INL/CON-23-74507-Revision-1

Qualifying nuclear graphite components using ASME guidelines

September 2023

Changing the World's Energy Future

Andrea L Mack, William M Hoffman, Jesse Quick, William E Windes

Idaho National Laboratory

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Qualifying nuclear graphite components using ASME guidelines

ART
Advanced Reactor Technologies

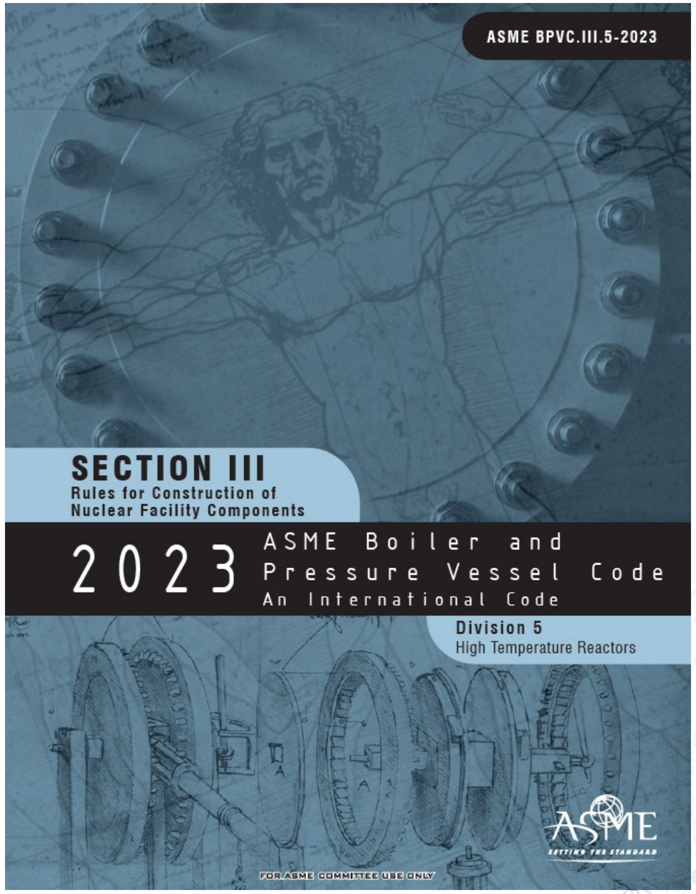
OUTLINE

- Background
- Pre-assessment analysis (inputs)
- Simplified assessment
- Full assessment
- Conclusions
- Ongoing work

BACKGROUND

ASME – American Society of Mechanical Engineers

- Boiler and Pressure Vessel Code (BPVC)
  - *Standard that regulates design and construction of boilers and pressure vessels*
  - *Our focus is on two primary Sections of Code; III and XI*
- **Section III** (Construction of Nuclear Facility Components), **Division 5** (High Temperature Reactors)
  - *New division, created to support unique issues surrounding construction of HTR designs*
  - *Subsection HH, Subarticle A (Graphite - HHA)*
  - *Subsection HH, Subarticle B (Composites - HHB)*
- **Section XI** (Rules for Inservice Inspection of Nuclear Power Plant Components), **Division 2** (Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants)
  - *Rules for observing performance of components during operation*
  - *Inspection for degradation, (potentially) damage tolerance*



*Information taken from [8].

SCOPE

- Graphite core components and graphite core assemblies
- For the reactor pressure vessel of a high temperature, graphite moderated fission reactor
- Not fuel compacts, bearings, seals, instrumentation, etc.
- Assessments provide design targets and may not accurately predict cracking rate
- The designer separately must evaluate the effects of cracking and ensure the assembly is damage tolerant

HHA-1110 ASPECTS COVERED

This Subpart establishes rules for Graphite Core Components and Graphite Core Assemblies, where 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.

HHA-1300 APPLICATION OF THESE RULES

(a) The rules shall apply to Graphite Core Components utilized in a high temperature, graphite moderated fission reactor. Graphite Core Components include fuel blocks, reflector blocks, shielding blocks, and any keys or dowels used to interconnect them.

(b) The rules shall also apply to the arrangement of Graphite Core Components that form the Graphite Core Assembly.

(c) The rules shall not apply to fuel compacts, bushings, bearings, seals, blanket materials, instrumentation, or components internal to the reactor other than those defined above.

HHA-3100

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.

*Information taken from [8].

Assessments

(a) SRC-1: The Structural Reliability of components in this class is important to safety. These parts may be subject to environmental degradation.

(b) SRC-2: The Structural Reliability of components in this class is not important to safety. These parts are subject to environmental degradation during life.

(c) SRC-3: The Structural Reliability of components in this class is not important to safety. These parts are not subject to environmental degradation during life.

(a) For SRC-1, the allowable value is the S_g value, derived to a Probability of Failure of 10^{-4} [$S_g(10^{-4})$].

(b) For SRC-2, the allowable value is both of the following:

(1) the S_g value, derived to a Probability of Failure of 10^{-4} [$S_g(10^{-4})$] prior to the inclusion of any internal stress due to irradiation

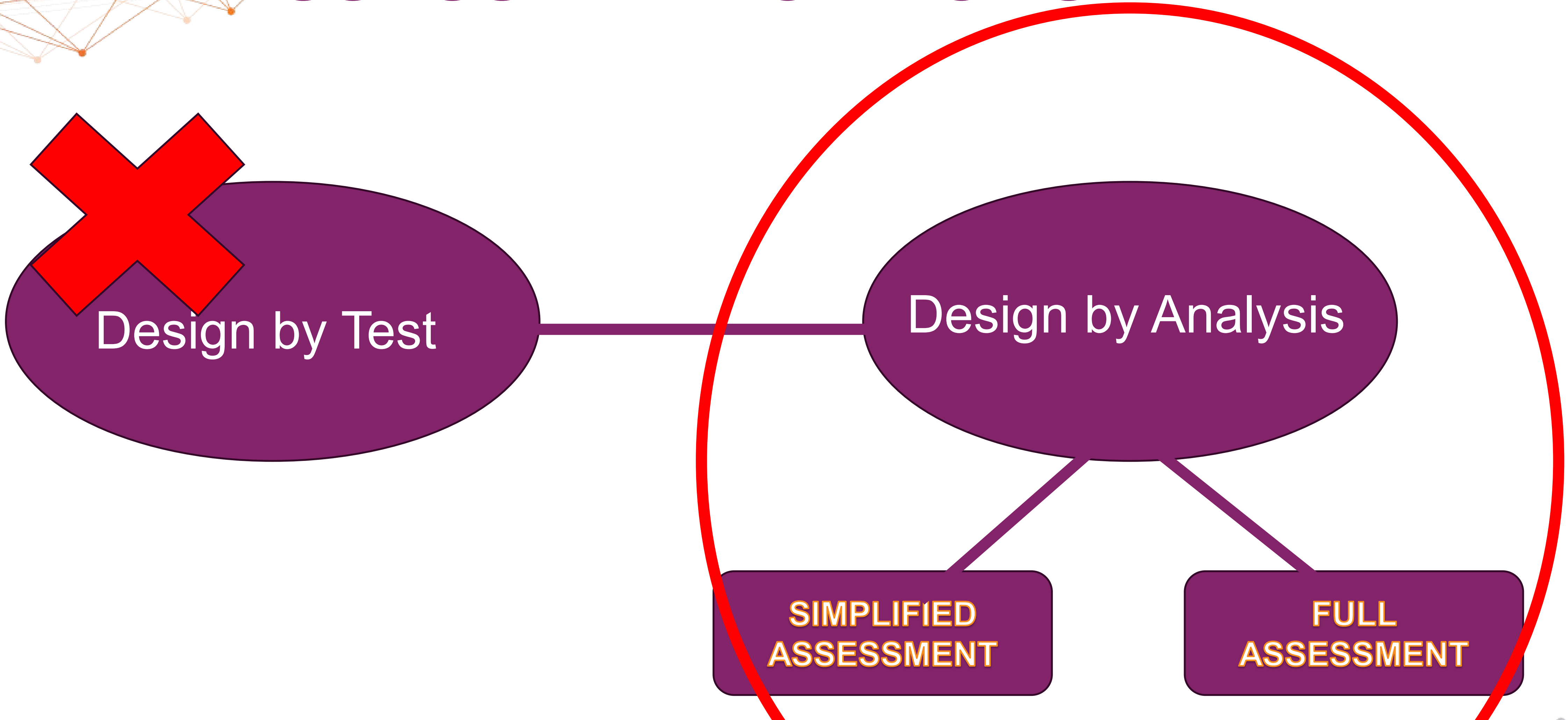
(2) the S_g value, derived to a Probability of Failure of 10^{-2} [$S_g(10^{-2})$] when including any internal stress due to irradiation at the design lifetime

(c) for SRC-3, the allowable value is the S_g value, derived to a Probability of Failure of 10^{-2} [$S_g(10^{-2})$].

*Information taken from [8].

- Nuclear graphite core components & assemblies
- Assessments: Full and simplified
  - Semi-probabilistic
- Design targets, not damage tolerance
- Design targets are a function of:
  - Material reliability curve
  - Component stress distribution
  - Component structural reliability class (SRC)
- Assessment **interpretation**: component passes/fails assessment
- Have to look deeper on a **component-by-component basis** as to **why** the component passes/fails the assessments
- The assessments do not account for oxidation/irradiation/etc. changes in material reliability curves (**yet**)
- Assessments presented as written (with the exception that the shape is updated in full)

ASSESSMENT OPTIONS



*Components must pass just ONE of the assessments.

WHERE DO THE ASME DESIGN CODES COME FROM?

- Basis for approach: Kerntechnischer Ausschuss (KTA) Nuclear Safety Standards Commission (German KTA-3232)
- Approach modified by Dr. Hindley, published in his thesis (2015), Stellenbosch University

ASSESSMENT ASSUMPTIONS

SIMPLIFIED & FULL

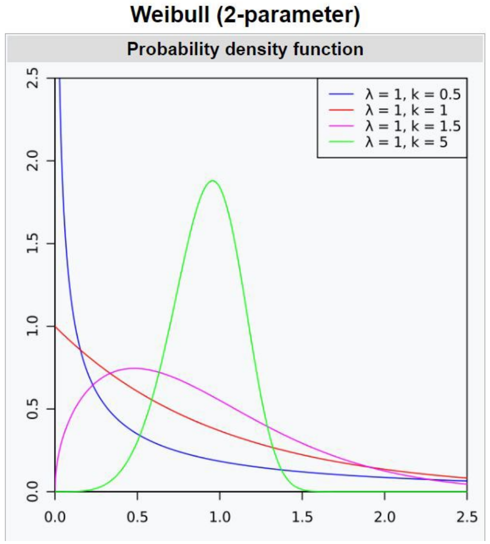
- Graphite material reliability curves are based on **tensile** strengths from dogbone specimens broken according to ASTM C739
- Tensile strength can be modeled by the 2- & 3-parameter **Weibull distributions** well
- Margin is sufficiently captured by using
  - Lower bounds of upper 95% confidence intervals on estimated Weibull parameters to account for **sampling uncertainty**
  - Low probability of failures (POFs), in accordance with **component SRC**
  - Assumes components are stressed in pure tension
- Simplified assessment is more conservative than the full
- Material strength distributions do not change with irradiation, oxidation, etc.

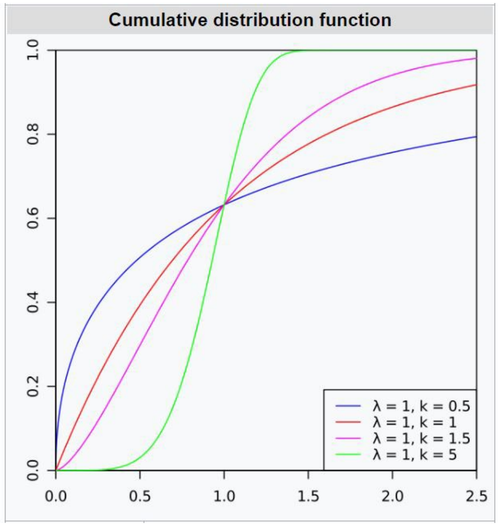
FULL ONLY

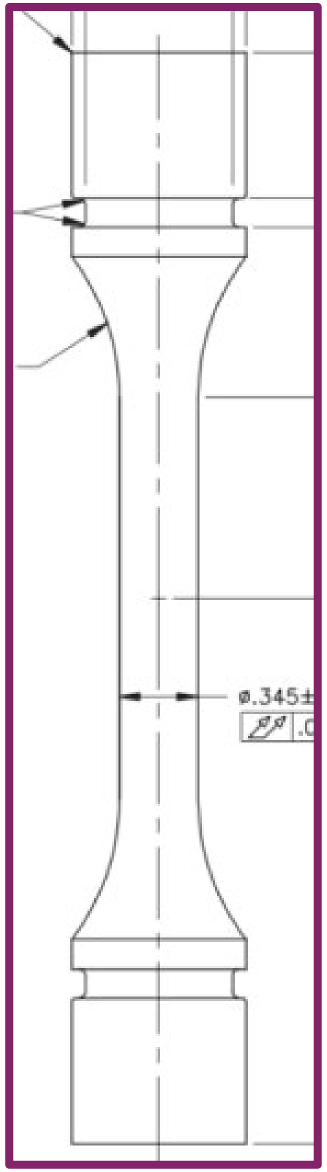
- Graphite behaves according to **weakest link theory**
- Graphite tensile strength **no longer changes** once a minimum volume (V_m) has been achieved

Weibull distributions

- Probability density function
- Cumulative density function
- Experimental **tensile** strength distribution
  - Threshold: Stresses below threshold have 0 POF
  - Characteristic strength: “Typical strength”
  - Shape: How failure rate changes with strength (skew)
- Estimation methods
-







Weibull CDF: $F(\sigma|\lambda, k, \mu) = 1 - e^{-\left(\frac{\sigma-\mu}{\lambda}\right)^k}$

*Images copied from [3] for illustration

Semi-probabilistic approach to design

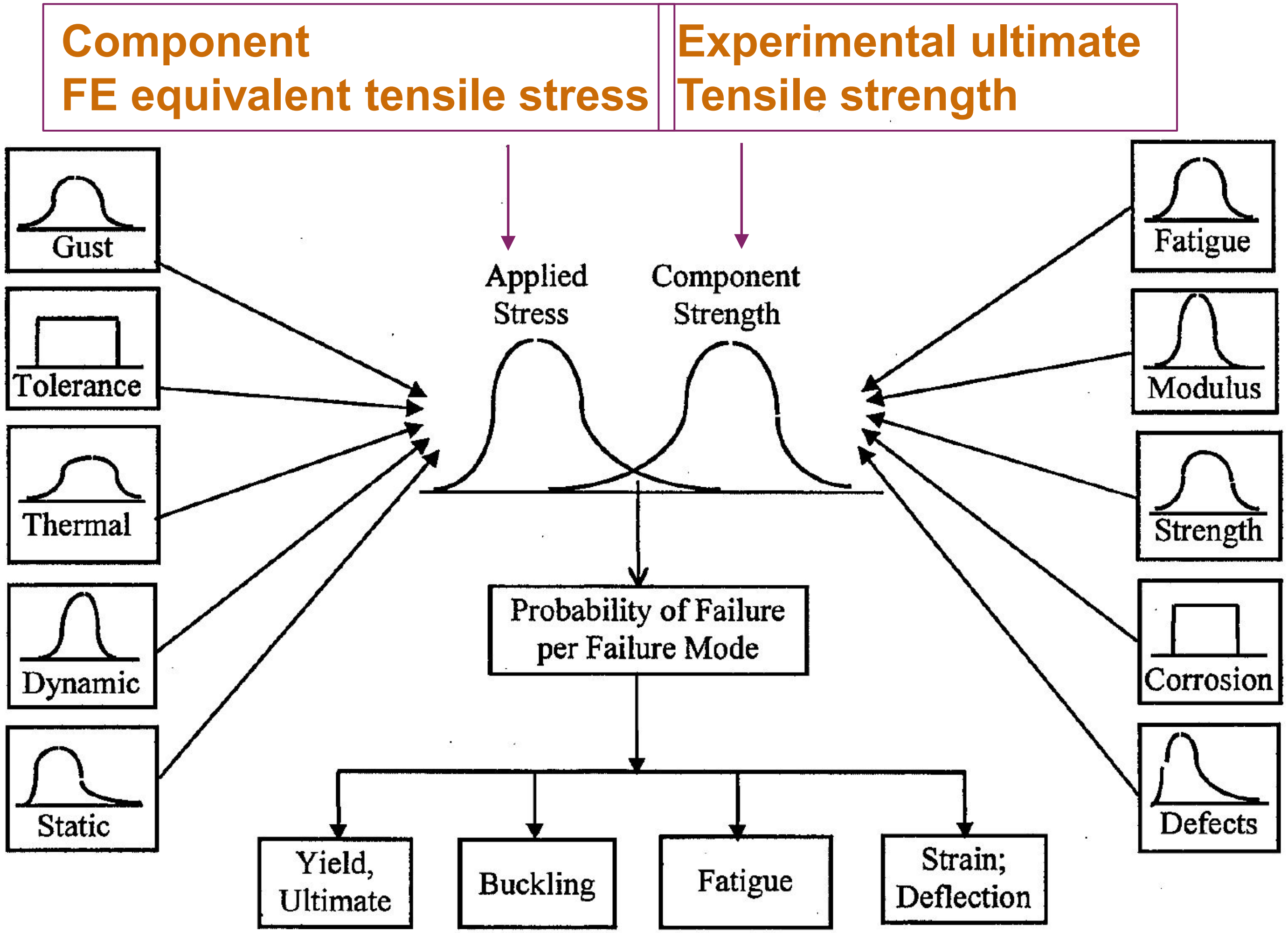
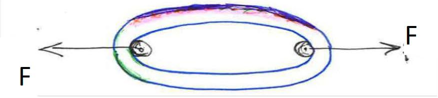


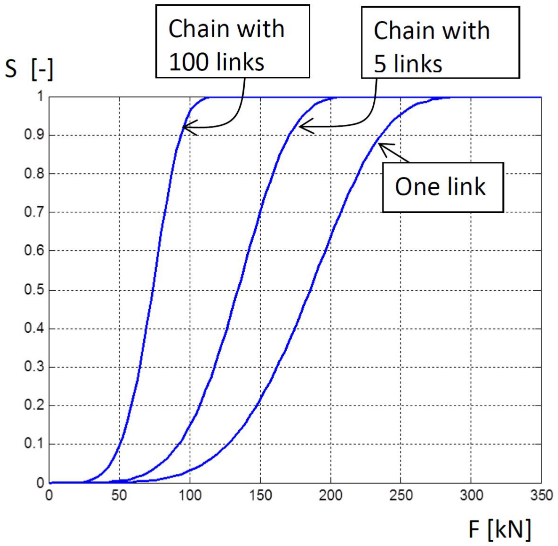
*Image copied from [7] for illustration

Weakest link theory of brittle materials

1) **The Weibull probability distribution function**, is much used in several areas of science and technology for definition of stochastic properties. For instance the stochastic strength properties of a link:

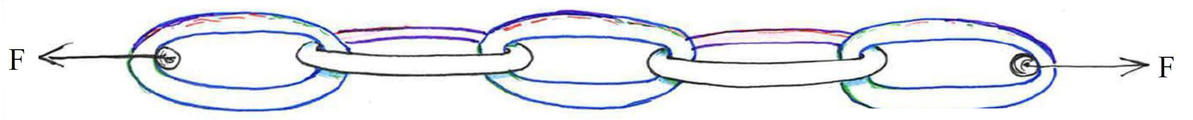


$$S(F) = \begin{cases} 1 - e^{-(F/F_o)^m} & \text{for } F \geq 0 \\ 0 & \text{for } F < 0 \end{cases}$$

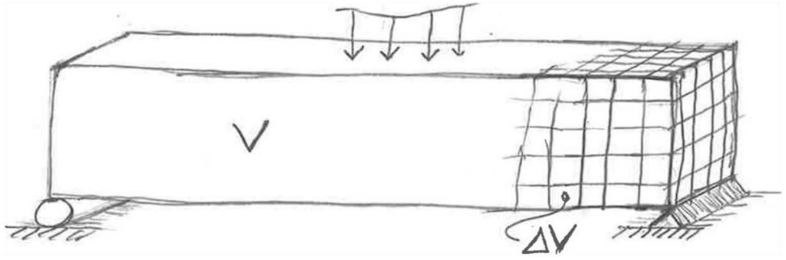


- S(F) is the cumulative probability distribution function for the strength of the link. This means that S(F) is the probability that the link will fail if loaded from zero load up to the load F.
- F_o and m are the two parameters that define the properties of the link ("material paramet."). (There is also a three parameter Weibull distribution, not discussed here.)

2) **The Weibull weakest link model,** is used for analysis of the strength of structural elements, e.g. the strength of a chain made up of several links:



Next the strength of a material volume V made up of small volumes ΔV or dV is analyzed as a chain made up of links.



*Slide is copied from Ref [4].

The volume ΔV_i is loaded by stress σ_i.

The strength properties of the volumes ΔV are defined by parameters σ_o and m.

Assumption: *The volume V is assumed to fail as soon as any of volumes ΔV fails. Brittle failure!*

PRE-ASSESSMENT TESTING AND ANALYSIS

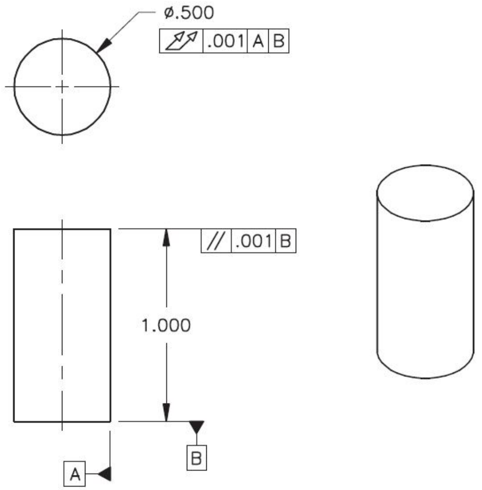
Pre-assessment analysis: Experimental data

- Experimental data
  - Material data sheet
  - Sample size requirements
  - Drawings

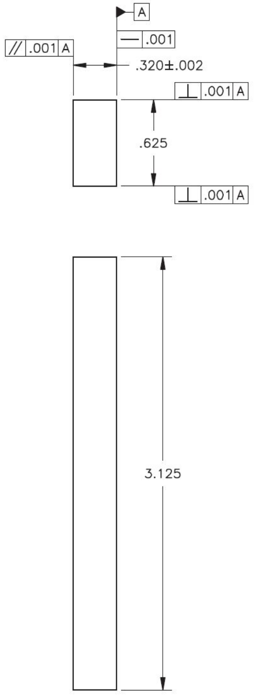
Design Strength and Material Reliability Curve Values

Ratio of compressive to tensile strength (R_{tc}) ⑰	Ratio of flexural to tensile strength (R_{tf}) ⑱	$S_{c_{0.05}}$ MPa ⑲	$m_{0.05}$ ⑳
	S'MPa ㉑	$S_{c'_{0.05}}$ MPa ㉒	$m'_{0.05}$ ㉓
$S_g(10^{-4})$ MPa ㉔	$S_g(10^{-3})$ MPa ㉕	$S_g(10^{-2})$ MPa ㉖	$S_g(5 \times 10^{-2})$ MPa ㉗

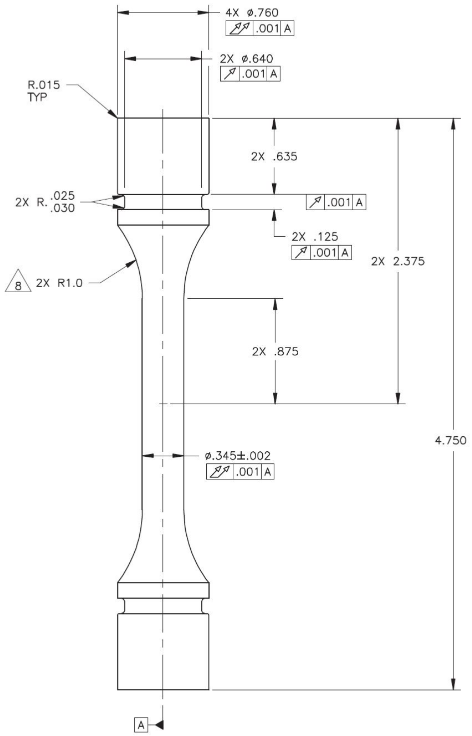
Compression



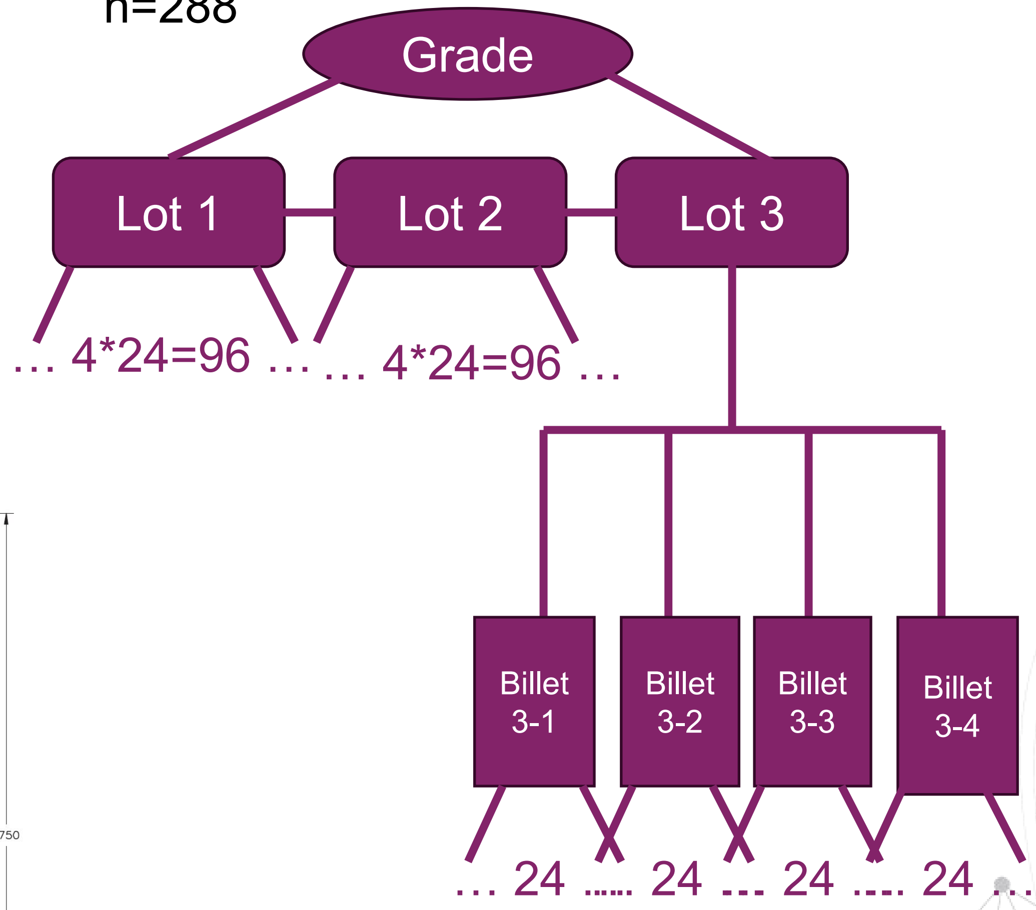
Flexural



Tensile

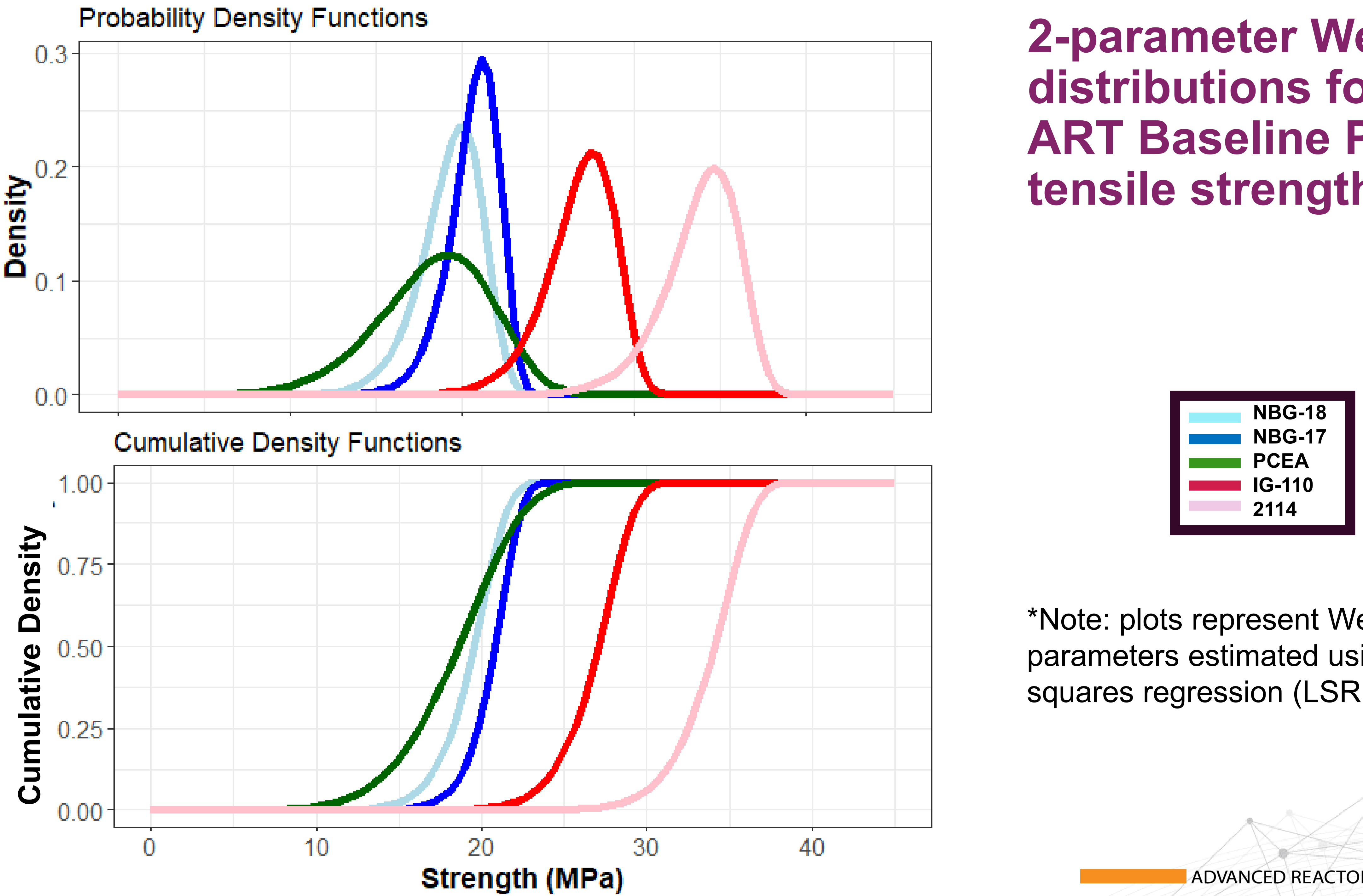


HHA-III-4100 Sampling Requirements: n=288



*Information taken from [8].

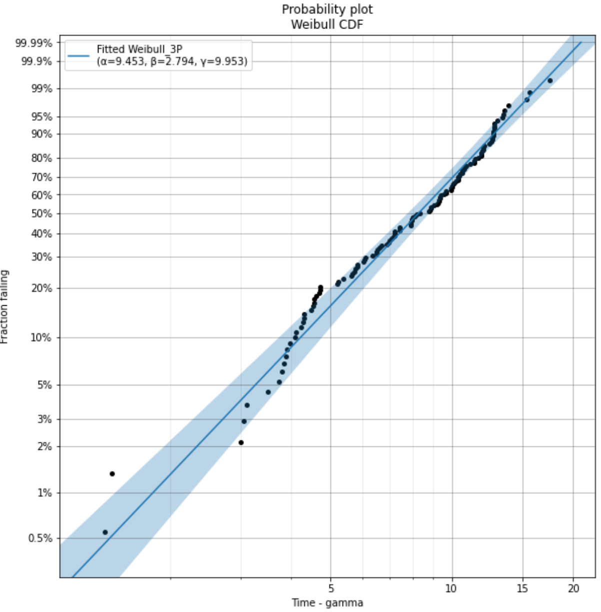
2-parameter Weibull distributions for DOE ART Baseline Program tensile strength data



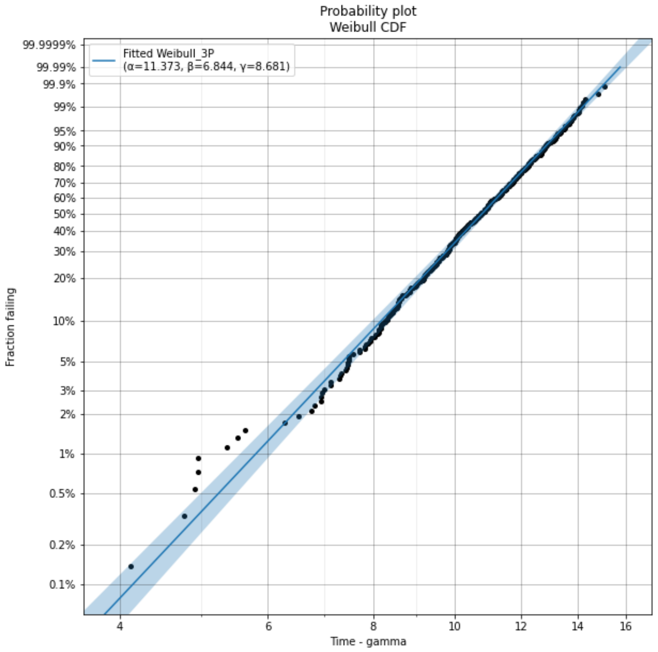
*Note: plots represent Weibull parameters estimated using least squares regression (LSR)

3-parameter MLE

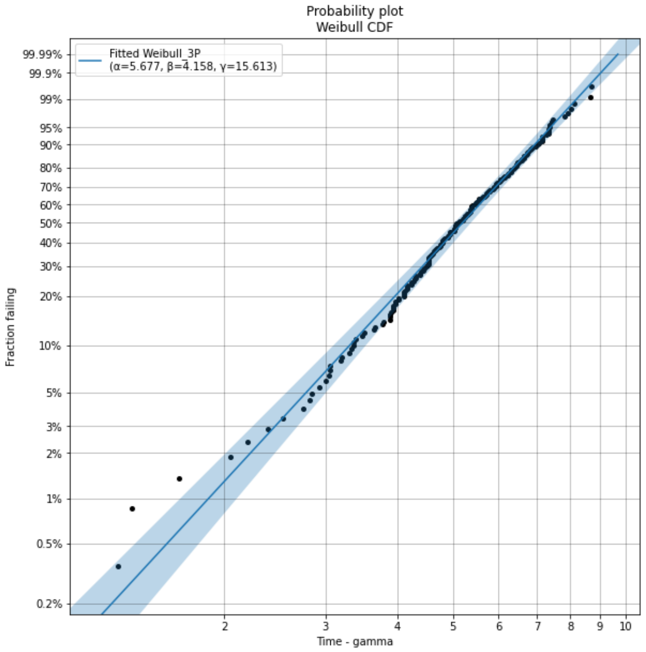
PCEA 01D3-36: n=127



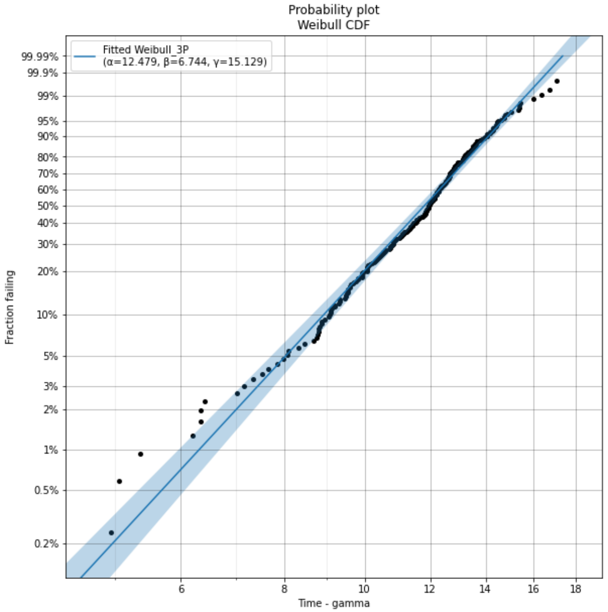
NBG-18 n=508

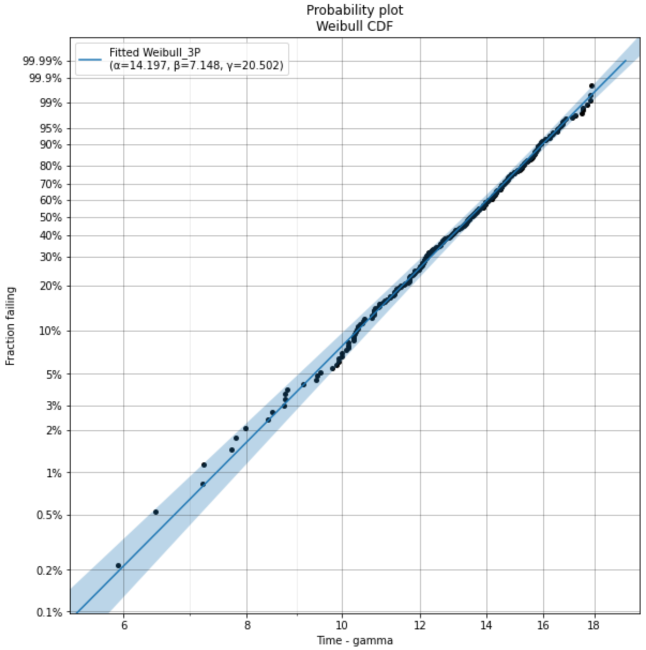


NBG-17 n=223



IG-110 n = 290





2114 n=324

ART Baseline Program [6]
Tensile Weibull Parameter Estimates

		2 Parameter Weibull LSR		2 Parameter Weibull LSR LB	
Material	**N**	**Char. Streng**	**Shape**	**Char. Streng**	**Shape**
PCEA-36	**127**	19.69265	6.492431	19.27309	5.74336
NBG18	**508**	20.09379	12.88491	19.97917	12.10394
NBG17	**223**	21.26848	17.04267	21.13391	15.56016
IG110	**290**	27.68002	16.03679	27.51515	14.80432
2114	**324**	34.76101	18.77677	34.59296	17.40437

		3 Parameter Weibull MLE			3 Parameter Weibull MLE LB	
Material	**N**	**Thres**	**Char. Streng**	**Shape**	**Char. Streng**	**Shape**
PCEA-36	**127**	9.95	19. 4053	2.794	18.8997	2.481
NBG18	**508**	15.613	21.2905	4.15761	21.1245	3.79762
NBG17	**223**	15.6131	21.2905	4.15761	21.1245	3.79762
IG110	**290**	15.129	27.975	6.74376	27.608	6.26451
2114	**324**	20.5019	34.6989	7.14811	34.5091	6.654

*Note that none of the graphite grades here meet the sampling requirements of ASME BPVC HHA-III-4100

Pre-assessment analysis: FE model

- FE model
  - Model of the geometry
  - All relevant loading conditions
  - Excel output

The theory of failure used in the rules of this Article for combining stresses is the maximum deformation energy theory. This allows for an arbitrary stress state at a point to be converted to an equivalent stress that shall be compared directly to the results of a uniaxial strength test. The equivalent stress, σ_v, at a point within a graphite structure shall be calculated as follows:

$$\sigma_v = \sqrt{\bar{\sigma}_1^2 + \bar{\sigma}_2^2 + \bar{\sigma}_3^2 - 2 \cdot \nu \cdot \left(\bar{\sigma}_1 \cdot \bar{\sigma}_2 + \bar{\sigma}_1 \cdot \bar{\sigma}_3 + \bar{\sigma}_2 \cdot \bar{\sigma}_3\right)}$$

with

$$\bar{\sigma}_i = f \cdot \sigma_i$$

and

$f = 1$ if σ_i (i=1,2,3) is a tensile stress and $f = \left(\frac{1}{R_{tc}}\right)$ if σ_i is a compressive stress, where

R_{tc} = the ratio of the mean compressive to mean tensile strength for the specific grade of graphite [from the Material Data Sheet (HHA-2200)]

ν = 0.15

*Information taken from [8].

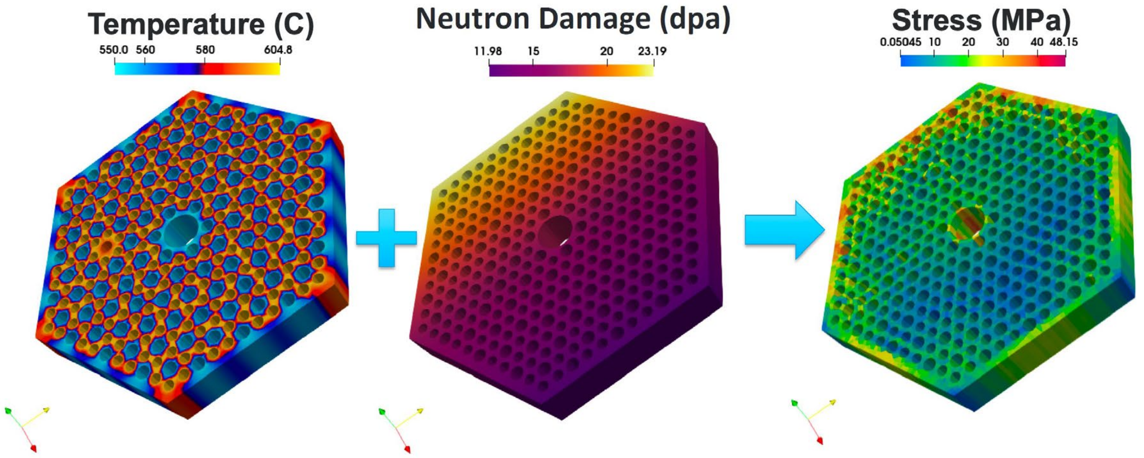


*Image above for illustration only, figure from [5]

id	max_principal_stress	mid_principal_stress	min_principal_stress	es	volume_mm3
51133	5109352	185006.1	16412.27	20.3501	0.01553273
101437	5109352	185006.1	16412.27	20.3501	0.01553273
151805	5109350	185009	16412.65	20.35009	0.01553273
893	5109349.743	185009.0487	16412.6454	20.35009	0.015532727
817	5109270.359	184997.539	16449.72884	20.34975	0.015554247
151729	5109270	184997.5	16449.73	20.34975	0.01555425
51441	5109265	185002.5	16450.78	20.34973	0.01555425
101745	5109265	185002.5	16450.78	20.34973	0.01555425
51129	5105595	185175.6	17767.89	20.33416	0.01693229
101433	5105595	185175.6	17767.89	20.33416	0.01693229
151801	5105595	185179.2	17768.33	20.33416	0.01693229
889	5105595.146	185179.1721	17768.32879	20.33416	0.016932288
818	5105467.177	185160.7044	17819.92385	20.33362	0.016970047
151730	5105467	185160.7	17819.92	20.33362	0.01697005
51442	5105457	185172.3	17820.88	20.33357	0.01697005
101746	5105457	185172.3	17820.88	20.33357	0.01697005
51456	5103673	184779.5	18442.29	20.32624	0.01763234
101760	5103673	184779.5	18442.29	20.32624	0.01763234
51073	5103256	184748.4	18621.41	20.32447	0.0178175

SIMPLIFIED ASSESSMENT

SIMPLIFIED ASSESSMENT APPROACH

Weibull CDF:

$$F\left(\sigma, S_{c_{0.05}}, m_{0.05}\right) = 1 - e^{-\left(\frac{\sigma}{S_{c_{0.05}}}\right)^{m_{0.05}}}$$

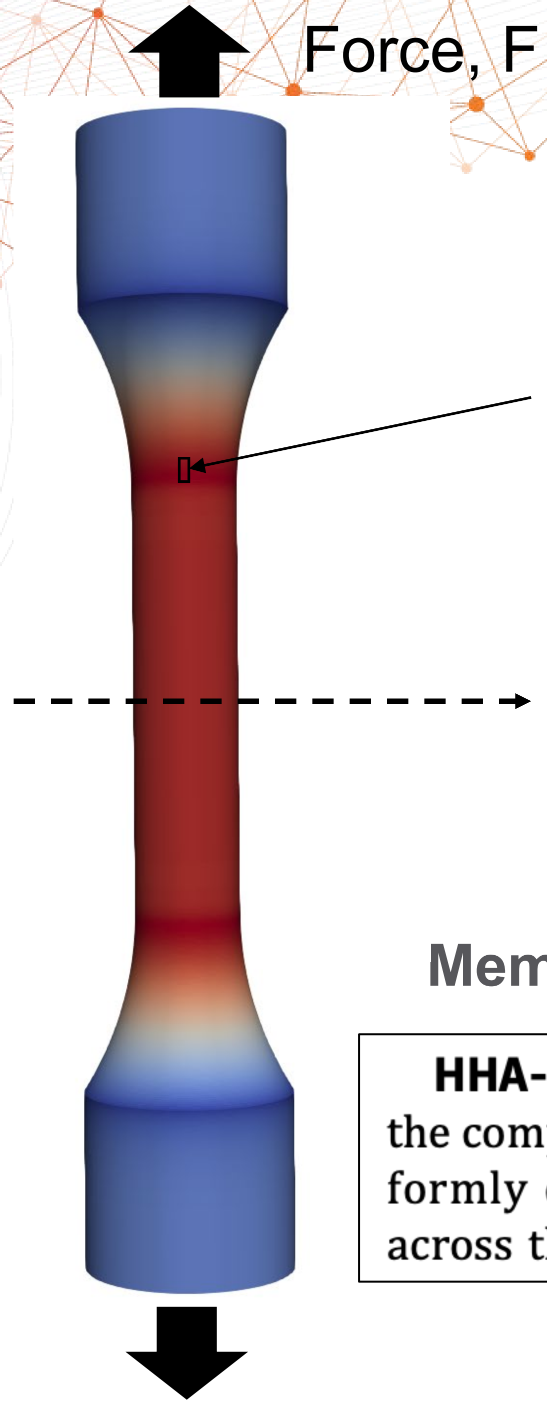
Allowable tensile stress SRC-1:

$$S_g(10^{-4}) = S_{c_{0.05}} * [-LN(1 - 10^{-4})]^{\frac{1}{m_{0.05}}}$$

Allowable flexural stress SRC-1:

$$R_{tf} * S_g(10^{-4})$$

Tensile Dogbone



Membrane Stress = Force/Area

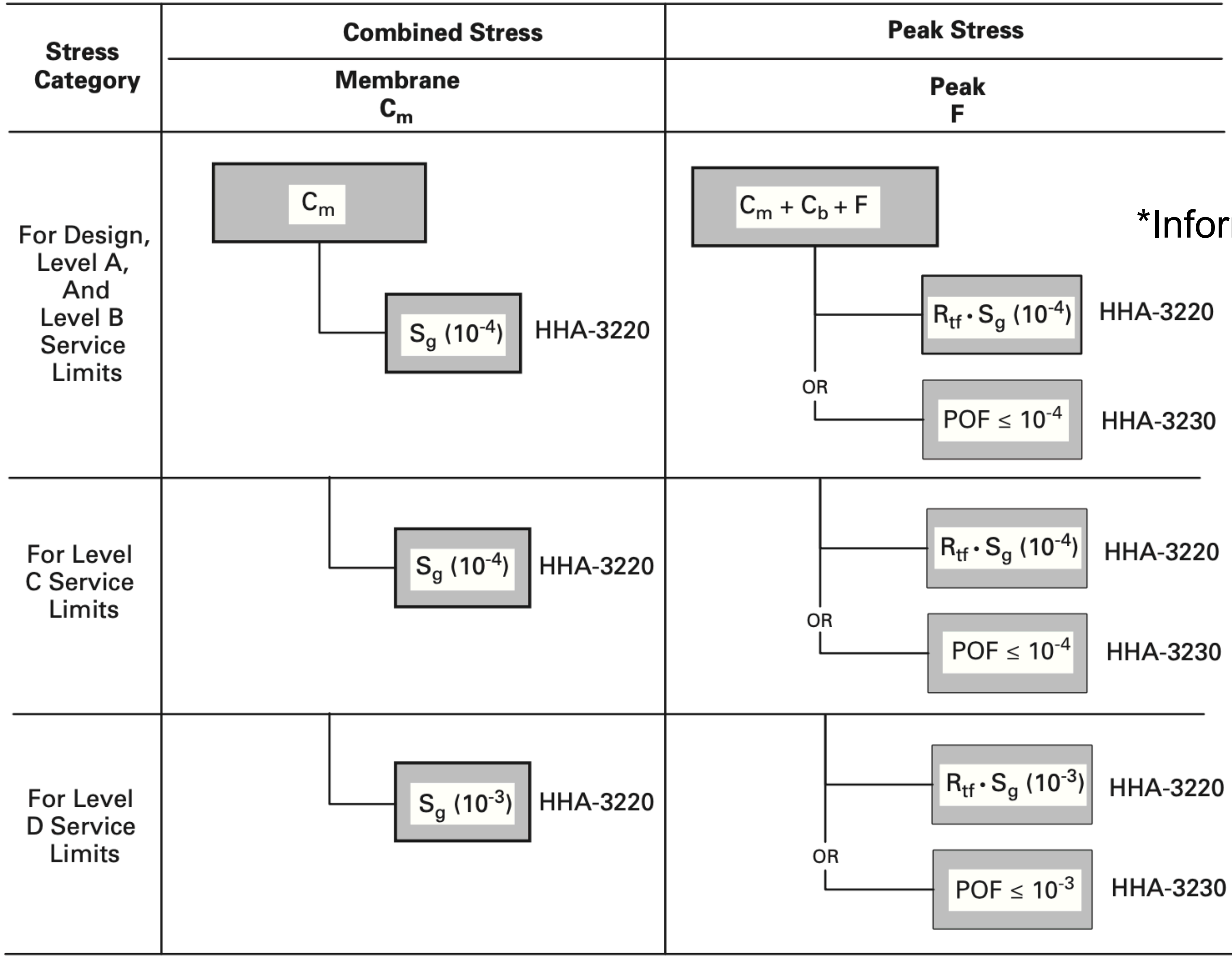
HHA-3214.5 Membrane Stress. Membrane stress is the component of normal stress (HHA-3214.3) that is uniformly distributed and equal to the average of stress across the thickness of the section under consideration.

Simplified Assessment Checks:

1. MS < Allowable tensile stress
2. PES < Allowable flexural stress

*note allowable stresses are fixed by grade and component SRC, however we wouldn't put this in the Code because graphite material properties may change

Figure HHA-3221-1
Design Allowable Stresses Flowchart for SRC-1 Graphite Core Component

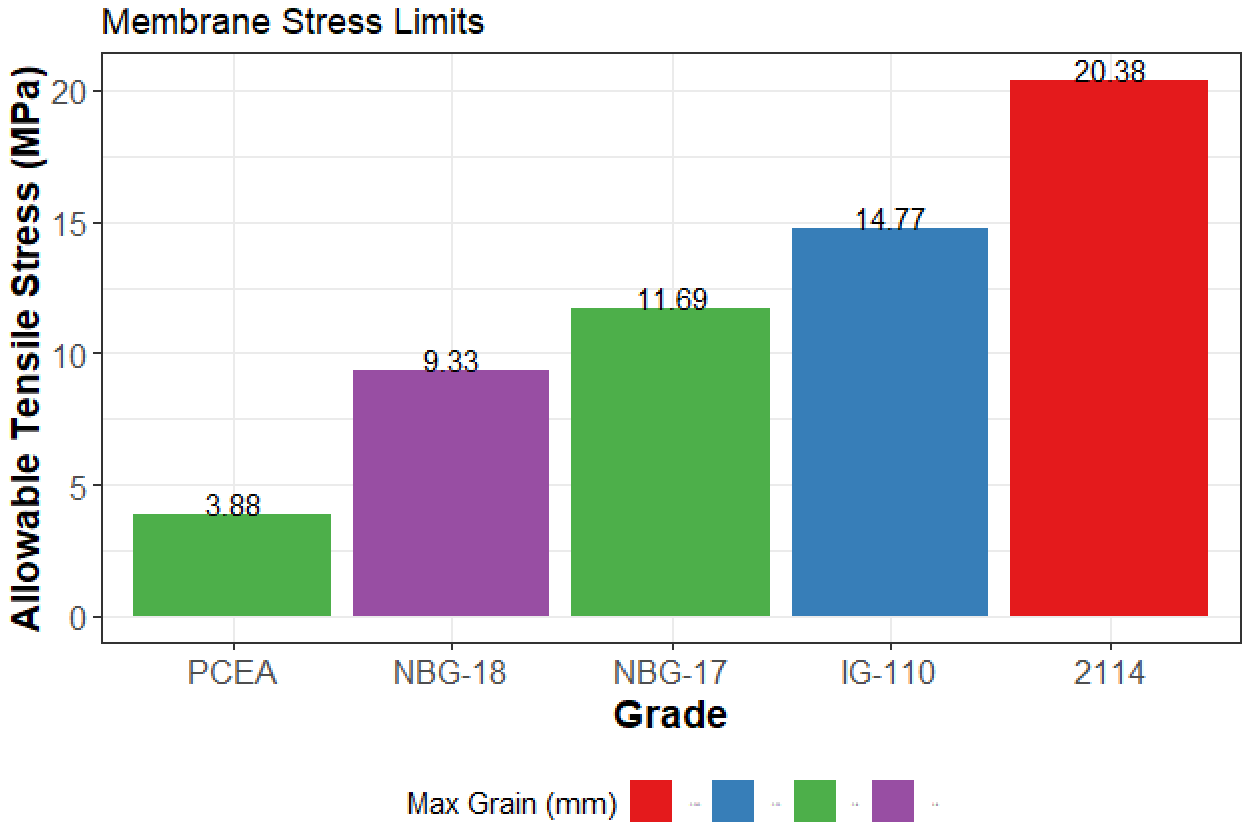


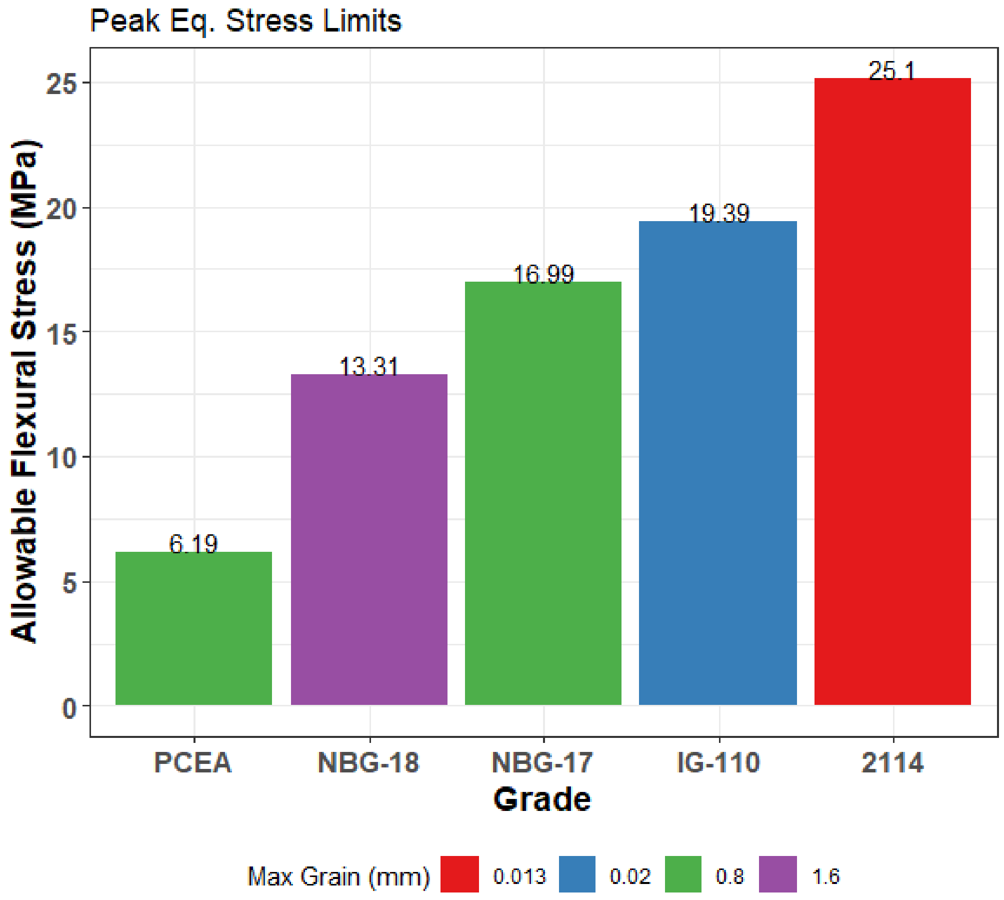
GENERAL NOTE: This only defines the allowables for SRC-1 components

*Information taken from [8].

ECHNOLOGIES

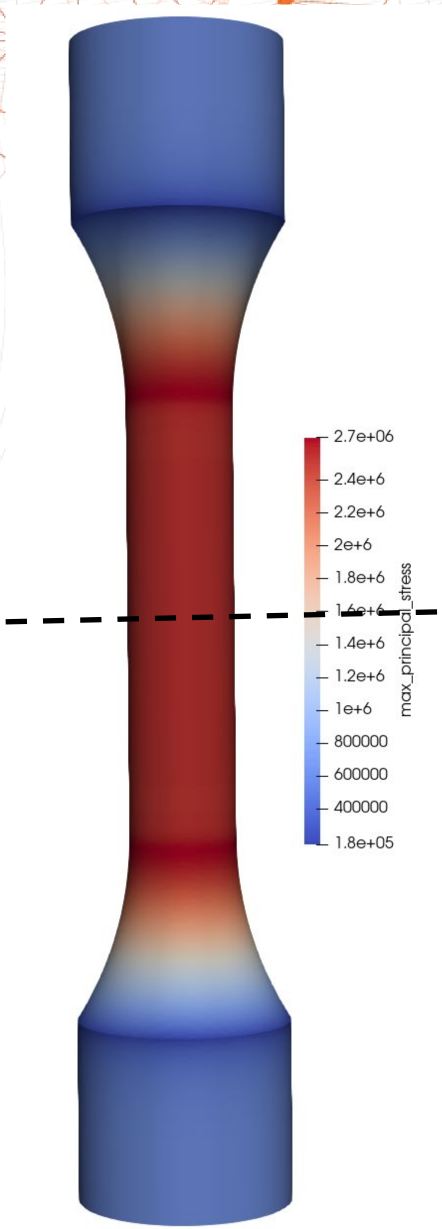
Simplified Assessment SRC-1 Stress Limits





Note: Simplified assessment limits are FIXED by GRADE and component SRC, they do not change by component stress distribution

DEFINING (INTERPRETING) "FAILURE" PER THE SIMPLIFIED ASSESSMENT



Peak Equivalent Stress

Cross sectional area, A

"THEORETICALLY" = "PRACTICALLY"

FULL ASSESSMENT

(2f)

(f) For each integration point, calculate the equivalent stress resulting from the three principal stresses using the equation in HHA-3213. This is designated σ_{vi}, the point equivalent stress.

(g) The following stress-volume integral is to be completed over the Graphite Core Component:

(1) Rank the integration volumes in decreasing order of the point equivalent stress (σ_{vi}).

(2g) (1)

(2g) (2)

Calculate Moving Threshold Value

$$S'' = S'$$

If max stress is higher then characteristic strength

$$S'' = \frac{\sigma_{max}}{S'_{c0.05}} S'$$

Else calculate the moving threshold

Full Assessment: Stress averaging through volume grouping, smearing the stress distribution

(3)

Truncate the stresses below the adjusted threshold parameter

$$X_i = \left[\frac{\sigma_{vi} - S''}{S'_{c0.05} - S''}\right]^{m'_{0.05}}$$

Calculate the exponential stress value

(4)

V_m AND Δ

Grouping based on volume and exponential stress change

Both conditions must be met

$$V_{\mathrm{I,\ II,\ III,}\ldots} > V_m$$

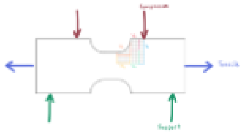
Volume

$$V_m = \left[\frac{\pi}{2} \times \left(\frac{K_{IC}}{\sigma_m}\right)^2\right]^3$$

The Process zone volume is calculated

$$\frac{\max.(X_{\mathrm{I,II,III}\ldots}) - \min.(X_{\mathrm{I,II,III}\ldots})}{\min.(X_{\mathrm{I,II,III}\ldots})} \geq \Delta$$

Delta = 20%



Volume grouping

(5)

$$L_I = \exp\left[-\left(\Sigma X_i \times \frac{v_i}{V_I}\right)\right]$$

Probability of survival for groups

Calculate probability of survival and probability of failure

$$L = \prod_I L_I$$

(6)

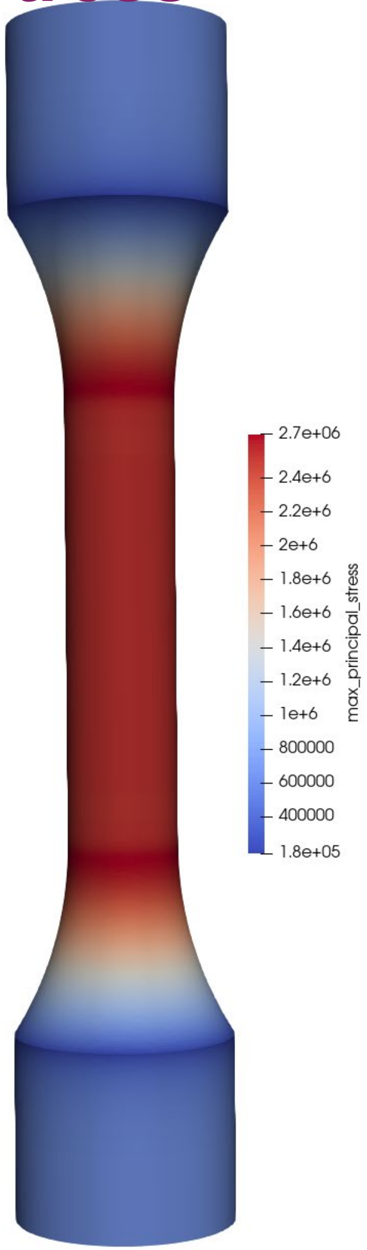
$$PoF = 1 - L$$

(7)

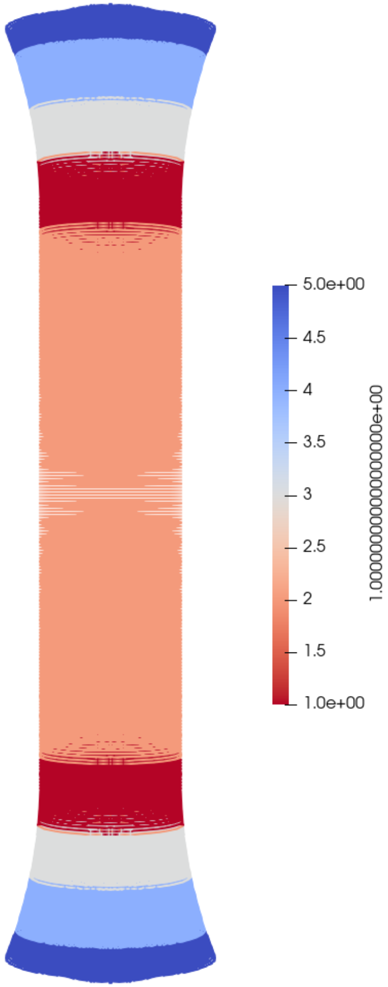
*Information taken from [8].

Mesh

Max Princ. Stress



Groups



Broken tensile specimen

FULL ASSESSMENT CASE STUDY 1: 3D REFLECTOR BLOCK

Reflector block application

- VHTR reflector block
- Temperature profile below
- Proximity to fuel bricks
- For design specification & material qualification (temperature, dose, oxidative environment), see references in [1] H-451 material properties

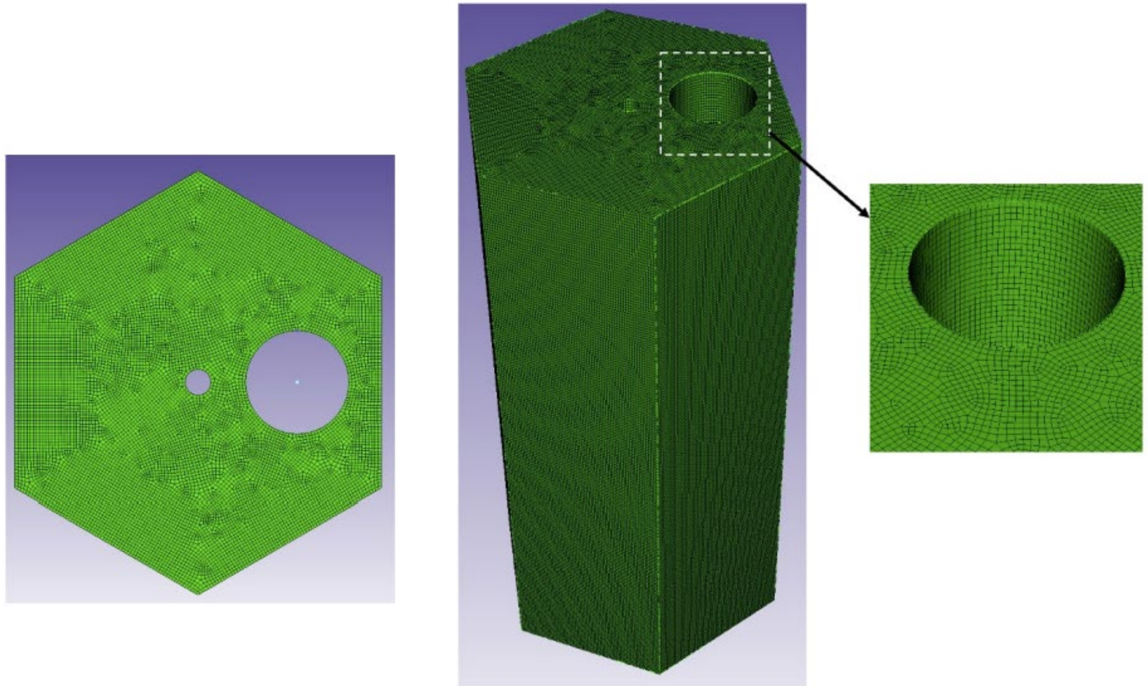
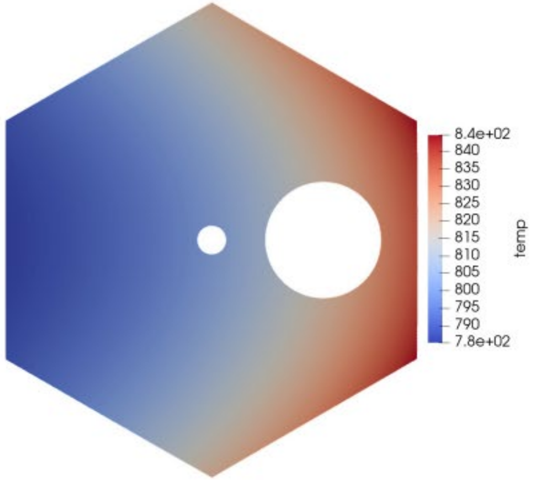
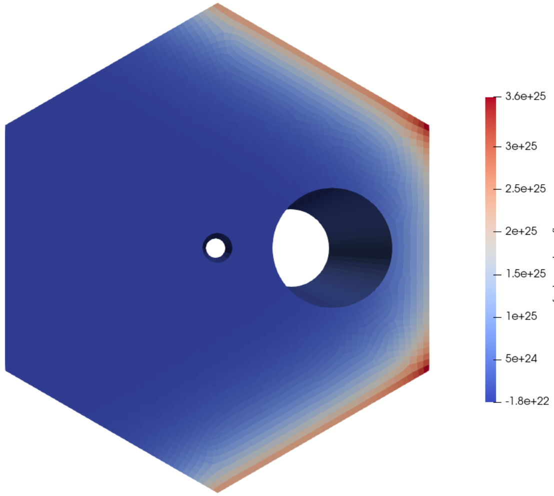


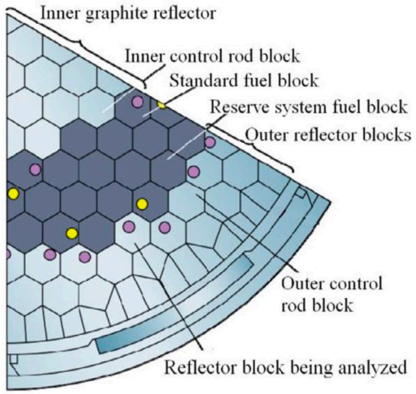
Figure 16: 2D and 3D finite element meshes of the VHTR reflector brick with an enlarged view of the control rod channel on the right.

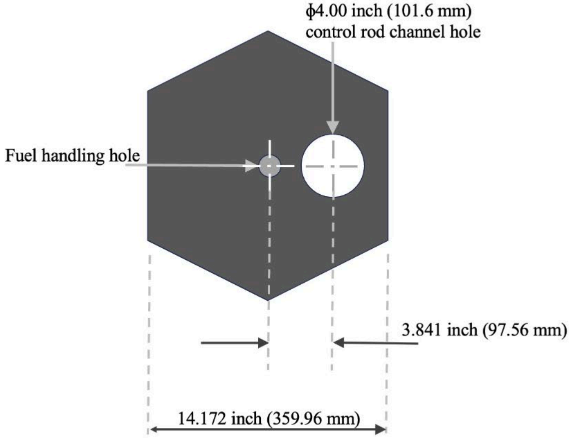


Temp (K)



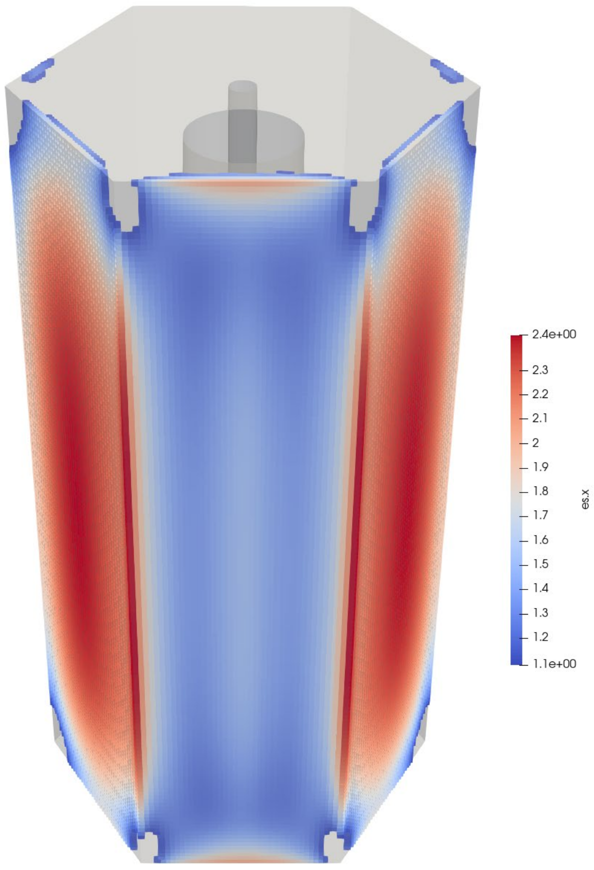
Fluence (n/m^2) after 8 years

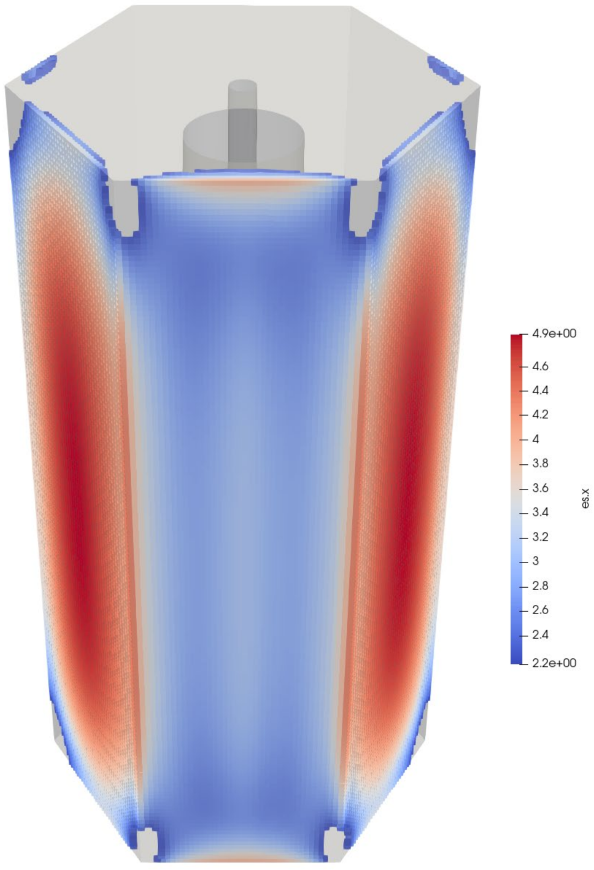


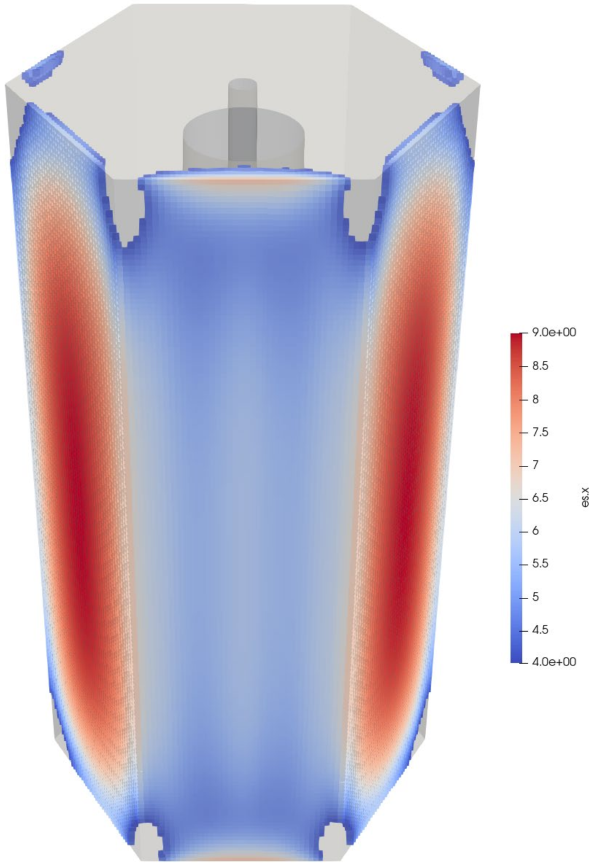


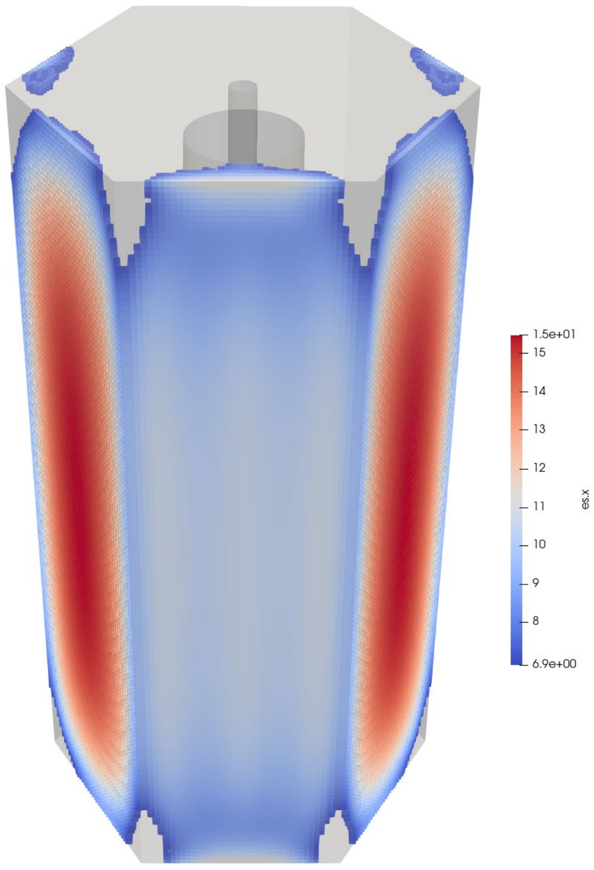
Images taken from [1]

Equivalent Stress Distributions Years 1,2,4,&8





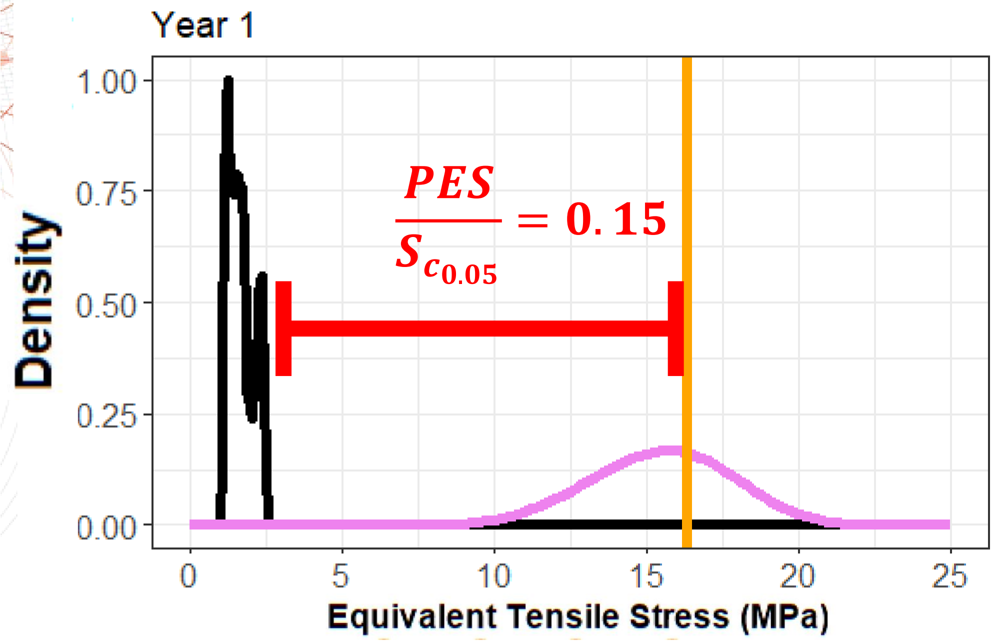




Full Assessment

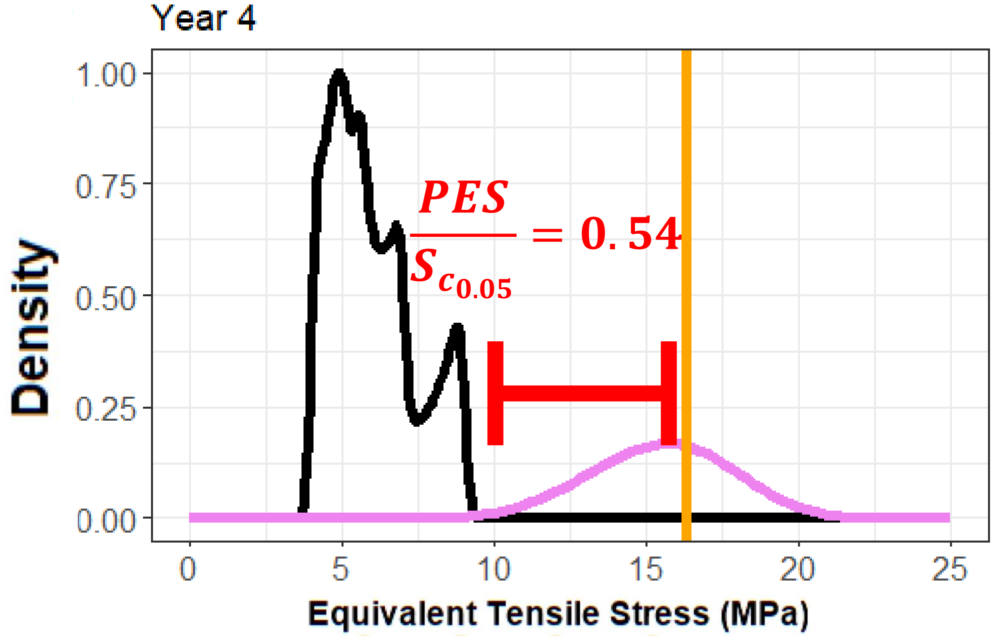
- Convert internal FE stresses to equivalent tensile stresses
- Threshold reduction step
  - Adjust strength distribution based on peak equivalent stress
- Remove elements with equivalent tensile stresses below the original threshold
  - Original mesh: 625,650 elements (coarsened relative to [1] for efficiency)
  - Truncated mesh: 47,116 elements
  - 7.5% of the elements remain for analysis after year 8

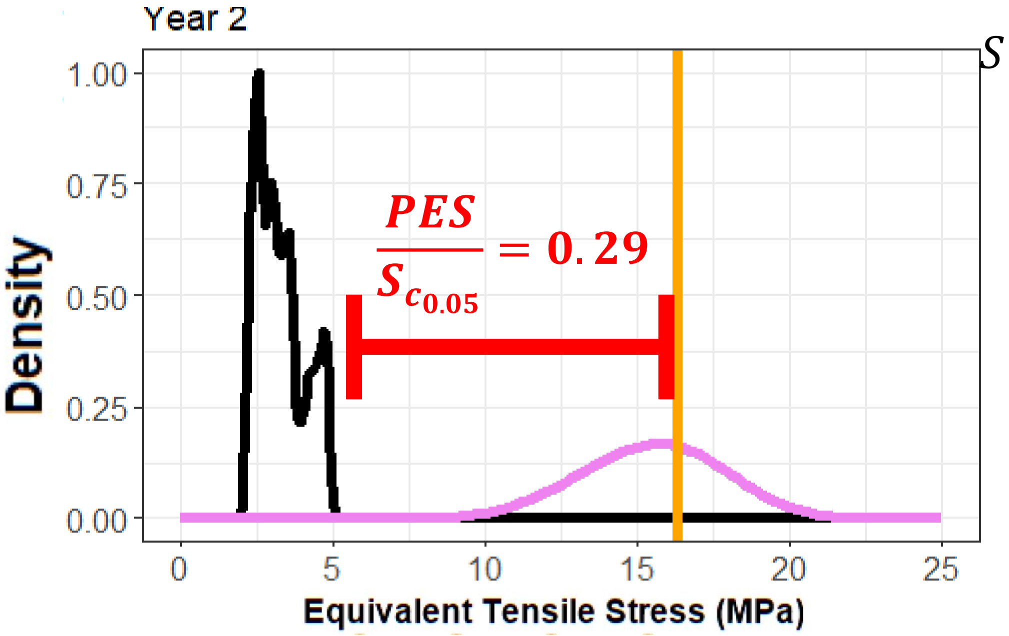
Threshold reduction: Years 1,2,4,&8; $S' = 7.26\ MPa$



$S'' = 1.09$

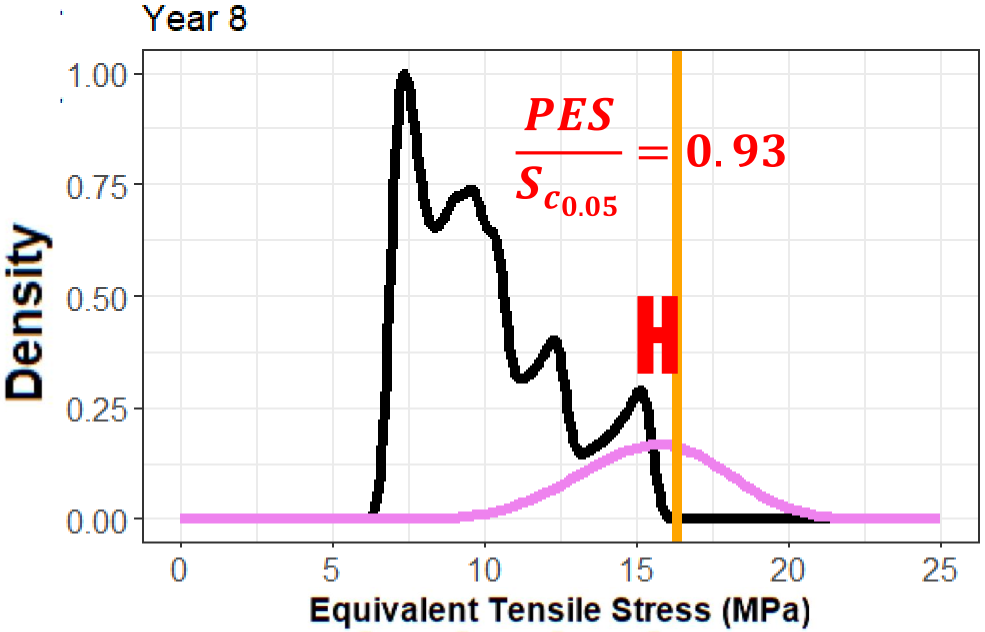
$S'' = 4$





$S'' = 2.16$

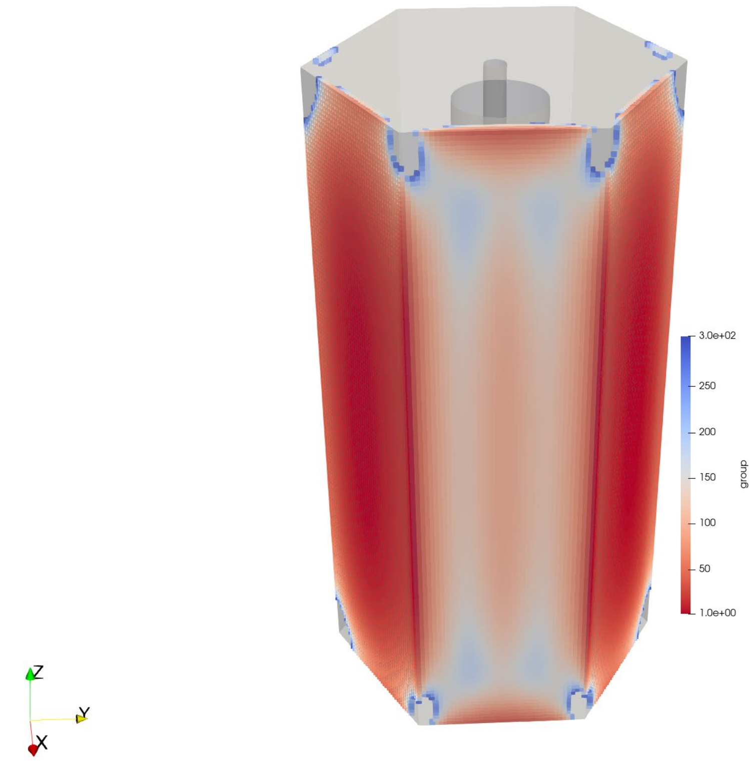
$S'' = 6.88$



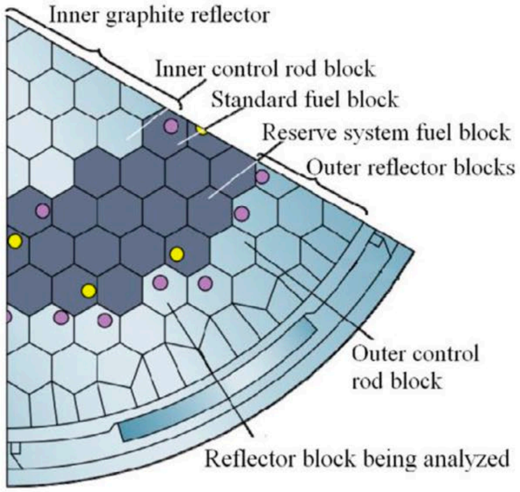
KEY POINTS

- Component stress distribution is closer to the original strength distribution each subsequent year
- As a consequence, the threshold is reduced **less** each subsequent year
- Components with larger peak stresses will be compared to stronger strength distributions, for the same material
- Components with lower peak stresses will be compared to weaker strength distributions, for the same material
- The threshold reduction based on the component's peak equivalent stress makes it harder to qualify components with low peak stresses (almost a penalty)
- However, the penalty is necessary because there is no lower bound used for the threshold parameter and for the lack in ability to capture the disparate flaw mode

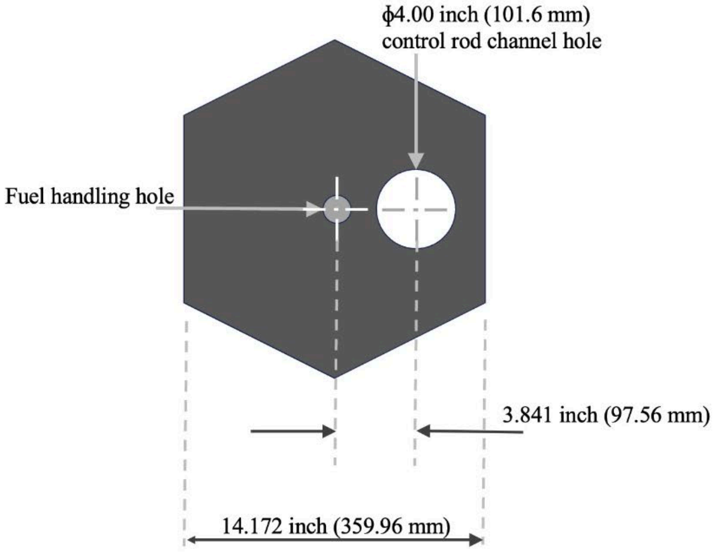
Groups



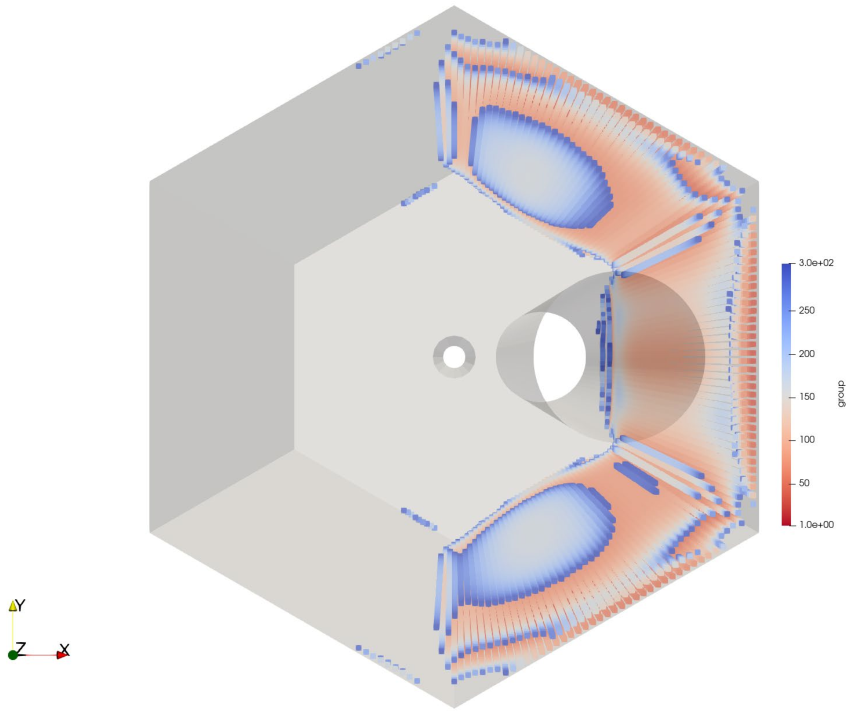
3.0e+02
250
200
150
100
50
1.0e+00
group
Z
Y
X



Inner graphite reflector
Inner control rod block
Standard fuel block
Reserve system fuel block
Outer reflector blocks
Outer control rod block
Reflector block being analyzed

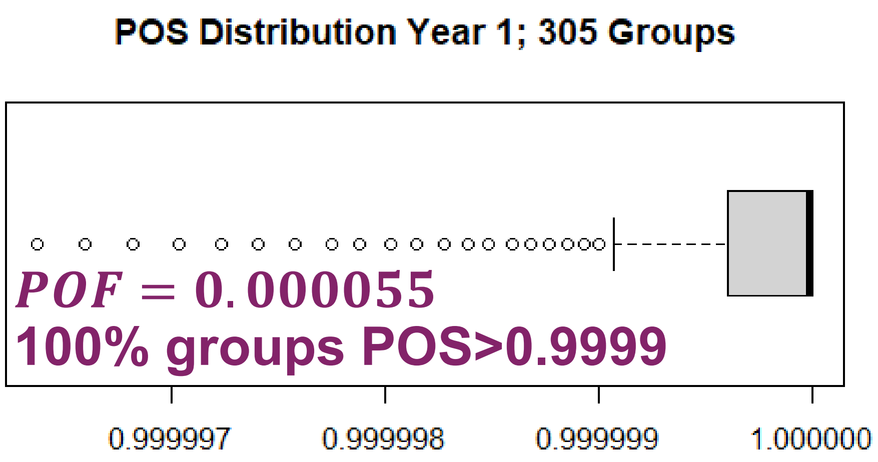


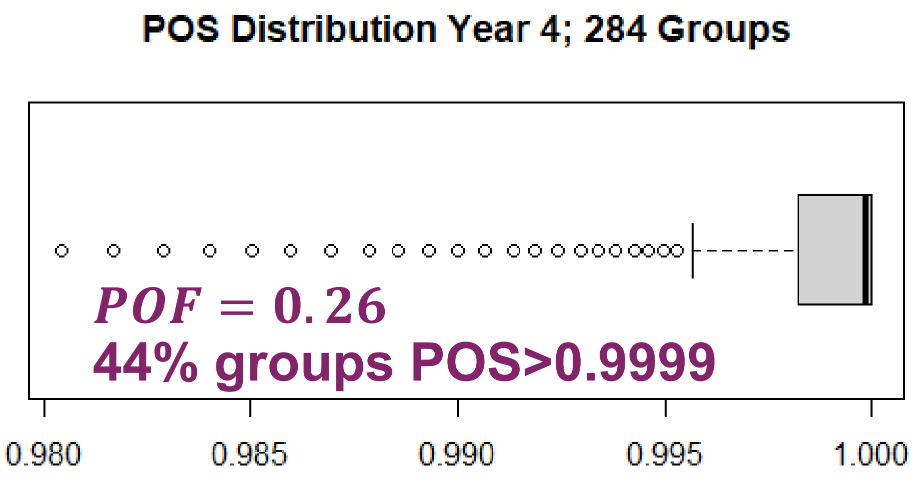
ϕ4.00 inch (101.6 mm) control rod channel hole
Fuel handling hole
3.841 inch (97.56 mm)
14.172 inch (359.96 mm)

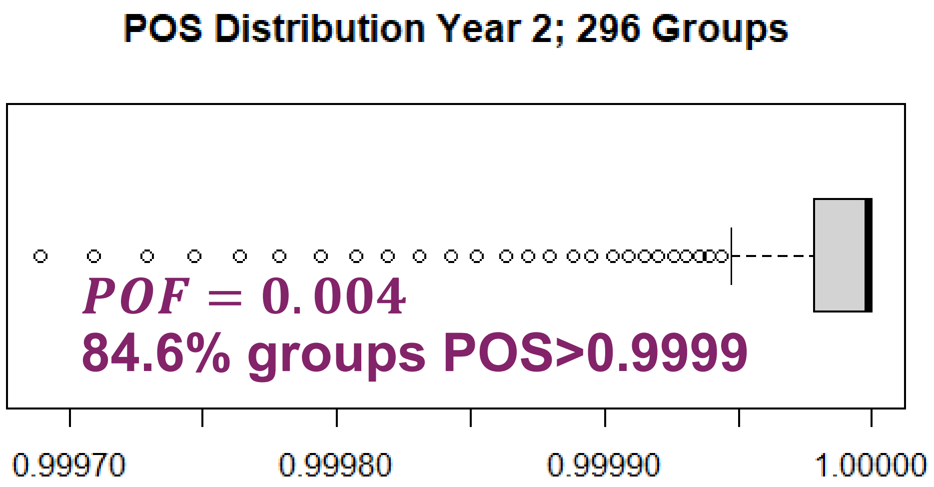


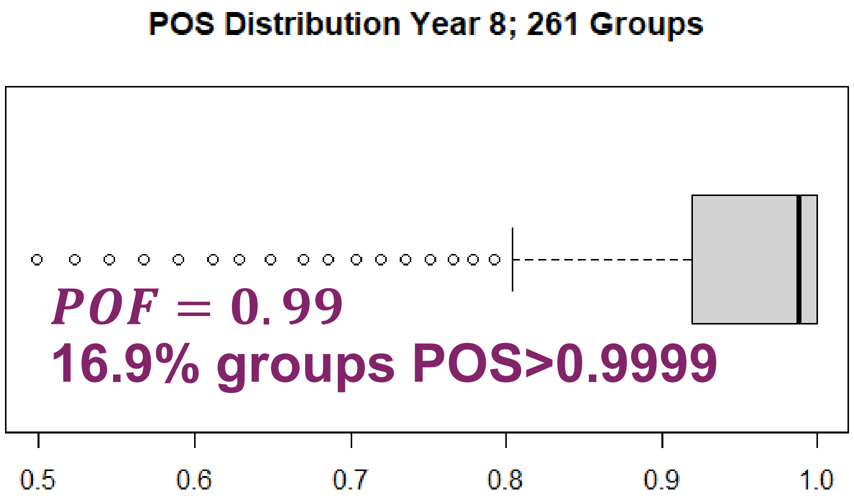
3.0e+02
250
200
150
100
50
1.0e+00
group
Y
Z
X

Why is the reflector block failing the assessment after 2, 4, & 8 years?

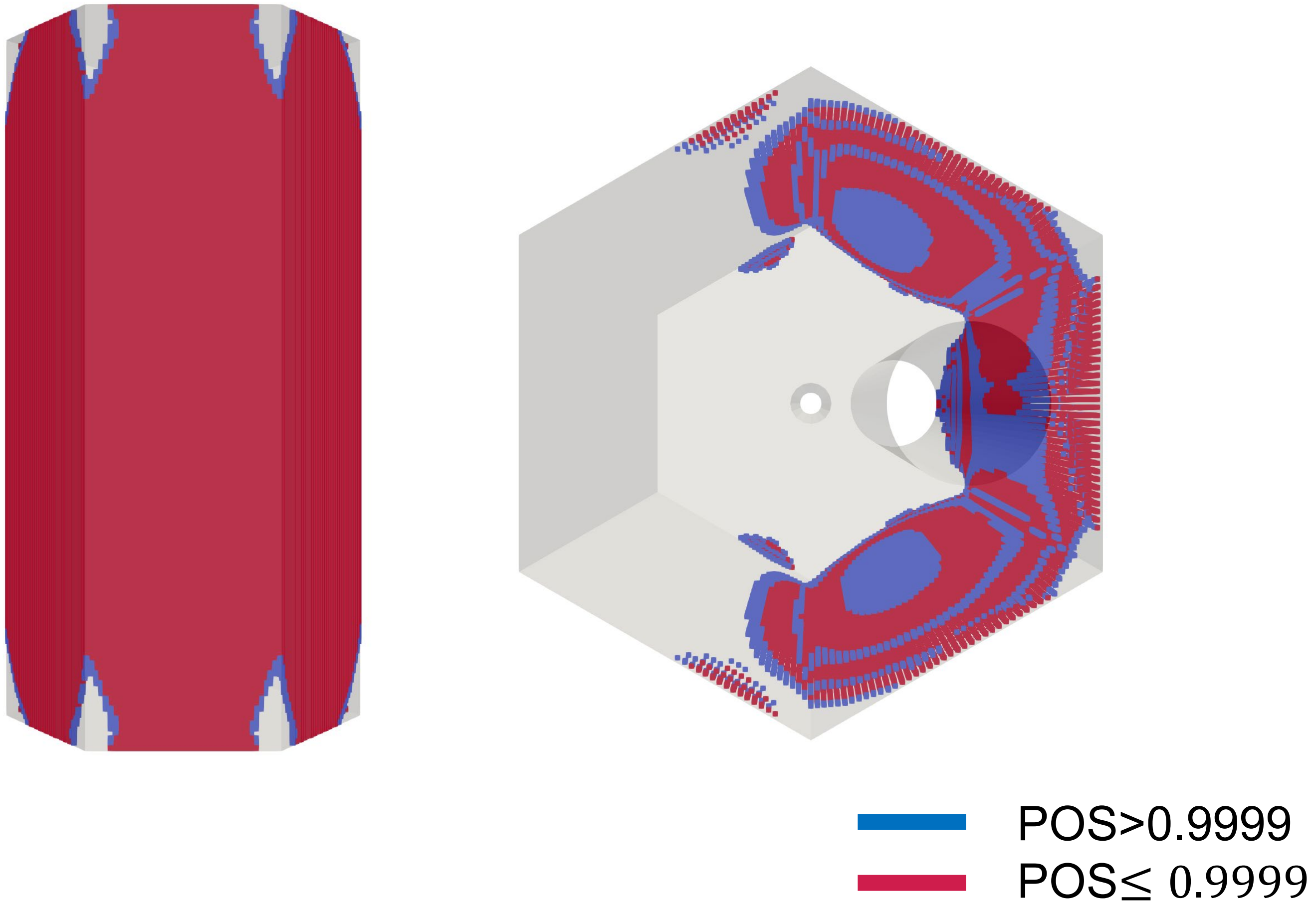


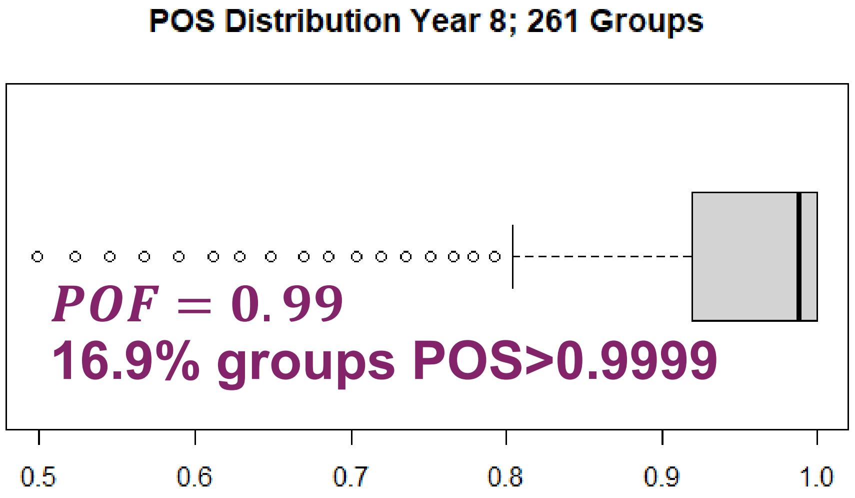




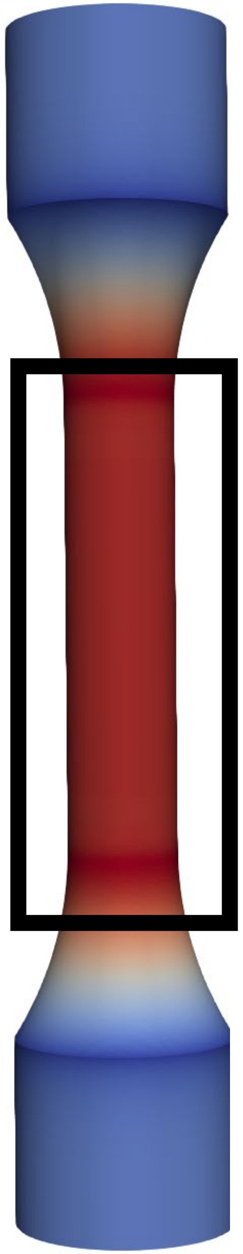


Visualizing POS output for Year 8





DEFINING “FAILURE” PER THE FULL ASSESSMENT



“THEORETICALLY”

VS.

“PRACTICALLY”

Interpreting the full assessment:
Why did this component fail the full assessment?

- THEORETICALLY: THERE IS ONE GROUP THAT IS THE WEAKEST GROUP, THAT CAUSES THE ENTIRE COMPONENT TO “FAIL THE ASSESSMENT”
- PRACTICALLY: IN THIS CASE, THE FRACTION OF GROUPS WITH HIGH POS HAD TO BE LARGE ENOUGH FOR THE COMPONENT TO PASS, LIKELY TO BE TRUE FOR ALL COMPONENTS WITH MANY GROUPS

Interpreting the full assessment:
Why might a general component fail the full assessment?

- NO GENERAL RULE, REASON COMPONENT FAILS WILL VARY BY COMPONENT AND STRESS DISTRIBUTION
- PRACTICALLY:
  - LARGE COMPONENTS WITH MANY GROUPS WILL BE MORE DIFFICULT TO PASS FULL ASSESSMENT, REGARDLESS OF STRESS DISTRIBUTION
  - SMALL COMPONENTS WITH HIGH STRESS CONCENTRATORS WILL BE DIFFICULT TO PASS FULL ASSESSMENT
  - OTHER GENERAL RULES TBD?

CONCLUSIONS

- ASME nuclear graphite component design Codes provide semi-probabilistic approaches to determining whether a component is suitable to be used in a nuclear reactor
- The suitability is a function of both the graphite grade's mechanical properties and the component's design, stress distribution, and SRC classification
- Two design by analysis options: the full and simplified assessments
- Requires both experimental data and FE stresses as inputs to assessments
- Margin is built in by using ultimate tensile strengths, accounting for sampling uncertainty in the graphite's tensile strength distribution, and only allowing lower POFs on the material reliability curve based on the component's function in supporting the core
- The outcome of the assessments is whether the component passes or fails the given assessment
- Subsequent analysis can be done to try and understand why the components fail the assessments, but this must be done on a component-by-component basis
- ASME provides NO guidelines to determine whether or not a group "fails", nor whether a group "cracks"
- Please refer to [1] for an example as to how others are determine when/where cracks initiate
- The assessments do not account for changes in mechanical strength as a function of oxidation/irradiation (yet)
- The assessments still have many issues that are being addressed by the Design TG

OVERVIEW

Figure KK-10120-1
Typical Graphite Core Component Design Sequence

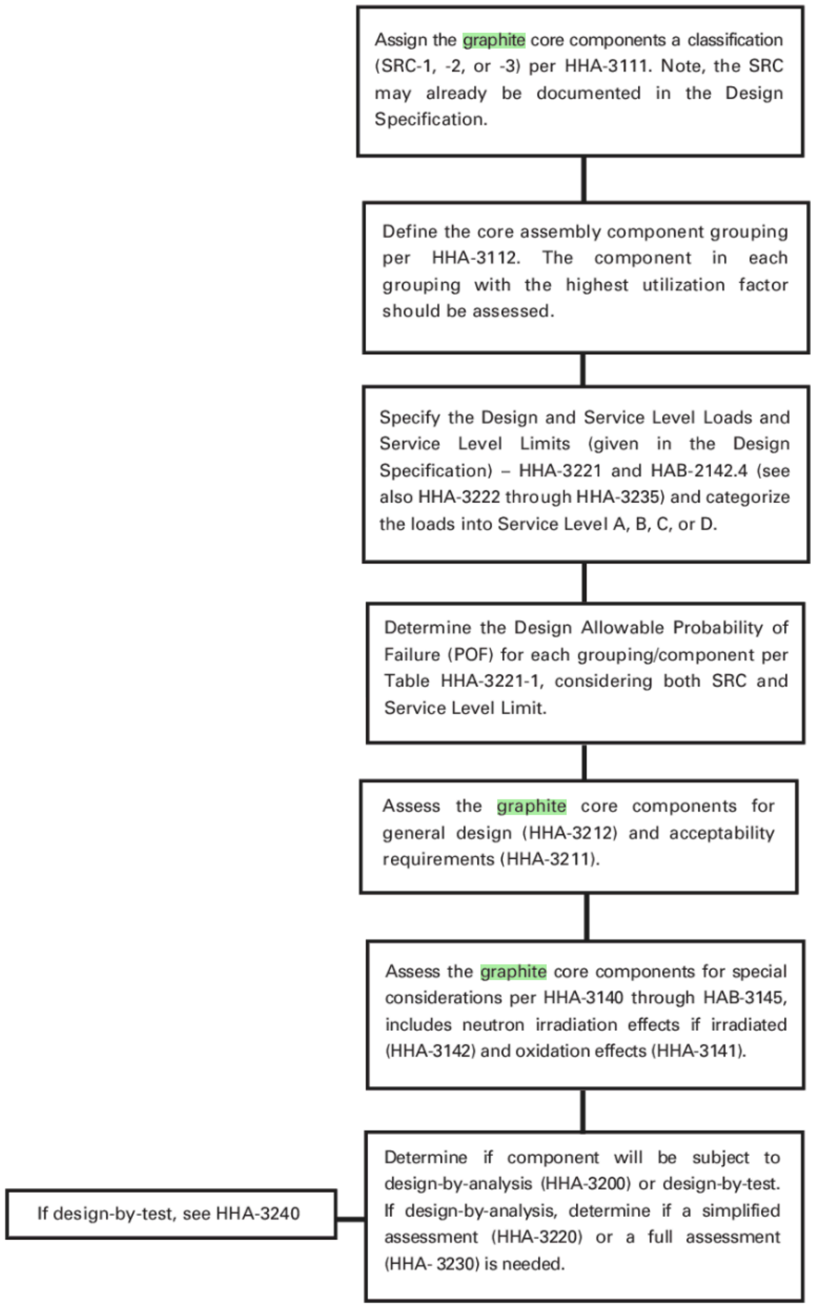
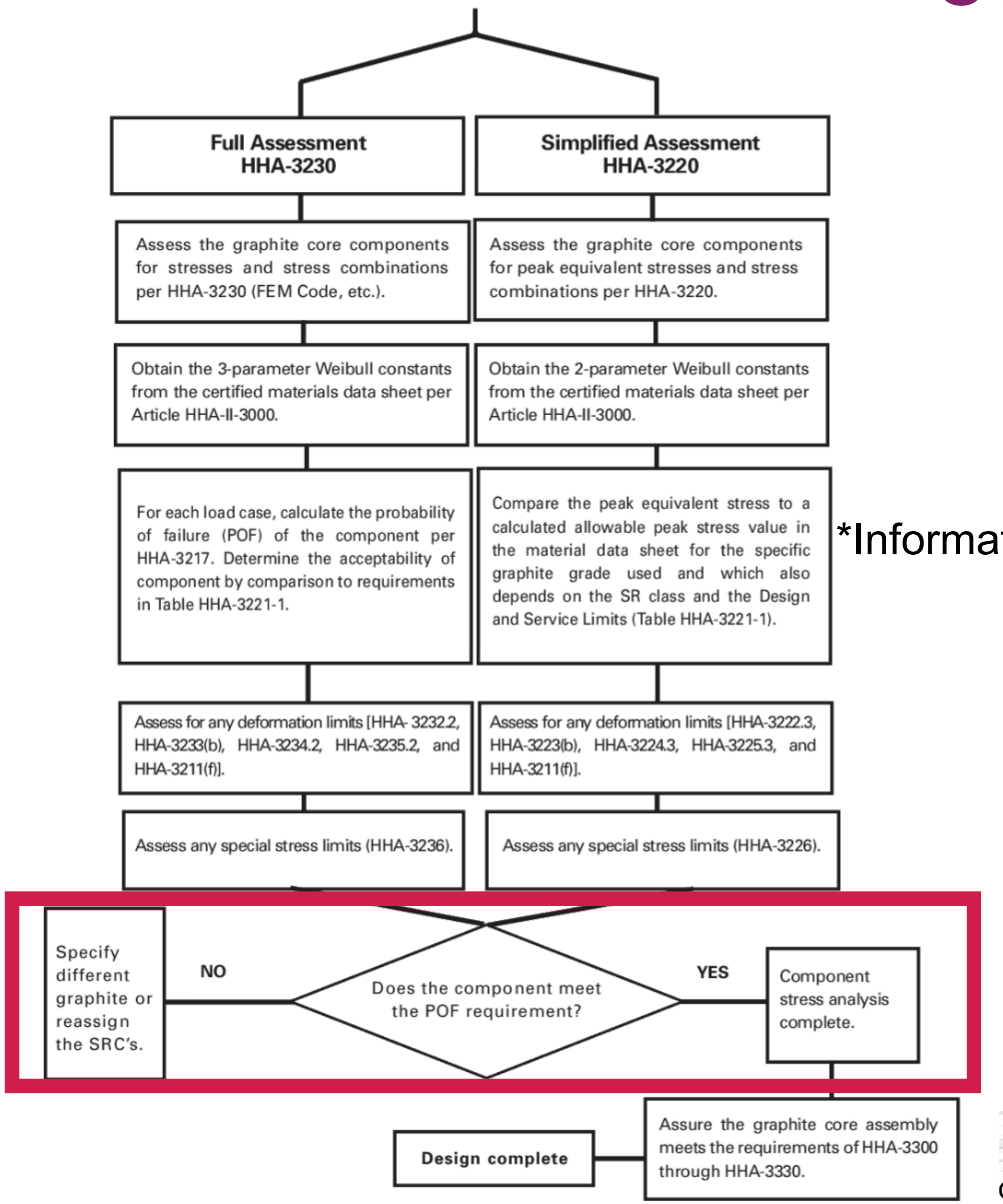


Figure KK-10120-1
Typical Graphite Core Component Design Sequence (Cont'd)



*Information taken from [8].

WHAT THE DESIGN TASK GROUP IS CURRENTLY WORKING ON

- Justifying the shape parameter update when the threshold is reduced in the full assessment
- Fixing the grouping rules in the full assessment
- Understanding where the SRC limits come from
- Correct interpretations of assessments
- Assessing volume effects on splitting disk strengths relative to dogbones
- Clarifying terminology
- Assessing margin

OTHER POTENTIAL INTERESTING WORK

- Compare ASME BPVC design guidelines to other Codes
- Experimental failure data from real size components (AGR block slices?)

SPECIAL THANKS TO THE DESIGN TASK GROUP, WHOSE MEMBERS ARE ALL WORKING COLLABORATIVELY TO CORRECT AND UNDERSTAND THE ASME GRAPHITE COMPONENT DESIGN CODES. THIS WORK COULD NOT BE COMPLETED WITHOUT THEIR CONTRIBUTIONS.

THANK YOU FOR YOUR TIME

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