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Revision 1

Graphite Degradation Modeling and Analysis

August 2022

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ABSTRACT

A graphite component in a nuclear reactor core is subjected to variety of stresses and can experience degradation during normal and off-normal operation. Understanding how a graphite component will behave in service is essential to ensuring core structural stability and safe reactor operation. This report summarizes a graphite modeling tool currently under development at Idaho National Laboratory. The model incorporates several of the anticipated stresses during service and includes the effects of oxidation and irradiation prior to turnaround. This tool is intended to be used to help assess the design of graphite components by utilizing design code rules found in Section III, Division 5 of the American Society of Mechanical Engineering Boiler and Pressure Vessel Code. Specifically, the tool uses the methodologies found within the Full and Simplified assessments from Article HHA-3000 to verify that a graphite component has an acceptably low probability of failure.

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ACRONYMS

ASA	Active Surface Area
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CTE	Coefficient of Thermal Expansion
INL	Idaho National Laboratory
MLE	Maximum Likelihood Estimate
MOOSE	Multiphysics Object-Oriented Simulation Environment
POF	Probability of Failure
SRC	Structural Reliability Class

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Graphite Degradation Modeling and Analysis

1. INTRODUCTION

Graphite is used as a moderator, reflector, and structural component in many high temperature nuclear reactor designs [1]. When assessing the design of a graphite core component, a designer must consider the anticipated stresses imposed upon the component and any degradation issues which may be experienced during normal and off-normal operation. Developing models, like the ones discussed in this report, is essential for understanding how a component will behave in a reactor environment and for ensuring safe operation throughout the component's life cycle. One of the goals of this work is to provide a tool which can be readily accessed and used by interested parties to assist in the design of graphite components. Consequently, the Section III, Division 5 of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) graphite component design code rules are used with this tool.

The purpose of this report is to provide an outline for the graphite modeling tool being developed at the Idaho National Laboratory (INL). The tool is comprised of multiple graphite behavior models as well as a reliability analysis. This report will cover the graphite physics which is included in the behavior models as well as some of the limitations of the tool. The report will also include the inputs, outputs and numerical formulations associated with the various graphite models and how they interact with a reliability analysis.

This report is laid out in the following way. Section 1.1 provides a very brief background on nuclear graphite. This background is intended to highlight physics and phenomena which effect graphite behavior in nuclear applications. Section 1.2 will discuss methodologies for assessing a graphite component according to the ASME BPVC. Section 2 outlines the graphite modeling capabilities, how to use the model, and how they connect to the ASME Code. Section 3 presents conclusions.

1.1 Graphite Behavior

Research on graphite properties has been conducted for decades. General trends in graphite properties as a function of temperature, oxidation, and irradiation are reasonably well substantiated, although, many different graphite grades exist, and every grade of graphite behaves slightly differently under similar operating conditions [2,3]. Therefore, while general trends are known, data specific to a particular grade are not necessarily readily available.

A designer must understand graphite behavior to appropriately assess how a component may fail. This begs the question, "what is failure?" This question is deceptively complex, and the answer will vary depending on the specifics associated with each component's application. Although, one sure way to fail any component is to have stresses which are too high. In a nuclear environment, stress can be generated in a graphite component from a multitude of sources. These include mechanical stresses such as those induced by the weight of stacked graphite components or pressure from the cooling fluid (i.e., dense molten salt coolant). However, the most significant stresses anticipated during nuclear operations will result from temperature and received irradiation dose gradients within a component. Of specific concern are stresses generated from non-uniform irradiation-induced dimensional changes. Stresses can be partially alleviated by irradiation-induced creep. While this is not an exhaustive list of what may cause stress within a graphite component in a reactor environment, these are some of the most prominent sources. A more complete list of loads to consider can be found in HHA-3122 in Section III, Division 5 of the ASME BPVC.

Some other important considerations in the discussion of graphite core component behavior are degradation and property changes. Graphite will readily oxidize if it is exposed to oxidants at sufficiently high temperature. The oxidation process is controlled by two main factors. One is the oxidant's diffusivity though the graphite and the second is the local kinetic rate. The diffusivity is a function of temperature as well as the graphite microstructure, and the local kinetic rate is a function of the temperature and the available active surface area (ASA) on the graphite crystallite. These two factors control when oxidation occurs, where oxidation occurs, and the extent of oxidation damage. Oxidation damage causes dramatic changes to a graphite's properties and understanding where and how much these local properties change is key to understanding how a component's bulk behavior is affected. Irradiation-induced graphite property changes are complex and can be significantly affected by the irradiation temperature as well as received dose. Accounting for oxidation, dose, and temperature effects on properties is necessary for understanding a component's behavior.

1.2 ASME Graphite Component Assessment

Article HHA-3000 in Section III, Division 5 of the ASME BPVC provides guidance on designing graphite core components [4]. Throughout the remainder of this report, text from Section III, Division 5 of the ASME BPVC will be referenced using their HHA article designations. HHA-3000 provides three methodologies for assessing a component: design by test, Simplified assessment, and Full assessment. The design by test is outlined in HHA-3240 through HHA-3243, and it provides guidelines on how to verify acceptable reliability from experimental testing. The Simplified assessment is contained in HHA-3220 and is performed by comparing an allowable stress value to the expected peak stress calculated in a component. The allowable stress is computed based on the graphite's material properties as well as the required reliability which is determined from the Structural Reliability Class (SRC). The Full assessment is slightly less conservative than the Simplified assessment and considers the full stress distribution in the component. In the Full assessment, the probability of failure (POF) is computed using the method in HHA-3217. Then, the computed POF is compared to the allowable POF determined from the SRC. This report will further discuss the application of the Simplified and Full assessments in Section 2.3. The design by test methodology will not be discussed further, because unlike the Simplified and Full assessments which make use of computing the internal stress in a component, the design by test methodology is experimentally based.

2. GRAPHITE COMPONENT ASSESSMENT

The purpose of this graphite modeling tool is to help assess the structural integrity of a graphite component's design. The tool accomplishes this by calculating stresses in a graphite component and potentially implementing those stresses in accordance with Section III, Division 5 of the ASME BPVC. The model which computes the stresses in graphite can accommodate mechanisms like oxidation and irradiation which may cause property changes during the life cycle of a component. A schematic of how this assessment methodology is structured is shown in Figure 1. This schematic includes all necessary inputs and outputs of the tool with the ultimate result coming from the ASME BPVC assessment. The following discussion will use the schematic as a road map to outline how the tool works.

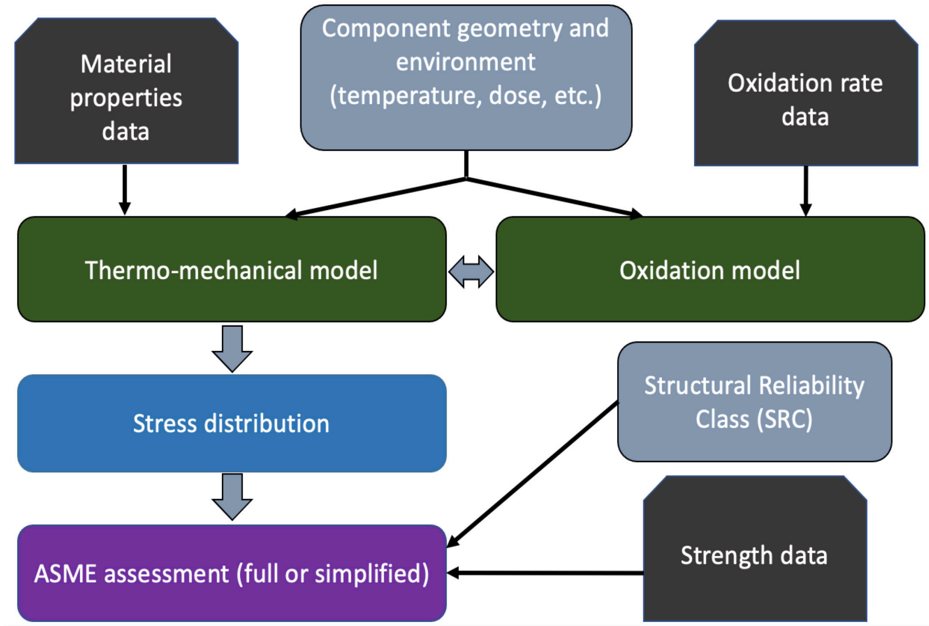

Figure 1. Schematic for assessing a graphite component based on the ASME BPVC.

In the flow diagram, there are three distinct models which require inputs. These models are labeled "Thermo-mechanical model", "Oxidation model" and "ASME assessment (full or simplified)" which will be referred to as the "Reliability model" for the remainder of this report. The Thermo-mechanical model and Oxidation model are implemented in the Multiphysics Object-Oriented Simulation Environment (MOOSE) which is an open-source, parallel finite-element framework. The Reliability model is implemented using Python. The other blocks in the schematic besides the "Stress distribution", which is an output of the Thermo-mechanical model, are required inputs. These required inputs mainly correspond to material property data as well as component geometry and the environment experienced in the reactor (temperature, dose, oxidant concentration, etc.).

This tool is not intended to provide a comprehensive analysis of a graphite component. The tool is only intended to model stress generation in graphite which has been oxidized or is prior to the turnaround dose. If applicable, these stresses can be used in the Simplified or Full assessments in the ASME Code. The turnaround dose is identified on a dimensional change *versus* dose plot as the dose value where the graphite stops shrinking and begins to expand. The model is limited to pre-turnaround doses because the scatter in the graphite behavior and properties becomes much larger after turnaround. Modeling the combined effect of irradiation and oxidation is possible using the Thermo-mechanical and Oxidation models, but it is not an intended application. At this time, the property relationships of graphite with combined oxidation and irradiation effects have not been well explored, which means material property data required by the models is not available. The tool's reliability analysis is also limited to the application of the 2021 edition of the ASME BPVC rules. This means that topics which are not directly addressed in the ASME BPVC will not be included in the Reliability model.

2.1 Thermo-mechanical Model

2.1.1 Thermo-mechanical Model Introduction

The evolution of the stresses and temperatures within a graphite component are computed by the Thermo-mechanical model. In the Simplified and Full assessment methodologies, computing stresses is necessary to assess the reliability of a component. The inputs for the Thermo-mechanical model are the component geometry, environment experienced throughout the life cycle (temperature, dose, mechanical loads), and material properties. The material properties which are required are the elastic modulus, thermal conductivity, coefficient of thermal expansion (CTE), and Poisson's ratio. The material properties of graphite change as a function of temperature, irradiation dose, and oxidation damage. It is suggested that input material properties are implemented as a function of these states.

2.1.2 Thermo-mechanical Model Numerical Formulation

The state variables which can evolve in the Thermo-mechanical model are the strains, ϵ, temperature, T, and dose, γ. The constitutive relation which governs the strain in the model is

$$\epsilon_{total} = \epsilon_{therm} + \epsilon_{irr} + \epsilon_{creep} + \epsilon_{elastic} \quad (1)$$

where ϵ_{total} is the total strain, ϵ_{therm} is strain from thermal expansion, ϵ_{irr} is strain from irradiation-induced swelling, ϵ_{creep} is strain from irradiation-induced creep, and $\epsilon_{elastic}$ is the elastic strain. The functional form of the thermally induced eigenstrain is

$$\epsilon_{therm} = CTE(T - T_o) \quad (2)$$

where CTE is the coefficient of thermal expansion, and T_o is the temperature where the strain is assumed to be zero. The irradiation-induced dimensional change is traditionally expressed as a function of temperature and dose.

$$\epsilon_{irr} = f(T, \gamma) \quad (3)$$

Experimental data is available to fit the relationship between the strain, dose, and temperature. MOOSE is flexible, and the functional form of the strain relationship can incorporate almost any function of the state variables. The irradiation-induced creep is comprised of a primary and secondary component.

$$\epsilon_{creep} = \epsilon_{Primary} + \epsilon_{Secondary} \quad (4)$$

The functional form of the primary- and secondary-creep strains is

$$\epsilon_{Primary} = A\sigma\big(1 - exp(-b\gamma)\big)/E \approx \sigma/E \quad (5)$$

$$\epsilon_{Secondary} = K\sigma \quad (6)$$

Where A and b are primary creep parameters, σ is the stress, E is the elastic modulus, and K is the secondary creep coefficient. The stresses in the component can be computed from

$$\sigma = E\epsilon_{elastic} \quad (7)$$

2.1.3 Thermo-mechanical Model Parameterization

In this model, the thermal conductivity, elastic modulus, CTE, and irradiation induced swelling should be implemented as a function of the temperature, dose, and, if oxidation is being simulated, density. As each grade of graphite behaves differently, a different parameterization will be required for every grade. Implementing the parameterization is relatively straight forward in MOOSE. The eigenstrains from the irradiation induced swelling and temperature can be implemented using the "ComputeVariableEigenstrain" material. The "prefactor" input in the "ComputeVariableEigenstrain" material is a “DerivativeParsedMaterial” object which is formulated as a function of the states. The dose and time-derivative of the dose can be implemented as Auxvariables which have associated “FunctionAux” AuxKernels. The thermal conductivity function is implemented in the PorousMediaBase.C source file by editing the kT variable. An isotropic elastic modulus which is a function of the states can be implemented by inputting the elastic modulus function as a “DerivativeParsedMaterial” and using the “DerivativeParsedMaterial” as an input to the “ComputeVariableIsotropicElasticityTensor” material object. The graphite irradiation creep behavior is built into the “GraphiteIrradiationCreep” material.

A parameterization for IG-110 is provided in equations 8 - 11 below. It should be noted that this parameterization is not intended to be used past turnaround. In the following equations, T is temperature is degrees Celsius and γ is the dose in dpa. The CTE, with units of 1/Kelvin, irradiation induced swelling ϵ_{irr}, elastic modulus, E, in GPa and thermal conductivity, K, in W/(m °C) can be expressed as:

$$CTE = 4.827e-6 - 3.9413e-11\,T - 1.149e-7\,\gamma - 2.648e-11\,T\,\gamma + 3e-9\,\gamma^2 \tag{8}$$

$$\epsilon_{irr} = 0.0006351 - 6.23e-7T - 0.003476\,\gamma - 4.26e-7\,T\,\gamma - 0.0002324\gamma^2 \tag{9}$$

$$E = 12.41 - 0.0007386\,T + 2.838\,\gamma - 0.00102\,T\,\gamma - 0.0753\,\gamma^2 \tag{10}$$

$$K = 117.8 - 0.08176\,T - 2.819\,\gamma \tag{11}$$

Images of the function fits on top of the experimental data are shown in Figure 2. This parameterization is provided in an example input file which is included with this work.

To compute stresses in an oxidized component, the material properties must be computed as a function of mass loss. Currently, very little data exist on the combined effects of oxidation and irradiation, so a parameterization combining the two effects is not advisable. The material properties as a function of mass loss are shown in equations 12-14 and the fits on top of the experimental data are shown in Figure 3. In the following equations X is the normalized mass loss.

$$CTE = 3.397e-6 + 1.446e-9T - 1.861e-8X - 3.54e-13T^2 + 8.08e-12\,XT \tag{12}$$

$$E = 10.67\,exp(-0.05256\,X) \tag{13}$$

$$K = 135.9 - 0.06048T - 148.9\,X + 0.06049\,X\,T + 14.92\,X^2 \tag{14}$$

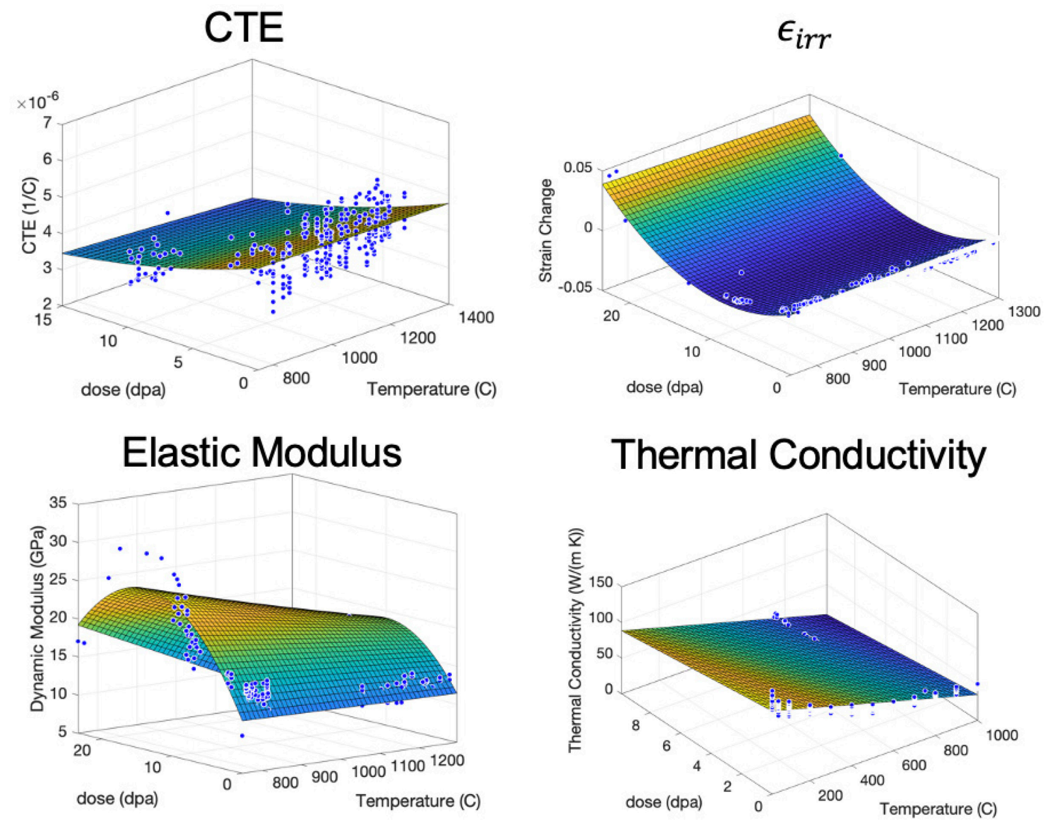

Figure 2. IG-110 parameterization of material properties as a function of temperature and dose.

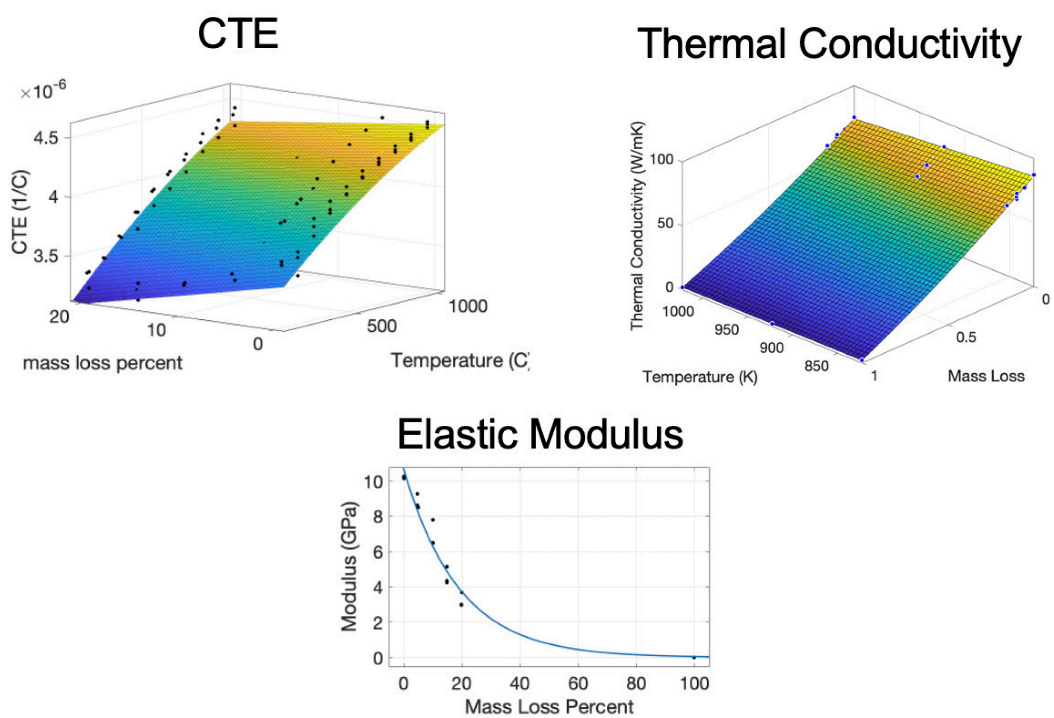

Figure 3. IG-110 parameterization of material properties as a function of temperature and mass loss.

2.1.4 Thermo-mechanical Model Discussion

The constitutive strain relationship allows for all loads mentioned in Section 1.1 to be incorporated. One of the advantages of MOOSE is a simple method for incorporating additional physics. Incorporating additional eigenstrains or modeling physics associated with a specific reactor type can be added in MOOSE with reduced effort relative to other modeling platforms.

The Thermo-mechanical model requires parameterization for multiple inputs including the material properties as well as the relationships between the strains and state variables. As every graphite grade behaves differently, it is not feasible to account for the variation between grades. Although, parameterizations for select grades will be provided in the tool. This Thermo-mechanical model is based upon the work done by Andrea Nicolas, so the interested reader will find a more in-depth discussion of a similar model in her work [5].

2.2 Oxidation Model

2.2.1 Oxidation Model Introduction

The Oxidation model computes when, where, and to what extent oxidation damage occurs. Perhaps most importantly, this model determines the density profile which is generated within a graphite component. The required inputs for this model are the component geometry, oxidant concentration (boundary conditions), environment (temperature), and material properties. The two nontrivial material properties needed to parameterize the Oxidation model are related to the chemical species diffusion and the ASA of the graphite. Note that both parameters will vary as a function of the local density in the graphite. Unlike the Thermo-mechanical model, material property parameterization of the Oxidation model for additional grades may be difficult due to scarcity of experimental data combined with a more complex parameterization procedure. The model will provide parameterizations for medium-grained NBG-18 and superfine-grained IG-110.

2.2.2 Oxidation Model Numerical Formulation

The state variables in the Oxidation model are the density, ρ, chemical species concentration, and temperature, T. Note that the Oxidation model can be coupled to the Thermo-mechanical model. The shared state variables between the models are the temperature and the density. Coupling through the density state variable requires that material properties in the Thermo-mechanical model are implemented as a function of density. The global reaction between graphite and oxygen in the Oxidation model is

$$C(s) + (1 - 0.5x)O_2 \rightarrow xCO + (1 - x)CO_2 \tag{15}$$

where $C(s)$ is the carbon in the graphite and x is the molar fraction of CO produced in the reaction products. The value of the x can change as a function of the states. The change in density of the graphite is computed by

$$\frac{\partial\rho}{\partial t} = k_{eff}^{''} S_A[O_2] \tag{16}$$

where $k_{eff}^{''}$ is the effective reaction rate normalized to the ASA, S_A is the ASA per unit volume and $[O_2]$ is the concentration of oxygen. The mass transfer and flux are computed by the following five equations

$$N_i \cong -[C_T]D_{eff}\nabla y_i + y_i N_i \tag{17}$$

$$\frac{\partial \varepsilon[CO2]}{\partial t} = -\nabla N_{CO_2} + (1-x)k_eff^{''}S_A[O_2] \tag{18}$$

$$\frac{\partial \varepsilon[CO]}{\partial t} = -\nabla N_{CO} + xk_eff^{''}S_A[O_2] \tag{19}$$

$$\frac{\partial \varepsilon[O2]}{\partial t} = -\nabla N_{O_2} + \left(1-\frac{x}{2}\right)k_{eff}^{''}S_A[O_2] \tag{20}$$

$$\frac{\partial \varepsilon[I]}{\partial t} = -\nabla N_I \tag{21}$$

Here, C_T is the total gas concentration, D_{eff} is the effective diffusivity, y_i is the mole fraction of chemical species i, N_i is the flux of chemical species i, ε is the porosity by volume fraction and I can be any additional chemical species. Equations 17-21 also account for the generation of carbon dioxide and carbon monoxide as well as the depletion of oxygen.

The reaction between graphite and oxygen is exothermic. At low temperatures where the reaction rate is slow, the effect of this exothermic reaction will likely be negligible. This is because at low temperatures, heat production is slow, and the generated heat can be dissipated before any significant temperature change occurs. At higher temperatures, the heat release from this reaction may cause a significant temperature change. The temperature evolution is computed by

$$\frac{\partial(\rho C_p T)}{\partial t} = \nabla \cdot (k_T \nabla \mathrm{T}) + k_{eff}^{''}S_A[O_2]\Delta H_{rx} \tag{22}$$

where C_p is the specific heat of graphite, k_T is the thermal conductivity, and ΔH_{rx} is the heat of reaction. The thermal conductivity in the model is implemented as a function of the states.

2.2.3 Oxidation Model Parameterization

The oxidation behavior of each graphite grade is different and therefore each grade requires its own parameterization. There are parameters associated with two physical features that must be parameterized. These are the diffusivity of the oxidants and the ASA parameters. Both will vary as the microstructure changes from oxidation mass loss. Currently, parameterizations are provided for IG-110 and NBG-18. Selecting from one of these grades can be done by editing the “graphite_type” input in the “PorousMediaBase” material.

To parameterize the model for additional grades, two sets of experiments data are needed. The first set is an effective diffusivity analysis. In the model it is assumed that the oxidant diffusivity varies with the square of the mass loss. Current experimentation is being performed at INL to confirm this behavior. To parameterize the diffusivity, the “Z” parameter in the PorousMediaBase.C source file should be set equal to the ratio of the effective diffusivity over the bulk diffusivity. The second experimental data set is the oxidation mass loss versus time at very low temperature. This should be determined using the methodology from ASTM D7542. This low-temperature data will allow for diffusion contributions to be minimized and therefore any change in the reaction rate can be attributed to a change in the ASA density. Measurements of the relative ASA have been performed previously at INL [6]. The evolution of the ratio of the ASA density over the initial ASA should be input in the PorousMediaBase.C source file in the _SA parameter. The final step to parameterize the model is to fit the “rate_scaling_factor” in the PorousMediaBase material. The parameter should be adjusted until the mass loss versus time trend matches the experimental data. An example of the successful validation is shown in Figure 4.

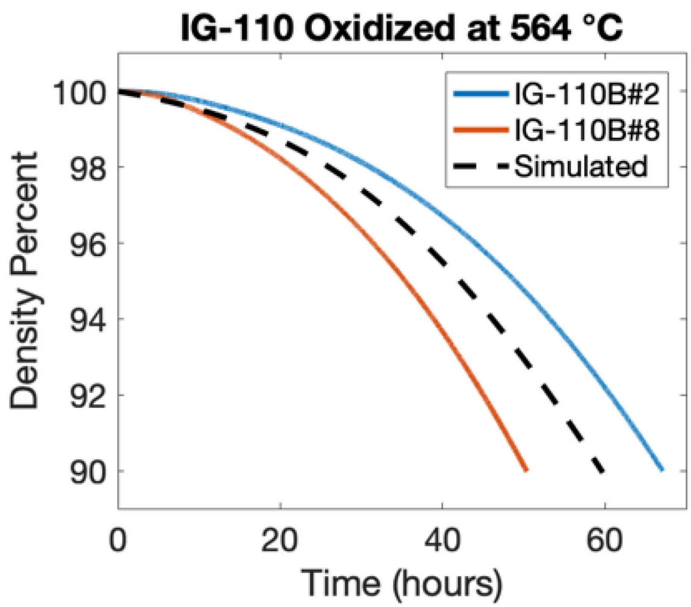

Figure 4. IG-110 Oxidation model parameterization result.

2.2.4 Oxidation Model Discussion

Oxidation in a reactor may be categorized as either acute or chronic. Acute oxidation is likely to occur only in an accident scenario when a large amount of oxidant enters the reactor. Chronic oxidation can occur due to trace amounts of oxidants present in the reactor. The Oxidation model is capable of modeling both types of oxidation by varying the oxidant concentration boundary conditions. It is worth mentioning that graphite can be oxidized by multiple chemical species including oxygen, carbon dioxide, steam as well as others. The Oxidation model was developed to investigate oxidation due to pure oxygen. Oxidation from oxygen is often the primary concern because the activation energy for the reaction between graphite and oxygen is lower than most other oxidants likely to be present. For a more in-depth discussion of oxidation and the model discussed above, the interested reader should investigate the work performed by Joshua Kane [7,8].

2.3 Reliability Model

2.3.1 Reliability Model Introduction

The Reliability model is directly taken from Article HHA-3000 in Section III, Division 5 of the ASME BPVC [4]. The Full and Simplified assessments in the 2021 edition will be implemented in Python. The program uses outputs from the Thermo-mechanical model along with material properties and component reliability requirements to assess a graphite component. The Reliability model does not attempt to provide analysis outside of the ASME BPVC. Multiple test problems were run using the ASME methodologies. The following discussion will cover the Full and Simplified assessments and will attempt to highlight potential issues which may arise during application of the assessments.

2.3.2 Reliability Model Numerical Formulation

This section outlines both the Simplified and Full assessments which are found in the ASME Code. Both the Simplified and Full assessments derive an allowable POF from a component's SRC as shown in Table HHA-3221-1 of the ASME BPVC. Designation of the SRC is based on the components service life and is defined in HHA-3111.

For the Simplified assessment, the required inputs are a two parameter Weibull distribution of the graphite's tensile strength, the flexural strength, and a distribution of equivalent stresses. The Code uses a method for determining an equivalent stress based on maximum deformation theory. The methodology for computing the equivalent stress is outlined in HHA-3213. A method for computing the Weibull shape, $m_{95,}$ and scale, Sc_{95}, parameters which correspond to a 95 percent one sided confidence interval and can be found in HHA-II-3100. The design allowable stress, S_g, is computed by

$$S_g = \mathrm{Sc}_{95}\left(-ln(1-POF)\right)^{\frac{1}{m_{95}}} \tag{23}$$

The allowable stress is compared directly to the peak equivalent stress computed in the Thermo-mechanical model. If the peak equivalent stress is lower than the allowable stress then the design passes the Simplified assessment; otherwise, the design fails the Simplified assessment.

For the Full assessment, the required inputs are a three parameter Weibull distribution of the graphite's strength, the element volumes from the mesh used in the finite-element analysis, and the equivalent stress distribution. A method for computing the Weibull shape, $m_{95,}$ scale, Sc_{95}, and threshold, S_0, parameters can be found in HHA-II-3200. Note that while the text and parameter notation in the Code refers to these as the lower bound values of a 95% confidence interval, the supplied equations appear to be maximum likelihood estimates (MLE)s for the parameters. The calculation for the POF is outlined in HHA-3217. This seven-step procedure for determining the POF has seen changes over the last few editions of the Code and will likely be seeing changes in the upcoming editions. As such, it is important for anyone implementing the code to take care to use the appropriate Code edition. Ultimately, if the allowable POF taken from table HHA-3221-1 is higher than the computed POF then the design passes the Full assessment; otherwise, the design fails the Full assessment.

2.3.3 Reliability Model Discussion

Section III, Division 5 is written in a generic way to encompass a variety of reactor types. To this point, the Forward in Section III, Division 5 states "The Code does not address all aspects of these (construction) activities". In the case of analyzing a graphite component, the Full and Simplified assessments do not fully address degradation caused by oxidation or irradiation. HHA- 3141 states that "Oxidation analysis shall be carried out in detail to estimate the weight loss profiles of graphite structures" and provides guidelines for analysis but does not specify how to account for the oxidation gradient in the Simplified or Full assessments. Therefore, the designer must provide an appropriate assessment methodology because gradients are outside the scope of the Full and Simplified assessments.

Beyond the limitations in the Code mentioned above, there are some important considerations when implementing the Code. First, while the methodologies in the code are tied to a POF, the assessments are only determining a probability of crack formation in a component. Crack formation does not necessarily directly correlate to a loss of function. This is a topic which will likely be addressed in future versions of the Code. Second, it is important to use a sufficiently fine mesh in the analysis of a component. If a coarse mesh is used, the assessments become less conservative. Currently, the Code does not place any restriction on the mesh size. Third, in the Full assessment, if only a portion of a component is used in an assessment, the POF will be affected. For example, if a component is symmetric about a center plane and a designer only models half the components with the understanding that the stress distribution will be symmetric about the plane, then the designer will need to account for the missing stressed volume in the POF calculation. The POF in the Full assessment does not account for spatial effects, so stresses from across a component, including opposite side can be grouped in the POF calculation.

3. CONCLUSIONS

Understanding graphite behavior is necessary for ensuring safe operation of a nuclear power plant. In this report, a tool was outlined which can model some primary sources of stress generation in a graphite component subjected to a reactor environment. This model strives to account for the effects of oxidation and irradiation prior to turnaround in graphite. Even if the stress distribution in a graphite component is known, a methodology for assessing a graphite component is not a trivial task. Graphite can serve multiple purposes in a reactor which makes defining a systematic method for assessing a component very difficult. This work has used the Simplified and Full assessments from Section III, Division 5 of the ASME BPVC as an assessment methodology.

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