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THE KEY DESIGN FEATURES OF THE INDIAN ADVANCED HEAVY WATER REACTOR

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Abstract

The 235 MWe Indian Advanced Heavy Water Reactor (AHWR) is a vertical, pressure tube type, boiling light water cooled reactor. The three key specific features of design of the AHWR, having a large impact on its viability, safety and economics, relate to its reactor physics, coolant channel, and passive safety features. The reactor physics design is tuned for maximising use of thorium based fuel, and achieving a slightly negative void coefficient of reactivity. The fulfilment of these requirements has been possible through use of PuO_2-ThO_2 MOX, and ThO_2-$U^{233}O_2$ MOX in different pins of the same fuel cluster, and use of a heterogeneous moderator consisting of pyrolytic carbon and heavy water in 80%-20% volume ratio. The coolant channels of AHWR are designed for easy replaceability of pressure tubes, during normal maintenance shutdowns. The removal of pressure tube along with bottom end-fitting, using rolled joint detachment technology, can be done in AHWR coolant channels without disturbing the top end-fitting, tail pipe and feeder connections, and all other appendages of the coolant channel. The AHWR incorporates several passive safety features. These include core heat removal through natural circulation, direct injection of Emergency Core Coolant System (ECCS) water in fuel, passive systems for containment cooling and isolation, and availability of a large inventory of borated water in overhead Gravity Driven Water Pool (GDWP) to facilitate sustenance of core decay heat removal, ECCS injection, and containment cooling for three days without invoking any active systems or operator action. Incorporation of these features has been done together with considerable design simplifications, and elimination of several reactor grade equipment. A rigorous evaluation of feasibility of AHWR design concept has been completed.. The economy enhancing aspects of its key design features are expected to compensate for relative complexity of the thorium fuel cycle activities required to support the operation of this reactor.

1. INTRODUCTION

The Indian Advanced Heavy Water Reactor (AHWR) is being designed as a vertical, pressure tube type, boiling light water cooled and heavy water moderated reactor. The reactor is designed to produce most of its power from thorium, aided by a small input of plutonium based fuel. The reactor will have a large number of advanced safety features, such as passive safety systems not requiring either external power or operator action for activation.

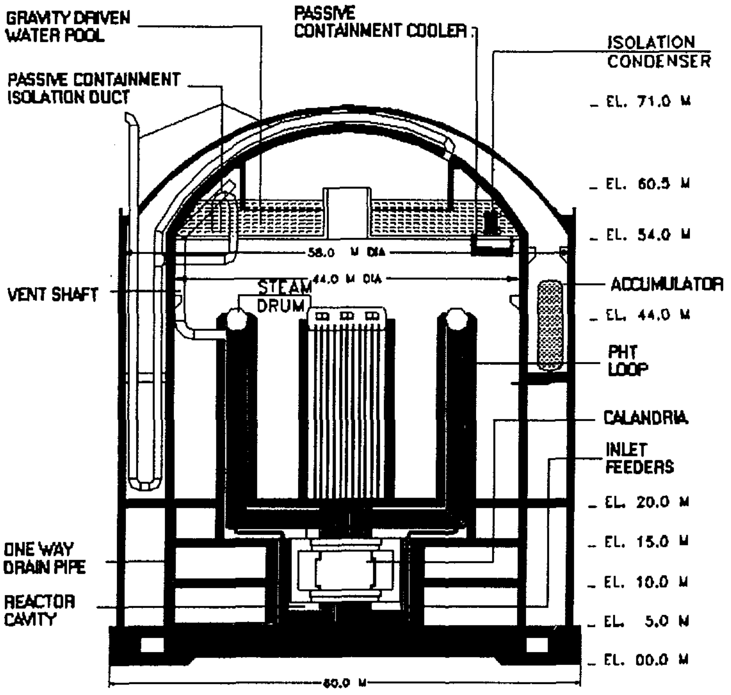
The basic design features of this reactor are indicated in Figure 1. At the current stage of development, the feasibility study for the reactor has been completed. Detailed design of the systems and components is in progress. It is envisaged that the first unit of AHWR will be commissioned in the early part of the second decade of the next century.

The three key features of design of the AHWR, having a large impact on its viability, safety and economics are:

a) Reactor physics design tuned for using thorium based fuel, with negative void coefficient of reactivity

b) Advanced coolant channel design features, with easily replaceable pressure tubes

c) Passive systems for core heat removal, containment cooling and containment isolation



- FUEL :U-233/THORIUM MOX + Pu-239/U-238 MOX
- COOLANT: BOILING LIGHT WATER
- MODERATOR: HEAVY WATER
- POWER: 235 MW(e)
- NEGATIVE VOID COEFFICIENT OF REACTIVITY
- PUMPLESS PRIMARY CIRCULATION
- PASSIVE DECAY HEAT REMOVAL
- ADVANCED EMERGENCY CORE COOLING
- HEAT SINK ALLOWING 3 DAYS GRACE PERIOD
- PASSIVE CONTAINMENT COOLING
- PASSIVE CONTAINMENT ISOLATION

FIG. 1. Advanced Heavy Water Reactor

2. REACTOR PHYSICS DESIGN

2.1 Main Features

The reactor physics design of AHWR has been based on the following main criteria:

a) Reactor power: 750 MWt

b) Fraction of power to be generated in thorium: 75 percent

c) Plutonium inventory in the core: 300 kg, maximum.

d) Slightly negative void coefficient of reactivity:

e) Boiling light water cooled vertical pressure tube type design

f) Burn up of fuel: 20,000 MWD/Te, minimum goal for prototype.

The fulfilment of these requirements has been possible through the use of PuO_2-ThO_2 (MOX), and ThO_2-$^{233}UO_2$ MOX in different pins of the same fuel cluster, and use of a heterogeneous moderator consisting of amorphous carbon and heavy water in 80%-20% volume ratio. As compared to a Pressurised Heavy Water Reactor (PHWR) the total heavy water inventory in AHWR is considerably reduced, and since the moderator heavy water operates under low pressure and temperature, loss of heavy water through leaks is practically zero, reducing spread of tritium based radioactivity. No special systems are needed for the minimisation of heavy water losses and the recovery of such losses. The negative void coefficient of reactivity considerably simplifies the burden on the reactor regulating system. Use of boiling light water coolant enables doing away with steam generator, and its substitution with steam drums of simple construction.

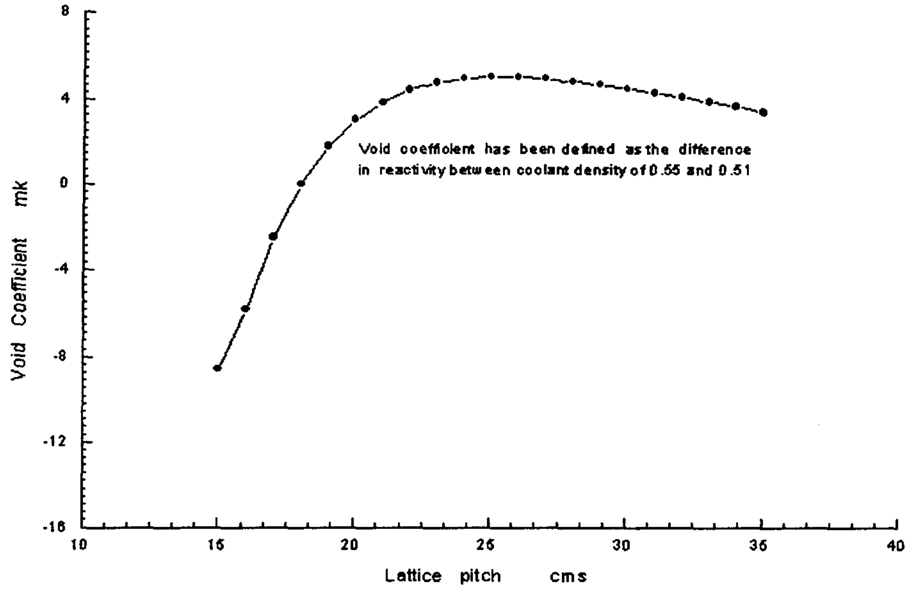


FIG. 2. Void Coefficient in the AHWR as a function of lattice pitch with heavy water moderator alone

2.2 Negative Void Coefficient of Reactivity

The ^{233}U enriched ThO_2 based fuel has a positive void coefficient, and is sub-critical, whereas the MOX fuel has a negative void coefficient of reactivity. With proper combination of MOX and ^{233}U-ThO_2 pins in a cluster it is possible to achieve overall negative void coefficient of reactivity under all operating conditions. With this inherent feature, the reactor will be shut down automatically if there is any increase in void due to any transient or accident condition. Achieving a slightly negative void coefficient for the AHWR core configuration requires a tighter lattice pitch than that required for a PHWR. This is illustrated in Figure 2.

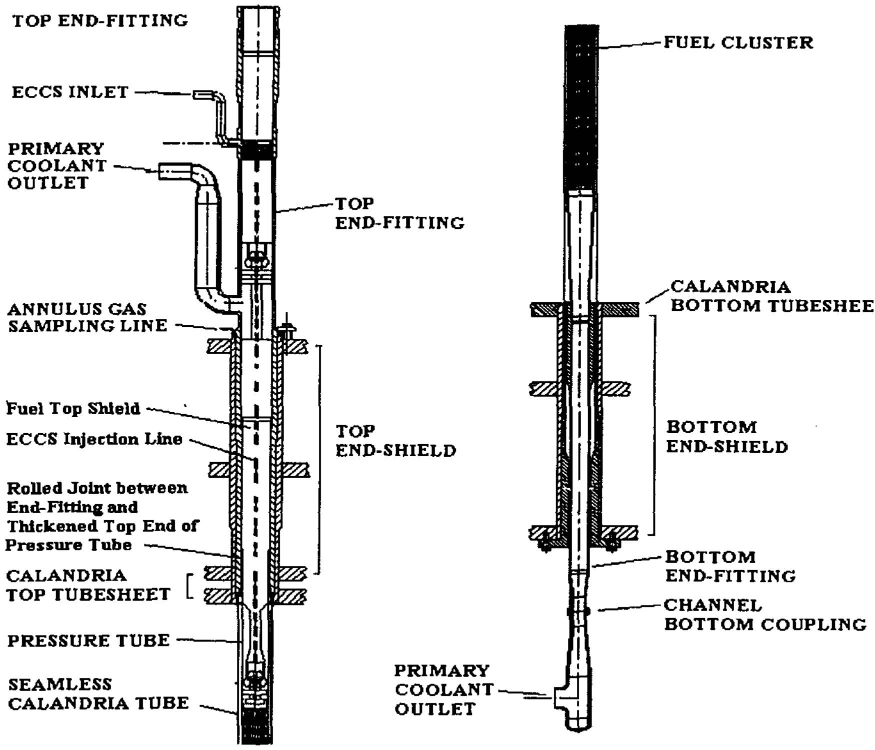
3. COOLANT CHANNEL

3.1 Main Features

Coolant channels of AHWR serve to accommodate the fuel, maintain thermal insulation between the coolant and the cold moderator, provide interfaces for coupling to the heat transport system at the two ends of the coolant channels and provide suitable interface to facilitate fuelling. The coolant channel has suitable features to facilitate its orientation within the given lattice position, to accommodate thermal expansion and creep/growth related dimensional changes of coolant channel, to facilitate easy replacement of coolant channel, and to inject water from Emergency Core Cooling System (ECCS) in the event of a Loss Of Coolant Accident (LOCA) directly into coolant channel

A general arrangement of the coolant channel assembly, along with fuel, and some portions of end-shields, is shown in Figure 3.

The coolant channel consists of a Zirconium alloy pressure tube, a stainless steel top end fitting and a stainless steel bottom end fitting. The pressure tube is located in the core portion. The core portion is extended in both directions with the help of top and bottom end fittings. Top end fitting has suitable feature for engaging fuelling machine to the channel, and for connecting it to a tail pipe and an ECCS injection pipe. Outlet tail pipe is directly welded to top end-fitting. The feeder pipe is connected to bottom end fitting using a special flanged connection with metal C-ring as sealing element. This facilitates disconnection of bottom end fitting from the feeder pipe whenever required. The coolant channel assembly is supported on the top end shield.



Upper Portion *Lower Portion*

FIG. 3. Coolant channel assembly of AHWR, also showing fuel, and portions of end-shields

The fuel assembly consists of a fuel cluster and a top shield connected to each other with a collet type of joint. The coolant enters the coolant channel at 270 °C through bottom end fitting and flows through pressure tube past the fuel assembly. Coolant at 285 °C flows out through the outlet tail pipe connected to top end fitting. Typically, at the outlet from the channel the coolant has a steam quality of 15 percent. The flow of primary coolant has to occur by natural convection, hence special attention has been paid to minimise the pressure drop in the channel

3.2 Annulus Gas Monitoring

The pressure tube carrying hot coolant is insulated from cold moderator (55 - 70 °C) with an annular space formed between pressure tube and a Zircaloy calandria tube. The two ends of the calandria tube are rolled into lattice tubes of top and bottom end shields respectively. The annulus around a pressure tube and its end fittings is open at the bottom and is sealed at the top. An annulus gas monitoring system is provided to monitor for any possible leakage of heavy water either from pressure tube or calandria tube due to any failure of these tubes and their rolled joints. The air sample from annulus is sucked through a tube communicating with the annulus by using a vacuum suction device and the sample is analysed for early detection of any through crack of pressure tube or calandria tube

3.3 Easy Replaceability

On account of lower values of neutron flux and maximum operating temperature in AHWR, as compared to those in PHWRs, the rate of in-service degradation of the pressure tubes in the former will be lower than that in the latter. Even then, most of the pressure tubes of the reactor may need to be replaced at least once during the ninety year design life of the reactor. The coolant channels are designed to facilitate quick replacement of pressure tubes, during normal maintenance shutdowns.

The removal of pressure tube along with bottom end-fitting, using rolled joint detachment technology, can be done in AHWR coolant channels without disturbing the top end-fitting, tail pipe and feeder connections, and all other appendages of the coolant channel. This considerably simplifies the task of pressure tube replacement and enables a substantial saving in the cost of tooling, replacement components and downtime.

3.4 Design simplification

The channel design has been simplified by eliminating channel annulus bellows, and by having tail pipes welded to the top end-fitting. Liner tubes, existing in the end-fittings of PHWRs to guide fuel bundles, have been eliminated. The closed annulus gas monitoring system of PHWRs has been substituted by a system connected to a sniffer tube joining the top of each channel annulus, with the bottom of the annulus open to reactor cavity environment.

4. PASSIVE SAFETY FEATURES

4.1 General Description of Passive Features in AHWR

Apart from establishing a slightly negative void coefficient of reactivity, the AHWR incorporates several other passive features. These include the following:

a) Heat removal through thermo-syphon driven natural circulation under both normal operation and hot shutdown conditions.

b) Direct injection of ECCS water in fuel.

c) Passive systems for containment cooling and isolation

d) Availability of a large inventory of borated water in overhead Gravity Driven Water Pool (GDWP) to facilitate sustenance of core decay heat removal, ECCS injection, and containment cooling for three days without invoking any active systems or operator action.

4.2 Natural Circulation of Primary Coolant

During normal reactor operation, full reactor power is removed by natural circulation. The necessary flow rate is achieved by locating the steam drums at a suitable height above the centre of the core, taking the advantage of reactor building height. Figure 4 shows variation in primary flow rate with power for the design configuration of the reactor.

By eliminating nuclear grade primary circulating pumps, their prime movers, associated valves, instrumentation, power supply and control system, the plant is made simpler, less expensive, and easier to maintain as compared to options involving forced circulation in the primary coolant circuit. The above factors also lead to considerable enhancement of system safety and reliability since pump related transients have been removed. A major experimental programme has been launched to confirm

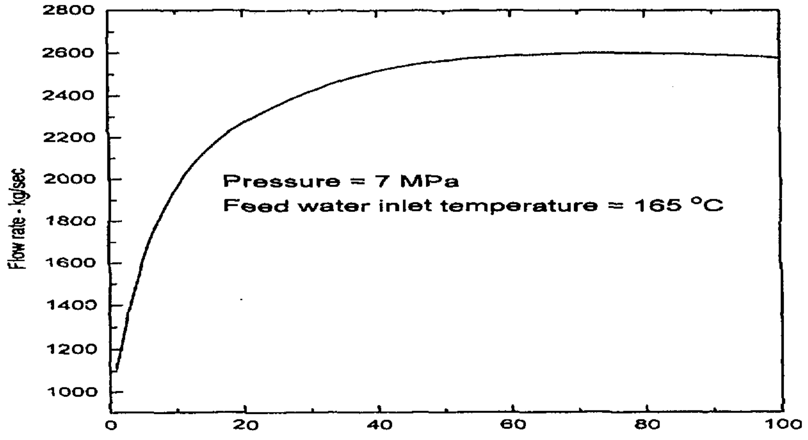


FIG. 4. Effect of power on primary flow rate

the analysis leading to the determination of loop height, and to study the thermal hydraulic stability of the Primary Heat Transport (PHT) loop.

4.3 Core Decay Heat Removal System

During normal reactor shut down condition core decay heat is removed by passive means by utilising Isolation Condensers (ICs) submerged in Gravity Driven Water Pool (GDWP) located above the steam drum. Core decay heat, in the form of enthalpy of steam, enters the IC pipe bundles through natural circulation. The steam condenses inside the pipes and heats up the surrounding pool water. The condensate returns by gravity to the core. The water inventory in the GDWP is adequate to cool the core for more than 3 days without any operator intervention and without boiling of GDWP water. A separate GDWP cooling system is provided to cool the GDWP inventory in case the temperature of GDWP inventory rises above a set value. An Active Shut Down Cooling System (ASDCS) is also provided to remove the core decay heat in case the ICs are not available.

4.4 Emergency Core Cooling System

During Loss Of Coolant Accident (LOCA) emergency coolant injection is provided by passive means to keep the core flooded so as to prevent overheating of the fuel. The emergency Core Cooling System (ECCS) is designed to fulfil the following two objectives.

a) To provide large amount of cold borated water directly into the core in the early stage of Loss of Coolant Accident (LOCA) and then a relatively small amount of cold borated water for a longer time to quench the core. This objective is achieved through use of a passive fluidic flow control device.

b) To provide water through Gravity Driven Water Pool (GDWP) to cool the core for more than 3 days.

Long term core cooling is achieved by active means by pumping water from reactor cavity to the core through heat exchangers.

The ECCS accumulators and GDWP are connected to the PHT system by rupture discs, check valves and the isolation valves kept in series. During reactor start-up, accumulators and GDWP are isolated by closing the isolation valves. When the PHT system pressure reaches the operating pressure level, these isolation valves are opened. The nitrogen pressure in accumulators is always maintained at 5 MPa to keep the system in a state of readiness. Following a postulated LOCA, when the PHT system pressure falls below 5 MPa, the rupture discs open out allowing cold borated water from accumulators to flow into the core. When accumulators get exhausted, low water level signal from accumulators results in closure of isolation valves and water from accumulator stops flowing into the core. At this stage, water from GDWP starts flowing into the core by gravity. Through an optimum

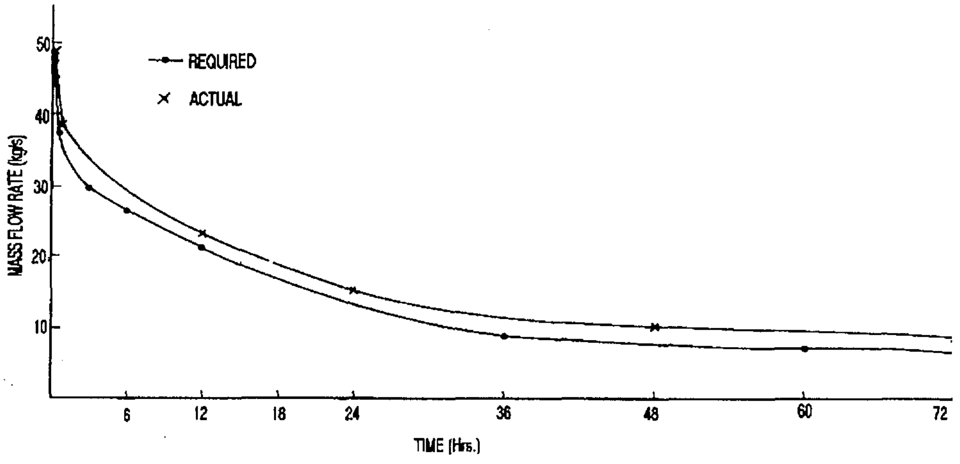


FIG. 5. GDWP flow rate for emergency core cooling

positioning of the discharge nozzles, the GDWP based ECCS flow rate is closely matched to the requirement for core decay heat removal, enabling an extended duration of availability of ECCS flow, for more than three days, as shown by the results provided in Figure 5.

After three days, water from the reactor cavity (which is filled up with hot water after spillage from ruptured pipe and water from accumulators and GDWP after cooling the core) is pumped back into the core through heat exchangers for long term recirculation mode. This heat is transferred, in the heat exchangers, to the process water which in turn dissipates its heat to the ultimate heat sink, i.e., to either sea water or to cooling tower.

4.5 Core Submergence

Following a postulated LOCA, water from the PHT system, ECCS accumulators and the GDWP, after cooling the core, will be guided and get collected in the space around the core called reactor cavity. Thus the core will be submerged under water. In the unlikely event of failure of GDWP to hold the water inventory, under any postulated scenario, the whole GDWP inventory will get collected in the reactor cavity and provide a heat sink for heat removal from the core.

4.6 Failure of ECCS during LOCA

AHWR contains, in and around its core, a large inventory of heavy water moderator and surrounding vault water. Although the possibility of failure of ECCS is very rare but if ECCS is not available during LOCA, under any postulated scenario, the fuel temperature will start rising and ballooning of pressure tubes will occur. Due to ballooning the pressure tubes will come in contact with calandria tubes and heat will be transferred to the moderator and then from moderator to vault water, thereby providing a large heat sink for the removal of core heat.

4.7 Passive Containment Isolation

For containment isolation, in addition to the normal inlet and outlet ventilation dampers, a passive system has been provided in the AHWR. The reactor building air supply and exhaust ducts are shaped in the form of U bends of sufficient height. In the event of LOCA, the containment gets

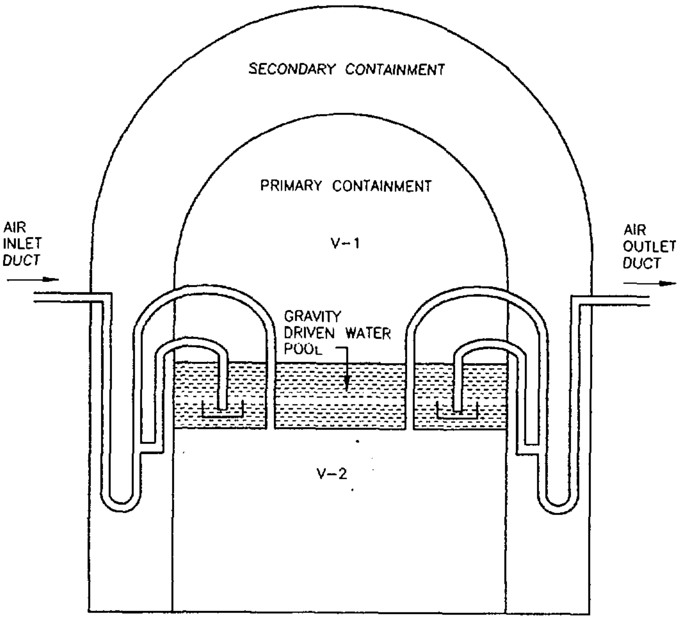


FIG. 6. Schematic of Passive Containment Isolation System

pressurised. This pressure acts on GDWP inventory and pours water by swift establishment of a siphon, into the ventilation duct U bends. Water in the U bends acts as seal between the containment and the external environment, providing the necessary isolation between the two. Drain connections provided to the U bends permit the re-establishment of containment ventilation manually when desired. A schematic of this system is shown in Figure 6.

4.8 Passive Containment Cooling

Passive Containment Coolers (PCCs) are utilised to achieve post-accident primary containment cooling by passive means and to limit the post-accident primary containment pressure. A set of PCCs are located below the GDWP and are connected to the GDWP inventory. During LOCA, the mixture of hot air and steam is directed to flow over the PCCs. Steam condenses and hot air cools down at the PCC tube surface and hence provides long term containment cooling after the accident.

5. CONCLUSION

A rigorous evaluation of the feasibility of the AHWR design concept has been concluded, and its detailed design, along with a programme for conducting supporting experimental and analytical studies is underway. A detailed quantification of the economics of AHWR operation will be done when some of this work is completed. However, the economy enhancing aspects of its key design features relating to reactor physics, coolant channels and passive safety are expected to compensate for relative complexity of the thorium fuel cycle activities required to support the operation of this reactor.