SECTION A. Project Title: (Kairos) Tritium Testing to Support Kairos Power Advanced Reactor Demonstration R2

SECTION B. Project Description and Purpose:

Revision 2:

In support of Kairos's Advanced Reactor Demonstration Program (ARDP) proposal, Idaho National Laboratory (INL) will execute scaled experiments at INL's Safety and Tritium Applied Research (STAR) facility (TRA-666/666A) for the purpose of obtaining validation data for Kairos' tritium transport models and demonstrating tritium capture and extraction technologies suitable for the Kairos Power fluoride salt-cooled high-temperature reactor (KP-FHR).

The experiments will cover multiple reactor-relevant systems and release pathways to develop a comprehensive tritium management strategy. As with any lithium fluoride and beryllium fluoride (FLiBe)-cooled reactor system, the KP-FHR produces significant amounts of tritium during operation because of (n,t) reactions with lithium (Li)-6 and beryllium (Be) in the FLiBe coolant. Tritium is a unique radiological hazard because of its ability to permeate directly through metal structures at high temperature, thereby creating a potential for release of radioactive material not just during off normal or accident scenarios, but during normal operation. A quantitative understanding of tritium transport in the KP-FHR and ancillary systems and the development of necessary mitigation technologies are therefore critical issues to support licensing of the KP-FHR.

Task 1: Tritium Gas Absorption/Permeation (TGAP) solubility/diffusivity measurements in FLiBe Salt

The most fundamental properties governing tritium transport in a salt are the solubility and diffusivity. The former dictates how much tritium will be retained in the salt, and the latter the rate at which it is transported to the cover gas or other reactor systems. These properties have previously been measured in FLiBe, but the current spread in literature data creates significant uncertainty in predictions made by tritium transport models. Similar transport data needs for the liquid metal PbLi in fusion reactors previously motivated the development of the TGAP experiment at the INL STAR facility. In TGAP, solubility and diffusivity are measured by injecting a small quantity of tritium gas (e.g., 0.1 milligram) into a high temperature liquid sample, and measuring the subsequent release rate of tritium from the liquid. TGAP will be used to perform these measurements at reactor-relevant temperatures in a FLiBe salt provided by Kairos.

Measuring the diffusivity and solubility of tritium in FLiBe will be a three-step process requiring: a) characterization of temperature profile and membrane permeability using blank runs in a test section without salt, b) confirmation of FLiBe diffusion-limited permeation by measuring dependence of permeation on Q2 (T2+H2) partial pressure, and c) measurement of tritium permeation at a single Q2 partial pressure and H:T ratio over a range of temperatures.

The minimum acceptable number of runs for each test series are:

- Task 1.a (test section characterization): measure membrane permeability at 3 temperatures
- Task 1.b (diffusion-limited permeation validation): measure tritium flux at 5 Q2 partial pressures for a single temperature.
- Task 1.c (diffusivity/solubility measurement): measure tritium diffusivity and solubility in FLiBe at 5 temperatures for a single Q2 partial pressure and H:T.

Task 2: FLiBe argon cover gas tritium extraction demonstration and study of KP-FHR environmental effects

Operation experience from the Molten Salt Reactor Experiment (MSRE) demonstrates that significant tritium transport to the primary salt cover gas can be expected, and therefore FLiBe cooled reactors require solutions for tritium capture and cleanup of inert gas process streams. While technologies for tritium cleanup of inert gases exist, the cleanup process is complicated by FLiBe and graphite in the reactor environment due to uncertainties in chemical form of tritium evolving from the salt, potential degradation of tritium capture systems by vapor species characteristic of molten FLiBe, and possible reaction pathways with FLiBe dissolved impurities which sequester tritium.

A FLiBe salt experiment paired with a candidate gas-space tritium capture system will be constructed for demonstrating the inert cover gas cleanup process. Additional tritium transport effects will also be explored to complement the tritium diffusivity and solubility measurements taken in Task 1. The Task 2 test program will explore the following effects: a) FLiBe off-gas tritium removal efficiency with a scaled capture system, b) methods for sampling and measuring concentrations of dissolved tritium in FLiBe, c) tritium permeation rates through 316H stainless steel at representative KP-FHR conditions and low Q2 partial pressures of 10 Pa or less, d) effects of cover gas purity on chemical forms of tritium and tritium distributions, and e) effects of salt purity and presence of graphite on tritium chemical forms and tritium distributions.

Tests will be carried out in multiple separate effects tests using a test section design similar to Task 1. Therefore, the test facility infrastructure such as tritium supply, gas distribution, tritium containment, furnace and temperature control, tritium measurement, and data acquisition systems can be reused from Task 1. The Task 2 test sections may be reused between multiple subtasks if resulting measurements are not compromised. In general, a new test section will be required when switching permeation membrane materials, changing salt conditions, changing permeation directions, or testing at low tritium partial pressures after a test section has experienced significantly higher partial pressures. Test sections will be fabricated at INL.

The minimum acceptable number of runs for each subtask are discussed below. Note that the salt sampling and cover gas cleanup subtasks may be completed simultaneously with other runs.

- Task 2.a (cover gas cleanup): measure time to tritium breakthrough for 3 cover gas cleanup configurations.
- Task 2.b (salt sampling): collect 5 FLiBe salt samples at steady-state permeation conditions and measure dissolved tritium activity.
- Task 2.c (316H surface-limited transition): measure tritium flux at 6 Q2 partial pressures for a single temperature.
- Task 2.d (effects of cover gas purity): measure tritium diffusivity, solubility, and chemical forms released from FLiBe under 6 different concentrations of gas impurity additives.
- Task 2.e (effects of salt purity): measure tritium diffusivity, solubility, and chemical forms released from FLiBe with 2 salt purity perturbations.

Task 3: Irradiation of Materials with Advanced Materials and Manufacturing Technology (AMMT)

This Task is on hold. If Kairos Power decides to resume this task, then new scope will be agreed to between Kairos Power and INL and added in a later agreement modification.

Task 4: QA Support and Testing for Structural Graphite Oxidation

The testing of Kairos Power's samples is a part of an on-going DOE project (INL Project #32138) for Test 1 and Test 2, and directly funded through this CRADA for Test 3 (See Task 4b). The testing is planned to be completed 28 weeks (7 months) after approval of CRADA Mod. 3.

- 4a. The objective of this task is to provide quality assurance support to Kairos Power to show that the structural graphite oxidation test data performed by INL through the Advanced Reactor Technologies (ART) meets the Kairos Power nuclear QA data requirements for supporting the Hermes Operating Licensing. INL will provide support to facilitate a data qualification that will be performed by Kairos Power. This will include at a minimum providing QA records for the equipment used to perform the tests including calibration records, providing a QAPP or a QIM similar to the QIM in Annex-A1, providing records for the qualification and training of technical and QA personnel involved in this oxidation testing, providing detailed test method and data, and responding to questions from the KP staff during the data qualification.

- 4b. This task will support Kairos Power by performing targeted oxidation tests to measure penetration depths in ET-10 in Kairos Power-specific conditions. Kairos Power will provide samples through its graphite vendor Ibiden. INL will conduct tests detailed in Table 1 - Test 3 "Corrosion and penetration depth." Oxidation of the specimens will be performed by INL. Post-oxidation characterization to measure penetration depth will be performed by Kairos Power. Once Test 3 activities start, INL will ship post-exposure Test 3 specimens after they have achieved desired oxidation levels for Kairos Power to conduct the penetration depth measurement. INL will provide a final report on Test 3 by Q2 CY 2025. INL and Kairos Power will collaborate on a journal publication focusing on Test 3 data.

Kairos Power will provide FLiBE samples through its graphite vendor Ibiden. Oxidation of the specimens will be performed by INL. Post-oxidation characterization to measure penetration depth will be performed by Kairos Power. Once Test 3 activities start, INL will ship post-exposure Test 3 specimens after they have achieved desired oxidation levels for Kairos Power to conduct the penetration depth measurement.

All off-site partners will comply with their local procedures and state/federal regulations as identified in contract agreements.

Revision 1:

In the original ECP Task 1 and Task 2 involved testing of nitrate salts (60% NaN03 - 40% KNO3); however, Kairos Power requests to test Fluoride molten salt (FLiBe) instead of nitrate salts for Tasks 1 and 2. Equipment purchased for this project will be ion chambers, pressure sensors, flow controllers, etc. As with any FLiBe-cooled reactor system, the KP-FHR produces significant amounts of tritium during operation because of (n,t) reactions with Li-6 and Be in the FLiBe coolant. Tritium is a unique radiological hazard because of its ability to permeate directly through metal structures at high temperature, thereby creating a potential for release of radioactive material not just during off normal or accident scenarios, but during normal operation. INL will execute scaled experiments at INL's Safety and Tritium Applied Research (STAR) facility Tritium Lab (TRA-666/666A) for the purpose of obtaining validation data for Kairos' tritium transport models, and demonstrating tritium capture and extraction technologies suitable for the KP-FHR. The experiments will cover multiple reactor-relevant systems and release pathways to develop a comprehensive tritium management strategy. In addition, Task 3 will be included to provide irradiation of materials.

Task 1: Tritium Gas Absorption/Permeation (TGAP) solubility/diffusivity measurements in FLiBe Salt In TGAP, solubility and diffusivity are measured by injecting a small quantity of tritium gas (e.g., 0.1 milligram) into a high temperature liquid sample, and measuring the subsequent release rate of tritium from the liquid. TGAP will be used to perform these measurements at reactor-relevant temperatures in a FLiBe salt provided by Kairos.

Task 2: FLiBe salt pot with dry air cover gas and tritium extraction A FLiBe salt experiment paired with a candidate tritium capture system will be constructed for demonstrating the inert cover gas cleanup process. The primary experimental apparatus will be fabricated by Kairos and operated at the INL STAR facility. This experiment will consist of the multiple materials that comprise the primary reactor system namely 1) 316H steel vessel for FLiBe containment, 2) structural and matrix graphite inserts to represent reflectors and pebbles, 3) argon cover gas, 4) a system to circulate and capture tritium from the cover gas, and 5) a system to introduce tritium into FLiBe (e.g. gas sparging or permeation probe). The objectives of this experiment are to 1) monitor the chemical forms of tritium evolving from Flibe (TF, HT, HTO, or CH3T), 2) measure the efficiency of tritium capture systems in the salt cover gas, 3) confirm a method for sampling and measurement of tritium concentration in Flibe, and 4) quantify the distribution of tritium between the salt, cover gas, and permeation losses through the FLiBe-containing steel vessel.

Task 3: Irradiation of Materials with Advanced Materials and Manufacturing Technology (AMMT)

The AMMT program has developed the Irradiation System for High-throughput Acquisition (ISHA), which is a drop-in experiment capsule for testing fuels and structural materials within the Advanced Test Reactor (ATR). This capsule will be used in this project to test containment alloys (316H) and the associated weld metal (AWS 16-8-2) for Kairos's reactor concepts. This test will expose the test specimens to neutron radiation at temperatures consistent with Kairos's reactor environment. Kairos will provide the materials to be irradiated. Material examination efforts will include mechanical testing for both non-irradiated and irradiated specimens. Testing will include creep, tensile, fracture toughness, and fractography testing. KP will also complete a series of tensile and creep tests on base metal, weld metal, and weldments using standard ASTM test sizes and methods in parallel to sub-sized specimen testing at INL (equivalent to those used in irradiation). The testing plan will be coordinated between KP and INL to ensure all material baselines are established. The use of ASTM standard tests with sub-size tests will ensure adequate interpretation of data collected from the irradiation tests. The experiment assembly will be at ATR Test Train Assembly Facility (TTAF) since the experiment will not undergo fission. For task 3, PIE will be completed at Fuels and Applied Science Building (FASB), Irradiated Materials Characterization Lab (IMCL) and SPL (if constructed in time for operations).Waste will be produced from PIE waste and from irradiated sample debris.

For Kairo's permeation reactor, the three tasks that are performed are connected by identifying certain research and development opportunities to address gaps within the Kairo's research mission. Generation of low radioactive waste and beryllium waste are to be expected from Task 1 and 2 of tritium work. TRU waste will not be generated during the experiment. There will be several bags of LLW waste produced by the tritium work that will estimated to be less than 10 cubic meters for tasks 1 and 2. Less than 1 cubic meter of waste for the irradiation work conducted in task 3 is to be expected.

Original:

Background and Purpose Kairos Power LLC (KP) mission is to enable the world's transition to clean energy, with the goal of dramatically improving people's quality of life while protecting the environment. KP is implementing innovative strategies that can reduce the cost and accelerate the initial demonstration of the Kairos Power Fluoride-salt-cooled, High-temperature Reactor (KP-FHR) to meet the needs of the U.S. electricity market by 2030. KP will design, construct, and operate its Hermes reduced-scale test reactor. Hermes is intended to lead to the development of Kairos Power's commercial-scale KP-FHR, a novel advanced nuclear reactor technology that leverages TRI-structural ISOtropic (TRISO) particle fuel in pebble form combined with a low-pressure fluoride salt coolant. This project is supported by the U.S. Department of Energy (DOE) through the Advanced Reactor Demonstration Program (ARDP; DE-FOA-0002271). KP submitted a proposal under the program's Risk Reduction for Future Demonstration Projects for its Hermes reduced-scale test reactor and recently received an award. Kairos Power LLC has partnered with Idaho National Laboratory (INL) under the Hermes project to provide critical research outcomes necessary for risk reduction for future demonstration projects. In support of Kairos's ARDP proposal, INL will conduct two scaled experiments at the Safety and Tritium Applied Research (STAR) facility (TRA-666/666a Lab 104) located at the Advanced Test Reactor Complex.

A brief overview of the project tasks and schedule of this project is presented below.

Task 1: Tritium Gas Absorption/Permeation (TGAP) solubility/diffusivity measurements in Nitrate salt (FY2021 Q4 and FY2022)

The most fundamental properties governing tritium transport in a salt are the solubility and diffusivity. The former dictates how much tritium will be retained in the salt, and the latter the rate at which it is transported to the cover gas or other reactor systems. These properties are presently unknown for nitrate salts (60% NaNO3 - 40% KNO3). Similar data needs for the liquid metal PbLi in fusion reactors previously motivated the development of the Tritium Gas Absorption Prmeation (TGAP) experiment at the INL STAR facility. In TGAP, solubility and diffusivity are measured by injecting a small quantity of tritium gas (e.g., 0.1 milligram) into a high temperature liquid sample, and measuring the subsequent release rate of tritium from the liquid. TGAP will be used to perform these measurements at reactor-relevant temperatures in a nitrate salt provided by Kairos.

Task 2: Nitrate salt pot with dry air cover gas and tritium extraction (FY2021 Q4, FY2022, and FY2023)

Present simulations suggest that a significant amount of the tritium produced in the KP-FHR will permeate through the primary heat exchanger into the intermediate nitrate salt coolant. One of the motivations for using this salt is to oxidize any tritium introduced to this system, enabling simpler removal strategies from the air cover gas (e.g. condensation of steam, T2O or HTO) and simultaneously limiting any permeation from this system to the environment. A number of assumptions underlying this strategy need to be verified. A nitrate salt experiment paired with a candidate tritium removal system will be constructed for this purpose; the primary experimental apparatus will be fabricated by Kairos and operated at the STAR facility. The auxiliary equipment needed to construct and operate these experiments (i.e., ion chambers, pressure sensors, flow controllers, etc.) will be purchased by INL when the design is finalized. This experiment will consist of the multiple materials that comprise the intermediate heat transfer system (IHTS), namely 1) a lower tritium gas reservoir with steel membrane representative of a heat exchanger tube, 2) nitrate salt pot, 3) air cover gas, 4) a steel membrane representative of an IHTS pipe wall, and 5) a system to circulate and capture T2O/HTO from the dry air cover gas. The objectives of this experiment are to 1) measure how tritium permeates into the system partitions between nitrate salt and air cover gas; 2) measure the chemical form of tritium present in the cover gas (e.g., T2O/HTO/T2/HT); 3) measure the efficiency of the T2O/HTO removal system, 4) determine whether (and at what rate, as a function of temperature and pressure) tritium in the cover gas permeates through the steel wall in contact with it; and 5) attempt to identify which transport processes are the rate-limiting steps in this process, considering also the likely presence of an oxide layer on the steel membrane in contact with the salt.

SECTION C. Environmental Aspects or Potential Sources of Impact:

Air Emissions

This work has the potential to emit small amounts of radioactive isotopes of hydrogen via The TRA-710 main stack. Emissions of regulated air pollutants, including radionuclides such as tritium and metals are expected to be far below limits established in APADs 00-24 and 01-79.

The ATR irradiation activities are not modifications in accordance with Idaho Administrative Procedures Act (IDAPA) 58.01.01.201 and 40 Code of Federal Regulation (CFR) 61 Subpart H. ATR radionuclide emissions are sampled and reported in accordance with Laboratory Wide Procedure (LWP)-8000 and 40 CFR 61 Subpart H. All experiments will be evaluated by Environmental Support and Services staff. All radionuclide release data (isotope specific in curies) directly associated with this proposal will be calculated and provided to the Environmental Support organization

Discharging to Surface-, Storm-, or Ground Water

NA

Disturbing Cultural or Biological Resources

Cultural: Pursuant to the 2023 Programmatic Agreement, this federal undertaking is excluded from Section 106 review and the proposed activity results in no historic properties affected.

Generating and Managing Waste

Generation of low radioactive waste and beryllium waste are to be expected from Task 1 and 2 of tritium work. TRU waste will not be generated during the experiment. There will be several bags of LLW waste produced by the tritium work that will be estimated to be less than 10 cubic meters for tasks 1 and 2. A list of the wastes generated includes: tritium contaminated fluoride molten salts, tritiated water solidified on Floor Dry, tritium contaminated equipment (ion chambers, thermocouples, flow controllers, pressure sensors, etc.), steel tubing, fittings, and hardware, and PPE.

Releasing Contaminants

When chemicals are used during the project there is the potential for spills that could impact the environment (air, water, soil).

Using, Reusing, and Conserving Natural Resources

All applicable waste will be diverted from disposal in the landfill when possible. Project personnel will use every opportunity to recycle, reuse, and recover materials and divert waste from the landfill when possible. The project will practice sustainable acquisition, as appropriate and practicable, by procuring construction materials that are energy efficient, water efficient, are bio-based in content, environmentally preferable, non-ozone depleting, have recycled content, and are non-toxic or less-toxic alternatives. New equipment will meet either the Energy Star or SNAP requirements as appropriate (see http://www.sftool.gov/GreenProcurement/ProductCategory/14).

Environmental Justice

According to the CEQ Climate and Economic Justice Screening Tool, the INL site as well as the Research and Education Campus in Idaho Falls, ID are located in U.S. Census tracts that are identified as disadvantaged communities. Census tracts identified as disadvantaged meet or exceed socioeconomic, environmental, health, or demographic thresholds identified by CEQ. Given that activities analyzed in this document will happen within the boundaries of existing DOE/INL land and/or facilities where there are no permanent residents, any impacts to Environmental Justice in surrounding communities are anticipated to be negligible.

Activities taking place off-site (outside of the boundaries of the INL site), are assumed to follow all applicable regulatory requirements as stated in the project description. Should all requirements and work control processes be adhered to, it is anticipated that any impacts to environmental justice for any offsite work would be negligible.

SECTION D. Determine Recommended Level of Environmental Review, Identify Reference(s), and State Justification: Identify the applicable categorical exclusion from 10 Code of Federal Regulation (CFR) 1021, Appendix B, give the appropriate justification, and the approval date.

For Categorical Exclusions (CXs), the proposed action must not: (1) threaten a violation of applicable statutory, regulatory, or permit requirements for environmental, safety, and health, or similar requirements of Department of Energy (DOE) or Executive Orders; (2) require siting and construction or major expansion of waste storage, disposal, recovery, or treatment or facilities; (3) disturb hazardous substances, pollutants, contaminants, or Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)-excluded petroleum and natural gas products that pre-exist in the environment such that there would be uncontrolled or unpermitted releases; (4) have the potential to cause significant impacts on environmentally sensitive resources (see 10 CFR 1021). In addition, no extraordinary circumstances related to the proposal exist that would affect the significance of the action. In addition, the action is not "connected" to other action actions (40 CFR 1508.25(a)(1) and is not related to other actions with individually insignificant but cumulatively significant impacts (40 CFR 1608.27(b)(7)).

References: B3.6 "Small-scale research and development, laboratory operations, and pilot projects"

Final Environmental Impact Statement (FEIS) and ROD (DOE/EIS-0203, 1995) and supplemental analyses (DOE/EIS-0203-SA-01 and DOE/EIS-0203-SA-02) and the Amended Record of Decision (February 1996).

Justification: B3.6 Siting, construction, modification, operation, and decommissioning of facilities for small-scale research and development projects; conventional laboratory operations (such as preparation of chemical standards and sample analysis); and small-scale pilot projects (generally less than 2 years) frequently conducted to verify a concept before demonstration actions, provided that construction or modification would be within or contiguous to a previously disturbed or developed area (where active utilities and currently used roads are readily accessible). Not included in this category are demonstration actions, meaning actions that are undertaken at a scale to show whether a technology would be viable on a larger scale and suitable for commercial deployment.

After PIE, irradiated test pin segments and PIE remnants will be stored with other similar DOEowned irradiated materials and experiments at MFC, most likely in the HFEF or the Radioactive Scrap and Waste Facility (RSWF) in accordance with DOE's Programmatic SNF Management and Idaho National Engineering Laboratory Environmental Restoration and Waste Management Programs Final Environmental Impact Statement (FEIS) and ROD (DOE/EIS-0203, 1995) and supplemental analyses (DOE/EIS-0203-SA-01 and DOE/EIS-0203-SA-02) and the Amended Record of Decision (February 1996). Ultimate disposal of the irradiated test pin segments and PIE remnants will be along with similar DOE-owned irradiated materials and experiments currently at MFC. Irradiated sample debris and secondary waste could total as much as 20-30 Kg. Categorizing this material as waste is supported under Department of Energy Order (DOE O) 435.1, Att. 1, Item 44, which states "…Test specimens of fissionable material irradiated for research and development purposes only…may be classified as waste and managed in accordance with this Order...".

Is the project funded by the American Recovery and Reinvestment Act of 2009 (Recovery Act) ☐ Yes ☒ No

Approved by Robert Douglas Herzog, DOE-ID NEPA Compliance Officer on: 6/25/2024