July 17, 2024

Honorable Christopher T. Hanson
Chair
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

SUBJECT: SAFETY EVALUATION OF THE KAIROS NON-POWER REACTOR HERMES 2 CONSTRUCTION PERMIT APPLICATION

Dear Chair Hanson:

During the 717th meeting of the Advisory Committee on Reactor Safeguards, July 10 through 12, 2024, we completed our review of the Kairos Non-Power Reactor Hermes 2 construction permit application and the associated safety evaluation (SE). Appendix I provides the dates that our Kairos Subcommittee reviewed this matter. Appendix II provides the list of memos with our detailed reviews of the application and associated SE in cases where technical issues were identified. 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. This report fulfills the requirements of Section 182b of the Atomic Energy Act, as amended, and Title 10 of the *Code of Federal Regulations* (10 CFR) 50.58(a).

CONCLUSIONS AND RECOMMENDATIONS

1. Because the design of Hermes 2 builds extensively on the design of Hermes 1, the staff performed a "delta" review of Hermes 2 by (a) comparing the applicant's preliminary safety analysis report (PSAR) with the corresponding PSAR for Hermes 1, and (b) using the guidance provided in NUREG-1537 for non-power reactors as the basis for their evaluation. We note that this was an efficient and effective approach to conducting the Hermes 2 safety evaluation.

2. We agree with the staff that there is confidence the facility can be constructed in accordance with relevant regulations and the design bases outlined in the PSAR. Detailed design, analysis, and technology qualification will be completed prior to the operating license (OL) review.

3. Our review indicated that the design changes in Hermes 2 have no adverse influence on the safety functions or their implementation. The Hermes 1 Maximum Hypothetical Accident (MHA) was still found to be bounding for Hermes 2, and the effects of two Hermes 2 reactors with a greater lifetime were appropriately accounted for in the source term estimates. The planned metallic materials and graphite testing will address potential corrosion and radiation damage concerns to accommodate the longer planned lifetime for Hermes 2.

4. A number of issues noted in this letter should be considered by the staff prior to the issuance of the OL. These issues are related to the consequences of a postulated superheater tube rupture into the atmospheric-pressure intermediate salt loop; REDOX[1] control in the Flibe (a molten salt coolant which is a eutectic mixture of LiF and BeF_2); and corrosion and tritium control in BeNaF (a mixture of BeF_2 and NaF), the salt used in the intermediate loop.

5. The construction permit application for Hermes 2 should be approved.

BACKGROUND

The Hermes 2 facility consists of two 35-MWth test reactors that share a common power conversion system. The design builds upon the Hermes 1 test reactor design and contains the following three major design changes: (1) each test reactor has an intermediate salt loop to transfer heat from the reactor, (2) each intermediate salt loop has a steam superheater that feeds a common turbine in the shared power conversion system, and (3) the lifetime of the facility is 11 years instead of the four year lifetime of Hermes 1. The facility will be licensed under 10 CFR Part 50.21 (a Class 104c license).

Hermes 2 shares many of the same safety characteristics of Hermes 1. They both use TRISO-fueled pebbles in Flibe, resulting in a high-temperature low-pressure system with the following robust inherent or passive safety characteristics: functional containment provided by TRISO fuel and Flibe; primary heat transport system that operates near atmospheric pressure; negative reactivity coefficients (fuel, moderator, and coolant temperature); and reactor vessel and other safety-related components located within a seismically-isolated structure.

DISCUSSION

The staff performed a “delta” review of Hermes 2 by (a) comparing the applicant’s PSAR with the corresponding PSAR for Hermes 1, and (b) using the guidance provided in NUREG-1537 for non-power reactors as the basis for their evaluation. The considerable commonality between the Hermes 2 and Hermes 1 designs provided for a more efficient review compared to past multi-phased safety reviews. Our approach built upon our review of Hermes 1 to determine the safety significance of design changes. For our review, a cognizant member of the Committee reviewed a given chapter of the PSAR and the associated staff SE chapter. A memo was written by the cognizant member if technical issues were identified for further discussion. If no issues were identified in a specific chapter, no memo was written. This approach was efficient and allowed us to concentrate on the key technical issues. We also note that Kairos’ identification of Hermes 2 PSAR text that had been changed from Hermes 1 helped focus and improve the efficiency of our review.

Safety Review Questions

Our review included the following questions when evaluating the safety aspects of the Hermes 2 design:

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[1] REDOX is nomenclature (REDuction OXidation) to describe the chemical potential of the system.

- Do the design changes affect the safety functions identified in the design (functional containment, decay heat removal, and reactivity control)? Do they change the structures, systems, and components that implement those safety functions?

- Do the design changes introduce new accident sequences that change the MHA? Do the changes impact normal and accident source terms for the design?

- Do the changes affect the list of items that need to be confirmed prior to issuance of an OL (the staff's Appendix A of the Hermes 1 SE)?

- Are the co-location effects of Hermes 1 and Hermes 2 accounted for?

- Do the design changes influence waste streams?

Our review indicated that the design changes in Hermes 2 had no adverse influence on the safety functions or their implementation. The Hermes 1 MHA was still found to be bounding for Hermes 2 and the effects of two Hermes 2 reactors with a greater lifetime were appropriately accounted for in the source term estimates. The planned metallic material and graphite testing will address potential corrosion and radiation damage concerns to accommodate the longer planned lifetime for Hermes 2. The effects of co-location and changes in waste streams are noted and details will be addressed in the OL application.

We find that Kairos' systematic examination of postulated events in Hermes 1 and Hermes 2 with their associated figures of merit (e.g., time-at-temperature and material at risk) and subsequent comparison against the bounding MHA to be an elegant, simple, and transparent approach to the overall safety analysis. Such an approach should be considered for potential microreactor applications.

The staff's use of Appendix A in their SE is an effective approach to track the large number of technology development issues for Hermes 1 and Hermes 2 that need to be resolved through testing prior to the OL issuance. Communicating the results of the testing to the staff as far in advance of the final safety analysis report (FSAR) application as possible will facilitate the review and approval process for the OL.

Technical Issues for Further Consideration

Based on our review, we have identified a number of technical issues that remain to be resolved prior to staff approval of an OL application.

<u>Superheater Tube Rupture Event</u>

A superheater tube rupture in the power generation system will quickly pressurize the intermediate heat transport system that is designed for near atmospheric pressure, potentially challenging the integrity of the tubes in the intermediate heat exchanger (IHX). Safety-related rupture disks are proposed by Kairos to prevent the pressure from reaching the point where the tubes in the IHX fail.

The staff identified the following information as necessary to assure that the IHX tubes are protected during this postulated event: design features; qualification testing results; piping geometry and location of rupture disks to adequately relieve pressure and provide a relief path for the steam from the break; the operating environment of the rupture disks including temperature and chemistry (e.g., hydrogen fluoride exposure); the potential for adverse impact on rupture disk function from material aging or degradation due to environment effects; potential for salt vapor deposition to impede rupture disk function; and design considerations such as redundancy and diversity that would provide adequate reliability. This event will be reassessed by the staff at the OL stage.

There is large uncertainty in the progression of events following a postulated superheater tube rupture, and little data exists on the chemical interactions between steam/water and Flibe. Limited data on water/salt interactions in the event of a spill were developed during the Aircraft Reactor Test (ART) and Molten Salt Reactor Experiment (MSRE) projects. The testing indicated pressurization of the test cell where the spill occurred due to the production of steam upon contact of the water and molten salt but no degradation of the salt. However, it is important to note that the mode of interaction in the Hermes 2 design is quite different than a spill geometry. High pressure steam or water, depending on the location of the break, would vigorously enter the atmospheric pressure intermediate salt loop. According to the safety analysis documentation for the MSRE, “in an accident involving contact between salt and water, fairly rapid generation of hydrofluoric acid is expected.”

The design of the passive rupture disks in the intermediate coolant loop and the time needed for disks to actuate (relative to the event-generated pressure wave and the speed of sound in the salt) will be critical in mitigating the progression of this event and limiting overall damage. In light of the uncertainties associated with the progression of this postulated event, we believe strong preventive measures are preferred over mitigative ones. Were Kairos to be unsuccessful in designing the rupture disks to protect the IHX tubes, the safety classification of the IHX, the intermediate loop, or both may have to be reconsidered. Alternatively, the bounding nature of the MHA may have to be re-evaluated.

This type of event is a broader safety issue related to any design where the reactor primary or intermediate loop at atmospheric pressure interfaces with a high-pressure steam power conversion system, particularly where the coolants involved are chemically reactive. Designing to address steam generator tube rupture can be a challenge. Other designs in the past have addressed this issue by designing the intermediate loop for high pressure. The staff should anticipate this situation for other advanced reactor system safety applications going forward.

<u>Material Properties of BeNaF</u>

The salt used in the intermediate coolant system, BeNaF, is different than Flibe. Upon a heat exchanger tube break, BeNaF and Flibe will mix. The resulting salt, FLiNaBe, has been studied in a limited manner and has a melting point of 305°C, lower than either Flibe or BeNaF making solidification upon mixing unlikely. Kairos has committed to performing compatibility tests between the two salts. They also will evaluate the potential for structural material corrosion with the BeNaF salt and with a mixture of the Flibe and BeNaF salts.

There is no discussion in the safety documentation of key material properties including density, heat capacity, melting point, eutectic formation, viscosity, and tritium transport properties of the BeNaF salt. A search of open literature (and documented in the Chapter 4, “Reactor Description,” memo) indicates that the properties of this salt are similar to Flibe. These open literature properties imply that no major surprises are expected when Kairos completes the compatibility tests described above.

REDOX Control in Flibe

In preparing for the Hermes 2 review, the Committee has come across some literature on REDOX control in fluoride high temperature reactors that suggests the approach proposed by the applicant could be unacceptable to control corrosion and may have deleterious side effects.[2] Numerous open literature references have pointed out that in a system with graphite, use of a sacrificial Be metal electrode would produce excessively reducing conditions in the reactor coolant resulting in the formation of metal carbides. The formation of metal carbides could degrade the graphite components in the core (e.g., fueled pebbles or reflector). Simple static corrosion tests of stainless steel and graphite in purified but non-REDOX controlled Flibe have identified the presence of a chromium carbide (Cr_7C_3) in grain boundaries of the steel. The net corrosion rate of the steel was 1.8 times greater in the presence of graphite.

Therefore, active REDOX control for prevention of material corrosion should be taken into account for both Hermes 1 and Hermes 2. Some of the planned material corrosion testing by Kairos will inform the control strategy. Because of the complexity of REDOX control at the system level given the temporal temperature gradients and complex flows in the reactor, this issue may only be resolved during operation of these reactor systems. Additional technical specifications may be necessary to monitor and assess the influence of REDOX control on the potential degradation of graphite components. In this regard, operation of Hermes 1 may inform the Hermes 2 operational approach to address this issue.

Tritium Control in the Intermediate Loop

The tritium cleanup system for the intermediate loop will use hydrofluorination to convert tritium to tritium fluoride by injecting about 100 ppm hydrogen fluoride (HF) into BeNaF, the intermediate coolant salt. As noted by the staff and from the open literature, HF is corrosive under these high temperature conditions. Hydrofluorination is an oxidative process that generally runs counter to maintaining reducing conditions in the salt to minimize corrosion. How these two competing chemical processes (corrosion versus tritium control) will be successfully implemented requires more design detail. At this stage of the design, Kairos has committed to maintaining the intermediate coolant salt within proposed impurity limits as a potential means to limit corrosion.

SUMMARY

Because the design of Hermes 2 builds extensively on the design of Hermes 1, the staff performed a “delta” review of Hermes 2 by (a) comparing the applicant’s PSAR with the corresponding PSAR for Hermes 1, and (b) using the guidance provided in NUREG-1537 for non-power reactors as the basis for their evaluation. We note that this was an efficient and effective approach to conducting the Hermes 2 safety evaluation. We agree with the staff that there is confidence the facility can be constructed in accordance with relevant regulations and

[2] Structural material corrosion by molten salt is a key concern. Neutron absorption in the Li-6 in the Flibe will produce tritium fluoride and can make the salt redox condition more oxidizing, resulting in the enhanced corrosion of transition metals such as Ni, Fe, and Cr in the structural components. The corrosion leads to both the degradation of the materials of construction and perturbation of the properties of the salt. The neutron absorption creates an increasingly oxidizing environment that requires REDOX control to avoid corrosion of metallic components.

the design bases outlined in the PSAR. Detailed design, analysis, and technology qualification will be completed prior to the OL review.

Our review indicated that the design changes in Hermes 2 have no adverse influence on the safety functions or their implementation. The Hermes 1 MHA was still found to be bounding for Hermes 2, and the effects of two Hermes 2 reactors with a greater lifetime were appropriately accounted for in the source term estimates. The planned metallic materials and graphite testing will address potential corrosion and radiation damage concerns to accommodate the longer planned lifetime for Hermes 2.

A number of issues noted in this letter should be considered by the staff prior to the issuance of the OL. These issues are related to the consequences of a postulated superheater tube rupture into the atmospheric-pressure intermediate salt loop; REDOX control in the Flibe; and corrosion and tritium control in BeNaF, the salt used in the intermediate loop.

The staff's use of Appendix A in their SE is an effective approach to track the large number of technology development issues for Hermes 1 and Hermes 2 that need to be resolved through testing prior to the OL issuance. Communicating the results of this testing to the staff as far in advance of the FSAR application as possible will facilitate the review and approval process for the OL.

The construction permit application for Hermes 2 should be approved.

Sincerely,

Walter L. Kirchner Signed by Kirchner, Walter on 07/17/24

Walter L. Kirchner
Chair

REFERENCES

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2. U.S. Nuclear Regulatory Commission, "Hermes 2 Advance SE Transmittals to ACRS," 2024 (ADAMS Package ML24179A149 and ML24180A139).

3. Kairos Power LLC, "Submittal of the Preliminary Safety Analysis Report for the Kairos Power Fluoride Salt-Cooled, High Temperature Non-Power Reactor (Hermes)," Revision 2, February 2023 (ADAMS Accession No. ML23055A674).

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13. Oak Ridge National Laboratory, “ART Reactor Hazards Tests,” ORNL-55-2, February 1955.

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15. Oak Ridge National Laboratory, “MSRE Design and Operations Report Part V Reactor Safety Analysis Report,” August 1964.

16. Jinsuo Zhang, et al., “Redox potential control in molten salt systems for corrosion mitigation,” Corrosion Science 144(2018), pp. 44-53.

Appendix I

ACRS Review of Construction Permit Application for Kairos Power Fluoride Salt-Cooled, High Temperature Non-Power Reactor – Hermes 2

Subcommittee (SC) Meetings	Date	Subject	Transcript Accession No.
SC	5/16/2024	Hermes 2 Non-Power Reactor Preliminary Safety Analysis	ML24177A224
SC	6/4/2024	Hermes 2 Non-Power Reactor Preliminary Safety Analysis	ML24189A000
SC	6/26/2024	Hermes 2 Non-Power Reactor Preliminary Safety Analysis	ML24198A003

Appendix II

Lead Member Memoranda on Preliminary SE Chapters on Kairos Power Hermes 2 Non-Power Reactor Preliminary Safety Analysis Report

Subject	**Date**	**ADAMS Accession No. *(Package No. is* ML24185A042*)***
Input for ACRS Review of Kairos Non-Power Reactor Hermes 2 Construction Permit Application - Safety Evaluation for Chapter 4, "REACTOR DESCRIPTION"	7/5/2024	ML24185A048
Input for ACRS Review of Kairos Non-Power Reactor Hermes 2 Construction Permit Application - Safety Evaluation for Chapter 5, "HEAT TRANSPORT SYSTEM"	7/5/2024	ML24185A050
Input for ACRS Review of Kairos Non-Power Reactor Hermes 2 Construction Permit Application –Safety Evaluation for Chapter 7, "INSTRUMENTATION AND CONTROL SYSTEMS" and Chapter 8, "ELECTRIC POWER SYSTEMS"	7/5/2024	ML24185A044
Input for ACRS Review of Kairos Non-Power Reactor Hermes 2 Construction Permit Application - Safety Evaluation for Chapter 13, "ACCIDENT ANALYSIS"	7/5/2024	ML24185A046

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Accession No: ML24197A152 **Publicly Available (Y/N):** Y **Sensitive (Y/N):** N
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