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

September 21, 2021

Ms. Margaret M. Doane
Executive Director for Operations
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: SAFETY EVALUATION OF THE KAIROS TOPICAL REPORT, KP-TR-010, REVISION 3, "KP-FHR FUEL PERFORMANCE METHODOLOGY"

Dear Ms. Doane:

During the 688th meeting of the Advisory Committee on Reactor Safeguards (ACRS), September 8-9, 2021, we completed our review of the NRC staff draft safety evaluation (SE) report of Kairos Topical Report, KP-TR-010, Revision 3, "KP-FHR Fuel Performance Methodology." Our Kairos Subcommittee also reviewed this matter on July 6, 2021. 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.

CONCLUSIONS AND RECOMMENDATIONS

1. The topic of fuel performance is highly interrelated with fuel qualification and mechanistic source term. An overall road map on the planned topical reports and sequencing for this multi-stage review approach should be provided.

2. To effectively facilitate this new staged process with Kairos and future design developers, staff should develop guidance clarifying the level of information required for staff review at each stage.

3. The limitations and conditions identified by the staff adequately addressed the lack of verification, validation, and a quantitative uncertainty analysis in the "KP-FHR Fuel Performance Methodology" topical report. The SE should be issued.

4. Given the staged nature of this review process, the staff should ensure that subsequent Kairos licensing documentation addresses the following:

    a. Failure Mechanism Concerns
    b. Fission Product Modeling Concerns
    c. Fuel Qualification Performance Envelope Concerns
    d. Potential Non-conservative Failure Rate Calculations

DISCUSSION

The topics of fuel performance, fuel qualification, and mechanistic source term are highly interrelated. A thorough review of the fuel performance methodology (i.e., how the fuel performs in the reactor, what failure mechanisms are anticipated, and associated fission product release from the failed fuel) requires an understanding of the overall fuel qualification approach (i.e., what performance data exist, what additional performance data may need to be developed, and how it applies to the design) and the associated mechanistic source term (i.e., data on the timing and magnitude of radionuclides released from the fuel under normal operation and accident scenario conditions). An overall road map on the planned topical reports that cover these topics and the associated sequencing for this multi-stage review approach are essential to provide reviewers with an integrated understanding; it would also enable a more effective review by the ACRS.

The staff considers this topical report review as the first step in a staged review approach. The staff was unable to make findings in several areas due to open items in the topical report (identified by the applicant), the lack of verification and validation (V&V), and quantitative uncertainty analysis at this stage in the review. As a result, specific limitations and conditions were developed by the staff in the SE, with which we agree. To effectively facilitate this new staged process with Kairos and future design developers, staff should develop guidance clarifying the level of information required for staff review at each stage.

The Kairos topical report presents a calculational framework for fuel performance and fission product release and an associated uncertainty analysis to determine the upper tolerance confidence limits associated with fission product release from intact and failed Tristructural Isotropic (TRISO)-coated particle fuel. The methodology depends on the use of the KP-BISON code. Because of limited information on the code and its V&V status, the staff explicitly did not review the code and focused instead on the calculational methodology. The calculational framework in the topical report is intended to support the Kairos test reactor, Hermes, and the power reactor, Kairos Power Fluoride High Temperature Reactor (KP-FHR).

The methodology includes three major sources of fission product release: (a) dispersed uranium outside of the Silicon Carbide (SiC) layer of the fuel particles and in the fuel matrix, (b) manufacturing defects that result in an exposed kernel or in a defective Pyrolytic Carbon or SiC layer, and (c) in-service failures. The first two sources are quantified as part of the fuel manufacturing process and governed by limits in the fuel specification; the last source is calculated mechanistically as outlined in the topical report.

The calculational modeling couples fuel performance calculations with the fission product release modeling in a Monte Carlo (MC) framework to assess the level of fuel failures and fission product releases and their associated uncertainties. The models solve for both temperature and stress in the coating layers for both intact and failed particles. The strength of the layers is a critical material property in the evaluation of failure probability.

Once the in-service failure rates are calculated for a variety of particle failure mechanisms, fission product release is calculated. The failure models in the methodology use a set of fuel attributes, material properties and design service conditions (temperature, burnup, and fast fluence). Key material property inputs include (a) thermomechanical properties of the coating layers, buffer, and kernel, (b) physiochemical properties of the kernel such as kernel swelling, and (c) fission product diffusivities in the kernel and coating layers.

The methodology also defines the design service conditions using conservative pebble trajectories through the core. While this approach appears to be conservative to the staff, the NRC reviewers requested additional justification about potential non-conservative non-linearities. The topical report does not discuss fuel performance for any design service conditions outside of normal operation (i.e., anticipated operational occurrences, design basis events, or beyond design basis events). The staff found that many parts of the overall calculation methodology associated with the MC simulations were not well enough defined to make a finding on its suitability.

The topical report also provides a high-level overview of the applicant's approach to V&V. Verification includes comparison of calculations to results from international calculational benchmarks performed under the auspices of the International Atomic Energy Agency and Generation-IV programs. Kairos also plans sub-model validation from advanced gas reactor (AGR) post-irradiation examination (PIE) data on kernel swelling of Uranium Oxycarbide (UCO), buffer shrinkage measurements, and levels of Inner Pyrolytic Carbon (IPyC) cracking measured during PIE. More integral validation is also planned using data from irradiations of German and Chinese Uranium Dioxide (UO_2) TRISO fuel and the results for UCO TRISO fuel from the AGR program. Integral fuel performance model validation can be challenging when using irradiations that were not specifically designed for that purpose. Previous code-to-model comparisons are available in the literature for legacy German and U.S. models that can be useful to determine the best set of irradiations to use for model validation.

Our technical concerns are identified in the remainder of this letter. Some of these issues may be related to fuel qualification and mechanistic source term which we have not yet had the opportunity to review. Given the staged nature of the review process, the staff should ensure that these concerns are addressed in subsequent Kairos licensing documentation.

Failure Mechanism Concerns

The in-service failure mechanisms considered in the Kairos methodology are based on historical experience of TRISO fuel. For UCO TRISO-coated particles, three relevant mechanisms are: (a) pressure vessel failure leading to failure of all coating layers, (b) fission product palladium attack/corrosion of the SiC layer leading to a SiC failure, and (c) IPyC cracking under irradiation causing the crack to propagate into the SiC layer leading to a failure of both the IPyC and SiC layers. In addition, the following phenomena can be important in some instances: (a) carbon monoxide (CO) production, a concern for UO_2 and not UCO, (b) kernel migration, a concern for UO_2 and not UCO, (c) debonding between the IPyC and SiC, a concern in older TRISO fuels but not observed in current TRISO fuel, and (d) SiC thermal decomposition that occurs only at very high temperature (> 2000° C). The methodology has implemented a subset of these failure mechanisms. It is recommended that the models that were not considered in the methodology be re-evaluated because some of these models could be important to incorporate for postulated reactivity events where high temperatures might occur (e.g., SiC decomposition) or for UO_2 TRISO fuels that were tested in Germany and China (e.g., CO attack of SiC) and are currently part of the applicant's validation plans.

These failure models have been well established in the open literature on coated particle fuels. However, it is unclear how these failure mechanisms capture the low-frequency failure mechanism observed in the AGR test program, namely fracture of the buffer leading to a crack in the IPyC and SiC layers followed by palladium penetration along the crack leading to cesium release measured during PIE of the AGR program. This failure mechanism is a quasi-hybrid of the historic TRISO failure mechanisms. Some clarification of how the failure mechanisms in the model account for the observed failure mechanism discussed in the NRC-approved TRISO particle performance Electric Power Research Institute (EPRI) report is recommended.

Fission Product Modeling Concerns

The fission product diffusivity database for TRISO fuel is largely based on long-lived fission products (Kr-85, Cs-134 and Cs-137, Sr-90, Eu-154, and Eu-155) and simple diffusion models can be used to calculate their release from the fuel during normal operation. Fission product groups in the methodology include noble gases, iodine, cesium, strontium, and silver. No mention of europium is provided in the Kairos topical report, yet europium release has been observed under irradiation and in high temperature safety testing of UCO TRISO fuel and should be added.

The topical report also does not clearly address how the methodology will consider the release of shorter-lived metallic fission product isotopes of iodine (e.g., I-131, I-132, and I-134) and tellurium that are expected to be released from the fuel and accumulate as circulating activity in the coolant. Some of these isotopes are important for public safety and others for estimating worker dose. The release of these short-lived isotopes has historically been calculated based on release-to-birth ratios because they establish equilibrium in the fuel particles very quickly.

Fuel Performance Qualification Envelope Concerns

The staff noted in the SE that the predicted performance of TRISO particles must stay within the design service operating envelope described by the NRC-approved EPRI report on TRISO particle fuel performance. While most of the operating conditions are well within that operating envelope, particle power is not. An evaluation of the effect of higher particle power on TRISO particle fuel performance is needed to assure the framework approach remains valid for both the test reactor Hermes and the KP-FHR.

Potential Non-conservative Calculation of Failure Rates

The topical report provides an illustrative example of the fuel failure rate calculational methodology. Some of these failure rates are very low, and hence will be very difficult to validate given the large particle population necessary to statistically establish the validity of the calculated failure rates. Furthermore, the calculated failure rates could be non-conservative relative to the experimentally derived failure rates presented in the NRC-approved EPRI report on UCO TRISO fuel particle performance. That report established 95% confidence bounds on both full particle and IPyC and SiC layer failure fractions based on the number of particles tested in the AGR program and failures observed during irradiation or measured in PIE. These experimentally established limits should serve as a minimum failure rate in any reactor safety analysis to capture the statistical limitation of testing from the AGR program.

SUMMARY

The staff SE on the KP-FHR Fuel Performance Methodology should be issued. The staff should ensure that the items identified in our letter report are addressed.

Sincerely,

Signed by Sunseri, Matthew on 09/21/21

Matthew W. Sunseri
Chairman

REFERENCES

1) Kairos Power LLC, “KP-FHR Fuel Performance Methodology,” KP-TR-010, Revision 3, June 10, 2021 (ML21162A349)

2) U.S. Nuclear Regulatory Commission, Draft Safety Evaluation Report, “Kairos Power LLC – Approval of Topical Report “KP-FHR Fuel Performance Methodology” (Revision 3) (EPID: L-2019-TOP-0056/CAC NO. 000431),” June 2021 (ML21161A193)

3) Electric Power Research Institute, "Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO) Coated Particle Fuel Performance: Topical Report EPRI-AR-1(NP)," Report 30020199780, Palo Alto, CA, November 2020 (ML20336A052)

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