On the Physics Design of Advanced Heavy Water Reactor

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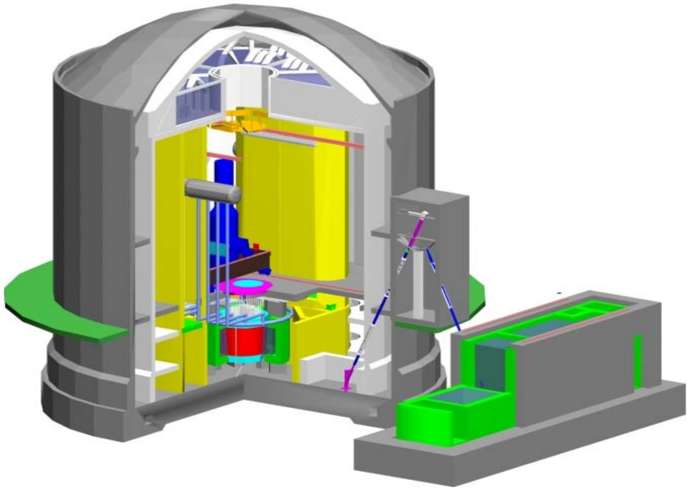
Advanced Heavy Water Reactor (AHWR)

- **Indian Nuclear Power Program is based on the fuel resource available within the country**
  - **First stage: Natural Uranium fuelled PHWRs**
  - **Second stage: MOX (Plutonium from first stage) fuelled Fast Reactors**
  - **Third stage : Thorium/ U-233 based Systems**
- **The main objective for design & development of AHWR is to expedite transition to third stage and demonstration of thorium fuel cycle technologies along with several other safety features required for next generation reactors/ sustainable development of nuclear energy.**



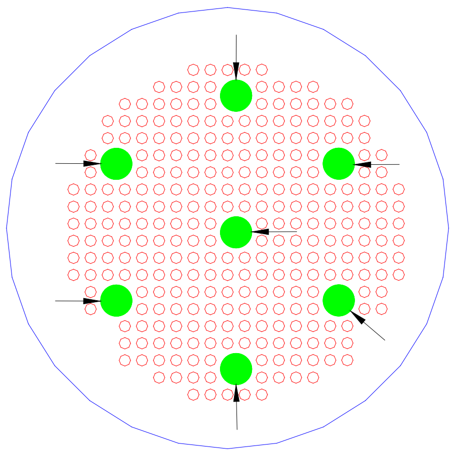
AHWR Description/ Design Objectives/ Challenges

- **AHWR is a 300 MWe, vertical, pressure tube type reactor cooled by boiling light water and moderated by heavy water.**
- **Fuel : (Th, U-233)MOX & (Th, Pu)MOX**
- **Power production largely from Th/U-233**
- **Self-sustaining in U-233**
  - ***in situ* generation of U-233 to be increased/ optimized**
- **Reasonably high fuel burn up (~ 30,000 MWd/te)**
- **Optimization of plutonium consumption**
- **Reduction in coolant void reactivity coefficient to turn it slightly negative from safety standpoint**
- **To extract 300 MWe from reasonable sized reactor with heat removal through natural circulation**
  - **Uniform/ flat radial core power distribution**
  - **Short height of core**
  - **Low power density**

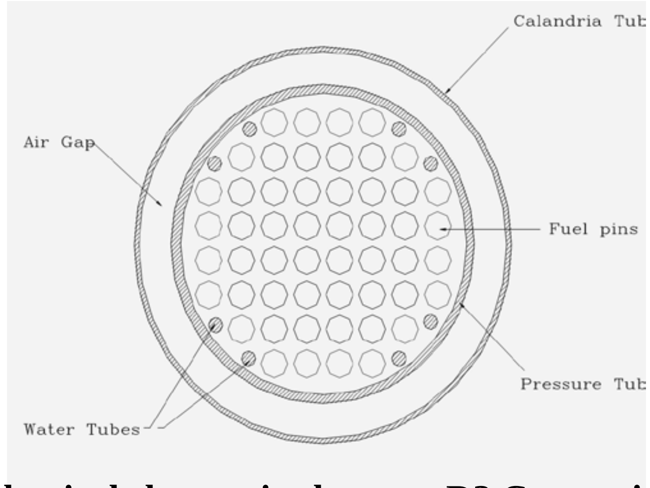
Design and Safety Features

- **Reactor Power - 300 MWe / 920 MWth**
- **On-power fuelling**
- **Low excess reactivity**
- **Low core power density**
- **Slightly negative coolant void coefficient**
- **Negative power and fuel temperature coefficient**
- **Heat removal by Natural circulation of coolant**
- **Direct injection of Emergency Core Cooling System (ECCS) water into fuel during Loss Of Cooling (LOCA) accident**
- **Passive containment cooling and Gravity driven water pool (GDWP) with capacity to cool the core for 72 hr following LOCA**

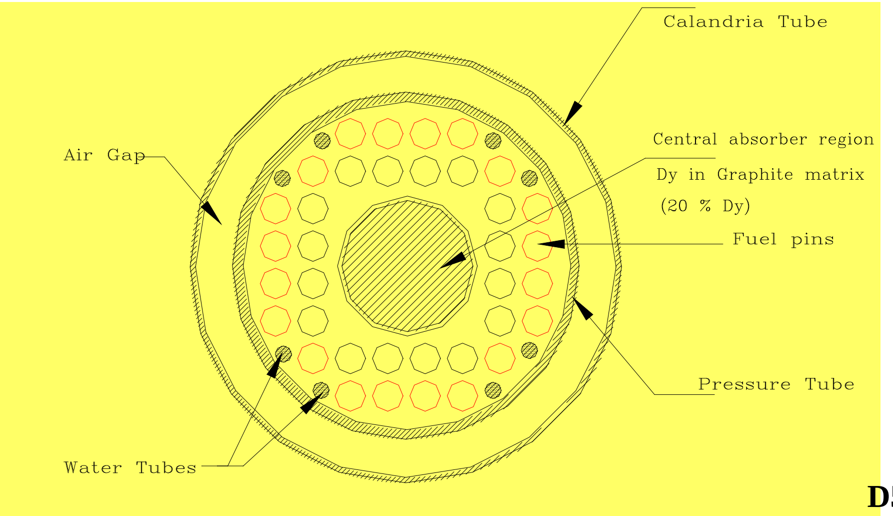
Evolution of Physics Design of AHWR



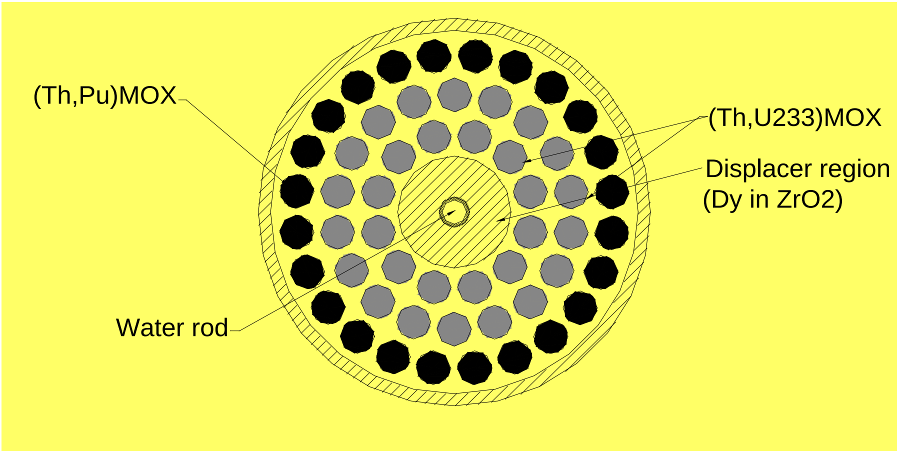
Seed-Blanket concept



Identical clusters in the core D3 Composite cluster; Carbon Balls submerged in moderator



D4 Composite cluster, large amount of Dy in the centre



D5 Composite cluster; ECCS & fuel pins relocated and Displacer region created for reduction of void coefficient; small amount of Dy in the centre

D5 Composite Cluster for Equilibrium Core

- **Fuel pins/ ECCS relocated by creating a multipurpose displacer in the centre of the cluster for void reactivity reduction**
- **54 Fuel pins arranged in three concentric rings**

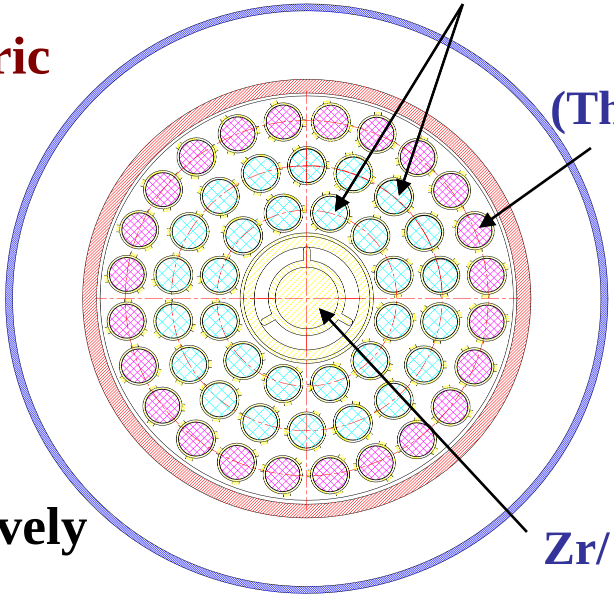
(Th, U233)MOX Fuel

12 pins in Inner Ring - 3.0% U-233

18 pins in **Middle Ring - 3.75% U-233**

(Th, Pu)MOX Fuel

24 pins in **Outer ring- 2.5/4.0% Pu in the upper half and lower half of fuel, respectively**



Standard D5 Composite Cluster

- **The Displacer unit having central displacer rod of grey absorber material, as required, for the fine tuning of void reactivity**

D5 Composite Cluster for Equilibrium Core

Table I. Description of the AHWR fuel assembly

Parameter	Value
Fuel:	
No. of Fuel pins	54
OD, mm	11.2
Clad: Material/ Thickness, mm	Zircaloy-2 / 0.6
Fuel Type/No. of Pins in/ Enrichment, wt%:	
Inner ring –standard cluster	(Th,U233) MOX / 12/ 3.0
Inner ring –alternate cluster	(Th,Pu) MOX / 12/ 4.0
Middle ring	(Th,U233) MOX / 18/ 3.75
Outer ring-Upper half	(Th,Pu) MOX / 24/ 2.5
Outer ring-Lower half	(Th,Pu) MOX / 24/ 4.0
Heavy Metal, kg	116.5
Lattice pitch, mm	225
Moderator	Heavy water
Coolant	Light Water

Multipurpose displacer in D5 composite cluster

- **Displacer is created by removing large quantity of water, hence called displacer, from the centre which is advantageous from the standpoint of reduction in coolant void reactivity**
- **Multipurpose Displacer Plays a key role in the design of D5 composite cluster in that it,**
  - **acts as conduit for ECCS**
  - **aid in fuel reconstitution,**
  - **helps in achieving desired void reactivity coefficient**
  - **facilitates use of different fuel-types effectively without significant change in design, and**
  - **along with on-line fuelling turns Fuel cycle flexibility into an inherent feature of system**

Cluster design- Plutonium as top up fuel

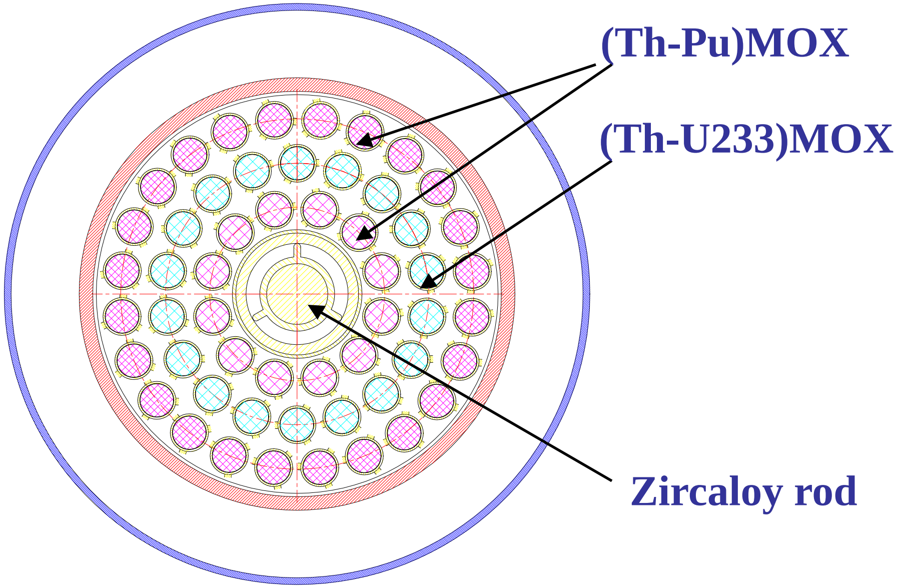
- **Closed fuel cycle adopted for efficient utilization of thorium**
- **Th/ U-233 in self-sustaining configuration in a heavy water reactor gives very low burn up in PHWR**
  - **A top up fuel is required for achieving reasonably high burn up**
- **Plutonium from the spent fuel of PHWRs is employed as make up/ top up fuel in AHWR**
  - **Availability of plutonium from PHWRs is limited**
- **Optimization of initial charge and annual feed of plutonium**
  - **Located in the outer ring where it faces highly thermalized flux for high reactivity and deep burning**
- **Total plutonium burnt ~ 75-80%**
- **Fissile isotopes, plutonium feed (from PHWRs) ~ 75%**
- **Fissile isotopes, Plutonium discharged ~25%**

Cluster design- Self sustaining characteristics in U-233

- **Closed fuel cycle is possible only if it is self-sustaining in Th/ U-233**
- **U-233 depletes in the inner (Th, U-233)MOX pins and builds up gradually in the outer (Th, Pu)MOX pins due to conversion from thorium**
- **Production of U-233 in the outer pins is however not sufficient to compensate for the burn up of U-233 in the inner pins**

➢ **An alternate cluster is designed that contains 4.0 wt% plutonium in place of 3.0 wt% U-233 used in the standard cluster in the 12 inner fuel pins**

➢ **Both the clusters to be fuelled in equal proportion for achieving self sufficiency in U-233**



Alternate AHWR cluster

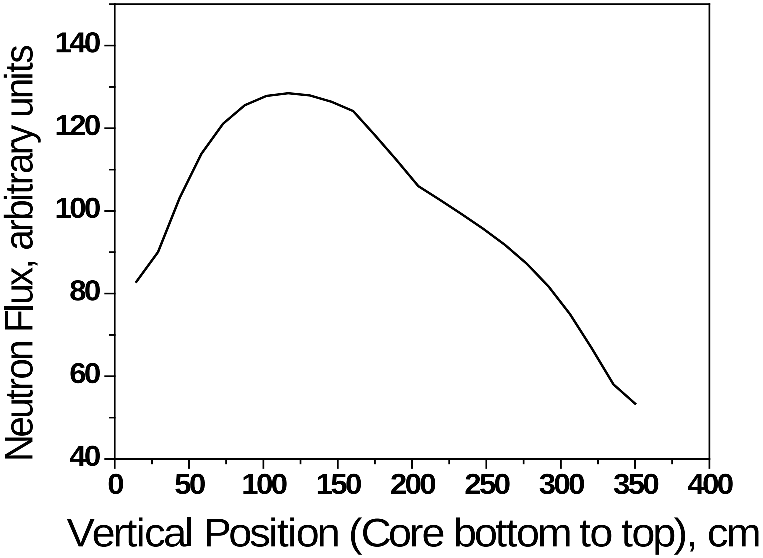
Fuel flow and multiple recycling of U-233

	Plutonium isotopic vector,%				
Fuel cluster	**Pu-238**	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**
Initial -Standard/ Alternate	**0.0**	**68.8**	**24.6**	**5.3**	**1.3**
Exit- Standard	**2.3**	**1.6**	**31.1**	**21.2**	**43.7**
Exit- Alternate	**1.7**	**6.2**	**42.2**	**22.6**	**27.3**

- **U-233 is self-sustaining**
- **Uranium from the discharged fuel contains U-234, U-235 and U-236**
- **Unlike recycling of MOX in PWRs, the rate of build-up of higher isotopes and their absorption cross-section is much lower**
- **It is possible to operate AHWR in successive cycles by employing the same enrichment of U-233.**

Axially graded Fuel- Power uprating

- **Axial flux distribution uniform as there is no bulk boiling of moderator in AHWR**
- **One way to increase the power derived from reactor is by decreasing the flux near core exit as that increases MCHFR and hence thermal margin**



Axial Power distribution in a high powered fuel channel

- ➢ **This is achieved by altering the plutonium content in the outer ring of fuel**
- ➢ **Lower half of assembly is loaded with 4.0 wt% and upper half with 2.5 wt% plutonium**
- ➢ **With this the power derived from reactor could be increased by 20%**

Reactor Core

Table II. Main core design features of AHWR

Parameter	Value
Power MWe/ MWth	300/ 920
Power from Thorium/U233, %	~65
Total no. of channels	513
No. of Fuel channels	452
Active fuel length, m	3.5
Fuelling rate, annual:	
a) No. of Fuel clusters	78
b) Plutonium, kg	175
c) ^{233}U, kg	Nil (Self-sustaining)
Peaking Factors (maximum):	
Local/ Radial/ Axial	1.3/ 1.2/ 1.5
Average discharge burnup, MWd/Te	~36,000
Average heat rating, kW/m	10.8
MCHFR at 20% over power	1.7

Physics Safety Parameters/ Data

Parameter	Value
Power Density	10 kW/*l*
Linear Heat Rating (Average/ Maximum)	10.8/ 32.8 kW/m
Fuel Temperature Coefficient	-2.1 x 10^{-5} Δk/k/°C (285°C to 800°C)
Channel Temperature Coefficient	+2.5 x 10^{-5} Δk/k/°C (27°C to 285°C)
Coolant Temperature Coefficient	+4.9 x 10^{-5} Δk/k/°C (27°C to 285°C)
Coolant Void Coefficient	-5.0 x 10^{-5} Δk/k/% void (0.74 to 0.0 g/cc)
Delayed Neutron Fraction	0.003
Neutron Generation time	0.22 ms
SDS-1 Worth (Two rods not available 35/37)	50 mk
Minimum Shutdown margin with SDS-1	10 mk
SDS2 shutdown Device Worth	>100 mk
Passive shutdown Device Worth	>100 mk
Delay Timings in initiation of shutdown Devices	~ 0.5 sec
Excess Reactivity	~20 mk
Worth of control rods for Loss of Regulation	11 mk in 600 sec
Neutronic Trips:	
High neutron flux	> 110 % of Full Power
High neutron log rate or period	> 10 %/s

Core configuration

- **513 lattice locations - 452 fuel channels**
- **24 Reactivity Control Devices in lattice locations**
- **Two independent and diverse shutdown systems**
- **On-power fuelling**
- **Two variant of the fuel cluster (standard and alternate) to be fuelled in equal proportion to achieve self sufficiency in U-233**
- **Core monitoring and flux mapping system with more than 150 Detectors (SPNDs)**
- **Three burn up zones for power distribution flattening**
- **No xenon override problems due to low flux**

Reactivity Control in AHWR

- On-power Fuelling – long-term bulk & spatial reactivity control
- Reactor Regulating System (RRS) – short-term control of reactivity to control bulk power/ power distribution, power setback, xenon override
  - 24 control rods, poison addition/ removal
  - Control rods divided in three groups each having a reactivity worth about 11 mk and located based on power distribution control requirement

Regulating Rods (RRs) 8 Nos. Partially IN

- Primary control devices for bulk & spatial reactivity control

Absorber Rods (ARs) 8Nos. fully IN

- Used for xenon override, supplement RRs by providing positive reactivity

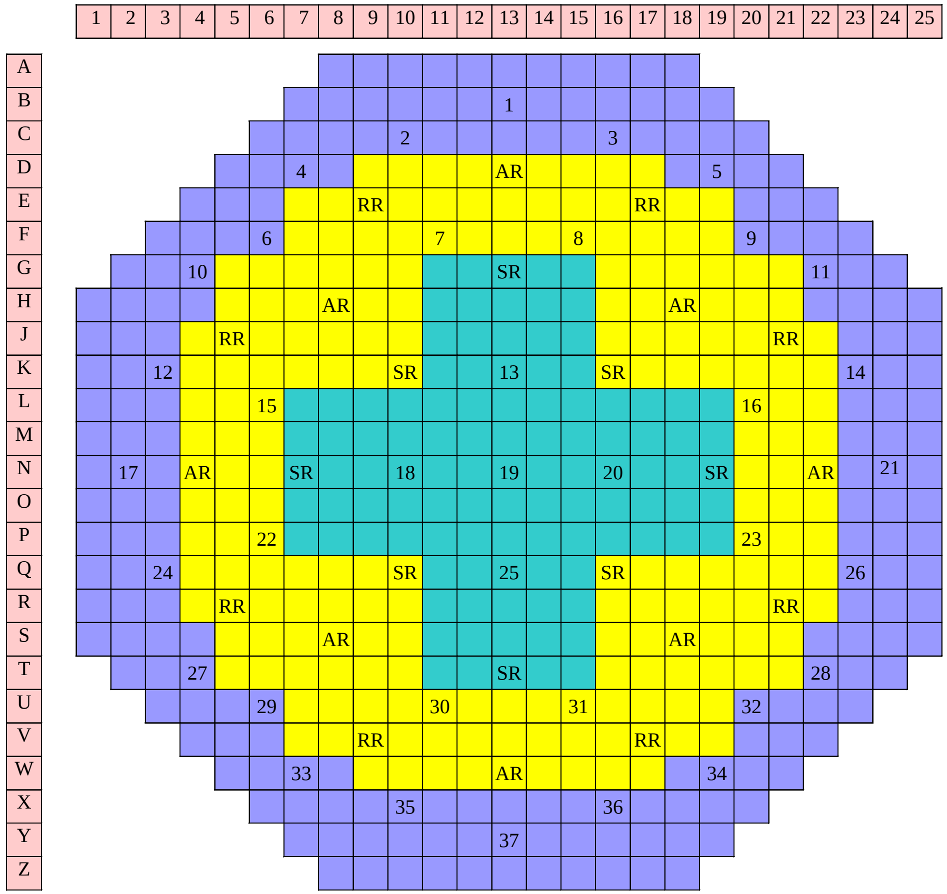
Shim Rods (SRs) 8Nos. fully OUT

- Used for power setback, supplement RRs by providing negative reactivity

Shutdown Systems in AHWR

- Two independent, fast acting & diverse shutdown systems (SDS)
- SDS-1 based on mechanical shut-off rods (Boron carbide) 37 Nos. dropping under gravity
- SDS-2 based on liquid poison injection (Gadolinium nitrate)
- Design objective is to provide initial reactivity insertion rate and depth to compensate all credible reactivity transients and enough reactivity depth to ensure sub-criticality following shut down with adequate sub-criticality margin (10 mk) assuming single failure
- SDS-1 reactivity worth 50 mk with two rods not available so as to meet shut down requirement under all conditions

Equilibrium core configuration - self sustaining in U-233



1-37 Shut-off Rods
RR Regulating Rods
AR Adjuster Rods
SR Shim Rods

48000 MWd/T
34500 MWd/T
28500 MWd/T

Optimized core power distribution (three burnup zones)

	28500MWd/te
	34500 MWd/te
	48000 MWd/te

Maximum channel power = 2.45 MW
Radial peaking factor=1.2
Core configuration - self sustaining in U-233

	13	12 14	11 15	10 16	9 17	8 18	7 19	6 20	5 21	4 22	3 23	2 24	1 25
A	2.04	1.87	1.78	1.72	1.63	1.66							
B	SOR	1.92	1.80	1.95	1.73	1.65	1.93						
C	1.82	1.73	1.99	SOR	1.99	1.79	1.96	2.1					
D	AR	1.72	1.90	2.10	1.98	2.07	SOR	2.07	2.13				
E	1.86	1.96	2.20	2.11	RR	2.03	2.22	2.20	1.93	2.13			
F	2.14	2.21	SOR	2.28	2.05	1.97	2.23	SOR	2.20	2.07	2.09		
G	SR	2.31	2.24	2.15	1.96	1.88	1.99	2.22	2.22	SOR	1.95	1.91	
H	2.32	2.15	2.08	2.15	1.97	AR	1.88	1.97	2.02	2.05	1.78	1.63	1.63
J	2.36	2.19	2.18	2.45	2.15	1.97	1.96	2.05	RR	1.96	1.97	1.71	1.59
K	SOR	2.40	2.39	SR	2.45	2.14	2.15	2.27	2.10	2.09	SOR	1.92	1.68
L	2.42	2.25	2.24	2.39	2.18	2.08	2.23	SOR	2.19	1.89	1.97	1.77	1.74
M	2.44	2.26	2.25	2.40	2.19	2.14	2.30	2.20	1.94	1.70	1.71	1.89	1.82
N	SOR	2.44	2.42	SOR	2.36	2.30	SR	2.14	1.84	AR	1.80	SOR	1.98

Reactivity balance in AHWR - Equilibrium core

Reactor core state	Reactivity, mk
Reactivity swings	
1. Cold to Hot Standby	
i) Channel Temperature (300 K to 558 K) { Coolant +11 mk ; Fuel -5.3 mk}	+ 5.7
ii) Moderator Temperature (300 K to 340.5 K)	+ 2.1
Total	**+ 7.8**
2a. Hot standby to Full power	
i) Fuel Temperature (558 K to 723 K)	- 3.5
ii) Coolant Void (Coolant density from 0.74 g/cc to 0.45 g/cc)	- 1.8
Total	**- 5.3**
2b. LOCA from Full power	
(Coolant density 0.45 g/cc to 0.03 g/cc)	**- 3.2**
3. Xenon Load	
i) Equilibrium load	**- 22.0**
ii) Transient load after Shutdown from full power (peak at about 7 hr)	**- 9.0**

Shutdown requirements in AHWR -Equilibrium core
Shutdown from full power

Shutdown requirement	Reactivity, mk	
Immediate		
Full power to hot standby	+ 5.3	
Hot standby to cold		- 7.8
Sub-criticality margin	+ 10.0	
Subtotal	+ *15.3*	
After one day		
Xenon decay	+ 22.0	
Subtotal	+ *37.3*	
After 3 days		
Pa-233 decay*	+ *1.0*	
Total	+ 38.3	

Negative reactivity is not taken into account
Loss of reactivity control = 11 mk
Shutdown Requirement 38.3 + 11 = 49.3 mk
Shutdown system reactivity worth 50 mk

Calculation Method/ model, accuracy & uncertainty

- **AHWR is a new thorium-based design**
- **Lattice calculation**
  - **Transport theory code WIMS-D/4 with 69 group ENDF/B-VI library**
  - **WIMS Code has been used extensively for PHWRs**
  - **For AHWR results compared with CLUB Core calculation**
  - **The validation of the WIMSD code for thorium fuelled lattices has been done as part of WLUP.**
- **Core calculations**
  - **3D code FEMINA/ FEMTAVG – a diffusion theory code based on higher order nodal expansion method incorporating on-power refuelling (time-averaged simulation)**
  - **Suitable for AHWR where mean free path is less due to use of light water coolant. And, large-sized mesh of fuel assembly dimensions can be taken without any loss in accuracy**

Calculation Method/ model, accuracy & uncertainty

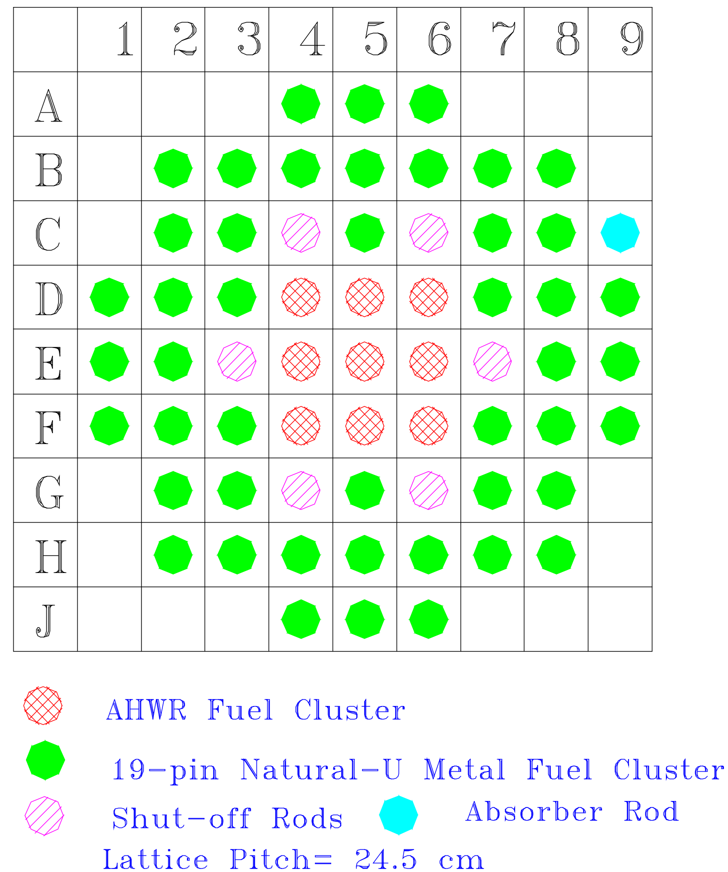
- FEMINA code has been tested extensively with various LWR and PHWR benchmarks.
- It has been used in simulations of PHWRs.
- Coolant density variations are simulated by carrying out a combined neutronic thermal hydraulic calculation iteratively using codes ARTHA & FEMINA/ FEMTAVG.

- **Major source of uncertainty - nuclear data**
  - sensitivity studies with respect to nuclear data for coolant temperature, void reactivity, fuel temperature, channel temperature have been done.
    - Coolant void reactivity spread : ~ 3 mk
    - Fuel temperature reactivity spread: 0.2 to 0.3 mk
    - Coolant temperature reactivity spread : ~ 2 mk

Calculation Method/ model, accuracy & uncertainty Critical Facility

- **Experiments planned in low power BARC Critical Facility for Validation of codes and data uncertainties**
- **Void coefficient measurement, Reaction rate measurements and Flux profiles inside/around the fuel assembly/cluster; by inserting activation foils in few pre-selected removable pins at specified locations.**
- **Experiments can be carried out at different lattice pitch**

Fig.3 AHWR CORE



Fuel cycle flexibility, multipurpose displacer & different fuel-types

- **Slightly negative void coefficient, negative fuel temperature and power coefficient are important physics safety features**
- **While AHWR is designed for thorium utilization Fuel cycle flexibility is an inherent feature of AHWR because of Online fuelling that leads to efficient use of fuel**
- **Multipurpose Displacer Plays key role in achieving Fuel cycle flexibility as it**
  - **acts as conduit for ECCS**
  - **aid in fuel reconstitution, and**
  - **helps in achieving desired void reactivity coefficient**
- **AHWR can use different type of fuel effectively without significant change in design**

Low Enriched Uranium (LEU) based AHWR

- LEU
  - 2.0 wt% U235 gives 25000 MWd/t compared to 20,000 Mwd/t of Candu ACR 700
  - Low cluster peaking factor, flatter variation of void coefficient with burn up
  - Fissile Inventory ratio low
- (Th, 19.75 %LEU)
  - 3.0 wt% U235 gives 30,000 MWd/t
  - Low cluster peaking factor (1.2), no significant variation of void coefficient
  - Core power distribution similar to AHWR equilibrium core can easily be obtained
  - Fissile Inventory ratio high at 0.6
- AHWR
  - 3.0 wt% fissile in AHWR gives 36,000 MWd/t in closed cycle

Both for LEU & LEU/Th no gray absorber is needed in displacer

Initial core and pre-equilibrium core

- **Initial core to be based largely on plutonium fuel for the generation of U-233 needed for equilibrium core**
- **Relatively lower discharge burn up obtainable in initial core due to various difficulties in core reactivity/ power distribution management**
- **Plutonium required for 54 fuel pin cluster is large**
- **As the availability of plutonium is limited a 42 fuel pin cluster with inner 12 pins replaced by zircaloy pins is designed especially for initial core**
- **This cluster permits substantially lower (78%) fuel loading at the cost of slightly lower power due to low peaking factor**
- **To further reduce plutonium requirement initially a combination of uranium and thorium based MOX fuel is proposed.**
- **Overall, the transition to equilibrium core may take 10-15 full power years.**

Xenon Spatial Instabilities

- **AHWR is neutronically a large sized reactor**
- **Characterized by low neutron leakage resulting in neutron decoupling**
- **Extent of decoupling is manifested in low eigenvalue separation of higher modes with respect to the fundamental mode**
- **Channel thermal hydraulics and void reactivity feedback can lead to flux distortions that could develop into instabilities at a very short time scale of seconds that are extremely difficult to control**
- **Xenon spatial instabilities occur under normal operating condition at the time scale of minutes to hours and are easy to control**
- **More pronounced in reactors with low enriched fuel such as PHWRs**
- **But not that acute in AHWR because of low-power-density and use of thorium fuel**
- **Large number of control rods (24) and in core detectors (150 SPNDs) distributed throughout the core for the control and monitoring of Xenon Spatial Instabilities**

AHWR & PHWR

	AHWR-300	PHWR-540
Fuel	$(Th,U233)O_2$ & $(Th,Pu)O_2$	UO_2
Coolant/ Moderator	H_2O/ D_2O	D_2O/ D_2O
Number of lattice/ fuel locations	513/452	392/ 392
Lattice pitch, mm	225	286
Number of fuel pins per cluster	54	37
Core height/ length, m	3.5	6.0
Core Diameter, m	2.9	3.1
power to coolant, MWth	920	1730
Fissile Material, wt% HM	3.0	0.7
Discharge burnup, MWd/te	36,000	6700
Power density, kW/l	10.1	10.0
Linear heat rating (maximum), kW/m	32.8	55

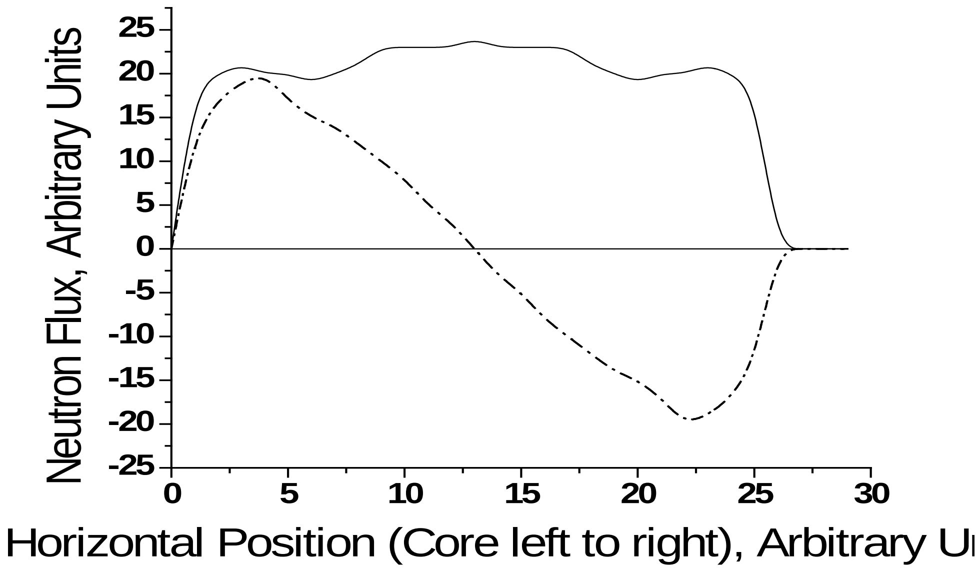
Xenon Spatial Instabilities - Effect of Reactor shape

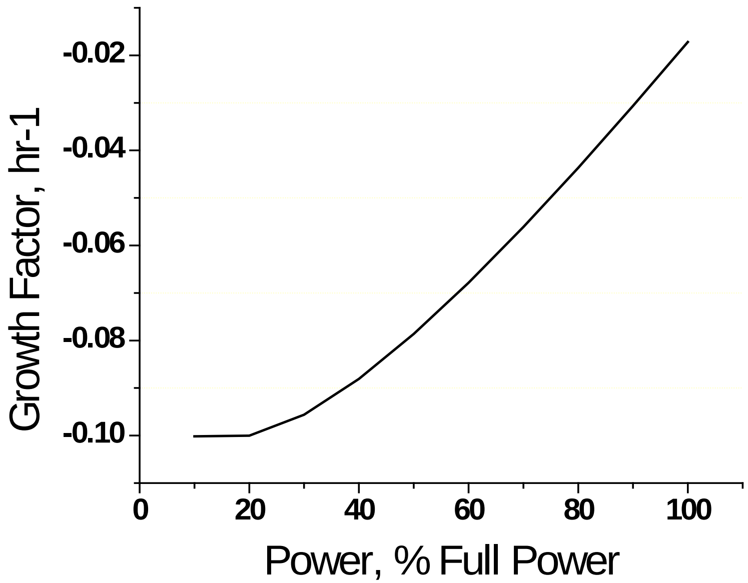
H/ D ratio low in AHWR

Table 4 . Realtive Size and Eigenvalue Separation, AHWR Vs PHWRs

Reactor/ Power, MWe	Core Radius, m	Migration length, M, m	R^2/ M^2	Eigenvalue Separation, 1st Azimuthal Mode, mk
PHWR/ 220	2.25	0.19	140	25
PHWR/ 540	3.15	0.20	250	15
AHWR/ 300	2.9	0.15	375	9.5

Xenon Spatial Instabilities - control of first azimuthal mode due to large core diameter





Shape of Fundamental mode and first azimuthal mode flux shapes (Left) and Growth of Xenon spatial instabilities at different power levels (Right) from linear stability analysis

With negative power feedback growth factor will be more negative

Conclusions

- ***The design of AHWR has evolved from a seed and blanket core to a uniform core consistent with the natural circulation of coolant to meet the objectives***
- ***Effective utilization of thorium in closed fuel cycle with almost two-third of power derived from Thorium/ U-233***
- ***Core averaged discharged burnup increased from 20,000 MWd/te to 36,000 MWd/te by extensive modification of cluster to improve neutron economy and void reactivity coefficient on one hand and engineering efforts in reduction of the lattice pitch on the other hand***
- ***Creation of multipurpose displacer has helped in engineering ECCS and obtaining desired void reactivity coefficient for different fuel types and a core configuration self sustaining in U-233***
- ***Design of Initial core and pre-equilibrium core for the generation of U-233 is presently being worked out***