ASME Design Code Rule Changes for Nuclear Graphite

INL/RPT-24-80217

Advanced Reactor Technologies

M2TG-24IN0501127

AUGUST 2024

Andrea Mack
William Hoffman

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

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Idaho National Laboratory
Advanced Reactor Technologies
Idaho Falls, Idaho 83415

http://www.inl.gov

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INL ART Program

ASME Design Code Rule Changes for Nuclear Graphite

INL/RPT-24-80217

August 2024

Technical Reviewer: (Confirmation of mathematical accuracy, and correctness of data and appropriateness of assumptions.)

______________________________	August 20, 2024
Nancy J. Lybeck Manager, Data Science & Applied Statistics	Date

Approved by:

______________________________	8/21/2024
Michael E. Davenport ART Project Manager	Date
______________________________	8/21/2024
Michelle T. Sharp INL Quality Assurance	Date

ABSTRACT

The American Society of Mechanical Engineers Boiler Pressure and Vessel Code (ASME BPVC) Section III, Division 5, Article HHA-3000 outlines graphite core component and graphite core assembly design guidelines. Graphite core components are defined as “components manufactured from graphite that are installed to form a graphite core assembly within the reactor pressure vessel of a high temperature, graphite moderated fission reactor” [1, p. 413]. Graphite’s inherent defect distributions do not allow for deterministic material reliability. Rather, graphite has variable strength distributions which change by grade. Article HHA-3000 outlines two semi-probabilistic methods, the full and simplified assessments, which set design load limit targets for each of the three component structural reliability classes. The Graphite Design Analysis Task Group (TG) was officially recognized as a specialized task group within ASME in November 2023 (even though group members have been collaborating since 2022).

The Graphite Design Analysis TG’s purpose is to correct, clarify, and make HHA-3000 function as intended. After the group has achieved its objectives, it will come to an end. Note the Graphite Design Analysis TG was specifically told not to write new Code. While there may be more precise and more accurate methods to determine reliability targets, the current methods are conservative, relatively simple to implement, and have thus far been considered satisfactory for setting design reliability targets. Much of the groundwork to write proposal files and background documents for records to make the changes needed to achieve the objective have been completed.

The Graphite Design Analysis TG has documented much of its work through papers, presentations, and memoranda. Three memoranda in which INL team members had substantial contributions are found in Appendix A, “FEA Modeling for the Baseline Program,” Appendix B, “Evaluating the Effects on Margin of Updating the Threshold and Shape Parameters in the Full Assessment,” and Appendix C, “Interpretations of the Full and Simplified Assessments in ASME BPVC.” Most of the ongoing work to achieve the Graphite Design Analysis TG’s objective will be addressing comments on existing records and moving records through the balloting process.

ACKNOWLEDGMENTS

Special thanks to the Graphite Design Analysis Task Group, whose members are all working collaboratively to correct and understand the ASME graphite component design codes. This work could not have been completed without their contributions.

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TABLES

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ACRONYMS

ASME	American Society of Mechanical Engineers
BPVC	Boiler & Pressure Vessel Code
DOE	Department of Energy
FE	Finite element
FEA	Finite element analysis
INL	Idaho National Laboratory
MDE	Maximum deformation energy
NRC	Nuclear Regulatory Commission
POF	Probability of failure
PVP	Pressure Vessel & Piping
SRC	Structural Reliability Class
TG	Task Group
WG-NMDM	Working Group on Nonmetallic Design and Materials

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ASME Design Code Rule Changes for Nuclear Graphite

1. BACKGROUND

The American Society of Mechanical Engineers Boiler Pressure and Vessel Code (ASME BPVC) Section III, Division 5, Article HHA-3000 outlines graphite core component and graphite core assembly design guidelines. Graphite core components are defined as "components manufactured from graphite that are installed to form a graphite core assembly within the reactor pressure vessel of a high temperature, graphite moderated fission reactor" [1, p. 413]. Graphite's inherent defect distributions do not allow for deterministic material reliability. Rather, graphite has variable strength distributions which change by grade. Article HHA-3000 outlines two semi-probabilistic methods, the full and simplified assessments, which set design load limit targets for each of the three component structural reliability classes.

Several mathematical errors, conceptual and terminology inconsistencies, and incomplete method sections currently exist in HHA-3000. Unfortunately, background documentation for the assessment methodologies is severely limited or non-existent, making it difficult or impossible to understand exactly the intent and justification of the original ASME BPVC (i.e., Code) authors. This presents issues with understanding the accuracy, margin, and limitations of the current Code assessments when implemented by actual commercial designers. Additionally, the lack of clear intent has made approving technical Code records by the ASME voting committees difficult. In August 2022, a kick-off meeting was held to form the Graphite Design Analysis Task Group (Design TG) to address these issues. The Design TG is composed of people working for commercial reactor vendors, an engineering consulting firm, and national laboratories. The Design TG became an official ASME specialized task group November of 2023. Its charter is:

> *The Graphite Design Analysis Task Group will correct, clarify, and modify to function as intended the Design Code rules for the use of graphite core components within a nuclear application, specifically within the article HHA-3000: Design. The Graphite Design Analysis Task Group will not write new Code. Specific strategic objectives include evaluating and modifying the Full and Simplified Assessment methodology along with the supporting sub-articles necessary to accurately complete the Design rules.*[a]

This milestone's purpose is to provide an update on the Design TG's progress toward completing the charter objective. Section 2 provides a refresher on the full and simplified assessment methods. Section 3 gives an update on tasks and associated records to make changes in the ASME BPVC. Section 4 provides concluding thoughts. Appendix A, Appendix B, and Appendix C include more detailed information that serve as background documents for records issued in the past year.

2. ASSESSMENTS

2.1. Inputs

There are three inputs required for the assessments:

- Two- or three-parameter Weibull material reliability curves and parameter lower bounds
- Component finite element (FE) model principal components output, converted to elemental equivalent tensile stresses

a. Publicly available at the ASME Codes & Standards Tools Website, https://cstools.asme.org/csconnect/CommitteePages.cfm?Committee=103797119.

- Component structural reliability class (SRC).

2.2. Simplified Assessment

2.2.1. Method

The simplified assessment requires two checks: the membrane stress must be less than the tensile reliability limit and the peak equivalent stress must be less than the flexural reliability limit. The tensile reliability limit is found by inverting the two-parameter lower bound material reliability curve based on the component's SRC. The flexural reliability limit is found by multiplying the tensile reliability limit by the ratio of the median flexural strength to the median tensile strength (R_{tf}). Both reliability requirements must be met for a component to pass the simplified assessment.

2.2.2. Output

The component's membrane stress and peak equivalent stress must both meet the calculated tensile and flexural reliability limits in order to pass the assessment.

The simplified assessment is meant to be more conservative than the full, per the spirit of the Code. If a component fails to meet the simplified assessment reliability limits, the designer may choose to use the full assessment.

2.3. Full Assessment

2.3.1. Method

The full assessment implements a modified Weibull-weakest link theory for brittle materials methodology. The full assessment uses the three-parameter lower bound Weibull distribution as the material reliability curve. The three-parameter Weibull distribution has a threshold, shape, and characteristic strength parameter. The full assessment method is as follows: modify the material reliability curve by reducing the threshold parameter based on the peak equivalent stress, group the FE model elements based on a minimum link volume criteria (V_m) and based on a minimum stress range criteria (Δ), and calculate group probability of survivals (POS_I) by averaging stress by the proportional group volume.

2.3.2. Output

The output of the full assessment is a conservative component probability of failure (POF) estimate, where $POF = 1 - \prod POS_I$. The component calculated POF is compared to the SRC reliability limit. As the Code states, the POF estimates but does not accurately predict the rate of cracking. Note depending on the design and loading configuration, cracking may or may not be related to safety (see Appendix C).

3. TASKS AND RECORDS UPDATE

3.1. Update on Tasks

3.1.1. Simplified Assessment Issues

Inconsistencies in stress terminology: The simplified assessment procedure is inconsistently defined throughout the Code. Depending on the section, the Code is said to rely on one or two stress-based failure criteria. Application of these criteria requires using linearized equivalent stresses obtained from either the normal stress or a tensile equivalent stress, which is derived from the maximum deformation energy (MDE) theory. MDE-based tensile equivalent stress was recommended for use in the simplified assessment. It was demonstrated that, for simple loading cases (e.g., compressive, tensile, and three-point bending tests), the simplified method remains conservative as long as the two failure criteria (i.e., on membrane and total stress) are being used. It is therefore recommended that these two failure criteria of the simplified assessment must be met using the tensile equivalent stress. Pierre-Alexandre Juan, from Kairos Power, is the record manager for R23-473 and is assigned to address these issues. It was determined that the record would be split into two: R24-1128 will address the "low hanging fruit" of this record, providing clarifications, and R23-473 will attempt to make more extensive changes by removing unused Code sections

Use of the 10^{-4} flexural limit: The FE peak equivalent tensile stress is compared to the 10^{-4} allowable tensile limit multiplied by the ratio of the mean experimental flexural strength to the mean experimental tensile strength (R_{tf}). Using the INL Advanced Reactor Technology's unirradiated Baseline Graphite Characterization Program's experimental data, it was verified that multiplying the 10^{-4} allowable tensile limit by R_{tf} raises the 10^{-4} tensile limit to an effective 10^{-4} flexural limit. The implication of using the R_{tf} factor on the simplified assessment's conservatism relative to the full is still being further reviewed. Adam Walker, Westinghouse, led an analysis effort to verify this, and the work has been accepted in the Pressure Vessel & Piping (PVP) conference [2].

3.1.2. Full Assessment Issues

Disparate flaw distribution: The full assessment contains a threshold reduction step when the graphite material strength curve is too high relative to the FE component stress distribution. The full assessment currently does not contain a step to update the shape parameter when the threshold is reduced, even though the two parameters are dependent. It is well documented in the literature that not adjusting the shape parameter with the threshold reduction allows the full assessment to become more conservative than the simplified assessment, contrary to the "spirit of the Code." Not updating the shape parameter may have been intentional, to artificially create a new distribution with more mass in the left tail to better capture graphite's disparate flaw mode. The disparate flaw mode of graphite is real, but thousands of samples are needed to accurately capture it experimentally, more than what is practical. This is demonstrated by the extensive mechanical strength data sets from British Power in association with the graphite fuel sleeves of the Advanced Gas Reactor design. The 95% lower bound three-parameter Weibull distribution with a reduced threshold and updated shape parameter appears to capture the disparate flaw modes seen in the Advance Reactor Technology's unirradiated Baseline Graphite Characterization Program data sets conservatively, similar to the two-parameter Weibull distribution used in the simplified assessment. This modification is associated with R21-1581. Noting that the first two digits indicate the year of record initiation, it has taken a while for this record to get to the Working Group on Nonmetallic Design and Materials (WG-NMDM) level. Progress was made with the addition of an analysis this year showing how updating the shape parameter affects margin in the full assessment. The margin analysis was conducted using only the dog-bone geometries for the graphite grades studied in the Advance Reactor Technology's unirradiated Baseline Graphite Characterization Program. For SRC-1 components, margin was reduced by a maximum of 40% of the median experimental load when updating the shape parameter and using the 2023 Code version. See Appendix B for the detailed analysis. R21-1581 has passed the WG-NMDM level and is continuing through the hierarchy of the ASME voting system.

Tuning the minimum link volume and the relative stress range parameters: The full assessment implements a modified weakest link theory, where FE exponentiated equivalent tensile stresses are formed into groups having minimum link volume (V_m) and a minimum exponentiated stress range parameter of Δ. The original 2013 Code rules set $V_m = 10 \ast$ maximum grain size. However, this method of calculating V_m produced exceedingly small group volumes for fine grain graphite, resulting in overly conservative load limits for these grades. The 2021 BPVC version modified the calculation of V_m to be based upon Griffith's theory and dependent upon the specific fracture toughness K_{Ic} of the graphite. This modification was primarily to increase V_m for fine grain graphite grades, which proved to be overly conservative for medium grain graphites.

The tuning subtask involved building and verifying FE model output for 31 component geometry and graphite grade combinations to determine the most limiting V_m. For a complete explanation of the FE modeling, please refer to Appendix A. Conclusions from these tuning studies indicate V_m is not a material property, as previously thought. Rather, this work suggests V_m is determined by the diameter of the gauge region of the tensile specimens tested to form the material reliability curve, regardless of graphite grade. This finding is consistent with what is in the literature. Michael Saitta from MPR Associates generated R23-2066 to adopt the change in V_m found from the tuning study. This record was not approved at the WG-NMDM level when balloted Spring 2024. Please refer to Michael Saitta for updates regarding this work.

3.1.3. Assessment Interpretation Issues

R22-486 changed all uses of probability of "failure" to probability of "crack initiation" in HHA-3000. This change was made before the Graphite Design Analysis Task Group had formed and before the WG-NMDM understood how the assessments worked. The WG-NMDM Chair tasked the Graphite Design Analysis Task Group with writing a consensus document on what the correct interpretations of the assessments in HHA-3000 are, why it is failure and not crack initiation, and suggestions moving forward (see Appendix C).

3.2. Papers, Presentations, and Memos from the Graphite Design Analysis Task Group

Over the past year, the Graphite Design Analysis Task Group has worked diligently to document progress on its tasks primarily through three mediums: papers, presentations, and memos. A reference list of those documents is provided below.

Papers and Presentations

- Mack, A., Hoffman, W., Bass, J., & Windes, W. 2023. Finite element model mesh refinement effects on qualification of nuclear grade graphite components, Proceedings of the ASME 2023 Pressure Vessels & Piping Conference, PVP2023-107369.
- Mack, A., Hoffman, W., Quick, J., & Windes, W. 2023. Qualifying nuclear graphite components using ASME guidelines, International Graphite Specialists Meeting 2023.
- Mack, A. & Hoffman, W. 2024. Understanding the semi-probabilistic approaches in structural reliability used to set design reliability targets for graphite components using ASME BPVC methods, Proceedings of the ASME 2024 Pressure Vessels & Piping Conference, PVP2024-123395.
- Walker, A. & Mack, A. & Hoffman, W. 2024. Evaluation of the simplified assessment peak equivalent stress design limit probability of failure, Proceedings of the ASME 2024 Pressure Vessels & Piping Conference, PVP2024-123465.
- Saitta, M. & Beirnaert, G. 2023. Simplified Method for Adjusting the Shape and Characteristic Strength Parameters of the Weibull Strength Distribution of Graphite Materials, Proceedings of the ASME 2023 Pressure Vessels & Piping Conference, PVP2023-105207

Memos

- 03/16/2023. Conservatism of full and simplified assessments. Memorandum to William Windes answering the NRC inquiry from January 2022, from Andrea Mack.
- 06/07/2023. Request for additional testing to complete the tuning Vm and delta subtask. Memorandum to William Windes and Wilna Geringer from Andrea Mack.
- 09/07/2023. WG-NMD: Graphite Design Analysis Task Group internal memo or stress delta from Jarryd Potgieter.

- 10/25/2023. FEA modeling for the Baseline Program. Memorandum to Gerhard Strydom from William Hoffman.
- 12/08/2023. Theoretical Vm for R23-2066. Memorandum to Michael Saitta from Andrea Mack.
- 12/29/2023. Background information on the procedure for the calculation of probability of failure (HHA-3217) in the ASME Boiler & Pressure Vessel Code (BPVC), Section III, Division 5. Memorandum to the ASME Working Group on Nonmetallic Design and Materials from Gwennael Beirnaert.
- 01/30/2024. Interpretations of the full and simplified assessments in ASME BPVC. Memorandum to ASME WG-NMDM from the ASME Graphite Design Analysis Task Group.
- 02/30/2024. Evaluating the effects on margin from updating the threshold and shape parameters in the full assessment (HHA-3217, ASME BPVC Section III Div. 5). Memorandum to ASME WG-NMDM from Andrea Mack.

3.3. Existing Records

Changes to the ASME BPVC are made by approving records with proposed changes through a balloting process. Each record must have two documents: a proposal file with the proposed changes to ASME BPVC and a background document justifying the changes. The Graphite Design Analysis TG does not have voting rights. Balloting begins at the WG-NMDM. Once it passes the WG-NMDM, the ballot moves up to the Subcommittee on Design and the Subgroup on High Temperature Materials. Pending approval at all lower levels, a record is balloted at the Section III Standards committee. This rigorous balloting process provides high quality Codes. The Graphite Design Analysis TG has generated several records to modify HHA-3000, based on the findings in its tasks. The records are at various stages of the balloting process. Table 1 summarizes the existing record titles, numbers, and project managers. Background documents associated with the bolded records in the table (R21-1581 and R24-432), as well as the memorandum explaining all the FE modeling decisions made for the used graphite specimens, are found in the appendices. These memoranda were chosen because the Idaho National Laboratory (INL) team contributed the most to them.

Table 1. ASME Graphite Design Analysis Task Group records summary (records in bold have background documents in the appendix).

Record Title	Record Number	Project Manager	Status
Modify notation and definitions	R20-1308	Andrea Mack (INL)	Approved
Update shape parameter in the full assessment	**R21-1581**	**Andrea Mack (INL)**	**In-process**
Correct notation and equations in HHA-II-3200	R23-170	Andrea Mack (INL)	Approved
Clarify use of LBs vs. MLEs in the full assessment	R23-2401	Andrea Mack (INL)	In-process

Record Title	Record Number	Project Manager	Status
Stress terminology in the simplified assessment: Major changes	R23-473	Pierre-Alexandre Juan (Kairos Power)	In-process
Full assessment flow chart	R23-1349	Gwennael Beirnaert (MPR)	Approved
Modify Vm	R23-2066	Michael Saitta (MPR)	In-process
Assessment interpretations: POF vs. POCI	**R24-432**	**Andrea Mack (INL)**	**In-process**
Stress terminology in the simplified assessment: Minor changes	R24-1128	Pierre-Alexandre Juan (Kairos Power)	In-process

4. SUMMARY

While there may be more precise and more accurate methods to determine reliability targets, the current methods are conservative, relatively simple to implement, and have thus far been considered satisfactory for setting design reliability targets. Much of the groundwork to write proposal files and background documents for records to make the changes needed to achieve the group's objective have been completed. The Graphite Design Analysis TG has documented much of its work through papers, presentations, and memoranda. Three memoranda in which INL team members had substantial contributions are found in Appendix A, "FEA Modeling for the Baseline Program," Appendix B, "Evaluating the Effects on Margin of Updating the Threshold and Shape Parameters in the Full Assessment," and Appendix C, "Interpretations of the Full and Simplified Assessments in ASME BPVC." Most of the ongoing work to achieve the Graphite Design Analysis TG's objective will be addressing comments on existing records and moving records through the balloting process.

5. REFERENCES

1. American Society of Mechanical Engineers (ASME). 2023. "Boiler Pressure and Vessel Code (ASME BPVC) Section III, Division 5, Article HHA-3000." New York: ASME.
2. Walker, A., A. Mack, and W. Hoffman. 2024. "Evaluation of the Simplified Assessment Peak Equivalent Stress Design Limit Probability of Failure." In Proceedings of the ASME 2024 Pressure Vessels & Piping Conference, PVP2024-123465.

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Appendix A

Memorandum on FEA Modeling for the Baseline Program

Memorandum

Date: February 1, 2024

To: WG-NMDM

From: William Hoffman, INL Technical Staff

Subject: FEA Modeling for the Baseline Program

1.0 Purpose

The purpose of this memo is to provide information on the modeling work done in support of record 23-2066, which changes the use of the V_m and Δ criteria defined in the full assessment (HHA-3230) in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section III, Division 5 (Reference 1). This memo will describe the finite element analysis (FEA) modeling approach, analysis and verification performed between two independent analysts using two different FEA modeling packages. The model results described here were used in the full assessment calculations shown in R23-2066.

2.0 Background

The full assessment method outlined in HHA-3230 of the design by analysis section of the code requires the component stress response to all applied loads to perform probability of failure (POF) calculations. This is easily achieved through the use of FEA. The full assessment method requires element principal stress values (converted to equivalent tensile stress, per HHA-3213), and element volumes. These values can be set to outputs from the FEA model and then used in a separate postprocessing script to conduct the full assessment.

In order to perform the optimization procedure necessary to test the current implementation of the V_m and Δ criteria, results from various FEA models were required. The work done by Hindley (reference 2) computing load factors of various mechanical test specimens using results of the full assessment served as a good starting point for this effort because it largely provided the basis for the criteria in question's implementation. Furthermore, having experimental data to use for validation of the tuning results seemed like a clear benefit. Along those same lines, the Baseline Unirradiated Graphite Program has data from dogbone tensile tests, four point bend flexural tests, and uniaxial compression tests.

3.0 Analysis

The baseline program experimental testing specimens chosen for analysis in this effort were the tensile (dogbone), flexural (four point bend), and the compression cylinder. Finite element modeling procedure, results and verification for each will be the subject of the following sections in this memo.

There were five grades of graphite used in the baseline program's experimental testing, NBG18, NBG17, IG110, 2114 and PCEA. Each test specimen was modeled by two independent analysts using MOOSE and ANSYS using identical properties from each of those five grades. FEA results from MOOSE and ANSYS were compared for the NBG18 specimens with the assumption that differences present in one grade (ideally minimal) would be consistent with only minor changes in material properties across the other grades. Material properties used for each grade are shown in Table 1 below.

Grade	Young's modulus (GPa)	Poisson's Ratio
NBG-18	14.93	0.230
NBG-17	13.71	0.230
IG-110	11.00	0.209
2114	10.72	0.204
PCEA	13.05	0.178

Table 1: graphite grades and elastic properties used in the analysis.

The models for each of the testing specimens were created consistent with the drawings shown in Figure 1 (NBG-18 specimens) and Figure 2 (NBG-17, IG-110, 2114 and PCEA specimens) below.

Each of the models were setup and run with an assumption of pure linear elastic behavior, which is consistent with the requirements of the code. Because of this assumption, the stress distribution computed in response to the applied load can be scaled to simulate any loading magnitude by simply multiplying the computed principal stress values by the appropriate scale factor. Therefore, all models were setup and run with an initial applied load of 125 newtons, and the corresponding stress field was then scaled to the appropriate value.

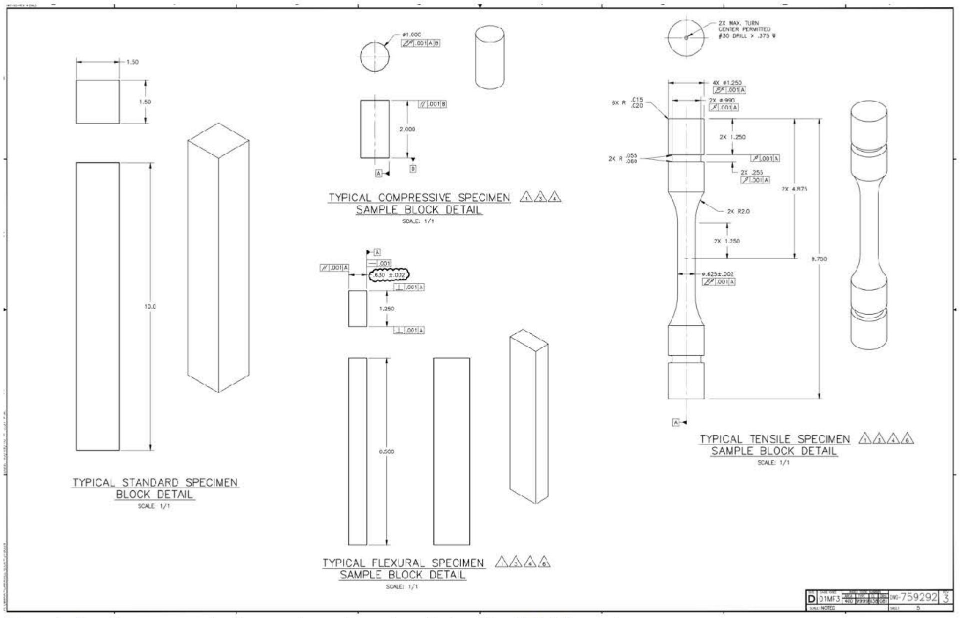

Figure 1: Baseline program testing specimen dimensions (inches) for NBG-18 samples.

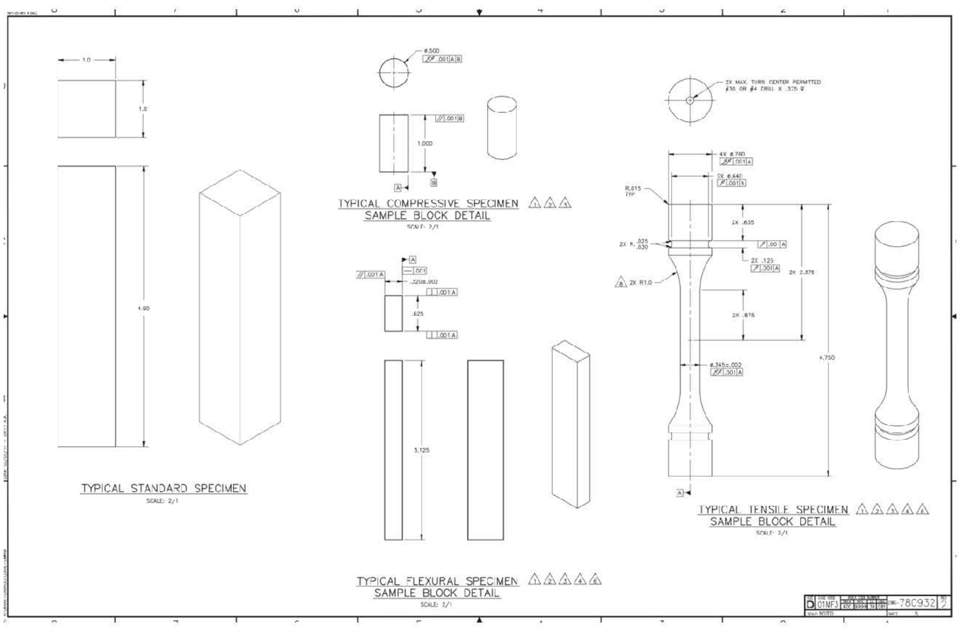

Figure 2: Baseline program testing specimen dimensions (inches) for NBG-17, IG-110 and PCEA grades.

Meshes for each of the finite element models were created independently using the two analysis tools previously mentioned. Mesh convergence effects were considered, and each of the components was created to have approximately 200,000 elements, which would make the elements small enough to have reasonably converged stresses. Symmetry conditions were also utilized in order to preserve computing time and resources.

3.1 Dogbone Tensile Strength Test

Due to the symmetric geometry of the dogbone tensile component, only one eight of the component was explicitly modeled. Zero displacement symmetry conditions were applied to the X Y and Z planes intersecting the dogbone, to reduce computational costs. A "dummy load" of 125 newtons was applied uniformly over the loading end surface. This configuration is shown in the figure below:

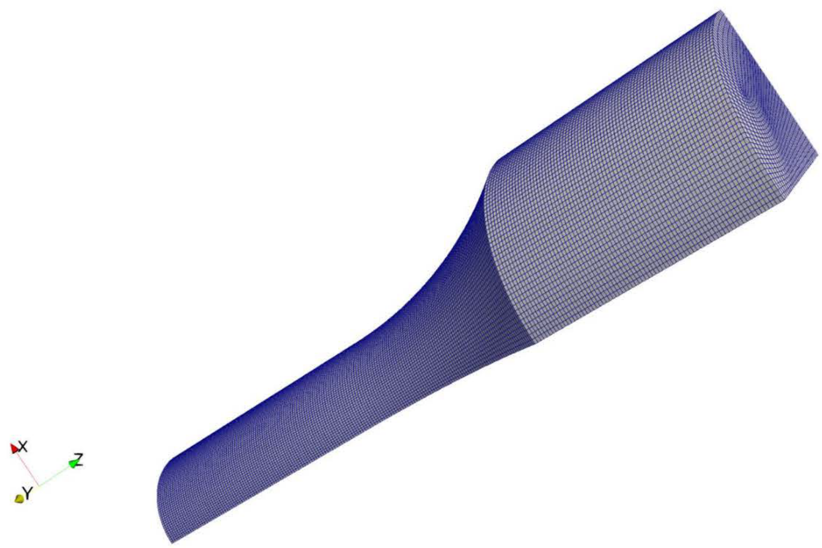

Figure 3: Dogbone tensile specimen modeled using 8th symmetry.

3.2 Flexural Strength Test

Due to the symmetric geometry of the flexural strength test component, zero displacement symmetry conditions were applied to the X and Z planes intersecting the specimen, to reduce computational costs. Rollers were included in the analysis with assumed material properties consistent with tool steel. Frictionless contact was used to capture the interaction effects between rollers and the graphite specimen. The bottom roller was fixed along the bottom surface and a “dummy load” of 250 newtons was applied uniformly over the top loading roller surface surface. This configuration is shown in the figure below:

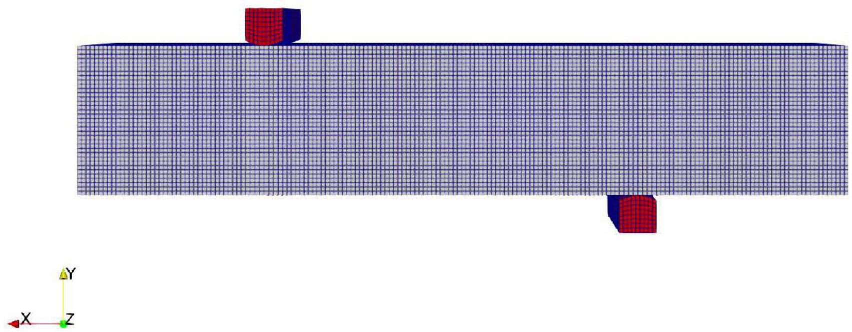

Figure 4: Flexural strength component modeled using quarter symmetry.

3.3 Compression Strength Test

Due to the symmetric geometry of the compression test component, zero displacement symmetry conditions were applied to the X Y and Z planes intersecting the specimen, to reduce computational costs. A loading block of assumed tool steel was included in the top of the model to capture the interaction effects between the graphite and the loading setup. A “dummy load” of 125 newtons was applied uniformly over the loading block. This configuration is shown in the figure below:

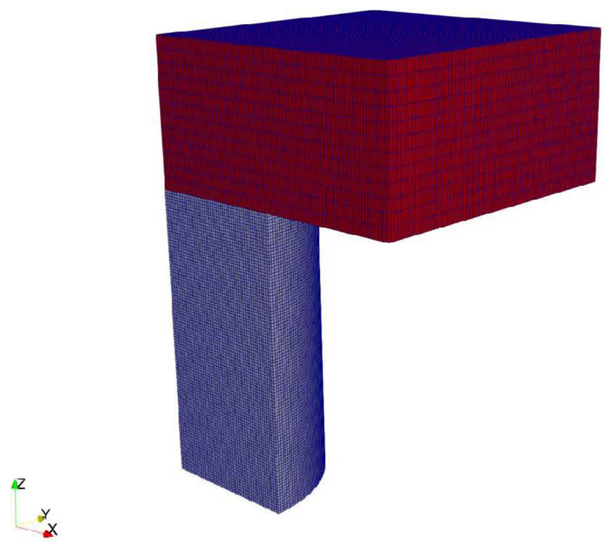

Figure 5: Compression strength component modeled using 8th symmery.

4.0 Summary of Results

Resulting displacements and stress fields were compared from the output files for each of the simulation tools used in this analysis. The results generally showed good agreement between the two simulation tools. Resulting peak stresses were within 5% which allows for both outputs to be used in the tuning study with minimal expected differences when run through the ASME procedure for calculation of probability of failure.

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Appendix B

Memorandum on Evaluating the Effects on Margin of Updating the Threshold and Shape Parameters in the Full Assessment

Memorandum

Date: February 06, 2024

To: ASME WG-NMDM

From: Andrea Mack

Subject: Evaluating the effects on margin from updating the threshold and shape parameters in the full assessment (HHA-3217, ASME BPVC Section III Div. 5)

Dear Interested Parties:

BACKGROUND

Record 21-1581 addresses a critical step in the full assessment for qualifying nuclear graphite components (HHA-3217) of the American Society of Mechanical Engineers Boiler Pressure and Vessel Code (ASME BPVC), Section III, Division 5.

The full assessment uses the 3-parameter Weibull distribution to estimate the tensile strength distribution for a graphite grade. The full assessment contains a step where the threshold is reduced if the maximum component equivalent stress is less than the 95% lower bound on the characteristic stress parameter.

The Weibull parameters are dependent on one another. If the threshold is reduced, that affects both the scale parameter (threshold + characteristic strength) and the shape parameter. HHA-3217 is written in such a way that the scale parameter is intrinsically (automatically) updated when the threshold is reduced. However, there is no adjustment to the shape parameter when the threshold is reduced.

R21-1581 proposes the update of the shape parameter when the threshold is reduced. There were inquiries about the effects on margin when the shape parameter is updated. The purpose of this memo is to illustrate the effects on margin when the shape parameter is updated using the 2023 Code grouping rules.

METHODS

Margin is assessed in reference to the load factor (L_f), define below:

$$L_f = \frac{L_{allowable}}{L_{experimental\ median}}$$

Where:

$L_{allowabale}$: the allowable load at the target POF, given the graphite grade, component, and assessment

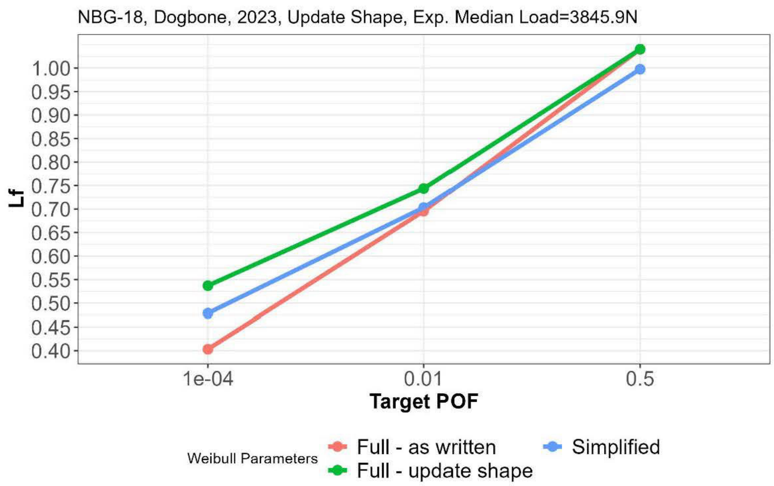
$L_{experimental\ median}$: the median experimental load for the graphite grade

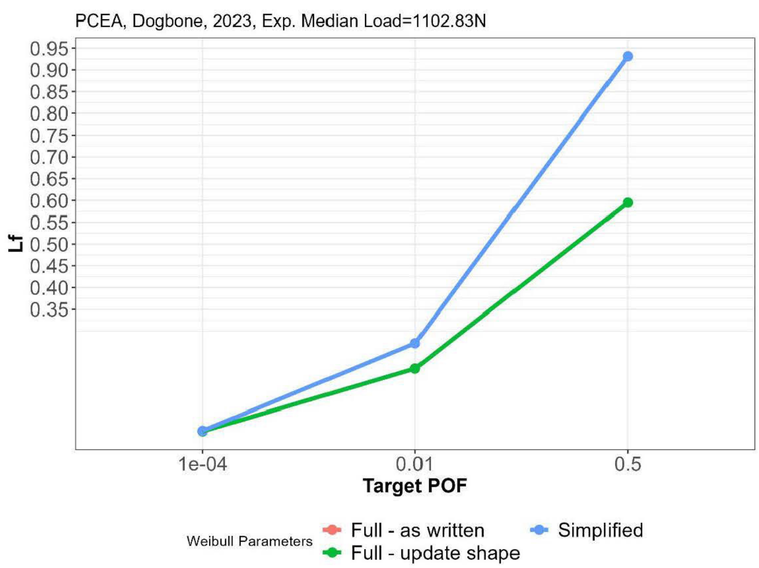
The only components considered in the analysis are the dogbone geometries, based on the dogbone specimens to estimate the Weibull distributions. The assessments are run for SRC-1, SRC-2 (10^{-4}, 10^{-2}) and the median (0.5) target failure probabilities. If the assessments work perfectly, the $L_f = 1$ when the target failure probability is 0.5. $L_f < 1$ indicates the assessment is conservative relative to the experimental median load. The smaller the L_f, the more conservative the assessment relative to the experimental median load.

The analysis was done for NBG-18, NBG-17, PCEA, IG-110, and 2114. The L_f is also affected by the grouping choices (V_m & Δ). The results presented below are using the 2023 BPVC grouping rules. Note that trends may not be as expected due to errors identified with the 2023 grouping criteria.

RESULTS

There were very slight differences (L_f = 0.07 vs. 0.08) in the L_f for PCEA at the 10^{-4} target POF. Since the MLE threshold for PCEA is 0, there is no threshold reduction. Therefore, the full assessment as written and the full assessment with the shape parameter updated produce the same results. Updating the shape parameter allows for higher loads than the current Code rules. For all grades except PCEA (which provides more conservative results), allowable loads at a target POF=0.01 (SRC-2) are between 65%-75% of the median experimental load at failure when updating the shape parameter. For NBG-18, IG-110, and 2114, updating the shape parameter increases the load factor (allowable load) by 10-20% at a target POF=0.0001 (SRC-1).


NBG-18, Dogbone, 2023, Update Shape, Exp. Median Load=3845.9N
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
Lf
1e-04
0.01
0.5
Target POF
Weibull Parameters
Full - as written
Full - update shape
Simplified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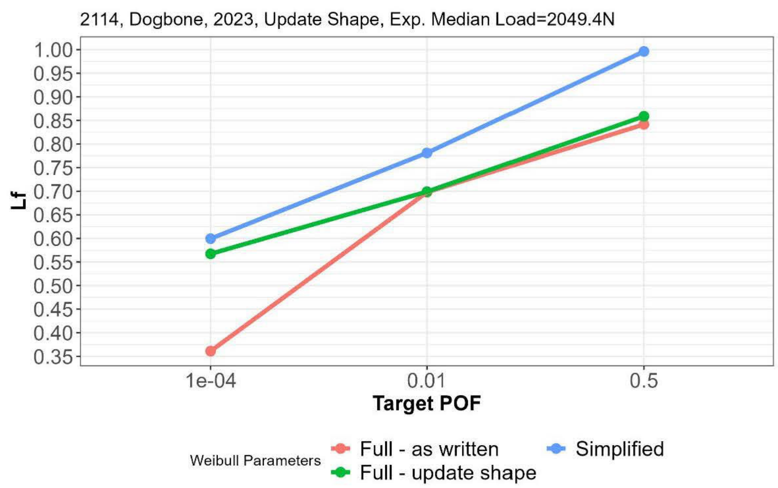
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
Lf
1e-04
0.01
0.5
Target POF
Weibull Parameters
Full - as written
Full - update shape
Simplified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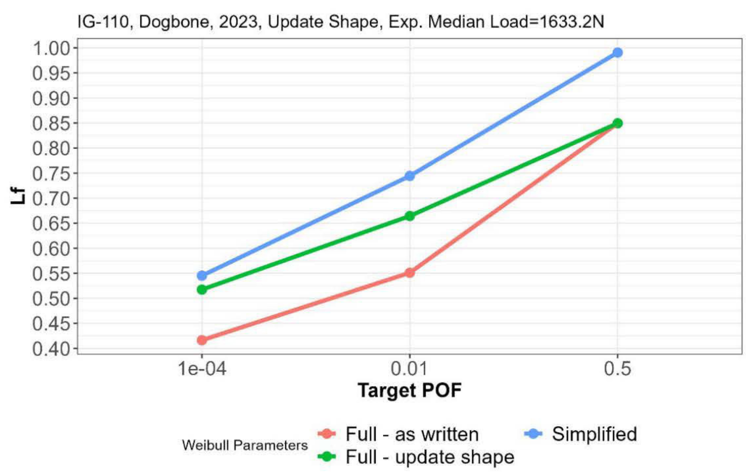
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
Lf
1e-04
0.01
0.5
Target POF
Weibull Parameters
Full - as written
Full - update shape
Simplified


IG-110, Dogbone, 2023, Update Shape, Exp. Median Load=1633.2N
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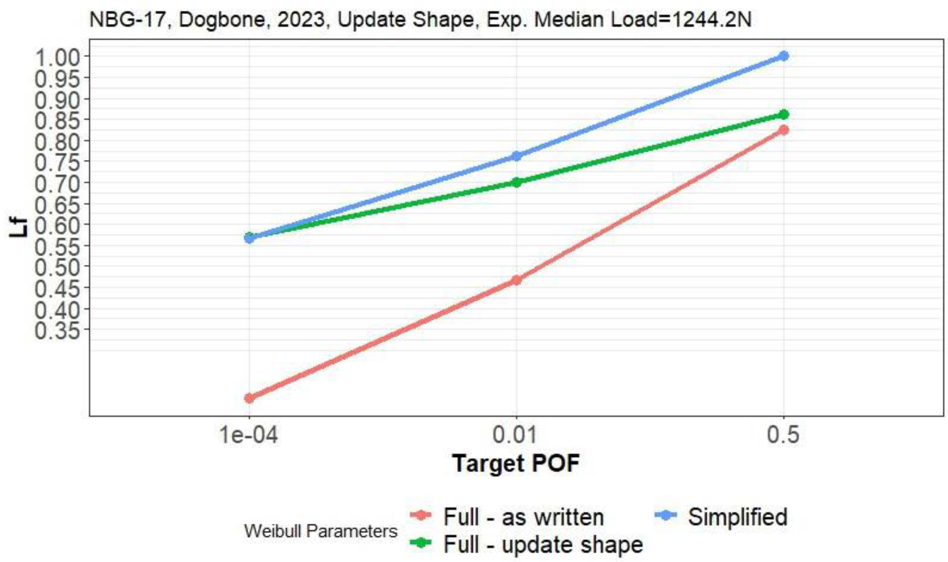
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
Lf
1e-04
0.01
0.5
Target POF
Weibull Parameters
Full - as written
Full - update shape
Simplified


NBG-17, Dogbone, 2023, Update Shape, Exp. Median Load=1244.2N
Lf
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0.90
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0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
1e-04
0.01
0.5
Target POF
Weibull Parameters
Full - as written
Full - update shape
Simplified

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Appendix C

Memorandum on Interpretations of the Full and Simplified Assessments in ASME BPVC

Memorandum

Date: January 30, 2024

To: ASME WG-NMDM

From: ASME Design Task Group

Subject: Interpretations of the full and simplified assessments in ASME BPVC

Dear Interested Parties:

1. ***Purpose***

The purpose of this memorandum is to provide the necessary background information to ensure proper interpretations of the simplified and full assessments defined in the ASME Boiler & Pressure Vessel Code, Section III, Division 5, Subsection HH, Subpart A, Article 3000. The memorandum also discusses R22-486.

2. ***Background***

2.1. Background on R22-486

R22-486 changed the text and interpretation in Section III, Division 5, Subsection HH Class SN Nonmetallic Core Components, Subpart A Graphite Materials, 3000 Design from Probability of Failure (POF) to Probability of Crack Initiation (POCI), under the premise that the change was not an exercise in semantics and that UK AGR reactors have safely operated with cracked bricks. (1) R22-486 acknowledged that other texts have referred to POF both as probability of failure and probability of fracture, but stated that specifically, the Code is only calculating the POCI (HHA-3214.14). (2) R22-486 further modified the Code (HHA-3215), stating that, "limits refer to crack initiation and do not reflect the likelihood of crack propagation. The significance of crack initiation and the potential for crack propagation must be assessed against the damage tolerance of the design." (3) In HHA-3300, R22-486 added statements putting the responsibility of defining the nuclear safety requirements of individual graphite components and core assemblies on the User to determine functionality of components and resistance to damage tolerance. (4) In HHA-3100, R22-486 added the statements, "Graphite components must be evaluated to ensure that safety functionality is achieved with/without cracks throughout their lifetime and validated as appropriate against routine monitoring and surveillance data."

The main purpose of R22-486 was to clarify that "failure" in the assessments do not mean "loss of functionality", but rather "failure" means crack initiation. The ASME Design Task Group does not agree with all the changes made in R22-486.

Referencing the HHA-3000 sections prior to R22-486, this memo will:

- Emphasize what the Code already states about the interpretation of the full and simplified assessments in HHA-3000
- Describe the methods and assumptions used for calculating design targets in HHA-3000 through the full and simplified assessments
- Describe practical implications of the assessment methods and assumptions in graphite components
- Provide recommendations

ASME BPVC Section III Division 5 HHA-3000

Figure 1 shows a snippet from HHA-3100 on the interpretations of the assessments.

> The design approach selected is semiprobabilistic, based on the variability in the strength data of the graphite grade. Due to the nature of the material, it is not possible to ensure absolute reliability, expressed as an absence of cracks, of Graphite Core Components. This is reflected in the setting of Probability of Failure (POF) targets. Also note that due to the complex nature of the loadings of graphite components in a reactor combined with the possibility of disparate failures of material due to undetectable manufacturing defects, the Probability of Failure values used as design targets may not be precisely accurate predictions of the rate of cracking of components in service. The Designer is required to evaluate the effects of cracking of individual Graphite Core Components in the course of the design of the Graphite Core Assembly and ensure that the assembly is damage tolerant.

Figure 1: Snippet from HHA-3100

From this paragraph, it is clear that failure in the material reliability curves is expressed (defined) as cracks in components. POF values are design reliability targets to predict the rate of cracking in graphite components. The Code acknowledges that the assessment methods may not be accurate due to the component loading configuration and the inability to capture the disparate flaw mode in the material reliability curve.

HHA-3100 specifically is defining reliability of the components as the absence of cracks. HHA-3100 suggests that when a component does not meet the POF reliability targets, the component has cracked. It does not state anything about the crack length/propagation. The rest of this document explains the context in which the word "failure" appears in HHA-3000 Articles, the methods and assumptions in the assessments, and how those assumptions manifest in graphite components.

Failure in HHA-3000

Brief Background
HHA-3000 contains two semi-probabilistic methods for qualifying graphite components and assemblies, the full and simplified assessments. In application, the material reliability curves are applied to every component's geometry and loading configuration to determine whether or not the pre-determined component structural reliability class (SRC) limits have been met. This is typically done through finite element (FE) modeling of the components and conversion of the three principal stresses to equivalent tensile stresses for alignment with the tensile-strength-based material reliability curves. Specifics of the methods in the full and simplified assessments will not be described here; please refer to HHA-3000.

Failure in material reliability curves
HHA-3000 determines component failure based on graphite material reliability curves. The material reliability curves are statistical in nature to account for the random strength variations due to the inherent defects (cracks, pores, etc.) within the graphite material. Weibull distributions have been chosen as the probability distributions to represent the material reliability curves. Weibull distributions map strengths to probabilities of failure. Failure in dogbone tensile specimens is fracture (through crack) in the gauge region. The strength data used to determine the material reliability curves in HHA-3000 come from fractured dogbone tensile specimens with fixed dimensions.

Failure in structural reliability classes (SRC)
The SRC limits are pre-defined allowable component failure probabilities. The SRC limits are implemented by comparing component failure probabilities to SRC allowable failure probabilities based on the Weibull tensile strength material reliability curves. The material reliability curves are estimated using dogbone specimens with cracks extending horizontally through the entire gauge region. The assumption is that component cracking rate can be estimated by the dogbone failure rate represented by the material reliability curves.

Failure in the simplified assessment

The simplified assessment does not calculate probability of failures for components. The definition of component failure should not be formally defined in the simplified assessment. A component fails to meet the requirements of the simplified assessment when membrane stresses exceed the allowable tensile stress and when the peak equivalent tensile stress limit exceeds the allowable flexural stress limit.

Exceedance of these limits could practically mean many different things for many different component designs and loading configurations. The Code does not explicitly assume nor prescribe practical implications of exceedance of the limits. However, it is commonly assumed that when the stress exceeds the strength limit, a crack has occurred. This does not preclude the designer from further evaluating the component's exceedance of the limits for practical implications and interpretations.

Failure in the full assessment
The full assessment calculates a probability of failure (POF) for the component in question using a modified weakest link theory approach. Weakest link theory for brittle materials assumes the strength of the entire component is determined by the strength of the weakest volume of material in the component. According to weakest link theory, once the weakest process zone volume has a through crack, that crack is more likely to propagate and extend through the full ligament thickness (e.g. in a prismatic core block this might mean a full crack between vertical channels, or it might mean a full crack from the outside of a brick to the control rod channel hole). The assumption is the full assessment failure definition is synonymous with through cracking and fracture, though, because graphite is a quasi-brittle material, this assumption is conservative.

Weakest Link Theory Assumptions in the Full Assessment
The semi-probabilistic POF analysis in the full assessment is based on a modified weakest link theory and is common in the literature. An assumption of the weakest link theory is that the strength of the entire component is determined by the strength of the weakest volume of material. That is, we conservatively assume that 'crack initiation' equals complete propagation.

The assumptions are explained more clearly in [1]. The excerpt below is copied from [1].

"The probabilistic models to be considered are those concerned with the instantaneous fracture as a result of unstable crack propagation when an initial load is applied. Fast fracture of structural components is generally assumed to depend on some property of the material from which the part was made. It is assumed that brittle materials contain microcracks which are uniformly distributed and randomly oriented. The probabilistic models for brittle fracture are based on the weakest link concept, because one crack almost always produces total failure in tension. The first of these was introduced by Weibull. Weibull assumed that the component of stress normal to the plane of the crack was the only one to contribute to its fracture. As a result, the shape of the crack is irrelevant and crack-crack interaction is not taken into account."

Practical Experience with Graphite Components

The failure methodology is based upon a modified Weibull weakest link method, however graphite does not strictly behave like this. In an engineering sense, 'failure' means loss of functionality. In the context of nuclear safety, this would specifically refer to loss of safety function(s). Whether or not cracking results in loss of functionality is strongly dependent on the reactor design. For example, in the AGRs, cracking of the fuel channel bricks does not directly affect safety, while, in the earlier Magnox reactors, a cracked fuel channel brick generally would be a safety problem as it could starve the fuel of coolant. The difference comes down to the specific coolant flow paths over the fuel in each reactor. In the AGRs, the main concern with cracking is that it may lead to greater distortion of channels, particularly during a seismic event, which might affect control rod entry. This is a property of the core as a whole, not any individual brick.

In reality, full cracking does not simply require the exceedance of some critical stress within a volume. Work must be done to propagate a crack, which comes from the release of internal strain energy and/or the application of external load. If there is not enough energy to create new crack surfaces, the crack will not grow. Real graphite components containing internal stress tend to be quite large, with complex geometries and steep stress gradients. It seems quite likely that cracks might not propagate fully in many cases. There are examples from the AGRs of cracks that appear to have propagated fully immediately after initiation and of cracks that appear to have been stable and part-thickness for many years. Also, some that propagated a bit, arrested, and then propagated further after additional irradiation.

In many cases, the full crack would be more like an AGR single axial crack, i.e., between the outside of the component and a hole/channel, or between two holes. The component would still hold together. See illustrative examples below drawn on a prismatic HTGR block in Figure 2: the red lines might represent fully-propagated cracks, but they would not split the component in two.

Figure 2: Illustrative example of cracking in a prismatic HTGR block

Computational or physical modelling of this problem is difficult: there are gradients not only in stress, but in material properties. For example, the non-uniform distribution of elastic modulus, fracture toughness etc. within the solid body, which are largely due to variation in irradiation conditions, although there is some initial within-brick variability in properties as well. Effect of unirradiated distribution of properties like CTE and DYM on stress is quite small. The crack follows an arbitrary path in three dimensions. Complete validation is nearly impossible due to complications in replicating required stress gradients, so some kind of conservative interpretation is usually required anyway. This is a problem for the designer. It is often possible to come up with appropriate simplifications of the crack propagation problem that make it more tractable than the current ASME BPVC assessment guidelines, depending on the geometry and stress state, but there are no general rules here.

While R22-486 claimed that some of the UK AGR bricks have cracked into two separate pieces and have still been able to perform their safety function (i.e. no engineering failure occurred), it is important to consider the effect of cracking in the AGR bricks in more detail. The UK AGR brick cracking highlights a number of potential issues (there are also others):

- Singly cracked brick opening: with further irradiation, a cylindrical brick with a full-height axial crack opens up in a 'C' shape, pushing against nearby components. This may cause core distortion.

- Induced cracking: when one brick cracks, it may apply loads to neighbors (particularly via the keying system), which can cause further cracks in those bricks. Initiation of a single crack in a channel may rapidly lead to several other cracks in a chain, or it may accelerate cracking after some further irradiation.

- Double cracking: if a brick splits in two, the halves are free to move, adding 'slack' to the core and potentially leading to larger displacements in a seismic event

- Fragments and debris: small parts may break off a cracked brick (often associated with the keying system); the potential effects of these on coolant flow need to be evaluated (in particular: can debris block a fuel assembly). There is also potential for debris to prevent fuel movement by jamming between the fuel and the fuel channel wall.

- Keying system disengagement due to large displacements: wide enough cracks or large movement of cracked brick parts could allow keys to move out of place. This would make it difficult to evaluate the structural integrity of the core.

- Cracking of the graphite fuel sleeve (a part of the fuel assembly that forms the coolant flow path over the fuel) could starve the fuel of coolant and lead to fuel failure. This would not be acceptable. 100% proof testing of fuel sleeves is used to eliminate weak outliers.

In modern HTGRs, an additional concern is the effect of cracking on passive heat removal through graphite by conduction. The AGRs do not make this claim.

CONCLUSIONS AND RECOMMENDATIONS MOVING FOWARD

The main conclusions from this memo are:

- The modified weakest link method used in the full assessment makes no distinction between crack initiation and through wall cracking. Both crack initiation and through wall cracking are treated as failure of the component to meet the reliability targets in the full assessment. Therefore, the parts of R22-486 that changed interpretations of probability of failure to probability of crack initiation are inaccurate and should be removed.
- The full assessment provides a conservative estimate of the probability of cracking.
- Experience tells us that cracking may or may not affect a component's ability to perform its function. Depending on the design and loading configuration, cracking may or may not result in component failure as defined in an engineering sense.
- A POF is not calculated in the simplified assessment. Practical implications of stress limit exceedance in the simplified assessment is design and loading configuration dependent.
- As HHA-3100 already states, it is up to the Designer to ensure the assembly is damage tolerant and the individual components meet the full/simplified assessment criteria.
- As HHA-3100 already states, the assessments do not provide accurate probabilities of cracking.

The authors of this memo recommend a record be generated that more explicitly and clearly emphasizes these points in HHA-3000 that uses this memo as a background document. We agree that the word 'failure' is ambiguous and prone to misinterpretation.

REFERENCES

[1] Powers, L.M. & Ghosn, L.J. (1989). Reliability based failure analysis of brittle materials. NASA Contractor Report. https://ntrs.nasa.gov/api/citations/19890011118/downloads/19890011118.pdf