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

7/5/24

MEMORANDUM TO: David Petti, Lead
Kairos Power Licensing Subcommittee
Advisory Committee on Reactor Safeguards

FROM: David Petti, Member David Petti Digitally signed by David Petti Date: 2024.07.05 18:31:05 -06'00'
Advisory Committee on Reactor Safeguards

SUBJECT: INPUT FOR ACRS REVIEW OF KAIROS NON-POWER REACTOR HERMES 2 CONSTRUCTION PERMIT APPLICATION – DRAFT SAFETY EVALUATION FOR CHAPTER 4, "REACTOR DESCRIPTION"

In response to the Subcommittee's request, I have reviewed the NRC staff's safety evaluation (SE) with no open items, and the associated section of the applicant's Preliminary Safety Analysis Report (PSAR), for Chapter 4, "Reactor Description." The following is my recommended course of action concerning further review of this chapter and the staff's associated safety evaluation.

Background

Chapter 4 describes the Hermes 2 reactor. The Hermes 2 facility contains two reactors. Each is a 35 MWth reactor that uses TRISO fueled pebbles in a low pressure chemically inert molten salt, Flibe coolant. Inlet temperature is 550°C and outlet temperature is 650°C. The core is 2 m^3 in volume and has a power density of 17.5 $MWth/m^3$. In Hermes 2, each reactor contains an intermediate heat transfer loops containing a secondary molten salt connected to a steam generator. The steam generator from each unit feeds a common power conversion system. PSAR Chapter 4 describes various important aspects of the reactor design, including the reactor core (fuel, control and shutdown system, and neutron startup source), reactor vessel and internals, biological shield, nuclear design, thermal-hydraulic design, and reactor vessel supports and their associated design criteria. The staff's safety evaluation focused on changes in the reactor design between Hermes and Hermes 2.

Discussion

In preparing for the Hermes 2 review, I have 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. Numerous open literature references have pointed out that in a system with graphite, use of a sacrificial metal electrode would produce excessively reducing conditions in the reactor coolant resulting in the formation of metal carbides. The formation of metal carbides would degrade the graphite components in the core (e.g. fueled pebbles or reflector). Static corrosion tests at 700°C in purified but not redox-controlled Flibe with both stainless steel and graphite have shown the presence of chromium carbide in the corrosion layer of the steel. Tests without graphite did not show any evidence of carbide formation. The net corrosion rate was 1.8x greater in the presence of graphite.

Being able to establish an acceptable level of redox control is an issue for both Hermes and Hermes 2. Kairos is aware of the issue and has seen no carburization (no interaction with graphite) in their recent testing, but they admit that intermittent application of the beryllium (Be) redox agent may be necessary during operation instead of continuous application to prevent the salt from becoming too reducing. This would imply the need to actively monitor the redox potential to assure the system remains within acceptable limits (neither too reducing or too oxidizing). Some of the planned material corrosion testing by the applicant will inform this issue. 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 systems. Additional technical specifications may be necessary to monitor and track the influence of redox control on the potential degradation of graphite components.

The tritium cleanup system for the intermediate loop will use hydrofluorination to convert tritium to tritium fluoride (TF) by injecting about 100 ppm hydrogen fluoride (HF) into the salt. This is an oxidative process which generally runs counter to keeping reducing conditions in the salt to minimize corrosion. As noted by the staff and from the open literature, HF is corrosive under these high temperature conditions. Removal or replacement of the secondary coolant salt to stay within proposed impurity limits is mentioned by Kairos as an option at this stage of the design as a means to limit corrosion. How these two competing chemical processes (corrosion control which favors reducing conditions and tritium control which favors oxidative conditions) will be successfully implemented requires more design detail and any relevant planned experimental results typical of that found in an operating license (OL) FSAR submittal.

The major differences in Chapter 4 revolve around the increase in reactor lifetime from 4 years in Hermes to 11 years in Hermes 2. The extended lifetime influences the graphite and materials qualification testing that is planned to qualify these materials in areas such as corrosion, creep, creep-fatigue, and weldment testing. Tables were added to Chapter 4 to reflect changes to planned testing; testing times are appropriately increased to address these issues.

The design of Hermes 2 also notes that the decay heat removal system (DHRS) for each unit is separate and independent, as is the reactor vessel and support system, both important safety considerations.

The chapter also mentions that the intermediate loop will be unavailable when the primary heat transport loop is unavailable so that decay heat removal is via the DHRS. This is an important design requirement. Without it, there is a potential for overcooling of the primary system if the intermediate salt coolant system were to continue to operate when the primary heat transport loop became unavailable, and this situation could challenge the bounding nature of the existing maximum hypothetical accident (MHA).

The applicant made modest changes to the PSAR and Kairos Topical Report KP-TR-022 to identify a tube break in the intermediate heat exchanger (IHX) as an event considered in evaluation the MHA. Neither the documentation from the applicant nor the staff SE address the technical basis for being able to perform steady state or transient analyses that involve the secondary salt coolant. There is no information on the thermophysical properties of the secondary salt coolant (NaF-BeF_2) such as heat capacity, viscosity, eutectic temperature nor how these properties change if the primary and secondary salts were to mix as anticipated in a tube rupture in the intermediate heat exchanger. I have found information in the open literature as shown in the table below.

The density, heat capacity and thermal conductivity are very similar. There is greater variation in the viscosity. Prandtl (Pr) numbers are similar at a given temperature. Based on this comparison, there are sufficient data to perform both steady state and transient analyses of both the primary and secondary salt. Were there to be a tube rupture when the two salts mix, a new salt, FLiNaBe, could form. The melting/eutectic point of that salt is even lower at 305°C. Thus, it appears that mixing will not pose an issue relative to solidification near the tube break and it appears that the MHA identified for Hermes remains bounding for Hermes 2. This will be confirmed in discussions with Kairos and the staff.

Comparison of Thermophysical Properties

Property	Flibe	NaF-BeF_2	Ratio
Melting Point (°C)	460	340	--
Density (g/cm^3)			
500°C	1.90	1.98	0.96
650°C	1.83	1.93	0.95
800°C	1.75	1.87	0.94
Heat Capacity – measured (J/kg-K)	2414	2175	1.10
Heat Capacity – theoretical (J/kg-K)	2368	1841	1.29
Thermal conductivity – theoretical prediction (W/mK)	0.79	0.58	1.36
Thermal conductivity – Russian correlation (W/mK)	1.0	0.87	1.15
Viscosity (cP)			
500°C	14.9	27.6	0.54
650°C	6.78	9.32	0.73
800°C	3.84	4.26	0.91
Pr Number			
500°C	45	103	0.43
650°C	21	35	0.59
800°C	12	16	0.73

Recommendation

As lead reviewer for Hermes SE Chapter 4, I recommend we note these issues were discussed with Kairos and the staff and any remaining concerns that should be addressed as part of the OL application for Hermes and Hermes 2 be noted in our final letter.

References

1) USNRC, “Hermes 2 Advance SE Transmittals to ACRS,” 2024 (Agencywide Documents Access and Management System (ADAMS) Package No. ML24179A149).

2) Kairos Power LLC, "Submittal of the Preliminary Safety Analysis Report for the Kairos Power Fluoride Salt-Cooled, High Temperature Non-Power Reactor, Revision 1 and the Postulated Event Analysis Methodology Technical Report, Revision 1", May 23, 2024 (ML24144A090).

3) Kairos Power LLC, KP-TR-022-NP, "Hermes 2 Postulated Event Methodology" Revision 1, May 23, 2024 (ML24144A094 and Proprietary Version ML24144A093).

4) STEMPIEN, J. "Tritium Transport, Corrosion, and Fuel Performance Modeling in the Fluoride Salt-Cooled High-Temperature Reactor (FHR)," Ph.D. Thesis, MIT, June 2015.

5) ENGEL, J.R., BAUMAN, H.F., DEARING, J.F., GRIMES, W.R., MCCOY, E.H., RHOADES, W.A., "Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fueling," ORNL/TM-7207, Oak Ridge National Laboratory, (1978).

6) WILLIAMS, D.F., TOTH, L.M., CLARNO, K.T., "Assessment of Candidate Molten Salt Coolants for the Advanced High Temperature Reactor (AHTR)," ORNL/TM-2006/12, Oak Ridge National Laboratory, (2006).

7) CANTOR, S., GRIMES, W.R., "Fused-Salt Corrosion and Its Control in Fusion Reactors," *Nuclear Technology*, 22, 120–126 (1974).

8) ZHENG, G., KELLEHER, B., CAO, G., ANDERSON, M., ALLEN, T. and SRIDHARAN, K., "Corrosion of 316 Stainless Steel in High Temperature Molten Li_2BeF_4 (FLiBe) Salt, Journal fo Nuclear Materials, 461, June 2015, pp. 143-150.

9) HOLCOMB. D. and CETINER, S., "An Overview of Liquid-Fluoride-Salt Heat Transport Systems," ORNL/TM-2010/156, September 2010.

10) JERDEN, J. "Molten Salt Thermophysical Properties Database Development: 2019 Update," ANL/CFCT-19/6, September 2019.

11) MCDONALD, J. M., NYGREN, R. E., LUTZ, T. J., TANAKA, T. J., ULRICKSON, M. A., BOYLE, T. J., & TRONCOSA, K. P. (2005). Measurement of the Melting Point Temperature of Several Lithium-Sodium-Beryllium Fluoride Salt (Flinabe) Mixtures. *Fusion Science and Technology*, *47*(3), 554–558. https://doi.org/10.13182/FST47-554.

7/5/24

SUBJECT: INPUT FOR ACRS REVIEW OF KAIROS NON-POWER REACTOR HERMES 2 CONSTRUCTION PERMIT APPLICATION - SAFETY EVALUATION FOR CHAPTER 4, “REACTOR DESCRIPTION”

Package No: ML24185A042
Memo Accession No: ML24185A048 **Publicly Available Y** **Sensitive N**
Viewing Rights: ☒ NRC Users or ACRS Only or See Restricted distribution *via e-mail

OFFICE	**ACRS/TSB***	**SUNSI Review***	**ACRS/TSB***	**ACRS***
NAME	WWang	WWang	LBurkhart	DPetti
DATE	7/03/2024	7/03/2024	7/05/2024	7/05/2024

OFFICIAL RECORD COPY