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# Thorium Based Nuclear Power Plant

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***Abstract***
India’s three-stage nuclear power programme is chalked out based on the domestic resource position of uranium and thorium. The first stage started with setting up of the Pressurised Heavy Water Reactors (PHWR) based on natural uranium and pressure tube technology. In the second phase the fissile material base will be multiplied in Fast Breeder Reactors using the plutonium obtained from the PHWRs. The third stage is focused on reactors designed to utilise the large thorium reserves based on thorium-233U fuel cycle. The Advanced Heavy Water Reactor (AHWR) has been designed to fulfil the need for the timely development of thorium-based technologies for the entire thorium fuel cycle. This paper highlights the recent activities carried out in the design and development of the AHWR, such as the core & process system design, nuclear data, fuel design and handling systems, safety analyses, analytical studies and experimental validation.

Nuclear power employing a closed fuel cycle is the only long term, sustainable option for meeting a major part of the Indian energy demand. Indian resources of thorium are larger than those of uranium. Thorium, therefore, is widely viewed as the ‘fuel of the future’.

***Keywords***- AHWR, PHWR, MHT, Calandria, GDWP.

## I. INTRODUCTION

Thorium is 3 to 4 times more abundant than uranium and is widely distributed in nature as an easily exploitable resource in many countries. Unlike natural uranium, which contains ~0.7% _fissile‘235U isotope, natural thorium does not contain any _fissile‘material and is made up of the _fertile‘232Th isotope only. Hence, thorium and thorium-based fuel as metal, oxide or carbide, has been utilized in combination with _fissile‘235U or 239Pu in nuclear research and power reactors for conversion to _fissile‘233U, thereby enlarging the _fissile‘material resources.

The first phase of the Indian nuclear power programme is based on natural uranium fuelled, heavy water moderated pressure tube type reactors commonly designated as Pressurized Heavy Water Reactors (PHWRs), also known as CANDUs for such reactors of Canadian origin. Fifteen out of seventeen Indian nuclear power reactors under operation, and three out of five Indian nuclear power reactors under construction, at the beginning of October 2009, are PHWRs. The first two of these reactors, Rajasthan units –1 and –2 are similar in design to the Canadian Douglas Point reactor. Rajasthan–1 was built at Rawatbhata in India with Canadian collaboration. This reactor started commercial operation in November 1972. Subsequently, the construction of Rajasthan– 2 and design and construction of all subsequent Indian PHWRs was done indigenously in India.

A large infrastructure was set up at Bhabha Atomic Research Centre (BARC), Mumbai to facilitate research, design, and development in several areas relevant to PHWRs. These areas include: materials technologies, critical components and new systems, reactor physics, thermal hydraulic and safety analysis codes, testing and qualification of reactor systems and equipment, and design and development of systems for in-service inspection and ageing management. The AHWR, being a pressure tube type heavy water moderated reactor, makes use of the PHWR specific technologies pertaining to pressure tube and low pressure moderator based design. These technologies are already developed and successfully demonstrated internationally. There are, however, several significant differences, between the PHWR and the AHWR. These differences are mainly related to the use of thorium based fuel with negative void coefficient of reactivity, the use of boiling light water in natural circulation mode as coolant.

This technology also include a critical facility, with a capability to simulate the AHWR core lattice and fuel configurations, and a full height integral test loop to simulate the Main Heat Transport (MHT) system of the AHWR

## II. IMPORTANT FEATURES OF THE AHWR

An easy way to comply with the conference paper formatting requirements is to use this document as a template and simply type your text into it.

i. Slightly negative void coefficient of reactivity.
ii. Passive safety systems working on natural laws.

iii. Large heat sink in the form of a Gravity Driven Water Pool with an inventory of 8000 m3 of water, located near the top of the Reactor Building.
iv. Removal of heat from core by natural circulation.
v. Emergency Core Cooling System injection directly inside the fuel.
vi. Two independent shutdown systems.
vii. Passive poison Injection in moderator in the event of non-availability of both the shutdown systems due to malevolent action.

Some Distinctive Features of the AHWR

i. Elimination of high-pressure heavy water coolant resulting in reduction of heavy water leakage losses, and eliminating heavy water recovery system
ii. Recovery of heat generated in the moderator for feed water heating.
iii. Elimination of major components and equipment such as primary coolant pumps and drive motors, associated control and power supply equipment and corresponding saving of electrical power required to run these pumps.
iv. Shop assembled coolant channels, with features to enable quick replacement of pressure tube alone, without affecting other installed channel components.
v. Replacement of steam generators by simpler steam drums.
vi. Higher steam pressure than in PHWRs.
vii. Production of 500 m3/day of demineralised water in Desalination Plant by using steam from LP Turbine.
viii. Hundred year design life of the reactor

## III. DESCRIPTION OF THE NUCLEAR SYSTEMS.

### a) *General*

AHWR is a land-based nuclear power station. The reactor is designed to produce 920 MW of thermal power, generating 300 MW(e) (gross), and 500 m3/day of desalinated water. The plant can be configured to deliver higher desalination capacities with some reduction in electricity generation. AHWR based plant can be operated in base load, as well as in load following mode. The target lifetime load factor and availability factors for AHWR are 80% and 90% respectively.

### *1) Main Characteristics Of The Primary Circuit*

A vertical cross-sectional view of the AHWR reactor block is shown in Fig.1, and a simplified schematic diagram of the AHWR based nuclear power plant is given in Fig.2. The reactor core is housed in calandria, a cylindrical stainless steel vessel containing heavy water, which acts as moderator and reflector. The calandria, located below ground level, contains vertical coolant channels in which the boiling light water coolant picks up heat from fuel assemblies suspended inside the pressure tubes. The coolant circulation is driven by natural convection through tail pipes to steam drums, where steam is separated for running the turbine cycle. The four steam drums (only one shown for clarity), receive feed water at stipulated temperature to provide optimum sub-cooling at reactor inlet.

Inside the calandria, a zircaloy–4 calandria tube surrounds each of the pressure tubes, to provide an annulus, open to air at the bottom, which separates the cold moderator from the hot pressure tube. An annulus leak monitoring system to detect any leakage from either pressure tube or calandria tube uses the gap between the pressure tube and the calandria tube Down-comers, four from each steam drum, bring the flow to a circular inlet header, which distributes the flow to each of the 452 coolant channels through individual feeders. During shutdown, passive valves establish communication of steam drums with the isolation condensers submerged inside a 8000 m3 capacity gravity driven water pool (GDWP) for decay heat removal, under hot shut-down condition.

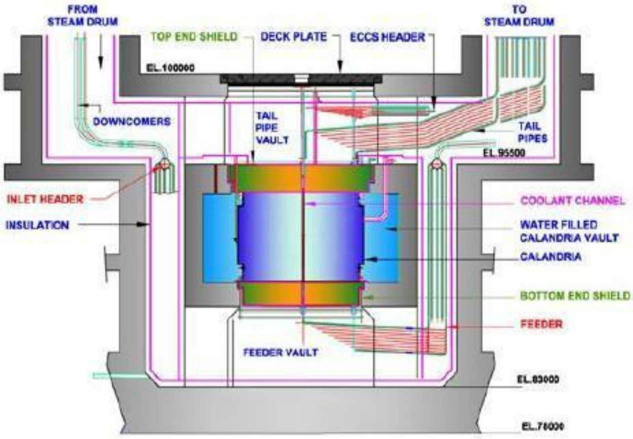


Fig 1: vertical cross-sectional view of AHWR reactor block

The pool acts as a heat sink for passive decay heat removal system. In the event of a loss of coolant accident (LOCA), four independent emergency core cooling system (ECCS) circuits (only one is shown for clarity) provide cooling of the core for at least 72 hours. A high pressure injection system using accumulators and a low pressure injection system using GDWP as source of water are passively brought into action, in a sequential manner, as the depressurisation of the MHT system progresses, following a LOCA.

The Reactor Protection System comprises two independent fast acting shutdown systems.

Shutdown System–1 (SDS–1) is based on mechanical shut-off rods with boron carbide based absorbers in forty lattice positions, providing a total negative reactivity worth of 74 mk with all rods inserted, and a worth of 51 mk with two maximum worth rods not available. Shutdown System–2 (SDS–2) is based on a liquid poison injection into the moderator. In addition, a pressurized addition of poison, passively driven by steam pressure, takes place in the event of over pressure in the MHT system. In addition, for long-term sub-criticality control, there is a provision to add boron to the moderator.

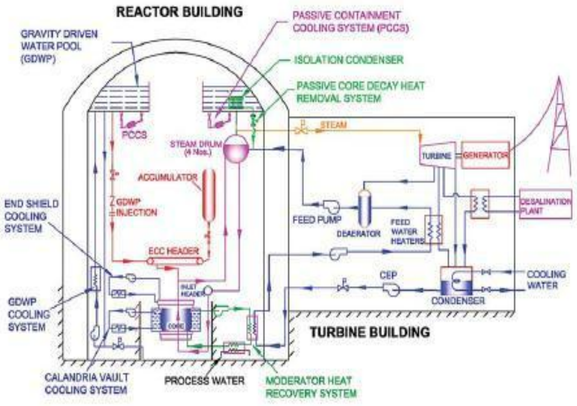


Fig 2: View of Reactor building

*2) Reactor core and fuel design*

The circular fuel cluster of AHWR (Figure 3) contains thirty (Th,233U) MOX pins and twenty-four (Th, Pu) MOX pins, along with a displacer rod at the centre. A ferrule type spacer design, while giving minimum resistance to coolant flow, offers an option to reconstitute the plutonium pins, thus enhancing fuel burn-up and power from thorium. The central structural tube along with holes in it, allows direct injection of ECCS water into the fuel cluster.

The composite cluster consists of a circular array of 54 fuel pins. The fuel assembly has a central structural tube made of Zircaloy-2. The fuel assembly also houses a central solid displacer rod. The inner and middle ring of 12 and 18 pins contain (Th,233U) MOX and the outer ring of 24 pins contain (Th,Pu)MOX. The inner ring of 12 pins has a 233U content of 3.0% by weight and the middle ring of 18 pins has 3.75% 233U. The outer ring of (Th,Pu)MOX pins have average of 3.25% by weight of total plutonium. The lower half of the active fuel will have 4.0 % Pu and the upper part will have 2.5 % Pu. The core consists of total 513 lattice locations arranged in square pitch of 225 mm. There are 452 coolant channel assemblies, 8 absorber rods, 8 regulating rods, 8 shim rods and 37 shut off rods in the core.

*3) Fuel handling systems*

Provision is made for on-line refuelling by the fuelling machine which is located on top of the reactor block. The Fuel Storage and Handling System is required to replace spent fuel cluster with new fuel cluster in the reactor core to maintain the requisite reactivity for reactor operation. New and spent fuel clusters are stored in Fuel Storage Bay, which is located in the Fuel Building. Each new fuel cluster is brought from fuel building located outside reactor building to Temporary Fuel Storage Bay located inside reactor building using an Inclined Fuel Transfer Machine (IFTM). The fuel cluster is then picked up from transfer pot of IFTM.

The shielded fuelling machine picks the fuel cluster from fuel port and loads into the pre-selected coolant channel. Each spent fuel cluster is removed from the channel by the fuelling machine and is transferred to the temporary fuel storage bay from where it is taken to the fuel building using inclined fuel transfer machine. To get optimum burn up from the fuel, reshuffling of the fuel clusters within the reactor core is carried out using the fuelling machine. Refuelling and transfer operation is carried out remotely from the main control room of the reactor.

*4) Primary circuit component description*

Following are the main components of primary circuit.

*i) Coolant Channel Assembly*: Channel Assembly consists of Zr 2.5% Nb pressure tube in the core region extended above the top end shield and below the bottom reflector region by top and bottom stainless steel end fittings respectively. The end fittings are attached to pressure tube by rolled joint.
Pressure tubes in the core region house the fuel assemblies and the hot coolant flows past it removing the heat from the fuel.

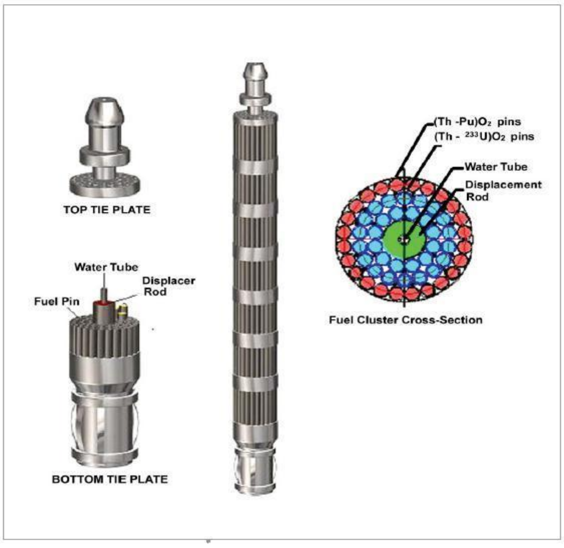


Fig 3: Fuel cluster of AHWR

Fig 4: Scaled Model (1:50) of AHWR Acrylic Material

It is located inside a Zircalloy-4 Calandria tube, which is rolled to the tube sheets of top and bottom end shields. The annular gap between pressure tube and calandria tube with air serves as thermal insulation between hot coolant and cold moderator. Coolant enters the channel through the feeder coupling of bottom end fitting, flows past the fuel assembly, and goes out through the tail pipe welded to top end fitting to the steam drum.

*ii) Steam Drum:* Steam drum is a, horizontally mounted, cylindrical vessel closed at both ends by the tori spherical heads. The two-phase steam-water mixture produced in the reactor core enters each of the four identical steam drums through tail pipes connected to the coolant channels. The feed water enters the steam drum through a sparger, which runs along the length of the steam drum and located in the space
between the partition plates. Steam is taken out from each steam drum through an outlet nozzle located on the top of the steam drum.

*iii) Downcomer***:** MHT water flows from each steam drum to the inlet header through downcomers. Four downcomers are connected to the bottom of the steam drum shell in between the partition plates

*iv) Inlet Header:* The header is the largest pipe in the MHT system. To facilitate core submergence even in case of a postulated rupture of the header, the header is installed 2.0 m above the active core. The header is connected to the 16 downcomers through forged nozzles. Water from the downcomer enters the header from the top through the 16 nozzles. Water leaves from the header through 452 nozzles to the feeders.

*v) Feeder Pipes:* The austenitic stainless steel feeders from the Inlet header are connected to the lower end of the martensitic stainless steel bottom end fittings by feeder couplings with self energising metal C-rings as sealing element. Feeder pipes supply cooling water to the coolant channel from the Inlet header

## IV. AUXILIARY SYSTEM

### *Shut Down Cooling System*

The Shutdown Cooling System (SDCS) is capable to remove the decay heat and cool down the Main Heat Transport System (MHTS) of AHWR. The primary mode of decay heat removal and cool down of MHTS is Main Steam Condenser. Normal cool down from 558 K to 423 K is achieved by Main Steam Condenser or passively by Isolation Condensers (if the main steam condenser is not available). During hot shut down condition, steam generated due to decay heat is fed to Main Steam Condenser. This steam, after condensation, will be pumped back to the steam drum by feed water pumps. In case of non-availability of Main Steam Condenser, a passive system is available to perform this function by diverting the steam flow to Isolation Condensers (ICs) by operation of passive valves. The ICs, submerged in GDWP, will dissipate the heat to the GDWP. Cooling of the MHTS from 423 K to 328 K and maintaining it at 328 K during prolonged shutdown is achieved by MHTS Purification Coolers.

### b) *The Gravity Driven Water Pool (Gdwp) Recirculation And Cooling System*

The Gravity Driven Water Pool (GDWP) is a large pool of water containing 8000 m3 of water inventory, located in the dome region of the reactor building, to cater to the cooling requirements of different systems during various reactor conditions. The GDWP consists of eight interconnected compartments. The GDWP is provided for

1. Heat dissipation from Passive Concrete Cooling System (PConCS)
2. Removal of core decay heat during shutdown (Hot & cold shutdown) by condensation of steam flowing through Isolation Condensers (ICs) (submerged in GDWP)
3. Low pressure coolant injection directly into the core (after the Loss of Coolant Accident (LOCA) for 3 days
4 Vapour suppression during LOCA.

The GDWP recirculation and cooling system, provided for cooling the GDWP inventory catering to above requirements as well as recirculating, filling and draining the water in each compartment of the GDWP. It consists of four heat exchangers, four pumps, filters, ion exchangers and a chemical addition tank to maintain the water chemistry.

## V. OPERATING MODES

### **a)** ***Start Up***

A separate cold start up procedure for the reactor is required to avoid low power flow oscillations. As per this start up scheme, boiling in the MHTS is permitted only at 7.0 MPa. To keep the system in single phase during cold start up, pressure in the steam drum is maintained at a value higher than the saturation pressure corresponding to core exit temperature. The desired pressure in the steam drum is maintained by supplying steam from the start-up boiler.

### b) *Full Power Operation*

In this operational state, all MHT auxiliary systems like pressure control, over pressure protection, feed and steam system; MHT purification system shall be in normal operating mode. While IC system, ECCS, GDWP and all safety systems shall be in readiness to operate.

Under normal operating conditions, the pressure in the steam drum is maintained at 7.0 MPa and the water level in the steam drum is maintained at 2.2m. The steam flow rate is about 408 kg/s. The feed water with the same mass flow rate enters the steam drum at 403 K. The primary circulation flow rate will be of the order of 2145 kg/s maintaining the average steam exit quality at about 19%.

### c) *Operation At Different Power Levels*

The natural circulation flow rate depends on the operating conditions such as the operating pressure, power and feed water flow rate and its temperature. The natural circulation flow rate has also been predicted at partial power conditions considering the feed water temperature variation and its effect. The flow rate increases with power, the increase being steep at low powers compared to that at higher powers. The required feed water temperature above 50% full power is 403 K considering the sub-cooling requirement to maintain adequate stability margin. However, at the reactor power levels less than 50% full power, the feed water temperatures need to be reset to different values

## *D. Description Of Safety Concept*

### 1. *Defence-In-Depth Description*

Elimination of The Hazard of Loss of Coolant Flow: Heat removal from the core under both normal full power operating condition as well as shutdown condition is by natural circulation of coolant. This eliminates the hazard of a loss of coolant flow. (B) Reduction of The Extent of Overpower Transient: The characteristics of AHWR design, which help to achieve this target, are as follows:

a. Slightly negative void co-efficient of reactivity.
b. Low core power density.
c. Negative fuel temperature coefficient of reactivity.
d. **Low excess reactivity.**

(C) Continuous Monitoring Of Plant State: The condition of all important equipment items and components will be continuously monitored on line. For example, the annulus leak monitoring system is incorporated to monitor any postulated leakage from either the pressure tube or the calandria tube.

### *LEVEL 1: CONTROL OF ABNORMAL OPERATION AND DETECTION OF FAILURE*

The characteristics of AHWR design, which help achieve this objective, are as follows:

a) An increased reliability of the control system achieved with the use of high reliability digital control using advanced information technology.

*ii)* Increased operator reliability achieved with the use of advanced displays and diagnostics using artificial

b) b)intelligence and expert systems. Large coolant inventory in the main coolant system.

### *LEVEL 2: CONTROL OF ACCIDENTS WITHIN THE DESIGN BASIS*

The following features contribute to the achievement of this objective:

a. Increased reliability of the ECC system, achieved through passive injection of cooling water (initially from an accumulator and later from the overhead GDWP) directly into a fuel cluster through four independent parallel trains.
b. Increased reliability of a shutdown, achieved by providing two independent shutdown systems, one comprising the mechanical shut off rods and the other employing injection of a liquid poison into the low pressure moderator. Each of the systems is capable of shutting down the reactor independently.
c. Further enhanced reliability of the shutdown, achieved by providing a passive shutdown device operated by steam pressure for injection of poison in case of extremely low probability case of failure of both shut down systems.
d. Increased reliability of decay heat removal, achieved through a passive decay heat removal system, which transfers the decay heat to GDWP by natural circulation.

### *LEVEL 3: CONTROL OF SEVERE PLANT CONDITIONS, INCLUDING PREVENTION OF ACCIDENT PROGRESSION AND MITIGATION OF CONSEQUENCES OF SEVERE ACCIDENTS*

The following features contribute to the achievement of this objective:

a. Use of moderator as heat sink.
b. Presence of water in the calandria vault.

Flooding of reactor cavity following a LOCA.

Safety analysis included the analysis of 4

transients due to failure of wired systems of SDS-1 and SDS-2 and reactor shut down effected passively by injection of poison in the moderator by usage of system steam pressure. Actual calculations indicate that in none of the design basis accident sequences mentioned above the fuel clad temperature exceeds 1073 K. For the purpose of containment design, a double-ended guillotine rupture of the 600 mm diameter inlet header has been considered as the design basis accident. However, even in these cases, including a case of a NPP blackout together with failures of both independent fast acting shut-down systems (SDS–1 and SDS–2), predictions by BARC are that none of the acceptance criteria for design basis accidents as indicated above has been violated.
*(*D) Provisions for Safety under Seismic Conditions: The AHWR structures, systems and equipment are being designed for high level and low probability seismic events such as operating basis earthquake (OBE) and safe shutdown earthquake (SSE). These are also called S1 and S2 level earthquake respectively. Seismic instrumentation is also planned in accordance with the national and international standards.

## VI. DESCRIPTION OF TURBINE GENERATOR SYSTEMS

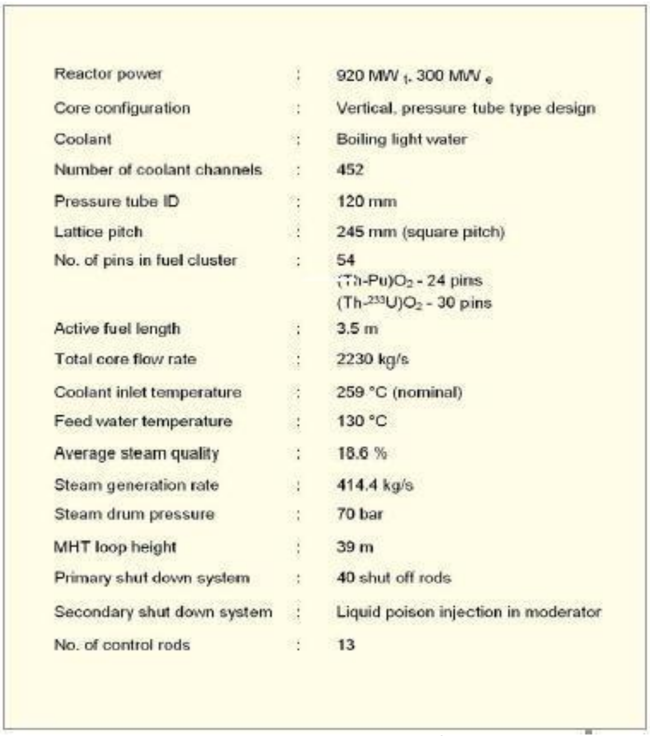
### a) *Steam and Feed Water System*

The primary function of the Steam and feed System is to transfer heat produced in the reactor core to turbine for production of electrical power. Steam and feed System forms an interface between the Main Heat Transport System and the Ultimate Heat Sink (Sea Water), and provides means for heat removal at various reactor-operating conditions.

The steam and feed system consists of steam mains, turbo-generator and auxiliaries, condensing system, condensate and feed water heating system, steam dumping and relief systems and on line full condensate flow purification. At normal full load a flow of 408 kg/s, 0.25% wet saturated steam, at pressure of 6.83 MPa from steam drum is delivered to the turbine throttle. After expansion in the High Pressure (HP) Turbine, steam is exhausted at pressure of 1.025 MPa. with wetness of 14.32%. Then it passes through external moisture separator reheater (MSR). Moisture separator reduces the wetness to 0.5%. Subsequently the steam is reheated in bled steam reheaters (BSR) to temperature of 503.2K.The steam enters the low pressure double flow turbine at 503.2 K temperature and pressure of 0.956 MPa, where it expands to a condenser back pressure of 8.3 kPa. The steam is condensed in a surface condenser and condensate at approx. saturation temperature (315.7 K) is taken out from the condenser. Heat is recovered by the condensate from the steam air ejector inter-after condenser and turbine gland steam condenser. Condensate is further heated up to 341.9 K by utilising the moderator heat of 36 MWth in moderator-feed water heat exchanger before entering into the Low Pressure (LP) heater. There are 2 nos. of LP heaters in series LP heater-1 and LP and drinking water requirements. It is placed adjacent to the turbine building. Sea water intake and discharge system comprises of condenser cooling water system and service water pump houses. DG Building accommodates equipment and supplies for DG sets to provide class-3 power supplies to plant facilities. Three DG buildings have been provided at physically separated location and fuel tanks. Waste Management Building accommodates features required for segregation, collection, treatment, conditioning, storage and safe disposal of liquid and solid radioactive disposable waste.

### b) *Safety Related Electrical Systems*

The various unit auxiliary loads to be connected to the electrical power supply system can be divided into two broad categories: Safety related loads and Non-safety related loads. While non-safety related loads can endure prolong power failure without affecting the safe operation of plant, and are generally connected to normal power supply system. The safety related loads depending on their criticality have defined limitation of duration of power failure to ensure safe operation of plant. The emergency power supply system ensures electrical power with specified quality to safety related loads which can take care of safe operation or shut down of plant after a postulated initiating event.



| | | |
|---|---|---|
| Reactor power | : | 920 MW $_t$, 300 MW $_e$ |
| Core configuration | : | Vertical, pressure tube type design |
| Coolant | : | Boiling light water |
| Number of coolant channels | : | 452 |
| Pressure tube ID | : | 120 mm |
| Lattice pitch | : | 245 mm (square pitch) |
| No. of pins in fuel cluster | : | 54<br>$(Th\text{-}Pu)O_2$ - 24 pins<br>$(Th\text{-}^{233}U)O_2$ - 30 pins |
| Active fuel length | : | 3.5 m |
| Total core flow rate | : | 2230 kg/s |
| Coolant inlet temperature | : | 259 °C (nominal) |
| Feed water temperature | : | 130 °C |
| Average steam quality | : | 18.6 % |
| Steam generation rate | : | 414.4 kg/s |
| Steam drum pressure | : | 70 bar |
| MHT loop height | : | 39 m |
| Primary shut down system | : | 40 shut off rods |
| Secondary shut down system | : | Liquid poison injection in moderator |
| No. of control rods | : | 13 |

Fig 6: Important Design Parameter of AHWR

## VII. CONCLUSIONS

The Thorium based nuclear power plant, Advanced Heavy Water Reactor is more efficient and useful in all respect as compared to PHWR, FBR and BWR etc. AHWR reduces the fuel cost, radiotoxic waste, and storage problems. Thorium is easily available in country like India and has not been exploited yet hence can be used in power generation. Thorium is therefore called as ―future fuel‖.

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