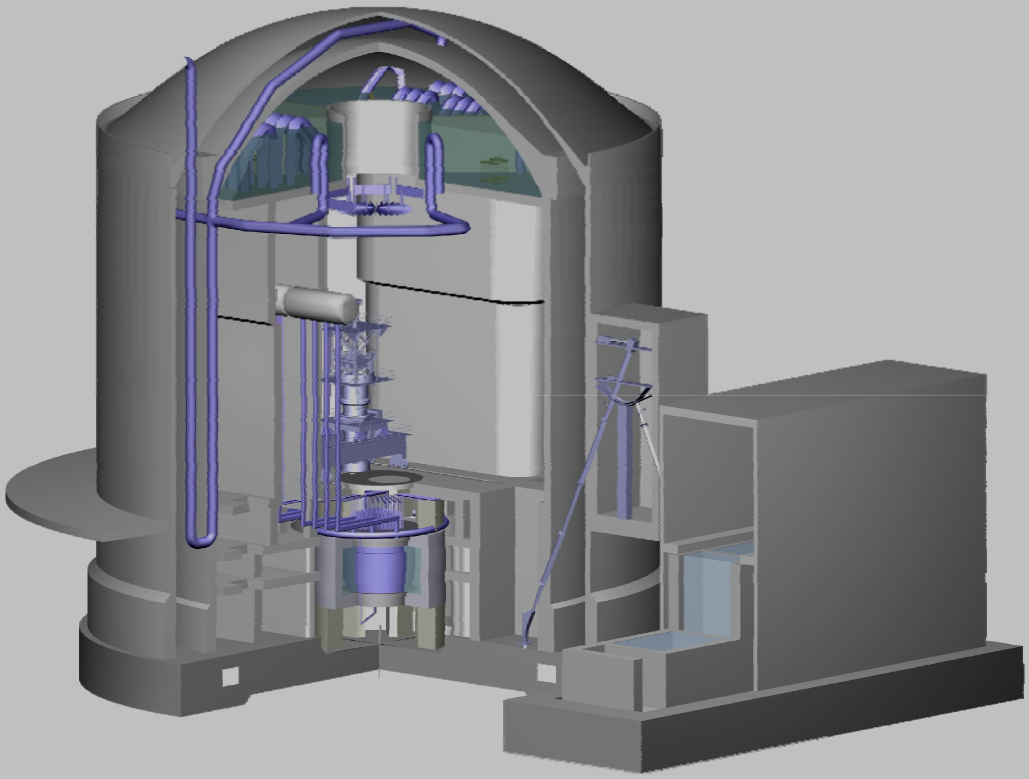
AHWR300-LEU

Advanced Heavy Water Reactor
with LEU-Th MOX Fuel



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An Acrylic Model of AHWR to Scale 1:50

Threat of climate change and importance of sustainable development has brought nuclear power in sharper focus in recent times. Growth of nuclear power worldwide, however, requires satisfactory technological response to challenges of very high level of safety and security assurance (as dictated by very large increase in number of reactors), ability to perform with lower level of technological infrastructure as it prevails in several developing countries, high degree of fuel use efficiency and superior waste disposal options.

Development of Advanced Heavy Water Reactor, AHWR300-LEU, is an effort to realise these futuristic objectives through innovative configuration of present day technologies.

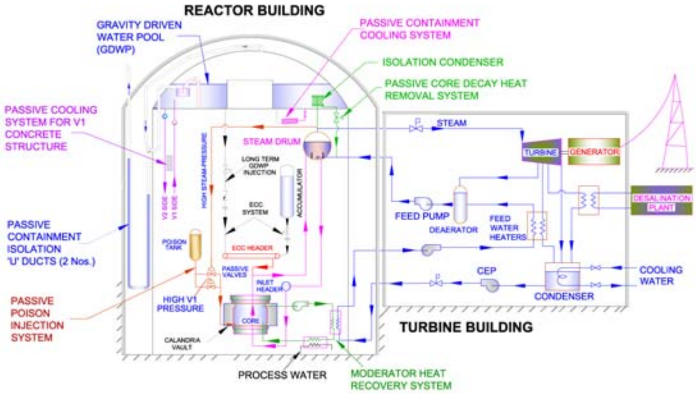
Advanced Heavy Water Reactor with LEU-Th MOX Fuel (AHWR300-LEU)

General Description

AHWR300-LEU is a 300 MWe, vertical, pressure tube type, boiling light water cooled, and heavy water moderated reactor. The reactor incorporates a number of passive safety features and is associated with a fuel cycle having reduced environmental impact. AHWR300-LEU possesses several features, which are likely to reduce its capital and operating costs.

- Using heavy water at low pressure reduces potential for leakages
- Recovery of heat generated in the moderator for feed water heating
- 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
- Shop assembled coolant channels, with features to enable quick replacement of pressure tube alone, without affecting other installed channel components
- Inherent advantages of using high pressure boiling water as coolant
    - Elimination of steam generators
    - Use of high-pressure steam
- Production of 500 m^3/day of demineralised water in Multi Effect Desalination Plant by using steam from LP Turbine (For plants located on the sea coast)
- Hundred year design life of the reactor
- A design objective requiring no exclusion zone beyond plant boundary on account of its advanced safety features

AHWR300-LEU employs natural circulation for removal of heat from the reactor core under operating and shutdown conditions. All event scenarios initiating from non-



Schematic of AHWR300-LEU main systems

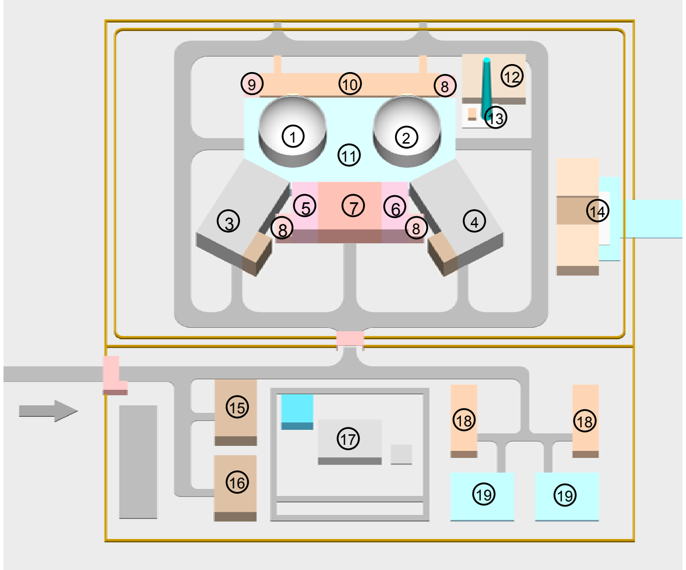
AHWR300-LEU employs natural circulation for removal of heat from the reactor core under operating and shutdown conditions. All event scenarios initiating from non-availability of main pumps are, therefore, excluded.

availability of main pumps are, therefore, excluded. The Main Heat Transport (MHT) System transports heat from fuel pins to steam drum using boiling light water as the coolant. The MHT system consists of a common circular inlet header from which feeders branch out to the coolant channels in the core. The outlets from the coolant channels are connected to tail pipes carrying steam-water mixture from the individual coolant channels to four steam drums. Steam is separated from the steam-water mixture in steam drums, and is supplied to the turbine. The condensate is heated in moderator heat exchangers and feed heaters and is returned to steam drums by feed pumps. Four downcomers connect each steam drum to the inlet header.

Emergency Core Cooling System (ECCS) is designed to remove the core heat by passive means in case of a postulated Loss of Coolant Accident (LOCA). In the event of a rupture in the primary coolant pressure boundary, the cooling is initially achieved by a large flow of water from accumulators. Later, cooling of the core is achieved by the injection of cold water from a large Gravity Driven Water Pool (GDWP) located near the top of the reactor building.

In AHWR300-LEU, subsequent to energy absorption in GDWP in vapour suppression mode, the Passive Containment Cooling System (PCCS) provides long term containment cooling following a postulated LOCA. GDWP serves as a passive heat sink yielding a grace period of three days. The core gets submerged in water from GDWP long before the end of this period.

AHWR300-LEU is provided with a double containment. For containment isolation, a passive system has been provided in AHWR300-LEU. 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 pressure acts on the water pool surface and drives water, by swift establishment of syphon, into the U-bends of the ventilation ducts. Water in the U-bends acts as a seal between the containment and the external environment, providing necessary isolation between the two.



Legend: 1: Reactor Building 1, 2: Reactor Building 2, 3: Turbine Building 1
4: Turbine Building 2, 5: Station Aux. Bldg. A, 6: Station Aux. Bldg. B
7: Control Building, 8: DG Bldg. 1, 2 & 3, 9: Supplementary Control Building
10: Fuel Building, 11: Service Building, 12: Waste Mgmt. Building, 13: Stack
14: CCW & SW Pump houses and Intake Structures, 15: Administrative Building, 16: Nuclear Training Centre, 17: GIS Switchyard, 18: Warehouses and workshops, 19; Fire and Emergency Water Reservoirs

Indicative Site Layout

AHWR300-LEU possesses several features, which are likely to reduce its capital and operating costs and make it ideally suited for leveraging the industrial capabilities available in several developing countries.

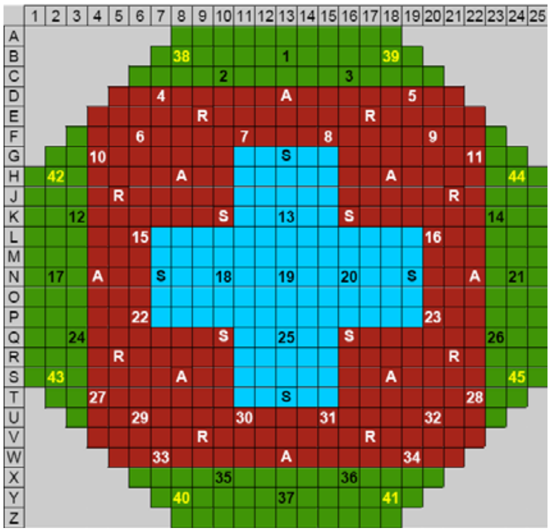
Emergency core cooling, containment heat removal and containment isolation are realised through passive means in AHWR300-LEU.

Important Characteristics of Reactor Physics Design

The reactor physics design of AHWR300-LEU is optimised to achieve high burn-up with the LEU-Thorium based fuel along with inherent safety characteristics like negative reactivity coefficients. The design provides for inherent safety characteristics through achievement of required reactivity coefficients. Some highlights of the reactor physics design of this reactor are mentioned below.

- Sufficient reactivity worth of shutdown systems is ensured under all accidental conditions, including LOCA and LORA (Loss Of Regulation Accident), even with two maximum worth shutoff rods being unavailable
- All reactivity and power coefficients, liable to be encountered during reactor startup, LOCA and under long shutdown are ensured to be negative

Properties	Value
Average discharge burnup (MWd/te)	64,000
Energy extracted per tonne equivalent mined uranium (MWd/te)	7,826
Power from thorium (%)	39
Number of control rods (Worth in mk)	Absorber rod: 8 (10.9) Regulating rod: 8 (11.6) Shim rod: 8 (9.9)
Regulating rod worth in normal operating condition (67% in) (mk)	5.33
Number of shutoff rods (Total worth in mk)	45(-83.25)
Total worth of shutoff rods if two maximum worth rods are unavailable (mk)	-60.28
Peaking factors (Local/Radial/Axial/Total)	1.35 / 1.2 / 1.29 / 2.1
Fuel temperature coefficient (Δk/k/K)	-2.82×10^{-5}
Channel temperature coefficient (Δk/k/K)	-3.73×10^{-5}
Void coefficient (Δk/k/% void)	-8.72×10^{-5}
Moderator temperature coefficient (Δk/k/K)	-3.09×10^{-5}



N	Shut off Rod (1-45)
AR	Absorber Rod
RR	Regulating Rod
SR	Shim Rod

🟦	74 GWd/te
🟥	64 GWd/te
🟩	61 GWd/te

Core map showing burnup distribution and position of safety devices

Critical Facility for AHWR

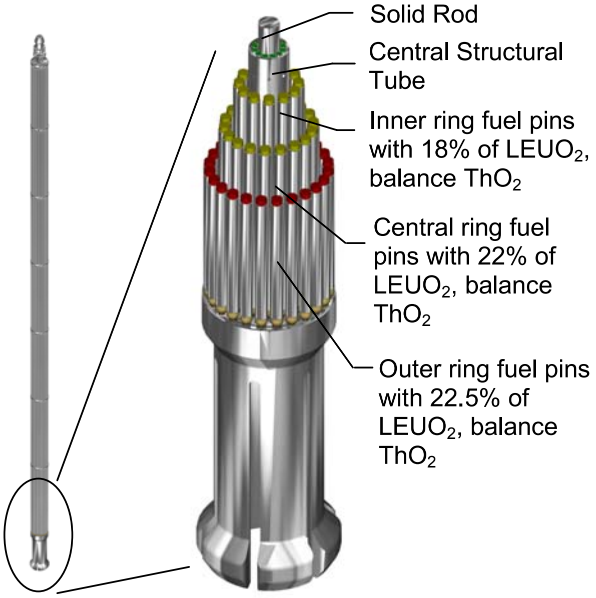
Physics design ensures inherent safety characteristics of the reactor, like negative reactivity coefficients and ability to shutdown even with two maximum worth shutoff rods being

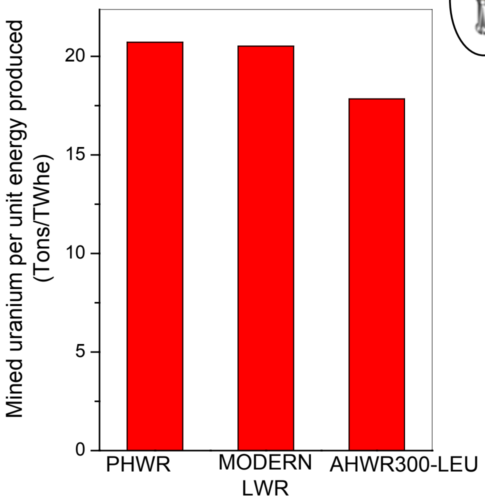
Fuel

The AHWR300-LEU fuel cluster contains 54 fuel pins arranged in three concentric circles surrounding a central displacer assembly. The Zircoloy-2 clad fuel pins in the three circles, starting from the innermost, contain 18%, 22% and 22.5% of $LEUO_2$ (with 19.75% enriched uranium) respectively and the balance ThO_2. The average fissile content is 4.21%. The fuel also incorporates a multipurpose displacer assembly for the spraying of ECCS water directly on fuel pins during a postulated LOCA and helps achieving negative void coefficient. The fuel is currently designed for an average burn-up of 64 GWd/te.

In comparison with modern LWRs[1], AHWR300-LEU requires about 13% less mined natural uranium for the same quantity of energy produced, thus making it a favourable option for efficient utilisation of natural uranium resources.

The reactor is configured to obtain a significant portion of power by fission of ^{233}U derived from in-situ conversion from ^{232}Th. On an average, about 39% of the power is obtained from thorium.





AHWR300-LEU requires less mined natural uranium for the same quantity of energy produced than a modern LWR

AHWR300-LEU provides a better utilisation of natural uranium, while ensuring that a significant fraction of the energy is extracted by fission of ^{233}U, converted in-situ from the thorium fertile host.

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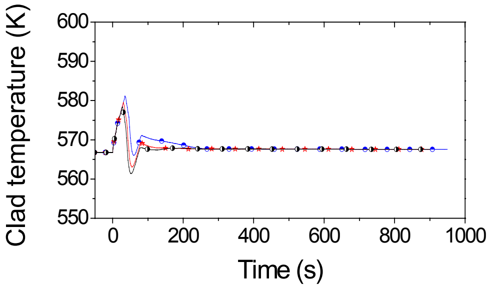
[1] The French N4 PWR is considered as representative of a modern LWR. This reactor has been referred from "Accelerator-driven Systems (ADS) and Fast Reactor (FR) in Advanced Nuclear Fuel Cycles", Organisation for Economic Co-operation and Development, OECD (2002)

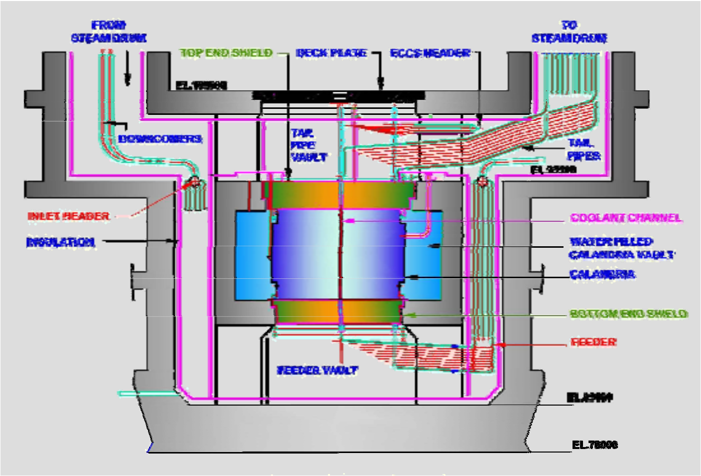
Advanced Safety Features of AHWR300-LEU

One of the most important design objectives of AHWR300-LEU is to eliminate any significant radiological impact, and therefore, the need for evacuation planning in the public domain, in a large-scale deployment scenario. This may facilitate siting of these reactors close to population centers. Some important safety features of AHWR300-LEU are given below.

- Slightly negative void coefficient of reactivity
- Passive safety systems working on natural laws
- Large heat sink in the form of Gravity Driven Water Pool with an inventory of 7000 m^3 of water, located near the top of Reactor Building
- Removal of heat from core by natural circulation
- Injection of cooling water by Emergency Core Cooling System directly inside the fuel cluster
- Two independent shutdown systems (primary and secondary)
- Passive poison injection in moderator in the event of non-availability of both the primary as well as the secondary shut down system due to failure or malevolent insider action



Peak clad temperature hardly rises even in the extreme condition of complete station blackout and failure of primary and secondary shutdown systems.



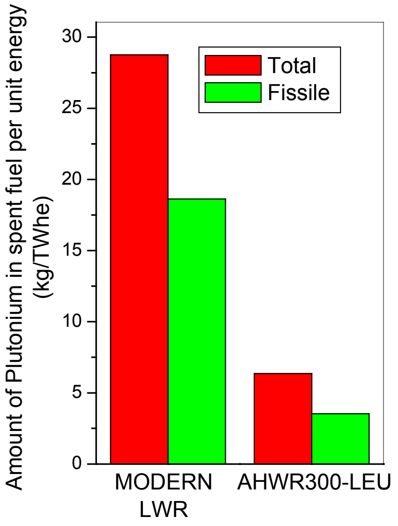
Reactor Block Components

AHWR300-LEU provides a robust design against external as well as internal threats, including insider malevolent acts. This feature contributes to outstanding security of the reactor through implementation of technological solutions.

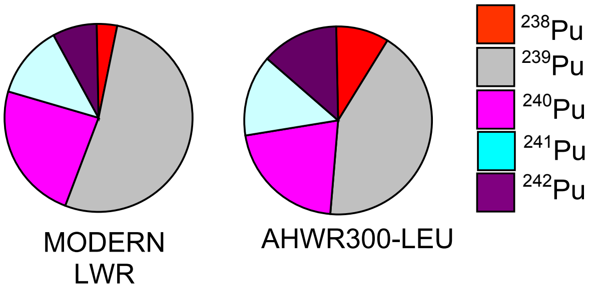
Enhanced Intrinsic Proliferation Resistant Features of AHWR300-LEU

Due to the use of LEU and thorium, AHWR300-LEU leads to reduced generation of Plutonium in spent fuel with lower fissile fraction and a high (~10%) fraction of ^{238}Pu. The fissile uranium in the spent fuel amounts to about 8% and it also contains about 200 ppm of ^{232}U, whose daughter products produce high-energy gamma radiation. These attributes form the basis of intrinsic proliferation resistant features of AHWR300-LEU.

Reduced Plutonium generation



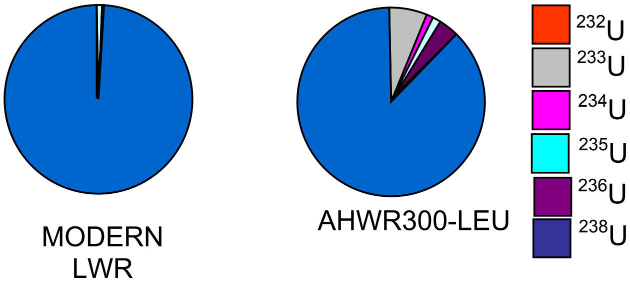
Higher ^{238}Pu fraction and lower fissile content of Plutonium



^{238}Pu	3.50	%
^{239}Pu	51.87	%
^{240}Pu	23.81	%
^{241}Pu	12.91	%
^{242}Pu	7.91	%

^{238}Pu	9.54	%
^{239}Pu	41.65	%
^{240}Pu	21.14	%
^{241}Pu	13.96	%
^{242}Pu	13.70	%

Presence of ^{232}U in uranium from spent fuel



^{232}U	0.00	%
^{233}U	0.00	%
^{234}U	0.00	%
^{235}U	0.82	%
^{236}U	0.59	%
^{238}U	98.59	%

^{232}U	0.02	%
^{233}U	6.51	%
^{234}U	1.24	%
^{235}U	1.62	%
^{236}U	3.27	%
^{238}U	87.35	%

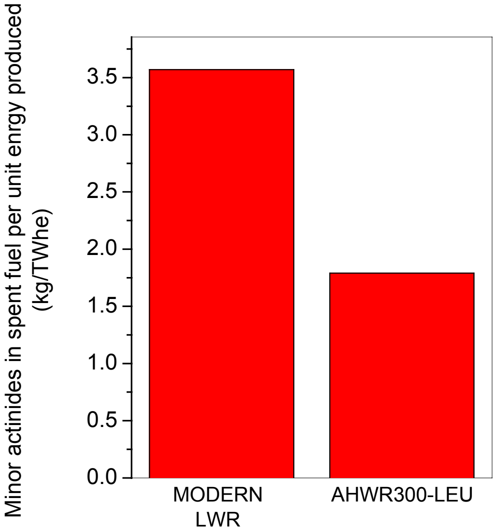
Uranium in the spent fuel contains about 8% fissile isotopes, and hence is suitable to be reused in other reactors. Further, it is also possible to reuse the Plutonium from spent fuel in fast reactors.

The composition of the fresh as well as the spent fuel of AHWR300-LEU makes the fuel cycle inherently proliferation resistant.

Waste Management Aspects of AHWR300-LEU

The AHWR300-LEU fuel contains a significant fraction of thorium as a fertile host. Thorium being lower in the periodic table, the quantity of minor actinides is significantly reduced. As compared with modern LWRs, the amount of minor actinides produced in AHWR300-LEU per unit energy is only half.

Further, thorium oxide is eminently suitable for long-term storage because of the inert nature of the matrix. It is on account of this inert nature of the matrix that reprocessing of the AHWR300-LEU fuel poses relatively complex challenges. The inert matrix gives considerable advantage in safe disposal of spent fuel in case of adoption of once through fuel cycle mode[2].



Physical characteristics of ThO_2 offer potential for high performance nuclear fuel with better thermo-mechanical properties and slower fuel deterioration

- The thermal conductivity of ThO_2 is higher than that of UO_2. As a result, fuel temperatures for ThO_2 fuel will be lower than UO_2 fuel, resulting in reduced fission gas release.
- The thermal expansion coefficient of ThO_2 is lower than that of UO_2, inducing less strain on the clad. ThO_2 retains dimensional stability at high burnup.
- ThO_2 has a very high melting point of 3300°C.
- The fission product release rates for ThO_2 based fuels are one order of magnitude lower than that of UO_2.
- Fuel deterioration is slow, allowing the fuel to reside in the reactor for longer periods.
- ThO_2 does not react with water - hence better capability to operate under failed fuel condition.

Use of thorium oxide based fuel in AHWR300-LEU reduces the production of minor actinides as well as gives advantage in safe disposal of spent fuel in case of adoption of once through fuel cycle mode[2].

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[2] The Indian nuclear programme is based on closure of the nuclear fuel cycle even with the use of thorium based fuel

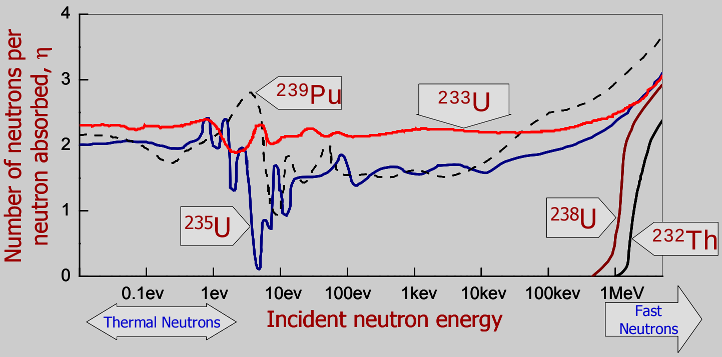
Important Design Parameters of AHWR300-LEU

Reactor power	:	920 MWth, 300 MWe
Core configuration	:	Vertical, pressure tube type design
Coolant	:	Boiling light water
Number of coolant channels	:	444
Pressure tube ID	:	120 mm
Lattice pitch	:	225 mm (square pitch)
No. of pins in fuel cluster	:	54
Active fuel length	:	3.5 m
Total core flow rate	:	2141 kg/s
Coolant inlet temperature	:	259 °C (nominal)
Feed water temperature	:	130 °C
Average steam quality	:	19.1 %
Steam generation rate	:	408 kg/s
Steam drum pressure	:	70 bar
MHT loop height	:	39 m
Primary shut down system	:	45 shut off rods
Secondary shut down system	:	Liquid poison injection in moderator
No. of control rods	:	24
Passive Poison Injection		Poison injection through a passive valve due to increase in steam pressure

Thorium Fuel Cycle

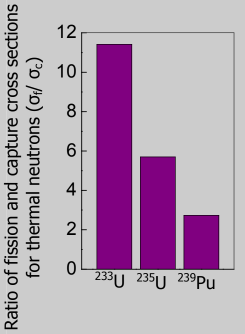
It is generally agreed that in the long term, nuclear power employing closed fuel cycle is the only sustainable option for meeting a major part of the world energy demand. World resources of thorium are larger than those of uranium. Thorium, therefore, is widely viewed as the 'fuel of the future'. Thorium based nuclear fuel cycle possesses several well-known characteristics indicated below.

- Using external fissile material ^{235}U, Plutonium or an accelerator driven neutron source, thorium can sustain a thermal breeding cycle.
- The cycle produces virtually no Plutonium.
- The waste products contain low amount of long-lived alpha-emitters

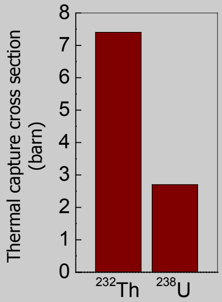


^{233}U has an η that remains nearly constant over a wide energy range, in thermal as well as epithermal regions, unlike ^{235}U and ^{239}Pu. This facilitates achievement of high conversion ratios with thorium utilisation in reactors operating in the thermal/epithermal spectrum.

η: Number of neutrons released per neutron absorbed



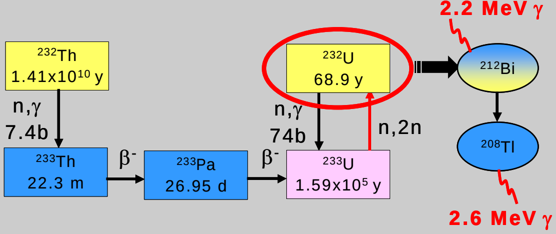
Capture cross section of ^{233}U is much smaller than ^{235}U and ^{239}Pu, the fission cross section being of the same order implying lower non-fissile absorption leading to higher isotopes. This favours the feasibility of multiple recycling of ^{233}U, as compared to Plutonium.



Cross section for capture of thermal neutrons in ^{232}Th is typically 2.47 times that in ^{238}U. Thus thorium offers greater competition to capture of the neutrons and lower losses to structural and other parasitic materials leading to an improvement in conversion of ^{232}Th to ^{233}U.

Irradiated fuel refabrication facility

Due to presence of ^{232}U in separated ^{233}U, thorium offers good proliferation-resistant characteristics. In a thorium based fertile host, ^{232}U is formed via (n, 2n) reactions, from ^{232}Th, ^{233}Pa and ^{233}U. The half-life of ^{232}U is about 69 years. The daughter products (^{208}Tl and ^{212}Bi) of ^{232}U are high-energy gamma emitting isotopes.



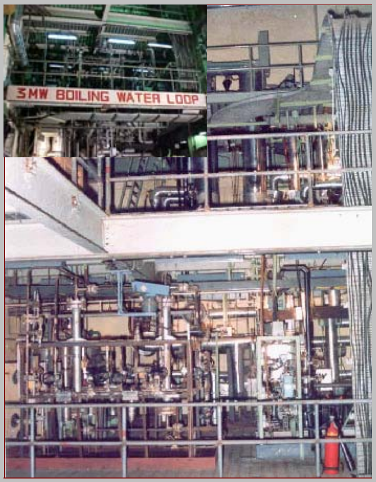
Some Experimental Facilities for Thermal Hydraulic Studies of AHWRs

Facility at Apsara Reactor for Flow Pattern Transition Studies by Neutron Radiography

Integral Test Loop (ITL): A scaled test facility based on power to volume scaling for thermal hydraulic simulation of AHWRs

Natural Circulation Loop (NCL) for Stability and Start-up Studies

Transparent Setup for Natural Circulation Flow Distribution Studies



3 MW Boiling Water Loop

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