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NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
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MEMORANDUM TO: David Petti, Lead
Kairos Power Licensing Subcommittee
Advisory Committee on Reactor Safeguards

FROM: Walter L. Kirchner, Chair
Advisory Committee on Reactor Safeguards

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SUBJECT: INPUT FOR ACRS REVIEW OF KAIROS HERMES 2 NON-POWER REACTOR CONSTRUCTION PERMIT APPLICATION – DRAFT SAFETY EVALUATION FOR CHAPTER 5, “HEAT TRANSPORT SYSTEMS”

In response to the Subcommittee’s request, I have reviewed the NRC staff’s draft safety evaluation (SE) with no open items, and the associated section of the applicant’s Preliminary Safety Analysis Report (PSAR), for Chapter 5, “Heat Transport Systems.” The following is my recommended course of action concerning further review of this chapter and the staff’s associated safety evaluation.

Background

Each Kairos Hermes 2 reactor has an independent primary heat transport system (PHTS), which transfers heat from the reactor core by circulating a chemically stable salt coolant (Flibe) between the pebble bed core and reflectors in the reactor vessel (RV) to an intermediate heat transport system (IHTS) during normal operations. The PHTS includes a primary salt pump (PSP), an auxiliary heat rejection subsystem (HRS), an intermediate heat exchanger (IHX) and associated piping. The heat removal subsystem includes a heat rejection radiator (HRR), heat rejection blower, and associated ducting. In the Hermes 2 Construction Permit (CP) application, each reactor also has an independent, secondary salt IHTS consisting of an intermediate heat exchanger (IHX), two intermediate salt vessels (ISVs), two intermediate salt pumps (ISPs), and steam superheater, both of the latter couple to a single power generation system (PGS).

The Flibe reactor coolant supports heat transport and reactivity control (negative moderator/coolant reactivity coefficient), accumulates fission products (from pebble release) and transmutation products (from Flibe and impurities), and the Flibe also serves as an additional barrier to release of radionuclides (part of “functional containment”). The PHTS piping is austenitic stainless steel designed to the ASME B31.3 Code and the HRS is designed to the ASME BPVC, Section VIII.

The PHTS and IHTS, outside the RV, are considered non-safety-related and are not functionally required to achieve safe, stable shutdown. This is predicated on the functioning of the fluidic-diodes and anti-siphon features of the core internals within the RV (Chapter 4) in preventing excess loss of coolant inventory in the vessel in event of an ex-vessel pipe rupture (i.e., maintaining the coolant level above the active pebble bed core). Also, the heat rejection blower and the PSP are tripped in event of an HRR tube failure to prevent forced air ingress to the system.

The PHTS also includes thermal management features to maintain the reactor coolant in the liquid phase when the reactor core is not generating heat, and the capability to drain external piping and the HRR to allow cooldown, inspection, and maintenance. Connected auxiliary systems (Chapter 9) include chemistry control, inert gas, inventory management, and thermal management systems (i.e., thermophysical property and purity control, limits on air ingress and circulating radionuclide inventory, fill and drain functions, and preventing freezing of coolant). Chapter 14, “Technical Specifications,” provides for associated limiting conditions of operations for the primary coolant systems.

The IHTS uses a secondary salt (NaF-BeF_2, or BeNaF) as the working heat transfer fluid. The PHTS loop is operated at slightly higher pressure than the IHTS by control of PSP and ISPs speeds and is monitored for potential ingress of secondary working salt “impurities.” Primary coolant enters the shell side of the IHX which is located above the free surface level of the ISV to maintain positive pressure differential when shutdown. The secondary coolant salt is on the tube side of the IHX. The IHTS is considered a non-safety related system, operating at near atmospheric pressure, and designed and built to the ASME B&PV Code Section VIII, Division 2, and associated piping code B31.3. There are two ISVs to provide for a low-pressure argon cover gas on the IHTS, and for tritium collection and monitoring. Tritium permeating from the PHTS is collected in the ISVs and vented to the intermediate gas collection system (IGS), and then to the tritium management system (TMS). To prevent overcooling transients, each reactor protection system provides an independent trip signal to the two ISPs in each IHTS. Overpressure protection of the IHX in event of superheater steam tube rupture in each IHTS is provided by “safety-related” rupture disks (SS 316H) mounted in the gas space of the ISVs. The applicant states that malfunction of these secondary systems does not lead to reactor damage, fuel failure, or uncontrolled release of radionuclides.

SE Summary

The staff evaluated the sufficiency of the preliminary information on the design of the Hermes 2 PHTS and IHTS, as described in PSAR Chapter 5 and other relevant portions of the PSAR, using the guidance and acceptance criteria from Section 5.2 of NUREG-1537, Parts 1 and 2. As part of its review, the staff evaluated whether PSAR Section 5.1 identified the appropriate principal design criteria (PDCs) and offered sufficient information and design description to provide reasonable assurance that the design bases will be met at the operating license (OL) stage. Based on the information provided by Kairos, the staff found that the applicant provided sufficient preliminary information in accordance with 10 CFR 50.34 to develop primary coolant system and intermediate coolant system designs that would accomplish the design functions of fuel integrity and sufficient heat removal, coolant loss prevention, conversion to passive natural-convection flow, limited corrosion of essential components, and sufficient radiation shielding for limiting personnel exposures. The staff did identify several matters that the addition of IHTSs coupled to a PGS introduces, including coolant compatibility concerns; IHX integrity and classification; pressure relief in event of a superheater tube rupture event, design, environmental qualification, and classification of the rupture disks; and tritium collection, monitoring and management.

The staff observed that the Hermes 2 design is such to likely preclude significant Flibe-water interactions in event of a superheater tube rupture event, but this may require reliance on IHX tube integrity. Based on preliminary design information, the staff was unable to confirm that the

IHX complies with the Hermes 2 definition of safety-related structures, systems, and components because the safety-related rupture disks may not be able to fully prevent a pressure increase on the IHX during a superheater tube rupture event. Final design details will be important in evaluating the IHX safety classification. To resolve this issue at the CP stage, Kairos committed in the final design to demonstrating that the IHX tubes are not safety-related, or their failure is not credible.

The staff laid out expectations for Kairos in design analyses to demonstrate the IHX tubes do not need to be safety-related: at a minimum, consider the potential for significant water or steam to reach the IHX and interact with Flibe, the potential for Flibe-steam interactions in the IHTS, and the potential for BeNaF ingress into the PHTS that could affect Flibe properties such that there could be an impact on natural circulation that could challenge the decay heat removal function. Alternatively, if the IHX tubes are relied upon to remain functional during and after a postulated event, Kairos will need to demonstrate IHX tube failure is not credible considering all relevant factors, such as the time history of postulated events, margin between tube design pressure and stress in the postulated event, potential tube degradation in service, and any augmented quality standards that would be applied to the design, construction, operation and maintenance of the IHX.

Staff noted that Kairos will need to provide a final design for the IHTS and the safety-related rupture disks that justifies that the rupture disks will reliably perform their safety function to provide overpressure protection in preventing gross failure of the IHX. The design features, potential qualification testing, or other justification should address design of the IHTS piping geometry and location of the rupture disks to adequately relieve pressure and provide a relief path for the steam from a postulated superheater tube 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 environmental effects (e.g., extended time at elevated temperatures impacting material properties and rupture disk performance); the potential for salt vapor deposition to impede rupture disk function, and design considerations (e.g., redundancy and independence) that would provide adequate reliability.

In conclusion, the staff found that most of these matters could be resolved at the OL stage, and that operational and accident scenarios introduced by the IHTS/PGS were bounded by the Maximum Hypothetical Accident (Chapter 13). Accordingly, the staff found that there is reasonable assurance that Hermes 2 reactor can be designed and built to comply with applicable regulatory requirements, and that a CP could be approved.

Discussion/Observations

I reiterate my first observation from our Kairos Hermes review that there remains a major premise, if not precedent, predicated on successful design and to be demonstrated performance of several novel and unique features of the Hermes 2 design, which is that the applicant proposes to redefine part of the “safety-related” definition (10 CFR Part 50.2) regarding “integrity of the reactor coolant pressure boundary” to “integrity of portions of the reactor coolant boundary relied upon to maintain the reactor coolant level above the active core” (Chapter 3). While this revised definition applied to design basis events involving a major break in the PHTS would address the continued cooling of the pebble bed core and passive decay heat removal (assuming the function of the RV anti-siphon features and demonstration of the fluidic diode device design), it potentially weakens overall defense-in-depth and independence of barriers/safety functions. Further, the introduction of the IHTS has an accompanying set of safety and design issues regarding classification of the IHX (including seismic), because of the potential for interfacing loss of coolant/pressurization events.

The staff accepted this novel safety classification on the basis that the piping performs no safety role and the functional containment capability of the TRISO fuel pebbles and Flibe coolant in the RV remains largely intact even during a spill. Kairos has also committed to protecting safety-related equipment in the reactor building and precluding Flibe/concrete interactions.

For PHTS salt coolant spills and unlimited air ingress to the RV (Chapter 13.1.3), exposed Flibe and graphite structures could lead to uncontrolled and unmitigated release of radionuclide volatiles and aerosols, possible chemical reaction with the coolant, and oxidation of graphite over a 7-day accident span. (The staff addresses this in their SE for Chapter 13 in part by suggesting that the coolant and metallic/graphite materials qualification programs will need to bound the postulated air ingress scenarios through a 7-day period to meet the requirements of principal design criterion 70.)

Secondly, classifying the PHTS piping as non-safety-related suggests that the system may not survive a design-basis earthquake, potentially endangering the integrity of the RV at the nozzle/piping interface with a break at that location. Kairos stated that the design of the PHTS piping at the RV connection is of sufficiently small wall thickness such that loads beyond the elastic limits would result in an inelastic response (hence break/rupture?) prior to any impact on the RV or decay heat removal system (DHRS). If this is indeed the design approach, further evaluation will have to wait until the OL stage, when detailed design information is available for the PHTS, and associated seismic analyses of support, restraint, and structural layout are completed. In Chapter 6, “Engineered Safety Features,” the applicant also identifies Flibe leaks as an external hazard to the DHRS in the reactor cell.

Classifying the PHTS as safety-related does not preclude a major pipe break, just as it does not in a light water reactor, but for this first-of-a-kind reactor, designing, analyzing, and constructing the PHTS to the same quality level as the RV (ASME BPVC, Section III, Division 5 design and construction, and Section 11 testing and inspection) and seismic criteria would enhance confidence in the low probability of significant pipe rupture (thermally or seismically induced). Finally, there is no credit for a “confinement” function provided by the reactor compartment design, therefore unmitigated air ingress and interaction with Flibe raises airborne toxicity (Be primarily) and radiotoxicity concerns. Potential occupational hazards of such a release or spill, including tritium exposure, will also need to be addressed.

The addition of an IHTS with an IHX between two different salt fluid systems raises issues of coolant compatibility (e.g., new eutectics, coolant thermophysical properties, corrosion, etc.) and the impacts of an overpressure event in the IHTS (e.g., superheater tube rupture) damaging the IHX. This raises further consequential issues about the design pressures and quality standards used for both the PHTS and IHTS components. These issues are largely solvable, but the current level of design detail and experimental data does not support definitive conclusions (e.g., it is not clear how the design of the ISVs and piping prevents steam/water pressurization of the IHX). Of relevance is the PRISM sodium fast reactor design approach for its intermediate heat transport system (also sodium). To accommodate a steam generator tube rupture, and ensuing rapid pressure pulses, the intermediate system design pressure was that of the steam generator, with redundant safety-related rupture disks set to relieve at about 325 psig. In the case of Hermes 2, the estimated steam/water pressure in the superheater is approximately 2000 psig.

Finally, several of these items, primarily coolant thermophysical properties, purity, and chemistry, circulating radionuclides, and entrained air and gases can be addressed through further research, development, and experiments (see Appendix A of SE), and/or mitigated by limiting conditions of operation (LCOs) as called for in Chapter 14 (Technical Specifications).

Recommendation

As lead reviewer for Hermes SE Chapter 5, I recommend that the staff document clearly their logic in accepting the applicant's revised safety-related definition and its application to the Hermes 2 design, specifically the PHTS and its IHX, and detail more explicitly expectations (i.e., fuel and coolant qualification, novel component and equipment test demonstrations such as rupture disk performance, test and inspection requirements, instrumentation, etc.) for the operating license phase. Appendix A of the staff's draft SE for Hermes does contain pointers to a number of these matters.

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13. Kairos Power LLC, “Metallic Materials Qualification for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor,” Topical Report KP-TR-013, Revision 4, September 30, 2022 (ML22263A456).

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