Kairos Power

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

Subject: Design Overview for the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor

This letter submits the subject technical report which describes the overall conceptual design of the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR). This report is provided for information and is intended to begin familiarizing the NRC staff with the Kairos Power design and provide backgound for upcoming licensing reports that will be submitted in the near future.

Portions of this technical 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 James Tomkins at tomkins@kairospower.com or (805) 215-6129.

Sincerely,

Peter Hastings, PE
Vice President, Regulatory Affairs and Quality

Enclosures:

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

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Enclosure 2

Design Overview of the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor

(Non-Proprietary)

(Note that the enclosed information is preliminary and pre-decisional and is subject to change during detailed planning and project execution. It is provided for planning and familiarization purposes in support of pre-application discussions with the NRC Staff.)

KP-TR-001

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Design Overview of the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor

Revision No. 0
Document Date: November 2018

Non-Proprietary

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Rev	Description of Change	Date
0	Initial Issuance	November 2018

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EXECUTIVE SUMMARY

This document describes the Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR), a new Generation IV nuclear reactor being developed by Kairos Power. The KP-FHR is a low-pressure, high-temperature reactor designed for commercial grid electricity production.

This document describes the overall conceptual design and the functions of major systems and sub-systems for the plant, as well as describing the plant architecture. The major plant systems are the Reactor System, the Primary Heat Transport System, the Intermediate Heat Transport System, and the Power Conversion System. The Power Conversion System utilizes a high-temperature superheated steam Rankine cycle. This document provides preliminary information on other major plant systems and subsystems such as the decay heat removal system and tritium control systems.

Note that the enclosed information is preliminary and pre-decisional and is subject to change during detailed planning and project execution. It is provided for planning and familiarization purposes in support of pre-application discussions with the Nuclear Regulatory Commission Staff.

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ABREVIATIONS

Abbreviation or Acronym	Definition
AGR	Advanced Gas Reactor
ASME	American Society of Mechanical Engineers
AVR	Arbeitsgemeinschaft Versuchsreaktor (German Experimental Reactor)
BPVC	Boiler and Pressure Vessel Code
CRDM	Control Rod Drive Mechanism
CVD	Chemical Vapor Deposition
DOE	Department of Energy
EAMS	Exhaust Air Monitoring System
GWd	Gigawatt-day
IHTS	Intermediate Heat Transport System
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
IPyC	Inner Pyrocarbon
KP-FHR	Kairos Power Fluoride Salt-Cooled, High Temperature Reactor
MHTGR	Modular High Temperature Gas Reactor
NRC	Nuclear Regulatory Commission
OPyC	Outer Pyrocarbon
PCS	Power Conversion System
PHSS	Pebble Handling and Storage System
PHTS	Primary Heat Transport System
PSP	Primary Salt Pump
SS	Stainless Steel
TRISO	Tri-structural Isotropic
UCO	Uranium Oxy-Carbide

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0 KP-FHR PLANT

This document is an overview of the current Kairos Power Fluoride Salt-Cooled, High Temperature Reactor (KP-FHR) design. As the design proceeds, there may be changes to some of the information presented in this document. The document is organized consistent with the plant architecture, shown in Figure 0-1.

0.1 KP-FHR Concept Description

The KP-FHR is a U.S.-developed Generation IV advanced reactor technology that has been developed over the last decade. This follows from Department of Energy (DOE) sponsored research and development at universities and national laboratories. The fundamental concept is the combination of tri-structural isotropic (TRISO) particle fuel coupled with molten fluoride salt coolant. This combination results in a high-temperature, low-pressure reactor with robust, fully-passive safety systems.

In the last decade, U.S. national laboratories and universities have developed pre-conceptual Fluoride Cooled High Temperature Reactor (FHR) designs with different fuel geometries, power cycles, and power levels. Most recently, University of California, Berkeley developed the Mark 1 pebble-bed FHR, incorporating lessons learned from the previous decade of pre-conceptual designs. Kairos Power builds on the foundation laid by DOE-sponsored university Integrated Research Projects to develop the KP-FHR.

The fuel in the KP-FHR is the TRISO-coated particle fuel developed for high temperature gas-cooled reactors, which can withstand fuel particle temperatures up to 1600°C. The reactor coolant is the chemically stable, low-pressure molten fluoride salt mixture, $2LiF:BeF_2$ (Flibe), with a boiling point of 1430°C, notably lower than 1600°C and yet functionally very high. The combination of extremely high-temperature-tolerant fuel and low-pressure, single-phase, chemically stable reactor coolant removes entire classes of potential fuel-damage scenarios, greatly simplifying the design and reducing the number of safety systems. The intrinsic low pressure of the reactor and associated piping, along with the functional containment provided by the TRISO fuel, enhances safety and eliminates the need for high-pressure containment structures.

A key measure of safety is the magnitude of the potential source term associated with off normal events. The source term represents the amount, timing and nature of the radioactive material released from the reactor core and available for release to the environment following a postulated accident. The KP-FHR design relies on a functional containment approach similar to the Modular High Temperature Gas-Cooled Reactor (MHTGR) 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 NRC Regulatory Guide 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, anticipated operational occurrences (AOOs), and accident conditions.” For the KP-FHR, the functional containment approach controls radionuclides primarily at their source within the coated TRISO fuel particle without requiring active design features or operator actions. The multiple barriers within the TRISO fuel particles and fuel pebble ensure that the dose at the EAB as a consequence of normal operations, AOOs, and design basis accident conditions meets regulatory limits. Additionally, the KP-FHR molten salt coolant also serves as a barrier providing retention of fission products that escape the fuel particle and fuel pebble barriers. These retention features are graphically represented in Figure 0-2 and are a key feature of the enhanced safety and reduced source term in the KP-FHR.

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The safety analysis for the KP-FHR is informed by mechanistic source term methodologies developed for other technologies such as Sodium Fast Reactor (Reference 1) and MHTGR (Reference 2). The consequences of accidents are anticipated to be sufficiently low to satisfy Environmental Protection Agency Protective Action Guides at the site boundary. This is due to the strong fission product retention within the TRISO particle and pebble, and the additional radiological retention of the Flibe coupled with the low operating pressure of the reactor coolant which removes the driving pressurization force to transport radionuclides off site.

KP-FHR is a low-pressure reactor [[ ]] comprised of stainless steel SS316H which results in a physically compact reactor. The inherent safety of the KP-FHR technology also results in fewer safety-related systems, reducing the burden on design and inspection during the construction phase. The KP-FHR design facilitates off-site fabrication and assembly, reducing the expense of custom on-site fabrication and associated inspection. [[

]]

0.2 KP-FHR Plant Description and Overview

The heart of the KP-FHR is the Reactor System, containing the reactor core which generates fission heat. The Reactor System also contains the major reactor supporting systems, such as the heat removal and normal shutdown cooling, fueling and defueling, as well as structural supports. The reactor core produces thermal power in the range of 280-320 MW depending on configuration options which will be finalized in conceptual design; this report is based on 320 MW. The reactor is fueled with spherical fuel elements, or pebbles, which contain a mix of matrix material (described in Section 1.1.1) and TRISO particle fuel.

The Primary Heat Transport System (PHTS) interfaces with the Reactor System to circulate the reactor coolant (Flibe) between a packed bed of the fuel elements (pebbles) and the Intermediate Heat Exchangers (IHXs). The PHTS contains two primary salt pumps (PSPs) located outside the reactor vessel. The IHXs transfer heat from the primary coolant to the intermediate coolant salt, which is a commercial nitrate solar salt. The Intermediate Heat Transport System (IHTS) circulates this salt between the steam generators, reheaters and Power Conversion System (PCS). The PCS for the KP-FHR is a high-temperature steam Rankine cycle system.

Figure 0-3 shows the plant process flow diagram. The system is designed to accommodate volume changes due to heat up, cool down, pebble handling, reactivity element movement, level transients and chemistry control. The use of an intermediate loop and PCS enable multiple heat sink options.

0.3 Nuclear Island

The KP-FHR nuclear island consists of the Reactor, PHTS, and other associated support systems shown in Figure 0-1. The KP-FHR design has significant portions of the nuclear island [[ ]] See Figure 0-4 below for the KP-FHR nuclear island.

The seismic requirements under consideration for KP-FHR are based upon a [[ ]] The nuclear island may be designed to use seismic isolation.

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[[

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Figure 0-1. Plant Overview and Architecture

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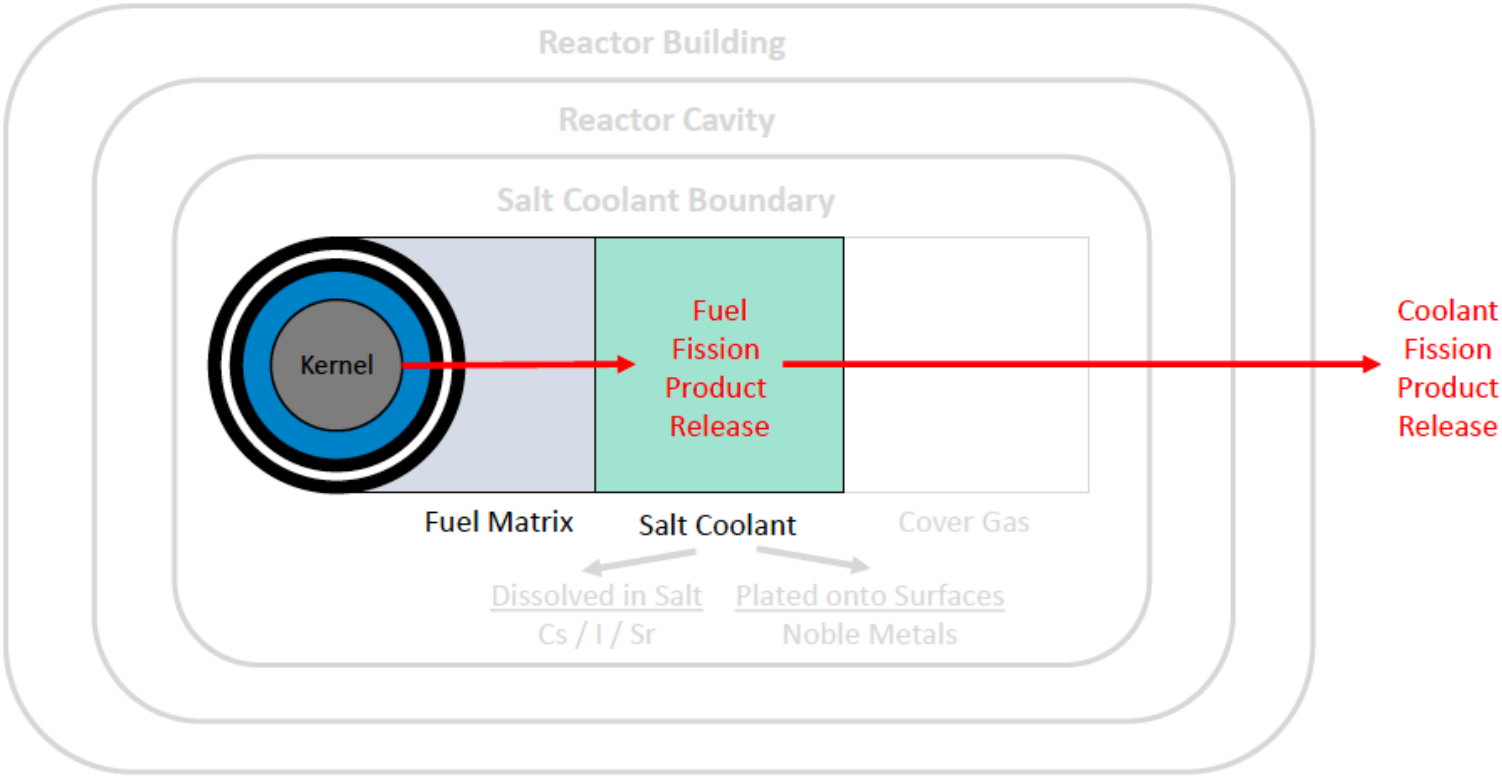

Figure 0-2. KP-FHR Radioactivity Retention

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Figure 0-3. KP-FHR Process Flow Diagram

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[[

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Figure 0-4. KP-FHR Nuclear Island Concept (Top View)

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1 REACTOR SYSTEM

The KP-FHR Reactor System is the architectural grouping of systems that produces and safely manages fission heat.

The main functions of the reactor system are summarized as follows:

- Generate fission heat to satisfy normal plant operations, start-up, shut-down, and power-level transitions
- Transfer heat to the PHTS
- Ensure that sufficient positive reactivity is inserted in the core to compensate for negative reactivity occurring as part of normal operations (such as fuel depletion and accumulation of fission products including xenon)
- Ensure that the reactor core is maintained in a sufficiently cooled geometry under normal operations, anticipated operational occurrences and design basis accidents
- Accommodate residual heat removal during normal and accident conditions
- Mitigate the generation, accumulation and release of tritium
- Provide for online monitoring, in-service inspection, maintenance and replacement activities and serviceable reactor components

Large-diameter hot and cold leg pipes [[ ]] All small diameter pipe connections for components [[ ]] The primary salt pumps [[ ]] The reactor vessel contains and supports the internal core structures and reactor coolant; and ensures that sufficient reactor coolant inventory remains in the core under design basis accidents and credible beyond design basis accidents.

The Reactor System contains the following systems:

- Reactor Vessel and Core
  - Fuel
  - Reactivity Control and Shutdown System
  - Reactor Internal Structures
  - Reactor Vessel
  - Reactor Startup System
- Normal Shutdown Cooling System, which provides post-shutdown cooling under normal shutdown conditions
- Passive Residual Heat Removal System, responsible for removing decay heat if normal shutdown cooling is not available
- Pebble Handling and Storage System, which transfers fuel to and from the core during normal operation
- Reactor Cavity System, which maintains the cavity integrity and geometry and facilitates tritium control
- Reactor Vessel Structural Support System, which provides structure support to the reactor vessel during normal and seismic or other external events

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- Reactor Unit Auxiliary Heating System, which provides electrical heating to components within the system

The nominal reactor parameters and the primary design constraints of reactor system components are given in Tables 1-1 and 1-2.

Table 1-1. Nominal Reactor Parameters

Parameter	Value
Reactor type	Fluoride-salt cooled, high temperature reactor
Core configuration	Pebble bed core, graphite moderator/reflector, and Flibe molten salt coolant
Reactor thermal power (MW)	320
Reactor operating pressure (bar)	<2
Reactor coolant outlet temperature (°C)	650
Reactor coolant inlet temperature (°C)	550
Reactor coolant flow rate (kg/second)	1200-1400
Core size (m^3)	[[ ]]

Table 1-2. Reactor System Primary Design Constraints

Constraint	Value
[[	
	]]

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1.1 Reactor

The KP-FHR reactor is a pebble-bed type core with spherical fuel pebbles (described in Section 1.1.1) forming the active region of the core. The core is operated at an average power density of approximately [[ ]] This power density is facilitated by the thermal properties of the reactor coolant and the design of the fuel pebbles (size and fuel packing) which [[ ]]

The design of the KP-FHR reactor core utilizes a cylindrical geometry with a graphite side-reflector and bottom and top graphite structures.

The reactor core internal graphite and metallic structures provide for the insertion of the reactivity control and shutdown system [[ ]] The main reactor core structural material is graphite which provides thermal inertia and moderation for the neutrons while reflecting the neutrons back into the active core region. The reactor vessel internal metallic structures define specific flow paths and support the graphite structures and are currently planned to be constructed of stainless steel SS316H.

The reactivity under normal operation, including normal startup and shutdown, is controlled by means of reactivity control elements. During anticipated operational occurrences and design basis accidents, reactor shutdown is achieved using the shutdown system. [[ ]]

A schematic layout of the reactor core is shown for illustration purposes in Figure 1-1. Pebbles are inserted into the reactor vessel [[ ]] The pebbles are then transferred to the active core region through [[ ]] The active core contains a diverging region at [[ ]] The KP-FHR core has [[ ]] Pebbles extracted from the core are then directed to the pebble handling system for inspection, segregation, recirculation and/or storage.

The reactor coolant from the cold leg pipe flows through the flow distributor located at the top of the downcomer, which is the annular flow area between the core barrel and reactor vessel sidewalls. The cold reactor coolant flows through the downcomer to the bottom plenum where it is directed to the active core region and to engineered coolant bypass flow channels. These coolant channels [[

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]] Hot coolant is collected at the hot wells through the coolant flow channels [[
]]

[[

]]

Figure 1-1. Schematic Layout of the KP-FHR

The side reflector surrounds the active core region and reflects the neutrons back to the core, increasing the fuel utilization while [[
]] and providing a large source of thermal inertia for the core.

The side-reflector is composed of graphite [[
]]

The equilibrium core is expected to contain [[
]] The pebbles are designed with an overall density slightly less than the reactor coolant such that they are positively buoyant in the reactor coolant at operating and accident temperatures.

The details of the fuel pebbles are described in Section 1.1.1. Nominal fuel pebbles reach a discharge burnup of [[ ]] while passing through the core on average [[ ]] times during their lifetime. The enrichment of the equilibrium fuel is less than [[ ]] U-235.

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Each of the pebbles contain approximately [[ ]] TRISO particles and each fuel pebble contains [[ ]] of heavy metal. The average power per TRISO particle is [[ ]] The equilibrium core requires approximately [[ ]], and the total number of pebbles circulated per day through the core and Pebble Handling and Storage System (PHSS) is approximately [[ ]] The values above are nominal values. The number of TRISO particles and uranium loading within a pebble are design parameters that may vary from the initial to equilibrium cycles.

1.1.1 Fuel

The KP-FHR fuel design is a spherical fuel element, or pebble, containing TRISO particle fuel. The fuel pebble contains an un-fueled central sub-dense core, surrounded by an annular region of TRISO particles packed into a partially-graphitized matrix. The outer layer of the fuel pebble is matrix material used as a protective layer to protect the TRISO particles from mechanical damage.

The high-level functions for the TRISO fuel pebble are defined as follows:

- Generate heat from fission for transfer to the reactor coolant (Flibe)
- Contain and confine the fissile material and the solid and gaseous fission products to mitigate potential contamination of the coolant
- [[

]]

Although there are differences, the KP-FHR pebble design is based on the TRISO particle fuel design used in the U.S. DOE Advanced Gas Reactor (AGR) Fuel Development and Qualification Program conducted at Idaho National Lab's (INL) Advanced Test Reactor. The AGR irradiation program started in 2006 and continues to this day, through a series of irradiation experiments (Reference 4): AGR-1 (shakedown), AGR-2 (fuel performance demonstration), AGR-3/4 (fission product transport), and AGR-5/6/7 (fuel qualification). The purpose of the AGR fuel program is to qualify TRISO-coated particle fuel in a fuel compact design operating under high-temperature gas-cooled reactor conditions.

TRISO particles contain high assay low enriched uranium (defined by 5 – 20% U-235 enrichment) fuel kernels in the form of uranium oxycarbide (UCO, a mixture of UO_2 + UC + UC_2). [[ ]] Figure 1-2 illustrates the TRISO fuel particle, including the UCO fuel kernel and TRISO particle coating layers consisting of a porous graphitic buffer layer, an inner pyrolytic carbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer pyrolytic carbon (OPyC) layer. The TRISO particle design for the KP-FHR is based on the TRISO design developed through the AGR fuel qualification program. The KP-FHR TRISO particle design has a TRISO kernel diameter of [[ ]]

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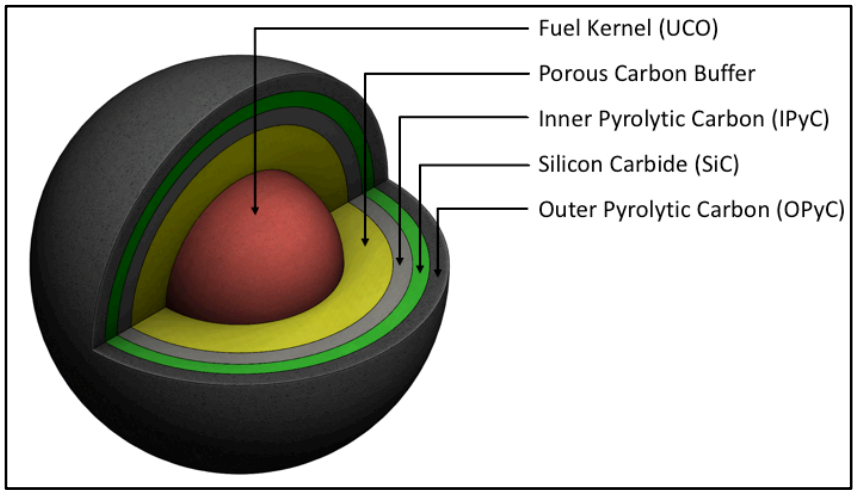

Figure 1-2. Graphical Depiction of TRISO-Coated Fuel Particle

The TRISO particles are [[

]] The overcoated particles are then pressed into a pebble, as shown in Figure 1-3. Table 1-3 presents the main properties including the details of the TRISO particles and nominal pebble geometry.

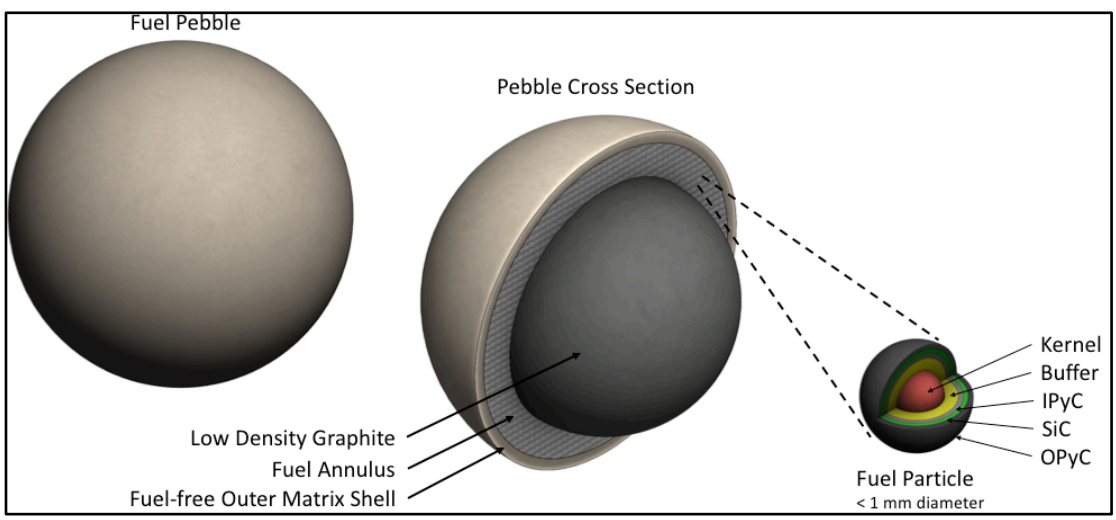

Figure 1-3. Design of the TRISO Particles and Fuel Element

The KP-FHR fuel is designed to generate heat through fission and transfer heat from the TRISO particles, through the matrix layers, and eventually to the coolant salt. The SiC coating in the particles is the primary fission product barrier, while the PyC layers and matrix act as secondary barriers for trapping or impeding the transport of fission products. The AGR-1 fuel irradiation campaign and post-irradiation examination confirmed this effective retention of most of the fission products by the SiC layer and the matrix (Reference 3).

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The low-density pebble core allows the overall pebble density to be less than that of the reactor coolant to ensure that pebbles float in the reactor coolant under normal and accident conditions. The annular fueled region ensures that fuel particles are closer to the outer surface of the pebble, decreasing the thermal resistance between the fuel and reactor coolant and limiting peak particle temperatures, [[ ]]

Table 1-3. Design Requirements for TRISO Fuel Particles

[[

]]

1.1.2 Reactivity Control and Shutdown System

The Reactivity Control and Shutdown System consists of two subsystems:

- Reactivity Control
  - [[ ]]

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- [[ ]]
- Reserve Shutdown

The reactivity control subsystem is used to control the reactivity for normal and off-normal operating conditions and shut down the reactor. [[

]]

[[

]]

1.1.3 Reactor Internal Structures

The Reactor Internal Structures include the graphite and mechanical structures that form the internals of the reactor. [[

]] Design of the core internal graphite structures complies with appropriate American Society of Mechanical Engineers (ASME) Section III Division 5 materials design codes for graphite in nuclear reactor systems.

The [[

]] are also located in the graphite structures.

The reactor core metallic structures include the downcomer flowpath (core barrel), [[

]] as well as the support structures for the top, bottom, and side graphite structures in the core.

1.1.4 Reactor Vessel

The reactor vessel is a vertical cylinder with a bottom and top head. The vessel is constructed from materials that are qualified by the ASME Boiler and Pressure Vessel Code (BPVC) and fabricated [[

]] The reactor vessel is shown in Figure 1-1.

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The reactor vessel, core barrel, and associated components are fabricated from a high-carbon grade (e.g. -H grade) of SS316 that satisfies the latest additional chemistry restrictions of the ASME Section III code in Division 5 (Table HBB-U-1, revised case 2581). The high temperature 316H grade of stainless steel is selected for its enhanced creep strength while also meeting coolant chemical compatibility requirements.

The reactor vessel serves as part of the reactor coolant boundary and supports and interfaces with other systems such as Control Rod Drive Mechanisms (CRDM), PHSS and PHTS. The reactor vessel is designed to withstand the operational loads imparted on it by the core structures, fuel, and coolant. Additionally, the reactor vessel is of sufficient strength and resiliency to withstand off-nominal conditions that are detailed by the ASME BPVC, Section III, Division 5, Level B, C, and D Service Conditions.

Known degradation mechanisms and in-service inspection programs are factored into design life basis for the reactor vessel structural materials.

1.1.5 Reactor Startup System

The Reactor Startup System is responsible for inserting and removing a neutron source from the core to enable reactor startup. The reactor startup system also contains reactor core instrumentation such as neutron flux detectors and temperature measuring instruments in the reactor core internal structures. For the initial (fresh-fuel) start-up, the external neutron source is [[

]]

The operating experience from the high temperature reactors in Germany, such as AVR, indicates that secondary neutron sources are unnecessary since a sufficient number of neutrons are released by fission product decay and by spontaneous fission after a few full power months of operation.

1.2 Passive Residual Heat Removal System

The Passive Residual Heat Removal System is designed to provide shutdown heat removal during postulated accidents if the normal shutdown cooling system is not available. The system provides a robust and effective method of meeting the requirements of extracting decay heat without direct intervention or active system operation. The system requires no electrical power to operate.

The design of normal heat removal is sufficiently reliable that the need to use the passive system is expected to occur less than once in the plant life.

[[

]]

- [[

]]

- Dissipated to the atmosphere by natural convection

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During normal power operation, the [[

]]

[[

]]

Figure 1-4. Passive Residual Heat Removal System

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1.3 Pebble Handling and Storage System

The PHSS performs the on-line circulation of fuel pebbles through the core and manipulates pebbles outside of the core. The PHSS performs the following functions:

- Add and remove fuel from the core during normal operations to support on-line refueling
- Maintain non-critical configuration of the fuel pebbles outside the reactor core
- Cool, contain, monitor, and maintain integrity of the used fuel pebbles and activated non-fuel pebbles throughout the handling and storage process
- Maintain integrity of the reactor system boundary

A representation of the process functional diagram of the PHSS is shown in Figure 1-5, identifying the subsystems and components in the general direction of pebble flow.

[[

]]

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[[

]]

Figure 1-5. Pebble Handling and Storage System Functional Elements

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1.4 Reactor Cavity System

The Reactor Cavity System is a concrete enclosure with inert gas surrounding the reactor vessel assembly and [[ ]] The Reactor Cavity System provides thermal management to ensure the cavity concrete remains below design temperature limits. The reactor cavity system provides a low-pressure low-leakage boundary but does not provide a traditional primary containment function. Figure 1-8 shows the arrangement of the reactor cavity.

[[

]]

Figure 1-6. Reactor Cavity Arrangement (Cross-Section)

1.5 Normal Shutdown Cooling System

The Normal Shutdown Cooling System removes reactor decay heat [[

]] The shutdown cooling system has the primary function of controlling the temperature of reactor [[ ]]

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This system also provides heat input during prolonged shutdowns to maintain the reactor coolant above its freezing temperature. This prevents localized freezing and supports timely restart of the reactor from the shutdown condition.

1.6 Reactor Vessel Structural Support System

The Reactor Vessel Structural Support System provides structural support for the reactor vessel. This system supports the weight of the reactor and transmits that load to the cavity structures during both normal operation and seismic events. The system also accommodates reactor vessel thermal expansion in transitioning between room temperature and operational temperature. The reactor vessel design allows thermal movement due to reactor startup, cooldown, and operational transients.

1.7 Reactor Auxiliary Heating System

The main function of the Reactor Auxiliary Heating System is to provide non-nuclear heating to the reactor system as needed for various operations including initial salt melt, startup, shutdown, and make-up heat during normal operation.

The source of the heat depends on the subsystem or component requiring the heat. For example, [[

]]

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2 PRIMARY HEAT TRANSPORT SYSTEM

The functions of the PHTS are to:

- Circulate heat, by means of the reactor coolant, from the Reactor System to the IHTS
- Manage thermal transients in the Reactor Core and PHTS during normal operations

This system is designed to allow online monitoring, in-service inspection, maintenance and replacement activities.

In addition to the reactor system and the IHTS, the PHTS interfaces with the reactor coolant chemistry control system, the primary loop initial conditioning system, the primary coolant inventory control system, the auxiliary heating systems, the cover gas system, and the tritium control and recovery system.

[[

]] See Figure 2-1 for the flow diagram.

The PHTS includes the following components:

- Primary salt pumps
- Intermediate heat exchanger
- Primary piping
- Primary loop auxiliary heating

The reactor coolant is $2LiF:BeF_2$ (Flibe) and it is based on an optimization of thermophysical properties, such as melting point and viscosity. [[

]] The properties of the Flibe are listed in Table 2-1. Thermophysical properties in the liquid phase provide for effective heat transfer.

Table 2-1. Reactor Coolant (Flibe Salt) Properties

Property	$2LiF:BeF_2$ (Flibe)
Density, ρ (kg/m^3)	1987 (@600°C)
Specific Heat, Cp (J/kg-C)	2386 (@600°C)
Viscosity, μ (cP)	8.55 (@600°C)
Thermal Conductivity, k (W/m-K)	1.10 (@600°C)
Latent Heat (kJ/kg)	447
Volume change at solidus phase transition, ΔV (%)	~2
Melting Point (°C)	459
Boiling Point (°C)	1430

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[[

]]

Figure 2-1. Primary and Intermediate Heat Transport System

2.1 Primary Salt Pump

The major function of the two PSPs is to circulate the reactor coolant between the core, where the coolant is heated in contact with the fuel, and the heat exchanger, where heat is transferred to the IHTS.

Flow rates of the system are based on maintaining a specified temperature change across the core as thermal output changes. The PSP has an inert gas space which is connected to the reactor vessel cover gas space. The pump maintains an effective seal between the cover gas and external atmosphere. The Reactor Cover Gas System is described in Section 5.2.

The PSP is designed to operate continuously at full thermal power flow rates and temperatures, as well as at reduced power and flow rates. The pump provides [[
]]

2.2 Intermediate Heat Exchanger

The IHX serves as the heat transfer interface and coolant boundary between the PHTS and the IHTS. The IHXs are configured in a tube and shell arrangement functioning to transfer heat between the reactor coolant [[ ]] and intermediate salts [[
]] and it is located adjacent to the reactor vessel. See Figure 2-1 for the flow diagram.

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The IHX performs the following functions:

- Transfer heat from the reactor coolant to the intermediate coolant
- [[ ]]
- Maintain the integrity of the reactor coolant boundary
- Allow for reactor coolant draining and flushing
- [[ ]]
- Provide for thermal conditioning of the salt to prevent undesired freezing and allow for startup
- Acts as a barrier to radionuclide transport between the primary loop and intermediate loop

The IHX is designed to allow for in-service inspection, tube plugging, and replacement.

2.3 Reactor Coolant Piping System

The Reactor Coolant Piping System consists of the interconnecting piping and supporting structures. See Figure 2-1 for the flow diagram.

A list of functions for the Primary Piping System includes the following:

- Provide a flow conduit for reactor coolant
- Maintain the integrity of the reactor coolant boundary
- Accommodate thermal expansion between the primary salt pump and the IHX, and the reactor vessel
- Act as a barrier for radionuclide transport, including tritium, between the reactor coolant and the pipe surrounding environment
- Provide for reactor coolant filling
- Provide for reactor coolant draining
- Provide for high-point venting
- [[ ]]

The primary piping system serves as the major interface between the IHX and the reactor system. Other interfaces include the chemistry control system and the inventory control system. The piping system must accommodate the coolant temperature, pressure and corrosion properties of the reactor system.

2.4 Primary Loop Auxiliary Heating Systems

The main function of the Primary Loop Auxiliary Heating System is to provide non-nuclear heating to the primary heat transport system as needed for various operations including initial salt melt, startup, shutdown, and make-up heat during normal operation. The functions for the auxiliary heating systems are:

- Provide non-nuclear heat for thermal conditioning of systems that contact primary coolant
- Provide heat for bringing the plant up to temperature from cold conditions
- Provide makeup heat to ensure salt freezing is avoided during conditions parasitic losses exceed heat input to the system

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The source of the heat depends on the subsystem or component requiring the heat. [[

]]

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3 INTERMEDIATE HEAT TRANSPORT SYSTEM

The IHTS thermally couples and serves as a barrier between the PHTS and the PCS. The IHTS also serves to physically separate the high-pressure steam of the PCS from the primary coolant circuit and also to provide an additional barrier to the transport of tritium and radionuclides.

The major function of the IHTS is to transport heat from the IHX to the PCS. The IHTS is comprised of several subsystems and components, including the intermediate piping system, the intermediate salt pump, and the steam generator.

Major functions of the IHTS are to:

- Transfer thermal energy from the PHTS for efficient use in the PCS
- Provide for thermal expansion between the IHX, steam generator, and interconnecting piping and components
- Maintain integrity of the intermediate coolant boundary (i.e. avoid steam ingress)
- Manage over-pressure protection
- Control and recover tritium that diffuses through the IHX

This system is designed to allow for on-line monitoring, in-service inspection, maintenance, and replacement activities. The IHTS design includes a cover gas to control intermediate salt chemistry to minimize corrosion.

Nitrate salt has been selected as the heat transport medium for this system. The concentrating solar power industry has long utilized a mixture of 60% by weight of sodium nitrate and 40% by weight of potassium nitrate as a heat transfer fluid (properties are provided in Table 3-1) also called “60/40 nitrate salt” or “Solar Salt” (Reference 5).

Table 3-1: Intermediate Nitrate Salt Properties

Property	60/40 Nitrate Salt
Density, ρ (kg/m^3)	1710 (@ 600 °C)
Specific Heat, Cp (J/kg-C)	1550 (@ 600 °C)
Viscosity, μ (cP)	1.02 (@ 600 °C)
Heat Conductivity, k (W/m-K)	0.56 (@ 600 °C)
Latent Heat (kJ/kg)	161
Volume change at solidus phase transition, ΔV (%)	4.6
Melting Point (°C)	238

[[

]] A diagram is shown in Figure 2-1 to illustrate the high-level layout of the four main plant systems, including the IHTS.

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The IHTS includes the following components:

- Intermediate salt pumps
- Intermediate piping
- Steam generators and reheaters
- Intermediate loop auxiliary heating

3.1 Intermediate Salt Pump

The intermediate salt pump provides the motive force for the circulation of intermediate coolant and provides the needed pressure and flow rate in the intermediate heat transport system. The pump provides forced circulation of the solar salt between the IHX and the steam generator. The intermediate salt pump will operate in an environment similar to, but not identical to, the duty cycle for pumps employed in solar thermal plants.

3.2 Intermediate Piping System

The Intermediate Piping System serves as the flow conduit within the IHTS. The Intermediate Piping System uses technology developed within the solar thermal industry [[ ]] The substantive difference from commercial technology is [[ ]]

The Intermediate Piping System performs the following functions:

- Provide a flow conduit for intermediate coolant
- [[ ]]
- Accommodate thermal expansion between the IHTS pumps, the IHXs, and steam generators and reheaters
- Provide for intermediate coolant filling and draining
- Provide for high-point venting
- Provide for inspection and maintenance activities

The Intermediate Piping System is designed to provide for inspection and maintenance activities. This system is also designed to operate continuously with full thermal power, and to operate under part load conditions at reduced flow rate.

3.3 Steam Generator

The steam generators and reheaters are designed to transfer heat from the intermediate salt to the PCS by [[ ]] The steam generator and reheater are similar to solar thermal steam generators and reheaters, as the same hot side coolant is used: nitrate molten salt. Differences in steam generator design are [[ ]]

The steam generator has a significant pressure differential across the tubes, and design experience from existing nitrate steam generators is used to ensure that the risk of significant tube rupture events, and the potential consequences of those events are minimized. The distance, barriers, thermal inertia,

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and volume of salt in the IHTS significantly limit the risk that steam ingress could credibly pose a challenge upstream to the Reactor and Primary Heat Transport Systems.

The steam generator and reheaters perform the following functions:

- Transfer thermal energy
- Contain the salt working fluid
- Ensure potential tube leaks/ruptures do not present a significant risk/consequence
- Provide for intermediate salt thermal conditioning (maintain salt in liquid state)
- Provide for salt introduction
- Provide for salt draining

The steam generator serves as the major interface between the IHTS and the PCS.

3.4 Intermediate Loop Auxiliary Heating

The main function of the auxiliary heating system is to provide non-nuclear heating as needed for various operations: initial salt melt, startup, shutdown, and make-up heat during normal operation.

[[

]]

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4 POWER CONVERSION SYSTEM

The purpose of the PCS is to convert thermal energy from the heat transport system into electricity. The major interfaces of the steam cycle are with the IHTS and the electric grid. The PCS is a [[ ]] steam Rankine cycle operating at [[ ]] The cycle has a feedwater heating train [[ ]]

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5 REACTOR COOLANT SUPPORT SYSTEMS

5.1 Reactor Coolant Chemistry Control System

The Reactor Coolant Chemistry Control System detects and remediates changes in the reactor coolant chemistry. These changes could come about because of normal reactor operations and include:

- [[ ]]
- [[ ]]
- [[ ]]
- [[ ]]

The Reactor Coolant Chemistry Control System is capable of [[ ]]

[[ ]]

The Reactor Coolant Chemistry Control System includes three subsystems:

- Detection and monitoring subsystem [[ ]]
- Removal subsystem [[ ]]
- Reducing agent subsystem [[ ]]

5.2 Reactor Cover Gas System

The Reactor Cover Gas System is designed to maintain an inert atmosphere by maintaining continuous circulation of argon gas over the Flibe free surface in the reactor. This cover gas removes tritium and other gases for further treatment. [[ ]] Reactor cover gas aids in maintaining a non-corrosive environment in concert with the Reactor Coolant Chemistry Control System.

5.3 Tritium Control System

Tritium has low solubility in Flibe and diffuses readily at KP-FHR operating temperatures through the metallic materials of the reactor coolant boundary. The [[ ]] are used to minimize generation of tritium. [[ ]] Existing technologies to oxidize tritium, [[ ]], also are used to convert tritium to a non-gaseous form.

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5.4 Inventory Control System

The Reactor Coolant Inventory Control System maintains reactor coolant levels within the primary heat transport system which includes filling, draining, and level management. The system stores the reactor coolant when the reactor is offline or in maintenance. Secondary functions of the system include providing initial salt loading and melting operations following delivery and receipt of salt coolant, and providing for certain offline chemistry control activities not handled by the Reactor Coolant Chemistry Control System.

This Reactor Coolant Inventory Control System performs the following functions:

- Provide for initial frozen reactor coolant loading and initial melting
- [[ ]]
- Control filling process for systems containing reactor coolant
- Control draining process for systems containing reactor coolant
- Control reactor coolant level excursions

The system includes subsystems for salt inventory [[ ]], drain tanks, and batch clean up equipment. [[ ]] The drain tanks are used primarily for filling and draining of the primary system and long-term storage [[ ]]

5.5 Beryllium Control

The purpose of the beryllium control program is to protect workers and the environment from inadvertent beryllium exposure and to prevent beryllium from transport outside of the reactor building. During operation, beryllium containing materials are contained within the PHTS, reactor core, or supporting systems. Inadvertent exposure to beryllium could arise during spills or leaks that occur under a variety of different circumstances and operations. Workers are required to utilize personal protective equipment (e.g. chemical resistant gloves, powered air purifying respirators). In addition, beryllium control is enhanced by leveraging commercial practices for directed air flow, high-efficiency-particulate filters (HEPA) used to remove beryllium particles from air, and air monitoring to minimize worker or environmental exposure.

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6 INSTRUMENTATION AND CONTROL SYSTEM

The Instrumentation and Control (I&C) Systems include the Reactor Protection System, which is responsible for ensuring control inputs and external events do not cause the plant to enter an unsafe state. The Plant Control System is responsible for normal operating inputs to systems within the plant. The Plant Health Monitoring System collects sensor data and analyzes the data to determine the plant operating condition. The main control room serves as the operator interface to the plant. The I&C systems are listed below:

- Reactor Protection System
- Plant Control System
- Plant Health Monitoring System
- Main Control Room

The I&C system [[

]]

6.1 Reactor Protection System

The Reactor Protection System provides safety related reactor instrumentation to monitor and control critical reactor parameters, such as temperature, vessel level, pressure, and neutron flux.

6.2 Plant Control System

The Plant Control System provides instrumentation system for primary, intermediate and power conversion loop that allows for efficient monitoring and control of heat transfer. The system covers a variety of instrumentation systems that monitor and provide controls for reactor and reactor reactivity, plant temperatures, coolant flow, pressure, etc.

6.3 Plant Health Monitoring System

The Plant Health Monitoring System provides health indication for various plant sensors, actuators and instrumentation systems in Main Control Room such that operator and/or maintenance actions can be performed.

6.4 Main Control Room

The Main Control Room provides indications for plant instrumentation, sensor and actuators with human factors considerations.

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7 PLANT AUXILIARY SYSTEMS

The KP-FHR plant is physically divided into multiple radiological zones based on the potential for radiation and contamination hazards during various operating scenarios. The plant auxiliary systems are located in various radiological zones of the KP-FHR plant. These systems are described below. More auxiliary systems will be identified as the conceptual design of KP-FHR progresses.

7.1 Exhaust Air Monitoring System

The Exhaust Air Monitoring System (EAMS) is connected to the plant ventilation system and other gaseous waste systems to monitor, detect and control the release of gases and radioactivity within the regulatory requirements. KP-FHR is zoned based on potential radiological levels. The plant ventilation system is designed such that airflow does not spread the potential airborne activity from a high to low radioactivity zone.

7.2 Remote Monitoring System

The Remote Monitoring System is designed to facilitate plant health monitoring, in-service inspection and maintenance activities. Remote handling ensures that minimum human intervention and physical presence is needed within the KP-FHR plant. Alarms, physical barriers and engineered systems are used to supplement administrative controls and procedures.

7.3 Fire Protection System

The Fire Protection System has design provisions for detection, prevention and mitigation of potential fire events. The overall objective is to ensure personnel, environmental, and radiation safety.

7.4 Decontamination Systems

KP-FHR is designed to detect and contain radiological contamination within a small area of the plant. The Decontamination System helps monitor, detect and prevent the spread of loose or bound contamination within and outside the operating plant. Dosimeters, contamination detection monitors, de-contamination equipment and shower facilities are provided when transitioning from a high radiological zone to low radiological zone.

7.5 Waste Handling Systems

The Waste Handling System ensures monitoring, segregation and disposal of low to medium level wastes including machines, tools and laundry. The system does not cover high level radioactive waste e.g. used fuel and core components. Solid and liquid wastes based on the contamination and/or radioactivity level are sampled and treated before disposal or storage in accordance with regulatory requirements. Gaseous wastes are monitored through the EAMS.

7.6 Security System

The Physical Security System is designed to detect, delay, and respond to unauthorized intrusion into the plant area. The Security System uses state of the art technologies to optimize the physical security presence at the plant.

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8 ELECTRICAL SYSTEM

The purpose of the Electrical System is to supply power to onsite components through both AC and DC distribution systems, as well as from the PCS to the offsite transmission system.

The Electrical System includes high, medium, and low voltage distribution systems, and the associated step-up and step-down transformers and switchgear. Portable diesel generators, uninterruptible power supply, and battery banks are available as appropriate.

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9 CIVIL STRUCTURES

The KP-FHR is a compact reactor and power plant. The number and size of civil structures is expected to be small. The major civil structures are briefly described below:

9.1 Reactor Building

The reactor building contains the structures, systems and components of the reactor vessel assembly, PHTS, and relevant support systems. Portions of the reactor building are relied on to provide protection of safety systems from design basis natural phenomena events.

9.2 Conventional Island

The conventional island consists of the power conversion structures, systems, and components.

9.3 Auxiliary and Site Buildings and Infrastructure

Facilities related to administration, offices, health and safety, fire protection, waste management, spent fuel and other systems fall under auxiliary, site building and infrastructure.

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10 REFERENCES

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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. Kairos' information contained in Enclosure 1 to this letter contains details of the Kairos Power conceptual design, intended among other things to initiate pre-application engagement with NRC staff and to begin familiarizing the staff with Kairos Power technology. These design details could give a competitor 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: November 30, 2018

Peter Hastings
Vice President, Regulatory Affairs and Quality