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FINAL SAFETY EVALUATION OF GRAPHITE MATERIAL QUALIFICATION FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH-TEMPERATURE REACTOR (KP-TR-014) KAIROS POWER, LLC EPID NO. 000431 / 99902069 / L-2021-TOP-0022

1.0 SPONSOR INFORMATION

Sponsor: Kairos Power, LLC (Kairos)

Address: 707 West Tower Ave.
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Project No.: 99902069 (Construction Permit Application Docket No. 05007513)

2.0 SUBMITTAL, CORRESPONDENCE, AND CONTRIBUTORS

2.1. Submittal Information

Revision	Submittal Date	Agencywide Documents Access and Management System (ADAMS) Accession No.	Document Number
Revision 1	July 8, 2021	ML21190A218	KP-TR-014, Revision 1
Revision 2	May 11, 2022	ML22132A202	KP-TR-014, Revision 2
Revision 3	July 13, 2022	ML22194A943	KP-TR-014, Revision 3
Revision 4	September 16, 2022	ML22259A142	KP-TR-014, Revision 4

2.2. NRC Correspondence and Communications

Communication Type	Date	ADAMS Accession No.
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	February 10, 2022 February 15, 2022 February 22, 2022 March 1, 2022 March 8, 2022 March 15, 2022	ML22035A326
	June 14, 2022	ML22161B040
	June 27, 2022	ML22167A084

2.3. Principal Contributor(s)

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3.0 BRIEF DESCRIPTION OF REQUEST AND BACKGROUND

The topical report (TR) describes the testing required to qualify the near-isotropic ET-10 nuclear grade graphite intended for safety-related components providing structural support in the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR) and the Hermes test reactor. Both reactors operate near atmospheric pressure and use tristructural-isotropic (TRISO) fuel embedded in pyrolytic graphite pebbles. The report describes the proposed testing to meet the requirements of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section III, Division 5, (Section III Division 5) Subsection HH, Subpart A, "Graphite Materials." The TR consists of three primary sections, 1) testing to measure the mechanical and thermal properties of unirradiated graphite, 2) irradiated creep testing, and 3) testing to demonstrate environmental compatibility of the graphite in the lithium fluoride and beryllium fluoride (FLiBe) coolant salt and the impact of oxidation on the graphite. The TR references historical data to qualify the mechanical and thermal properties of irradiated graphite without the application of an external stress. Historical irradiated creep data will be used to qualify ET-10 for the Hermes test reactor.

The documents located at the ADAMS Accession number(s) identified in Section 2 of this safety evaluation (SE) have additional details on the submittal.

4.0 EVALUATION CRITERIA

4.1 Regulatory Requirements

Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.10, “License required; limited work authorization,” which provides the requirements for information to be contained in a limited work authorization.

10 CFR 50.34, “Contents of applications; technical information,” which includes the requirements for information to be contained in safety analyses for facilities licensed under 10 CFR Part 50, “Domestic licensing of production and utilization facilities.”

10 CFR 50.34(a)(1)(i), “The assessment must contain an analysis and evaluation of the major structures, systems, and components of the facility which bear significantly on the acceptability of the site under the site evaluation factors.”

10 CFR 50.34(a)(1)(ii)(B), “The extent to which generally accepted engineering standards are applied to the design of the reactor.”

10 CFR 50.34(a)(1)(ii)(C), “The extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accident release of radioactive materials.”

10 CFR 50.34(a)(2), "A summary description and discussion of the facility, with special attention to design and operating characteristics, unusual or novel design features, and principal safety considerations."

10 CFR 50.34(a)(3)(ii), The preliminary design of the facility including "The design bases and relation of the design bases to the principal design criteria."

10 CFR 52.47(a)(2), "A description and analysis of the structures, systems, and components (SSCs) of the facility, with emphasis upon performance requirements, the bases, with technical justification therefor, upon which these requirements have been established, and the evaluations required to show that safety functions will be accomplished."

10 CFR 52.47(a)(2)(ii), "The extent to which generally accepted engineering standards are applied to the design of the reactor."

10 CFR 52.47(a)(2)(iii), "The extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials."

10 CFR 52.47(a)(2)(iv), "The safety features that are to be engineered into the facility and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur."

10 CFR 52.47(a)(3)(ii), "The design bases and the relation of the design bases to the principal design criteria."

10 CFR 52.79, "Contents of applications; technical information in final safety analysis report," which includes the requirements for information to be contained in safety analyses for facilities licensed under 10 CFR 52.

10 CFR 52.79(a)(2), "A description and analysis of the structures, systems, and components of the facility with emphasis upon performance requirements, the bases, with technical justification therefor, upon which these requirements have been established, and the evaluations required to show that safety functions will be accomplished."

10 CFR 52.79(a)(2)(ii), "The extent to which generally accepted engineering standards are applied to the design of the reactor."

10 CFR 52.79(a)(2)(iii), "The extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials."

10 CFR 52.79(a)(2)(iv), "The safety features that are to be engineered into the facility and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur."

10 CFR 52.79(a)(4)(ii), The design of the facility including "[t]he design bases and the relation of the design bases to the principal design criteria."

10 CFR 52.47, “Contents of applications; technical information,” which includes the requirements for information to be contained in a design certification and the requirements for information to be contained in safety analyses for standard design certifications.

10 CFR 52.47(a)(2), “A description and analysis of the structures, systems, and components (SSCs) of the facility, with emphasis upon performance requirements, the bases, with technical justification therefore, upon which these requirements have been established, and the evaluations required to show that safety functions will be accomplished.”

10 CFR 52.47(a)(2)(ii), “The extent to which generally accepted engineering standards are applied to the design of the reactor.”

10 CFR 52.47(a)(2)(iii), “The extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials.”

10 CFR 52.47(a)(2)(iv), “The safety features that are to be engineered into the facility and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur.”

10 CFR 52.47(a)(3)(ii), “The design bases and the relation of the design bases to the principal design criteria."

10 CFR 52.137, “Contents of applications; technical information,” which includes the requirements for information to be contained in a standard design.

10 CFR 52.137(a)(2), “A description and analysis of the SSCs of the facility, with emphasis upon performance requirements, the bases, with technical justification, upon which the requirements have been established, and the evaluations required to show that safety functions will be accomplished.”

10 CFR 52.137(a)(2)(ii), “The extent to which generally accepted engineering standards are applied to the design of the reactor.”

10 CFR 52.137(a)(2)(iii), “The extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials.”

10 CFR 52.137(a)(2)(iv), “The safety features that are to be engineered into the facility and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur.”

10 CFR 52.137(a)(3)(ii), “The design bases and the relation of the design bases to the principal design criteria."

10 CFR 52.157, “Contents of applications; technical information in final safety analysis report,” which includes the requirements for information to be contained in a manufacturing license.

10 CFR 52.157(b), “The design bases and the relation of the design bases to the principal design criteria.”

10 CFR 52.157(c), "A description and analysis of the structures, systems, and components of the reactor to be manufactured, with emphasis upon the materials of manufacture, performance requirements, the bases, with technical justification therefor, upon which the performance requirements have been established, and the evaluations required to show that safety functions will be accomplished."

10 CFR 52.157(c)(2), "The extent to which generally accepted engineering standards are applied to the design of the reactor."

10 CFR 52.157(c)(3), "The extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials."

10 CFR 52.157(d), "The safety features that are engineered into the reactor and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur."

10 CFR 50.10(d)(3)(i), "A safety analysis report required by 10 CFR 50.34, 10 CFR 52.17 or 10 CFR 52.79 of this chapter, as applicable, a description of the activities requested to be performed, and the design and construction information otherwise required by the Commission's rules and regulations to be submitted for a construction permit or combined license, but limited to those portions of the facility that are within the scope of the limited work authorization."

4.2 Principal Design Criteria for the KP-FHR, Approved by the NRC Staff

In addition to the regulations cited above, the TR KP-TR-003-NP-A, "Principal Design Criteria (PDC) for the Kairos Power Fluoride Salt Cooled High Temperature Reactor," Revision 1, dated June 12, 2020 (ML20167A174), provides PDCs for the KP-FHR design that were reviewed and approved by the NRC staff. PDCs below are applicable to qualification of graphite components for the KP-FHR.

KP PDC 1, "Quality standards and records," which states that safety significant structures, systems, and components (SSCs) "shall be designed, fabricated, erected, and tested to quality standards commensurate with the safety significance of the functions to be performed." Additionally, PDC 1 states that generally recognized codes and standards shall be identified and evaluated to assure a quality product corresponding to the required safety function.

KP PDC 34, "Residual heat removal," which requires that the residual heat removal safety system shall function to maintain radionuclide release design limits and reactor coolant boundary limits during normal operations and anticipated operational occurrences. The safety functions of the graphite reflector include maintaining physical geometry of the reactor core and supporting core cooling and heat removal.

KP PDC 35, "Passive residual heat removal," which requires sufficient core cooling during postulated accidents and the removal of residual heat after postulated accidents. The safety functions of the graphite reflector include maintaining physical geometry of the reactor core and supporting core cooling and heat removal.

KP PDC 74, "Reactor vessel and reactor system structural design basis," which requires the reactor system to be designed so that integrity is maintained during postulated accidents to ensure passive heat removal as well as to permit sufficient insertion of neutron absorbers for reactor shutdown. The safety functions of the graphite reflector include providing a pathway for reactivity control elements insertion.

4.3 Codes, Standards, and Guidance Documents

Applicable Codes and Standards:

American Society of Mechanical Engineers (ASME) BPVC Section III Division 5, "High Temperature Reactors," 2017 Edition, contains the requirements to qualify graphite for use in a high temperature reactor. The NRC staff endorsed the use of this portion of the ASME BPVC via NUREG-2245, "Acceptability of ASME Code Section III, Division 5, High Temperature Reactors," dated January 2023 (ML23030B636), and Regulatory Guide (RG) 1.87, "Acceptability of ASME Code Section III, Division 5, High Temperature Reactors," Revision 2, dated January 2023 (ML22101A263). Kairos stated that it generally follows the ASME Code rules for graphite qualification. The NRC staff reviewed this TR against Code rules, NUREG-2245, RG 1.87, Revision 2, and the conditions on the use of ASME Code Section III Division 5 outlined in these guidance documents (Limitation and Condition 3).

Guidance Documents:

NUREG-2245, "Acceptability of ASME Code Section III, Division 5, High Temperature Reactors," dated January 2023 (ML23030B636).

Regulatory Guide (RG) 1.87, "Acceptability of ASME Code Section III, Division 5, High Temperature Reactors," Revision 2, dated January 2023 (ML22101A263).

Technical Letter Report, NUMARK Associates, "Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, "High Temperature Reactors": Subsection HH, "Class A Nonmetallic Core Support Structures," Subpart A, "Graphite Materials,"" dated December 2020 (ML20344A001).

5.0 STAFF EVALUATION

5.1 Staff Evaluation Discussion

TR Section 3.1, "Mechanical and Thermal Properties"

In this Section of the TR, Kairos Power (KP) describes the process to qualify the ET-10 graphite for the KP-FHR design. This section describes the unirradiated properties to be tested, number of samples to be tested, and applicable test standards. It also describes areas where KP has proposed alternatives to the requirements in Section III Division 5 as well as qualification testing for environmental compatibility that is not specified in Section III Division 5.

The NRC staff reviewed the KP methodology to qualify mechanical and thermal properties of the KP graphite material against the applicable parts of Section III Division 5 and the NRC staff endorsement of Section III Division 5.

Section III Division 5 Article HHA-2132 "Qualification of Materials," states material qualification shall be in accordance with HHA-2200, "Material Properties for Design." HHA-2200 states that the graphite properties used for design shall be determined by the Designer and published in the material data sheet (MDS). This part of Section III Division 5 also requires that the MDS define properties in as-manufactured, irradiated, and oxidized conditions as defined in HHA-2210, 2220, and 2230, and that testing shall be as defined in Mandatory Appendix HHA-III, "Properties to Be Determined."

Section III Division 5 HHA-2210, "As-Manufactured Material Properties," requires the MDS to include properties in Mandatory Appendix HHA-II and that the temperature range for property measurements envelopes the temperature range defined in HHA-2131(b). Subarticle HHA-III-3100, "As-Manufactured Graphite," contains the properties to be measured for unirradiated graphite.

The NRC staff finds the testing described in Section 3.1 and Table 6 of the TR acceptable because it contains tests for the properties required by Section III Division 5 Subarticle HHA-III-3100, "As-Manufactured Graphite." The staff endorsement of this portion of Section III Division 5 is found in section 3.27.3, "Article HHA-III-3100 As-Manufactured Graphite," of NUREG-2245. The KP qualification program will measure the room temperature tensile strength, compressive strength, flexural strength, dynamic elastic modulus, shear modulus, and Poisson's ratio. The values for these parameters, measured at room temperature, will be used at elevated temperatures, as these parameters will not be measured at elevated temperatures. The staff finds this approach acceptable, because these properties will improve relative to the unirradiated room temperature properties below turnaround based on the data in Figure 4 of the TR (e.g., graphite strength improves with temperature). Therefore, use of the room temperature values is conservative.

The coefficient of thermal expansion (CTE) and thermal conductivity will be measured from room temperature to 825°C in 200°C temperature increments. The staff finds this approach acceptable because the temperature increments conform with the requirements of HHA-II-2000 and the maximum testing temperature envelopes the maximum temperature of the KP-FHR under normal and postulated accident conditions.

Section III Division 5 Article HHA-III-4000, "Requirement for Representative Data," contains the requirements for how to sample graphite in order to obtain representative properties from different locations within a charge or a billet. HHA-III-4100, "As-Manufactured Graphite," contains the requirements to sample unirradiated graphite. The KP graphite testing program accounts for the variation of properties between individual charges and billets, within billets, and manufacturing orientation by testing a number of samples taken from locations of the charges and billets to be tested, that meet the requirements of HHA-III-4100, "As-Manufactured Graphite." The NRC staff finds this testing approach acceptable because, as described in section 3.27.4, "Article HHA-III-4000 Requirement for Representative Data," of NUREG-2245, the specified number of samples provide a minimum acceptable sample size to generate representative data for as-manufactured graphite.

Measurement of fracture toughness is required in Section III Division 5 Article HHA-III-3100. However, the TR states that fracture toughness is not measured as part of this program because the KP-FHR design will not rely on the use of this parameter.

The staff finds it acceptable to deviate from these Section III Division 5 requirements and not test for fracture toughness only if an applicant can demonstrate it is not needed in the design of the graphite reflector. The exclusion of fracture toughness testing may prevent graphite acceptance under Section III Division 5 Subarticle HHA-4233.4 and criteria for repair of defects (Subarticle HHA-4233.5). Therefore, the staff will need to evaluate the proposed method for flaw evaluation in a future application if a method other than fracture toughness is used to determine flaw acceptability. This is captured in Limitation and Condition 7.

TR Section 3.1.1, <u>"Fatigue"</u>

This section of the TR describes the anticipated effects of fatigue on the structural integrity of the graphite reflector for both the Hermes and KP-X designs. It provides a description of two historical grades of graphite (i.e., PGX and H-451) and the trends in fatigue behavior for these grades of graphite. KP states that the trends for these grades of graphite will be applicable to the ET-10 grade, although the magnitude of the change will be different. KP also states that the ET-10 graphite will be subjected to unirradiated fatigue testing to ensure the fatigue response follows the trends of historical grades of graphite described. KP also states that if fatigue test data for ET-10 show that the ASME allowable stresses are higher than the fatigue strength, KP will adjust the allowable stresses to be conservative.

The NRC staff finds it acceptable to perform unirradiated fatigue testing to demonstrate applicability of fatigue trends in the historical grades of graphite. Irradiation studies of H-451 demonstrated irradiation improved the fatigue strength limits of the H-451. Therefore, the staff finds that fatigue testing of unirradiated ET-10 is acceptable in lieu of irradiated ET-10, subject to Limitation and Condition 2.a, which requires an applicant to demonstrate that ET-10 follows the same unirradiated fatigue trends as the referenced historical grades of graphite. Additionally, the staff finds this approach acceptable because the TR states that the allowable stresses will be conservatively adjusted if test data for ET-10 shows ASME allowable stresses to be higher than the fatigue strength.

TR Section 3.2, <u>"Property Variation"</u>

This section of the TR discusses how testing in the proposed methodology will account for variations in graphite properties. It includes considerations of billet uniformity (intra-billet variation), as well as lot-to-lot variations in properties. In order to account for intra-billet variation, KP has proposed to compare local variation data collected by Ibiden (the manufacturer and supplier for ET-10 graphite) to the data that will be collected under this qualification plan. To account for lot-to-lot variation, KP has proposed to use historical data from Ibiden for production lots over an extended period of time (e.g., decades) in order to develop a range of possible property values and combine these ranges with data generated under the KP qualification testing program to finalize the specification for the ET-10 graphite. Both approaches will use test data from the graphite manufacturer over a longer time span combined with data that will be generated by KP resulting from the qualification testing. The KP qualification testing results will also be used to demonstrate applicability of the irradiation tests performed for the ET-10 graphite as described in Appendix B of the TR.

The NRC staff evaluated the proposed method to account for intra-billet property variation within the graphite material. Due to the nature of graphite and its processing, it is possible for graphite properties to vary within a billet or lot (Section III Division 5 Nonmandatory Appendix HHA-A, and NUMARK Associates report acknowledge this potential variation). KP proposed to compare data from the ET-10 manufacturer to the data that will be collected as per Table 6 in the TR to account for intra-billet variability. Sampling requirements in Article HHA-III-4000 describe how samples must be taken to account for property variation within a billet. The NRC staff finds that this approach is acceptable because it uses test data from the as-manufactured material consistent with HHA-III-4000 sampling requirements and compares this data to additional historical data to identify how properties vary within a billet of ET-10 graphite. It is also acceptable because the TR states that this data will be used to determine the cutting pattern to produce reflector blocks. This will allow KP to ensure that the graphite blocks will be able to meet the specification that will be defined as described in Section 3.4 of the TR.

The NRC staff finds the method to determine lot-to-lot variability to be acceptable because it will examine years of historical data on variation from processing the same grade of graphite and create a baseline to identify property shifts over time. Additionally, the TR states that the property variation of a 10-year span will be analyzed to determine a range and variation for the properties in Table 6 of the TR. This will be used in combination with data generated in Section 3.1 of the TR and modeling results to finalize property specifications. The staff finds this approach acceptable because it will account for lot-to-lot property variation when determining the graphite specification (i.e., accept/reject criteria) described in Section 3.4 of the TR.

Section 3.2 of the TR also discusses the use of Section III Division 5 Article HHA-III-5000, “Use of Historical Data,” to demonstrate that historical data can be used to evaluate local property variation, lot-to-lot property variation, and the ET-10 irradiation data from Oak Ridge National Laboratory (ORNL). Appendix B of the TR provides the process proposed by KP to demonstrate the applicability of historical data.

Section III Division 5 Article HHA-III-5000, “Use of Historical Data,” allows for the use of existing test data for graphite qualification as long as it meets the requirements of Appendix HHA, and it can be demonstrated that the grade of graphite tested is the same grade, as defined in HAB-5000 and HAB-9000, as the production material. The definition of “graphite grade” in Section III Division 5 Subarticle HAB-9200, “Definitions,” states that a graphite grade is produced from the same raw materials to the same specification and using the same process.

The NRC staff finds the process to use historical data to evaluate both property variation and irradiated basic properties (i.e., non-creep) acceptable because Section III Division 5 allows for the use of historical data in graphite qualification. Also, KP has proposed to demonstrate that the previously tested material is the same grade as the production material, per the conditions described in Appendix B of the TR. The staff finds that the proposed process in Appendix B of the TR is acceptable because it will ensure that the raw material specification, process, and as-manufactured properties of the graphite match the values used for the ET-10 irradiation specimens, which is consistent with the Section III Division 5 requirements described above. Additionally, the staff finds that applying the proposed process in Appendix B of the TR to the irradiated test data is acceptable because it uses the lot-to-lot variations in properties over time to correct for these variations in the irradiated data. Use of historical data is subject to Limitation and Condition 2.b.

TR Section 3.3, <u>“Purity”</u>

The NRC staff reviewed the chemical impurity limits for ET-10 to confirm boron equivalency, ash content, and elements listed in Table X.1, “Impurities,” of ASTM (formerly known as “American Society for Testing and Materials”, now ASTM International) D7219, “Standard

Specification for Isotropic and near-Isotropic Nuclear Graphites," 2008 edition. ASTM D7219-08 is considered acceptable as per the staff's endorsement of Section III Division 5 Mandatory appendix HHA-I, "Graphite Material Specifications," Subarticle HHA-I-1110, "Material Specifications," (NUREG-2245 section 3.25.1, "Article HHA-I-1000 Introduction") because the specifications adequately cover classification, processing, and properties of nuclear grade graphite billets of a sufficient size for nuclear reactor designers. Therefore, the staff finds it acceptable to use ASTM D7219-08 to establish a purity specification for the power and non-power test reactor designs. The chemical impurity limits for boron equivalency and ash content detailed by KP meet the requirements of ASTM D7219-08, which the staff finds acceptable. ASTM D7219-08 states that the impurity limits for elements of consideration in Table X.1 are to be determined between supplier and purchaser. The upper limit of elements that could potentially accelerate oxidation of the graphite will be based upon oxidation test results. Impurities which affect activation of metallic corrosion do not directly affect the ability of the graphite reflector to perform its structural safety function and as such, are not addressed in the TR.

TR Section 3.4, <u>"Defining a Structural Graphite Specification"</u>

This section of the TR describes the process by which KP will determine the required acceptance criteria for the use of structural graphite in the KP-FHR design. The TR references purity standards from ASTM D7219-08 to set a graphite specification, but it does not reference this standard for mechanical properties of graphite. It instead states that properties from testing conducted under Section 3.1 of the TR will be assessed in conjunction with variations in these properties to determine acceptance criteria that would be established to meet allowable stress limits and probabilities of failure.

The NRC staff finds the process acceptable because it will rely on the results of the qualification program to establish acceptance criteria for the as-manufactured graphite to meet allowable stress limits and probabilities of failure. Although Section III Division 5 cites ASTM D7219-08 as an acceptable graphite specification, the staff finds it acceptable to set a specification based on the needs of a specific reactor design because this method will set acceptance criteria for graphite materials to be used in the reactor based on test data, property variance, and design-specific requirements for graphite properties in both the power and non-power test reactors.

TR Section 4.1, <u>"Irradiation Environment"</u>

This section describes the graphite reflector, the temperature and fluence ranges it is expected to see during operation. Kairos states that the **[** [redacted] **]** as the qualification envelope. This information is only a description of the reflector and therefore the NRC staff did not evaluate this part of the TR.

TR Section 4.2, <u>"ASME Irradiation Qualification Requirements for Structural Graphite"</u>

TR Section 4.2.1, <u>"Irradiated Basic Properties"</u>

This section of the TR discusses the parts of the ASME Code which require irradiated test data for graphite qualification. KP provides a list of basic irradiated properties needed to qualify the ET-10 grade of graphite.

The NRC staff finds the list of irradiated graphite properties acceptable because it contains the required properties of Articles HHA-2220, "Irradiated Material Properties," (which the staff found acceptable as per NUREG-2245 section 3.24.2) and HHA-III-3000, "Irradiated Graphite" (which the staff found acceptable as per NUREG-2245 section 3.27.3). Additionally, this section states that the operating temperature range of the graphite will be enveloped by the test data, and have maximum temperature test intervals of 200ºC, which are consistent with Section III Division 5 requirements. The requirement to obtain the creep coefficients of irradiated graphite in HHA-III-3300, "Irradiated Graphite" is addressed in Section 4.2.2 of the KP Graphite Qualification Program.

TR Section 4.2.2, <u>"Irradiated Creep Properties"</u>

This section of the TR discusses how KP intends to address Section III Division 5 requirements for irradiated creep data for graphite qualification. KP states that the irradiation-induced creep coefficient(s) and the effect of creep strain on the CTE and elastic modulus will be determined as part of the qualification testing.

The NRC staff finds this approach acceptable because measurement of the irradiation-induced creep coefficient and the effect of creep strain on the CTE and elastic modulus are required by HHA-2220 and HHA-III-3300. In the NRC staff's endorsement of HHA-2220 (NUREG-2245 section 3.24.2), the staff noted that more than one creep coefficient may be needed to model the irradiation creep response. Therefore, the staff finds that it is acceptable for KP to determine multiple creep coefficients.

TR Section 4.3, <u>"Irradiation Qualification Programs"</u>

In this section of the TR, KP states that the irradiation qualification program for the graphite material will rely on a combination of historical data, existing data, and additional data from irradiation testing. These data will create a qualification envelope that KP will demonstrate bounds the operating conditions for the power and non-power test reactor designs. KP also stated that the data will be used to estimate the turnaround fluence.

The NRC staff reviewed this section of the TR and finds it is consistent with Section III Division 5 requirements because the KP irradiation qualification program will rely on historical data as well as additional testing to gather required irradiated properties. This data will bound the operating conditions for both the power and non-power test reactors (Limitation and Condition 2.c). Additionally, the staff notes that the use of irradiated data to estimate the turnaround fluence is necessary to model changes in graphite properties (e.g., creep) and ensure there is margin to maintaining component integrity. Therefore, the staff finds that this approach is acceptable subject to Limitation and Condition 2.d, which requires an applicant to provide to the staff the turnaround fluence as a function of irradiation temperature for its evaluation of the reflector design and lifetime. Turnaround fluence is important for the NRC staff to evaluate operational lifetime of the graphite component in conjunction with other considerations, such as surveillance, monitoring, inspection, design margin, and damage tolerance (including consequences of failure). This Limitation and Condition is required because changes to graphite properties become more significant after turnaround and typically have greater associated uncertainties.

TR Section 4.3.1, "Irradiation Qualification Envelope and Program for a Power KP-FHR"

TR Section 4.3.1.1, "Basic Properties"

This section of the TR describes how the irradiation qualification program for basic properties conforms to Section III Division 5 requirements. It also states that the irradiation data needed to demonstrate consistency with Section III Division 5 requirements has been collected by ORNL using the ASTM standards as described in the TR. The TR states that this data will be used to create a qualification envelope for the basic irradiated properties required by Section III Division 5. Additionally, this section of the TR states that the method to determine the qualification envelope for each property will use the ORNL irradiation data, fit a model as a function of temperature and fluence (described in Appendix C of the topical report), and account for uncertainties the model fit.

The NRC staff reviewed this section of the TR and finds it consistent with Section III Division 5 requirements for qualification of irradiated graphite. The data include the irradiated graphite properties required by Section III Division 5 HHA-II-4000 and HHA-III-3300, which were found acceptable by the NRC staff in NUREG-2245 Sections 3.26.4 and 3.27.3. Irradiation creep is discussed in Section 4.3.1.2 of this SE. The staff finds the test data provided in Campbell et al. are acceptable and satisfy the qualification envelope of the KP-FHR as defined in Section III Division 5 HHA-2131(a), "Design Specifications," which was found acceptable by the staff in NUREG-2245 Section 3.24.2. Test data is available that bounds the qualification envelope **[[**[redacted]**]]** fluence for the basic properties described in the TR. The test data is subject to Limitation and Condition 9, which requires an applicant to demonstrate plant operating conditions (i.e., temperature and dose) are bounded by this data or collect additional irradiation data otherwise. The staff confirmed that the irradiated graphite test data that will be used to populate the MDS for the KP graphite will be reported in accordance with ASTM C625-05, "Standard Practice for Reporting Irradiation Results in Graphite" as required by HHA-III-3300, "Irradiated Graphite." The applicant will demonstrate irradiated graphite test data meet the requirements of HAB-3125,"Subcontracted Services" HAB-3127,"Subcontracted Testing Services" (endorsed in NUREG-2245 section 3.2.3) subject to Limitation and Condition 10, and HHA-III-2000 for irradiation testing performed by Campbell et al. Section 3.2 of this SE describes the NRC staff evaluation of the process to qualify a grade of graphite using historical data as per Section III Division 5 Article HHA-III-5000. The same rationale applies to the process to use historical irradiated data to qualify a grade of graphite, and therefore the staff finds it acceptable to use the ORNL irradiation data to qualify the ET-10 graphite. This is subject to Limitations and Conditions 9 and 10, to demonstrate applicability of the data to the KP-FHR design and qualification envelope.

The NRC staff finds it acceptable to use the ORNL irradiation data to model each of the irradiated graphite properties described in Section 4.3.1.1 and Appendix C of the TR. This is acceptable because KP will model the property as a function of both temperature and fluence and the uncertainty of the model is accounted for in each of the parameters modeled.

The NRC staff finds that it is acceptable to use the test data described in the TR subject to Limitation and Condition 6, which requires an applicant to demonstrate that appropriate uncertainties were accounted for, and the final graphite reflector design has sufficient margin to accomplish its safety function(s) after consideration of uncertainties in property data. This is necessary because irradiated graphite test data is subject to non-trivial uncertainties and data scatter, which could impact property values, and changes with increasing dose and temperature.

TR Section 4.3.1.2, "Irradiation Creep Properties"

In this section of the TR, KP describes the irradiation creep testing program.
The description includes test temperatures, fluence, applied stresses, the test matrix, and post-irradiation examination.

The NRC staff finds the proposed creep testing program acceptable because it meets the requirements of HHA-III-3300 (b-f), "Irradiated Graphite," (endorsed in NUREG-2245 Section 3.27.3) as the proposed tests will allow KP to determine creep coefficient(s) and the impact on the CTE and Young's modulus. The proposed testing program is also consistent with the Section III Division 5 requirements for the qualification envelope, as the creep test conditions will bound operating temperature-fluence qualification envelope of **[[** [redacted] **]]** fluence. This is because irradiation creep test conditions will be conducted between 500 and 700°C and at fluences from 0 to 20-30x10^{21} n/cm^2. This testing program is also subject to Limitation and Condition 9, which requires an applicant referencing this TR to demonstrate that irradiation data bounds plant operating conditions for temperature and fluence. If the data is not bounding, an applicant may need to generate additional irradiation data.

The NRC staff found the minimum number of creep test samples in the program to be acceptable, provided test conditions are sufficiently controlled to ensure test temperature and fluence meet targeted test parameters, test results demonstrate reasonable consistency and precision, tertiary creep can be identified from test results if it occurs (Limitation and Condition 2.f), and the data are sufficient to develop an acceptable creep model (Limitation and Condition 8). Additionally, the NRC staff finds the proposed number of creep samples acceptable, because it is consistent with previous graphite irradiation creep experiments, which have generated data that is consistent with creep rate models (Windes, et. al., 2019).

The NRC staff finds that the post-irradiation examination is acceptable because the creep strain, and its effect on CTE and Young's modulus, will be measured; this examination is subject to Limitation and Condition 11, which requires that all dimensional changes for the specimens be measured and recorded.

TR Section 4.3.2, "Irradiation Qualification Envelope and Program for a Non-Power KP-FHR"

TR Section 4.3.2.1, "Basic Properties"

This section states that the irradiation qualification program for the basic properties for the non-power reactor is the same as for the power reactor. Therefore, the NRC staff finds this acceptable based on the evaluation in section 4.3.1.1 of this SE. This is acceptable because the same grade of graphite will be used for both the power and non-power test reactor, and because the irradiation qualification envelope for the power reactor will bound the non-power reactor.

TR Section 4.3.2.2, "Irradiation Creep Properties"

This section of the TR describes the proposed approach to determine creep coefficient(s) for the non-power reactor. KP proposed to develop a model for pre-turnaround graphite based on existing irradiation creep data and fitting a simple model to the data as described in the TR. Additionally, the TR states that the irradiated property data described in Section 4.3.1.1 of the TR will be used to calculate a turnaround fluence for the non-power reactor. This will be used to verify that no portion of the graphite reflector exceeds the turnaround fluence.

The NRC staff reviewed this section and finds the approach acceptable because the proposed creep model for primary and secondary creep is adequate, acceptable, and consistent with a well-established creep model of irradiated graphite. The NRC staff finds it acceptable to use the referenced data to develop a steady-state creep coefficient subject to Limitation and Condition 12.b. This condition states that an applicant referencing this TR will need to demonstrate that a conservative creep coefficient can be derived from this data and show margin to ensure the graphite components can perform their safety functions. Additionally, the staff finds this approach acceptable because KP states that that it will calculate the turnaround fluence from the ORNL test data using two approaches. The smallest fluence will then be compared to the largest anticipated operating fluence to ensure that the non-power test reactor does not reach turnaround (Limitation and Condition 2.g). This approach is acceptable subject to Limitation and Condition 12.c, which requires an applicant to demonstrate that the non-power test reactor will not reach turnaround of the graphite components. This is because creep behavior follows different trends post-turnaround and, therefore, use of this data and proposed correlations may not be appropriate if the graphite components reach turnaround.

Finally, the staff finds this approach acceptable, because it is only used for the non-power test reactor (Limitation and Condition 12.d). The approach to irradiation creep for the non-power reactor is also subject to Limitation and Condition 12.e, which requires that an applicant demonstrate that irradiation-induced stress-driven failure of graphite would not occur in the component's lifetime. Additionally, creep test data developed prior to the development of H-451 graphite is not applicable for modeling the creep response of ET-10, because graphite developed before H-451 are not sufficiently isotropic to be analogous to ET-10 (Limitation and Condition 12.a).

TR Section 5.1, "Interaction of Graphite and Flibe"

The following sections evaluate several potential interactions between the graphite reflectors, and the Flibe coolant. Although Section III Division 5 does not yet contain specific rules for qualification of graphite in molten salts, NUREG-2245 Section 3.24.1, "Article HHA-1000 Introduction," states that the NRC staff believes it is appropriate to evaluate the coolant interaction when applicable. Therefore, it is still necessary to demonstrate that graphite components are compatible with their environment and will be able to adequately perform the necessary safety functions. Additionally, the TR states that the interaction of Flibe and graphite is limited to the structural graphite in the reflector, and that the qualification of graphite in the TRISO fuel pebbles is outside the scope of this TR. The NRC staff finds this acceptable because the effects of Flibe on materials used for TRISO fuel should be assessed in fuel qualification and not in structural graphite qualification.

TR Section 5.1.1, "Molten Salt Infiltration in Graphite"

In this section of the TR KP states that the molten salt infiltration testing plan will follow ASTM D8091-16, "Standard Guide for Impregnation of Graphite with Molten Salt." Additionally, KP provides a description of the infiltration test unit and its components. The TR also outlines the testing conditions to include a test temperature of 750ºC and a range of test pressures of 100 to 500 kPa, which is up to 2.5 times greater than the pressure at the bottom of the power reactor vessel, per available design details.

The NRC staff evaluated the potential for Flibe to infiltrate the graphite given KP-FHR operating conditions, as well as potential impacts on mechanical properties of the graphite. The TR provides a description of infiltration testing to determine whether Flibe infiltration impacts the mechanical properties of the graphite reflector under KP-FHR conditions. The staff finds that the use of ASTM D8091-16 is acceptable because it is a consensus standard for the tests proposed by KP in this TR. The staff finds that the infiltration test plan is acceptable because the infiltration temperature is 50°C higher than the maximum temperature of the graphite reflector under normal operation conditions and the test pressure exceeds the pressure on the graphite reflector of the KP-FHR by a factor of approximately 2.5. The use of a test pressure greater than the anticipated operating pressure is conservative because it is expected to induce greater Flibe infiltration than would be expected for the lower anticipated operating pressure.

TR Section 5.1.2, <u>"Effect of Molten Salt Infiltration on Graphite Mechanical and Thermal Properties"</u>

This section of the TR describes how proposed testing by KP will validate the effects of molten salt infiltration on graphite mechanical properties. The TR states that after infiltration the salt will be removed, and the strength of the graphite will be measured. It also states that the strength will be compared pre-and post-infiltration to determine whether there is an effect on the graphite strength, and the magnitude of any effect.

The NRC staff finds the testing program to confirm the impact of Flibe on graphite acceptable. The testing program requires infiltration of the Flibe salt into representative samples of the graphite at conservative infiltration pressures. Residual salt in the graphite will be removed, prior to mechanical testing. This approach is acceptable, as Flibe salt is not expected to solidify within graphite pores during operation of the reactor and removal of the salt will ensure the strength of only the graphite (and not the graphite combined with salt) is measured. Similarly, no changes to the thermal properties of the graphite will occur if the Flibe salt remains liquid. The infiltration testing is also acceptable because KP stated that it will measure pre-and post-infiltration strength to determine what effect, if any, molten salt infiltration has on the graphite strength.

TR Section 5.1.3, <u>"Chemical Compatibility of Fluoride Molten Salt with Graphite"</u>

In this section of the TR, KP describes how the molten salt coolant in the power and non-power test reactors may interact with the graphite reflector. Although KP states an interaction is not likely to occur, the TR states that KP will characterize the graphite surface in contact with Flibe to confirm that there is no significant degradation from graphite interactions with Flibe.

The NRC staff evaluated this part of the qualification methodology and finds it acceptable to determine compatibility of Flibe with graphite because KP states that it will characterize the potential interaction between Flibe and graphite to confirm it does not cause significant degradation. This is acceptable because ET-10 graphite will be exposed to Flibe in order to determine whether there are interactions that cause graphite degradation. If significant degradation of the graphite is found, then an applicant referencing this TR will need, to account for this degradation in graphite component design subject to Limitation and Condition 13.

TR Section 5.1.4, <u>"Effect of Infiltration on Neutronics"</u>

This section describes potential effects of Flibe infiltration into graphite on core neutronics. In this section of the TR, KP states that no testing to determine the effect of Flibe infiltration into graphite is needed for this qualification plan.

The staff finds it acceptable to not perform additional testing related to effects of Flibe intrusion into graphite on neutronics as part of the qualification program since this testing is not needed for qualification of structural graphite. The NRC staff did not assess the impacts of Flibe intrusion on neutronics as part of this TR. Effects of Flibe infiltration into the graphite, and subsequent impacts on neutronics, may be considered as part of a license application.

TR Section 5.2, <u>"Abrasion and Erosion"</u>

This section of the TR describes how abrasion and erosion can be the cause of degradation of the graphite in the power and non-power test reactors. Degradation can be caused either by relative motion between pebbles sliding against the graphite reflector, or by flowing Flibe. KP states that it will perform tribology testing with pebbles against ET-10 graphite in Flibe to quantify wear rates of the graphite material. It will also confirm erosive effects through inspections of the corrosion test system which will include graphite samples in moving Flibe.

The NRC staff finds this approach acceptable because KP will perform confirmatory testing to quantify the impacts of abrasion and erosion on the graphite reflector. The method to determine potential erosion is acceptable, because KP will examine graphite that has been exposed to moving carbon matrix pebbles to determine if erosion occurred. The method to determine abrasion is acceptable, because KP stated graphite exposed to moving Flibe in the rotating cage loop test system will be examined to confirm that there is no significant loss of volume due to erosion. These tests will provide data needed to determine wear rates of the graphite reflector. The staff finds that this approach is consistent with ASME Code Article HHA-3143, "Abrasion and Erosion," and is, therefore, acceptable. Additionally, it is consistent with the staff's endorsement of HHA-3143 NUREG-2245 and the staff comments that abrasion and erosion may be applicable in molten salt environments. This is subject to Limitation and Condition 2.h.

TR Section 5.3, <u>"Oxidation of Graphite"</u>

This section of the TR describes the oxidation assessment portion of the qualification methodology. The TR states that KP will conduct design-specific testing and analysis to determine the effect of oxidation on weight loss and strength reduction in the ET-10 graphite. This section describes the tasks that will be performed in order to assess the impact of oxidation.

The NRC staff finds this approach acceptable, as it is consistent with Section III Division 5 HHA-3141, "Oxidation," and HHA-III-3200, "Oxidized Graphite," (endorsed in NUREG-2245 sections 3.24.4 and 3.27.3, respectively) with exceptions, as discussed below. The proposed testing will include oxidation analysis to determine reduction in strength as a function of weight loss, which is consistent with Section III Division 5 requirements. It is necessary for KP to perform an analysis to determine the effect of weight loss due to oxidation on graphite strength, because the NRC staff endorsement of Section III Division 5 noted that Figures HHA-3141-1 and -2 are not generically applicable to all graphite grades. This is described in Section 3.24.3 of the staff's endorsement of HHA-3141 Section III Division 5. Because the staff did not endorse the use of Section III Division 5 Figures HHA-3141-1 and -2, in order to qualify ET-10 graphite, the effects of oxidation need to be determined through testing. Although Section III Division 5 also requires the oxidized elastic modulus and thermal conductivity for the Materials Data Sheet (MDS), the KP methodology proposes to use a conservative value for the elastic modulus and does not credit heat transfer from oxidized graphite. This deviation from the code is acceptable because a conservative elastic modulus value will be used and because thermal conductivity is not needed for the reflector design. If oxidized thermal conductivity is needed for the design, it will need to be determined outside the scope of this program consistent with Limitation and Condition 14.

Oxidation testing will be performed within the kinetically controlled regime (550–750°C) in conformance with ASTM D7542," Standard Test Method for Air Oxidation of Carbon and Graphite in the Kinetic Regime." The staff finds the use of ASTM D7542 acceptable, because it is the most widely accepted industry consensus standard for the oxidation of graphite. The proposed test temperature range is acceptable because it is consistent with service conditions per HHA-III-3200 requirements and includes testing in the kinetically controlled regime. Compressive strength will be measured as part of the testing program, which the staff finds acceptable, as it is required by HHA-III-3200, "Oxidized Graphite." The sponsor will use the unoxidized values for dynamic elastic modulus for oxidized graphite in their design analysis. The staff finds this approach acceptable, because the use of unoxidized values will yield more conservative values in the stress analyses of the graphite reflector relative to the oxidized graphite. The sponsor proposed to not measure the thermal conductivity of oxidized graphite. The staff finds this acceptable, because the TR states that the design of the KP-FHR does not consider heat dissipation from the top portion of the reflector to the cover gas. Therefore, thermal conductivity of the graphite will not impact the safety analyses of the graphite reflector during the oxygen ingress accident scenario, where the top portion of the graphite reflector is oxidized.

Additionally, the TR states that the uncovered portions of the reflector that would be subject to oxidation in the event of air ingress are not irradiated. TR Section 7.2, "Limitations," states that the reflector and reactor vessel design preclude coincident effects of oxidation and irradiation, and this will be described in a future license application. Therefore, the NRC staff finds it acceptable that testing does not consider coincident irradiation and oxidation, subject to Limitation and Condition 1 of this SE. This is also subject to future NRC staff review and approval of the design features meant to preclude coincident oxidation and irradiation.

TR Section 6, <u>"Seismic Response"</u>

The TR states that the seismic response is outside the scope of the graphite qualification report. The NRC staff finds this acceptable as seismic response analyses to qualify a grade of graphite are not covered by Section III Division 5 and will require detailed design information that is not covered by this TR, to perform. Further, the TR states that seismic qualification of graphite will be addressed in a separate submittal.

5.2 Evaluation Summary

Based on the technical evaluation above, the NRC staff has reasonable assurance that the graphite material qualification described in this TR meets KP-FHR PDCs, 1, 34, 35, and 74, in part. The qualification program partially satisfies KP-FHR PDC 1 because qualification data will be captured under appropriate quality programs, consistent with the requirements in Section III Division 5. KP-FHR PDCs 34, 35, and 74 are partially met because the data from this qualification program provide reasonable assurance that the graphite components can be designed so their geometry allows for passive residual heat removal (including during postulated accidents), and allow for sufficient insertion of neutron absorbers to provide for reactor shutdown, over the qualification envelope (e.g., temperature, dose, oxidation conditions) for both the non-power test reactor, and the power reactor. This is based on the NRC staff's conclusion that the qualification program will allow KP to collect the necessary data as required by Section III Division 5 to design the graphite components, and because testing will be performed to evaluate environmental effects (e.g., coolant infiltration and interactions, and oxidation). This data is needed to ensure the graphite components maintain their functionality over the anticipated conditions (e.g., temperature, dose, coolant) for both the non-power test reactor, and the power reactor.

The staff has reasonable assurance the qualification program meets the requirements listed in Section 4.1 described above, as they relate to the qualification of graphite components, because the program describes the use of generally accepted engineering standards, unique safety features, novel design features, and the relation of facility design to the PDC.

6.0 LIMITATIONS AND CONDITIONS

An applicant may reference the TR only if the applicant demonstrates compliance with the following limitations and conditions. Some of the Limitations and Conditions below are not referenced to specific sections of the NRC staff SE, because there are some design details that were not available at the time the staff reviewed this TR and will need to be reviewed by the NRC staff to ensure applicability of this TR.

1. The NRC staff finds that it is necessary to limit applicability of the TR consistent with the limitations listed by Kairos in Section 7.2, "Limitations," of the TR. An applicant referencing this TR will need to demonstrate that these limitations are met at the time of a license application, subject to NRC staff review and approval.

2. In the TR, KP described several action items to be performed in the future. These action items, as described below, are subject to NRC staff review and approval once submitted with an application:

    a. Section 3.1.1 states that KP will perform low cycle fatigue testing to demonstrate that ET-10 follows the same fatigue trends as H-451 and PGX.
    b. Section 3.2 states that in order to use historical data, KP will verify that the historical data is applicable as per the process described in Appendix B of the TR.
    c. Section 4.3 states that the qualification envelope from the irradiation data will be shown to envelope the operating conditions of the reactor.

d. Section 4.3 states that the ORNL irradiation data will be used to estimate the turnaround fluence with confidence intervals.
e. Section 4.3.1.2 states that irradiation creep target test temperatures are selected to bound operating conditions, and that the power reactor lifetime is bounded by irradiation creep testing conditions.
f. Section 4.3.1.2 states that tertiary creep will be identified if it occurs.
g. Section 4.3.2.2 states that a conservative turnaround fluence limit will be calculated, and that it will be shown that the non-power reactor does not exceed this limit.
h. Section 5.2 states that KP will quantify wear rates of the graphite via tribological testing with the carbon pebbles and confirm that no significant loss of volume occurs due to erosion via visual inspection of graphite exposed to moving Flibe.
i. Section 7.2 states that the design will preclude the coincident effects of oxidation and irradiation that may inhibit the reflector from performing its safety function.

3. The NRC staff's review and approval of this TR was conducted against the 2017 Edition of Section III Division 5 and the associated staff endorsement, and associated conditions. Therefore, approval of this TR is only applicable for the 2017 Edition and any deviations not described in this TR or use of updated BPVC versions would require separate review and approval.

4. The approval of this qualification methodology is only applicable to the Kairos' power and non-power test reactor designs. Graphite will experience different changes to its properties as a function of its operating environment (e.g., temperature, fluence, coolant). Additionally, graphite components may have different safety functions and damage tolerance depending on the specific reactor design. Therefore, the specifics of this methodology may not be applicable to other designs.

5. If a salt other than the Flibe used as the primary coolant (e.g., nitrate) salt is used in the intermediate loop for either the power or non-power reactor designs, an applicant referencing this TR must demonstrate that no adverse effects of graphite exposure to the intermediate salt will occur and quantify these effects to demonstrate that the graphite components can perform their safety functions.

6. The approval of this TR is limited to the qualification testing methodology for ET-10 graphite. The NRC staff did not review topics such as the reflector design, margins, monitoring, surveillance, or inspection programs. The approval of this TR does not include a determination of an acceptable operating life for the graphite components. An applicant will need to demonstrate an acceptable graphite component lifetime based on intended function of the graphite blocks, damage tolerance, reflector design, margins, monitoring, surveillance, and/or inspection programs.

7. An applicant referencing this TR must describe how flaw acceptance will occur without using fracture toughness.

8. The NRC staff does not currently accept the use of any known documented creep model in literature for modeling tertiary creep of graphite. The staff does not accept the use of the United Kingdom Atomic Energy Authority (UKAEA) creep model, as it was developed on the irradiation response of Gilsonite. Therefore, an applicant referencing this TR will need to develop its own creep model and demonstrate that it adequately models creep behavior for ET-10 graphite. This includes identification of tertiary creep if it occurs and determination of creep coefficients.

9. An applicant referencing this TR must demonstrate that the irradiated test data for both basic properties and creep properties bounds the temperature and fluence profiles for the qualification envelope without extrapolation of the data. If this cannot be demonstrated, then the applicant will be required to obtain additional irradiated test data to bound anticipated operating conditions (i.e., temperature and fluence combinations).

10. An applicant referencing this TR must demonstrate how the data (irradiated and unirradiated) meet the quality assurance requirements in Section III Division 5 (e.g., HAB-3125, 3127, 3800, and 4000) for graphite qualification for the power reactor design.

11. Dimensional changes of creep samples must be measured and recorded in both the with grain (WG) and against grain (AG) directions, as required by HHA-II-4000, Detailed Requirements for Derivation of the Material Datasheet – Irradiated Material Properties.

12. The following Limitations and Conditions apply to creep modeling for the non-power reactor:

    a. An applicant referencing this TR must demonstrate that a creep model can be developed for the non-power reactor without using creep data that pre-dates H-451.
    b. Demonstrate that a conservative creep coefficient can be derived from data described in Section 4.3.2.2 of the TR and show margin to ensure that the graphite components can perform their safety functions.
    c. The proposed creep model is only acceptable because it is limited to applications before turnaround. Additionally, an applicant referencing this TR must submit the turnaround fluence to the NRC staff for review to confirm that the non-power reactor does not reach turnaround.
    d. Development of a creep model based on the historical data referenced is only acceptable for a non-power reactor.
    e. As stated in Section 4.3.2.2 of the TR, an applicant must demonstrate that no irradiation-induced stress-driven failure of graphite will occur pre-turnaround.

13. If results of the testing described in Section 5.1.3 of the TR indicate that there is significant degradation of graphite exposed to the Flibe, then this effect must be accounted for in the design of the graphite reflector.

14. If properties that are not included in this qualification program are needed for the graphite reflector design, an applicant referencing this TR must perform the necessary testing to obtain properties not included in the qualification program.

7.0 CONCLUSION

The NRC staff has determined that the KP TR “Graphite Material Qualification for the Kairos Power Fluoride-Salt Cooled High-Temperature Reactor,” (KP-TR-014, Revision 3) provides an acceptable methodology to qualify the ET-10 graphite for use in the power and non-power test reactor designs. This methodology is acceptable based on the NRC staff’s technical evaluation, which determined that the methodology is generally consistent with applicable portions of the ASME Code, with departures as evaluated by the staff, related to graphite material qualification, and associated data requirements. The described methodology will characterize the effects of the environment (i.e., molten salt and pebbles) on graphite, will provide data that can be used to demonstrate compliance, in part, with KP-FHR PDCs 1, 34, 35, and 74, and will satisfy the requirements of 10 CFR 50 and 52, as described in Section 4.1 above, with respect to contents of applications, subject to the limitations and conditions discussed above. Accordingly, the NRC staff concludes that the KP TR “Graphite Material Qualification for the Kairos Power Fluoride-Salt Cooled High-Temperature Reactor,” complies with the applicable NRC regulations and can be used to qualify ET-10 graphite for use in a KP-FHR design.

8.0 REFERENCES

1. American Society of Mechanical Engineers (ASME), Section III, Division 5, “High Temperature Reactors,” 2017.

2. NRC, NUREG-2245, “Acceptability of ASME Code Section III, Division 5, High Temperature Reactors,” dated January 2023 (ML23030B636).

3. NRC, Regulatory Guide (RG) 1.87, “Acceptability of ASME Code Section III, Division 5, High Temperature Reactors,” Revision 2, dated January 2023 (ML22101A263).

4. Technical Letter Report, “Technical Input for the U.S. Nuclear Regulatory Commission Review of the 2017 Edition of ASME Boiler and Pressure Vessel Code, Section III, Division 5, “High Temperature Reactors”: Subsection HH, “Class A Nonmetallic Core Support Structures,” Subpart A, "Graphite Materials,"" dated December 2020 (ML20344A001).

5. Campbell, Anne A., Katoh, Yutai. and Selby, Aaron P., "Report on Effects of Irradiation on Material ETU-10," ORNL/TM-2017/737, dated January 2017, NON-PUBLIC.

6. Windes, William E., Rohrbaugh, David T., Swank, W. David, “AGC-3 Irradiation Creep Strain Data Analysis,” dated July 2019.

7. ASTM International, ASTM C625-05, "Standard Practice for Reporting Irradiation Results in Graphite," 2005.

8. ASTM International, ASTM D7219-08, "Standard Specification for Isotropic and near-Isotropic Nuclear Graphites," 2008.

9. ASTM International, ASTM D8091-16, "Standard Guide for Impregnation of Graphite with Molten Salt," 2016.

10. ASTM International, ASTM D7542-21, "Standard Test Method for Air Oxidation of Carbon and Graphite in the Kinetic Regime," 2021.