U.S. Nuclear Regulatory Commission Preliminary Comments on Kairos Power LLC Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor Topical Report

By letter dated March 8, 2019, Kairos Power LLC (Kairos) submitted for U.S. Nuclear Regulatory Commission (NRC) staff review, "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor Topical Report" (Agencywide Documents Access and Management System (ADAMS) Accession No. ML19079A324). In this letter, Kairos requested NRC staff approval for specification information and thermophysical properties for reactor coolant for the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR).

The NRC staff has completed an initial review of the topical report and developed preliminary questions to facilitate its understanding of the information in the report. These questions are intended to inform future discussions with Kairos and support the NRC staff in obtaining clarifying information. Based on the outcome of its discussions with Kairos on the topics identified below, the NRC staff may develop formal requests for additional information to complete its review of the topical report.

Preliminary Questions

Topic 1: Molten Salt Chemistry

(1) Section 2.2.2, "Corrosion Requirements," states, "MSRE found no attack of the graphite moderator during operation, with no change in graphite surface finish after 2.5 years of exposure." Recent research has shown that nuclear graphite experiences fluorination when exposed to FLiBe salt (see Journal of Fluorine Chemistry 211 (2018) pages 159-170). The molten salt interaction with graphite may potentially have adverse impacts on long term fuel performance. The NRC staff is seeking clarification from Kairos on its plan, if any, to address the potential for FLiBe salt interactions with graphite and how it could affect long term fuel performance. The TRISO fuel pebbles contain layers with graphite as well as other materials such as silicon carbide (SiC). The staff is seeking clarification from Kairos on its plan, if any, to address potential interactions between the FLiBe salt and any component of the TRISO fuel pebble. As an example, Reference 9 discusses the chemical compatibility of SiC in molten fluoride salts and notes that the corrosion tests have shown potential reactivity between SiC and dissolved metal impurities.

(2) Section 2.2.2, "Corrosion Requirements," states that while carbon-based- materials are included in the high temperature materials testing programs, the structural materials are the basis to set corrosion requirements because the Molten Salt Reactor Experiment (MSRE) found no graphite moderator attack during operation. However, according to the ASM handbook: "Corrosion in High- Temperature Environments" (Reference 8) the MSRE and the KP-FHR are not identical designs because nickel (Ni) inhibits carburization. Additionally, page 77 of reference 10 "Chemical Aspects of MSRE Operations" discusses an apparent effect whereby the graphite moderator acts as a sink for Chromium (Cr) and promotes corrosion of the structural alloy. Further experiments in reference 1 and reference 4, found carburization when performing tests in a graphite

crucible and a higher rate of corrosion of the alloys due to the combined effects of graphite and neutron radiation. Since a potential for graphite corrosion is present, the NRC staff is seeking clarification on the following:

(a) How does Kairos plan to demonstrate this is not a limiting factor (as compared to fuel corrosion or structural material corrosion)?

(b) The NRC staff would like clarification on whether small corrosion of the graphite moderator could cause large neutronic impacts. If so, how much weight would be given in comparison to the structural material corrosion?

(c) Reference 11 of this document suggests a potential gap in understanding how irradiation affects corrosive properties of the salt. The NRC staff would like clarification on Kairos's material testing programs consideration of impacts of the reactor coolant chemistry/purity on the graphite moderator and fuel as well as structural materials. Has the potential for carburization and irradiation of structural alloys been considered in the design and/or corrosion allowances?

(3) Table 4 of the Kairos Reactor Coolant Topical Report proposes a [[

]] The NRC staff is seeking clarification on the following:

(a) [[

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(b) If one of the listed impurities has a more deleterious effect than the others, is it possible to tolerate the impacts if this one impurity accounts for [[
]] for an unspecified period of time?

(c) How do impurity limits account for off-normal chemistry or transients? [[
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(d) During the high temperature materials corrosion testing, what impurities and at what levels will be tested in the salt? To establish limits for certain corrosive impurities test data should be validated. Will the corrosion rates from the materials testing be used to ensure that the proposed corrosion rates, allowances, and impurities are conservative?

i. [[

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(e) [[

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(f) The NRC staff would like clarification on whether a technical specification (TS) will be proposed for impurity/contaminant limits and if it will include associated corrective actions.

(g) Reference 6 of this document indicates fluoride salts are vulnerable to radiolytic decomposition at low temperatures. Are impacts of multiple startups/shutdowns and transients on corrosion rates and stability of the fluoride salt analyzed? Section 2.2.2 “Corrosion” of the Reactor Coolant TR seems to indicate [[

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(h) Table 4 discusses [[

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(i) Section 2.2.2, “Corrosion,” of the TR discusses the potential mechanisms for structural alloys to corrode and references a list of elements in Table 5 that may lead to corrosion. The NRC staff would like clarification on the purpose and/or basis of the table.

(j) Have the solubilities of contaminants (e.g. oxidizers, corrosion products, fission products) been determined?

(4) Section 2.2, “Flibe Specification,” of the Kairos reactor coolant TR states that [[

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(a) The NRC staff would like clarification on [[

(b)

(c)

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(5) Appendix B of the TR provides calculated electrochemical fluoride potentials. Since the electrolyte can have significant influence on the behavior of a redox couple, the NRC staff would like Kairos to clarify [[

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(6) Section 2.5 of the Reactor Coolant TR notes that [[

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(7) Section 2.2.2, "Corrosion Requirements," of the Reactor Coolant TR references [[

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(a) Additionally, Section 3.2, Limitation," states that the high temperature materials testing will confirm corrosion allowances. Does this include transient corrosion impacts or only steady state? Since this test will be done in FLiBe, would these results change information in Appendix B which provides electrochemical potentials of fluorides?

(b) The NRC staff would like clarification on whether [[

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(c) Reactor Coolant TR Table 5 and Appendix B presents electrochemical potentials for fluorides. The NRC staff would like clarification on whether these values [[

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Section 2.4, "Salt Chemistry Control During KP-FHR Operation," notes that [[

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(9) Does Kairos plan to evaluate potential impacts on thermophysical and/or chemical properties of the reactor coolant from impurities such as metallic impurities, water, oxygen, nitrate salt, organics, oil, transmutation products, fission products, products of chemical reactions, etc., that may intrude into the PHTS? Clarify if any of the impurities listed above may have thresholds where they may impact properties of the salt or increase corrosion of structural materials. (Reference 11, Technical Gap Assessment for Materials and Component Integrity Issues for Molten Salt Reactors suggests a gap in understanding how fission products impact corrosion). In another example, the ORNL "Chemical Aspects of MSRE Operations," states that the extent of oil leakage must be known due to operational implications and due to chemical effects induced by hydrocarbon degradation products.

(10) Research from ORNL (Heat Transfer Salt for High Temperature Steam Generation; ORNL-TM-3777) indicates that nitrate salts may experience vigorous exothermic reactions with graphite. Clarify if this reaction has been considered in the KP-FHR design and have steps been taken to mitigate the potential impact?

(11) Clarify how online purification will be conducted during power operations. Clarify if the KP-FHR will remove constituents like water and other substances that may leak into the PHTS and if so, how it will be done.

(12) Does Kairos plan to conduct testing to demonstrate the initial purification and synthesis of FLiBe? Additionally, clarify where the initial FLiBe purification will be conducted and how is it transported to the PHTS. The NRC staff would like clarification on whether controls are in place to limit impurities during transport and storage and if so a description of them will assist in understanding the topic.

(13) Section 2.3, "Flibe Synthesis and Purification," of the Reactor Coolant TR mentions the use of a gas sparge to remove impurities from the raw salt mixture once melted. Additionally, gas sparges may be used to control salt chemistry during KP-FHR operation. Clarify how adequate contact between the sparging gas and the targeted impurities will be maintained to have adequate removal of impurities (Reference 6).

(14) The NRC staff would like to clarify if additional detail regarding the on-line reactor coolant purification system, including items such as capacity of the system, methods used to remove impurities, fission products, etc, is available at this time or if it will be developed as part of another TR. This detail will help the staff have reasonable assurance that the capability exists to support the reactor coolant parameters proposed by Kairos.

(15) The NRC staff would like to clarify if FLiBe has any activation products besides ^{7}Li?

(16) Section 2.1, "Flibe for Primary Heat Transport System," and Table 1, "Thermophysical Properties of the KP-FHR Primary Coolant," Vapor Pressure

(a) The Reactor Coolant TR cites a different value/correlation for calculating the vapor pressure of FLiBe (method based on Raoult's Law and the correlation in Table 1). Clarify which one will be used and the basis for using it.

(b) Additionally, the TR notes that vapor pressure considerations regarding dilute solutions of fission products will be addressed in the source term TR. Depending on the form of these fission products, is there a possibility that these cause a corrosion concern if plated out in the vapor space?

(17) Section 1.1.2, "Key Design Features of the KPFHR," states that the reactor coolant is a chemical-ly stable molten fluoride salt mixture. Clarify how Kairos plans to demonstrate the salt is chemically, radiologically, and neutronically stable in the conditions of the KPFHR. Even though the MSRE used a FLiBe salt as an intermediate coolant the conditions it experienced are not identical to the proposed KP-FHR (e.g. much less radiation dose). Does Kairos plan to demonstrate stability of the salt in KP-FHR conditions (e.g. no gas generation, changes in physical/chemical composition, chemical reactions, etc.)? FHR conditions (e.g. no gas generation, changes in physical/chemical composition, chemical reactions, etc.)?

Topic 2: Thermal-Fluid Modeling

(1) Based on the current design of the primary systems that will contain the coolant salt, are there any 'cold spots' that could cause a potential phase change resulting in a loss of salt flow, or precipitation of impurities? Precipitated impurities may be corrosive or emit radiation in a concentrated area. Experiments at the University of Wisconsin (Reference 1) have shown strong thermal stratification in salt flow which could result in development of 'cold spots.' The NRC staff is seeking clarification on the following:

(a) If there is a potential to develop such areas, are there plans to ensure a loss of salt flow doesn't occur?

(b) If impurities may precipitate out, are there provisions to clean the impurities from the surfaces of structural materials?

(2) Section 2.2.1, “Thermophysical Properties,” states that Kairos will [[

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(3) Section 3.1, “Conclusions,” states that NRC approval is requested for the “…reactor design characteristics represented by the reactor coolant specification in Table 4 and the thermophysical properties provided in Table 1 … to be used in the performance of safety analyses….” The NRC staff would like clarification on the meaning of that statement.

(a) Additionally, any safety analyses will need to consider uncertainties in the thermophysical property data. Will the safety analyses use the uncertainties stated in Table 1? Additionally, earlier in the TR, in Section 2.2, “Flibe Specification,” it was stated that [[

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(b) Reference 13 of the Reactor Coolant TR (Reference 7 here) states the difficulty of obtaining thermal conductivity data. The thermal conductivity of the salt is important to decay heat removal and safety analyses. How will this property be confirmed given its importance?

i. Additionally, Reference 6 states that sources of uncertainty include salt purity, film layers/deposits, and temperature. Are these effects accounted for in the test plans?

(4) Section 2.2 of the Reactor Coolant TR – how was it determined that [[

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(5) Section 2.2.1, “Thermophysical Properties,” states, [[

]] NRC staff is seeking clarification of this statement. [[

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Topic 3: Neutronic Requirements

(1) Section 2.2.3, "Neutronic Requirements," states that, [[

]] The supporting analysis for this statement is provided in Appendix E, "Neutronic Impurity Limit Assessment." It is not clear to NRC staff how the analysis presented in Appendix E accounts for [[

]] Does Kairos Power plan to [[

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(2) Section 2.2.4, "Impurity Limits Assessment Methodology," references [[

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(3) Appendix E, "Neutronic Impurity Limit Assessment," includes [[

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Topic 4: Corrosion

(1) Clarify if erosion of reactor coolant boundary components from TRISO pebbles been considered in the corrosion allowance.

(2) Are there ways to measure redox conditions in FLiBe (like ECP)?

(3) Clarify if the effects of irradiation were considered in conjunction with the salt purity when determining potential corrosion.

(4) Section 2.2.2, "Corrosion," of the Reactor Coolant TR states that [[
]] Clarify if another structural material is in contact with the FLiBe. If so, clarify whether corrosion/material compatibility issues been considered for this material.

(5) Does Kairos have plans to inspect components for corrosion (e.g. cracking, remaining wall thickness, etc.) or replace them, if necessary?

(6) The ORNL MSRE used Hastelloy N as its structural alloy. The KP-FHR proposes to use 316H SS. The KP-FHR design appears to rely on data collected from the ORNL MSRE to justify, in part, assumptions about corrosion of structural materials, reactor coolant

purity limits, [[   ]], etc. Given the difference in structural materials clarify how the MSRE experience applies to the KP-FHR. Additionally, given the proposed testing by Kairos, clarify how the test data may be used to validate these assumptions and what weight will be given to the experimental results if higher corrosion rates or lower tolerance for impurities are observed?

(7) Is there a cladding proposed for the 316H SS due to Cr depletion considerations?

Topic 5: General Comments and Questions

(1) Credit for the reactor coolant, or its properties, in safety analyses, etc. that wasn't fully described in this TR may be subject to NRC review and approval at the time it is discovered. The NRC would like clarification on how the NRC staff will be notified if the safety analysis function of the reactor coolant changes. Additionally, does Kairos have plans/arrangements to notify the NRC if any previously unknown/unanticipated issues occur during the Kairos test program?

(2) Kairos has stated that the FLiBe to be used in the KP-FHR will be similar to the FLiBe used in the ORNL MSRE intermediate coolant salt but there will be some differences such as presence of radiation, fuel types, structural material alloys, etc. The NRC staff would like clarification on why it is appropriate to use ORNL MSRE data in the KP-FHR given certain differences between the designs.

References

(1) Center for Advanced Nuclear Energy Systems, Forsberg, C.W., et. al., MIT-ANP-TR-180 "Integrated FHR Technology Development: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal Hydraulics and Neutronics, Associated Benchmarking and Commercial Basis," October 2018.

(2) Oak Ridge National Laboratory, Bohlmann, E.G, ORNL--TM--3777, "Heat Transfer Salt for High Temperature Steam Generation," December 1972.

(3) Oak Ridge National Laboratory, Busby, J., et. al., ORNL/SPR-2019/1089, "Technical Gap Assessment for Materials and Component Integrity Issues for Molten Salt Reactors, March 2019 (ADAMS Accession No. ML19077A137).

(4) Annals of Nuclear Energy, Volume 120, Chan, Kevin J., et. al., "Carburization effects on the corrosion of Cr, FE, Ni, W, and Mo. In fluoride-salt cooled high temperature reactor (FHR) coolant," October 2018.

(5) Corrosion Science Volume 144, Zhang, Jinsuo, et. al., "Redox potential control in molten salt systems for corrosion mitigation," November 2018.

(6) https://www.nrc.gov/docs/ML1733/ML17331B115.pdf Accessed 10/4/19.

(7) R.R. Romatoski, L.W. Hu / Annals of Nuclear Energy 109 (2017) 635–647.

(8) https://dl.asminternational.org/handbooks/book/26/chapter/355608/Corrosion-in-High-Temperature-Environments/ Accessed 10/8/19.

(9) Journal of Nuclear Materials Volume 524, pp. 119-134, Lee, Jo Jo, et. al., “Chemical compatibility of silicon carbide in molten fluoride salts for the fluoride salt-cooled high temperature reactor,” July 2019.

(10) Oak Ridge National Laboratory ORNL-4658 UC-80 – Reactor Technology, Thomas, Roy E., “Chemical Aspects of MSRE Operations,” December 1971.

(11) Oak Ridge National Laboratory ORNL/SPR-2019/1089, Busby, Jay, et. al, “Technical Gap Assessment for Materials and Component Integrity Issues for Molten Salt Reactors,” March 2019 (ADAMS Accession No ML19077A137).

(12) Journal of Nuclear Materials, Volume 300 pages 270-272, D. Olander, “Redox condition in molten fluoride salts Definition and control,” dated October 25, 2001.