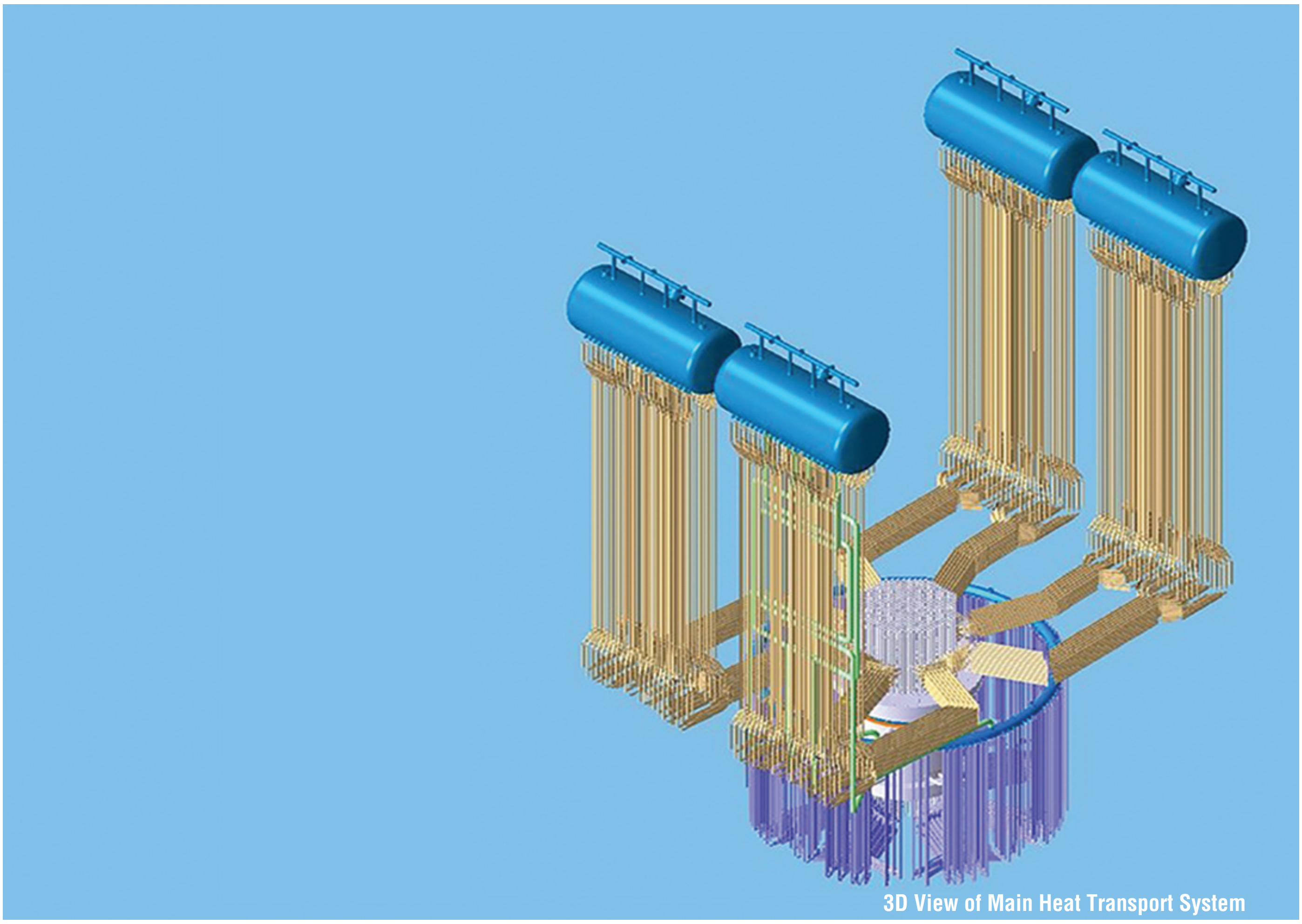

3D View of Main Heat Transport System

Advanced Heavy Water Reactor for Thorium Utilisation and Enhanced Safety

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The Advanced Heavy Water Reactor (AHWR) is designed and developed to demonstrate large-scale use of thorium for the generation of commercial nuclear power. AHWR is a 300 MWe, vertical pressure tube type, boiling light water cooled and heavy water moderated reactor. It incorporates several passive safety features and inherent safety characteristics including many First Of A Kind (FOAK) systems. Additionally, AHWR will produce desalinated water utilising process steam and waste heat. This article provides an overview of the AHWR design, fuel design, fuel cycle proposed, safety philosophy and experimental design validation undertaken.

Introduction

Long term sustainability of energy resources calls for the use of thorium as it is three to four times more abundant than uranium globally. In the context of Indian nuclear programme, thorium has a prominent place due to the unique resource position of having large thorium deposits, but limited uranium reserves.

To optimally utilise modest uranium but large thorium reserves in the country, the Department of Atomic Energy has adopted a three stage nuclear power programme. This is aimed towards achieving long term energy security and is based on a closed nuclear fuel cycle. The three stage nuclear power programme, which is being implemented sequentially, aims to multiply the domestically available fissile resources through the use of natural Uranium in Pressurised Heavy Water Reactors (PHWRs) in first stage, followed by use of Plutonium obtained from the spent fuel of PHWRs in Fast Breeder Reactors (FBRs), in the second stage. Large scale use of thorium is contemplated in the third stage, making use of fissile Uranium-233 (^{233}U) based breeder reactors, when adequate nuclear installed capacity in the country has been achieved. The third stage reactors are aimed to be self-sustaining reactors requiring only thorium as feed. Work has therefore been carried out on all aspects of thorium fuel cycle including mining, ore conversion, fuel fabrication, irradiation in reactors and fuel reprocessing [1].

After demonstrating the technologies at laboratory-scale and pilot-plant scale, currently, the focus is on development of all technologies related to development of thorium based reactor systems, so that, a mature technology is in place, well before beginning of large scale deployment of the thorium based reactors.

Advanced Heavy Water Reactor (AHWR) has been conceptualized as one of the options to provide impetus to the different thorium fuel cycle development programmes. It will demonstrate large scale use of thorium and associated technologies for generation of commercial nuclear power, at the same time, demonstrating advanced safety systems envisaged for next generation of nuclear reactors. Additionally, AHWR will produce desalinated water utilising process steam and waste heat. AHWR being a pressure tube type, heavy water moderated reactor, builds on use of the proven technologies developed in PHWR especially pertaining to pressure tube and low pressure moderator based design. At the same time, AHWR will demonstrate extensive use of passive systems and inherent safety characteristics for reactor operation and reactor safety under all operating conditions [2]. The implicit safety objective of AHWR is to limit impact of design basis as well as beyond design basis accidents to plant site, so as to have negligible impact in public domain. Its basic design and experimental development in areas required to establish feasibility of the basic design have been completed at BARC. Several major experimental facilities have been set-up and some others are under development to produce additional data.

Apart from above objectives, AHWR also addresses the concerns regarding long term sustainability and proliferation resistance. It will also have lower environmental impact due to lower long term radioactive waste generation including minor actinides.

Brief Description of Reactor

AHWR is a 300 MW_e, vertical pressure tube type, boiling light water cooled and heavy water moderated nuclear reactor [2]. AHWR uses thorium based fuel with slightly negative void coefficient of reactivity and boiling light water in natural circulation mode as coolant.

Simplified schematic of AHWR is shown in Figure 1. 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 452 number of 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 individual 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. 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. The coolant channel consists of a pressure tube and end fittings at top and bottom ends.

In AHWR, emergency core cooling system (ECCS) is made highly efficient by employment of direct injection of ECCS water into the coolant channels and thereby on the fuel pins. In case of loss of coolant accident (LOCA), the emergency core cooling system (ECCS) with four independent circuits (only one is shown for clarity) is actuated in passive mode. ECCS operation consists of passive high pressure injection system using accumulators and passive low pressure injection system using Gravity Driven Water Pool (GDWP) as source of water, in a sequential manner. This can provide core cooling for at least 7 days by ECCS water flooding feeder and tail pipe vaults in V1 volume.

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 37 lattice positions, designed to provide sufficient negative reactivity worth even in case when 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 Main Heat Transport (MHT) system. In addition, for long-term sub-criticality control, there is a provision to add boron to the moderator.

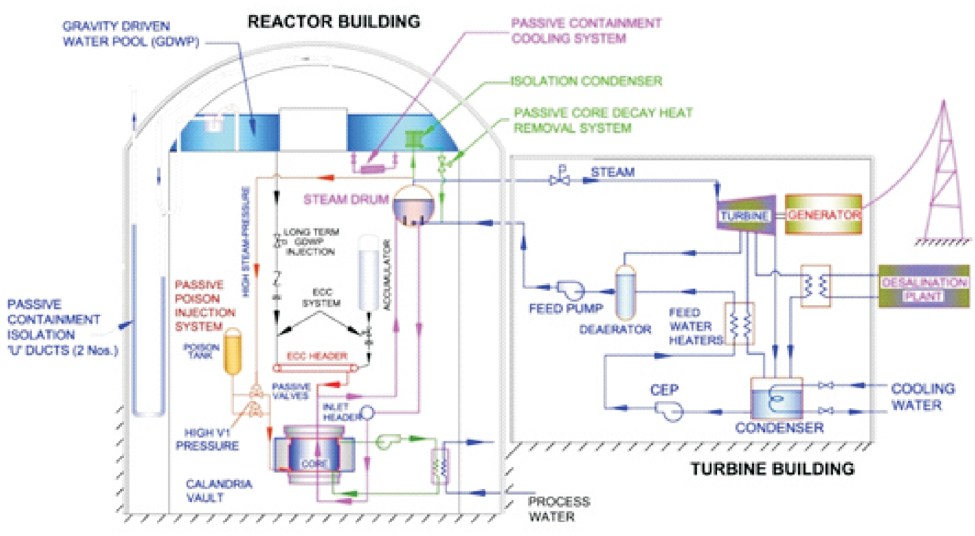

Figure 1: Schematic of AHWR

Main design features of AHWR	
Reactor thermal output	920 MW_{th}
Power plant output, gross	304 MW_e
Primary Coolant	Boiling light water
Moderator	Heavy water
Fuel material	(Th, ^{233}U)MOX and (Th, Pu)MOX
Number of fuel assemblies	452 Nos at pitch of 225 mm
Coolant Channel (Vertical pressure tube design)	PT: Zr-2.5%Nb-20% cold worked CT: Zr-4
Average discharge burn-up of fuel	38000 MWd/T
Active core height	3.5 m (Calandria - ID 6900 x 5000 ht)
Reactor operating pressure	70 bar
Core coolant inlet temperature	532.5 K (259.5^{o}C)
Core coolant outlet temperature	558 K (285^{o}C)
Average exit quality	19%
Non-electric application	Desalination - 2650 m^3/day
Design Life	100 years

Table 1: Important design data of AHWR

Reactor Core and Fuel Design

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.

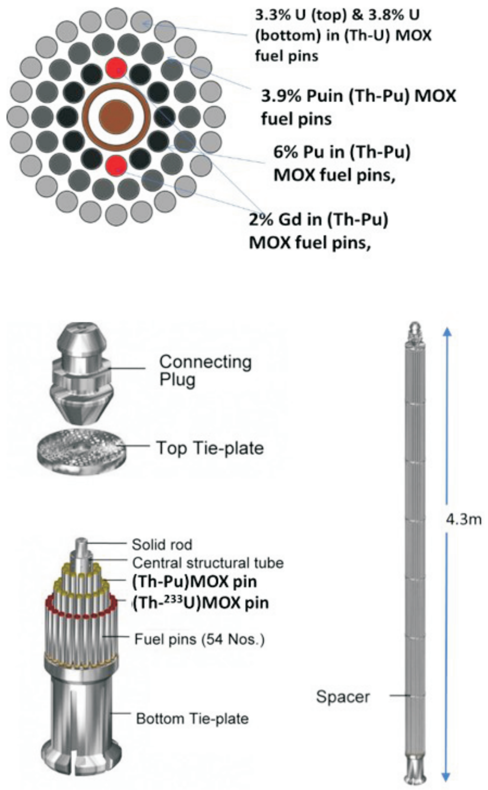

Figure 2: Details of fuel rod cluster of AHWR

The circular fuel cluster of AHWR (Figure 2) contains twenty-four (Th, ^{233}U)MOX pins in the outer ring and thirty (Th, Pu)MOX pins in the inner and middle ring, along with a displacer rod at the centre. The outer ring of (Th, ^{233}U)MOX pins have higher enrichment in bottom half of the cluster to maximise safety margins in operating conditions including normal operation.

Thorium Fuel Cycle Development Related Activities

Atomic Minerals Directorate for Exploration & Research (AMD) has identified 12.47 million tons of Monazite deposits (primary source of Thorium in India) which correspond to about 1 million tons of Thorium oxide. As part of operations of mining and separation of beach sand minerals, Indian Rare Earths Limited (IREL) has processed a few lakhs of tons of monazite ore. The process of producing nuclear grade Thorium oxide, called thoria powder from the monazite ore containing beach sands has been established. The fuel fabrication process for thoria based fuels by powder-pellet method is now well understood. Few tonnes of thoria fuel pellets have been fabricated at BARC and NFC for various irradiations in research and power reactors.

The large-scale utilisation of thorium requires the adoption of closed fuel cycle, wherein, there are challenges on both front-end and back-end. The highly stable thoria poses problems in dissolution in pure nitric acid for reprocessing the spent fuel. This problem is mitigated by small additions of fluoride, which however enhances the corrosion of stainless steel used as the material of construction for equipments. Another major concern with the thorium fuel cycle is the presence of ^{232}U along with ^{233}U. The daughter products of ^{232}U, ^{212}Bi and ^{208}Tl are emitters of hard gamma rays. This requires fuel fabrication and recycling of uranium to be carried out remotely in shielded hot-cells with a high level of automation.

The use of thorium in nuclear reactor is backed by experience of research reactors like PURNIMA, KAMINI, FBTR, CIRUS, Dhruva as well as commercial PHWRs (where it has been used for flux flattening). Reactor physics experiments in AHWR-Critical Facility have been initiated using thoria based test fuel pins. AHWR uses closed fuel cycle and will provide platform for development and demonstration of THOREX reprocessing on an industrial scale and the remote fuel fabrication of the highly radioactive ^{233}U based fuel in shielded hot-cells.

Back end of the fuel cycle is also well understood based on experience of Uranium Thorium Separation Facility (UTSF) and fuel reprocessing at IGCAR, Power Reactor Thoria Reprocessing Facility (PRTRF) etc.

AHWR will demonstrate use of thorium for generation of commercial nuclear power along with development of front and back end activities of thorium fuel cycle.

Safety Philosophy of AHWR

Following the Fukushima accident, more emphasis is laid globally on very low or nil radiological impact in the public domain and no requirement of evacuation in the spirit of "more good than harm". Nuclear reactors like AHWR come closer to these requirements. With deployment of mostly passive and a few active safety systems, and many inherent safety characteristics, AHWR can manage Design Extension Conditions (DEC) including Anticipated Transients without Scram (ATWS) without any impact in public domain. The broader safety objectives of AHWR are reducing Core Damage Frequency (CDF) and Large Early Release Frequency (LERF) to an insignificant level [4]. The design also has enhanced robustness to malevolent acts. The reactor is designed to provide at least 7 days of grace period during postulated accident events. However, it has also demonstrated its robustness for several beyond design basis accidents like Fukushima event [5].

Defense in Depth is followed as guiding principle in nuclear reactor design and safety, at all levels from operation to severe accident management. Innovation in safety requires adoption of higher degree of inherent safety characteristics or passive safety characteristics instead of depending on Engineered Safety Features (ESFs) at each level. Many First Of A Kind (FOAK) systems are developed for this purpose.

Inherent safety features rely on choice of design concept, laws of nature, materials or internal stored energy etc. Passive safety operate based on natural physical laws like gravity, buoyancy, etc. and may involve engineering mechanisms like flow, valves etc. It can use active components in very limited way to initiate subsequent passive operation. Both kinds of systems do not need operator intervention.

Inherent safety characteristics of AHWR:

- Negative fuel temperature coefficient of reactivity
- Negative power coefficient of reactivity
- Negative coolant void reactivity coefficient of reactivity
- Adequate shutdown margin even without two rods
- Low specific power to facilitate energy removal by natural circulation
- Fuel design characteristics like radial grading in fuel cluster and axial grading (bottom peaking) fuel to have better
- Conventional features like double containment, emergency planning zones etc.
- Thorium as robust nuclear fuel due to higher thermal conductivity, lower thermal expansion coefficient, higher specific heat, higher melting point, lower fission gas release characteristics and better dimensional stability at high burnups

Passive safety systems of AHWR

AHWR relies highly on passive safety systems and natural circulation systems play important role in achieving the safety objective. Natural circulation leads to robust response to deviation from normal conditions as well as to accidental conditions, like elimination of primary pump in MHT system eliminates PIEs due to pump unavailability or valve failures, at the same time providing better economics.

AHWR has large pool of water called Gravity Driven Water Pool (GDWP), which is located near the top of the containment. GDWP serves as a heat sink for some of the passive systems and also acts as suppression pool and a source of water for low-pressure emergency core cooling.

Under LOCA conditions, ECCS injection is followed by core submergence in reactor cavity providing additional effective cooling for extended period. In case of severe accidents including extended SBO, safety features like Calandria vault water and moderator etc. act as ultimate heat sink, and passive end shield and moderator cooling systems help in retarding the process of such accident. Severe accident management systems like core catcher and cooling systems, passive venting of containment, passive catalytic re-combiners ensure that radioactivity is contained.

Human error or malevolent actions by insider, which by nature are difficult to counter, have been addressed in this reactor design. In the very low probability event of failure of both the wired shutdown systems, poison injection through passive means is designed to cover high pressure ATWS scenarios. In such event, MHT system pressure rises, which causes to open passive valves and initiate the poison injection into the moderator. Major passive systems with their safety functions are listed in Table 2.

Experimental Validation Programme

A large scale R&D has been carried out for design validation of various features related to physics, engineering and safety. Some are listed as follows:

- Critical Facility of AHWR - Validation of AHWR reactor physics design.
- Safety assessment of reactor – Experimental Thermal Hydraulics Studies.
- Separate Effect Test Facilities - Stability, CHF, Condensation in presence of non-condensables, Carry Over/Carry Under, Poison Injection & Distribution, Core Catcher, etc.

About 25 major Test Facilities have been established in various Divisions and Groups of BARC, wherein, extensive experiments have been conducted to conclusively validate the design and safety aspects of AHWR. Figure 3 shows some of the installations viz. AHWR Critical Facility (AHWR_CF), Integral Test Loop (ITL) at Trombay and PARTH (Proving Advanced Reactor Thermal Hydraulics) test facility at Tarapur.

Passive Systems with their Safety Functions

Postulated event / safety function	Passive system
Normal operation	Natural circulation in MHT system
Shut Down / Station Black out	Isolation condenser for Decay Heat Removal System
LOCA	1. Passive ECCS injection a. High pressure injection b. Low pressure injection c. Direct injection of ECCS water on fuel 2. Vapour suppression in GDWP 3. Core submergence
Containment cooling	Passive Containment Cooling System (PCCS)
Systems cooling	Passive Moderator Cooling System (PMCS) Passive End Shield Cooling System (PESCS)
Severe accident	GDWP water cooling of core catcher Core submergence in reactor cavity
Response to malevolent action	Passive Poison injection system (PPIS)
Containment Isolation	Passive Containment Isolation System (PCIS)
Hydrogen management	Passive Autocatalytic Re-combiners (PARC)
Depressurisation of MHT	Passive Auto Depressurization System (PADS)
Containment Venting	Passive Containment Filtered Venting System (PCFVS)
Core damage state	Core Catcher

Table 2 Passive Systems with their Safety Functions

Figure 3: Installations having Critical Facility, Integral Test Loop and PARTH

Safety and Engineering aspects

Basic design including reactor physics, fuel design, shielding, fuel handling systems and reactor systems/structures/components has been completed. Safety analysis of AHWR was carried out for an exhaustive list of Postulated Initiating Events (PIE). Probabilistic Safety Analysis (PSA) Level 1, 2 and 3 PSA Analysis has been carried out for AHWR [6]. Design and Detailed Engineering of reactor and auxiliary systems/ structures/ components is being pursued. Plant Design and Plant lifecycle Management (PDPLM) is implemented for integrated plant design of AHWR which can be used for design, layout, construction management, training etc (Figure 4). Feasibility studies and design of steam turbine with associated steam and feed cycle has been carried out. Figure 5 shows bird's eye view of the AHWR plant.

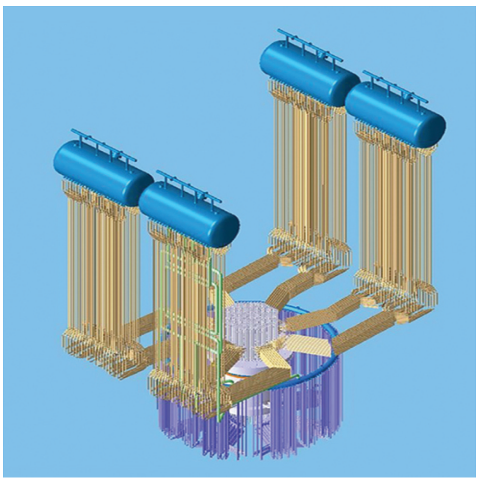

Figure 4: 3D View of Main Heat Transport System

Figure 5: 3D view of AHWR plant

Summary

AHWR will demonstrate industrial-scale use of thorium for the generation of commercial nuclear power. Technology for thorium based fuel fabrication and reprocessing has been demonstrated. The reactor incorporates several First Of A Kind (FOAK) passive safety features. With enhanced safety, AHWR is expected to have minimum impact in public domain.

The development of AHWR has been supported by a robust R&D infrastructure developed at BARC and many experimental facilities have been built to validate AHWR design. AHWR will be important step towards realization of long term energy security for India using indigenous thorium reserves.

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