

January 16, 2020

Project No. 99902069

US Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, DC 20555-0001

Subject: Kairos Power LLC
Topical Report Submittal
Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor,
Revision 1

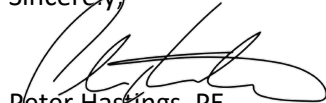
- References:
1. Letter, Kairos Power LLC to Document Control Desk, "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor Topical Report," Revision 0, March 8, 2019 (ML19079A325)
 2. Email, Nuclear Regulatory Commission Lissette Candelario to Darrell Gardner, "NRC Staff Preliminary Clarification Questions for the Kairos Reactor Coolant Topical Report," November 21, 2019 (ML20013G646)
 3. Nuclear Regulatory Commission, Letter from Steven Lynch to Peter Hastings, "Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor Topical Report" (CAC NO. 000431), August 9, 2019 (ML19221B585)

Kairos Power submitted Revision 0 of the subject topical report for Nuclear Regulatory Commission (NRC) review on March 8, 2019 (Reference 1). NRC provided review questions on Revision 0 of the report by email dated November 21, 2019 (Reference 2). This letter transmits Revision 1 of the Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor topical report which addresses these questions to facilitate completion of the review consistent with the NRC letter dated August 9, 2019 (Reference 3).

Portions of the attached report are considered proprietary, and Kairos Power requests it be withheld from public disclosure in accordance with the provisions of 10 CFR 2.390. Enclosure 1 provides the proprietary version of the report and Enclosure 2 provides the non-proprietary report. An affidavit supporting the withholding request is provided in Enclosure 3. Additionally, the information indicated as proprietary has also been determined to contain Export Controlled Information. This information must be protected from disclosure pursuant to the requirements of 10 CFR 810.

If you have any questions or need any additional information, please contact John Price at price@kairospower.com or (972) 754-8221, or Darrell Gardner at gardner@kairospower.com or (704) 769-1226.

Sincerely,



Peter Hastings, PE

Vice President, Regulatory Affairs and Quality

Enclosures:

- 1) Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor, Revision 1 (Proprietary)
- 2) Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor, Revision 1 (Non-Proprietary)
- 3) Affidavit Supporting Request for Withholding from Public Disclosure (10 CFR 2.390)

xc (w/enclosure):

Benjamin Beasley, Chief, Advanced Reactor Licensing Branch
Stewart Magruder, Project Manager, Advanced Reactor Licensing Branch

Enclosure 2

**Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor, Revision 1
(Non-Proprietary)**



Kairos Power LLC
707 W. Tower Ave
Alameda, CA 94501

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor

Topical Report

Revision No. 1
Document Date: January 2020

Non Proprietary

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

COPYRIGHT NOTICE

This document is the property of Kairos Power LLC (Kairos Power) and was prepared in support of the development of the KP Fluoride Salt-Cooled High Temperature Reactor (KP-FHR) design. Other than by the NRC and its contractors as part of regulatory reviews of the KP-FHR design, the content herein may not be reproduced, disclosed, or used, without prior written approval of Kairos Power.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Rev	Description of Change	Date
0	Initial Issuance	March 2019
1	Revised to address NRC questions, provided by email dated November 21, 2019 on the initial revision.	January 2020

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Executive Summary

This topical report describes the specification limits and thermophysical properties of the reactor coolant for the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR).

The reactor coolant is a mixture of lithium fluoride (LiF) and beryllium fluoride (BeF₂) in the nominal composition of 2LiF:BeF₂. The reactor coolant specification includes limits on the ratio of LiF to BeF₂ along with limits on impurities that affect corrosion and neutronic behavior. Methods and assumptions for setting the specification limits are provided within this report.

The reactor coolant is a key design feature of the KP-FHR technology and supports the enhanced safety performance, including limiting the consequences of accidental release of radioactive materials to the environment. Kairos Power is requesting Nuclear Regulatory Commission review and approval of the reactor coolant specification and thermophysical properties for the performance of design and safety analysis by license applicants under 10 CFR 50 or 10 CFR 52.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table of Contents

1.	Introduction	7
1.1	Design Features	7
1.1.1	Design Background	7
1.1.2	Key Design Features of the KP-FHR	8
1.2	Regulatory Review	8
2	Heat Transport System Fluids	11
2.1	Flibe for Primary Heat Transport System	11
2.2	Flibe Specification.....	14
2.2.1	Thermophysical Properties.....	15
2.2.2	Corrosion Requirements	16
2.2.3	Neutronic Requirements.....	18
2.2.4	Impurity Limits Assessment Methodology	18
2.3	Flibe Synthesis and Purification (Prior to use in KP-FHR)	19
2.4	Salt Chemistry Control During KP-FHR Operation	21
2.5	Analytical Chemistry Method Development	22
2.6	Compatibility of Flibe and Nitrate Salt	22
3	Conclusions and Limitations	24
3.1	Conclusions.....	24
3.2	Limitations	24
4	References	25
APPENDIX A.	Thermal Neutron Absorption Impurities in Flibe	38
APPENDIX B.	Electrochemical Potentials of Fluorides.....	41
APPENDIX C.	Thermophysical Property Qualification	46
APPENDIX D.	Chromium Oxidant Allowable Calculation	49
APPENDIX E.	Not Used.....	50
APPENDIX F.	Effect of LiF-BeF ₂ Composition on Viscosity	51

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

ABREVIATIONS

Abbreviation or Acronym	Definition
ASTM	American Society for Testing and Materials
AOO	Abnormal Operating Occurrence
CSP	Concentrated Solar Power
DOE	Department of Energy
DPRA	Dynamic Probabilistic Risk Assessment
EAB	Exclusion Area Boundary
FHR	Fluoride Salt-Cooled High Temperature Reactor
FSAR	Final Safety Analysis Report
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IHTS	Intermediate Heat Transport System
IHX	Intermediate Heat Exchanger
IRP	Integrated Research Projects
KP-FHR	Kairos Power Fluoride Salt-Cooled, High Temperature Reactor
MHTGR	Modular High Temperature Gas Reactor
MSRE	Molten Salt Reactor Experiment
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PDC	Principal Design Criteria
PHTS	Primary Heat Transport System
PSAR	Preliminary Safety Analysis Report
ROM	Reduced Order Model
TRISO	Tri-structural Isotropic

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

1. INTRODUCTION

Kairos Power LLC (Kairos Power) is pursuing the design, licensing, and deployment of the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR). To support these objectives, Kairos Power is developing this report to describe the reactor coolant properties used in the KP-FHR. These include the design specification, physical properties, nuclear properties, and chemical factors relevant for use as a reactor coolant.

NRC regulations in 10 CFR 50 and 10 CFR 52 require reactor license applicants provide a safety analysis report that in part requires a description of features that are unique, unusual or having a significant bearing on the probability or consequences of accidental release of radioactive materials; and barriers that must be breached as a result of an accident before a release of radioactive material to the environment can occur. The reactor coolant for the KP-FHR is a feature which performs or supports the performance of these functions. The properties and characteristics of the reactor coolant also satisfy portions of the Principal Design Criteria (PDC) established in the Kairos Power Topical Report, Principal Design Criteria for the Kairos Power Fluoride Salt Cooled High Temperature Reactor (Reference [1]).

Kairos Power requests NRC review and approval of reactor design characteristics represented by the reactor coolant specification in Table 4 and the thermophysical properties in Table 1 of this topical report to be used in the performance of safety analyses by licensing applicants of the KP-FHR design requesting standard design certifications, combined licenses, standard design approvals, and manufacturing licenses under the applicable regulations in 10 CFR 52; and limited work authorizations, construction permits, and operating licenses under 10 CFR 50. Safety analyses which rely on or credit the use of the KP-FHR reactor coolant specification and thermophysical properties to satisfy regulatory requirements will be provided within specific licensing application documents (e.g., safety analysis reports) required to be submitted by the cited regulations.

1.1 DESIGN FEATURES

1.1.1 DESIGN BACKGROUND

To facilitate NRC review and approval of this report, key design features are provided in this Section 1.1.2 which are considered inherent to the KP-FHR technology. These features are not expected to change during the design development by Kairos Power and provide the basis to support the safety review of this report. Should fundamental changes occur to these key design features or new or revised regulations be promulgated that affect the description and conclusions in this report, such changes would be reconciled and addressed in future license application submittals.

The KP-FHR is a U.S.-developed Generation IV advanced reactor technology. In the last decade, U.S. national laboratories and universities have developed pre-conceptual Fluoride High-Temperature Reactor (FHR) designs with different fuel geometries, core configurations, heat transport system configurations, power cycles, and power levels. More recently, University of California at Berkeley developed the Mark 1 pebble-bed FHR (Mk1 PB-FHR), incorporating lessons learned from the previous decade of pre-conceptual designs (Reference [2]). Kairos Power has built on the foundation laid by Department of Energy (DOE)-sponsored university Integrated Research Projects (IRPs) to develop the KP-FHR.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Although not intended to support the findings necessary to approve this report, additional design description information is provided in the “Design Overview of the Kairos Power Fluoride Salt Cooled, High Temperature Reactor (KP-FHR)” Technical Report (Reference [3]).

1.1.2 KEY DESIGN FEATURES OF THE KP-FHR

The KP-FHR is a high temperature reactor with molten fluoride salt coolant operating at near-atmospheric pressure. The fuel in the KP-FHR is based on the tri-structural isotropic (TRISO) high-temperature, carbonaceous-matrix coated particle fuel (originally developed for high-temperature gas-cooled reactors) in a pebble fuel element. Coatings on the particle fuel provide retention of fission products. The reactor coolant is a chemically stable molten fluoride salt mixture, 2LiF:BeF₂ (Flibe with [[]]) which also provides retention of fission products that escape from any fuel defects. A primary coolant loop circulates the reactor coolant using pumps and transfers the heat to an intermediate coolant loop via a heat exchanger. The pumped flow intermediate coolant loop utilizes a nitrate salt, compatible with the reactor coolant, and transfers heat from the reactor coolant to the power conversion system through a steam generator. The design includes two decay heat removal systems. A normal decay heat removal system is used following normal shutdowns and anticipated operational occurrences. A separate passive decay heat removal system, which along with natural circulation in the reactor vessel, removes decay heat in response to a design basis accident and does not rely on electrical power.

The KP-FHR design uses a functional containment approach similar to the MHTGR instead of the typical LWR low-leakage, pressure retaining containment structure. The KP-FHR functional containment design objective is to meet 10 CFR 50.34 (10 CFR 52.79) offsite dose requirements at the plant's exclusion area boundary (EAB) with margin. A functional containment is defined in RG 1.232 as a "barrier, or set of barriers taken together, that effectively limit the physical transport and release of radionuclides to the environment across a full range of normal operating conditions, AOOs, and accident conditions." RG 1.232 includes an example design criterion for the functional containment (MHTGR Criterion 16). As also stated in RG 1.232, the NRC has reviewed the functional containment concept and found it “generally acceptable,” provided that “appropriate performance requirements and criteria” are developed. The NRC staff has developed a proposed methodology for establishing functional containment performance criteria for non-LWRs, which is presented in SECY-18-0096. This SECY document has been approved by the Commission.

The functional containment approach for the KP-FHR is to control radionuclides primarily at their source within the coated fuel particle under normal operations and accident conditions without requiring active design features or operator actions. The KP-FHR design relies primarily on the multiple barriers within the TRISO fuel particles and fuel pebble to ensure that the dose at the site boundary as a consequence of postulated accidents meets regulatory limits. However, in contrast to the MHTGR, the KP-FHR molten salt coolant also serves as a distinct barrier providing retention of fission products that escape the fuel particle and fuel pebble barriers. This additional retention is a key feature of the enhanced safety and reduced source term in the KP-FHR.

1.2 REGULATORY REVIEW

Applicants for construction permits for facilities licensed under 10 CFR 50 are required to provide a preliminary safety analysis report (PSAR) which provides a safety assessment of the facility, including a description of reactor design characteristics, in accordance with 10 CFR 50.34(a). Applicants for a limited

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

work authorization (LWA) are required to submit a safety analysis that meets 10 CFR 50.34 for the scope of the LWA per 10 CFR 50.10(d)(3)(i). Subsections within 10 CFR 50.34(a) relevant to the requirement to describe design characteristics of the KP-FHR reactor coolant are listed below (note these are required to be updated as part of the operating license application in the FSAR per 10 CFR 50.34(b)(4)):

50.34(a)(1)(ii)(C) 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

50.34(a)(1)(ii)(D) 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. Special attention must be directed to plant design features intended to mitigate the radiological consequences of accidents

50.34(a)(2) 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.

Similarly, applicants for combined licenses for facilities licensed under 10 CFR 52 are required to provide a final safety analysis report (FSAR) which provides a safety assessment of the facility, including a description of reactor design characteristics, in accordance with 10 CFR 52.79. Subsections relevant to the requirement to describe reactor design characteristics of the reactor coolant are listed below:

52.79(a)(2) A description and analysis of the structures, systems, and components of the facility with emphasis upon performance requirements, the bases, with technical justification therefor, upon which these requirements have been established, and the evaluations required to show that safety functions will be accomplished. It is expected that reactors will reflect through their design, construction, and operation an extremely low probability for accidents that could result in the release of significant quantities of radioactive fission products. The descriptions shall be sufficient to permit understanding of the system designs and their relationship to safety evaluations. Items such as the reactor core, reactor coolant system, instrumentation and control systems, electrical systems, containment system, other engineered safety features, auxiliary and emergency systems, power conversion systems, radioactive waste handling systems, and fuel handling systems shall be discussed insofar as they are pertinent...

52.79(a)(2)(iii) 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;

52.79(a)(2)(iv) 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. Special attention must be directed to plant design features intended to mitigate the radiological consequences of accidents...

Similar requirements to these are also included in 10 CFR 52.47 for Standard Design Certifications; 10 CFR 52.137 for Standard Design Approvals; and 10 CFR 52.157 for Manufacturing licenses.

The design characteristics of the KP-FHR reactor coolant are unique from the typical water-based coolant used in light water reactors typical of the operating fleet. The design and thermophysical properties of the KP-FHR reactor coolant enhances the safety of operations and reduces the probability

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

of events by providing significant thermal capacity while remaining in a liquid phase. The design and thermophysical properties of the KP-FHR reactor coolant also provides additional functional containment protection, beyond that provided by the TRISO fuel particle, by absorbing fission products that escape the TRISO protective layer. This design feature reduces the probability of accidental release of radioactive materials. This report describes the thermophysical properties and characteristics of the KP-FHR coolant that are relevant for demonstrating these enhanced safety features as required by the requirements in 10 CFR 50 and 10 CFR 52 cited above. The demonstration of fission product retention capabilities of the KP-FHR reactor coolant will be provided in a separate topical report describing the source term. Safety analyses which rely on or credit the use of the KP-FHR reactor coolant specification and thermophysical properties to satisfy regulatory performance requirements will be provided within specific licensing application documents (e.g., safety analysis reports) required to be submitted by the cited regulations.

Facilities licensed under 10 CFR Part 50 are also required to describe principal design criteria (PDC) in their preliminary safety analysis report supporting a construction permit and operating license application as described in 10 CFR 50.34(a)(3)(i). Likewise, applicants for standard design certifications, combined licenses, standard design approvals, and manufacturing licenses must include the PDC for a facility as described in 10 CFR 52.47(a)(3)(i), 10 CFR 52.79(a)(4)(i), 10 CFR 52.137(a)(3)(i), and 10 CFR 52.157(a). The PDC for the KP-FHR have been established in the Kairos Power Topical Report, Principal Design Criteria for the Kairos Power Fluoride Salt Cooled High Temperature Reactor (Reference 1). The specific PDC in this report which rely on or credit the design and performance of the KP-FHR reactor coolant include PDC 14, 16, 26, 31, 60, 70, and 73. The design characteristics of the reactor coolant which satisfy, in part, these PDC are identified below.

Corrosion of structural materials is important consideration for maintaining the integrity of the safety-significant portions of the reactor coolant boundary (PDC 14 and PDC 31). The KP-FHR reactor coolant design characteristics related to acceptable corrosion controls which satisfy PDC 14 and PDC 31 as discussed in Section 2 of this report.

The design characteristics of the reactor coolant mix enables the KP-FHR core to be designed with a negative coolant temperature coefficient of reactivity. This is a key feature of the coolant which supports inherent reactor protection to compensate for rapid increases in reactivity (PDC 11). The neutronic characteristics of the KP-FHR reactor coolant design which satisfy PDC 11 are discussed in this report.

The design of the reactor coolant mix provides, in part, a means to control the accidental release of radioactive materials during normal reactor operation and anticipated operational occurrences (PDC 60) and supports, in part, demonstration of the functional containment aspects required by PDC 16. The design aspects of the KP-FHR reactor coolant are discussed in this report. The demonstration of the fission product retention capabilities of the reactor coolant will be provided in a separate topical report describing the KP-FHR mechanistic source term.

The purity of the reactor coolant is an important design characteristic for corrosion control and neutronic performance. Chemistry control provisions are specified to maintain the purity of reactor coolant within specified design limits (PDC 70). Reactor coolant purity provisions which satisfy PDC 70 are discussed in this report.

Compatibility of the reactor coolant and intermediate coolants is important with respect to PDC 73. The design characteristics of the reactor coolant which affect chemical compatibility considerations relevant to PDC 73 are discussed in this report and will be demonstrated as acceptable as part of safety analyses within individual license applications.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

2 HEAT TRANSPORT SYSTEM FLUIDS

The KP-FHR transfers heat generated by the core to the power conversion unit using both a primary heat transport system (PHTS) and intermediate heat transport system (IHTS), each with different heat transfer fluids as illustrated in Figure 1. The primary heat transport system salt, which transports heat from the TRISO particle-based fuel pebbles to the intermediate heat transfer system, uses a lithium fluoride (LiF), beryllium fluoride (BeF₂) salt. The molar ratio is approximately 2LiF:BeF₂ (i.e., Li₂BeF₄) and is also referred to as “Flibe”.

Thermal power is transferred from PHTS fluid to the IHTS system fluid through intermediate heat exchangers (IHX). The intermediate heat transfer system is responsible for moving heat from the primary heat transport system to the steam generators. The Intermediate heat transport system fluid utilizes a blend of 60 weight percent sodium nitrate salt (NaNO₃) and 40 weight percent potassium nitrate (KNO₃). This thermal fluid is referred to by several names; solar salt, nitrate salt, or 60/40 salt; in this report it is referred to by the simple term “nitrate salt.” Nitrate salt is utilized by the concentrated solar power (CSP) industry and has a well-developed supply chain for raw materials, specific allowable impurities, and components. Although this report focuses on the reactor coolant, interactions between the Flibe and nitrate salts are considered to address PDC 73 for high temperature compatibility if mixed together due to a potential leak in the IHX.

This report does not explicitly consider retention of fission products released into Flibe during operation, which can arise from fuel defects. Fission product retention and methods for predicting retention will be addressed in a separate source term topical report.

2.1 FLIBE FOR PRIMARY HEAT TRANSPORT SYSTEM

As noted above, the Flibe is composed of a nominal 2LiF:BeF₂ (See Figure 2 for the diagram, note the Li₂BeF₄ phase is Flibe, See Table 1 for thermophysical properties), a peritectic with a melting point of 459°C. In the 1960’s Oak Ridge National Laboratory (ORNL) was funded by the United States Government through the Atomic Energy Commission for more than a decade to design molten salt reactors. This work served as the basis for the selection of Flibe for use in the Molten Salt Reactor Experiment (MSRE), which is also relevant to the KP-FHR, where the primary criteria is summarized in Table 2 (Reference [4]). MSRE used two salts, a fuel salt in the primary circuit (Flibe + ZrF₄ + UF₃/UF₄ + fission products), and a heat transport salt in the intermediate circuit (Flibe with nominally the same composition as KP-FHR Flibe).

The MSRE fuel salt was a slightly LiF-rich Flibe (0.69[LiF] – 0.31[BeF₂]) with additions of 5 mole% ZrF₄ and 0.9% fissile UF₃/UF₄, resulting in a final composition of 0.65[LiF] - 0.291[BeF₂] - 0.05[ZrF₄] - 0.009[UF₃/UF₄]. The purpose of the ZrF₄ addition was to preferentially react with atmospheric leaks to form ZrO₂ instead of UO₂, mitigating the concern for a criticality accident from UO₂ precipitation and accumulation. The MSRE fuel salt was stable under irradiation, where the uranium and zirconium inventories during operation were nearly perfectly accounted for. ZrF₄ is a volatile species, but as a Lewis acid it receives fluoride ions from LiF (a Lewis base) to form ZrF₆²⁻, a non-volatile species. Analogously, BeF₂ is a Lewis acid that forms BeF₄²⁻ ions. In the Lewis acid-base sense, substitution of BeF₂ for ZrF₄ changes very little about the salt chemistry. For this reason, pure Flibe is expected to behave nearly identically as MSRE fuel salt during irradiation.

Although there are several important selection criteria, the neutronic considerations were the key deciding factor in selecting Flibe as the primary coolant. Flibe enables the FHR cores to be designed with

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

a negative coolant temperature coefficient of reactivity, which provides a safety benefit supporting reactivity control (PDC 26), low parasitic neutron absorption that allows for effective fuel utilization, and minimal short-term and long-term activation of the coolant for improved operations and maintenance (only fluorine, with a half-life of less than one minute, is activated). These neutronic factors, in combination with the other positive benefits of Flibe described below, led to its selection as the primary coolant choice for the KP-FHR.

Stability at high temperature is a desirable coolant property criterion because it precludes chemical degradation, ensures low vapor pressures, and increases radiation stability. Flibe does not decompose at operating temperatures and has a very low vapor pressure at operating temperature, approximately 1×10^{-2} mmHg (~ 0.6 Pa) at 650°C , and increases to 3 mmHg (400 Pa) at 950°C . Water, as a familiar point of reference, at 25°C is ~ 23 mmHg. A low vapor pressure at and above normal operating conditions is advantageous by limiting “frosting” of the coolant on cooler vapor space structures, where condensation of the vapor salt can result in solid phase formation. These resemble a frosted or snow-like appearance.

Vapor pressure correlations for Flibe, as provided in Table 2, were measured above KP-FHR operational temperatures. Since Flibe has a low vapor pressure below 900°C it was not been measured at the operational temperatures of the KP-FHR PHTS (550 – 650°C). However, two approaches can be taken to approximate the vapor pressure. First, extrapolation of the correlation to operational temperatures and, second, using Raoult’s Law for ideal mixtures. Raoult’s method can only be used if the partial pressures of the pure component are available, data for LiF, BeF_2 is provided in Table 3. Raoult’s Law is applied as follows:

$$P = 0.667P_{\text{LiF}}^* + 0.333P_{\text{BeF}_2}^* \quad \text{Equation 1}$$

P^* are partial pressures, at temperature, for each pure component. Using vapor pressures for LiF and BeF_2 at 650°C , provided in Table 3, this calculated value (14×10^{-3} mmHg) is approximately three times higher than calculated value of the extrapolated equation provided in Table 1 (5×10^{-3} mmHg). This difference, while relatively large, is within error as provided in Reference [5].

Vapor pressure of Flibe at normal temperatures of KP-FHR operation is low during normal operation. For mechanistic source term considerations, vapor pressures of dilute solutions of fission products released from failed TRISO fuel particles into the Flibe coolant are an important consideration. This consideration will be addressed in a separate source term topical report for the KP-FHR.

An acceptably low melting point is an important criterion to enable the use of molten salts as a suitable reactor coolant. The melting point of single constituent salts are quite high with BeF_2 being the lowest melting at 555°C (Figure 2). System designs must ensure that the selected heat transport fluid remains liquid during operation. As melting point temperatures increase, system design solutions become complex and costly to implement. Lower melting point compositions using ternary or higher salt constituents are possible (an example is LiF–NaF– BeF_2 provided in Figure 3), but introduces elements (e.g., sodium) that increase parasitic neutron capture. As noted above, neutronic considerations are a major performance parameter that motivates the selection of Flibe for FHRs. Therefore, a binary mixture of LiF and BeF_2 was selected to obtain an acceptably low melting point below 500°C , while minimizing chemical and neutronic impacts.

Operating experience from MSRE demonstrated minimal corrosion of structural materials which is important for maintaining the integrity of the safety-significant portions of the reactor coolant boundary.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

The primary corrosion reaction of importance is chromium oxidation of the structural alloy. Chromium is oxidized from the elemental form to a soluble fluoride. During reactor operation, there is generation of small amounts of tritium fluoride, which oxidizes chromium through the following reaction (Reference [6]):



In addition to tritium generation, the MSRE fuel salt was determined to be corrosive due the stoichiometric excess of free fluorine (in the form of fluorine radicals) that were a consequence of the smaller number of fluoride anions needed to satisfy the stoichiometric requirements of fission product cations compared to fluorides released during UF₄ fissioning. MSRE employed a corrosion buffer in the fuel salt, specifically a small concentration of UF₃, allowing the free fluorine to be mitigated through the reactions:



Corrosion control in this way was quite successful and Hastelloy N did not significantly degrade during reactor operation (Reference [7]).

The UF₃/UF₄ ratio was typically < 0.01 in MSRE. When the reserve of UF₃ became too low small amounts of metallic beryllium were added to the reactor to reduce UF₄ to UF₃ with the formation of BeF₂ thereby recharging the U³⁺/U⁴⁺ buffer. It was shown that additions of metallic beryllium protect ferrous alloys with high chromium content (i.e. stainless steel alloy 316) such that the corrosion rate was below 10 microns per year (Reference [6]). Having a clean salt, free of moisture, is important for maintain such low corrosion rates and is discussed in Sections 2.3 and 2.4. MSRE salt observed formation of radiolytic formation of F₂ at temperatures below 100°C and conclusions were that salt temperatures above 200°C prevented radiolysis (Reference [8]). By comparison, frozen KP-FHR salt is not expected to receive a high fluence of radiation causing radiolytic fluorine gas generation. This is due to the relatively low concentration of radioactive species that are expected to accumulate in the reactor coolant under normal operation. Furthermore, under normal conditions, the Flibe coolant is not expected to be in a frozen state and will be on- and off-loaded in the molten state. When off-loaded, it will be trace-heated to remain molten. If the salt freezes in the drain/storage tank, the generation rate of fluorine gas is expected to be low and measures will be taken for mitigation. Lastly, beryllium metal resident in the salt will help arrest radiolytic fluorine, therefore, no dedicated corrosion allowance is included for this phenomenon. Mitigation of the relatively small amount of radiolytic fluorine is easily achieved during storage of frozen KP-FHR Flibe.

Flibe was determined to be an excellent solvent for metal fluorides, dissolved fuel, and fission products during MSRE. Credit for fission product retention in the molten salt is an important part of the KP-FHR safety case demonstrating conformance to the functional containment requirements. While the demonstration of fission product retention will occur in a future source term topical report, the key nuclides of interest for source term analysis, taken from the mechanistic source terms white paper for High Temperature Gas Reactors, are iodine (I⁻), cesium (Cs⁺), and strontium (Sr²⁺) (Reference [9]). Results from the MSRE found that oxidized or reduced states of many of these were readily soluble in Flibe (Reference [10]) and, in KP-FHR, it is expected that these fission products will remain in the Flibe, either as a metallic or as a salt. The concentration of fission products in the KP-FHR coolant will be orders of magnitude lower than in the MSRE due to retention in the TRISO fuel form (Reference [11]). As a result,

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

the demonstration of high fission product loading of the MSRE fuel salt strongly suggests that KP-FHR Flibe will be able to retain fuel or fission products, either as a metallic or salt, due to fuel TRISO and pebble fuel failures. The retention properties of fission products from TRISO fuels in Flibe will be addressed in a separate topical report on source term for the KP-FHR.

2.2 FLIBE SPECIFICATION

Based on the considerations described in Section 2.1, Flibe was chosen as the reactor coolant for the KP-FHR. Table 4 establishes the design specification for the KP-FHR reactor coolant to be used for operations and for analysis. [[

]] The limits as defined are for normal

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

operation. Consideration of off-normal or transient limits and impurities will be informed by material testing, specifically air, water, and nitrate ingress conditions and will be addressed in the KP-FHR High Temperature Materials Topical Report.

2.2.1 THERMOPHYSICAL PROPERTIES

The thermophysical properties for Flibe have been studied extensively, including work for the MSRE program and as part of subsequent fusion energy research (Reference [14]). Thermophysical properties are predominately derived from measurements made in preparation for the MSRE where the resulting correlations, along with expected uncertainties, are provided in Table 1(References [4, 15]), which were measured using 2LiF:BeF₂ for MSRE.

Molten salts show an exponential decrease in viscosity with reciprocal temperature. Due to this behavior, viscosity varies the most with temperature compared to other thermophysical properties as shown by Cantor (Reference [5]). Furthermore, the large difference in viscosity for the pure components of the binary lithium fluoride – beryllium fluoride system leads to a large viscosity dependence on the binary mixture composition. For this reason, a specification for the mole ratio of LiF to BeF₂ has been established such that the composition-dependent viscosity does not vary by more than the uncertainty associated with the temperature-dependent viscosity (illustrated in Figure F4).

The temperature-dependent viscosity equation in Table 1 was developed by Cantor (Reference [5]).
[[

]]

Data generated by the MSRE research teams are the best available and represent the MSRE program team’s depth and breadth of expertise, as well as their ability to validate properties through operational experience and traceable standards where possible. As such, Kairos Power believes that the thermophysical properties of Flibe established by national laboratory research efforts associated with the MSRE are appropriate for use in design and analysis. OPEN ITEM: Kairos Power will perform data corroboration and peer review of the MSRE data used for Table 1 for purposes of bringing the historical thermophysical property data under the Kairos Power QA program.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

2.2.2 CORROSION REQUIREMENTS

Material compatibility with the reactor coolant (structural materials, moderator, fuel pebbles) are impacted by Flibe purity and chemistry. MSRE found no attack of the graphite moderator during operation, with no change in graphite surface finish after 2.5 years of exposure (Reference [7]) despite the fact that the MSRE fuel salt included a wide range of elements, due to generation of fission products. Therefore, while carbon-based materials (moderator and fuel pebbles) are included as part of the Kairos Power high temperature materials testing programs, the structural materials are the basis for setting the corrosion requirements. Note that the KP-FHR High Temperature Materials Topical Report will address corrosion considerations of graphite and characterization of long-term exposure of graphite in a stainless-steel system with Flibe, The High Temperature Materials Topical Report will also discuss testing that will be to ensure that the degradation of structural components is bounded by design margin.

Corrosion of stainless steels occur primarily through oxidation of chromium (Cr) from metal form (i.e. structural alloy) to a soluble fluoride in hot regions, and transport to cold regions (via precipitation). KP-FHR is pursuing 316H as the structural alloy, which has chromium content ranging from 16-18 weight percent. [[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

2.2.3 NEUTRONIC REQUIREMENTS

The neutronic requirements of Flibe is defined by both safety and economic considerations. The presence of parasitic neutron absorbers (poisons) in the Flibe will reduce the magnitude of the negative coolant temperature reactivity feedback, if not make it positive, and decrease the fuel utilization. [[

]]

2.2.4 IMPURITY LIMITS ASSESSMENT METHODOLOGY

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

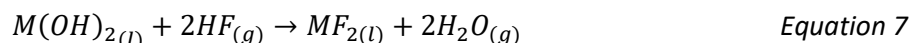
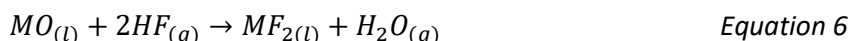
2.3 FLIBE SYNTHESIS AND PURIFICATION

As received raw materials for Flibe, ${}^7\text{LiF}$ and BeF_2 , require additional purification steps prior to utilization in the KP-FHR. Impurities within the salt arise from different sources, ranging from raw materials to environmental contaminants. Raw materials, even relatively high-grade materials, can have a variety of dissolved impurities such as NiF_2 , FeF_2 , CdF_2 , PbF_2 , sulfur, chlorine, etc. Environmental contaminants are primarily moisture which produces oxides, hydroxides, and hydrogen fluoride. For reasons provided in Section 2.2.2 they must be removed for materials compatibility.

Operating experience with the MSRE purification process, which removed environmental contamination, moisture and oxygen, and metal fluorides, sulfur, and chloride (Reference [10]) provides a basis for processing KP-FHR Flibe. MSRE used a batch chemical reactor, with a multi-step process of co-melting the raw constituents, gas sparging, and mechanical filtration to adequately remove impurities prior to reactor use. Figure 4 provides a high-level overview of the process along with the approximate temperatures and reason for each process step.

After loading and co-melting solid LiF and BeF_2 , an inert gas sparge of argon or helium was introduced into the reaction vessel. The vessel was heated from room temperature to 600°C , removing most of the absorbed moisture and melting Flibe into the peritectic. Once at temperature, the argon sparge was replaced with a mixture of anhydrous hydrogen fluoride (HF) and hydrogen (H_2) gas.

The mixed gas sparge of HF and H_2 were used to remove oxygen and hydrogen impurities from the melt. These impurities, present as oxides and hydroxides, were removed via a substitution reaction with a metal oxide or metal hydroxide via the following reactions:



HF was converted to water in these reactions. Therefore, changes in HF concentration in the effluent gas were used to signify process completion. Additionally, the HF: H_2 sparge facilitated removal of sulfur by gas evolution (H_2S), boron by gas evolution (BF_3), and chloride by gas evolution (HCl). The MSRE purification procedure required approximately 94 moles of HF to remove 12 moles of oxide, which equated to roughly a three-day sparge at 0.5 L/min of HF for their 50kg batch reactor (Reference [18]).

Upon completion of the HF: H_2 step the HF flow was replaced with an H_2 sparge to enable reduction of metals in the melt. For example, a metal fluoride (i.e. NiF_2), will be reduced to a metal through the following reaction:



HF was the byproduct generated during this reaction step and will be present in the effluent gas. Reduced metals were insoluble in Flibe and will tend to nucleate to form larger metal agglomerates or deposit on metallic surfaces and are removed via filtration. The final gas sparge step was introduction of argon (or helium) to remove any remaining H_2 .

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

2.4 SALT CHEMISTRY CONTROL DURING KP-FHR OPERATION

During reactor operation, impurities will be introduced into the coolant as part of normal operation. The main purpose of chemistry control is to ensure reliability of components, through minimizing corrosion. The KP-FHR concept for chemistry control during operation, including reactions of interests and strategies on controlling chemical behavior are described below.

Air or moisture ingress in the reactor coolant may occur in addition to small levels of tritium generation through transmutation of BeF_2 through the following reactions:



${}^6_2\text{He}$ decomposes through a beta decay which results in ${}^6_3\text{Li}$. ${}^6\text{Li}$ then undergoes transmutation via the following:



Both reactions yield species that corrode structures, either as excess fluoride/fluorine (F or F_2) or tritium fluoride (${}^3_1\text{HF}$). Beryllium additions, supplied through the chemistry control system (Figure 5), will getter either HF or F . Metallic beryllium reduces HF to hydrogen gas and reacts with fluoride ions, where both reactions form BeF_2 :



This approach has been quite effective for controlling corrosion rates of stainless steels, where clean Flibe without metallic beryllium was 10 - 30 microns per year, and Flibe with metallic beryllium was less than 10 microns (References [6, 19, 20]), therefore the need to have metallic beryllium is viewed as an operational consideration for prolonging component lifetime and is not established to address a specific safety requirement. Beryllium has low solubility in Flibe, [[

]]

A further positive implication in metallic beryllium addition is beryllium's ability to getter oxygen-based impurities that commonly arise from high temperature oxygen-based corrosion:



[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

2.5 ANALYTICAL CHEMISTRY METHOD DEVELOPMENT

[[

]]

2.6 COMPATIBILITY OF FLIBE AND NITRATE SALT

During KP-FHR operation, a heat exchanger leak would result in the mixing of the reactor coolant (Flibe) and the intermediate heat transport loop coolant (nitrate salt). Reference [22] reported that a foaming reaction was observed when LiF-BeF₂-ThF₄ salt was mixed with a nitrate-nitrite salt (HITEC). The salt compositions used in Reference [22] differed from the KP-FHR coolants and cannot be used to predict behavior for the KP-FHR.

Thermodynamic analysis was performed using the KP-FHR coolants. Based on this analysis, it is anticipated that the following endothermic chemical reaction will occur between the KP-FHR reactor coolant salt and intermediate nitrate salt:



Sodium is shown as the nitrate cation for simplicity; substitution of other alkali or alkaline earth metals changes little about the characteristics of the reaction. Figure 6 plots the Gibbs Free Energy, enthalpy, and equilibrium constant for Equation 14, as predicted by HSC thermodynamic database (Reference [23]). At KP-FHR operating temperatures (550-650°C), the endothermic reaction is

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

thermodynamically favorable due to the high entropy resulting from five moles of gas (four moles of NO₂ and one mole of O₂) produced for every four moles of nitrate consumed.

The kinetics of the reaction cannot be calculated in the absence of experimental data and details on how the two molten salts are expected to interact must be resolved through testing. It is expected that the rate of gas production from this reaction will be manageable, based upon the endothermic nature of the reaction. Additional characterization of the Flibe-nitrate salt interaction will be addressed through testing, modeling, and validation as part of specific licensing applications.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

3 CONCLUSIONS AND LIMITATIONS

3.1 CONCLUSIONS

The design characteristics and thermophysical properties of the reactor coolant are key design features that support the enhanced safety performance of the KP-FHR, including limiting the accidental release of radioactive materials to the environment. The properties and characteristics of the reactor coolant are also used to satisfy, in part, portions of the PDC 14, 16, 26, 31, 60, 70, and 73 established in the Kairos Power PDC Topical Report (Reference [1]).

Kairos Power requests NRC review and approval of the reactor design characteristics represented by the reactor coolant specification in Table 4 and the thermophysical properties provided in Table 1 of this topical report (subject to the limitations described below). The specification and thermophysical properties will be used in the performance of safety analyses by licensing applicants of the KP-FHR design requesting standard design certifications, combined licenses, standard design approvals, and manufacturing licenses under the applicable regulations in 10 CFR 52; or construction permits and operating licenses under 10 CFR 50. Safety analyses which rely on or credit the use of the KP-FHR reactor coolant specification and thermophysical properties to satisfy regulatory requirements will be provided within specific license application documents (e.g., safety analysis reports) required to be submitted by the cited regulations.

3.2 LIMITATIONS

As discussed in Section 2.2.1, Kairos Power believes that the thermophysical properties of Flibe established by national laboratory research efforts associated with the MSRE are appropriate for use in design and analysis and form the basis for the content in Table 1. OPEN ITEM: Kairos Power will perform data corroboration and peer review for purposes of bringing the historical thermophysical property data under the Kairos Power QA program.

With respect to the uncertainties in thermophysical properties, safety analysis for the KP-FHR will consider the stated uncertainties in Table 1 in an uncertainty quantification (UQ) analysis and identify the dominant uncertainty parameters associated with anticipated operational occurrences in the KP-FHR. If the uncertainty for a specific thermophysical property is determined safety significant, then additional measurements of that property will be performed to confirm the reported uncertainties. These measurements will be guided by comparable methods reported in Reference [16] to confirm the quality of the data previously acquired and to gather data that is outside the parameter ranges (i.e. temperature) required, as discussed in Appendix C. If confirmatory testing is determined necessary from associated safety analysis, Kairos Power will either present updated thermophysical property data in a revision to this Topical Report or describe the confirmatory measurements as part of a license application.

Corrosion performance of 316H in Flibe, consistent with impurity limits specified in Table 4, will be addressed as part of the KP-FHR High Temperature Materials Topical Report. This will confirm the corrosion allowances used for engineering and design considerations. These development efforts will also include confirming the solubility limit established of metallic beryllium in Flibe.

Characterization of the KP-FHR reactor coolant and intermediate coolant mixing will be addressed in license applications documents which demonstrate conformance to PDC 73.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

4 REFERENCES

1. Kairos Power, L., *Principal Design Criteria for the Kairos Power Fluoride Salt Cooled High Temperature Reactor*. November 2018.
2. Nuclear Engineering, University of California Berkeley, *Fluoride Salt Cooled High Temperature Reactor*. [ONLINE] Available at: <http://fhr.nuc.berkeley.edu>. [Accessed 26 June 2018]. 2015.
3. Kairos Power, LLC., *Design Overview of the Kairos Power Fluoride Salt Cooled, High Temperature Reactor*. November 2018.
4. Williams, D.F., et al., *Assessment of Candidate Molten Salt Coolants for the Advanced High Temperature Reactor (AHTR)*, ORNL/TM-2006/12. 2006.
5. Cantor, S., *PHYSICAL PROPERTIES OF MOLTEN-SALT REACTOR FUEL, COOLANT, AND FLUSH SALTS*, ORNL-TM-2316. 1968.
6. Keiser, J.R., J.H. DeVan, and D.L. Manning, *Corrosion resistance of type 316 stainless steel to Li₂BeF₄. [66-34 Mole % LiF--BeF₂]*, ORNL/TM-5782. 1977.
7. Engel, J. and T. Oak Ridge National Lab, *EXPERIENCE WITH THE MOLTEN-SALT REACTOR EXPERIMENT*. Nucl. Appl. Technol. 8: 118-36(Feb 1970). 1970.
8. Briggs, R.B., *MOLTEN-SALT REACTOR PROGRAM SEMI-ANNUAL PROGRESS REPORT FOR PERIOD ENDING JULY 31, 1964*. 1964, ; Oak Ridge National Lab., Tenn. p. Medium: ED; Size: Pages: 397.
9. Idaho National, L., et al., *HTGR Mechanistic Source Terms White Paper*. 2010.
10. Oak Ridge National Lab, T., *DEVELOPMENT STATUS OF MOLTEN-SALT BREEDER REACTORS*, ORNL-4812. 1972, United States.
11. *A Review of Radionuclide Release From HTGR Cores During Normal Operation*. 2003, EPRI: Palo Alto, CA.
12. Fukada, S., et al., *Reaction rate of beryllium with fluorine ion for Flibe redox control*. JOURNAL OF NUCLEAR MATERIALS, 2007. 367/370: p. 1190-1196.
13. Anderl, R.A., et al., *Beryllium Interactions in Molten Salts*. 2006.
14. Romatoski, R.R. and L.W. Hu, *Fluoride salt coolant properties for nuclear reactor applications: A review*. Annals of nuclear energy., 2017. 109: p. 635-647.
15. Cantor, S. and T. Oak Ridge National Lab, *Density and viscosity of several molten fluoride mixtures*, ORNL-TM-4308 1973, United States.
16. Idaho National, L., et al., *Implementation Plan for Qualification of Sodium-Cooled Fast Reactor Technology Information*. 2016.
17. Koger, J. and T. Oak Ridge National Lab, *Evaluation of Hastelloy N alloys after nine years exposure to both a molten fluoride salt and air at temperatures from 700 to 560°C*. 1972, United States.
18. Shaffer, J.H., *PREPARATION AND HANDLING OF SALT MIXTURES FOR THE MOLTEN SALT REACTOR EXPERIMENT*, ORNL-4616. 1971.
19. Zhang, J., et al., *Redox potential control in molten salt systems for corrosion mitigation*. Corrosion Science, 2018. 144: p. 44-53.
20. Simpson, M.F., et al., *Quantitative measurement of beryllium-controlled redox of hydrogen fluoride in molten Flibe*. FUSION Fusion Engineering and Design, 2006. 81(1-7): p. 541-547.
21. Oak Ridge National Lab, T., *REACTOR CHEMISTRY DIVISION ANNUAL PROGRESS REPORT FOR PERIOD ENDING DECEMBER 31, 1966*. 1967, United States.
22. Bohlmann, E. and T. Oak Ridge National Lab, *HEAT TRANSFER SALT FOR HIGH TEMPERATURE STEAM GENERATION*. 1972, United States.
23. *HSC Chemistry 9*. 2018, Outotec.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

24. Kato, Y., et al., *Thermal diffusivity measurement of molten salts by use of a simple ceramic cell*. Vol. 15. 1983. 191-198.
25. Oak Ridge National, L., et al., *CHEMICAL ASPECTS OF MSRE OPERATIONS*. 1971.
26. Lane, J.A., U.S.A.E. Commission, and E. United Nations International Conference on the Peaceful Uses of Atomic. *Fluid fuel reactors*. Reading, Mass.: Addison-Wesley Pub. Co.
27. Zheng, G., et al., *Corrosion of 316 stainless steel in high temperature molten Li₂BeF₄ (FLiBe) salt*. NUMA Journal of Nuclear Materials, 2015. 461: p. 143-150.
28. Fukuda, G.T., et al., *Thermodynamics of the LiF-NaF-BeF₂ system at high temperatures*. FLUID PHASE EQUILIBRIA, 2007. **255**(1): p. 1-10.
29. Kelleher, B.C., *Purification and chemical control of molten Li₂BeF₄ for a fluoride salt cooled reactor / Brian Christopher Kelleher*. 2015.
30. Blanke, B.C., et al., *Density and viscosity of fused mixtures of lithium, beryllium, and uranium fluorides*. 1959.
31. Douglas, T.B. and W.H. Payne, *Measured enthalpy and derived thermodynamic properties of solid and liquid lithium tetrafluoroberyllate, Li₂BeF₄, from 273 to 900 K*. J. RES. NATL. BUR. STAN. SECT. A. Journal of Research of the National Bureau of Standards Section A: Physics and Chemistry, 1969. 73A(5): p. 479.
32. Jones, T. and T. Oak Ridge National Lab, *VISCOSITY MEASUREMENTS ON MOLTEN FLUORIDE MIXTURES*. 1957, United States.
33. Guymon, R.H., *MSRE systems and components performance*. 1973,; ed. and comp.; Oak Ridge National Lab., Tenn. (USA). p. Medium: ED; Size: Pages: 422.
34. Cantor, S., W.T. Ward, and C.T. Moynihan, *Viscosity and Density in Molten BeF₂/LiF Solutions*. The Journal of Chemical Physics The Journal of Chemical Physics, 1969. 50(7): p. 2874-2879.
35. Furukawa, K. and H. Ohno, *Databook for molten materials: 1 – Molten LiF-BeF₂ (FLIBE)*. 1980: Society of Molten-Salt Thermal Technology, Japan Nuclear-Energy Information Center.

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table 1: Thermophysical Properties of the KP-FHR Primary Coolant

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table 2: ORNL Fluid Selection Criteria Conclusions Applied to KP-FHR Technology

Criteria	KP-FHR Requirements	Flibe Information	References
1. Stability at high temperatures	Low vapor pressure enables high temperature operation.	Vapor pressure is low over operational temperatures.	[4, 5, 26]
2. Stability under radiation	Fluid does not degrade significantly in radiation	Minimal degradation if using ^7Li	[4, 26]
3. Melting point below 500°C	Engineering Consideration for system design	The melting point of Flibe is 459°C	[4, 26]
4. Materials compatible	Predictable behavior of structural alloys, graphite moderators, and fuel pebbles	Clean Flibe has low corrosivity. Small additions of metallic beryllium have shown viability in controlling corrosion to less than 30 micron/year	[4, 6, 26, 27]
5. Effective solvent for fissile material and fission products	Safety consideration, radioactive source containment	MSRE fuel salt included Flibe and was able to dissolve both fuel and most fission products. KP-FHR Flibe will retain most fuel and fission products.	[4]
6. Negative coolant reactivity	Safety considerations	Coolant density coefficient: -\$0.01 per 100°C Coolant Void Ratio: -\$0.11 <i>Void ratio calculated based upon Advanced Gas Reactor Geometries found in Reference [4]</i>	[4]
7. Low short-term activation and no long-life activation	Safety considerations	Short-term/long-term activation is small.	[4, 26]
8. Low relative neutron capture	Good fuel utilization	8x neutron capture relative to graphite.	[4]
9. Thermophysical properties	Properties must be acceptable for engineering application	See Table 1.	

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table 3: Vapor Pressures for Individual Species ($\times 10^3 \text{Pa}$) Reported from Reference [28].

Species/Temperature	500°C	550°C	600°C	650°C	700°C
LiF	0.021 Pa	0.23 Pa	1.9 Pa	12 Pa	63 Pa
BeF₂	28 Pa	200 Pa	1200 Pa	5600 Pa	23000 Pa
<i>1 mmHg = 133.322 Pa, i.e. BeF₂ at 650 °C: 5.6Pa = 0.042mmHg</i>					

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table 4: Design Specification for KP-FHR Reactor Coolant

[[

]]

|

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table 5: List of Corrosive Impurities toward Chromium

[[

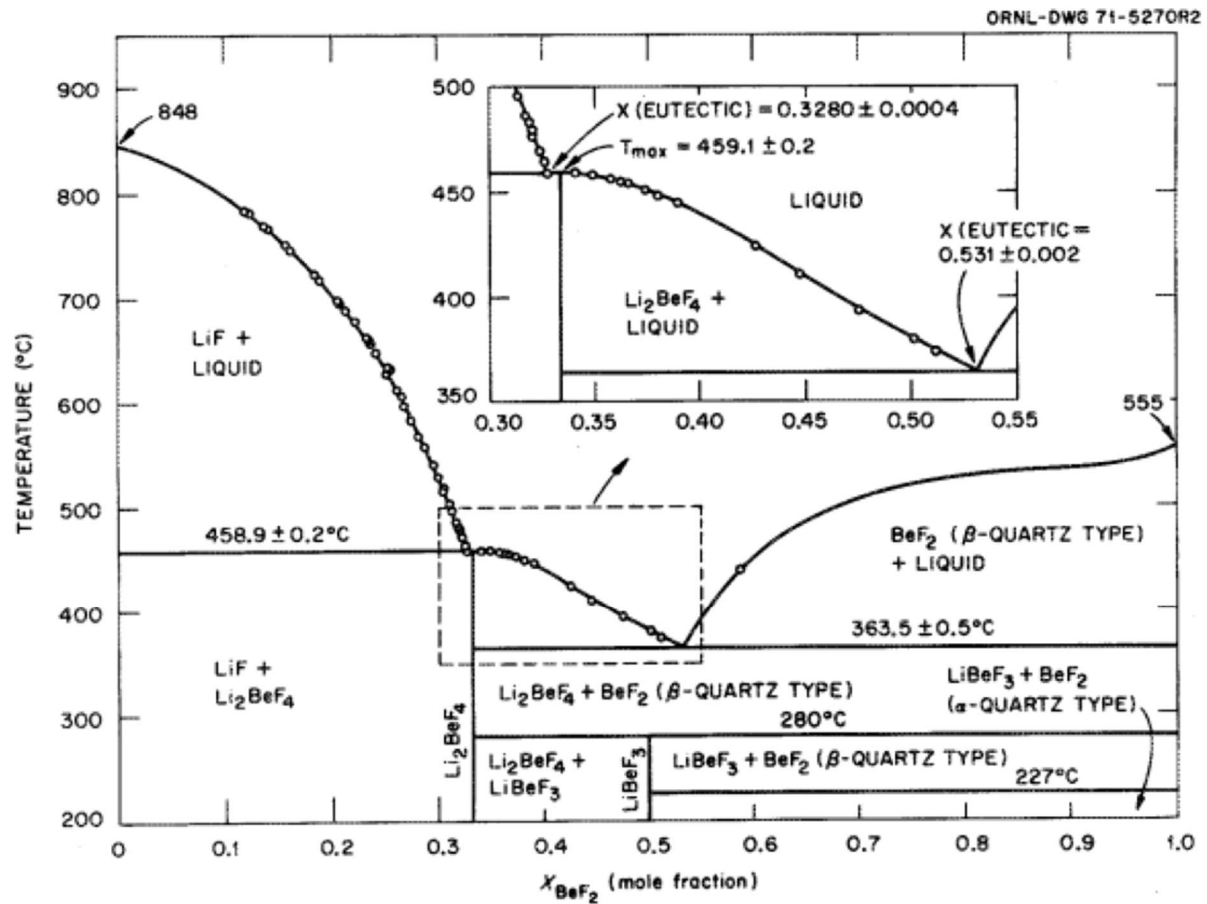
]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

Figure 1: Schematic of KP-FHR

]]

Figure 2: BeF₂, LiF Binary Phase Diagram from Reference [10]

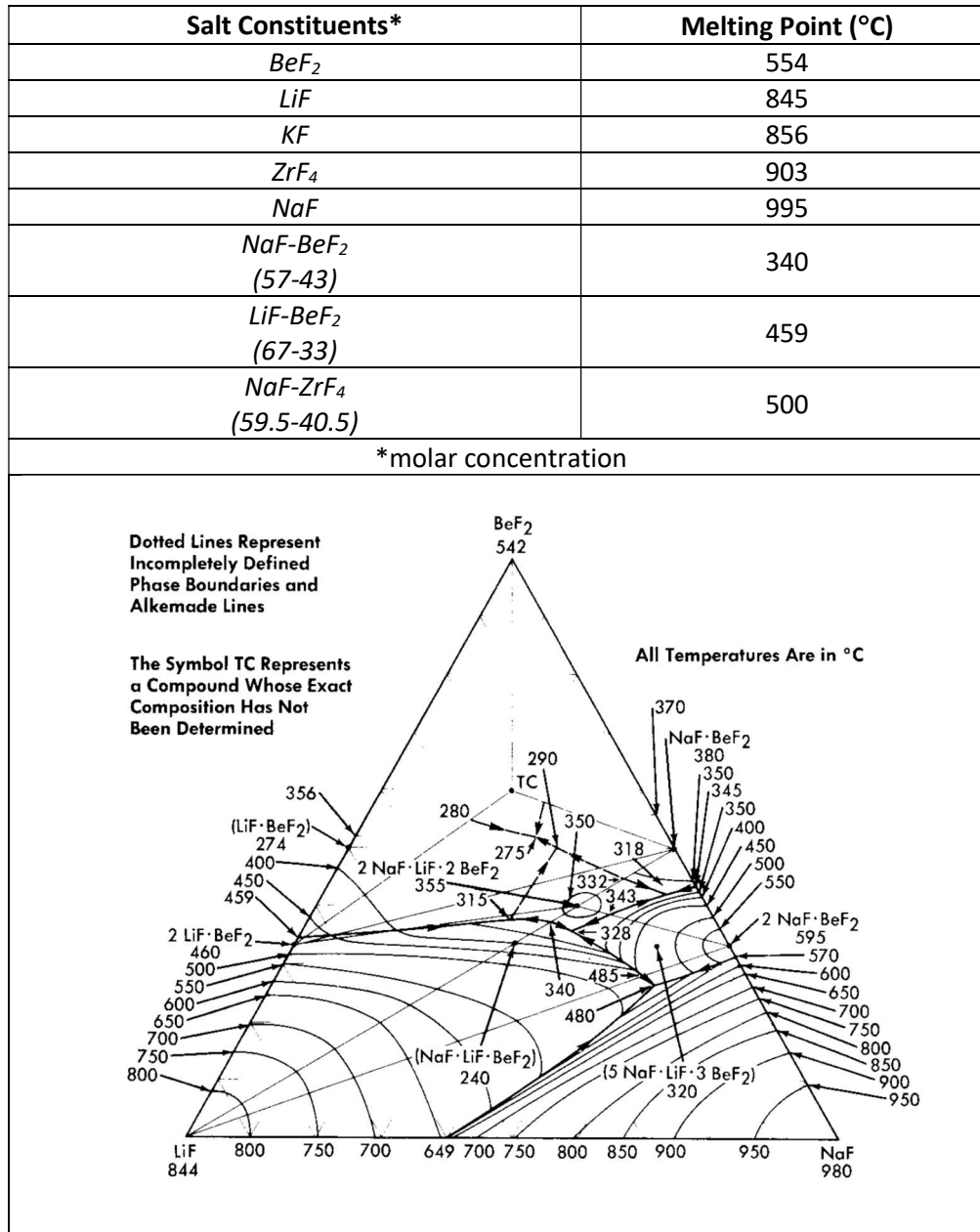


Figure 3: Melting points for Key Compounds and Example of a LiF-NaF-BeF₂ Phase Diagram Taken From Reference [26]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

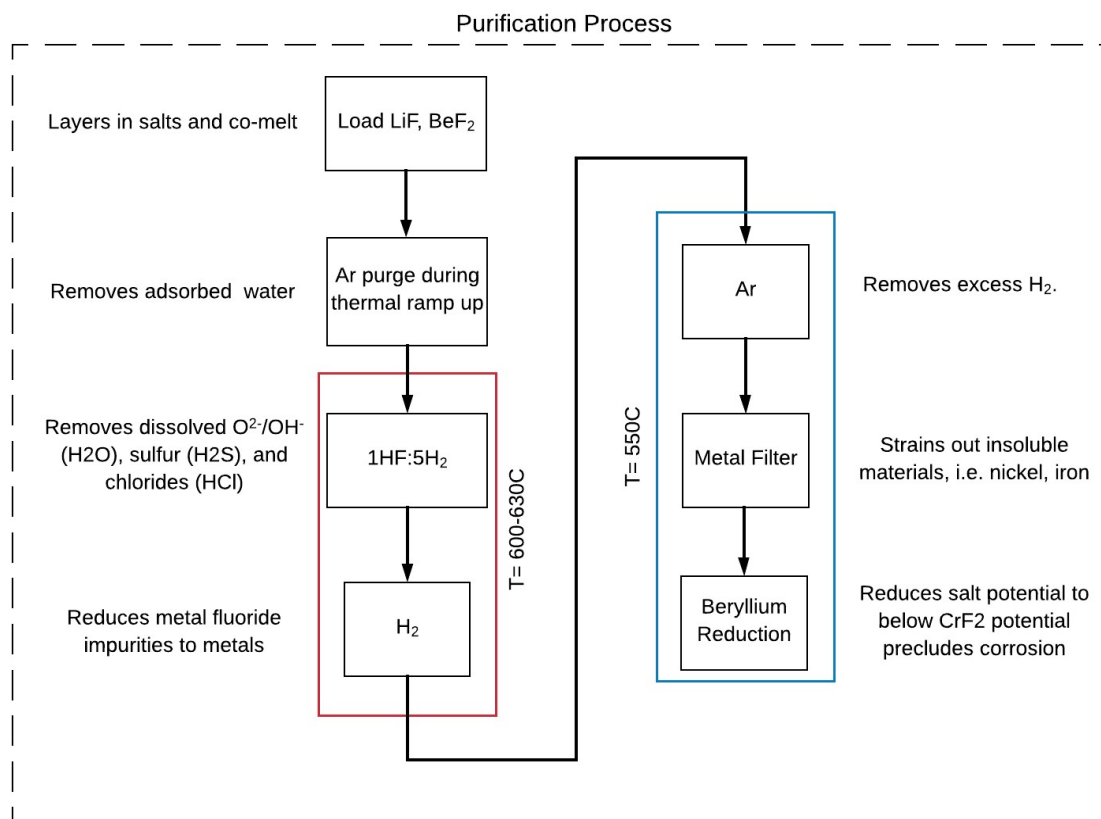


Figure 4: Flow Diagram of Flibe Purification Process Summarized from References [18, 29]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Figure 5: Schematic of Notional Kairos Power Chemistry Control System

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Figure 6. Enthalpy, Gibbs Free Energy, and the log of Equilibrium Constant for Reaction 14

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

APPENDIX A. THERMAL NEUTRON ABSORPTION IMPURITIES IN FLIBE

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table A1: Ranking of the Elements by Specific Thermal Neutron Absorption Cross Section

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table A2: List of Isotopes in Flibe as a Result of Neutron Irradiation

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

APPENDIX B. ELECTROCHEMICAL POTENTIALS OF FLUORIDES

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table B1: Electrochemical Potentials of Fluorides

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

APPENDIX D. CHROMIUM OXIDANT ALLOWABLE CALCULATION

Corrosion of structural materials that contain chromium within FHRs are expected to be primarily driven by chromium oxidation based on work from References [6, 19]. Therefore, any species that oxidize chromium should be controlled and limits established to ensure predictable performance within the reactor. Known oxidants are fluorides with a larger free energy of formation or standard reduction potential than chromium fluoride. A list of oxidants is provided in Appendix B. [[

— — —

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

APPENDIX C. THERMOPHYSICAL PROPERTY CONFIRMATION

Flibe thermophysical properties were generated during preparatory work for the MSRE program. The MSRE coolant salt, used to remove heat from the fuel salt, was Flibe in the same composition to be used for the KP-FHR. ORNL performed comprehensive measurements, as compiled in Reference [5]. Data generated and compiled during the MSRE report was performed over more than a decade of research, where researchers diligently measured many different molten salts under differing conditions. As errors were found throughout the span of the MSRE preparatory work, it was compiled and refined, so data near the end of the experiment was the best available.

Reference 5 provides the following discussion with regards to uncertainty:

Each contributor has stated what he believes is the error associated with the experimental result or with the estimated quantity. For most cases, the uncertainty represents considerably more than either "goodness of fit" of an interpolation or internal consistency available from thermodynamics. Instead, the uncertainty may be considered as the largest probable combination of systematic and random errors associated with the value given for the property. Where the listing is a property-temperature equation, the uncertainty is for the property calculated at the temperature substituted in the equation.

Although this data was used in the physical design of MSRE, it was not generated through a formal quality assurance program. However, the data were collected by national laboratory researchers, sponsored by the US Government, under controlled research processes. Additionally, some of the properties (heat capacity) were confirmed by independent organizations, such as the National Bureau of Standards. As such, Kairos Power considers this information to be acceptable for engineering and safety analysis application use and intends to perform limited confirmatory measurements, using the applicable quality assurance provisions in 10 CFR Appendix B. These measurements will utilize comparable methods to confirm the quality of the original data as well as obtain additional data that is outside the parameter ranges (i.e. temperature) required to further the understanding of these properties.

[[

.]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Heat Capacity:

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

APPENDIX E. NOT USED

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

APPENDIX F. EFFECT OF LIF-BEF₂ COMPOSITION ON VISCOSITY

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Table F1: Summary of Linear Regression Analyses of the Data in Figure F2

[[

--	--	--	--	--

]]

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Figure F1: Viscosity at 600°C vs. Composition for the $y\text{LiF-xBeF}_2$ Binary System

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[



]]

Figure F2: Viscosity vs. %BeF₂ at Indicated Temperatures

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

[[

]]

Figure F3: Effect of Flibe Stoichiometry Variation on Viscosity

Reactor Coolant for the Kairos Power Fluoride Salt-Cooled High Temperature Reactor			
Non-Proprietary	Doc Number	Rev	Effective Date
	KP-TR-005-NP	1	January 2020

Figure F4. Effect of Flibe compositional variation on the temperature-dependent viscosity.

Enclosure 3

Kairos Power LLC Affidavit and Request for Withholding from Public Disclosure (10 CFR 2.390)

I, Peter Hastings, hereby state:

1. I am Vice President, Regulatory Affairs and Quality at Kairos Power LLC ("Kairos"), and as such I have been authorized by Kairos to review information sought to be withheld from public disclosure in connection with the development, testing, licensing, and deployment of the Kairos reactor and its associated structures, systems, and components, and to apply for its withholding from public disclosure on behalf of Kairos.
2. The information sought to be withheld, in its entirety, is contained in Kairos' Enclosure 1 to this letter.
3. I am making this request for withholding, and executing this affidavit in support thereof, pursuant to the provisions of 10 CFR 2.390(b)(1).
4. I have personal knowledge of the criteria and procedures utilized by Kairos in designating information as a trade secret, privileged, or as confidential commercial or financial information. Some examples of information Kairos considers proprietary and eligible for withholding under §2.390(a)(4) include:
 - a. Information which discloses process, method, or apparatus, including supporting data and analyses, where prevention of its use by Kairos competitors without license or contract from Kairos constitutes a competitive economic advantage over other companies in the industry;
 - b. Information, which if used by a competitor, would reduce his expenditure of resources or improve his competitive position in design, manufacture, shipment, installation, assurance of quality;
 - c. Information which reveals cost or price information, production capacities, budget levels, or commercial strategies of Kairos, its customers, its partners, or its suppliers;
 - d. Information which reveals aspects of past, present, or future Kairos or customer funded development plans or programs, of potential commercial value to Kairos;
 - e. Information which discloses patentable subject matter for which it may be desirable to obtain patent protection; and/or
 - f. Information obtained through Kairos actions which could reveal additional insights into reactor system development, testing, qualification processes, and/or regulatory proceedings, and which are not otherwise readily obtainable by a competitor.
5. Information contained in Enclosure 1 to this letter contains details of Kairos Power's design and scaled testing information intended to support NRC staff review. This information includes details of Kairos Power's design and testing plans that could provide a competitor with a commercial advantage if the information were to be revealed publicly.

6. Pursuant to the provisions of §2.390(b)(4), the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld:
- a. The information sought to be withheld from public disclosure is owned and has been held in confidence by Kairos.
 - b. The information is of a type customarily held in confidence by Kairos and not customarily disclosed to the public. Kairos has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitute Kairos policy and provide the rational basis required.
 - c. The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR 2.390, it is to be received in confidence by the Commission.
 - d. This information is not readily available in public sources.
 - e. Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Kairos, because it would enhance the ability of competitors to provide similar products and services by reducing their expenditure of resources using similar project methods, equipment, testing approach, contractors, or licensing approaches. This information is the result of considerable expense to Kairos and has great value in that it will assist Kairos in providing products and services to new, expanding markets not currently served by the company.
 - f. The information could reveal or could be used to infer price information, cost information, budget levels, or commercial strategies of Kairos.
 - g. Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Kairos of a competitive advantage.
 - h. Unrestricted disclosure would jeopardize the position of Kairos in the world market, and thereby give a market advantage to the competition in those countries.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on: January 16, 2020

A handwritten signature in black ink, appearing to read 'Peter Hastings', is written over a horizontal line.

Peter Hastings

Vice President, Regulatory Affairs and Quality