On the Physics Design of Advanced Heavy Water Reactor (AHWR)

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Abstract: Nuclear power programme of India envisages a large-scale utilization of thorium as it has large deposits of thorium while the availability of uranium is limited. A thorium based Advanced Heavy Water Reactor (AHWR) is being designed and developed in India for thorium utilization. AHWR is a 920 MWth / 300 MWe, vertical pressure tube type thorium-based reactor cooled by boiling light water and moderated by heavy water. It uses thorium in closed fuel cycle with ^{233}U in a self-sustaining configuration employing plutonium as the external fissile feed and derives about two-third of its power from thorium fuel. It has several passive safety features including negative coolant void reactivity coefficient and heat removal through natural circulation. All through the design development of AHWR use has been made of our experience in design, operation and safety aspects of Pressurized Heavy Water Reactors (PHWRs) and Boiling Water Reactors (BWRs) currently operating in India. In this paper, we give a brief account of the physics design features/ objectives and how they have been achieved in the current design.

1. INTRODUCTION

The AHWR is a 300MWe/ 920 MWth, vertical pressure tube type thorium-based reactor cooled by boiling light water and moderated by heavy water. The prime objective is to produce power utilizing thorium available abundantly in India from a relatively simple system with enhanced safety level [1-6]. It is endowed with several innovative safety features such as negative coolant void reactivity, heat removal through natural circulation and passive containment cooling. The development of reactor design has drawn heavily on the experience generated through design and operation of Pressurized Heavy Water Reactors (PHWR) and Boiling Water Reactor (BWR) in India. It was an opportunity to develop a reactor system using thorium-based fuel and gain some valuable experience. A non-proliferate thorium/ ^{233}U based closed fuel cycle is chosen for AHWR. Plutonium discharged from PHWRs is used as the fissile seed fuel with thorium for the generation of ^{233}U and then as a top-up fuel in the equilibrium core along with self-sustaining ^{233}U in the thorium matrix. The physics design has several challenges in achieving negative void reactivity, fuel cycle, spatial core control, on-line fuelling and minimization of inventory of plutonium fuel.

It is difficult to achieve negative coolant void coefficient in a heavy water moderated pressure tube type reactor. For this a multi-pronged approach involving pitch reduction, heterogeneous cluster design and use of mild absorbers is chosen. Plutonium bearing fuel is located separately in the outer region of the cluster with self-sustaining ^{233}U bearing fuel in the inner region of the cluster. A small amount of mild absorber if required can be placed in the multipurpose displacer located in the centre of the cluster [7]. The void coefficient varies with burn up and it is a challenge to have it negative throughout the core. The state of nuclear data for the elements of interest and type of neutron spectrum in the reactor puts heavy demand on the calculation models and validation of reactivity coefficients to ensure safety [8]. A critical facility has especially been designed to carry out various lattice experiments to validate calculation models and nuclear data.

AHWR is a reactor with largely thermal spectrum and employs on-line fueling. Fuel cycle flexibility is its inherent characteristics and the current design works very well with the LEU fuel and also with thorium/ LEU fuel [9-10]. Equilibrium core is designed to run on self-sustaining closed fuel cycle of ^{233}U with plutonium discharged from PHWRs added as top-up fuel to gain in fuel burn up. Two variants of the fuel cluster with different fraction of plutonium are used to achieve self-sustaining thorium/ ^{233}U fuel cycle. It is seen that uranium fuel does not rapidly get degraded in the closed fuel cycle in AHWR and ensuring same inventory of ^{233}U in the reprocessed uranium suffices to a large extent to run the next cycle. However, to arrive at equilibrium core configuration ^{233}U must be generated in situ. For this purpose, initial and pre-equilibrium core is loaded largely with thorium-plutonium fuel. To overcome the scarcity of fissile plutonium, uranium-plutonium fuel is also used in the initial core of AHWR.

AHWR is neutronically a large reactor in comparison to the currently operating PHWRs that makes it susceptible to xenon induced oscillations and other spatial instabilities. It is seen that the first azimuthal mode is close to unstable and requires spatial control and monitoring. It is difficult to provide a large number of control elements and in-core detectors at a relatively tight lattice pitch. A quadrant control scheme is chosen that matches with the thermal hydraulic design of the reactor. There are six control elements in each quarter to control the reactivity and power distribution. About 150 SPNDs are installed in the core for on-line flux mapping and core monitoring. Further analysis is being carried out to ascertain the need of in-core detectors for the safety purpose.

2. PHYSICS DESIGN FEATURES

Heat removal by natural convection in normal operation and in accident condition is basic design feature of AHWR and dictates other characteristics. Effective and efficient utilization of thorium and the top up fuel plutonium with enhanced safety features is the prime objective from physics standpoint. Efficient utilization of thorium is possible in self sustaining mode in the closed fuel cycle only. As the plutonium that comes from the reprocessing of PHWR spent fuel is also scarce, its use too must be optimized to get high discharge fuel burn up. To achieve the above objectives, the physics design has evolved from a seed-blanket core design to a core consisting of a single type of cluster called D5 composite cluster containing both (Th-^{233}U) and (Th-Pu) MOX fuel pins in the equilibrium core configuration [7]. Some of the important physics design safety features are detailed below.

2.1 Reactivity coefficients / Fuel cluster

The coolant void reactivity coefficient in a pressure tube system is normally positive as the system is over moderated. In AHWR coolant has been replaced by light water coolant and that would make it more positive. The cluster design is mainly dictated by the objective of achieving negative void reactivity coefficient. To achieve the above objectives, the physics design has evolved from a seed-blanket core design with widely varying cluster types to a core consisting of a single type of cluster called D5 composite cluster. The void reactivity can be made negative with harder spectrum, which could be achieved either by changing the properties of the moderating medium or by decreasing the inventory of moderator. It is also possible to achieve negative void coefficient by using a burnable absorber in the fuel or in isolated pins in an inert matrix [6-7]. On voiding, burnable absorber is made to absorb more neutrons. In an earlier design of AHWR a burnable absorber was employed in the centre of the cluster which made the void coefficient of reactivity negative [6]. The fuel utilization, however, suffered a lot due to large quantity of burnable absorber required. A radical modification in the cluster design was then carried out by putting fuel in the area of high neutron importance and relocating the ECCS in a multipurpose displacer in the centre of the cluster. With this change in the cluster design there was significant reduction in the void reactivity coefficient and increase in fuel utilization [7]. Target fuel discharge burn up could now be increased to 36,000 MWd/T from 20,000 MWd/T. In the current design, lattice pitch is further reduced to 225 mm to obtain harder neutron spectrum and that helped in the elimination of dysprosium absorber [12-13]. Now only a small quantity of grey absorber Zr/ SS is needed to be used, if required, in the displacer region. Fuel reconstitution and usage of different fuel types has also become very easy with the introduction of multi-purpose displacer. Void coefficient of reactivity varies with burn up but core averaged void reactivity is always negative. Fuel temperature coefficient is always negative and increases slightly with burn up as plutonium burns. Power coefficient is also negative throughout the range of interest.

The standard equilibrium core cluster is heterogeneous fuel assembly comprising (Th,^{233}U)MOX and (Th, Pu)MOX both and is called the D5 composite cluster arranged in a circular array of 54 fuel pins [7].The inner and middle ring of 12 and 18 pins contain (Th, ^{233}U) MOX and the outer 24 pins contain (Th, Pu)MOX. The inner ring of 12 pins has a ^{233}U content of 3.0 wt% by weight and the middle 18 pins have 3.75 wt% ^{233}U. The outer ring of (Th, Pu)MOX pins have an average of 3.25 wt% of total plutonium. The lower half of the active fuel will have 4.0 wt% plutonium and the upper part will have 2.5 wt% plutonium [7]. The design data of fuel channel and fuel is given in Table I. The cross section of the fuel cluster is shown in Fig. 1.

Table 1. 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
Pressure Tube: Material, ID/OD, mm	Zr-2.5% Nb, 120.0/128.0
Calandria Tube: Material, ID/OD, mm	Zircaloy-2, 163.8/168.0
***Multi purpose Displacer Tube*:**	
Material/OD/ ID, mm	Zircaloy -2 / 36/ 30
Solid Rod of grey material inside Displacer	Zircaloy -2 / SS

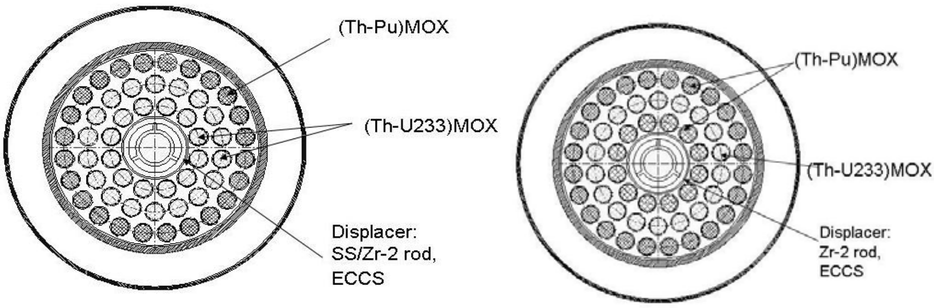


Fig. 1. Standard and alternate AHWR Fuel Clusters, respectively.

2.2. ^{233}U in self-sustaining configuration

One of the major objectives is to operate AHWR in the closed fuel cycle. The ^{233}U burns and is bred in situ in the cluster. It is possible only if system is self-sustaining in ^{233}U. With irradiation, the ^{233}U content would deplete in the inner (Th,^{233}U)MOX pins and would gradually build-up in the outer (Th, Pu)MOX pins due to conversion from thorium. The production of ^{233}U in the outer pins is however not sufficient to compensate for the burn up of ^{233}U in the inner pins. An alternate cluster is designed for this purpose. The alternate cluster as shown in FIG.1 is basically same as the standard cluster except that the 12 fuel pins in the alternate cluster contain 4.0 wt% plutonium in place of 3.0 wt% ^{233}U used in the standard cluster [11]. Reactor is fuelled with both the clusters in equal proportion. It is now possible to achieve the self-sustaining characteristics of ^{233}U with the annual plutonium consumption increasing by about 50 kg to 175 kg. The uranium from the discharged fuel would contain other isotopes of uranium like ^{234}U, ^{235}U and ^{236}U. But unlike the problem associated with the recycling of MOX in PWRs, the situation here is simple as the rate of build-up of higher isotopes and their absorption cross-section is much lower. The even higher isotopes do absorb neutrons but their reactivity load is compensated by ^{235}U. And it is possible to operate AHWR in successive cycles by employing the same enrichment of ^{233}U.

2.3. Plutonium as top up fuel

The usage and location of the plutonium in the cluster is important from the basic design objective of minimising the plutonium requirement. This is done by locating the plutonium pins in the outermost ring of the cluster, where it faces the highly thermalized flux. The plutonium used as top up fuel comes from the spent fuel of PHWRs. It has about 75% fissile plutonium. By virtue of being placed in the region of higher thermal flux, the plutonium leads to high fuel burn up. It however depletes at a faster rate that result in strong burn up dependence of some safety parameters such as void reactivity coefficient.

2.4. Graded fuel enrichment/ power uprating

The axial power profile is bottom-peaked in a BWR due to bulk boiling that leads to decreased moderation in the upper part of the core. In AHWR, in the absence of bulk boiling, the axial flux distribution is not enough distorted as there is not much change in the neutron moderation. The neutron flux with uniform fuel enrichment would therefore be nearly the same in the top and bottom portion of the core. One way to increase the power derived from the reactor is by decreasing the flux at core exit that increases minimum critical heat flux ratio (MCHFR) and hence thermal margins. An increased thermal margin translates directly into increased power. Desirable axial power distribution for this purpose is achieved by altering the plutonium content in the outer pins only; the lower half of the fuel assembly is loaded with 4.0 wt% plutonium and upper half with 2.5 wt% plutonium [7]. With this the power derived from the reactor could be increased by about 20%.

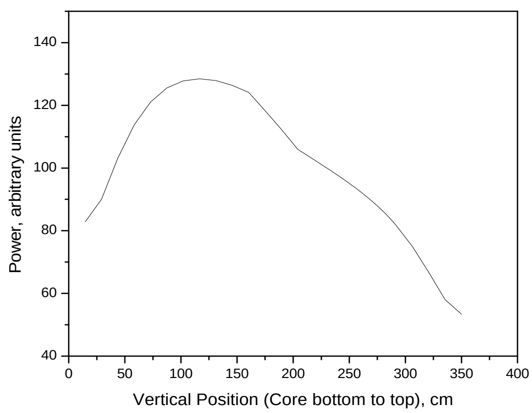


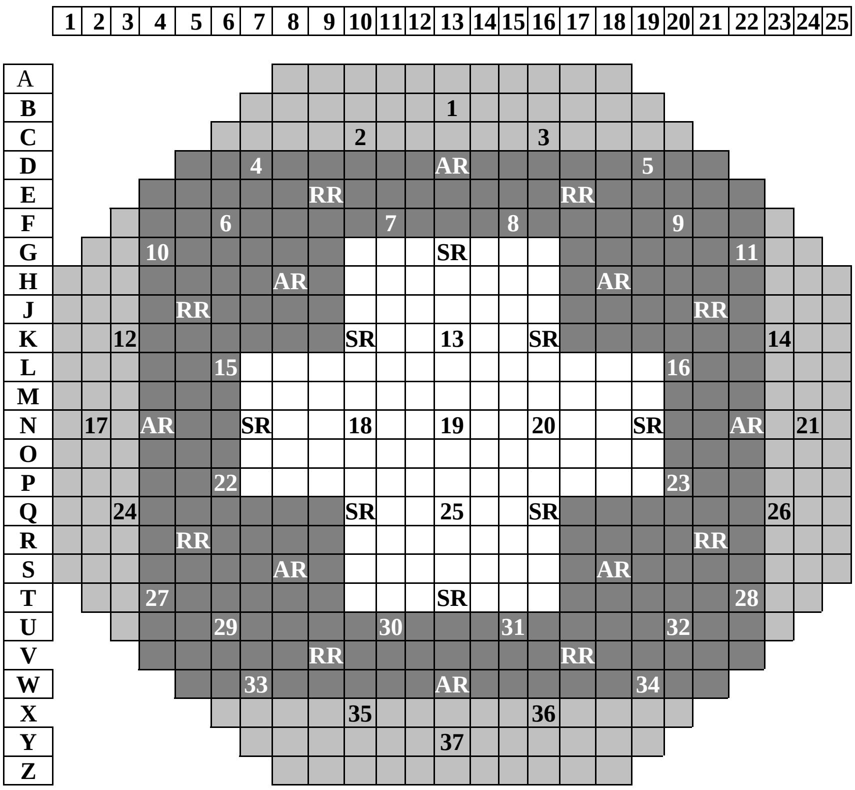
Fig. 2. Axial power distribution in a high powered channel

2.5 Multi-purpose displacer

The fuel cluster was redesigned by creating a region in the centre of cluster by displacing good amount of water, hence called displacer. ECCS was also shifted to this region and, in addition, it acts as an aid (support structure) for fuel reconstitution [7]. The region called multi-purpose displacer is basically a zircaloy-2 tube of 36 mm OD/ 30 mm ID housing ECCS with small holes radially for cooling fuel pins. To achieve desired negative coolant void reactivity characteristics a grey rod of an appropriate material may be located in the centre of displacer as shown in FIG. 1 for the equilibrium core cluster.

3. LATTICE AND CORE CALCULATIONS/ COMPUTER CODES/ SOURCES OF UNCERTAINTY

The lattice evaluations have been carried out by WIMS-D/4 code [14] and employ the 69 group library based on the ENDF-B/VI.8 dataset obtained from IAEA. This library comprises 14 fast, 13 resonance and 42 thermal groups. The D5 cluster has been modelled as a circular array cluster using the WIMSD code system. The methodology adopted was a heterogeneous infinite lattice cell calculation followed by a homogenous leakage calculation. The sequence of calculation is a detailed flux spectrum in the 69 groups for each of the principal regions of the lattice and then a detailed geometrical representation for a more accurate spatial solution using transport theory methods. The burn-up calculations have been performed with critical flux spectrum and operating temperatures. The results have been tested with the other code CLUB [15] developed in BARC and widely used for PHWR simulations. The burn up, temperature and void/ coolant density dependent two energy group parameters are generated by the lattice calculations. These are used in the core simulation. The core calculations are carried out by 3D code FEMINA [16] based on the higher order nodal expansion method. The advantage of this method is that meshes as large as fuel assembly size can be taken without any loss in accuracy. Heterogeneity within the core too is simulated accurately. As AHWR is a thermal system two energy group formulations appears sufficient for the core simulation. The code has been tested with several LWR/ PHWR benchmarks and has been used for PHWR calculations.



N	**Shut off Rod (1-37)**
AR	**Absorber Rod**
RR	**Regulating Rod**
SR	**Shim Rod**

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

Fig. 3. Layout of AHWR equilibrium core

Heat removal through natural convection is an important feature of this reactor, which would require a uniform coolant flow and a low power density. In order to have good thermal hydraulic and neutronic coupling, a uniform radial power distribution is preferred. It also requires the height of the active core to be kept small with respect to the diameter of the core. The core height has been chosen to be 3.5 m [5] and the vessel Calandria ID is 6.9 m from this point of view. Hence the number of lattice locations / channels is large at 513 in the core, out of which 452 locations are occupied by fuel and the rest by reactivity devices. Main core design and safety features are given in Table II. Layout of AHWR equilibrium core configuration self-sustaining in ^{233}U is shown in FIG.3.

Table 2. 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 target discharge burnup, MWd/Te	36,000
Average heat rating, kW/m	10.8
MCHFR at 20% over power	1.7
Control rods (CRs), Nos./ Reactivity worth, mk	24; Comprising 8 rods each of Absorber rods (ARs), Regulating rods (RRs) and Shim rods (SRs) / ~11 mk in each group, total 33 mk
Shut Down System-1	
Shutoff rods No. / Reactivity worth	37 Nos. / 70 mk (50 mk with two maximum worth rods not available)
Shut Down System-2	Liquid poison injection
Safety parameters:	
Delayed neutron fraction, β	0.003 (without photo-neutrons)
Prompt neutron generation time, Λ, ms	0.22
Core averaged reactivity coefficients in operating range:	
Fuel temperature, Δk/k/°C	-2.1×10^{-5}
Channel temperature , Δk/k/°C	$+2.5 \times 10^{-5}$
Void coefficient, Δk/k / % void	-5.0×10^{-5}
Coolant temperature , Δk/k/°C	$+4.9 \times 10^{-5}$

A	1.86	1.72	1.65	1.6	1.52	1.52							
B	SOR	1.87	1.77	1.9	1.71	1.62	1.8						
C	1.9	1.83	2.08	SOR	2.07	1.89	2.01	2.07					
D	AR	1.82	1.99	2.16	2.04	2.12	SOR	2.1	2.08				
E	1.92	2.02	2.25	2.12	RR	2.06	2.24	2.24	1.97	2.07			
F	2.36	2.42	SOR	2.27	2.02	1.94	2.2	SOR	2.23	2.09	2.06		
G	SR	2.37	2.27	2.12	1.92	1.83	1.95	2.2	2.24	SOR	2.01	1.8	
H	2.34	2.17	2.08	2.1	1.91	AR	1.83	1.94	2.06	2.12	1.88	1.61	1.5
I	2.38	2.19	2.16	2.39	2.08	1.91	1.91	2.02	RR	2.03	2.06	1.7	1.5
J	SOR	2.39	2.37	SR	2.39	2.1	2.12	2.26	2.11	2.15	SOR	1.89	1.58
K	2.4	2.23	2.21	2.37	2.16	2.08	2.27	SOR	2.24	1.98	2.07	1.75	1.62
L	2.42	2.24	2.23	2.39	2.19	2.17	2.36	2.41	2.02	1.81	1.82	1.86	1.69

Moderator temperature, Δk/k/°C $+5.5 \times 10^{-5}$

Fig. 4. Equilibrium core power distribution

The core simulations presented here have been done for the equilibrium core configuration. The time-averaged simulations are done to get optimum discharge burn up and flattened channel power distribution for the equilibrium core configuration, whereas homogeneous simulations were used to calculate worth of reactivity devices. The limits on channel power are governed by the minimum critical heat flux in the channel. For this, physics and thermal hydraulic iterations are necessary. For this purpose, the neutronics code and the thermal hydraulic code has been combined to run in tandem.

Table 3. Reactivity balance in AHWR

Reactor core state	Reactivity, mk
Reactivity swings	
1. Cold to Hot Standby	
i) Moderator Temperature (300 K to 340.5 K)	+ 2.1
ii) Channel Temperature (340.5 K to 558 K)	+5.7
{Coolant +11.0 mk; Fuel -5.3 mk}	
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	
2b. LOCA from Full power	- 5.3
(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

Starting with the same average coolant density and iteratively modifying the coolant density with respect to power distribution [17]. These iterations are continued till a convergence of <0.1% in the mesh powers is obtained. The channel power converges in 3 to 4 iterations. The converged power distribution in quarter core for the equilibrium core self-sustaining in ^{233}U is shown in FIG. 3.

The reactivity balance is listed in Table III. . It can be seen that overall reactivity swing from cold critical to hot standby, excluding reactivity changes coming from fission products, is quite low at about 8 mk. Though the coolant temperature coefficient is positive with a total swing of about 11.0 mk, the channel temperature coefficient is about 6.0 mk positive and can easily be controlled by Reactor Regulating System (RRS). Moderator temperature coefficient, too, is low positive and is within the range of regulating system. All reactivity swings from cold critical to hot zero power and hot zero power to full power are well within the range of reactor regulating system. The reactor start-up is slow operation carried out under supervision of RRS. There is enough reactivity depth in RRS to take care of reactivity changes during start-up. Though the coolant temperature coefficient is positive, fuel temperature coefficient is prompt and negative which is of prime importance during a transient. Equilibrium xenon is about 22 mk, which can be controlled either by boron or by gadolinium in moderator. Transient load of xenon following reactor shut down is only 9.0 mk due to considerably low levels of thermal flux.

As stated above, computer codes used in the calculations are well tested and benchmarked. Major source of uncertainty, however, comes from the nuclear data used. Main physics safety parameters coolant temperature and coolant void reactivity coefficients are highly susceptible to the multigroup library used for the lattice calculations [8]. Fuel temperature coefficient is, however, high negative throughout the burn up range and does not depend much on the multigroup library/ dataset used. A series of experiments are planned in the low power critical facility for this purpose.

4. FUEL CYCLE FLEXIBILITY

The design of AHWR has evolved from the presently operating PHWRs and BWRs in India. It is basically a heavy water reactor with coolant replaced by boiling light water. The important feature of online fuelling of PHWRs has been retained. The displacer in AHWR cluster is multipurpose in that, first, it acts as a conduit for ECCS; second, it acts as an aid in fuel reconstitution; and, third, it helps in achieving desired void reactivity coefficient. It is the last property of negative void coefficient that is important from physics standpoint. AHWR is designed primarily for the utilization of thorium. However, fuel cycle flexibility is an inherent feature of AHWR and a variety of fuel-types could successfully be used for generating power efficiently [9-10]. This is achieved largely by making some minor changes in the design of multipurpose displacer. For the present AHWR equilibrium core fuel, a grey rod of SS/zircaloy is used to achieve desired void reactivity coefficient. For LEU fuel, with no thorium, it was seen that no grey material is required in the displacer and desired void reactivity is easily obtained. In fact, the discharge burn up of about 25000 MWd/te can be achieved with 2.0 wt% enriched uranium fuel. Not only this, a relatively low cluster peaking factor of 1.2 is obtained. This is quite encouraging in comparison to about 20000 MWd/te for Candu ACR-700 with 2.1 wt% enriched uranium fuel. For the Thorium/ 19.75% LEU fuel with a fissile ^{235}U enrichment of 3.0 wt% a discharge burn up of about 30000 MWd/te is achieved. Also, for this fuel variation of void coefficient with burn up is practically flat and a low cluster peaking factor is obtained. Higher discharge burn up of 55000 MWd/te can be obtained from 4.0 wt% fissile, but then online fuelling is difficult at very high discharge burnups. For the initial core of AHWR that uses thorium/plutonium fuel to start with, it was seen that a zircaloy-2 rod may be used. Power distribution is optimized by adopting multi-zone fuelling in a time-averaged calculation for online fuelling. It may be noted that a similar power distribution is easily achieved for different fuel cycles and that radial/axial form factors remain practically unchanged. In this way, one can fuel online to a multi-zone core with different discharge burnups with a variety of fuel-types. However, with online fuelling discharge burn up cannot be too high due to reactivity considerations. AHWR can therefore efficiently generate power from a variety of fuel-types. The multipurpose displacer plays a key role in achieving this objective. In fact, discharge burn up for LEU fuel is seen to be higher in comparison to CANDU ACR as the latter is constraint to use burnable absorber. Also, for most of above fuel-types the void reactivity exhibits a favourable flatter variation with burn up and cluster peaking factor is relatively low.

5. INITIAL CORE AND PRE-EQUILIBRIUM CORE

The basic fuel cycle is based on the fact that the AHWR core will be self-sufficient in ^{233}U. This is made possible/ achieved by using plutonium as top-up fuel. The much needed plutonium inventory will come from fuel irradiated in PHWRs currently operating in India. The ^{233}U required is to be bred *in situ*, which implies that the initial core will be based largely on plutonium fuel. There will be gradual transition from the initial core to the equilibrium core – a phase normally referred to as pre-equilibrium core phase. And, during this transition phase a relatively larger quantity of plutonium would be required. As the availability of plutonium from fuel irradiated in PHWRs is scarce, it is imperative to optimize the plutonium consumption in AHWR initial and pre-equilibrium core.

A new 42 pin cluster has been designed especially for this phase of reactor core. Its design is same as the standard fuel cluster except that the 12 fuel pins in the inner ring are replaced by the zircaloy-2 pins [18]. Its major attractive feature is that cluster peaking factor is quite low and reactivity coefficients are in desired range. This cluster permits substantially lower (78%) fuel loading at the cost of slightly lower power. Yet the initial charge of plutonium and annual feed until the induction of ^{233}U is high at 1.0 te and 400 kg respectively. This is because about 3-3.5 wt% of plutonium enrichment is required for thorium fuel to have an acceptable discharge burn up of around 15,000 MWd/te. Further, Initial core fuel gives relatively lower burn up due to various difficulties in core reactivity/ power distribution management. During this phase, refuelling and reshuffling is adopted to minimise fresh fuel consumption and approach the design equilibrium power distribution as early as possible. To get around this difficulty, it is proposed that the initial core be fed on a combination of uranium based and thorium based fuels. This will result in lower initial plutonium requirement. The core has to be refuelled with the (Th, Pu)MOX fuel until some ^{233}U is available from the discharged fuel. Thereafter, core may be refuelled with a combination of (Th, Pu)MOX clusters and composite clusters. Overall, the transition to equilibrium core may take 10-15 full power years.

6. XENON SPATIAL OSCILLATIONS

AHWR is neutronically a large sized reactor and like most of the currently operating reactors would need core power distribution control and monitoring. Large reactors are characterized by low neutron leakage resulting in neutron decoupling. The extent of decoupling is manifested in low eigenvalue separation of higher modes with respect to the fundamental mode. And it gives rise to the power distribution distortions due to the excitations of higher modes. In Table IV, size of different reactors in terms of migration area and the eigenvalue separation for the first azimuthal mode are listed. A 3D code MODCAL based on power iteration scheme has been used for the simulation of higher modes and corresponding eigenvalue separation. The flux distribution for the fundamental mode and the first azimuthal mode is shown in FIG. 4. Relatively lower values for the large reactors are responsible for their decreased core stability. The transient power distribution requires spatial control on different time scales depending on the type of perturbation and the feedback involved. 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. It is extremely difficult to control such instabilities and efforts are made to identify and avoid such operational regimes and, if possible to make remedial changes in reactor design. Other instabilities occurring under normal operating condition at the time scale of minutes to hours due to feedback effect of xenon have acquired great importance from the standpoint of spatial control. The problem is more pronounced in reactors with low enriched fuel such as PHWRs [19]. As seen from Table IV the eigenvalue separation for the first azimuthal mode for AHWR is lower than the 540 MWe PHWR. AHWR core is therefore more decoupled in comparison to the 540 MWe PHWR core. A quadrant control scheme that conforms to the thermal hydraulics design of the reactor is used to control the power distribution. It is carried out by the RRS. There are 24 control elements 6 in each quarter to control the power distribution. About 150 SPNDs are installed in the core for on-line flux mapping and core monitoring. The problem of xenon oscillations is however not acute in AHWR because of low-power-density and use of thorium fuel. A linear stability analysis, similar to the one carried out for the 540 MWe PHWR [19], was done for the first azimuthal mode in AHWR. The growth factor of the xenon spatial instability is seen to be negative all through the operating range, as shown in FIG. 5, indicating damped oscillations. Negative power feedback is not considered here which is expected to further damp the oscillations.

Table 4. Relative 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

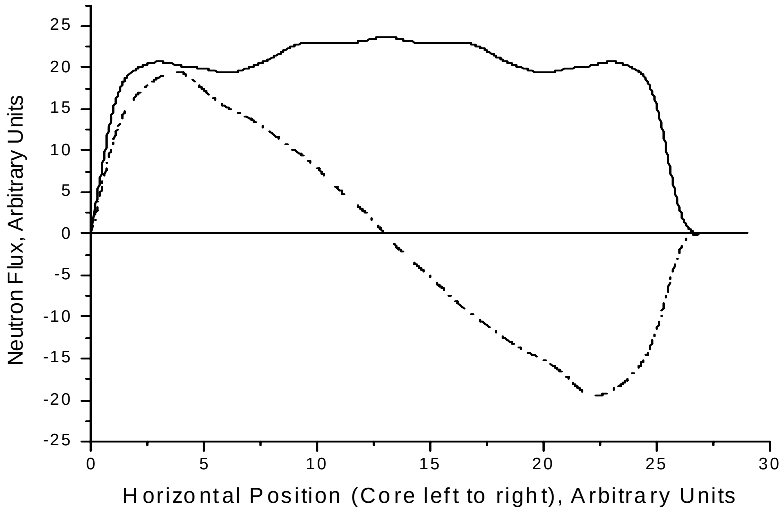


Fig. 4. Neutron flux distribution in the fundamental mode and first azimuthal mode, respectively, for AHWR

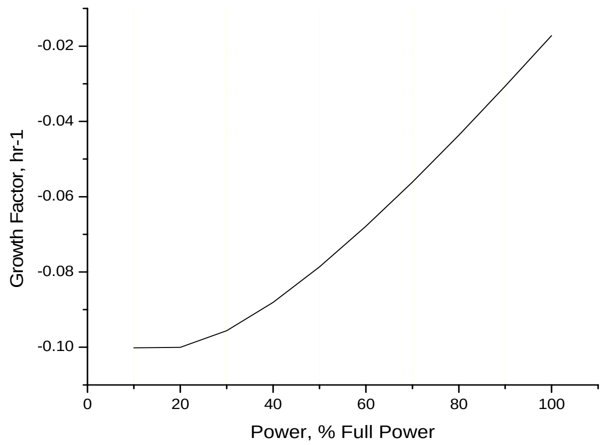


Fig. 5. Growth factor of xenon spatial instabilities Vs power level for the first azimuthal mode

7. CONCLUSIONS

Enhanced safety features and demonstration of technologies for thorium fuel have been the basic tenants of AHWR designed and developed for thorium utilization. The physics design of AHWR has evolved along with the engineering design from a seed and blanket core to a uniform core with composite clusters and has been consistent with the innovative safety features including heat removal by natural circulation to achieve the objectives of thorium utilization. It is now possible to derive almost two-third of power from Th/ ^{233}U fuel in the closed fuel cycle self-sustaining in ^{233}U. The core average discharge burn up could be increased from 20000 MWd/Te to 36000 MWd/Te with the radical changes made in the cluster design and lattice pitch reduction while achieving slightly negative coolant void reactivity coefficient without using burnable absorber. Creation of multipurpose displacer in the central part of cluster has made it possible to use various fuel-types with ease. It is seen that because of low power density and use of thorium fuel xenon spatial oscillations are not unstable and can easily be controlled by the reactor regulation system. Presently, the design of an initial core and pre-equilibrium core for accumulation of ^{233}U is being optimized.

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