Enclosure 1

Changes to the PSAR

(Non-Proprietary)

CHAPTER 4 REACTOR DESCRIPTION

4.1 SUMMARY DESCRIPTION

The reactor is designed with a functional capability to achieve a rated thermal power of up to 35 MWth at a ~~maximum~~ reactor ~~coolant~~ outlet temperature of ~~620~~650°C. The normal reactor inlet temperature is 550°C. The reactor design employs a high-temperature graphite-matrix coated tri-structural isotropic (TRISO) particle fuel and a chemically stable, low-pressure molten fluoride salt coolant (Flibe). TRISO fuel and Flibe constitute the functional containment which is relied on as a means of retaining fission products and preventing radionuclide release to the environment during normal operations and postulated events.

This chapter provides a description of the reactor which includes:

- Reactor Core (Section 4.2)
  - Reactor Fuel (Section 4.2.1)
  - Reactivity Control and Shutdown System (Section 4.2.2)
  - Neutron Startup Source (Section 4.2.3)
- Reactor Vessel and the Reactor Vessel Internals (Section 4.3)
- Biological Shield (Section 4.4)
- Nuclear Design (Section 4.5)
- Thermal Hydraulic Design (Section 4.6)
- Reactor Vessel Support System (Section 4.7)

The reactor generates heat by the controlled fission of material contained within the TRISO fuel. The reactor transfers heat to the reactor coolant and provides for circulation of reactor coolant through the reactor core. Control elements are provided to control the reactivity of the core. A separate and independent set of shutdown elements provides for safe shutdown of the reactor during off-normal conditions. A neutron source is provided during initial pre-critical operations to assist with initial startup of the reactor core. The online refueling capability of the reactor compensates for changes in reactivity due to depletion of fuel and accumulation of fission products. The design of the reactor vessel and internals ensures that a coolable geometry is maintained for the reactor core under all normal operations and postulated events. The reactor design includes provisions for online monitoring to support control and protection functions, as well as the capability for in-service inspection, maintenance, and replacement activities. Shielding is included to limit radiation doses to workers and equipment.

Table 4.1-1 provides a summary of key parameters for the reactor.

Table 4.1-1: Reactor Parameters

Parameter	**Value**
Thermal Power (MWth)	35
Reactor ~~Coolant~~ Outlet Temperature (°C)	650~~20~~
Reactor ~~Coolant~~ Inlet Temperature (°C)	550
Reactor Vessel Operating Pressure (bar)	< 2
Reactor Coolant Type	Flibe
Fuel Type	TRISO particle; UCO kernel
Fuel Matrix	Pebble
Equilibrium Fuel Enrichment (wt%)	$\leq$ 19.75
Reflector Type	ETU-10 Graphite
Control Material	B_4C
Neutron Spectrum	Thermal

The methodology for determining shutdown margin is described in the “KP-FHR Core Design and Analysis Methodology” technical report (Reference 1).

Hot shutdown is defined as the state where reactor is subcritical at a temperature of 550 °C. The shutdown margin is defined for the most limiting core at the reactor coolant freezing temperature. The shutdown margin design criterion is that k-effective must be less than 0.99.

4.5.1.5 Nuclear Transient Parameters

The key kinetic parameters that are used in transient analysis are:

- Prompt neutron lifetime
- Delayed neutron fraction groups and their decay constants

In addition, core power distribution and reactivity coefficients are also provided as initial condition inputs to the transient analysis. The methodology for calculating these coefficients is provided in Reference 1.

4.5.1.6 Analytical Methods

The core design methods are comprised of the Serpent 2, Star-CCM+, KPACS, and KPATH computer codes. The Serpent 2 code is a multi-purpose, three dimensional continuous-energy Monte Carlo particle (neutrons and gammas) transport code. ~~STAR-CCM+ is a discrete element model of pebble flow through the core and is the thermal hydraulic engine with the porous media approximation.~~ STAR-CCM+ is a computational fluid dynamics simulation software that uses discrete element modeling and porous media approximation capabilities for thermal-hydraulic characterization of pebble bed flow and temperature. KPACS is a fuel cycle analysis code. KPATH is used for coupling Serpent 2 and Star-CCM+.

The method for validation and verification of these codes including the method for determining uncertainty factors is described in Reference 1.

4.5.2 Design Bases

The design bases related to nuclear design are as follows:

Consistent with PDC 10, the reactor core has appropriate margin to assure that the specified acceptable system radionuclide release design limits (SARRDLs) are not exceeded. SARRDLs are described in Section 6.2.

Consistent with PDC 11, the reactor core is designed so that in the power operating range the net effect of prompt inherent nuclear feedback tends to compensate for rapid increase in reactivity.

Consistent with PDC 12, the reactor core assures that power oscillations which can result in conditions exceeding SARRDLs are not possible or can be reliably and readily detected and suppressed.

Consistent with PDC 26, the nuclear design analysis is performed to confirm that the reactor control and shutdown system (RCSS) provide a means for (1) inserting negative reactivity such that SARRDLs, are not exceeded and safe shutdown can be achieved during normal operation; (2) reliably controlling reactivity changes during normal operation; (3) inserting negative reactivity of a sufficient amount to cool the core and maintain safe shutdown following an accident; and (4) holding the reactor shutdown during fuel loading, inspection, and repair.

4.5.3 Nuclear Design Evaluation

This section provides an evaluation of the nuclear design and describes how the nuclear design bases in Section 4.5.2 are met. In addition, this section also discusses nuclear design analyses that are provided as input to other parts of the design.

Table 4.5-1: Comparison of KP-FHR Test Reactor with Light Water Reactor

Nuclear Parameter	**KP-FHR Reactor**	**Small Light Water Reactor**
Power Level (MWth)	35	200
Reactor Inlet/Outlet Temperature (°C)	550/650~~20~~	258/310
Power Density (MWth/m^3)	17.5	58.9
Core Volume (m^3)	2	3.4
Number of Reactivity Control Elements	7	16
Shutdown Margin at Equilibrium (pcm)	4997	2696
Discharge Burnup (% FIMA)	6	4.3
Enrichment (% U-235)	< 20	<5

4.6 THERMAL-HYDRAULIC DESIGN

4.6.1 Description

The thermal hydraulic design of the reactor is a combination of design features that enable effective heat transport from the fuel pebble to the reactor coolant and eventually to the heat rejection system of the reactor, considering the effects of bypass flow and flow non-uniformity. The design features that play a key role in the thermal-hydraulic design of the reactor system include the fuel pebble (see Section 4.2.1), reactor coolant (see Section 5.1), reactor vessel and reactor vessel internal structures (see Section 4.3), the primary heat transport system (PHTS) (see Section 5.1), and the primary heat rejection system (PHRS) (see Section 5.2).

4.6.1.1 Core Geometry

The core geometry is maintained in part by the reactor vessel internals including the reflector blocks which keep the pebbles in a general cylindrical core shape. Coolant inlet channels in the graphite reflector blocks are employed to limit the core pressure drop. The use of pebbles in a packed bed configuration also creates local velocity fields that enhance pebble-to-coolant heat transfer. The reactor thermal hydraulic design uses the following heat transfer mechanisms to extract the fission heat.

- Pebble-to-coolant convective heat transfer
- Pebble radiative heat transfer
- Pebble-to-pebble heat transfer by pebble contact conduction
- Pebble-to-pebble heat transfer by conduction through the reactor coolant
- Heat transfer to the graphite reflector by modes of conduction, convection, and radiation.

4.6.1.2 Coolant Flow Path

During normal operation, reactor coolant at approximately 550°C enters the reactor vessel from two PHTS cold leg nozzles and flows through a downcomer formed between the metallic core barrel and the reactor vessel shell as shown in Figure 4.6-1. The coolant is distributed along the vessel bottom head through the reflector support structure, up through coolant inlet channels in the reflector blocks and the fueling chute and into the core with a portion of the coolant bypassing the core via gaps between the reflector blocks. The coolant transfers heat from fuel pebbles which are buoyant in the coolant and provides cooling to the reflector blocks and the control elements via engineered bypass flow. Coolant travels out of the active core through the upper plenum via the coolant outlet channels and exits the reactor vessel via the PHTS outlet. The ~~maximum~~ nominal core ~~vessel exit~~ outlet temperature is ~~620°C and~~ dependent on the amount of corresponding bypass flow ~~through the reflector blocks~~.

During postulated events where the normal heat removal path through the PHTS is no longer available, including when the PHTS is drained, a fluidic diode (see Section 4.3), is used to create an alternate flow path. During such events, forced flow from the primary salt pump (PSP) is also not available. The fluidic diode then directs flow from the hot well to the downcomer as shown in Figure 4.6-1. This opens the path for continuous flow via natural circulation. During normal operation, while the PSP is in operation, the fluidic diode minimizes reverse flow.

4.6.2 Design Basis

Consistent with PDC 10, the thermal-hydraulic design provides adequate transfer of heat from the fuel to the coolant to ensure that the specified acceptable system radionuclide release design limits (SARRDLs) will not be exceeded during normal operation and unplanned transients.

Table 4.6-1: Summary of Thermal Hydraulic Parameters

Parameter	**Nominal Value**
Core Power (MWth)	35
Reactor Inlet Temperature (°C)	550
Maximum Core ~~Exit~~ Outlet Temperature (°C)	~~620~~650[1]
Maximum ~~Core~~ Reactor Mass Flow Rate (kg/s)	210[1]
~~Maximum~~ Core Pressure Drop at Maximum Flow Rate (kPa)	~~2~~12[1]
Core Volume (m^3)	2.0
Core Packing Fraction (%)	60
Total Pebbles (Fuel and Moderator)	36,000
Power Density (MW/m^3)	17.5

Notes:

1. Value does not account for bypass flow

The RCS controls reactivity for normal operations and normal shutdown using reactor control elements and reactor shutdown elements in the reactivity control and shutdown system (RCSS) (see Section 4.2). The RCS is capable of incrementally changing the position of reactor control elements and of releasing the control and shutdown elements. The RCS is only capable of withdrawing elements one at a time and the RCS includes a limit on the rate at which a control element can be withdrawn, as also discussed in Section 4.2.2. In this way the design precludes, with margin, the potential for prompt criticality and rapid reactivity insertions. The RCS inputs include ~~core~~ reactor ~~average coolant~~ outlet temperature~~s~~ and reactor inlet temperature sensors and source and power range neutron detectors. The RCS also provides a reactor monitoring function to monitor plant components that are associated with reactor functions. The RCS uses source and power range sensors that are located outside the reactor vessel for reactor control.

The RCS controls pebble insertion and extraction, in-vessel pebble handling, and ex-vessel pebble handling in the pebble handling and storage system (PHSS) (see Section 9.3). The RCS is capable of counting linearized pebbles external to the vessel, controlling the rate of pebble insertion and removal from the vessel, and controlling pebble distribution within the PHSS.

The RCS controls the reactor thermal management system (RTMS) (see Section 9.1.5) to monitor the temperature of the primary system to maintain it within the normal operating envelope and to implement planned transients. The RCS controls external heating elements in the RTMS to prevent overcooling.

7.2.1.2 Reactor Coolant Auxiliary Control System

The RCACS controls and monitors systems and components that support normal operation in the core. The system supports the following capabilities in the core:

- Chemistry control in the primary system
- Inventory management system control
- Inert gas system control in the primary loops
- Tritium management system monitoring and control

The RCACS controls the chemistry control system (see Section 9.1.1) to monitor reactor coolant chemistry. The monitoring systems provide information to facilitate maintaining coolant purity and circulating activity within specifications for the system.

The RCACS receives input from the inventory management system (see Section 9.1.4) which monitors primary coolant level during normal operations. The system also provides control for changes to primary inventory during planned primary filling and draining operations.

The RCACS also controls the inert gas system (see Section 9.1.2). During normal operation, the system provides control signal to maintain cover gas pressure and flow, monitors venting gas for impurities above specified limits in the gas space of the primary system. During startup, the system monitors and controls inert gas flow and temperature to support initial heating of the primary system.

The RCACS receives input from the tritium management system (see Section 9.1.3) and provides control signal to remove tritium from the cover gas in the primary system.

7.2.1.3 Primary Heat Transport Control System

The PHTCS controls and monitors systems and components that support normal operation of the primary heat transport system (PHTS). The system supports the following capabilities:

- Control of the flow rate through the PHTS

Table 7.2-1: Plant Control Variables

Control Variables (Inputs)	Primary Loop • PSP speed • Control rod drive position ~~• Loop and vessel temperatures~~ • Inert gas pressure
	Intermediate Loop • ISP speed • Valve positions • Loop temperatures
Controlled Variables (Outputs)	Primary Loop • Neutron flux (self-powered neutron detectors and ion cambers) ~~• Core inlet temperature~~ • ~~Core~~ Reactor outlet temperature • Coolant ~~Core~~ mass flow rate
	Intermediate Loop • Intermediate Loop flowrate • IHX inlet/outlet temperature • Heat Rejection Radiator Inlet/outlet temperature
Constrained Variables (Outputs)	Primary Loop • Excess reactivity margin • Reactor i~~I~~nlet temperature

The water tank isolation valves also fail open upon loss of power. The decay heat removal portion of the RPS can receive the actuation signal from either an automatic or manual source.

The decay heat removal portion of the RPS uses core temperature and neutron detectors as inputs through hardwired, analog, safety-related signal wireways that are terminated at local cabinets. Section 7.5 provides additional information about the sensors that provide input to the RPS.

The decay heat removal portion of the RPS also includes a manual actuation capability from the main control room and the remote onsite shutdown panel. Section 7.4 includes a discussion of the human interface with the decay heat removal portion of the RPS.

Table 7.3-2 provides a list of interlocks implemented for RPS systems. Before sufficient fission products and subsequent decay heat is produced in the core, for example during startup, DHRS has no safety function. During this period, the decay heat removal portion of the RPS includes a manual inhibition of the DHRS that is available to plant operators to allow for additional thermal management capabilities. Once decay heat is produced at a sufficient rate in the core, the RPS blocks the manual inhibition capability utilizing safety-related actuations. After shutdown, once fission product decay heat production has dropped to levels not requiring DHRS, the RPS removes the block on the manual inhibition capability. The parameters the RPS uses to determine if the manual inhibition is to be permitted or blocked are neutron detectors (source and power range) and ~~reactor~~ core ~~vessel~~ temperature.

7.3.2 Design Bases

- Consistent with PDC 1, the RPS is designed using relevant industry codes and standards and the Quality Assurance program.
- Consistent with PDC 2, the RPS is designed to withstand and be able to perform during natural phenomena events.
- Consistent with PDC 3, the RPS is designed and located to minimize, consistent with other safety requirements, the probability and effect of fires and explosions.
- Consistent with PDC 4, the RPS is designed for the environmental conditions associated with normal operation, maintenance, testing, and postulated events.
- Consistent with PDC 10 and 20, the RPS provides reactor trip and decay heat removal actuation that ensure radionuclide release design limits are not exceeded during normal operation.
- The RPS implements PDC 13 in that the system includes sensors that monitor core temperature, vessel level, and power level. The sensors monitor variables and systems over their anticipated ranges for normal operation and for postulated event conditions.
- Consistent with PDC 15, the RPS provides reactor trip and decay heat removal actuation to ensure that the design conditions of the reactor coolant boundary are not exceeded during normal operation.
- Consistent with PDC 20, the RPS provides automatic reactor trip and decay heat removal actuation to ensure radionuclide release design limits are not exceeded as a result of postulated events. The RPS is also designed to identify postulated event conditions and initiate passive insertion of reactivity shutdown elements and passive decay heat removal.
- Consistent with PDC 21, the RPS is designed with sufficient redundancy and independence to assure than no single failure results in loss of its protection function. Individual components of the RPS may be removed from service for testing without loss of required minimum redundancy. The RPS is designed to permit periodic testing.
- Consistent with PDC 22, the effects of natural phenomena, and of normal operating, maintenance, testing, and postulated event conditions, do not result in loss of the protection function for the RPS.

The RPS is designed with sufficient functional and component diversity to prevent the loss of function for the RPS.

- Upon loss of electrical power or detection of adverse environmental conditions, the RPS fails to a safe state, consistent with PDC 23.
- The RPS system functionally independent from the control systems, consistent with PDC 24.
- Consistent with PDC 25, the RPS is designed to ensure that radionuclide release design limits are not exceeded upon reactor trip actuation, including in the event of a single failure of the reactivity control system.
- Consistent with PDC 28, the RPS setpoints are designed to limit the potential amount and rate of reactivity to ensure sufficient protection from postulated events involving reactivity transients. The limits are set such that reactivity events cannot result in damage to the reactor coolant boundary greater than limited local yielding, and cannot sufficiently disturb the core, its support structures, or other reactor vessel internals to impair significantly the capability to cool the core.
- The RPS is designed to be redundant and diverse to assure there is a high probability of accomplishing its safety-related functions in postulated events, consistent with PDC 29.
- Consistent with 10 CFR 50.55(i), RPS is designed, fabricated, erected, constructed, tested, and inspected to quality standards commensurate with the safety function to be performed.
- Consistent with 10 CFR 50.55a(h)(3), the RPS is designed in accordance with IEEE Std 603-2018 (Reference 1). The RPS implements the 2018 edition of IEEE Std 603 as an alternative code to IEEE Std 603-1991 (Reference 2) and the correction sheet dated January 30, 1995.

7.3.3 System Evaluation

The RPS provides automatic reactor trip (1) if plant parameters exceed the normal operation envelope (PDC 20), (2) in the event of station blackout, and (3) manually using signal from the main control room or remote onsite shutdown panel. The RPS also ensures that the DHRS is running when the reactor trips. The RPS is consistent with 10 CFR 50.55a(h)(3) and NUREG-1537, “Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors,” by meeting IEEE 603-2018. Table 7.3-1 provides a list of the consensus standards to which the RPS is designed.

Chapter 13 describes the postulated events to which the RPS is designed to respond. The RPS uses the same set of operating parameters in the trip and actuation logic for all modes of reactor operation. The setpoints are established to ensure that the design conditions of the reactor coolant boundary are not exceeded during operation within the design basis. This is consistent with PDC 25 because maintaining the reactor coolant boundary within design basis bounds will ensure that radionuclide release design limits are not exceeded. The setpoints are established and calibrated using the method described in Section 7.1.2.

Consistent with 10 CFR 50.55a(h)(3), reactor trips implemented by the RPS meet IEEE 603-2018, Section 4. The primary plant trip signal is based on ~~average~~ core temperature measurements. In addition, the plant will also have a trip signal for high flux rate based on input from the neutron detector sensors and a trip of the reactor upon detection of a break in the PHSS extraction line. When the temperature or flux rate are outside the normal operating range or when a PHSS extraction line break is detected, the primary plant trip deenergizes the RSS trip device, the DHRS loop trip device, and the PCS inhibitor trip device. Redundant trip devices are provided for each signal pathway. See Figure 7.3-1 for a schematic of the RPS trip logic. Trip setpoints are established and calibrated using the methods described in Section 7.1.2. The PCS inhibitor trip device functionally isolates the RPS from the PCS. This includes tripping the PSP, discussed in Section 7.2.1.3. The RPS also provides alarm signals to the main control room, which will be described in the Operating License application.