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

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

FROM: Walter L. Kirchner, Chair Walter L. Kirchner Digitally signed by Walter L. Kirchner Date: 2024.07.05 20:20:14 -04'00'
Advisory Committee on Reactor Safeguards

SUBJECT: INPUT FOR ACRS REVIEW OF KAIROS 2 CONSTRUCTION PERMIT APPLICATION – DRAFT SAFETY EVALUATION FOR CHAPTER 13, "ACCIDENT ANALYSIS"

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 13, "Accident Analysis." The following is my recommended course of action concerning further review of this chapter and the staff's associated safety evaluation.

Background

This accident analysis chapter provides information and analyses to evaluate the potential radiological consequences in the event of malfunctions and the capability of the facility to accommodate disturbances such that no postulated credible event leads to unacceptable radiological consequences to the public. (The health and safety of the workers will be addressed with the application for an Operating License (OL).) The Kairos Hermes 2 reactor design relies primarily on a functional containment approach (TRISO pebble fuel/Flibe molten salt coolant) to retain the majority of the radioactive material available for release during a postulated event. This chapter provides material to demonstrate that the facility design features, and bounding values for parameters expected to be controlled by technical specifications, will ensure that no postulated event in the facility design basis leads to unacceptable radiological consequences to the public or the environment.

The applicant's accident analysis presented in this chapter seeks to bound all potential accident releases in the reactor's design basis by evaluating the dose consequences of a Maximum Hypothetical Accident (MHA). The MHA analysis is mainly built off the analysis methodology in KP-TR-012, "Mechanistic Source Term Topical Report," and the assumptions that the reactor protection system and reactor/primary heat transport system function as designed, most importantly keeping the reactor core covered with Flibe.

Chapter 13 references KP-TR-018-NP, "Postulated Event Methodology Technical Report," Revision 1, which provides analysis details to support the conclusions in the various PSAR sections. The potential radiological releases from analyzed initiating events or groups of events for this test reactor's design basis are then compared using figures of merit (time and temperature of the reactor fuel and internals – see PSAR Figure 13.2-1, material at risk – MAR, etc.), as surrogates for dose. The events analyzed included: (a) insertion of excess reactivity; (b) salt spills; (c) loss of forced circulation (heat-up and cool-down); (d) mishandling/malfunction of the pebble handling and storage system; (e) radioactive release from subsystems and components (e.g., MAR in auxiliary systems for salt coolant cleanup); (f) general challenges to normal operation; and (g) internal/external events (e.g., seismic and flooding). Conservative assumptions were selectively applied to analyses of each group and specific events. These included single failure criteria, assumption of highest worth control rod stuck out, conservative assumptions of radioisotope releases and rates (i.e., from fuel, structure, and Flibe, tritium and Argon-41 releases, etc.), and three out of four decay heat removal system trains available. The suite of accident analyses also included unprotected events and those prevented or precluded by design and the rationale for their exclusion (e.g., failure to shut down the reactor, significant ingress of air, etc.). Each analysis was compared to selected figures of merit to assure that the results are bounded/enveloped by the MHA.

Hermes 2 employs the same functional containment strategy as Hermes, and includes the safety features (e.g., decay heat removal system) of the Hermes design (as described above). The Hermes 2 postulated event methodology (KP-TR-022) augments the event narratives and methods described in KP-TR-018 by assessing new potential event initiators identified for the Hermes 2 design, mainly an intermediate heat transport system (IHTS) and a power generation system as described in PSAR Chapters 5 and 9, respectively. Additional safety features in Hermes 2 include the IHTS rupture discs to guard against over-pressurization of the intermediate heat exchanger (IHX) in the event of a superheater tube rupture, and a reactor protection system (RPS) trip on the intermediate salt pumps (ISPs) to guard against overcooling transients. Material at risk limits (primarily tritium) in the IHTS and power generation systems, and limits on the allowable amounts of Flibe and water in the IHTS are defined. These additional safety features and proposed limits ensure that events resulting from postulated failures of the IHTS or power generation systems are either prevented by design, or can be grouped within the event categories described in KP-TR-018. That is IHTS spill, superheater tube rupture, ISP failure events, etc., do not introduce new phenomena that require additional figures of merit to be evaluated to ensure that their consequences are bounded by the MHA analysis.

The dose consequences of the MHA analysis then are used to demonstrate the acceptability of the design when compared to regulatory dose limits in 10 CFR 100.11 (at exclusion area boundary and low population zone) for siting of a non-power reactor. The MHA analysis bounding dose consequences presented are significantly lower than those specified in 10 CFR 100.11. MHA and postulated events presented in this chapter apply to each unit and are evaluated against the siting criteria for each unit separately.

Additionally, the PSAR notes that components containing Flibe will be located in areas that have design features such as steel liners to prevent Flibe-concrete interaction. Components containing BeNaF, the secondary salt coolant, that are located where BeNaF-concrete interactions could prevent safety-related structures, systems, and components (SSCs) from performing their function will be in locations that have design features such as steel liners to prevent BeNaF-concrete interactions. Turbine blade missiles could be generated due to a postulated turbine failure; however, those missiles will not affect safety-related SSCs to the extent that they could not perform their safety function due to the favorable orientation of the turbine. Piping associated with the steam, condensate, and feedwater systems is routed such that postulated failures do not adversely affect safety-related SSCs.

SE Summary

The staff evaluated the sufficiency of the information on the preliminary design of the Hermes test reactor, and accident analysis as described in the Chapter 13 and other relevant portions of the PSAR, against applicable regulations and the guidance and acceptance criteria from NUREG-1537, Parts 1 and 2. The staff reviewed the MHA analysis and its application in bounding all credible accident scenarios and releases, and in demonstrating that the reactor siting criteria in 10 CFR Part 100.11 are met. The staff also evaluated the applicant's "deterministic" safety analyses for postulated equipment failures and malfunctions, and used to determine the limiting conditions for operation (LCOs), limiting safety system settings, and design specifications for safety-related components and systems. The analyzed event scenarios and figures of merit used as surrogates for detailed dose calculations were thoroughly reviewed. The staff's review emphasized the importance of identifying all MAR throughout the facility; the role of temperature and time in the retention or transport of radionuclides; and bounding assumptions or conservative selection of inputs for initiating events and scenarios analyses. While the SE notes that Kairos did not request approval of any specific safety feature, nor was any approved, the staff cited that the functional containment approach is consistent with the approved SECY-18-0096 on the topic. The staff's review highlighted several of the aforementioned considerations in its review: the importance of identifying MAR throughout the facility; temperature versus time for evaluating retention and release of fission products and radioisotopes; and the application of conservative inputs to event analyses.

The staff also performed scoping calculations of several of the events to gain confidence in Kairos's calculational results. The results presented showed good agreement on key parameters (i.e., peak fuel and reactor vessel wall temperatures) with those of the applicant for selected important scenarios such as reactivity insertion and loss of forced circulation events.

For Hermes 2 the staff also evaluated the delta impacts of adding the IHTS and power generation system (PGS) to the initial Hermes design, including: new safety features such as the rupture disks in the IHTS and a RPS trip of the ISP, allowable amount of material at risk for release in the IHTS and PGS, and limits on allowable amounts of Flibe and water in the IHTS. New phenomena evaluated included leaks from the intermediate heat transport system that contains a non-Flibe coolant, which may contain a non-zero amount of radionuclides; IHX tube break or leak; potential internal or external events involving the IHTS or PGS that could prevent safety-related SSCs from performing their safety function; and gross failure of the IHX due to a PGS superheater tube rupture or leak.

In the absence of any explicit design modeling or experimental data, the staff found that there is large uncertainty in the progression of events following a postulated superheater tube break or rupture. It appears that the IHX tubes are relied upon to prevent Flibe-water interaction during this event; however, as discussed in SE Chapter 5, the IHTS (including the IHX tubes) is considered non-safety related by Kairos except for one component, the rupture disks. Consequently, the staff was unable to confirm that the IHX complies with the Hermes 2 definition of "safety-related" SSCs. In response to a request for confirmation, Kairos stated that the final design for Hermes 2 will demonstrate that the IHX tubes will not need to be classified as a safety-related SSC, or, if the IHX tubes are relied upon to remain functional during and after a postulated event, Kairos will demonstrate that their failure is not credible considering all relevant factors. Given the descriptions in the Hermes 2 PSAR, the staff found it plausible for Kairos to produce a final IHTS design, including IHX and rupture disks, that meets its design bases. The staff will confirm the adequacy of the rupture disks and overall IHTS design to preclude significant Flibe-water interaction resulting from a superheater tube break or rupture as part of its review of the OL application.

The staff previously found that the preliminary design of the Kairos Hermes reactor complies with applicable requirements. For Kairos Hermes 2 they found that the MHA still bounds the additional event sequences (e.g., reactivity transients, potential overcooling, intermediate salt spills, etc.) introduced by the IHTS and PGS. At the OL application review stage, subject to qualification testing, research and development program demonstrations, and confirmation that the final design conforms to the design basis, they concluded that safety questions can be adequately resolved and that such further technical or design information as may be required to complete the safety analysis can reasonably be left for later consideration, and will be supplied in the FSAR as part of the OL application. Further, taking into consideration the site criteria (10 CFR 100), the reactor can be constructed and operated at the proposed location without undue risk to the health and safety of the public. Based on its findings, the staff concludes that the issuance of CPs in accordance with 10 CFR 50.35 and 10 CFR 50.40 is possible.

Discussion/Observations

I did not identify any specific deficiencies in my initial review for Kairos Hermes. The applicant's documentation was thorough and complete at this preliminary design stage in identifying initiating events, assumptions and limitations, supporting methodologies, and presenting bounding results, as was the staff's evaluation. Several of the event groups identified warrant further attention and detailed review at the OL stage including, but not limited to: design of the primary heat transport system piping, pipe breaks, and assumptions about salt coolant inventory loss (potentially leading to uncovered fuel pebbles); functioning of the fluidic diodes to support natural circulation to enhance decay heat removal (probably more important in concept for eventual application in a larger power reactor); features to preclude salt spill sprays and salt interaction with safety-related components and structures (i.e., concrete – the applicant has committed to design measures to preclude these interactions); air ingress to the reactor vessel (i.e., oxidation of fuel and graphite, generation of combustible gases, and fuel/graphite/metallic materials qualification for a 7-day period following such an event as Kairos does not take credit for the confinement structure of the reactor building in mitigating air ingress); pebble handling system malfunctions; and seismic events (e.g., core/reflector disruptions and impact on reactivity control and shutdown).

Of historic note, the potential for air and water ingress into a high-temperature reactor's vessel, core, and structures was and remains a safety concern, and was addressed in the MHTGR programs. At high temperatures (about 1000 degrees Celsius), air (oxygen) interaction with carbon (graphite) results in an exothermic reaction and produces carbon monoxide and dioxide. The type of graphite and how it was manufactured and machined are significant factors, as well as temperature-time history, in the rate and yield of these reactions. Introduction of water by internal flooding, although the ensuing reaction is endothermic, potentially results in significant combustible gas generation (carbon monoxide and hydrogen) and concerns about corrosion and fuel integrity. Resolution of these potential scenarios will depend on the final design choices, details, and plant layout, and consideration of internal and external initiating events.

Regarding the major issue of concern with the addition of the IHTS and PGS, superheater tube rupture, there appears to be plausible design options to mitigate this impact. However, large uncertainties remain given the lack of detailed design description (e.g., system component layout, pressure rating, performance of rupture disks, etc.) and unknowns regarding steam/water and BeNaF interaction. As noted in our Chapter 5 review, the PRISM reactor approach to its intermediate heat transport system design provides a useful option for consideration in mitigating the consequences of this interfacing loss of coolant/break event scenario.

Recommendation

As lead reviewer for Hermes SE Chapter 13, I recommend no further review at this time of Chapter 13, "Accident Analysis." I do note that Appendix A to the staff's draft SE is a useful compendium of items important to safety to be addressed at the time of the review of an OL application.

References

1. 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 (Agencywide Documents Access and Management System (ADAMS) No. ML23055A674).

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. USNRC, Draft Safety Evaluation for Hermes Non-Power Reactor Preliminary Safety Analysis Report Chapters 2 ,3, 4, 5, 6, and 13, January 2023 (ML23017A120 and ML23065A010).

4. USNRC, "Hermes 2 Advance SE Transmittals to ACRS," 2024 (ADAMS Package ML24179A149).

5. NUREG-1537, "Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors," Parts 1 and 2, 1996 ((ML042430055 and ML042430048)

6. USNRC, SECY-18-0096, "Functional Containment Performance Criteria for Non-Light-Water-Reactors" (ML18114A546).

7. USNRC, SRM-SECY-18-0096, "Staff Requirements – SECY-18-0096 - Functional Containment Performance Criteria for Non-Light-Water-Reactors" (ML18338A502).

8. Kairos Power LLC, KP-TR-003-NP-A, Revision 1, "Principal Design Criteria for the Kairos Power Fluoride Salt-Cooled, High-Temperature Reactor," July 2019 (ML19212A756).

9. Kairos Power LLC, KP-TR-005-NP-A, Revision 1. "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor," January 16, 2020 (ML20016A486 and Proprietary version ML20016A487).

10. Kairos Power LLC, KP-TR-011-NP, "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR), Revision 2," June 2022 (ML22186A212).

11. Kairos Power LLC, KP-TR-012-NP-A, “Mechanistic Source Term Methodology for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor,” Revision 3, May 16, 2022 (ML22088A231 and proprietary ML22136A290)

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

13. Kairos Power LLC, KP-TR-014-NP, Revision 4, “Graphite Material Qualification for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor,” September 2022 (ML22259A145)

14. Kairos Power LLC, KP-TR-018-NP, Revision 2, Postulated Event Methodology for the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor,” Feb 28, 2023 (ML23055A676).

15. Kairos Power LLC, Kairos Power LLC, “Hermes 2 Postulated Event Methodology Technical Report,” KP-TR-022-NP, Revision 1. May 23, 2024 (ML24144A094 and Proprietary Version ML24144A093).

16. USNRC, NUREG-1368, “Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM) Liquid-Metal Reactor.” February 1994

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