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

June 1, 2020

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-005-P, REVISION 1, “REACTOR COOLANT FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH TEMPERATURE REACTOR”

Dear Ms. Doane:

During the 672nd and 673rd meetings of the Advisory Committee on Reactor Safeguards, April 8-10, 2020 and May 6-8, 2020, we conducted our review of the NRC staff evaluation (SE) report of Kairos Topical Report KP-TR-005-P, Revision 1, “Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor.” Our Kairos Subcommittee also reviewed this matter on February 21, 2020. 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 thermophysical properties and design specification limits in Tables 1 and 4 of KP-TR-005-P with the limitations and conditions imposed by the staff SE report provide acceptable initial values for design and safety analyses of the Kairos Power Fluoride High Temperature Reactor (KP-FHR).

2. Limitations and conditions imposed by the staff require an updated version of information in Tables 1 and 4 of KP-TR-005-P be submitted after confirmatory data are obtained under an approved quality assurance program.

3. The SE report should be issued.

4. The proposed Kairos reactor design and limited operational experience with molten salt coolants present several technical issues that could affect either the coolant material properties or the coolant specifications. It is important that information in Tables 1 and 4 be finalized because material properties and coolant specifications are required for acceptance of data obtained from scaled testing using surrogate fluids and are fundamental input to many reactor safety analyses.

BACKGROUND

FLiBe is the molten salt coolant proposed for the KP-FHR. It is a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF_2), with a nominal chemical composition of 2LiF:BeF_2.

Kairos has requested NRC staff review and approve the FliBe thermophysical properties provided in Table 1, "Thermophysical Properties of the KP-FHR Primary Coolant," and the reactor coolant specification provided in Table 4, "Design Specification for the KP-FHR Reactor Coolant," of the KP-TR-005-P. Final versions of these properties and specifications can be used by applicants in future licensing submittals under Title 10 of the *Code of Federal Regulations* (10 CFR) Parts 50 or 52.

DISCUSSION

KP-TR-005-P discusses the known properties of the FliBe coolant and the constraints or limits under which the coolant must operate to (a) assure the coolant maintains its proper thermophysical properties, (b) control corrosion, and (c) limit reactivity effects. In this topical report, Kairos provides documentation to support that the information in Tables 1 and 4 can be used by an applicant to demonstrate compliance with KP-FHR Principal Design Criteria, subject to the Limitations and Conditions identified in the staff SE report. The information provided in Tables 1 and 4 of KP-TR-005-P establishes initial values for certain characteristics of the reactor coolant that will support unique design features of the KP-FHR as well as its safety and operation. Table 1 lists physical properties of the reactor coolant and associated estimates of the uncertainties. Table 4 contains design specifications for the reactor coolant. The limitations and conditions imposed by the SE report are related to specific aspects of the KP-FHR design and the need for significant additional testing to gather relevant design and safety data with associated uncertainties related to FliBe thermophysical properties, corrosion control, and/or reactivity control for the range of conditions required for reactor safety evaluations. The additional testing is to be performed under an approved quality assurance program to validate the properties and design specifications for the range of conditions used in the KP-FHR design and safety analysis. The staff has noted that the results from this testing must be submitted to NRC for review and approval.

The proposed Kairos reactor design and limited operational experience with molten salt coolants present several technical issues that the staff should ensure are addressed in future interactions. We summarize each of these issues below because they could either affect the material properties of the coolant, change a current specification of the coolant, or result in additional specifications that are the subject of the topical report. FliBe is highly toxic, and its use introduces significant occupational and safety hazards and waste disposition concerns.

While the topical report states that 'frosting' is not expected given the low vapor pressure of FliBe compared to water, the actual experience from the Molten Salt Reactor Experiment (MSRE) is somewhat more nuanced. Beryllium fluoride was found to condense and grow dendritically at cold spots in the system (e.g., on valve stems), was easily friable, and could become airborne. Because of the toxicity of Be, this will be an important consideration for worker occupational safety as the design evolves.

We note that, of all the thermophysical properties, the coolant viscosity is most sensitive to the composition of the salt. If more BeF_2 were to be added to the salt, its viscosity would increase. Thus, it is important to maintain the viscosity in a narrow range with tight composition control of the Be and Li fluorides of the salt. In addition, the Kairos-recommended uncertainty range for coolant viscosity is different than that recommended in other publications when evaluating fluoride salt coolant properties for nuclear reactor applications, such as the referenced paper by Romatoski and Hu. This reference notes that the uncertainty in the viscosity is large with about half associated with measurement error and half with composition error. The Kairos reactor chemistry control system will have to adjust the salt composition during operation to stay within the bounds of the design specification. The influence of impurities on the salt's viscosity should also be considered to determine if there is a limit that must be specified.

There are many ways to control the chemistry in the salt. We caution the staff that should Be metal be used to adjust and control the salt reduction/oxidation reaction (redox) potential, this Be addition will change the overall composition of the salt over time and could affect the viscosity and other properties of the salt. It is unclear how all these uncertainties associated with Be addition would affect the design and performance of a FliBe chemistry control system and how they will also affect the safety performance of the system, if Be metal addition is used to control the salt redox potential.

Kairos stresses in the topical report the need to maintain a clean salt that is free of moisture. The two most important sources of both air and moisture in the Kairos reactor design are the graphite reflector and the fuel pebbles. Carbonaceous materials adsorb fair amounts of air and humidity before they are inserted into the reactor, even after the high temperature heat treatments that are part of the graphite and pebble manufacturing processes. Outgassing of these materials have been observed during operation of high temperature gas cooled reactors both after initial core load and following refueling when new fuel is added to the core. With new pebbles being added to the core continuously, a continuous source of moisture and air will be added to the reactor core. This continuous source of impurities will certainly be a challenge to the chemical control system since moisture and air will react with metallic components on the surface of structural materials or dissolved in the salt to produce oxide impurities in the salt. Kairos has established a corrosion limit in the coolant. It is unclear if this limit can be met given the constant source of moisture and air introduced by the pebbles. Given the limited historical operating experience of FliBe in MSRE (about one effective full power year) and the importance of the redox state of the salt to both corrosion and tritium behavior, an on-line system may be prudent to monitor the redox state of the coolant during operation (e.g., cyclic voltammetry).

While Kairos notes that FliBe and graphite are known to be compatible, recent data from China confirms historic data, indicating that the salt could intrude into the fuel matrix material of a pebble. The salt intrusion makes the pebble heavier and impacts the ability to maintain a buoyant pebble bed. This is a critical issue that needs to be evaluated. In addition, the potential for salt attack of TRISO fuel particles needs to be assessed.

Kairos has established a limit on impurities to ensure the coolant has negative reactivity feedback. In this regard, it is important to note that although the TRISO fuel has excellent fission product retention capabilities, releases of silver, palladium and europium are expected at temperatures above 1100°C in the fuel. Small levels of cesium and strontium could also be released to the coolant based on uranium contamination levels of the fuel. Estimates of the release of these fission products are needed to assess their impact on the reactivity feedback characteristics of the coolant. Cleanup of these fission products from the coolant may be required during operation. Experimental data on the solubilities of these fission products will probably be required to provide a sound basis for the design of the cleanup system.

Transition metals (Fe, Cr, and Ni) are known to attack the silicon carbide layer (SiC) of the TRISO particles. While these elements do not impose reactivity penalties on the reactor, these elements should be minimized to the extent possible in the FliBe coolant to reduce the potential for TRISO particle failure.

The use of FliBe salt in a nuclear reactor will produce tritium via neutron absorption in Li-6. In a high temperature reactor where significant permeation through the metallic components might be expected, tritium may be challenging to contain relative to the stringent tritium release standards based on drinking water standards in the U.S. Tritium permeation through high temperature components will also be an occupational hazard.

The use of FliBe as a coolant will generate a mixed hazardous waste that will have to be addressed during operation and decommissioning.

SUMMARY

The thermophysical properties and design specification limits in KP-TR-005-P with the limitations and conditions imposed by the staff SE report provide acceptable initial values for design and safety analyses of the KP-FHR. Limitations and conditions imposed by the staff require an updated version of information in Tables 1 and 4 of KP-TR-005-P be submitted after confirmatory data are obtained under an approved quality assurance program. The staff SE report should be issued.

Based on the proposed Kairos reactor design and the limited operational experience with molten salt coolants, we document in this letter a number of technical issues that could affect either the coolant material properties or the coolant specifications. It is important that information in Tables 1 and 4 be finalized because material properties and coolant specifications are required for acceptance of data obtained from scaled testing using surrogate fluids and are fundamental input to many reactor safety analyses.

Sincerely,

Matthew W. Sunseri Digitally signed by Matthew W. Sunseri Date: 2020.06.01 12:31:30 -04'00'

Matthew W. Sunseri
Chairman

References

1) Kairos Power LLC, letter KP-NRC-1903-002, Topical Report KP-TR-005 Submittal, "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor", March 8, 2019 (ADAMS Accession No. ML19079A325 and Proprietary version ML19079A326).

2) Kairos Power LLC, letter KP-NRC-2001-001, Topical Repot KP-TR-005 Submittal, "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor", Revision 1, January 16, 2020 (ADAMS Accession No. ML20016A486 and Proprietary version ML20016A487).

3) U.S. Nuclear Regulatory Commission, Safety Evaluation for Kairos Topical Report "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor", Revision 1, January 2020 (ADAMS Accession No. ML20035E008).

4) R.R. Romatoski and L. W. Hu, "Fluoride Salt coolant properties for nuclear reactor applications: A review," Annals of Nuclear Energy, 109 (2017), 635-647.

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