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ASME BPVC Section III Division 5 Application

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Changing the World's Energy Future

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ADVANCED REACTOR TECHNOLOGIES

Outline

Using AMSE assessments

- Simplified assessment
  - overview
  - Implementation
  - Limitation and important considerations
  - Example problems
- Full Assessment
  - overview
  - Implementation
  - Limitation and important considerations
  - Example problems

Limitation of the code

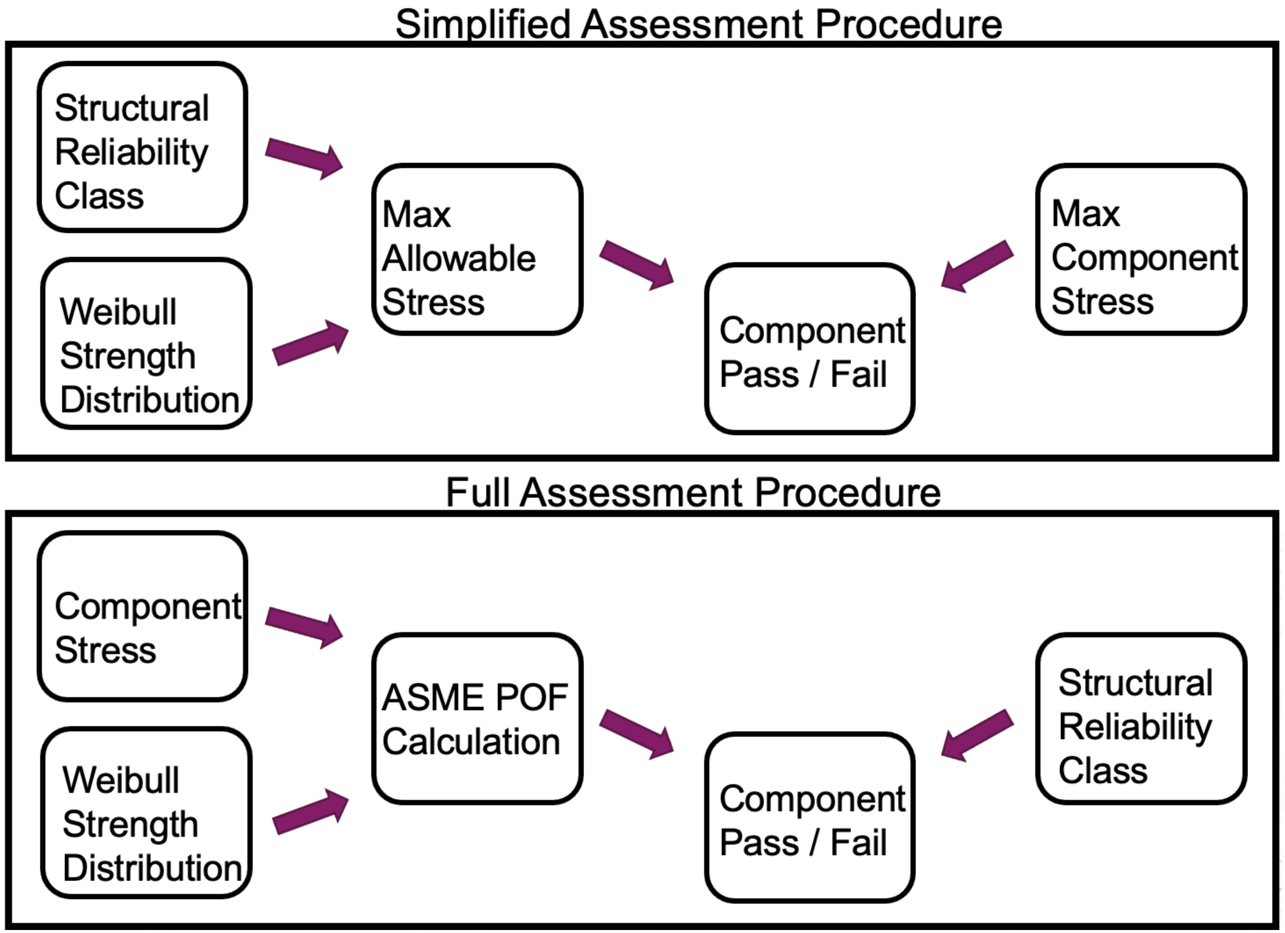
Application of Design by Analysis

The Simplified and Full assessments are similar in that they both require:

1. Component stresses (FEA analysis)
2. A Weibull distribution of strength
3. A structural reliability class

Both methods are aimed at determining if a crack will form in the component.

The main differences come from the fact that the full assessment considers the full stress distribution in a component, and the simple assessment only considers the maximum stress. This causes the simplified assessment to be more conservative



Assessment Pitfalls

While implementation of full and simplified assessments is relatively straight forward there are many pitfalls which can make use of the methodologies not straight forward. These include:

1. Ambiguities in the Code
   - How to determine parameter used in the assessment
   - Disconnect between variable names and presented equations
2. Variation between editions of the ASME code
   - Which edition of the Code should be implemented
3. Limitations in the code
   - Homogeneous material property implication
   - Mesh size requirements
   - Attaining material property data

How to apply the code and avoid these pitfalls (when possible) is discussed in the following slides.

A python code was written to implement the ASME design methodologies, but it has not been distributed because it is the presenter's opinion that implementing the code is simple and a provided code may act as a black box which would promote falling into the pitfalls listed above.

Example Problems

In this presentation on application of the ASME code we will revolve around 2 test problems.

Problem 1 Setup:

1. A graphite component with the geometry shown right is under a tensile load.
2. The component is not expected to experience degradation and is not essential to safety.

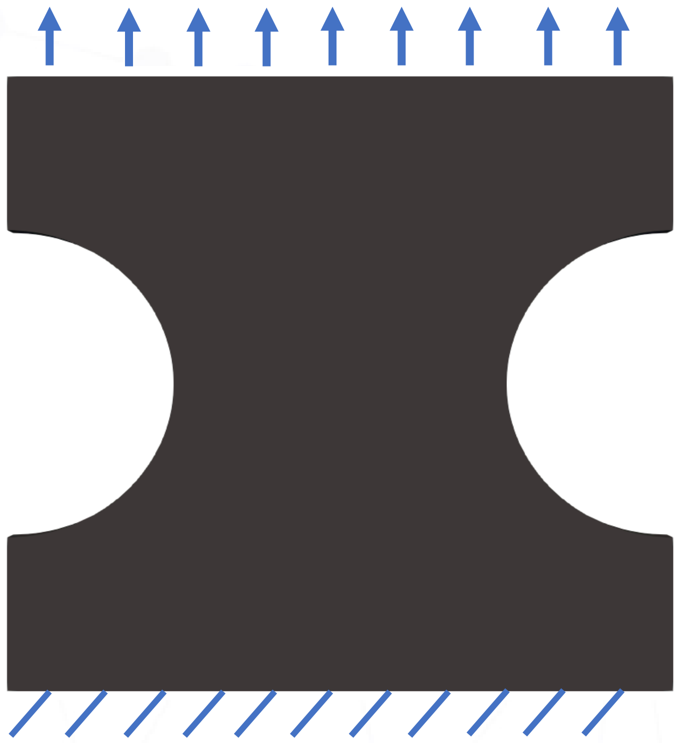
Problem 2 Setup:

1. A graphite component with the geometry shown right is under a tensile load.
2. The component will be degraded (from oxidation) and is essential to safety.

Purpose of Problems:

1. Go through how to apply the code
2. Compare the simplified and full assessments
3. Highlight limitations of the code

Problem Geometry



Required Inputs for the Problem (Material)

The simplified and full assessments require slightly different materials property inputs.

In this example problem we will assume that the material is IG-110.

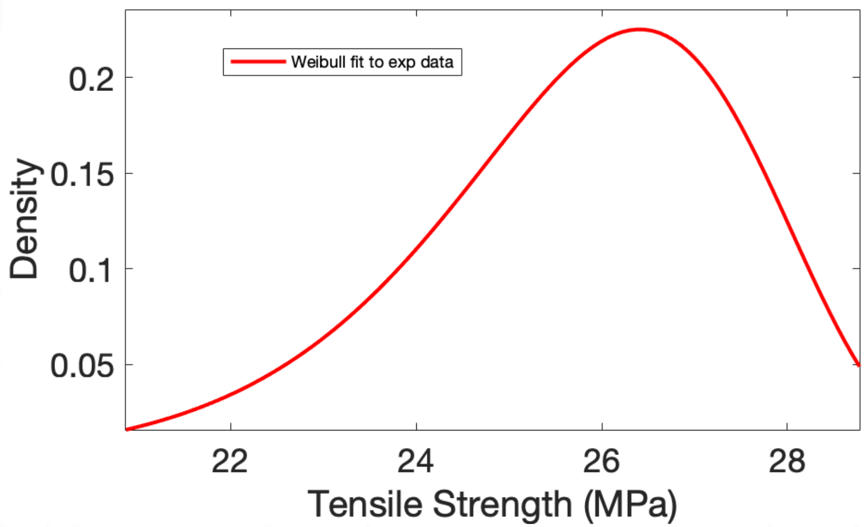
Simplified Assessment:

1. 2-parameter Weibull fit to tensile data
2. Number of tensile specimens tests
3. Mean flexural strength
4. Mean tensile strength
5. Mean compressive strength

Full Assessment:

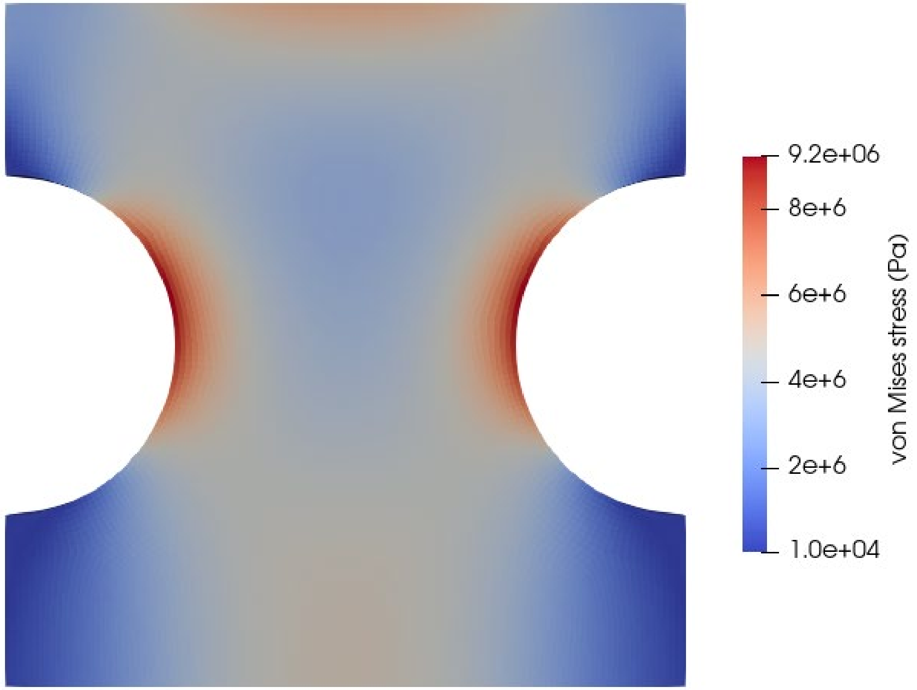
1. 3-parameter Weibull fit to tensile data
2. Experimental tensile data
3. Mean compressive strength
4. Mean tensile strength

Weibull fit to IG-110 tensile data



Required Inputs for the Problem (Modeling)

The ASME methodologies determine a pass/fail based on a stress distribution. The assessments uses an equivalent stress which is based on maximum deformation energy theory



An equivalent stress at each element is computed.

$$\sigma_{eq} = \left(\hat{\sigma}_1^2 + \hat{\sigma}_2^2 + \hat{\sigma}_3^2 - 2\nu(\hat{\sigma}_1\hat{\sigma}_2 + \hat{\sigma}_1\hat{\sigma}_3 + \hat{\sigma}_2\hat{\sigma}_3)\right)^{.5}$$

where

$$\hat{\sigma} = \begin{cases} \sigma_i & \sigma_i > 0 \\ \frac{\sigma_i}{R_{tc}} & \sigma_i \leq 0 \end{cases}$$

Simplified Assessment: Application

How to implement the simplified assessment (HHA-3220)

The simplified assessment compares an allowable stress to the peak equivalent stress in a component.

The steps for the simplified assessment can be summarized as follows:

1. Determine the allowable stress based:
   - Determine POF based on SRC and design level
   - Compute lower-bound Weibull parameters

$$m_{95\%} = \frac{m^*}{t(n; 0.95)} \qquad S_{c95\%} = S_c^* \times \exp[-t'(n; 0.95)/m^*]$$

   - Compute S_g and allowable stress based on loading stress type

$$S_g(\mathrm{POF}) = S_{c95\%}\left(-\ln(1 - \mathrm{POF})\right)^{\frac{1}{m_{95\%}}}$$

2. Compare the highest equivalent stress (peak) to the allowable stress to determine pass/fail.

Table HHA-3221-1
Design Allowable Probability of Failure

SRC	Design	Service Limit 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}

Figure HHA-II-3100-1
Correction Factor T of the Shape Parameter M of Two-Parameter Weibull Distribution (γ = 0.95)

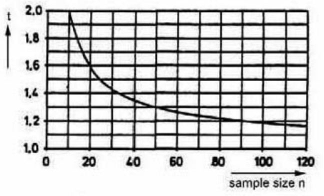
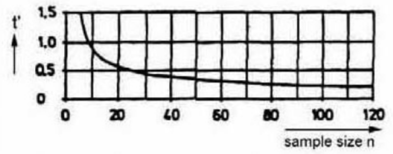


Figure HHA-II-3100-2
Correction Factor T' of the Characteristic Value S_c of Two-Parameter Weibull Distribution (γ = 0.95)



Simplified Code Application

Implementing the simplified assessment for the two example problems we find the following:

Problem 1

Input load (MPa)	Pass/fail
3	Pass
4	Pass
5	Pass
6	fail
7	fail
8	fail

Problem 2

Input load (MPa)	Pass/fail
3	Pass
4	Pass
5	Pass
6	fail
7	fail
8	fail

Full Assessment (HHA-3217)

Once the equivalent stresses and 3-parameter Weibull (HHA-II-3200) have been determined the following step are taken in the full assessment to determine the POF:

1. "Rank the integration volumes in decreasing order of the point equivalent stress".
2. Recompute the threshold value if the maximum equivalent stress is below the characteristic strength (S_{c095}) by $S_0' = S_0 * \sigma_{max}/S_{c095}$. Then truncate equivalent stresses to those above S_0'.
3. Compute χ values each volume

$$X_i = \left[\frac{\sigma_{vi} - S'_0}{S_{c095\%} - S'_0}\right]^{m_{095\%}}$$

4. Group the χ based on minimum summed volume and stresses
5. Compute probability of failure as shown below

Theory

$$V_m = \left[\frac{1}{2\pi}\left(\frac{K_{IC}}{\sigma_m}\right)^2\right]^3$$

Current Code

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

NRC Endorsed code (2017)

$$V_m = [10 * grain]^3$$

Group probability of survival (POS)

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

Combined POS

$$L = \prod_I L_I$$

POF

$$\mathrm{POF} = 1 - L$$

Full Assessment Full Assessment Pitfalls

There are ambiguities in the Code which still need to be addressed:

1. Which is the appropriate volume grouping to use?

NRC Endorsed code (2017)	Theory	Current Code
$V_m = [10 * grain]^3$	$V_m = \left[\frac{1}{2\pi}\left(\frac{K_{IC}}{\sigma_m}\right)^2\right]^3$	$V_m = \left[\frac{\pi}{2}\left(\frac{K_{IC}}{\sigma_m}\right)^2\right]^3$

2. Should the other Weibull parameters be updated if the threshold is updated (step 2)?
   - If the answer is yes then a designer needs to have the experimental data points not just a Weibull fit.

3. Should the 3-parameter Weibull parameters be lower bounds or MLEs?
   - The equations in HHA-II-3200 are for MLEs, but the text and variable definitions both call them lower bound.
   - If they are lower bounds, there is not a method in the code for determining lower bound values.

These questions as well as others still need to be addressed in order to apply the ASME full assessment in a consistent manner.

Full Assessment: Example Problem

If we follow the code using MLEs, and not updating Weibull parameters and using $V_m = \left[\frac{1}{2\pi}\left(\frac{K_{IC}}{\sigma_m}\right)^2\right]^3$

Problem 1

Simplified

Input load (MPa)	Pass/fail
3	Pass
4	Pass
5	Pass
6	fail
7	fail
8	fail

Full

Input load (MPa)	POF	Pass/fail
3	.1	Pass
4	.1	Pass
5	.1	Pass
6	.2	fail
7	.2	fail
8	.2	fail

Problem 2

Simplified

Input load (MPa)	Pass/fail
3	Pass
4	Pass
5	Pass
6	fail
7	fail
8	fail

Full

Input load (MPa)	POF	Pass/fail
3	.1	Pass
4	.1	Pass
5	.1	Pass
6	.2	fail
7	.2	fail
8	.2	fail

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ADVANCED REACTOR TECHNOLOGIES

Full Assessment: Limitations

Application of the ASME code has identified some limitations in the methodology in the Full assessment.

The Full assessment does not account for location.

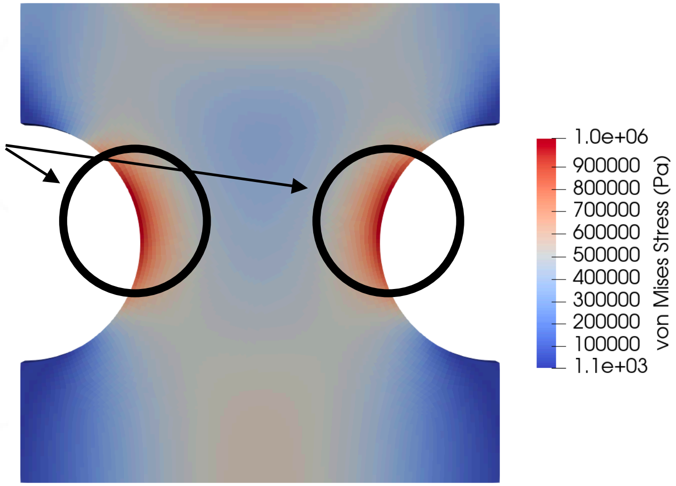
This causes:

1. Volume grouping is location independent.
2. Property gradients are not appropriately account for.
3. Crack formation in a non-critical location is the same a critical location

It is also important to note that acquiring the necessary experimental data is always easily achieved.

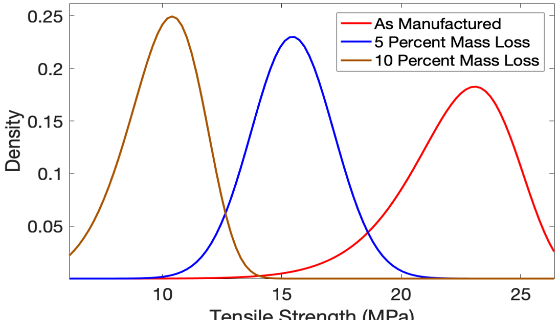
Grouping is done by stress magnitude so multiple locations can be put in one group.

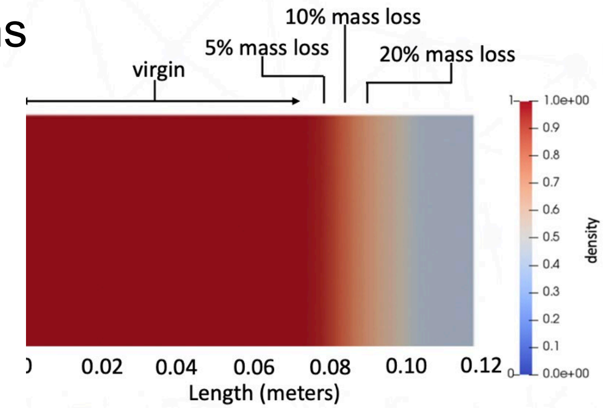
The first group will include elements from multiple locations



Accounting for degradation gradients is not considered in the full assessment

Oxidation Strength Distributions





Considerations: Oxidation

What does the ASME code say on assessing oxidized components?

1. HHA-3141 designates:
   - mass loss gradients must be computed
   - what constitutes oxidized graphite
   - General strength changes for oxidized graphite
   - FEA analysis guidance
   - Combined irradiation and oxidation is beyond the scope of the Code
2. HHA-3215.4 designates that oxidation dependent properties (HHA-2230) shall be used in a stress calculation.

HHA-3215.4 Stress Analysis of Oxidized Graphite Core Components. For oxidized Graphite Core Components (HHA-3141), the effect of oxidation on the dimensions of the Graphite Core Component and the distribution of material properties in the Graphite Core Component shall be considered in the completion of the stress analysis.

Although a method for implementing these stresses in an assessment is not provided

HHA-3141 Oxidation

Graphite Core Components may be oxidized by hydrogen, oxygen, or carbon dioxide in the coolant. The corroding gas mixtures diffuse into the porous structure of the graphite. The weight loss in the Graphite Core Component varies depending on the conditions at which the oxidation occurs and the distance from the surface exposed to the gas flow.

Oxidation analysis shall be carried out in detail to estimate the weight loss profiles of graphite structures, since reaction rates depend on the temperature, reactants, and graphite grade. Assessment of oxidized Graphite Core Components shall comply with (a) through (d) below.

(a) Material is considered oxidized if the weight loss is greater than 1%.

(b) Strength Reduction. The strength (both tensile and compressive) decreases as a function of weight loss as shown in Figures HHA-3141-1 and HHA-3141-2 (or alternatively from the Material Data Sheet HHA-2200). The stress evaluation shall be made according to this relation. The region where strength decreases to less than 50% shall not be credited in the stress evaluation.

(c) Geometry Reduction. The region where the amount of weight loss exceeds 30% shall be regarded as completely removed from the structure for both oxidation and strength calculations.

(d) Combinations of weight loss and irradiation where the resulting strength is lower than the nonirradiated strength are excluded from the scope of these code requirements. Oxidation to high weight loss (>1%) occurring simultaneously with significant irradiation (>0.25 dpa) is excluded from the scope of these code requirements. Note that large-scale oxidation resulting from accidental air or water ingress occurs over a short time scale without significant irradiation of the material and thus still falls within the scope of these rules.

Considerations: Irradiation

What does the ASME code say on assessing irradiated components?

1. HHA-3142 designates:
   - What is irradiated graphite and when do irradiated properties need to be accounted for.
   - "**Materials within the core shall be limited by the range of temperature and fast neutron damage dose over which the material is characterized**".
   - Wigner energy shall be accounted for if the temperature is bellow 473 K.
   - A visco-elastic model shall be used to compute stresses and account for irradiation induced dimensional change, irradiation creep, and irradiation effects on properties.
   - All load shall be accounted for.
2. HHA-3215.3 designates:
   - "The designer is responsible for the accuracy and acceptability of the analysis methods used".
3. HHA-2220 designates:
   - Properties which irradiation affects.

HHA-3142.3 Internal Stresses Due to Irradiation. The internal stresses in irradiated Graphite Core Components [that exceed the dose limits described in HHA-3142.1(c)] shall be calculated. This calculation shall be completed by viscoelastic modeling of the material behavior.

(a) Irradiation-induced dimensional change, creep, and changes in properties (elastic modulus, coefficient of thermal expansion, thermal conductivity) shall be accounted for in this analysis. The interaction between irradiation-induced creep and the coefficient of thermal expansion shall be included in this assessment.

(b) The analysis shall account for stress concentrations resulting from the Graphite Core Component geometry.

(c) The stress analysis shall account for superposition of the stresses resulting from all of the loads that a Graphite Core Component is exposed to simultaneously.

Conclusions and Future Work

Currently the code:

1. Presents multiple methods for assessing graphite components
2. Highlights possible sources which cause property changes and degradation (molten salt is addressed in Article HHA-B-4000, but it is not included in HHA-3000 Design).
3. The simplified and full assessments have limitations and ambiguities which are in the process of being addressed. A workshop on the ASME full assessment is being held August 30-31. People interested in attending should contact Andrea Mack at andrea.mack@inl.gov

Future assessment work:

1. Gradients in the material properties pose a problem for the full assessment. Oxidized graphite is more easily produced and can provide validation data methods which account for material property gradients.
2. Implementing models which account for MSR issues in the stress calculation are needed for assessments.

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