Fuel cycle flexibility in Advanced Heavy Water Reactor (AHWR) with the use of Th-LEU fuel

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Abstract

The Advanced Heavy Water Reactor (AHWR) is being designed for large scale commercial utilization of thorium (Th) and integrated technological demonstration of the thorium cycle in India. The AHWR is a 920 MW(th), vertical pressure tube type cooled by boiling light water and moderated by heavy water. Heat removal through natural circulation and on-line fuelling are some of the salient features of AHWR design. The physics design of AHWR offers considerable flexibility to accommodate different kinds of fuel cycles. Our recent efforts have been directed towards a case study for the use of Th-LEU fuel cycle in a once-through mode. The discharged Uranium from Th-LEU cycle has proliferation resistant characteristics. This paper gives the initial core, fuel cycle characteristics and online refueling strategy of Th-LEU fuel in AHWR.

1. Introduction

The AHWR [1-4] design offers considerable flexibility to accommodate different kinds of fuel cycles. Use of Low Enriched Uranium (LEU) fuel with Thorium (Th) in AHWR has several attractive features like enhanced safety where the reactivity coefficients like channel temperature coefficient and void reactivity coefficient during normal and transient situations are negative by design. The delayed neutron parameter β will be larger than the reference AHWR fuelled with (Th, Pu) MOX and (Th, ^{233}U) MOX and hence enhanced controllability. The Th-LEU fuel has better proliferation resistant characteristics. The fuel cycle would be operated in a once-through mode. AHWR with (Th, LEU) MOX (AHWR-LEU) fuel is also 920 MW(th) vertical tube type thorium based boiling light water cooled and heavy water moderated reactor [5]. The fuel consisting of low enriched uranium with initial configuration 19.75% ^{235}U and 80.25% ^{238}U was used along with thorium in all the 54 pins of the AHWR fuel cluster designated as D5 cluster. The cluster is axially graded to improve thermal hydraulic margins.

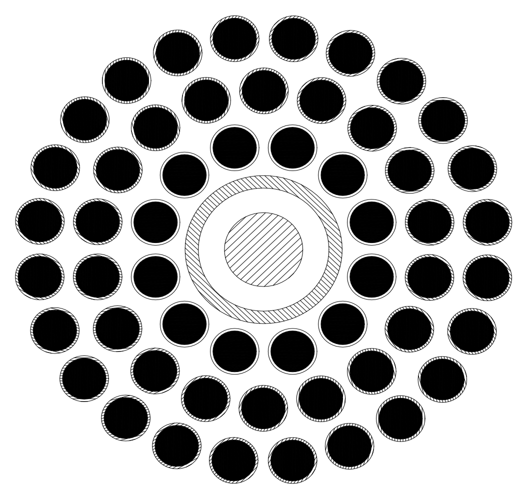


Fig.1 Cross section of AHWR cluster

2. Computation Tools

2.1 Modeling for lattice calculations

The lattice calculations were performed by using Neutron Transport Theory computer code ITRAN [6-7]. The computer code ITRAN is indigenously developed very versatile tool for lattice calculations. It can perform the calculations either based on a combination of interface current formalism and collision probability method (called as IC method) or the pure collision probability (CP) method. The calculations were performed using 69- group library based on ENDF-B VI.8 nuclear data obtained from IAEA [8].

2.2 Core calculations

The core calculations were carried out by using 3D diffusion theory code FEMTAVG [9] for global calculations, which uses nodal expansion method to solve for the fluxes in two-group. For the core optimisation studies we have used the two-group formalism. The time-averaged simulations were performed to optimize the discharge burnup for a flat neutron flux / power distribution for the equilibrium core configuration by the diffusion theory code FEMTAVG. The initial core optimization and core followup studies along with fuel management studies have been carried out by the diffusion theory code FEMFOL [9], which uses nodal expansion method to solve for the fluxes in two-group

2.3 Refueling

On power refueling has been simulated by using core followup code FEMFOL. The rules for selecting a channel for on power refueling were designed on the basis of experiences earned in PHWRs operation. The channel selection rules for refueling were improved or modified to suit the requirements of AHWR-LEU. The channel selection rules were converted into logics to select the channels automatically for refueling and a set of such selected channels for refueling were simulated by FEMFOL. Hence a computer program was developed for automatic selection of channels for refueling and reshuffling for fuel cycle study of AHWR. This program was found to be very useful in the present study of the fuel cycle and the core behavior from initial core to equilibrium core.

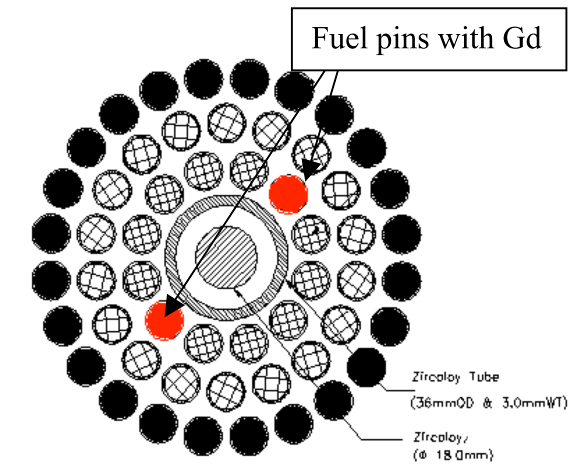
3. Equilibrium Core Cluster

In order to realise the benefit of Thorium as a fertile host, the design discharge burnup should be high (say between 50.0 GWd/Te to 60.0 GWd/Te), hence the cluster should be designed for higher reactivity. The average fissile enrichment for getting a target burnup of 60GWd/Te is ~ 4.2%. To suppress initial high reactivity of cluster (in order to control the power ripple), various options of mixing poison in the equilibrium core cluster were considered for an average discharge burnup about 60.0 GWd/Te. The followings are some typical cases studied in the present context.

a. Uniformly distributed burnable poison (Gadolinium) in all the fuel pins of the different rings (inner/middle/outer) of the cluster
b. Slow burning poison Erbium (Er) in outermost ring of the cluster
c. High concentration of burnable poison (Gadolinium) in only few pins of innermost ring of cluster

Earlier studies [10] showed that the presence of Gadolinium (Gd) uniformly in all the pins of a given ring of a cluster becomes ineffective after a burnup of about 2.0 GWd/Te. The very fast burning characteristics of the Gd are not useful for the core with very high discharge burnup (60 GWd/Te). Therefore while studying the on power refuelling of the core with the clusters containing uniformly distributed Gd in the fuel pins of a given ring, the power peaking was controlled only to a limited extent.

The subsequent studies were carried out with a slow burning poison Erbium (Er) uniformly distributed in all the pins of the outermost ring of the cluster. In a typical case the outermost ring was containing about 0.7 % of Er (average). The on power refuelling studies with the cluster showed that power peaking due to refuelling can be controlled to considerable extent. However, the burnup penalty due to Er was significantly high (~6-8GWD/Te) [11].



Another alternative is to study the effect of high concentration of Gd in few pins of the innermost ring. Different types of cluster designs containing 3 %, or 5 % or 7 % Gd in two pins or three pins of the innermost ring were studied. Finally a cluster with 5% Gd in the two pins of the innermost ring was considered for further core calculations. The cluster containing 5 % Gd in the two pins of inneremost ring was found to be most suitable for on power refuelling. The burnup penalty due to presence of Gd in this case is found to be ~3GWd/Te. The LEU content in different rings of the cluster is given in Table-1. The cross-section view of AHWR-LEU cluster containing 5 % Gd in the two pins is shown in Fig-2. The average discharge burn up of the cluster using time average calculations (FEMTAVG) was estimated to be about 61.0 GWd/Te. The cluster has been designed to have maximum ring power peaking of about 1.15 and the preliminary thermal hydraulic analysis revealed that the allowable maximum channel power for the cluster is about 2.85 MW. The ring power peaking factors of the cluster for various burnup are given in Table-2.

Table-1

Fuel Type (Fissile Content)	Axial Gradation	LEU content (%) in various rings of cluster				U-235 Content	K_∞ (0 MWd/Te Xe Sat.)
		Inner	Middle	Outer	Cluster Average		
^{235}U-Th (4.29%)	Upper	30	24	14	20.88	4.12 %	1.173
	Lower	30	24	18	22.66	4.47 %	1.215

Table-2

LEU	Burnup	Ring power factors of various rings	U-235 Content

Content	(GWd/Te)	of cluster			in %
		Inner	Middle	Outer	
Upper Half, Avg. LEU is 20.88%	0	0.87	1.04	1.04	4.12% U-235
	10	0.98	1.02	0.99	
	30	1.05	0.99	0.98	
	70	0.92	0.91	1.11	
	90	0.86	0.89	1.15	
Lower Half, Avg. LEU is 22.66%	0	0.80	0.93	1.15	4.47% U-235
	10	0.90	0.94	1.09	
	30	1.01	0.96	1.03	
	70	0.94	0.91	1.10	
	90	0.87	0.90	1.14	

4. Initial Core

The initial core loading with equilibrium core cluster requires large amount of neutron poison (boron) to be dissolved in moderator to quench the initial core excess reactivity. Moreover, in order to achieve full power from the beginning flux flattening is required for the initial core. Generally, flux flattening is achieved by using differential enrichment in the central and outer region of the core. Hence two types of fuel clusters with lower content of LEU (Type-1 & Type-2) have been proposed to load with differential LEU content and loading pattern has been chosen such that power distribution with low power peaking is achieved. Both the fuel types are axially graded to improve thermal hydraulic margins and the LEU content in these clusters have been selected such that the boron management in the moderator is not difficult. *Table-3* gives the composition of two clusters used in the initial core loading. The cluster has been designed to have maximum ring power peaking of about 1.16 such that maximum channel power limit of 2.85 MW is applicable to initial core too. *Table-4* gives the variation of ring power peaking factors with burnup for both the clusters used in initial core.

Table-3

Fuel Type (Fissile Content)	Axial Gradation	LEU content (%) In Various Rings Of Cluster				U-235 Content	K_∞ (0 MWd/Te Xe Sat.)
		Inner	Middle	Outer	Cluster Average		
Type-1	Upper	18	15	10	13.44	2.65 %	1.1149
	Lower	18	15	12	14.33	2.83 %	1.1471
Type-2	Upper	14	11	08	10.33	2.04 %	1.0168
	Lower	14	11	11	11.66	2.30 %	1.0783

Table-4

Ring Power Factors	Type-1 (Upper Half)		Type-1 (Lower Half)		Type-2 (Upper Half)		Type-2 (Lower Half)	
Burnup (GWd/Te)	0.0	10.0	0.0	10.0	0.0	10.0	0.0	10.0
Inner Ring	1.00	0.99	0.94	0.95	1.04	0.99	0.92	0.92
Middle Ring	1.0	0.98	0.92	0.93	0.97	0.94	0.84	0.87
Outer Ring	1.0	1.02	1.09	1.08	1.00	1.05	1.16	1.13

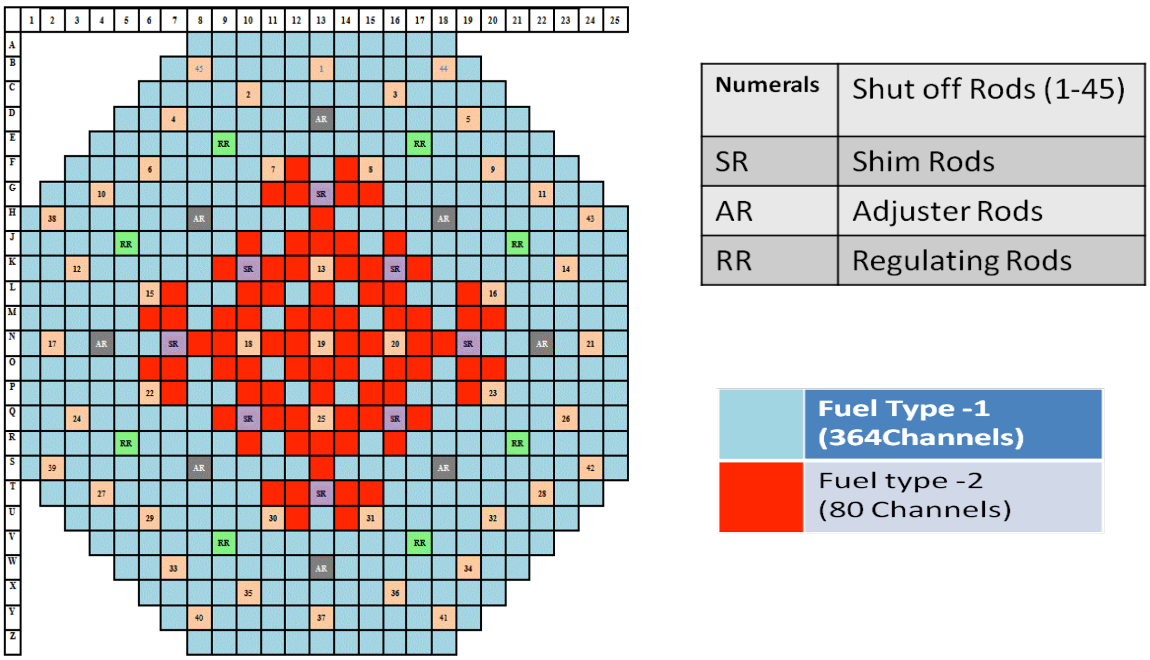


Fig. 3 Initial core loading pattern

The initial core loading pattern consists of 80 channels loaded with Type-2 fuel distributed in the central region and remaining 364 channels are loaded with Type-1 fuel. The core loading pattern is given in Fig. 3. The core consists of 45 shut off rods, 8 shim rods, 8 adjuster rods and 8 regulating rods. Hence the fuel has been loaded in 444 channels.

The core simulation with the above loading pattern was carried out and core excess reactivity was estimated to be about 80 mk for hot operating conditions with saturated xenon. The core excess reactivity 80 mk can be quenched by adding about 36 ppm of boron in moderator. The core followup was carried out by reducing boron in moderator in small steps of 4 ppm till the boron in moderator becomes zero. The zero boron in moderator was achieved after about 479 FPD of operation. Thus after 479 FPD of operation the refuelling of the core is necessary for further operation of the reactor.

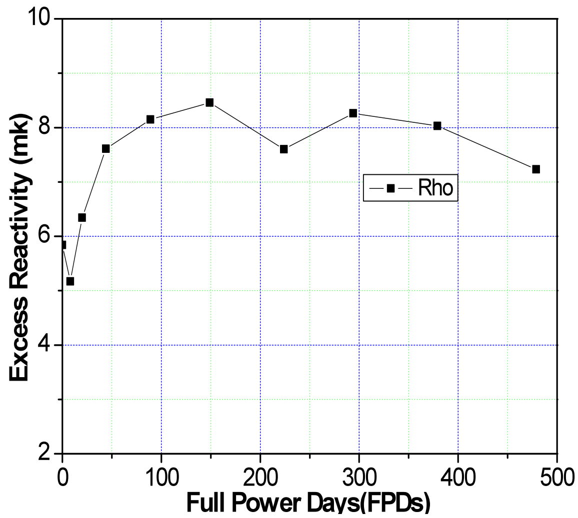


Fig. 4(a) Core Excess reactivityVs FPD

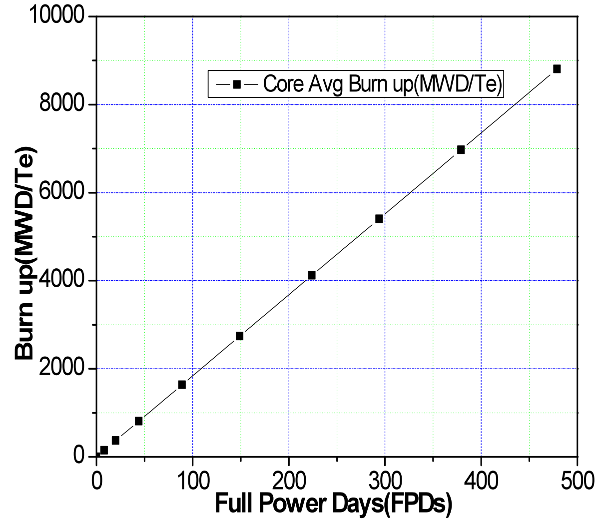


Fig. 4(b) Core Avg. BurnupVs FPD

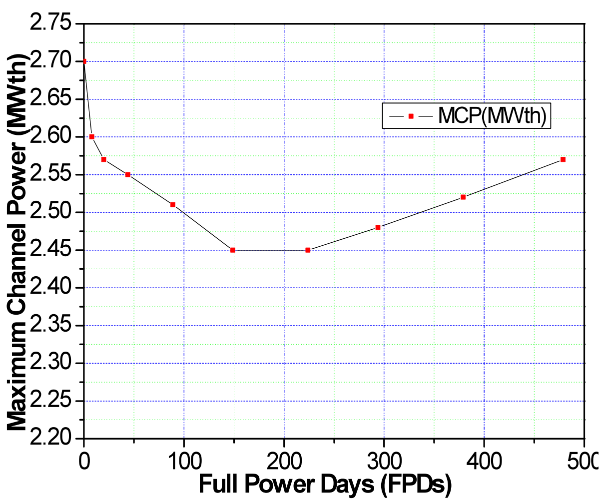


Fig. 5(a) MCP Vs FPD

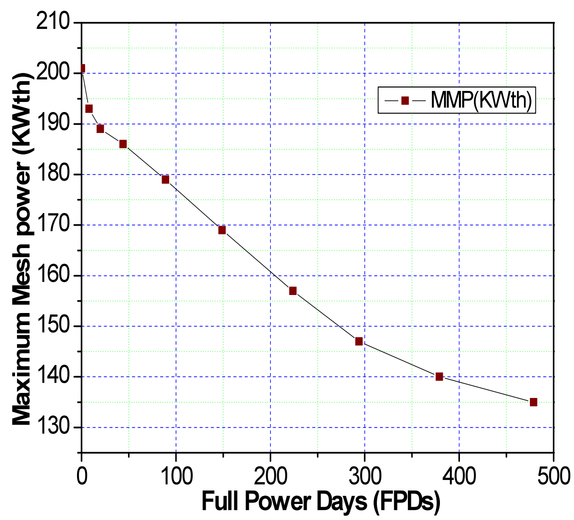


Fig. 5(b) MMP Vs FPD

During the core followup the core excess reactivity was maintained between 6 mk to 8 mk as shown in fig. 4(a) and the observed in-core burnup variation with Full Power Days (FPDs) is shown in fig. 4(b). Similarly the estimated maximum channel power (MCP) and maximum mesh power (MMP) during the core followup upto onset of refueling are shown in fig. 5(a) and fig. 5(b) respectively. It has been observed that MCP was maintained less than 2.85 MW.

5. Refuelling Scheme

After the onset of refueling the prime objective of the fuel management is to reach the equilibrium core while operating the reactor at full power and maintaining all operational parameters in their design limits. The U-235 content in the equilibrium core cluster ((Th,LEU) MOX) is about 4.29 % and it is being termed as high fissile content fuel cluster for a heavy water moderated reactor. Even with 5% of Gd in two pins of innermost ring, a single channel refueling of the core with the above mentioned cluster lead to very high power peaking (channel power of 4 MW to 5 MW). In order to control the power peaking a mini batch (consisting of four or eight channels) refueling scheme was adopted and the local power peaking was reduced to about 3 MW. A set of four or eight channels were selected such that the quadrant symmetry is maintained. In order to further improve the power peaking, the in-core reshuffling scheme was also incorporated along with the mini batch refueling scheme. However, during the reshuffling as well as refueling quadrant symmetry was maintained. Therefore all refueling/ reshuffling operations were carried out in mini batches. For the transition from initial to equilibrium core the following options were tried to meet the fuel management objective.

5.1 Refueling with single reshuffling

The core is divided in to two zones called Inner zone and outer zone. Generally the flux distribution with low power peaking is achieved by differential refueling scheme. Hence central zone of the core consists of fuel with higher burnup than the outer zone. In order to maintain the flat flux distribution in the core, the fresh fuel cluster was loaded in a low flux region (outer zone) to replace the partially burnt fuel cluster and the partially burnt cluster from outer zone are moved to the inner zone to replace the highly burnt fuel cluster which is due for discharge to spent fuel bay. Hence, one refuelling operation requires one reshuffling operation as shown in fig 6.

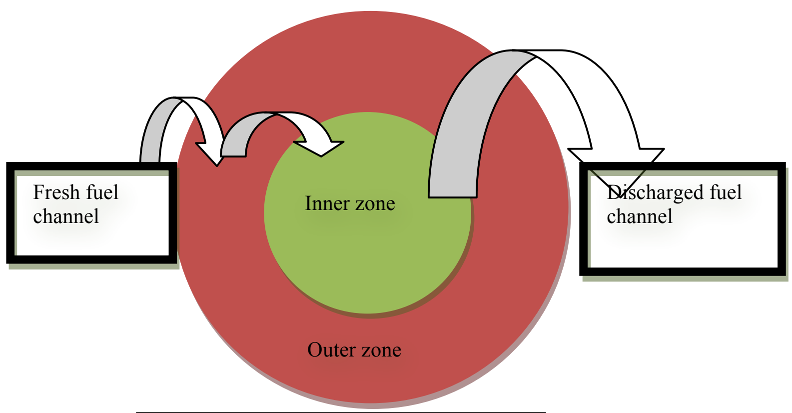


Fig 6 Refueling with single reshuffling

5.2 Refueling with double reshuffling

This refueling scheme requires one refueling operation followed by two reshuffling operations. The initial core is having different fuel hence during the transition phase from initial core to equilibrium core this kind of refueling scheme was found to be more suitable than refueling with single reshuffling scheme for controlling power peaking. In this scheme the core is assumed to be divided in to three zones (namely inner, middle and outer zones). The outer zone channel with lower burnup (say about 10GWd/Te) is replaced with fresh fuel cluster and the irradiated cluster from the outer zone is shifted to middle zone to replace the cluster with relatively higher burnup (say about 20 GWd/Te). Finally the irradiated cluster from the middle zone is shifted to the central zone to replace the fuel clusters which are due for discharge to spent fuel bay. The typical burnup ranges as mentioned above are applicable to the fuel clusters belonging to fuel type-1. These ranges can be changed according to the type of the fuel clusters being reshuffled. By following this scheme, the on power refueling was observed to be feasible during the transistion phase and all the operational parameters were observed to remain within their design limits. Fig 7 shows the schemetic diagram of refueling with double reshuffling scheme.

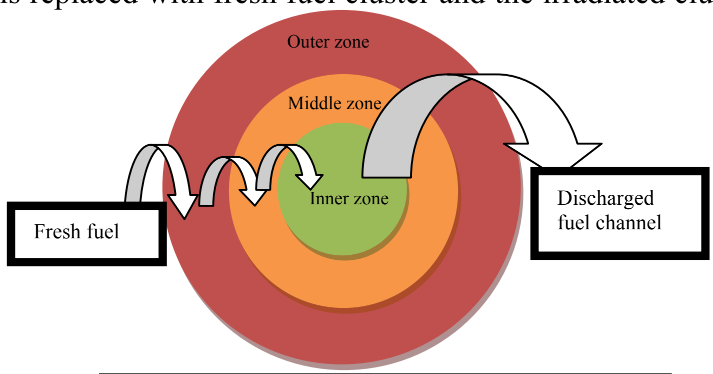


Fig 7 Refueling with double reshuffling

6. Results

Initial core for AHWR-LEU is optimised with lower enriched fuel (~2.5% ^{235}U) in order to limit the boron management and power peaking in initial phase. This core has been followed up to 479 Full power days by reducing boron. From 479 FPD onwards, on power refuelling was carried out by adopting suitable reshuffling scheme as discussed above. The channels selection was such that the operational parameters (maximum channel power (MCP) and maximum mesh power (MMP) are maintained within their limit of 2.85MWth and 200kWth respectively. The linear heat rating is estimated to be 29.2kW/m for the maximum rated pin / ring. The core has been followed up to about 5700 FPDs of reactor operation. During the core followup the variation of incore burnup and excess reactivity with reactor operation are given in fig 8a and 8b respectively. Similarly, the variation of maximum channel power and maximum mesh power with reactor operation are given in fig. 9(a) and 9(b).

As a good fuel management practice the fuel clusters used for initial core loading (Type-1 & Type-2) were preferentially discharged upto 3200 FPD of operation. The equilibrium core cluster discharge was initiated only when all the initial core clusters have been discharged (see fig. 10(a)). Among the equilibrium core clusters discharged, initial 100 clusters have attained the average discharge burn up of about 55.0GWD/Te. However, subsequently the average discharge burnup of the equilibrium core clusters was observed to be very close to the design discharge burnup of ~60 GWD/Te (see fig. 10(b)). The average incore burnup has gradually improved to ~31.0 GWD/Te (see fig. 8b).

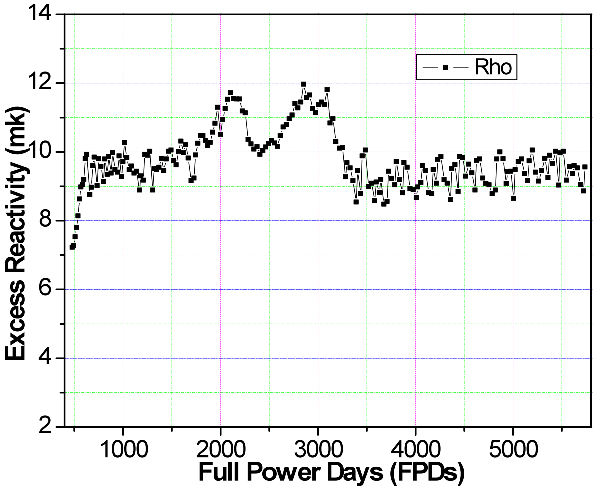


Fig. 8(a) Core excess reactivity Vs FPDs

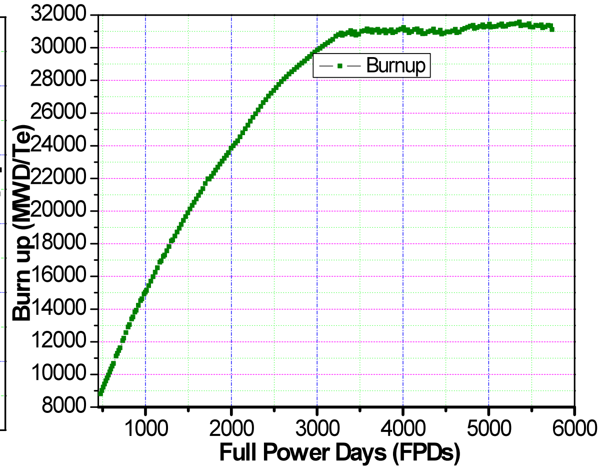


Fig. 8(b) Core avg burnup Vs FPDs

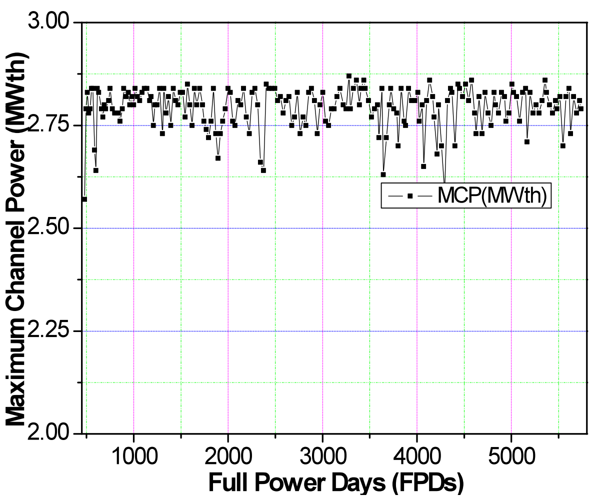


Fig. 9(a) MCP Vs FPD

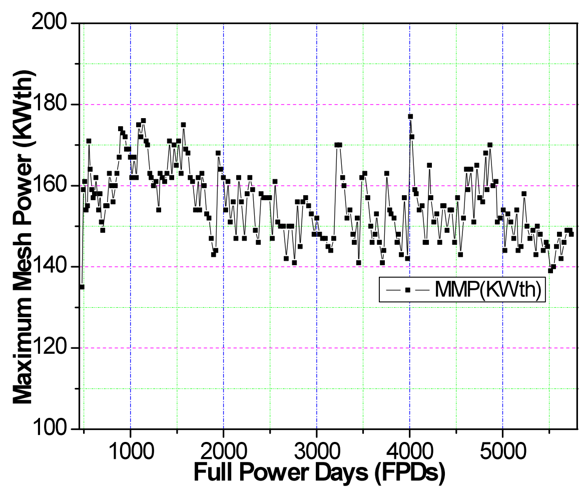


Fig. 9(b) MMP Vs FPD

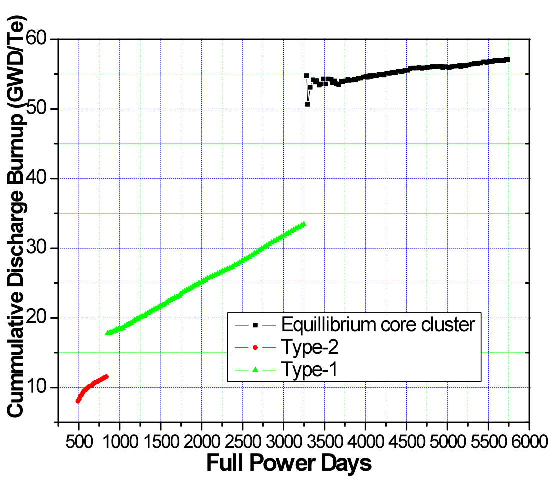


Fig 10a Cummulative discharge burnup Vs FPD

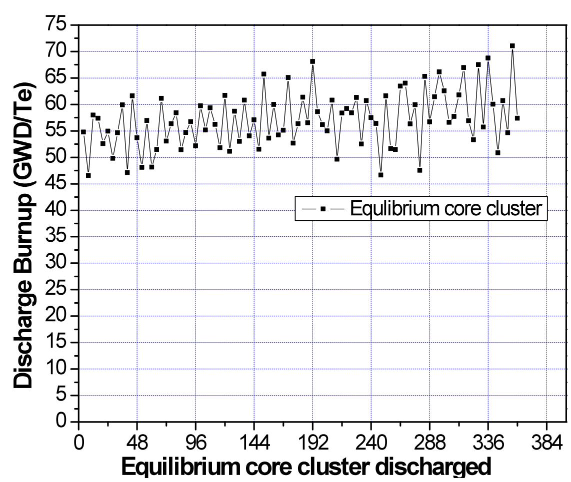


Fig. 10(b)

7. Conclusions

The study of AHWR with Th-LEU fuel cycle study with on power refuelling has been carried out to observe the core behaviour from initial phase to equilibrium phase and a suitable refuelling strategy was worked out for the equilibrium core cluster with a target discharge burnup of about 60 GWd/Te. The study shows that reactor operation at full power is feasible all the time by adopting the suitable on power refuelling scheme. The average fuel requirement works out to be about 0.14 clusters /FPD.

8. References

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