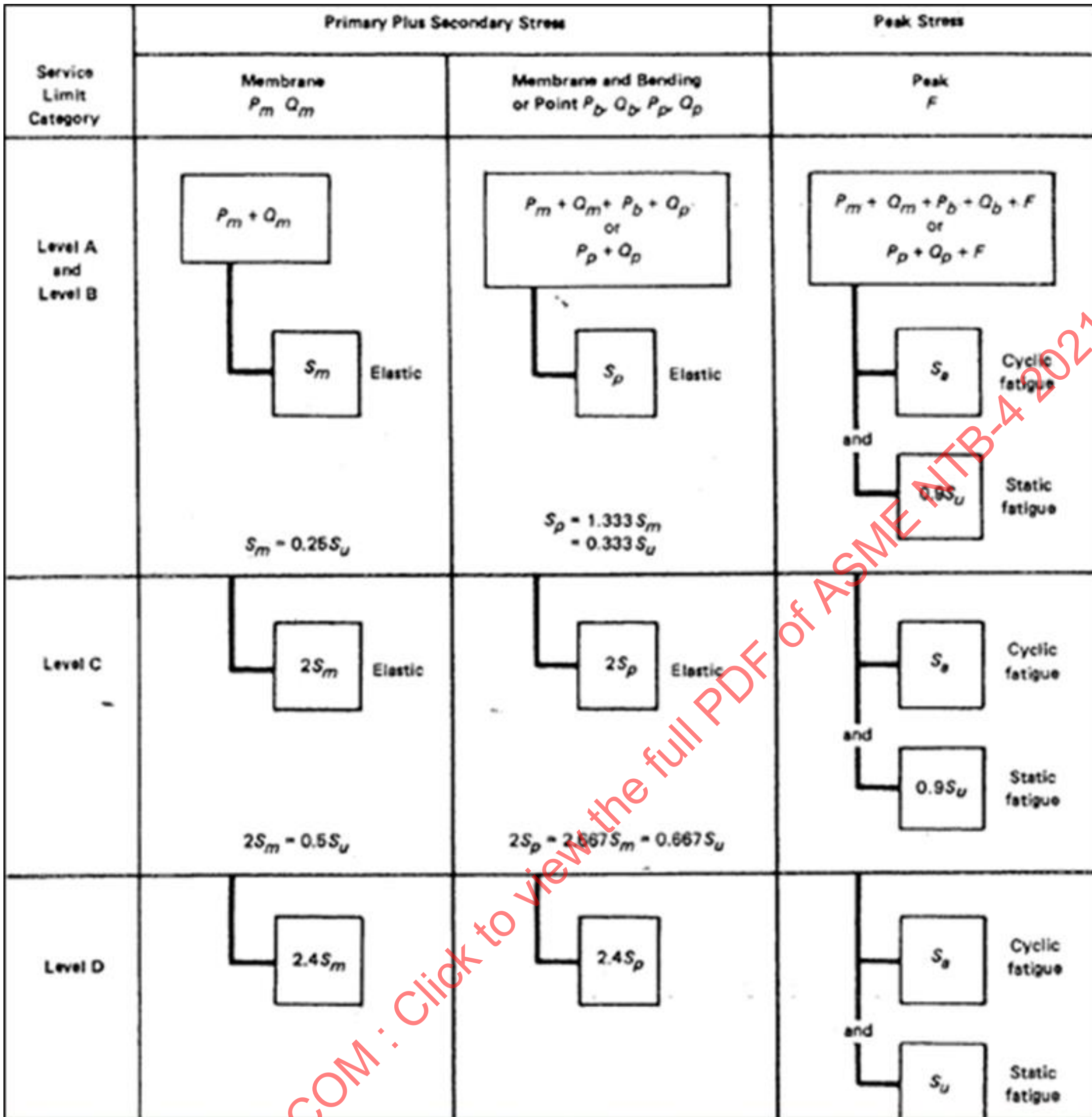
(a)



(b)

Figure 1: JAEA Methodology: (a) Design Stress Limit for Core Support Graphite and (b) Fracture Probability Density Function

The proposed ASME Section III Division 2 Subsection CE draft method similarly defines primary, secondary, and peak stresses and associated allowable design limits for different service levels as shown in Figure 2. The allowable design limits are defined in terms of S_m (the primary and secondary membrane allowable stress limit), S_p (the primary plus secondary plus bending allowable limit or primary and secondary point allowable stress limit), S_o (the allowable fatigue stress amplitude), and S_u (the minimum ultimate tensile strength) [24].



GENERAL NOTES:
(a) "Elastic" refers to stress calculated by linearly elastic methods.
(b) "Cyclic fatigue" is failure caused by repeated loads.
(c) "Static fatigue" is failure caused by long term application of a static load.

Figure 2: Proposed ASME CE-3550-1 Service Categories and Stress Intensity Levels

The KTA methodology used Weibull theory to determine design margins. The KTA 3232 draft rule (adopted as the current ASME HHA method [9], [22]) suggested a probability density function (PDF) of the strength distribution determined from measured strength values using a Weibull distribution, as shown in Eq. (1). Allowable POF values of 10^{-4} to 10^{-2} were defined for class 1 and class 2 components, respectively. The parameters are defined as the Weibull modulus (m) and the characteristic strength (S_c,) [27]. The design margin is calculated as a function of the required POF and material variability defined by m.

$$f(x) = \left(\frac{x}{S_c}\right)^{m-1} . \frac{m}{S_c} exp\left[-\left(\frac{x}{S_c}\right)^{m}\right]; x > 0 . \qquad (1)$$

UK AGR values are based on a safety factor (SF) or reserve strength factor (RSF) deterministic approach. The SF and RSF approaches have had several historical evolutions. In the most current approach [28], the SF is equal to the ratio of strength (S) and stress (σ), as shown in Eq. (2). The RSF shows how much reserve the core has to handle external loads, as shown in Eq. (3).

$$SF = \left(\frac{S}{\sigma_{int}+\sigma_{ext}}\right). \quad (2)$$

$$RSF = \left(\frac{S-\sigma_{int}}{\sigma_{ext}}\right). \quad (3)$$

Figure 3 illustrates the basis for how design margins are compared, given a typical graphite. For SF comparison, the ratio of the median of the tensile strength distribution (S_t) to the design stress (S_m) is compared with the UK AGR safety factor.

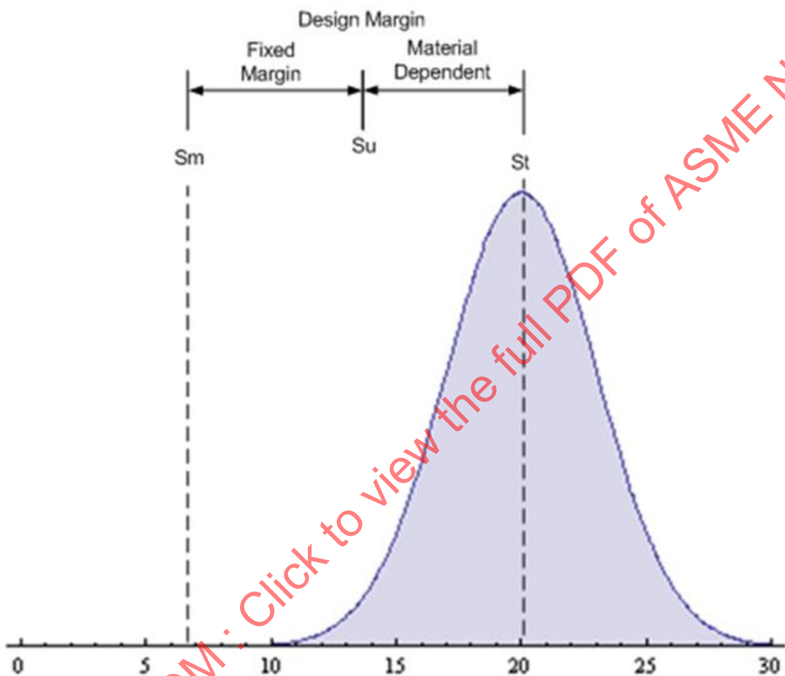


Figure 3: Illustration of Design Margin

Table 2 [20] compares the various methodology design margins for core supports. The comparison is based on a Weibull modulus of between 5 and 15, which is typical for a nuclear graphite.

Table 2: Safety Margins for Core Support Structures (In Tensile Loading)

	JAEA (ASME CE)	*KTA	UK AGR
Level A	5.3 - 9.3	1.8 - 5.9	RSF=5.0 (SF 3)
Level B	5.3 - 9.3	1.8 - 5.9	RSF=3.0 (SF 2)
Level C	2.7 - 4.7	1.8 - 5.9	RSF=2.0 (SF 1.5)
Level D	2.2 - 3.9	1.6 - 3.7	RSF=1.5 (SF 1.25)

*RSF: reserve strength factor; SF: safety factor; *Weibull moduli from m=5 to m=15*

The code-mandated design allowable POF and design allowable stresses are shown in Table 3 and Figure 3, respectively [22]. Note that Figure 4 demonstrates the breakdown for Structural Reliability Class (SRC) - 1, Graphite Core Component as an example of the code application. It also shows the categorical design and service level limits breakdown from HAB-2142 that were discussed earlier [23].

Table 3: Design Allowable Probability of Failure

Table HHA-3221-1
Design Allowable Probability of Failure

		Service Limit			
SRC	Design	Level A	Level B	Level C	Level D
SRC-1	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-3}
SRC-2 [Note (1)]	10^{-4} (10^{-2})	10^{-4} (10^{-2})	10^{-4} (10^{-2})	5×10^{-2}	5×10^{-2}
SRC-3	10^{-2}	10^{-2}	10^{-2}	5×10^{-2}	5×10^{-2}

NOTE:
(1) This applies to the SRC-2 Design as well as Service Level A and B limits. The change in limits is to indicate that this Article allows for the degradation of Graphite Core Components (or increase in stresses) caused by irradiation during service. The difference between the initial allowable stress value and the allowable stress value in parentheses makes sure that there is margin for material degradation or increase of stresses in service.

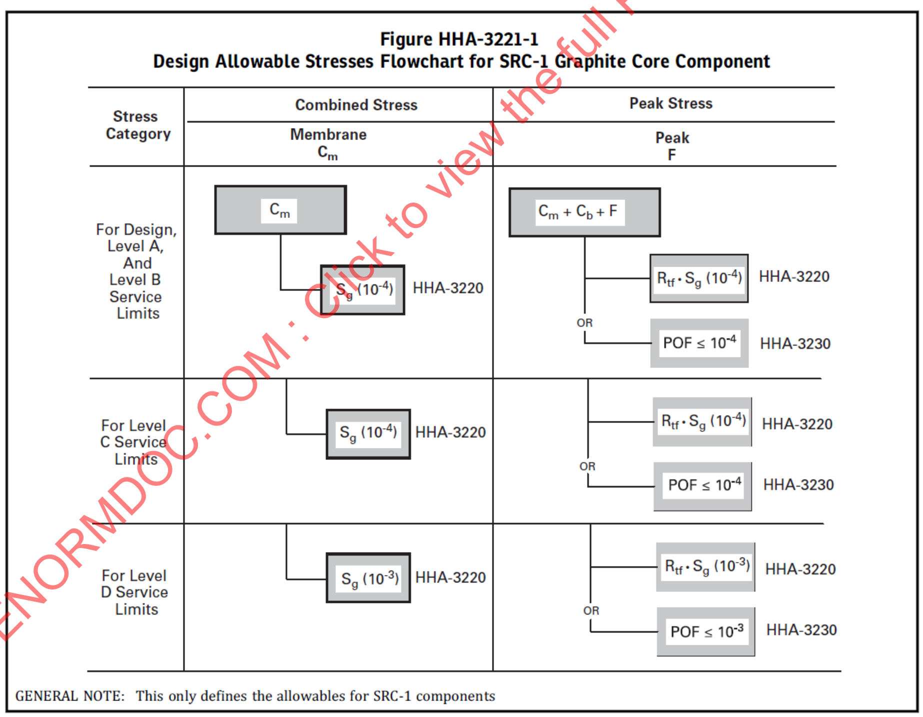


Figure 4: Design Allowable Stresses Flowchart for SRC-1

HAB-3250 [29] provides a guide to the preparation of the design specification required by Division 5 for nonmetallic core components. This document is referenced several times and provides specific inputs to the design process [22], [30]. Before the design process begins, several parameters should be defined and reported in the design specification (which includes the SRC as well as the design and service level loadings and limits).

The declared target or POF value, determined from the component classification and loading level assessment, are then compared with the determined POF for the component, based on any one of the three design approaches discussed in the design rules in HHA-3000 [22]. The design process can be summarized as follows:

- Classify the part, then establish and categorize the loads that are to be applied. Determine the reliability targets for the parts for the various load conditions.
- Calculate the stresses (expressed as an equivalent stress — as explained in Section 4) in the part when it is exposed to the various load combinations.
- Compare the stresses in the part with the allowable limits by one of two methods:

  – Simple assessment [31]: Compare the predicted stress state (for the load case) with stress limits derived from the allowable POF and the material test data, as demonstrated by the cumulative density functions (CDF) in Figure 5 [20]. The design margin is incorporated through the use of the lower 95% confidence bound on the Weibull parameters (according to the procedures and requirements established in [6], [32]) and the selection of the target reliability value. The simple assessment assumes that the failure distribution is the same at all parts of the component. This also means that the calculated allowable (or equivalent) stress, S_g, (Eq. (4)) for a given POF, is the same stress at all parts of the component and equal to the overlap area referenced in the plot (Figure 5). The allowable stress is compared with the peak equivalent stress. This two-parameter Weibull method has been demonstrated to be conservative for graphite components with low POFs [18].

$$S_g = S_c \left[-ln(1 - POF)^{\frac{1}{m}}\right] \quad (4)$$

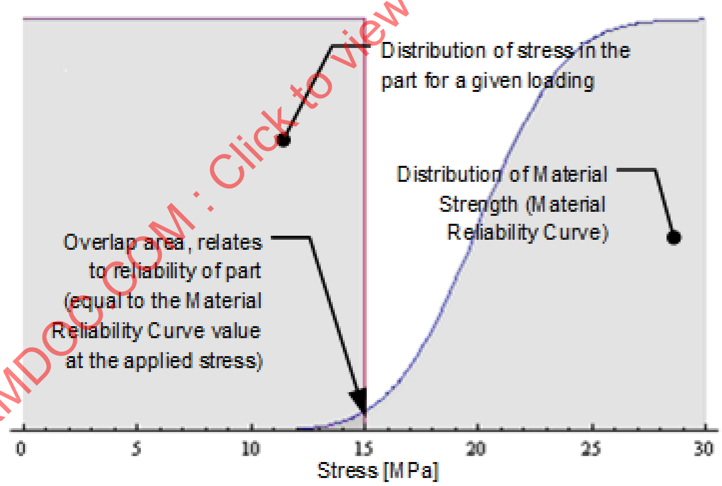


Figure 5: Schematic of Simplified Assessment Methodology (CDF)

  – Full assessment [33]: Calculate the POF for a part exposed to a specific load and compare a calculated POF directly with the target POF, as illustrated in Figure 6. The distribution of the stress over the volume of the part is convoluted with the distribution of strength in the material, as shown for the PDF in Figure 7 [20].

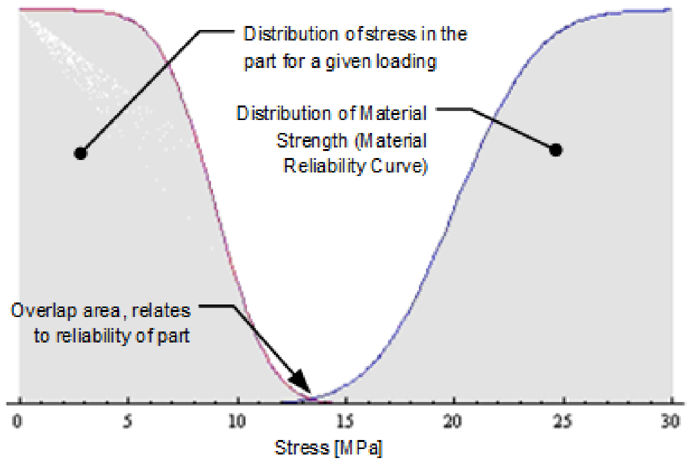


Figure 6: Schematic of Full Assessment Methodology (CDF)

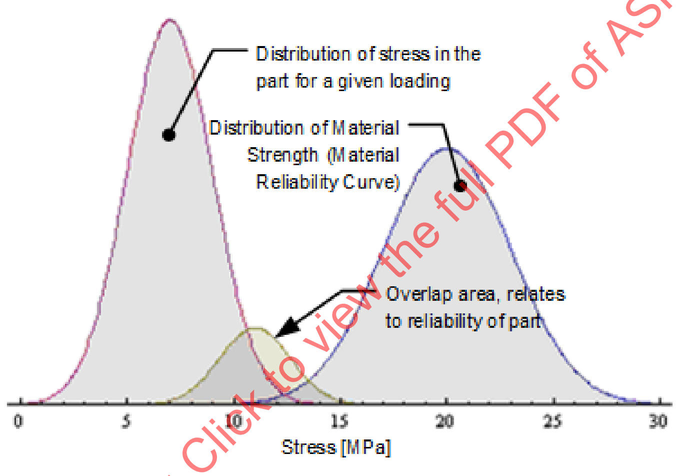


Figure 7: Weibull Probability Failure Prediction with the Full Assessment Method (PDF)

The full assessment method takes account of the actual distribution of stress in the part so that smaller volumes of material at the same stress level will result in a lower POF for that volume group of the part [20]. Owing to stress concentrations in real components, a material is not subjected to the enveloping stress value. The method accounts for the actual stress distribution subject to the material reliability curve. The method implemented in the code is Denninghof's modified Weibull weakest-link formulation [34]. This three-parameter modified Weibull method has been validated and is discussed in more detail in Section 4.

The simple assessment considers the peak equivalent stress of the entire part, whereas the full assessment considers the point equivalent stress for each integration point or a section of the part.

If neither calculation method is applied, the component may be designed and demonstrated by testing or experimental proof, with margins derived from the material reliability curve.

If the declared POF targets (from the design specification) are met, and all additional design requirements (again as listed in the design specification) are met, the component design is complete. If the component fails to meet the declared POF targets or any of the additional design requirements, then the designer is obliged to either redesign the component or select a different graphite grade (with a less variable, higher strength).

The summarized process is shown in Figure 8 and Figure 9, extracted from later editions of the Section III appendices [35].

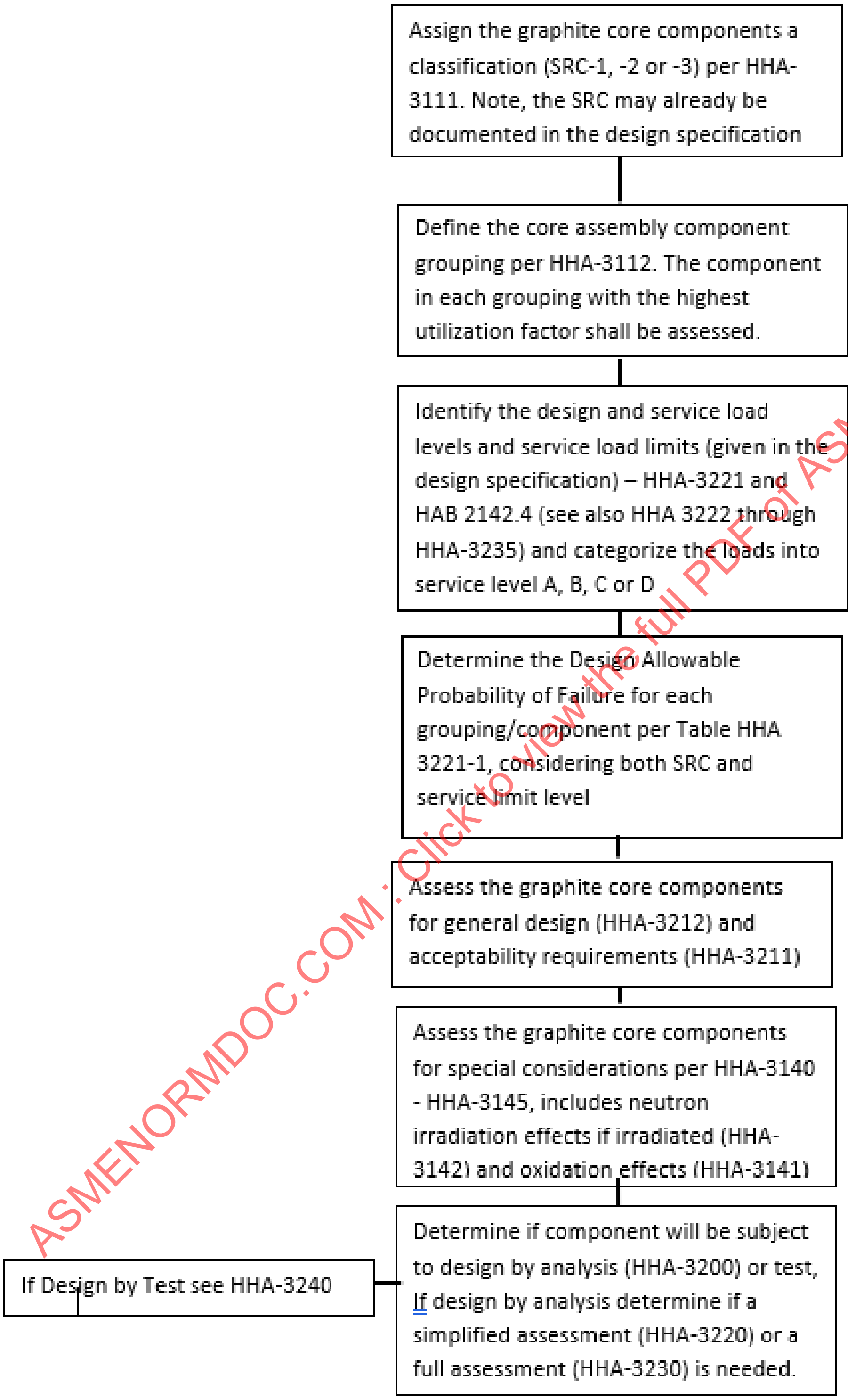


Figure 8: Typical Graphite Core Component Design Sequence

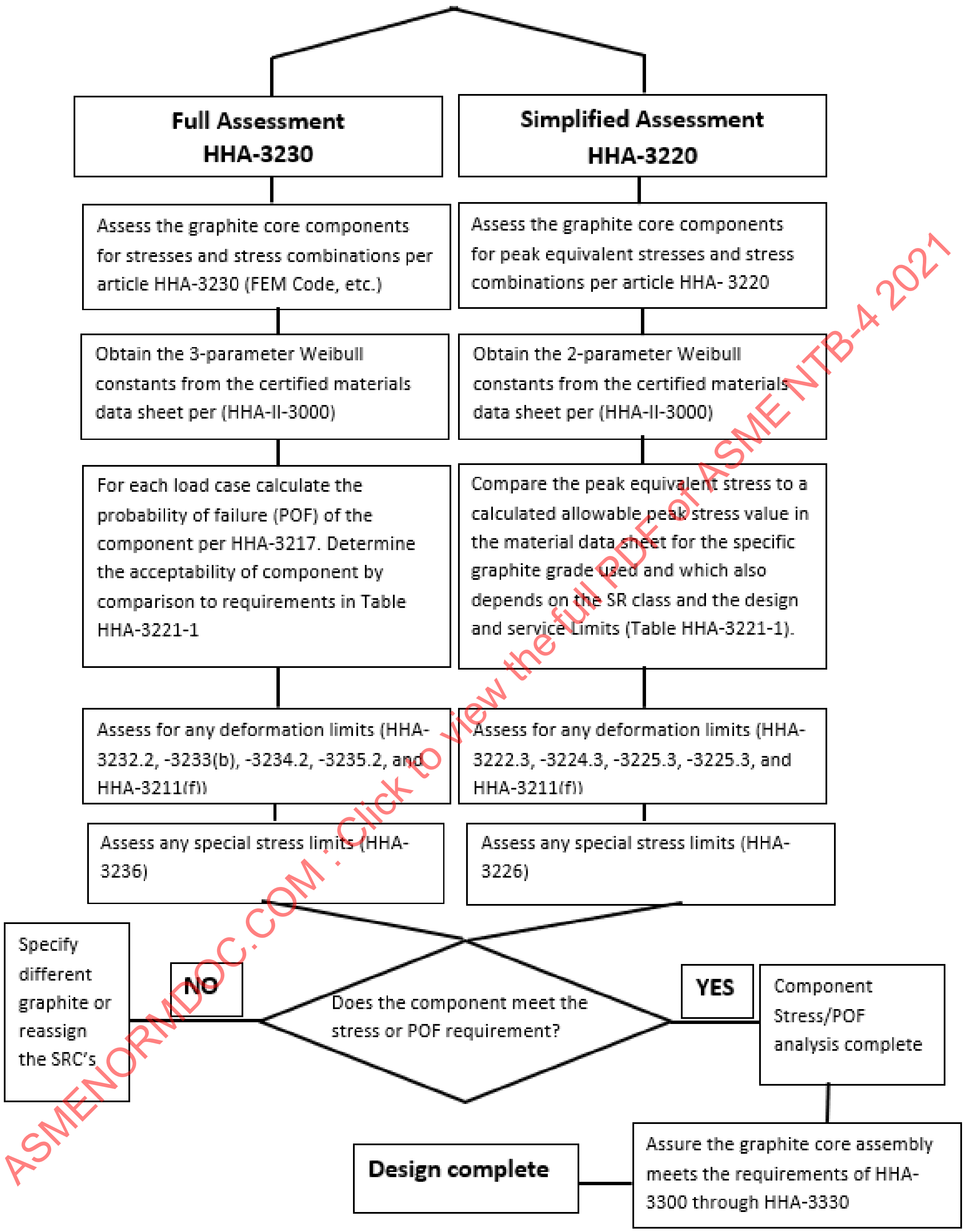


Figure 9: Typical Graphite Core Component Design Sequence (Continued)

3 GRAPHITE STRENGTH

The ASME graphite design code is essentially a design methodology that compares the stress on a graphite component with the material's strength distribution. The major factors affecting graphite strength are presented in this section, along with the relevant sections of the ASME graphite code.

The bond anisotropy of single-crystal graphite (in-plane strong covalent bonds, between-planes weak van der Waals bonds) contributes to the inherent anisotropy of the polycrystalline material, even though the behavior is more isotropic than single-crystal graphite. Moreover, the manufacture of polycrystalline graphite gives rise to the distribution of the size, location, and orientation of porosity in a graphite [36]. The variability in the porosity in proportion to the length scale of the filler particles of a specific size (and thus density) influences the strength of the material, with higher-density graphite exhibiting higher strength. The structure, and hence the strength, of a graphite is a strong function of the exact manufacturing route employed. Several manufacturing features can be identified which impact the structure and properties of the material:

- Filler particle type and size
- Forming method (extrusion, molding, isostatic pressing)
- Process variables (filler particle type, impregnation type, processing temperatures)

Depending upon the extent of the materials anisotropy, the strength may be quoted as pertaining to the with-grain (WG) or against grain (AG) orientation. Generally, the WG strength is greater than AG strength. Because of the many potential variations in production of different grades of graphite, each grade will have different properties. It is important, therefore, that the graphite grade be carefully specified. The ASME graphite code [37] requires that the graphite be compliant to either ASTM D7219 [38] or ASTM D7301 [39]. If irradiation-induced dimensional change is not a significant design consideration (the amount of dimensional change is not considered), an isotropy ratio (α_{AG}/α_{WG}) of greater than 1.15, defined in terms of the coefficient of thermal expansion (CTE), ASTM D7301, may be used.

Because of the inherent variability of the graphite flaw structure within the microstructure, the strength is usually described statistically. The ASME code requires that the designer determine and record the parameters of the Weibull distribution that best describe the strength [4].

Several environmental factors also influence the strength of graphite. For example, the strength increases with increasing temperature. This increase is ~50% over the temperature range from 20°C to greater than 1500°C for most graphite grades [36]. Typically, the data from which the Weibull distribution of strength is derived are obtained by ambient-temperature tensile testing. No credit is taken for this increase in the graphite strength caused by temperature, which provides added conservatism. However, if the designer chooses to consider the strength increase induced by higher temperature, elevated-temperature strength testing must be conducted over the anticipated operating temperature conditions of the core. Additionally, other required material property values must be tested at elevated temperatures, as required by the material data sheets [4].

Moreover, the strength is markedly influenced by neutron irradiation. At low and intermediate doses, the strength will increase with increasing neutron dose, the initial increase being very rapid. At high doses, the strength will decrease and eventually (at much higher doses) reach zero. The ASME graphite code posits a cohesive life limit [40] (i.e., the dose at which the WG dimensional change is +10%). Beyond this limit, the graphite cannot be considered to contribute to a component's structural integrity. The exact behavior of strength with neutron dose for any selected graphite will need to be determined experimentally. Doing so is the responsibility of the designer.

The ASME graphite code additionally provides lower dose limits [41]. For example, if the dose at any point in a component is greater than 0.25 displacement per atom (dpa), all effects of irradiation (including strength) shall be considered. Thus, a low-dose component can, for the purpose of structural assessment, be considered unirradiated and only irradiation effects on thermal conductivity (thermal stresses) must be considered. (Note that most applications of this code will be in reactors, where passive safety features relying on inherent material properties, such as heat removal by conduction to the environment, will be part of the design. This approach is beyond the traditional application of ASME BPVC).

The final environmental effect on strength that must be considered is oxidation [42]. Oxidation (acute due to gasification by air or chronic due to gasification by impurities in the coolant) reduces the graphite strength, elastic modulus, and thermal conductivity. Data for the effects of oxidation shall be provided. Design curves are provided in the BPVC [43] for normalized strength loss of graphite classes IIHP (isomolded, isotropic, high purity), INHP (isomolded, near-isotropic, high purity) and classes EIHP (extruded, isotropic, high purity), ENHP (extruded, near-isotropic, high purity), MIHP (molded, isotropic, high purity), and MNHP (molded, near-isotropic, high purity) [38].

Situations in which chronic oxidation (greater than 1%) occurs simultaneously with neutron irradiation (greater than 0.25 dpa) are currently excluded from the scope of the code. This is partly because of limited access to experimental and theoretical data. Moreover, the expected use for the code was originally focused on He cooled high temperature reactors.

Additional information on nuclear graphite materials with reference to the relative bulk production, material structure, chemical and physical properties and characteristics is summarized elsewhere [36], [44]-[46].

4 CODE VERIFICATION

The behaviors of nuclear graphite and design methods are described in Section 2 and Section 3. This section discusses the work that was done to verify the basis of the code. The code uses a probabilistic approach because of the variability in strength data and graphite grades [17], [18].

The material strength depends on inherent defects like pores, inclusions, cracks, and microstructural irregularities that are common to graphite. These defects act as stress-concentrating features that may not sustain low loads and may result in fracture. There is also a large scatter in material strength test measurements due to the variability associated with the defects in the material. When the material is loaded, the damage accumulates until a critical damage level is reached. This was earlier demonstrated by the conceptual and mathematical fracture model proposed by Burchell [47]. Additionally, experimental data for the behavior of graphite showed that for specimens of the same material of similar size, failure stresses for compression and bending were both higher than stresses for tension [48], [49]. For small sample sizes (close to the filler particle size), it was demonstrated that the strength of graphite was independent of the volume [50], [51].

Because graphite's tensile strength is less than its compression or bending strength, only tensile specimen test data were used to calculate the code-defined Weibull failure model of the different modeled geometries, applying the full assessment approach. The results were then compared with results of experimental testing of various geometries to validate the applied methodology.

The variability of the material strength lends itself to the use of a probabilistic design approach, in which a PDF is applied to describe the reliability of the material [8], [51].

Weibull's theory is most commonly used for load-bearing structures of brittle material, as it is assumed that the strength of a brittle solid is controlled by its flaws [10]. It was previously discussed [50] that Weibull assumes that the POF increases with increasing volume (more flaws or unfavorable defects in a larger volume) and, subsequently, increasing stress will increase the POF. This has been demonstrated to be true for experimental test results for nuclear graphite observing the bending strength. However, this volume effect does not support the tensile behavior. The tensile strength appears to be independent at small volumes, but it was observed that volume does affect small specimens in which the volume approaches the grain size. Thus, Weibull's volume theory is consistent, as it predicts that specimens under bending will fail at higher stresses than specimens under tension (because of the difference in the highly stressed volume of the material). Still, it is inconsistent with the experimental results of small tensile specimen tests, in which the strength of a tensile specimen decreased as the gauge diameter decreased and approached the grain size. Therefore, the standard Weibull approach poorly represent nuclear graphite, but the characteristics of nuclear graphite have been studied and a Weibull modification was proposed. Denninghof's modified-volume, normalized Weibull weakest-link failure criterion approach, as reported by Hindley [34], describes the POF of a graphite component under a stress state. This approach is adapted in the ASME design code [33] as the full assessment method. The formulation of the probability of survival (POS) and the POF are shown in Eqs. (5) and (6) respectively.

$$L_I = exp\left[-\left(\sum_{i=1}^{n_I}\left(\frac{\sigma_{vi} - S'_0}{S_{c_{095\%}} - S'_0}\right)^{m_{095\%}} \frac{V_i}{V_I}\right)\right];\quad L_{II} = exp\left[-\left(\sum_{i=1}^{n_{II}}\left(\frac{\sigma_{vi} - S'_0}{S_{c_{095\%}} - S'_0}\right)^{m_{095\%}} \frac{V_i}{V_{II}}\right)\right] \tag{5}$$

$$POF = 1 - \Pi_l\, L_l \tag{6}$$

The weakest-link formulation (Eq. (5)) defines the POS of a group (or link), *L*, where subscripts I, II etc. denote group one, two etc., V_i is the volume associated with the link, V_I, V_{II}, etc. is the total volume of the group, n_I, n_{II}, *etc.* is the sub-element number at the end of group one, two etc., $S_{c095\%}$ is the characteristic strength (computed at a 95% confidence interval), S'_0 is the threshold value, $m_{095\%}$, is the shape parameter (computed at a 95% confidence interval) and σ_{vi} is the applied stress (or point equivalent stress) [50], [52]. The POF, as in Eq. (6), is now defined as one minus the POS, where the POS is defined as the product of the L_l of all the groups.

The maximum-deformation-energy theory is used in the code to allow an arbitrary stress state to be converted to an equivalent stress. All principle stress components are converted to their equivalent tensile stresses, σ_v as shown in Eq. (7).

$$\sigma_v = \sqrt{\bar{\sigma}_1^2 + \bar{\sigma}_2^2 + \bar{\sigma}_3^2 - 2 \cdot v \cdot (\bar{\sigma}_1 \cdot \bar{\sigma}_2 + \bar{\sigma}_1 \cdot \bar{\sigma}_3 + \bar{\sigma}_2 \cdot \bar{\sigma}_3 \cdot)} \quad (7)$$

where σ_1, σ_2 and σ_3 are the principal stresses and *v* is the Poisson's ratio [53].

The criteria in Eq. (7) are founded on the basis that the elastic energy per unit of volume that is stored in a given element, at the moment of fracture, is equal to the energy that is stored in the uniaxial loaded test specimen at fracture. This approach simplifies the complex multiaxial stress analysis. The difference in the tensile and compressive strengths of graphite is accommodated by using a weighting factor, *f* (which is 1 for tensile strength or $1/R_{tc}$, for compressive strength, where R_{tc} is the ratio of mean compressive to mean tensile strength) for a specific graphite, as shown in Eq. (8).

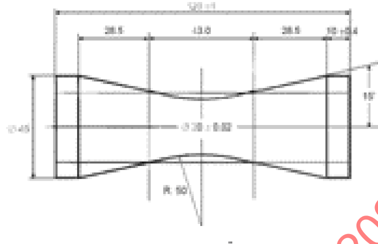
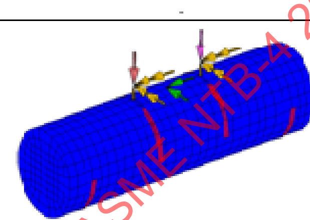
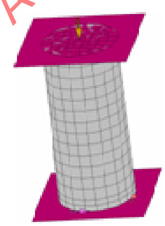
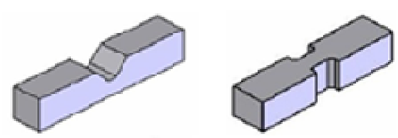
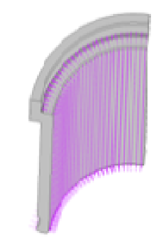
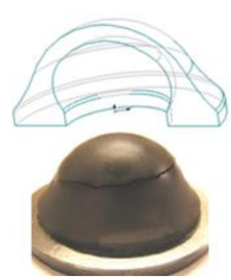
$$\bar{\sigma}_i = f . \sigma_i . \quad (8)$$

The code verification work is based on the implementation of the full assessment methodology [33]. Verification problems (VPs) or test cases were performed for graphite specimens that were not irradiated or oxidized.

Finite element (FE) models of the test cases were created to verify the POF according to HHA-3230 [33]. These models were broken into sub-elements of principle stresses and volume values. Equivalent stress values were then calculated from the principle stresses and volume values for each sub-element. The calculation algorithm is discussed elsewhere [50]. It describes (1) the application of a sliding threshold (applicable when material failure is subject to conditions under which the applied equivalent stress is lower than the characteristic material strength), (2) the sub-element calculation (an arbitrary value that represents the basic three-parameter Weibull distribution element), (3) the grouping criteria (the total volume of a group should be greater than the cube with a side length 10 times the maximum grain size), and (4) the weakest-link calculation (by which the POS, as defined in Eq. (5), is determined from the sum or POS of each group). This approach is a good application for medium-grain graphite but is very conservative for finer-grain graphite because of its grain size reference. (Note: In later BPVC Section III editions, it was decided to use the process zone instead of the grain size. This decision was made after it was observed that the process zone could be calculated and adequately accommodate both medium-grain and fine-grain graphite.)

Several experimental test cases were modeled that consisted of specimens ranging from simple to complex geometries. The specimens were constructed and fabricated from medium-grain-size graphite (NBG-18), and the test scenarios consisted of various loading conditions and stress states. The experimental test data points from the test cases were compared with the created FE model. The set of experimental cases or VPs is shown in Table 4 [34].

Table 4: Set of Verification Problems (VP)

Geometry	Description	Data points	Illustration
VP-00	Tensile test specimen	370	
VP-01	Cylinders used for four-point bend tests	260	
VP-19	Compressive strength tests	262	
VP-12	Beams with stress-concentrating geometric features undergoing four-point bend tests	160	
VP-15	Sleeve burst tests	6	
VP-17	Specimens used for tensile and compressive strength tests	Mean reported value	
VP-18	Multi-axial fatigue test specimens used for static tensile and compressive strength tests	Mean reported value	

The output from the tensile geometry FE model (VP-00) was calibrated with the tensile experimental test results, summarized in reference [7]. The same methodology was applied to determine the predicted load factor for the other test geometries used for the VPs (see Table 4). The objective of the failure methodology is to predict the 50% POF load of each test case (VP). The results are shown in Figure 10 [34], where the 50% predicted failure load is normalized to the median 50% experimental failure load for each test case (as indicated by the predicted load factor data points in Figure 10). If a load factor is predicted to be greater than 1, it is considered not conservative; whereas if the load factor is less than 1, it is considered conservative. In the case of VP-00, the agreement is very good (as expected) because the model is optimized for tensile specimens. In the case of VP-18, the agreement is poorer but is conservative because the predicted POF is lower than the mean reported failure strength.

A 50% POF was selected as a basis for comparison of the model output with the median experimental results. It was previously reported [50] that 50% of all tensile specimens failed, and that the highest number of failures occurred at the average experimental failure load, which corresponds to a 50% POF load predicted by the model. There can be several reasons for differences in the theoretical and experimental results, such as experimental error, error in failure prediction, and/or variability in the material itself. To illustrate materials' billet-to-billet variation, experimental data were collected from 24 billets of NBG-18. The assessment of the mean tensile strength from the 24 billets showed that only 50% of the billets fell within the reported ± 6% of the material mean, and 95% of the billets fell within the reported ± 18% of the material mean [20], [34]. These bands are plotted in Figure 10 and are compared with the calculated predicted load factor. On this basis, only the predicted load factors that fall within the ±6% band are considered accurate, and calculated results between ±6% and ±18% are considered acceptable. The predicted load factors that fall below 0.82% are considered conservative. It is noticeable that all the VPs were conservative. The most accurate 50% POF failure load predictions were applicable to specimens subjected to a uniaxial (or approximate) tensile stress state.

Initially, Hindley et al. [50] made these comparisons of the actual VP failure load with the predicted 50% POF for the VP being modeled using a Weibull distribution (Figure 10). The selection of a Weibull distribution was based on prior work [51]. However, the POF limits mandated by the code are 10^{-2} and 10^{-4} [22], depending on the SRC as specified for the applicable service limit shown in Table 3.

Subsequently, the predictions of the model were extended to the code-prescribed limits of 10^{-2} and 10^{-4} [22]. Figure 11 shows the implementation of the method applying the code design–allowable POF loading as it relates to tests performed on NBG-18. The results are conservative for all the VPs.

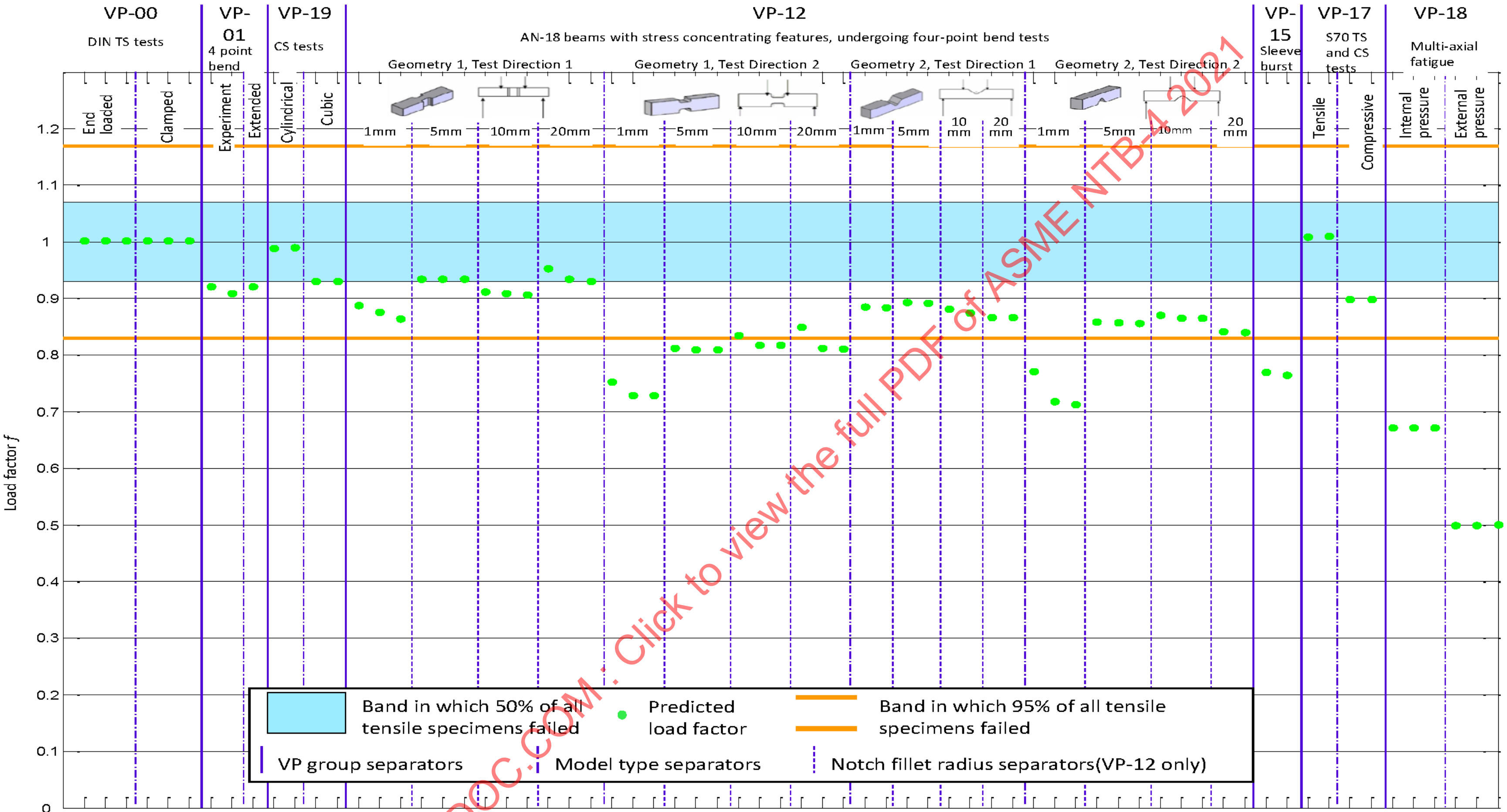


Figure 10: Comparison of Predicted and Experimental Mean Failure Load for Verification Problems

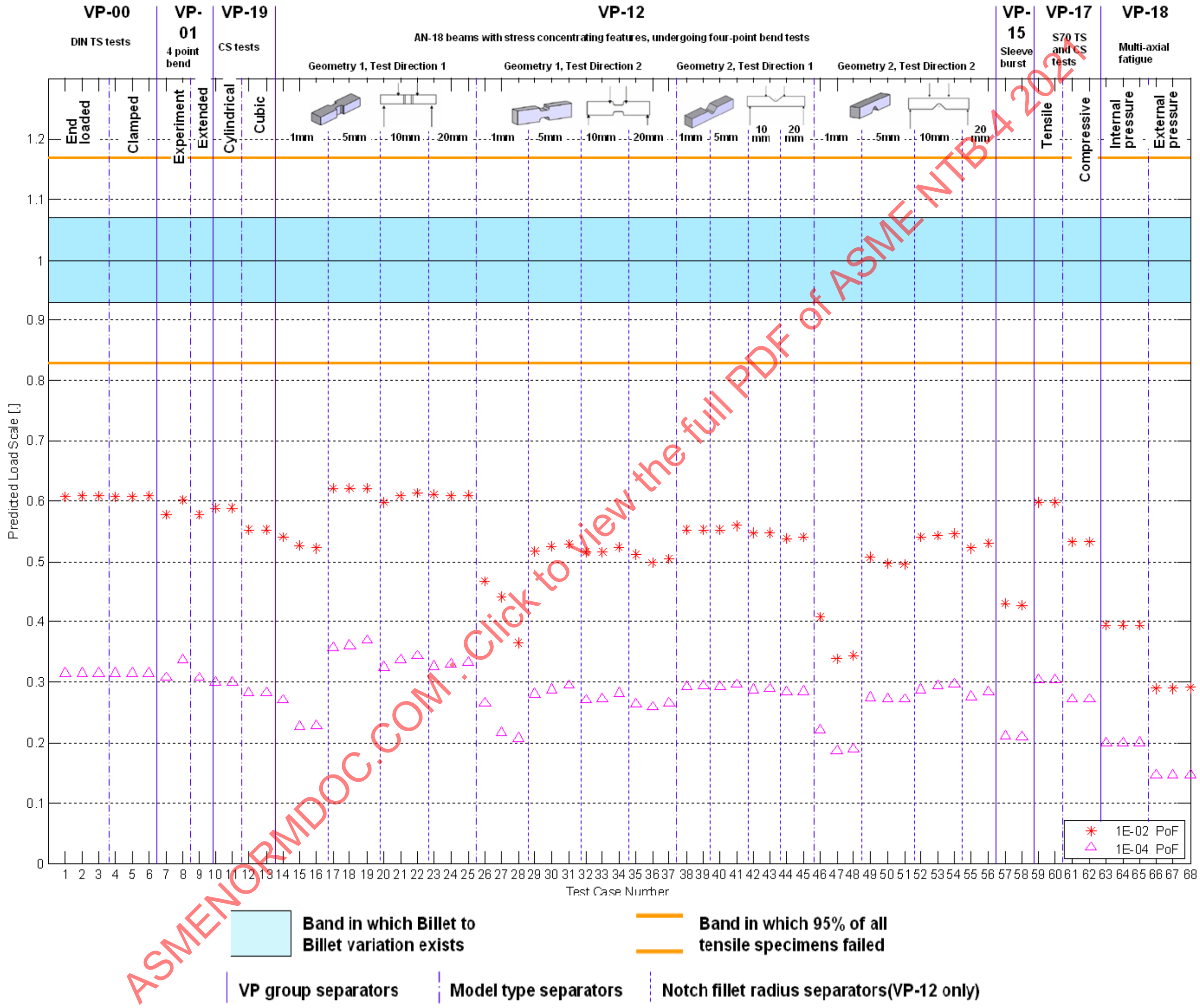


Figure 11: Comparison of Experimental Mean Failure Load and Code-Allowable Loads for Verification Problems

5 SUMMARY

The semi-probabilistic design approach for graphite materials defined for nonmetallic design, Subsection HH subpart A, is different from the defined deterministic approach relevant to metallic components defined in Section III, Division 5 of the ASME BPVC. This document provides a brief background and description that support the basis of the rules for graphite components. Details for typical graphite material properties and behavior are provided in the ASME STLLC technical report STP-NU-009 *Graphite for High Temperature Gas-Cooled Reactors* [36].

The design rules define two analysis methods — simplified assessment (two-parameter) and full assessment (three-parameter) — based on a semi-probabilistic Weibull approach that describes the material reliability to accommodate the characteristic billet-to-billet and strength variability of graphite materials. The probabilistic failure criteria were verified, and it was shown that the failure methodology conservatively predicted real reactor components with larger volumes than tensile specimens.

The code validation was largely done for isotropic or near-isotropic graphite material. To accommodate transversely isotropic graphite materials, the methodology needs to be expanded and the maximum deformation energy stress formulation, defined in the component failure probability, needs to be revaluated.

This report is supplementary to the gap analysis report that will assess whether the current ASME Section III Division 5 Subsection HH Subpart A rules provide reasonable assurance of adequate protection against identified structural failure modes.

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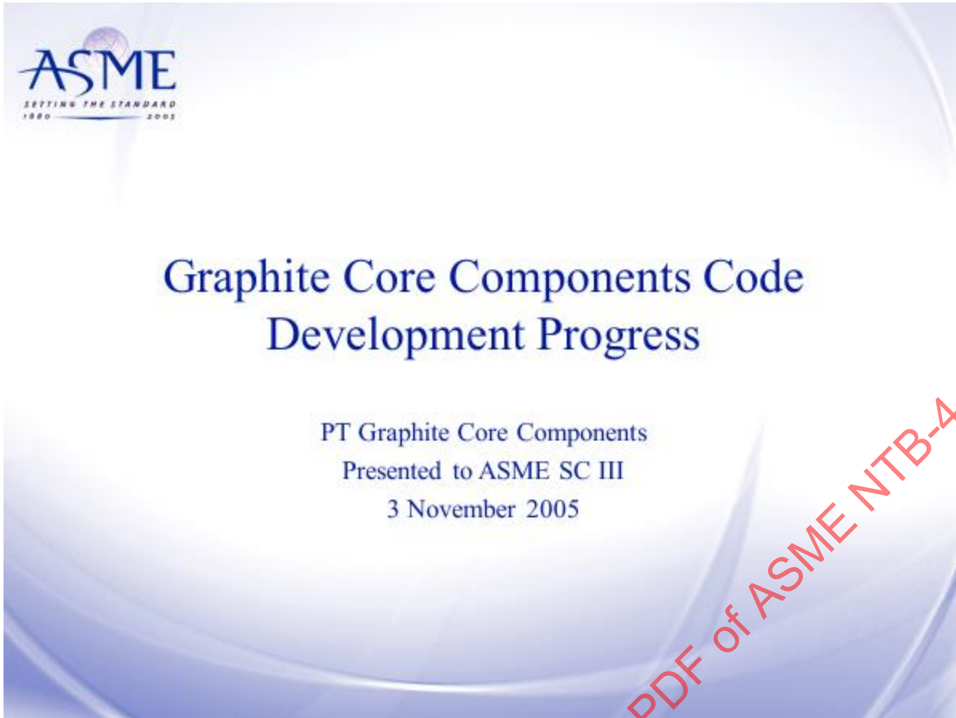
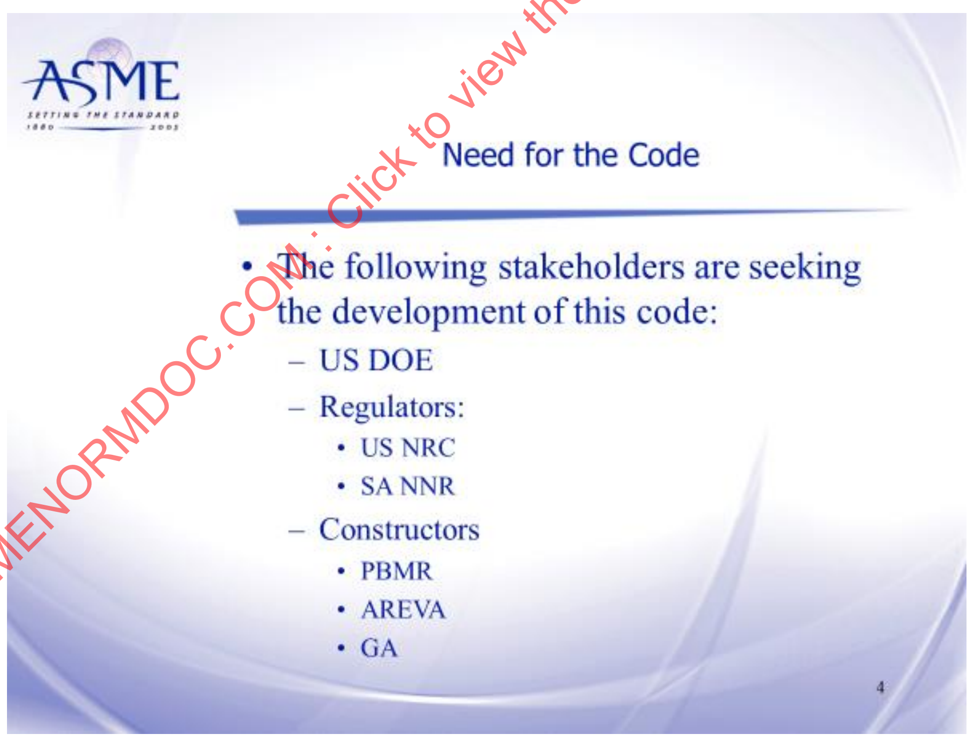
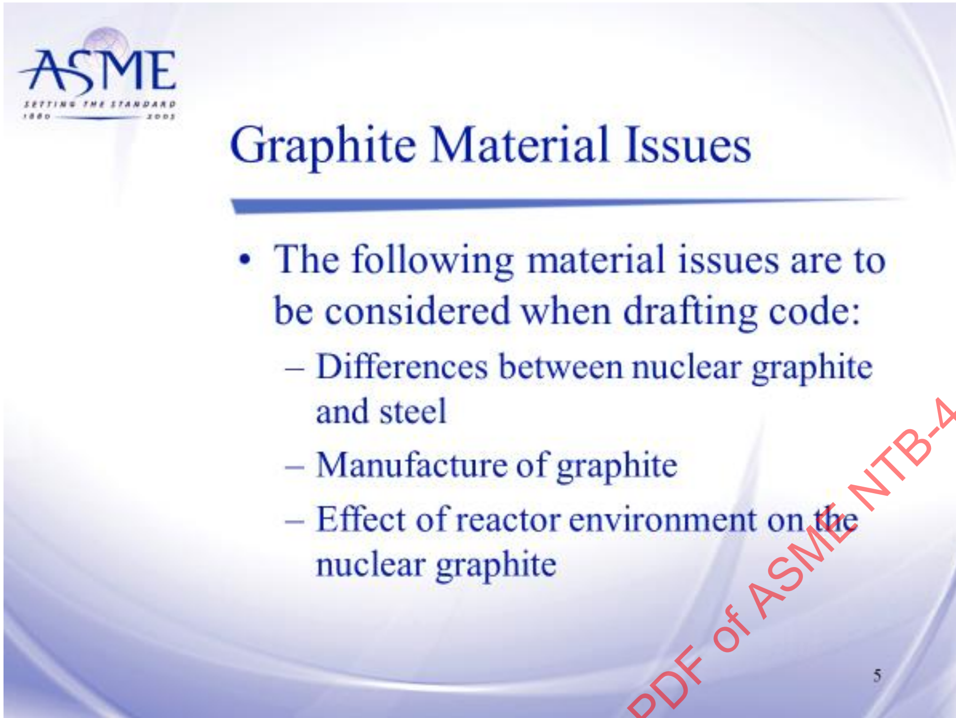
APPENDIX A: GRAPHITE CORE COMPONENTS CODE DEVELOPMENT PROGRESS PRESENTED TO ASME SECTION III (2005)

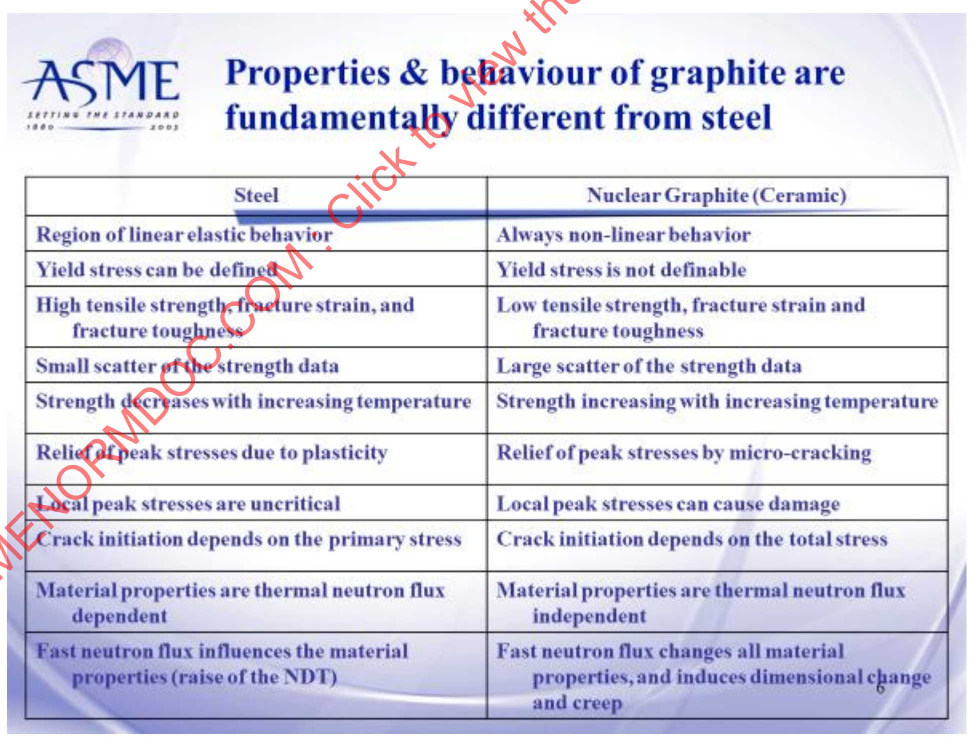

ASME
SETTING THE STANDARD
Graphite Core Components Code Development Progress
PT Graphite Core Components
Presented to ASME SC III
3 November 2005


ASME
SETTING THE STANDARD
Contents
• Introduction to the Project Team on graphite
• Technical approach and challenges
– Material
– Design
• Schedule for code development
2


ASME
SETTING THE STANDARD
Introduction
• Project Team's objective
– Develop Design and Construction code on Graphite Core Components for VHTR Application.
• Project Team
– Active Members 10 (5 International)
– NRC and SA NNR participation
• Meetings
– 4 per year
• 2 per year with BPVC Week
• 1 international, tied to INGSM
• 1 overseas (UK in 2006)
3


ASME
SETTING THE STANDARD
Need for the Code
• The following stakeholders are seeking the development of this code:
– US DOE
– Regulators:
• US NRC
• SA NNR
– Constructors
• PBMR
• AREVA
• GA
4





Steel	Nuclear Graphite (Ceramic)
Region of linear elastic behavior	Always non-linear behavior
Yield stress can be defined	Yield stress is not definable
High tensile strength, fracture strain, and fracture toughness	Low tensile strength, fracture strain and fracture toughness
Small scatter of the strength data	Large scatter of the strength data
Strength decreases with increasing temperature	Strength increasing with increasing temperature
Relief of peak stresses due to plasticity	Relief of peak stresses by micro-cracking
Local peak stresses are uncritical	Local peak stresses can cause damage
Crack initiation depends on the primary stress	Crack initiation depends on the total stress
Material properties are thermal neutron flux dependent	Material properties are thermal neutron flux independent
Fast neutron flux influences the material properties (raise of the NDT)	Fast neutron flux changes all material properties, and induces dimensional change and creep

ASME SETTING THE STANDARD

Nuclear Graphite Manufacture

- Not totally standardized
  - ASTM Nuclear Graphite Specification (recently approved) provides minimum requirements for properties and QA
  - ASME code may augment this
- Current production grades requires complete characterization for reactor design
- Grades are supplier specific at present.

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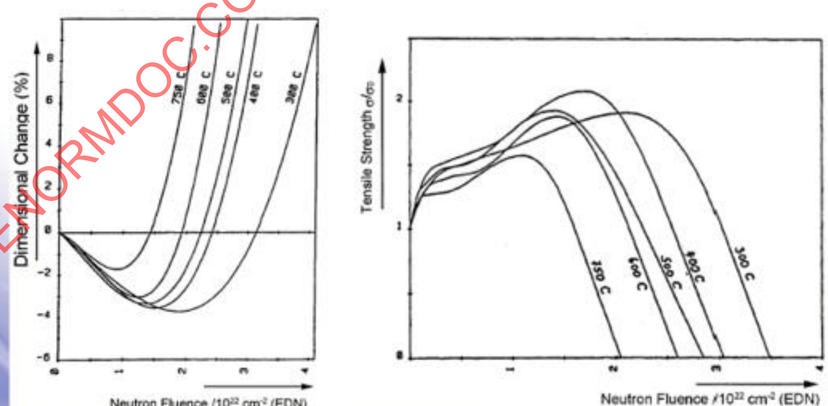
ASME SETTING THE STANDARD

Environmental Effects - Irradiation

All properties change during lifetime due to fast neutron irradiation damage



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