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

December 20, 2022

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

SUBJECT: SAFETY EVALUATION OF THE KAIROS TOPICAL REPORT KP-TR-011, REVISION 2, "FUEL QUALIFICATION METHODOLOGY FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH TEMPERATURE REACTOR (KP-FHR)"

Dear Mr. Dorman:

During the 701st meeting of the Advisory Committee on Reactor Safeguards, November 29 - December 2, 2022, we completed our review of the NRC safety evaluation (SE) of Kairos Topical Report KP-TR-011, Revision 2, "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)." Our Kairos Subcommittee also reviewed this matter on October 17, 2022. 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.

RECOMMENDATIONS

1. The topical report and the associated SE should acknowledge two concerns that affect assurance of Tri-structural Isotropic (TRISO) particle silicon carbide (SiC) layer integrity and radionuclide retention in the Kairos FHR designs:

    a. Material compatibility between the Flibe[1] molten salt with impurities (e.g., Fe, Cr, Ni) and the fuel pebble containing TRISO particles, and

    b. Irradiation performance of the Kairos fuel pebbles fabricated at production-scale prior to Hermes operation.

2. The SE should explicitly consider the value of Hermes as a prototype. The results of Hermes operation and the associated fuel surveillance plans should be considered as a compensatory measure to address Recommendation 1.

[1] A eutectic mixture of LiF and Be_2F

3. The SE should explicitly acknowledge how the flexibility provided by the Atomic Energy Act for test reactors factored into the finding for acceptability of the fuel qualification methodology for Hermes.

4. After these items are addressed, the SE should be issued.

BACKGROUND

Kairos has submitted a topical report on fuel qualification that applies to test and power KP-FHRs. The fuel form for Kairos is TRISO-coated uranium oxycarbide (UCO) fuel particles embedded in a carbonaceous matrix in a small pebble. The pebble contains an unfueled core of matrix material surrounded by a spherical annulus of particles in a matrix followed by another unfueled layer of matrix material. This is a unique fuel form compared to traditional larger pebble designs used in German and Chinese high temperature gas cooled pebble bed reactors and cylindrical compacts (rods) used in U.S. and Japanese prismatic high temperature gas cooled reactors (HTGRs).

The Kairos licensing strategy invokes the concept of functional containment. Several barriers are considered: the kernel of the TRISO particles; the TRISO particle inner pyrolytic carbon (IPyC), SiC, and outer pyrolytic carbide (OPyC) layers; and the Flibe coolant. Kairos also anticipates using the concept of Specified Acceptable System Radionuclide Release Design Limit (SARRDL) as part of their design criteria.

KAIROS TOPICAL REPORT

<u>Fuel Qualification Strategy</u>

As part of their strategy, Kairos completed a fuel pebble Phenomena Identification and Ranking Table (PIRT) covering three areas: manufacturing of pebbles and particles, normal operations, and licensing basis events, including events in the pebble handling system. The phenomena ranked to have high, medium, or low importance levels of knowledge were identified and used as a basis for the fuel qualification strategy. The goal is to confirm that fuel particle integrity performance during initial reactor startup and operation will meet or exceed that observed in the Department of Energy (DOE)-sponsored Advanced Gas Reactor (AGR) program.

Key elements of the Kairos fuel qualification strategy include:

1. Lab testing to assess mechanical integrity, buoyancy, and materials compatibility with Flibe using surrogate TRISO fuel particles. The testing also includes compression, impact, and tribology testing of the Kairos pebbles.

2. Irradiation testing if the fuel operating envelope exceeds the testing envelope explored in the DOE AGR irradiation program, as documented in the Electric Power Research Institute (EPRI) Topical Report on TRISO coated particles.

3. Fuel surveillance in the KP-FHR by monitoring the contents of both the cover gas and Flibe coolant for their fission product content, inspecting pebbles in the pebble handling system, and destructively examining select pebbles[2].

Fuel Design and Performance Envelope

The TRISO particles in the KP-FHR use a 425-micron kernel of UCO enriched to 19.55 wt% U-235. While the burnup and other operational performance parameters for the Hermes test reactor are within the AGR testing envelope, the anticipated burnup of the particles in the larger power producing KP-FHR will be significantly higher than was tested in the AGR-2 irradiation[3]. Although the anticipated burnups in the commercial KP-FHR were achieved in the AGR-1 irradiation, the UCO kernel size was 350 microns. The KP-FHR fuel testing for higher burnup will require an irradiation of a statistically significant number of pebbles. While not prototypic, the irradiation will use a helium sweep gas rather than Flibe. The fission gas contents of the helium sweep gas will be monitored to provide direct evidence of fuel performance.

In terms of transient behavior, Kairos will use two limits for assessing fuel performance: (1) keeping the temperature of the SiC layer below 1600°C for long term transients that could lead to SiC layer degradation and radionuclide release, and (2) keeping the temperature of the kernel below 2350°C, the melting point of the carbide phase in the kernel. The topical report provides an excellent description of the current international database on reactivity testing of TRISO particles. In those tests, particles were heated much more rapidly than in the conditions anticipated in graphite-moderated reactor systems. The database indicates that reactivity insertions must be large enough to melt the kernel to induce fuel damage. This corresponds to a threshold of ~ 1000 J/g. As a result, Kairos proposes to limit reactivity insertions to levels less than this damage threshold. The database and some recent modeling results from the literature suggest that no damage is anticipated at insertions of 400 to 600 J/g because the fuel kernel remains below melting and the SiC layer remains in compression. Preliminary analysis from Kairos suggests that reactivity events for Hermes will stay below this damage threshold; thus, Kairos claims no additional reactivity testing is required. For a larger power producing KP-FHR, further justification will be required to determine whether additional reactivity testing is necessary.

Lab Test Program

The lab test program will use surrogate TRISO particles in Kairos pebbles. Pebble crush strength will be measured as will the coefficient of friction and wear (tribology). Infiltration tests are planned to measure the ability of Flibe to penetrate the porosity of the pebble matrix material at relevant temperatures and pressures. The degree of infiltration is a function of the pore size and the pressure. The KP-FHR will operate at pressures below the level at which previous data show infiltration. Materials compatibility testing will be performed to examine interactions between Flibe and the matrix material under both reducing and oxidizing salt conditions. Matrix/air reaction testing at moderate temperatures is also planned. It is not clear in the qualification plan whether the compatibility testing will consider technical specifications limits of impurities in the Flibe and will be performed under flowing conditions.

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[2] Whereas monitoring of the Flibe content for metallic fission products in principle can provide a direct indication of the SiC layer integrity, its usefulness in assessing the condition of the SiC barrier is problematic because the high sorptivity of metallic fission products in the carbon matrix material will limit their release into the Flibe.

[3] Details of the AGR-1 and AGR-2 irradiations are summarized in the EPRI Topical Report

Fuel Manufacturing

The fuel qualification plan will leverage the fuel specification developed in the AGR program. While processes have been developed in the AGR program to produce particles, additional process development is planned to develop the capability to fabricate this unique pebble. Kairos will leverage much of the quality control procedures developed under the AGR program to demonstrate compliance with their fuel specification. Of particular note, the traditional deconsolidation leach burn leach (DLBL) quality control technique will be used to assess SiC integrity and the number of broken particles during fabrication.

STAFF SAFETY EVALUATION

The staff evaluated each element of the fuel qualification plan, including the planned operating window of the fuel relative to the qualification envelope in the approved EPRI topical report on TRISO particles. They also evaluated the proposed lab testing outlined earlier in this letter. The staff found the methodology and testing approach acceptable and concluded it will support fuel qualification for the KP-FHR power and test reactor designs. They imposed one limitation that "future license applications for non-power KP-FHRs will include justification of applicability of this methodology during rapid reactor transient events."

ACRS OBSERVATIONS

The Kairos fuel qualification plan assumes a separation of irradiation effects from all other effects. There is no Flibe present in the proposed fuel pebble irradiation tests, and all testing with Flibe is done without the presence of neutrons. Given the first-of-a-kind application of these two technologies (pebbles and Flibe) together in a reactor operating at high temperature, potential synergistic effects should be addressed.

Of specific concern is the potential effect of impurities present in the Flibe on the fuel behavior. It is well known that transition metals must be kept away from TRISO fuel particles because of the deleterious interaction between those metals and the SiC layer of the particles, which may cause particle failure. As indicated in several references provided in this letter, the literature suggests significant corrosion of the SiC could occur at the temperatures considered in the Kairos design, albeit in different configurations. It is also known that there will be thermal gradient induced corrosion of Fe, Cr, and Ni from the steel in the system because of the differences in chemical potential at the hot and cold legs in the system. Between the hot leg Flibe and the cold leg Flibe sits a pebble bed with massive surface area that could act as a filter for the Fe, Cr and Ni which could then attack the SiC layer in the particles. The exact behavior is difficult to predict because it depends on the mass transfer rates and concentration-, temperature-, and time-dependent chemical kinetics that are not well known. Data are needed to quantify this type of synergistic effect. These data could be obtained in an out-of-pile Flibe loop with surrogate pebbles and representative levels of impurities.

Of greater importance is the lack of any irradiation testing of the actual fueled pebbles that will be used in Hermes. The manufacturing of this unique pebble differs in both its geometry (physically smaller than a German pebble) and in its contents [three zones: a fuel free core, an annular fuel region of high packing fraction (~35-40%) TRISO particles, and a fuel free outer zone]. Thus, it is quite different from manufacturing prismatic compacts and is yet different still from manufacturing a German pebble which contains a solid sphere of low packing fraction TRISO particles (10-15%) and an outer fuel free zone. The concern in fabricating the fuel element is not only breakage of particles, which can be deduced from DLBL. There is also the potential for partial cracks in the SiC layer, which would not be identified by DLBL, to grow under irradiation.

This new fuel element should undergo irradiation testing. Such testing has been a hallmark of *all international TRISO* fuel programs. The Germans tested their pebble fuel in the High Flux Reactor (HFR)-Petten HFR-K5 and K6 irradiations in the mid-1980s. The Japanese irradiated their TRISO fuel in the Japanese Materials Test Reactor and the Oak Ridge National Laboratory High Flux Isotope Reactor to support High-Temperature Test Reactor (HTTR) operation. The Chinese tested their lab-scale pebble fuel for the 10 MW High Temperature Reactor (HTR-10) in Russia in the IVV-2M reactor, and their production line pebble fuel for HTR-PM in the HFR-Petten. The US DOE program is conducting this irradiation testing for cylindrical compacts as part of the AGR testing program. These irradiations increase confidence that something unanticipated did not occur in production-scale fabrication. Furthermore, this testing is consistent with the requirements outlined in NUREG-2246 on fuel qualification for advanced reactors. Such unanticipated fuel failures have been seen in all nuclear fuel systems over the past 50 years and motivate the need for irradiation testing of fuel from the actual production-scale manufacturing process.

These two technical concerns are raised because the TRISO fuel is a critical part of the functional containment for Hermes. These concerns should be acknowledged as potential issues when Hermes enters initial operation. While these technical concerns can result in particle failure and fission product release, the safety impact depends on the level of particle failure. Were significant particle failures (~ 0.01 to 0.1%) to occur in Hermes, the resulting fission product release could challenge the yet-to-be-defined technical specifications on radionuclide activity in the Flibe and cover gas (SARRDLs) that are established to protect the safety of the public.

During our discussions, Kairos and the NRC staff asserted that the Kairos fuel qualification plan is adequate to reach a finding of reasonable assurance regarding the safety of Hermes. This is in large part because of the differences in burden of proof allowed by the Atomic Energy Act for test reactors compared to power reactors. The SE should explicitly acknowledge how the flexibility provided by the Atomic Energy Act for test reactors factored into the finding for acceptability of the fuel qualification methodology for Hermes.

There is currently a lack of data to resolve these concerns given that such a system has never been built and operated. Hermes is a unique test bed for this new technology and can serve as an integral assessment of fuel performance in Flibe to resolve uncertainties that cannot be obtained from the existing set of Kairos fuel qualification plans. The SE should explicitly consider the value of Hermes as a prototype to supplement the Kairos fuel qualification plans. It should require that the results of Hermes operation and the associated fuel surveillance plans be used as a compensatory measure to confirm (a) the lack of interaction between Flibe impurities and the SiC layer of the TRISO particles and (b) the overall integrity of Kairos pebbles under irradiation.

SUMMARY

The topical report and the associated SE should acknowledge two concerns that affect assurance of TRISO particle SiC layer integrity and radionuclide retention in the Kairos FHR designs:

- Material compatibility between the Flibe molten salt with impurities (e.g., Fe, Cr, Ni) and the fuel pebble containing TRISO particles, and

- Irradiation performance of the Kairos fuel pebbles fabricated at production-scale prior to Hermes operation.

The SE should explicitly consider the value of Hermes as a prototype. The results of Hermes operation and the associated fuel surveillance plans should be considered as a compensatory measure to address Recommendation 1. The SE also should explicitly acknowledge how the flexibility provided by the Atomic Energy Act for test reactors factored into the finding for acceptability of the fuel qualification methodology for Hermes. After these items are addressed, the SE should be issued.

Sincerely,

Signed by Rempe, Joy
on 12/20/22

Joy L. Rempe
Chairman

REFERENCES

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