UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 2, 2023

Mr. Peter Hastings
Vice President, Regulatory Affairs
and Quality
Kairos Power LLC
707 W Tower Ave
Alameda, CA 94501

SUBJECT: KAIROS POWER LLC – FINAL SAFETY EVALUATION FOR TOPICAL REPORT "FUEL QUALIFICATION METHODOLOGY FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH TEMPERATURE REACTOR (KP-FHR)" (REVISION 2) (EPID: L-2020-TOP-0046/CAC NO. 000431)

Dear Mr. Hastings:

This letter provides the final safety evaluation for the Kairos Power LLC (Kairos) topical report "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)." By letter dated June 30, 2020, Kairos submitted the topical report for the U.S. Nuclear Regulatory Commission (NRC) staff's review (Agencywide Documents Access and Management System (ADAMS) Package Accession No. ML20182A830). The NRC staff provided questions on the topical report to Kairos on November 20, 2020 (ML20328A147), and August 4, 2021 (ML21216A398). On October 13, 2021, February 8, 2022, May 2, 2022, May 16, 2022, June 2, 2022, and June 23, 2022, the NRC staff and Kairos held closed meetings to discuss additional clarification questions. Kairos submitted Revision 1 of the topical report by letter dated April 5, 2022, and Revision 2 by letter dated July 5, 2022 (ML22095A277 and ML22186A213, respectively).

The NRC staff's final safety evaluation for "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)," Revision 2, is enclosed. The NRC staff provided a draft of the safety evaluation to Kairos for the purpose of identifying proprietary information and Kairos confirmed that the draft safety evaluation did not contain proprietary information on October 5, 2022 (ML22278B094).

The Advisory Committee on Reactor Safeguards (ACRS) was briefed on this topical report and the NRC staff's draft safety evaluation on October 17, 2022, and November 30, 2022. The ACRS provided its recommendations for the publication of this safety evaluation in a letter dated December 20, 2022 (ML22340A628). By letter dated February 8, 2023 (ML23024A263), the NRC staff provided its response to the ACRS recommendations. The enclosed safety evaluation is final and is publicly available.

The NRC staff requests that Kairos publish an accepted version of this topical report within 3 months of receipt of this letter. The accepted version shall incorporate this letter and the enclosed safety evaluation after the title page. The accepted version shall include an “-A” (designating accepted) following the topical report identification symbol.

If you have any questions, please contact Ben Beasley at (301) 415-2062 or via email at Benjamin.Beasley@nrc.gov.

Sincerely,

Signed by Jessup, William
on 03/02/23

William Jessup, Chief
Advanced Reactor Licensing Branch 1
Division of Advanced Reactors and Non-Power
Production and Utilization Facilities
Office of Nuclear Reactor Regulation

Docket No.: 99902069

Enclosure:
As stated

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SUBJECT: KAIROS POWER LLC – FINAL SAFETY EVALUATION FOR TOPICAL REPORT "FUEL QUALIFICATION METHODOLOGY FOR THE KAIROS POWER FLUORIDE SALT-COOLED HIGH TEMPERATURE REACTOR (KP-FHR)" (REVISION 2) (EPID: L-2020-TOP-0046/CAC NO. 000431) DATED: MARCH 2, 2023

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FINAL SAFETY EVALUATION FOR TOPICAL REPORT KP-TR-011, REVISION 2, "FUEL QUALIFICATION METHODOLOGY FOR THE KAIROS POWER FLOURIDE SALT-COOLED HIGH TEMPERATURE REACTOR (KP-FHR)" (EPID L-2020-TOP-0046)

APPLICANT INFORMATION

Applicant: Kairos Power LLC

Applicant Address: 707 W. Tower Ave.
Alameda, CA 94501

Docket /Project No(s).: 99902069

APPLICATION INFORMATION

Submittal Date: June 30, 2020

Submittal Agencywide Documents Access and Management System (ADAMS) Accession No.: ML20182A830

Revision letter Dates and ADAMS Accession Nos: Revision 1, April 5, 2022 (ML22095A276), Revision 2, July 5, 2022 (ML22186A212)

Brief Description of the Topical Report: This topical report (TR) describes the fuel qualification methodology for the Kairos Power Fluoride Salt Cooled High Temperature Reactor (KP-FHR) power and test reactors. Kairos Power LLC (Kairos, the vendor) relies on the Electric Power Research Institute (EPRI) TR on "Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO)-Coated Particle Fuel Performance" (Reference 1) for qualification of the TRISO fuel particles, but KP-TR-011-P TR details the qualification of the fuel pebble form which is used in the KP-FHR power and test reactor designs. The qualification methodology relies on an evaluation of a KP-FHR Phenomena Identification and Ranking Table (PIRT) to provide the scope of the qualification needs. Kairos presents seven limitations in Section 4.2 of the TR, which serve to provide boundaries to the applicability of the TR.

The methodology considers mechanical and structural performance as well as chemical, thermal, and irradiation effects. Mechanical and chemical performance are established or confirmed by laboratory testing. Thermal and irradiation performance is established by the Advanced Gas Reactor (AGR)-2 testing program or additional irradiation testing, if outside the AGR-2 performance envelope. AGR-2 is the second of the planned irradiations for the AGR Fuel Development and Qualification Program, a program at the Idaho National Laboratory funded by the Department of Energy for purposes of determining irradiated TRISO particle behavior.

Enclosure

The KP-FHR power and test reactor fuel qualification methodology is intended to provide reasonable assurance that the KP-FHR power and test reactor fuel pebbles can operate with a low failure fraction similar to what has been previously demonstrated for the AGR TRISO fuel particles. To that end, this TR presents a series of tests, available data, and surveillance plans to support the qualification of KP-FHR power and test reactor fuel pebbles.

For additional details on the submittal, please refer to the documents located at the ADAMS Accession numbers identified above.

EVALUATION CRITERIA

Regulations

For construction permit applications, Title 10 of the *Code of Federal Regulations* (10 CFR) 50.34(a) provides that each application for a construction permit shall include a preliminary safety analysis report (PSAR) and describe the minimum information to the be included in the PSAR.

The regulation at 10 CFR 50.34(a)(1)(ii)(C) provides that the application shall include the extent to which the reactor incorporates unique, unusual or enhanced safety features having a significant bearing on the probability or consequences of accidental release of radioactive materials.

The regulation at 10 CFR 50.34(a)(1)(ii)(D) provides, in part, that the application shall include the safety features that are to be engineered into the facility and those barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur.

The regulation at 10 CFR 50.34(a)(2) provides that the application shall include a summary description and discussion of the facility, with special attention to design and operating characteristics, unusual or novel design features, and principal safety considerations.

For operating license applications, 10 CFR 50.34(b)(4) requires that each application, for an operating license, include a final safety analysis report that includes an analysis and evaluation of the design and performance of structures, systems, and components with the objective of evaluating the risk to the public. The analysis and evaluation shall take into account any pertinent information developed since the submittal of the PSAR. Similar regulations exist for Part 52 applications.

The requirements in 10 CFR 50.34(a) and 10 CFR 50.34(b), specified above, apply to this TR because the TRISO particle is the primary means of fission product retention.

The regulation at 10 CFR 50.41(b) provides additional standards for class 104 test reactor licenses, including that in addition to applying the standards set forth in 10 CFR 50.40, the Commission will permit the conduct of widespread and diverse research and development.

The regulation at 10 CFR 50.43(e) provides requirements regarding analysis, appropriate test programs, and experience for designs that differ significantly from light water reactors designs licensed before 1997.

The regulation at 10 CFR Part 100, “Reactor Siting Criteria,” establishes approval requirements for proposed sites for stationary power and testing reactors subject to 10 CFR Part 50 or Part 52. The regulation in 10 CFR 100.11, “Determination of exclusion area, low population zone, and population center distance” requires, in part, the determination of an exclusion area, a low population zone, and a population center distance. The vendor plans to credit the retention of the TRISO particle to inform its dose analysis, and this TR will, therefore, play a role in the NRC staff’s review of the siting criteria.

Principal Design Criteria

The regulation in 10 CFR 50.34(a)(3)(i) requires, in part, that an applicant for a construction permit to build a reactor is to provide principal design criteria (PDC) for the facility. The NRC staff approved PDC for the KP-FHR in KP-TR-003-NP-A, Revision 1 (ML20167A174).

KP-FHR PDC 10, “Reactor design” states “[t]he reactor core and associated heat removal, control, and protection systems shall be designed with appropriate margin to ensure that specified acceptable system radionuclide release design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.” Establishing fuel design limits and ensuring these limits are not exceeded represent a fundamental underpinning of the safety assessment of a nuclear power plant required by 10 CFR 50.34(a)(1).

KP-FHR PDC 16, “Containment Design” states that the “[r]eactor functional containment, consisting of multiple barriers internal and/or external to the reactor and its cooling system, shall be provided to control the release of radioactivity to the environment and to ensure that the functional containment design conditions which are safety significant are not exceeded for as long as postulated accident conditions require.” Preventing uncontrolled release of radioactivity represents a fundamental underpinning of the safety assessment of a nuclear power plant required by 10 CFR 50.34(a)(1).

TECHNICAL EVALUATION

In the following technical evaluation, a section, table, or figure number without additional description refers to the vendor’s TR. If section, table, or figure numbers are referenced from other reports or sections for this safety evaluation, additional descriptive information will be provided.

Applicability of Existing Data

Section 2 of TR KP-TR-011-P, “Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)” provides a description of the KP-FHR fuel design. The NRC staff compared the KP-FHR particle and pebble design with existing designs to understand the applicability of existing data. Specifically, the NRC staff compared Table 2-2 with Tables 5-2 and 5-3 of TR EPRI–AR-1(NP)-A, “Uranium Oxycarbide (UCO) Tristructural Isotropic (TRISO)-Coated Particle Fuel Performance” (Reference 1). Based on its review, the NRC staff determined that the KP-FHR particle design is acceptable because it is in good agreement with the kernel dimensions for the AGR-2 experiments.

Table 3-17 lists the desired fuel performance parameters for the planned KP-FHR power and test reactor equilibrium cores in comparison with the AGR-1 and AGR-2 experiments. Since the Kairos fuel particles are designed with the AGR-2 kernel specifications, the AGR-2 fuel performance envelope is used to determine the operability bounds. The NRC staff notes that the desired KP-FHR power reactor equilibrium core fuel performance parameters exceed the AGR-2 program fuel performance parameters with the exception of time-averaged temperature. As stated in TR Limitation #3, Kairos will develop additional supporting data per Reference 1 before extending the operability bounds. Section 3.7 details the process by which additional data will be collected to support extension of the operability bounds.

Based on the findings above regarding KP-FHR fuel particle specifications and Limitation #3 as presented in Section 4.2, the NRC staff finds that the use of existing data from the AGR program (Reference 1) is acceptable for operations within the AGR-2 performance envelope. As stated in Limitation #3 of Section 4.2, additional data will be necessary to support reactor operations outside of the AGR-2 envelope.

Fresh Fuel Pebble Laboratory Testing

As discussed in Section 2.2.2, the Kairos fuel pebble design is slightly smaller than traditional TRISO fuel pebbles and has a non-fueled low-density carbon matrix center. The next layer of the Kairos fuel pebbles is a carbon matrix with embedded TRISO fuel particles. The final (outside) layer of the Kairos fuel pebble is fuel-free matrix material. Although the Kairos pebble design is different, the TRISO fuel particle specifications are consistent with the AGR-2 particle specifications.

Kairos developed a PIRT to identify fuel pebble phenomena with a low to medium knowledge base and develop a testing program to increase the knowledge base for these phenomena. Section 3.6 summarizes the laboratory testing used to support fuel qualification of the KP-FHR fuel pebbles based on the PIRT. The NRC staff reviewed mechanical, tribology, buoyancy, and material compatibility testing to determine if these tests would support a fuel qualification determination and reasonable assurance finding for the fuel pebbles to be used in the KP-FHR power and test reactors.

The mechanical testing consists of compression tests and impact tests. Irradiated mechanical testing of the fuel pebbles is not planned due to the increase in strength that is expected based on publicly available experimental results from the German test program on TRISO pebble fuel (Reference 2). Similarly, the tests will be performed at room temperature due to publicly available information demonstrating that strength increases with temperature. The compression tests involve compressing fresh fuel pebbles between two steel plates until failure at room temperature.

The impact tests will be performed either by: (1) dropping a pebble onto a non-yielding surface from a height bounding all possible drop heights that could occur in the core, pebble handling systems, or during storage/transportation, or (2) accelerating a pebble to a velocity bounding all possible drop heights and striking a non-yielding target. The NRC staff reviewed References 2, 3, and open literature regarding temperature and irradiation effects on carbon and agrees that for the temperatures of interest, fresh fuel mechanical testing at room temperature would provide bounding results compared with irradiated fuel and operating temperatures. Based on the NRC staff's review of the mechanical testing methods in comparison with previous TRISO pebble testing methods, the NRC staff finds the Kairos mechanical testing methods acceptable for determining crush and impact strength for the Kairos fuel pebbles.

Kairos presented the acceptance criteria for both the crush strength and impact testing in Section 3.6.1. The NRC staff reviewed the acceptance criteria and confirmed that they would reasonably cover any expected loads and that they were consistent with historical TRISO fuel pebble acceptance criteria. Therefore, the NRC staff finds that the crush strength and impact load acceptance criteria are conservative, and they provide reasonable assurance that the pebbles will not fail as a result of anticipated mechanical loads.

Kairos states that a subset of the failed pebbles from mechanical testing will be investigated to determine the failure fraction of TRISO particles. The deconsolidation leach burn leach (DLBL) method will be used to determine the particle failure fraction, which the NRC staff notes is consistent with the method used to investigate TRISO particle failed fuel fractions in EPRI-AR-1(NP)-A (Reference 1). Therefore, the NRC staff concludes that the method for determining mechanical limits of the pebbles and failed fuel fractions of the particles is acceptable.

Kairos states in Section 3.6.2, that tribology tests will be conducted on fresh pebbles to obtain coefficient of friction and bounding wear rate data for comparison with Discrete Element Modeling (DEM). This DEM will be used to confirm the pebble lifetime, single point contact wear rate. The tribology tests are designed to bound pebble degradation as a result of wear against other pebbles, stainless steel, and graphite. The NRC staff reviewed the temperature ranges, method of testing, and applied force. The procedure used is based on American Society of Testing and Materials standard G99-17, “Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus,” but the test conditions were chosen to reflect the Kairos pebble design and reactor conditions. While the maximum temperature used during testing does not bound all possible accident conditions, the NRC staff agrees with Kairos’s justification in that the limited time expected above the maximum tested conditions for any accident is insufficient for excessive wear to occur. Additionally, the NRC staff reviewed publicly available data on the graphite coefficient of friction as a function of temperature and noted that the coefficient of friction at the maximum accident conditions for KP-FHR is bounded by the coefficient of friction at the lower test conditions. The NRC staff reviewed the assumptions used to develop the tribology testing and wear calculations and finds that they are conservative. The NRC staff finds that: (1) the tribology testing proposed for the KP-FHR power and KP-FHR test reactor is acceptable, and (2) the assumptions used to model lifetime wear of pebbles (e.g., the use of a single contact point) are conservative, and therefore, acceptable.

In Section 3.6.3, Kairos presents the analytical data and experimental methods which will be used to ensure the ability of the Kairos pebble to maintain net positive buoyancy under normal operations and licensing basis event conditions, as well as identify salt intrusion characteristics for the Kairos fuel pebbles in a molten salt environment. Three phenomena affecting buoyancy of the Kairos pebbles are: (1) salt infiltration, (2) densification of graphite with irradiation, and (3) densification of graphite with increasing temperature. Densification due to temperature and irradiation has been publicly investigated and can be addressed in fuel performance modeling. Salt infiltration into a graphite matrix has also been studied, but Kairos will perform additional testing to collect data based on Kairos materials over the expected temperature and pressure ranges.

The NRC staff reviewed the salt intrusion test parameters and notes that the temperature ranges bound the expected pebble temperatures as presented in Table 3-17. Additionally, the pressure used to investigate salt intrusion conservatively bounds the expected maximum pressure which is at the vessel inlet. The salt intrusion tests are performed on an unirradiated pebble which maximizes salt ingress as the carbon matrix pore size decreases with irradiation due to graphite densification. This is conservative since the maximum pebble fluence for the non-power and power KP-FHRs is less than the turnaround fluence where continued densification stops, and the minimum pore size is achieved.

Based on the NRC staff's review of the buoyancy testing methods and parameters described in the TR relative to the planned reactor operating conditions, and a review of the references associated with salt intrusion and graphite density changes as a function of temperature and irradiation (References 4, 5, and 6), the NRC staff finds the method of determining buoyancy based on densification and salt intrusion characteristics for the Kairos fuel pebbles to be acceptable.

Section 3.6.4 covers material compatibility between the Kairos pebble carbon matrix and Flibe. Flibe is a lithium fluoride, beryllium fluoride salt mixture which serves as the coolant in KP-FHR reactors. Kairos presents a test plan to investigate material compatibility behavior between the Kairos pebble carbon matrix with Flibe and air. The NRC staff confirmed that the Kairos test plan parameters bound pebble surface temperatures expected during normal operation and cycle times for a pebble to pass through the core. Kairos plans to also investigate the test specimens from the salt intrusion test for material compatibility at accident conditions.

In addition to the planned testing for Kairos fuel pebble graphitic material, Kairos cites available information from the Molten Salt Reactor Experiment (MSRE), University of Wisconsin-Madison (UW), the Chinese Thorium Molten Salt Reactor Energy System–Solid Fuel (TMSR–SF), and Massachusetts Institute of Technology (MIT). The MSRE operated for 3 years in which a graphitic core was submerged in Flibe. The UW, TMSR–SF, and MIT experiments investigated salt intrusion into TRISO particles which contained a graphitic overpack. The NRC staff notes that while the MSRE, UW, TMSR–SF, and MIT data was not collected from specimens that were identical to the Kairos design, they are similar and still serve to support the data which will be collected by Kairos in its material compatibility test program.

Kairos' test plans also include material compatibility with air which will be used to develop oxidation models for the Kairos fuel pebble. The NRC staff reviewed the material presented in Section 3.6.4 and finds that the test plan for the Kairos fuel pebble in combination with Kairos' use of available data to investigate the interactions of Flibe and the graphitic carbon matrix of the Kairos' fuel pebble are acceptable for developing appropriate correlations to model Flibe and air material compatibility with pebble matrix graphite. It should be noted that the NRC staff makes no finding as to the acceptability of the future correlations based on the Kairos tests and supporting information. The acceptability of any future correlations will be addressed in future licensing actions.

Irradiation Testing

In Section 3.7, Kairos describes planned irradiation testing to support Kairos fuel pebble qualification if the planned KP-FHR operations exceed the operating ranges investigated in the AGR-2 program (Reference 1). The test plan covers the KP-FHR equilibrium core conditions, which is the most limiting of the planned operating conditions. The NRC staff reviewed the test plan, post-irradiation examination (PIE) description, and the acceptance criteria as presented by Kairos.

The test plan involves Kairos' pebble irradiation in a non-KP-FHR facility within a gas environment. The NRC staff reviewed the test plan based on the information provided in Section 3.7.1 and Table 3-19, and finds that the test plan can successfully be used to simulate pebble exposure in equilibrium core conditions if these conditions exceed the AGR-2 testing envelope because the test conditions will bound operating conditions as addressed in Limitation #3 of the TR. The NRC staff notes that the test plan does not cover transient conditions. However, this is addressed in Limitation #5 in Section 4.2 which states, "[f]uture license applications for the commercial electric power KP-FHRs will include justification (testing or analysis based on an approved methodology) of the applicability of this methodology during rapid reactor transient events." The NRC staff notes that Limitation #5 does not apply to the non-power test reactor. The need for reactivity transient testing in a non-power reactor will be addressed in the NRC staff's safety evaluation for that facility and is identified as Limitation and Condition #1 of this safety evaluation.

In Section 3.2.2, Kairos states that while it is expected that the Kairos fuel pebble design can safely operate within the desired fuel performance parameters, KP-FHR will be limited to AGR-2 parameter values until the results of testing (as outlined in Section 3.7) can be completed and used to support operation within the desired fuel performance envelope. This is further discussed in TR Table 3-4, "Limitations and Conditions from SER on TRISO Topical Report" in relation to Condition 1 of the referenced EPRI TR (Reference 1).

Section 3.7 presents the testing and statistical methods which will be used to support operation of KP-FHR beyond the fuel performance parameters used in the AGR-2 program. The NRC staff reviewed this irradiation test plan and notes that it generally aligns with the AGR-2 test methods but would operate at the desired more limiting conditions. Based on the foregoing, the NRC staff finds this test plan to be acceptable for developing a database to support future operation at the desired KP-FHR equilibrium core conditions. Based on the NRC staff's review of the statistical methods described in Section 3.7.4, the NRC staff finds that the statistical methods use a well-known statistical analysis methodology, are appropriate for calculating the upper confidence bounds, and are acceptable for determining the minimum number of test fuel particles needed to support operation at the desired KP-FHR equilibrium conditions.

Kairos plans to use Non-Destructive Examination (NDE) and Destructive Examination (DE) techniques as part of the PIE of the TRISO particles. The NRC staff reviewed the NDE techniques described in Section 3.7.2 and finds them to be reasonable for confirming the burnup and identifying any gross external damage of the fuel pebbles. Fuel pebble burnup is determined by gamma spectrometry and is a standard industry method to determine burnup. Follow-on pebble destructive testing will also be used to confirm the gamma spectrometry determined burnup. Kairos also states that KP-FHR reactors will be capable of evaluating two surface criteria, both of which evaluate pebble surface degradation that could expose TRISO particles to Flibe coolant. The NRC staff agrees that these are reasonable pebble surface criteria to determine if significant pebble surface degradation exists leading to potential TRISO particle/Flibe interactions.

Kairos will use DLBL techniques for DE of the TRISO particles from the irradiation experiment in order to determine the particle failure fraction. The NRC staff notes that this technique is the same technique used by the AGR program to determine the condition of the TRISO particle layers and was used to support determination of the particle failure fraction in the approved EPRI TR (Reference 1).

The NRC staff notes that the irradiation test plan presented in Section 3.7 of the TR does not include testing prior to reactor startup of fuel pebbles which have been irradiated in a molten salt environment and were manufactured using the planned production process. Experiments with TRISO compacts (as opposed to pebbles) in a gas environment have shown chemical attack of the TRISO particle SiC layer from contaminants (Fe, Cr, or Ni). For the KP-FHR design, the NRC staff observes that:

1. KP-FHR designs will control salt coolant chemistry, including minimizing oxidation potential;

2. KP-FHR designs will perform NDE of the pebbles as they transit the pebble handling systems;

3. KP-FHR designs will monitor cover gas and coolant activity for indications of TRISO particle failures;

4. there was a lack of non-gaseous precursor fission product migration in the MSRE graphite core; and

5. a reduction in pebble graphite matrix pore size with irradiation will reduce the migration of salt impurities which could damage the TRISO particle.

The NRC staff finds that these observations provide reasonable assurance that the fuel pebbles will have an acceptably low failure fraction. The NRC staff notes, however, that it is appropriate to seek confirmation prior to commercial reactor operation that corrosion products in the KP-FHR design do not attack the SiC layer. Therefore, the NRC staff has included Limitation and Condition #2 in this safety evaluation to address the need for confirmatory data on Kairos fuel pebble irradiation in a molten salt environment to support fuel qualification for a commercial power KP-FHR.

The NRC staff notes that Limitation and Condition #2 does not apply to a non-power test reactor. A commercial power KP-FHR contains significantly more pebbles, operates at a higher power density, and will result in higher fuel burnup compared to test reactors. Further, as noted above, the NRC staff finds that there is reasonable assurance that the fuel pebbles will have an acceptably low failure fraction. Therefore, the NRC staff concludes that no additional fuel pebble testing beyond that which has already been addressed in the TR and this safety evaluation is necessary for a non-power test version of the KP-FHR. The NRC staff notes that data gained from the destructive examination of fuel pebbles from a non-power test version of a KP-FHR may be used to support the qualification of fuel pebbles in a commercial power KP-FHR, thereby satisfying Limitation and Condition #2. This is consistent with 10 CFR 50.41(b) which permits the conduct of widespread and diverse research and development for class 104 test reactor licenses.

Based on the findings in the preceding paragraphs, the NRC staff concludes that:

- given the limitations on use presented in Limitations #3 and 5 of the TR, the Kairos irradiation test plan and PIE can be used to acquire data to support the fuel qualification of the Kairos fuel pebbles for operating conditions which exceed the AGR-2 test envelope;

- the statistical analysis presented in the TR is acceptable for identifying the number of pebbles and particles necessary to provide the desired confidence level and to calculate the failure fraction;

- the PIE methods and irradiation test acceptance criteria are acceptable for identifying failed particles;

- evaluation of irradiated test reactor fuel as described in Limitation and Condition #2 of this safety evaluation will provide data to support full qualification of commercial power reactor fuel; and

- irradiation testing described in the TR for test reactor fuel is sufficient for referencing in future test reactor operating license applications.

Fuel Performance Modeling

Section 3.8 addresses fuel performance modeling of the Kairos fuel pebbles. The report addresses both TRISO particle and fuel pebble modeling. The TRISO modeling is based on KP-Bison code and the fuel pebble modeling utilizes DEM and Finite Element Method (FEM). While the NRC staff is aware of these tools, the correlations built from testing have not been developed yet; therefore, the NRC staff can make no findings regarding the use of KP-Bison, DEM, or FEM beyond the use of any approval already obtained. Once the data have been collected from the tests as outlined in the fuel qualification TR, correlations can be either validated or modified, as necessary. The NRC staff makes no findings regarding fuel performance modeling as part of this safety evaluation; any information derived from the fuel qualification testing program which impacts the fuel performance modeling will be incorporated in a future licensing submittal.

Fuel Surveillance Program

Section 3.9 presents the KP-FHR fuel surveillance program, which utilizes different techniques to monitor the fuel and ensure it performs as designed. Specifically, the surveillance program includes the following:

1. use of online cover gas and coolant activity monitoring to detect failed fuel of sufficient quantity to result in a detectible release of reactivity into the coolant and cover gas;

2. gamma spectroscopy measurements of pebbles as they transit the pebble handling systems to detect burnup and ensure that burnup limits are not exceeded by reintroduction into the core;

3. pebble inspections for damage which could lead to particle failure if the pebbles were reintroduced into the core; and

4. destructive examinations in both the power and non-power KP-FHR reactors of a select number of initial core pebbles to confirm other aspects of the surveillance program and to provide validation data for particle failure fractions.

Based on the NRC staff's review of the above elements of the surveillance program, the NRC staff concludes that the surveillance program is robust and can detect failed particles, pebbles at the end of life, and damaged pebbles which could lead to particle failure. Therefore, the NRC staff finds the surveillance program as described in Section 3.9, to be acceptable.

LIMITATIONS AND CONDITIONS

Kairos included seven limitations on the use of this TR in Section 4.2. The NRC staff considered these limitations in the technical review presented in this safety evaluation. The NRC staff applies the following additional limitations and conditions on the acceptance of this TR:

1. Future license applications for non-power KP-FHRs shall include justification of the applicability of this methodology during rapid reactor transient events.

2. Future operating license applications for a commercial power KP-FHR shall provide information demonstrating that TRISO particle failures due to chemical attack from impurities (e.g., Fe, Cr, or Ni) in the molten salt coolant during expected reactor conditions are precluded or can be demonstrated to be insignificant. This information shall include test data from representative fuel pebbles in salt under irradiated conditions (e.g., in a test reactor).

CONCLUSION

As discussed above, the NRC staff has determined that Kairos' TR "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor" provides an acceptable methodology to qualify fuel for the KP-FHR power reactor and KP-FHR test reactor based on: (1) identification of knowledge gaps pertaining to the Kairos fuel pebble, (2) a test plan to build the necessary pebble knowledge database, (3) a surveillance program to validate fuel performance, and (4) destructive examinations designed to support reactor operations which exceed the AGR-2 parameters. Accordingly, the NRC staff concludes that Kairos' TR "Fuel Qualification Methodology for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor," complies with the applicable NRC regulations and can be used to support fuel qualification for the KP-FHR power and KP-FHR test reactor designs, subject to the limitations and conditions discussed above.

Based on the technical evaluations presented above, the NRC staff concludes that the TR is consistent with KP-FHR PDC 10 because the testing plan outlined in the TR will increase fuel behavior knowledge which supports the ability to demonstrate that specified acceptable radionuclide release design limits (SARRDLs) are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

Based on the NRC staff's technical evaluations of the Kairos fuel design, the NRC staff concludes that the TR is consistent with KP-FHR PDC 16 because the use of TRISO particles, within the operating conditions allowed by the TR, provides multiple barriers internal to the reactor and its cooling system to control the release of radioactivity to the environment and to ensure that the functional containment design conditions which are safety significant are not exceeded for as long as postulated accident conditions require.

The NRC staff finds that the qualification plan outlined in the TR can be used to support a finding that 10 CFR 50.43(e) is met because: (1) the safety aspects of the Kairos fuel design are demonstrated through a combination of analysis, test programs, and experience, (2) interdependent effects among the safety features of the Kairos fuel design are acceptable, as demonstrated by analysis, appropriate test programs, experience, and (3) sufficient data exist on the safety features of the Kairos fuel design to assess the analytical tools used for safety analyses over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions.

The NRC staff finds that the qualification plan outlined in the TR can be used to support a finding that 10 CFR 100.11 is met by supporting the determination of the exclusion area, low population zone, and population center distance.

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