UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, DC 20555 - 0001

February 13, 2023

Mr. Daniel H. Dorman
Executive Director for Operations
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: DRAFT SAFETY EVALUATION OF THE KAIROS TOPICAL REPORT, KP-TR-014, REVISION 4, "GRAPHITE MATERIAL QUALIFICATION FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH-TEMPERATURE REACTOR"

Dear Mr. Dorman:

During the 702nd meeting of the Advisory Committee on Reactor Safeguards, February 1-3, 2023, we completed our review of Kairos Topical Report, KP-TR-014, Revision 4, "Graphite Material Qualification for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor," and the associated NRC staff evaluation (SE). Our Kairos Subcommittee also reviewed this matter on January 12, 2023. During these meetings, we had the benefit of discussions with NRC staff and representatives from Kairos Power, LLC (Kairos). We also had the benefit of the referenced documents.

CONCLUSION AND RECOMMENDATION

1) The Kairos methodology to qualify safety-related graphite is technically sound. Its applicability should be governed by the limitations and conditions in the staff SE.

2) The staff SE should be issued.

BACKGROUND AND PURPOSE

The purpose of this topical report is to describe the methodology that Kairos will use to qualify safety-related graphite for components in their non-power and power reactor Fluoride High Temperature Reactors (FHRs). The approach leverages the requirements in the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (BPVC), Section III, Division 5. For the non-power reactor, Kairos will use ANSI/ANS-15.8-1995 for their quality assurance plan, which is endorsed by the NRC for test reactors. For the power reactor, they will use the National Quality Assurance (NQA-1) standard as required by the BPVC.

There are four principal design criteria (PDC) that are relevant to the graphite reflector assembly: quality assurance (PDC-1), residual heat removal during normal operation and anticipated operating occurrences (PDC-34), residual heat removal during postulated accidents (PDC-35), and ensuring physical geometry (flow paths) for heat removal and enabling insertion of negative reactivity (PDC-74).

Kairos has selected ET-10, a Japanese fine-grain isostatically molded graphite for their reflector. This grade of graphite has less material property and irradiation performance data than other grades available today. The ultra-fine grain nature of this graphite will minimize the potential for Flibe[1] infiltration based on the ultra-fine grain graphite that was used in the Molten Salt Reactor Experiment (MSRE) but is no longer available today.

QUALIFICATION PLAN

The objectives of the Kairos graphite qualification plan are to: (1) confirm the unirradiated mechanical and thermal properties of ET-10, (2) confirm that ET-10 will maintain its structural integrity under neutron irradiation, and (3) confirm ET-10 is compatible with Flibe.

The forming and densification processes used during graphite fabrication result in graphite billets that have natural variations in material properties within a billet. Variations have also been seen from billet to billet within a batch and from production lot to production lot.

The intra-billet and billet-to-billet variation in key material properties will be characterized using samples, both with the grain and against the grain, from numerous locations in multiple billets. Key material properties to be measured at room temperature include: flexural, tensile and compressive strength; bulk density; and dynamic Young's and shear moduli. The thermal conductivity and coefficient of thermal explanation (CTE) will be measured in temperature increments between 25 and 825 °C. No fracture toughness testing is planned. This could be an issue with code acceptance when interpreting defect data from inspections.

Lot-to-lot variation will be characterized using historical data obtained over decades of fabrication provided by the graphite vendor. Purity is also an important characteristic relative to both oxidation behavior (i.e., due to catalytic effects of impurities on oxidation) and neutron absorption. Available data suggest ET-10 can meet the high purity specification typical of nuclear graphite. This unirradiated graphite characterization portion of the qualification program is the same for both the power reactor and the non-power reactor Kairos FHR.

For the Kairos power reactor, fluences will be very high (10 to 25 dpa) and will exceed the turnaround fluence (i.e., the fluence at which graphite changes from volumetric shrinkage to swelling). Because the turnaround fluence and irradiation-induced material property changes are a function of temperature and graphite grade, neutron exposure of ET-10 is planned to characterize changes in physical dimensions, strength, CTE, elastic modulus, and thermal conductivity. Special test rigs using stressed and unstressed samples will be irradiated to characterize irradiation-induced creep and the effect of creep strain on both CTE and the elastic modulus. A range of reactor-relevant temperatures and fluences are planned for the irradiation campaign. The methodology will also leverage the historical database and the existing literature data on irradiation creep. For the non-power reactor, no irradiation testing is planned because the peak end-of-life fluence on the graphite reflector is less than the turnaround fluence so that existing data adequately capture the anticipated creep behavior.

---

[1] Flibe is a eutectic mixture of LiF and BeF2.

A series of tests are planned to evaluate the environmental compatibility of graphite and Flibe. Infiltration is not expected in the non-power reactor version of the Kairos FHR because the pressure in the salt is below that at which infiltration is anticipated. For the power reactor, Kairos FHR, the pressure of the salt is higher, and some infiltration is anticipated. As a result, tests are planned to measure the infiltration of Flibe into graphite over a range of reactor-relevant temperatures and salt pressures. Other potential chemical effects due to fluorination, intercalation, and chromium carbide formation were evaluated and found not to be a concern for the Kairos designs. Abrasion and erosion testing is planned to confirm the lack of erosion with the structural reflector graphite. (More erosion is anticipated for the fueled pebbles since the graphite matrix of the pebble is much softer than the graphite reflector.) Oxidation testing is planned, and analytic evaluations of oxidation and its effect on the weight loss and strength of the graphite will be performed as part of the safety analysis. Any testing related to seismic qualification of the graphite is explicitly outside the scope of this topical report.

STAFF SAFETY EVALUATION

The staff found that the topical report provides an acceptable methodology to qualify ET-10 graphite. They include 26 limitations and conditions in their safety evaluation. Many of the limitations relate to confirming that the reactor operating conditions (i.e., temperature and fast neutron fluence) are bounded by the experimental database (both historic and those planned by Kairos), especially with respect to the turnaround fluence. If the reactor conditions are outside of the database envelope, then new data would be required. Other important limitations relate to what actions are required in the event testing does not confirm expectations and assumptions noted in the topical report (e.g., substantial interaction between Flibe and graphite, erosion greater than expected, tertiary creep observed in ET-10 at high fluence, or intermediate salt compatibility with graphite). In these cases, the effect must be considered in the design or additional data must be generated.

SUMMARY

The purpose of this topical report is to describe the methodology that Kairos will use to qualify safety-related graphite for components in their non-power and power reactor FHRs. The methodology proposes characterizing material properties of unirradiated graphite, testing to characterize the change in material properties under neutron irradiation, and environmental compatibility testing.

The Kairos methodology to qualify safety-related graphite is technically sound. Its applicability should be governed by the limitations and conditions in the staff SE. The staff SE should be issued.

No response to this letter is required.

Sincerely,

Joy L. Rempe Signed by Rempe, Joy on 02/13/23

Joy L. Rempe
Chairman

REFERENCES

1. Kairos Power LLC, "Graphite Material Qualification for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor," Topical Report KP-TR-014-NP, Revision 4, September 2022 (ML22259A145)

2. U.S. Nuclear Regulatory Commission, "[Redacted] Draft 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," December 2022 (ML23011A105)

3. American Society of Mechanical Engineers (ASME), Rules for Construction of Nuclear Power Plant Components, High Temperature Reactors, Boiler and Pressure Vessel Code, Section III, Division 5, 2017 Edition

4. ANSI/ANS-15.8-1995, "Quality Assurance Program Requirements for Research Reactors," American Nuclear Society, La Grange Park, IL, reaffirmed September 2005

5. Kairos Power LLC, "Principal Design Criteria for the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor," June 12, 2020 (ML20167A174)

February 13, 2023

SUBJECT: DRAFT SAFETY EVALUATION OF THE KAIROS TOPICAL REPORT, KP-TR-014, REVISION 4, “GRAPHITE MATERIAL QUALIFICATION FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH-TEMPERATURE REACTOR”

Accession No: ML23038A168 **Publicly Available (Y/N):** Y **Sensitive (Y/N):** N
If Sensitive, which category?
Viewing Rights: ☒ NRC Users or ☐ ACRS only or ☐ See restricted distribution

OFFICE	ACRS*	SUNSI Review*	ACRS*	ACRS*	ACRS*
NAME	WWang	WWang	LBurkhart	SMoore	JRempe
DATE	02/7/2023	02/7/2023	02/7/2023	02/10/2023	02/13/2023

OFFICIAL RECORD COPY