Design of High Power Density Annular Fuel Rod Core for Advanced Heavy Water Reactor

A.P. Deokule (a) **A.K.Vishnoi** (b) **K.Umasankari** (b) **D.K.Chandraker** (b) **P.K.Vijayan** (b)

(a) Homi Bhabha National Institute, Mumbai-400 085, India.

(b) Bhabha Atomic Research Centre, Trombay, Mumbai-400 085, India.

Email-abhijit.deokule1986@gmail.com

Abstract

For the deployment of annular fuel rod cluster in AHWR, whole core calculations with annular fuel rod are necessary. A coupled neutronic thermal hydraulic analytical technique is used for whole core calculations. In this technique reactor physics and thermal hydraulic calculations are carried out iteratively until reactor physics and thermal hydraulically feasible core configuration is reached. Reactor physics calculations are carried out by FEMINA and thermal hydraulic calculations are carried out by coupled code ARTHA and ANUFAN. In this core a power up rating of approximately 33 percent is achieved without any major design modifications in the original design. This up rating increases reactor thermal power up to 1200 MW and the burn up to 60,000 MWd/ton. The designed core has negative coolant void of reactivity and adequate thermal margin.

Key words- AHWR, Annular fuel, ARTHA, FEMINA, ANUFAN, MCHFR

1.0 Introduction

Advanced Heavy Water Reactor (AHWR) [1] (Sinha, R.K.and Kakodkar A., 2006) is heavy water moderated and boiling light water cooled vertical pressure tube type reactor. The reactor adopts natural circulation core cooling during start up as well as normal full power operating conditions. This eliminates all safety and maintenance issues associated with failure of primary circulating pump besides reduction of operating and maintainace cost. The thermal hydraulic characteristic of such a natural circulation reactor depends on the geometry of system. Pressure, inlet subcooling, radial and axial power distribution in the core, the channel flow distribution etc. are the governing parameters in the core calculations. To study the thermal hydraulic behavior of AHWR a computer programme ARTHA (AHWR Thermal Hydraulic Analysis) [2] (Chandraker et.al.2002) has been developed. In the AHWR natural circulation is used for heat removal which needs the height of the riser has to be much larger than that in a forced circulation type Boiling Water Reactor. Adequate thermal margin against the occurrence of critical heat flux (CHF) is one of the thermal hydraulic constraints of pressure tube type boiling water reactor.

The studies on annular fuel rod clusters consisting of 33 and 19 pins have respectively shown that a suitable annular fuel rod cluster for advanced heavy water reactor can be designed without any major modifications in the current core. The designed annular fuel rod cluster has better performance parameters from physics as well as thermal hydraulic point of view such as negative coolant void reactivity and Minimum Critical Heat Flux Ratio (MCHFR). A detailed design of 33pin annular fuel rod cluster for AHWR [3] (Deokule et.al, 2012) and design of 19 pin annular fuel rod cluster for pressurized heavy water reactor is explained in an earlier work. [4]. In this paper, the core simulations have been done with the optimized 19 pin assembly.

The equilibrium core consisting of clusters of 19 pins with (Th-LEU) O_2 is proposed. Use of annular pins increases the thermal margins. The fissile content in the annular fuel cluster has been optimized to achieve other design objectives such as discharge burn up and negative coolant void coefficient. With the use of annular pins, the gross thermal power level could be increased to1200 MW_{th} from the current 920 MW_{th} which uses solid pins.

2.0 Advantage of Using Annular Fuel Rod Cluster

Internally and externally cooled annular fuel rod cluster provides larger surface area which increases heat transfer from its surface. Due to enhanced heat transfer burn up can be increased. The peak temperature inside the fuel is less than that of corresponding equivalent solid fuel pin. This is advantageous in improving the power rating of the cluster as the limitation is mainly due to extraction of heat from fuel rod cluster.

It has been estimated that the 19 pin annular fuel rod cluster provides a thermal margin of 10% at peak operating power of 3.2 MW [4]. For ready reference some of the design details of the 19 pin annular fuel rod cluster are given here. The cross section of 19 pin annular fuel rod cluster is shown in the fig. 1.

The special feature of the annular fuel is that the coolant flows both through the inner and outer passages inside the fuel assembly. Subchannel analysis of the annular fuel rod cluster shows that reducing the sub channel flow area on the outside, diverts the flow through the hottest inner channel improving the MCHFR margin in the hottest channel. The MCHFR for this fuel cluster as a function of bundle length is shown in Fig.2 .From the analysis it can be made clear that final design with 19 pin annular fuel rod cluster is suitable for generation of higher power. It is clear from the fig.2 that for all node values the MCHFR is well above unity giving a safe design.

A comparison between solid and annular fuel rod cluster is carried out in table 2. It is clear from the table 2 that annular fuel rod cluster is having maximum channel power 3.2 MW and MCHFR 1.1.Therefore design is safe under operating conditions.

Table 1 Design Details of Annular Fuel Rod Cluster for Advanced Heavy Water Reactor

Description	Dimension
Fuel	
No. of fuel pins	19
Fuel pin ID /OD,mm	11.8/22.3
Fuelpellet,ID/OD,mm	13.3/19.8
Coolant annulus ,mm	11.8
Inner clad Material, ID/OD mm	11.8/13.1
Outer clad Material,ID/OD mm	20.06/22.3
Clad Material, Density, g/cc	Zircaloy-2/6.55
Inner Clad thickness, mm	0.65
Outer clad thickness, mm	1.2
Fuel density, g/cc	9.3
No. of fuel rings	2
No of fuel pins in each ring	1/6/12
Pitch circle diameters of the fuel rings mm	0/47.4/93.3
Enrichments and Burn Up	
Ring 1	(Th,LEU)MOX LEU content (20%)
Ring 2	(Th,LEU)MOX LEU content (20%)
Ring 3	(Th,LEU)MOX LEU content (20%)
Pressure tube Dimensions	
ID / OD mm	120 / 128
Material/ Density, g/cc	Zr-2.5%Nb / 6.55
Calandria Tube Dimension	
ID / OD mm	163.8 / 168
Material / Density, g/cc	Zircaloy-2 / 6.55
Coolant	
Material	Light water
Average coolant Temperature/ average density °C / (g/cc)	285 / 0.45

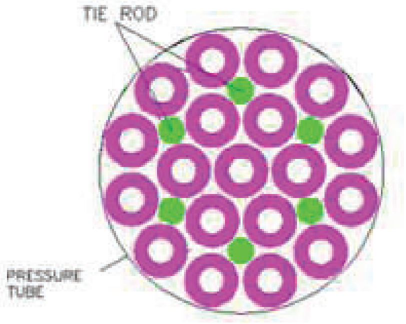


Fig.1 Plan View of the 19 Pin Annular Fuel Rod Cluster Designed for Up Rating of AHWR

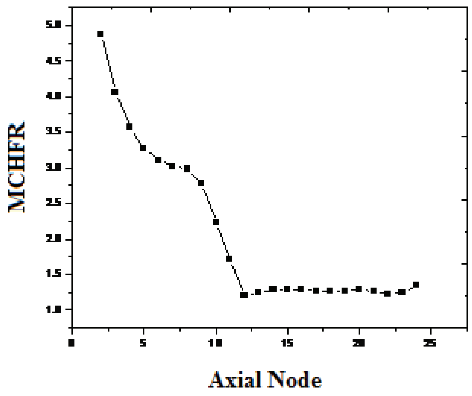


Fig.2 Critical Heat Flux Ratio Curve for Designed 19 Pin Annular Fuel Rod Bundle

(By Look up Table Approach)

Table 2 Comparison between Solid and Annular Fuel Rod Cluster

Type of fuel	No. of pins	Bundle Power (MW)	Max.Fuel Temp.(K)	MCHFR
Solid Fuel*	54	2.6	1293	1.16
Annular Fuel	19	3.2	933	1.10

* AHWR 54 pin solid fuel rod cluster [1]

3.0 Design of Annular Fuel Rod Core for Advanced Heavy Water Reactor

After the fuel has been designed to meet the requirements of thermal hydraulics, reactor physics, the vertical pressure tube type configuration has guided the structural design of the fuel assembly. The fuel assembly is 10.5m in length and is suspended from the top in the coolant channel. The main core design features with annular fuel are shown in table 3.

Table 3 Main Core Design Features with Annular Fuel.

Parameter	Value
Total no. of lattice locations	505
Number of fuel channels	444
Number of lattice locations for control rod	24 (8,8,8)
Number of lattice locations for shut off rod	41
Lattice pitch(mm)	225
Active core length(m)	3.5
Calandria	
Inner diameter of main shell(m)	7.4
Inner diameter of the sub shell at each end(m)	6.8
Length(m)	5.3
Tube material	
Pressure tube	Zr2.5Nb
Calandria tube	Zircaloy-4
Tube dimensions	
Inner diameter/W.T. of Pressure tube, mm	120/4
Outer diameter/W.T. of Calandria tube,mm	168/2
Reflector thickness(D_2O) axial/radial,mm	750/600

4.0 Reactor Physics and Thermal Hydraulic Design of The Core

Reactor Physics design calculations of the core are done by **F**lux **E**xpansion **M**ethod **I**n **N**odal **A**nalysis (FEMINA) [5] (Kumar et.al 1984). For AHWR simulations we have used FEMTAVG version of this code where the time averaged simulations are done. The AHWR core has been divided into three distinct burnup zones from effective flux flattening. The mesh dependent cross sections are interpolated both over burnup and the coolant density as calculated by the thermal hydraulic code. This code calculates flux and k-effective of the core using nodal expansion method. It gives power distribution and peaking factors which are subsequently used in thermal hydraulic design of the core. For the thermal hydraulic design of the core the ARTHA (AHWR Reactor Thermal Hydraulic Analysis) code and ANUFAN (ANnUlar Fuel Rod ANalysis) [6] (Vishnoi et.al 2013) have been coupled. The Coupled ARTHA and ANUFAN are used to calculate density variation in the reactor core at every nodal point. This density variation is used for the reactor physics simulations by FEMTAVG. This iterative procedure is used until an equilibrium core is reached to obtain a flat flux profile. The iterations are done by external coupling of the codes. The equilibrium flux profile of this core is shown in the fig.3.The power profile of the equilibrium core is shown in the fig.4 in a quarter core representation. The typical power distribution before thermal hydraulic iteration is shown in fig.5 and optimized core flow rates after thermal hydraulic iterations are shown in fig.6.

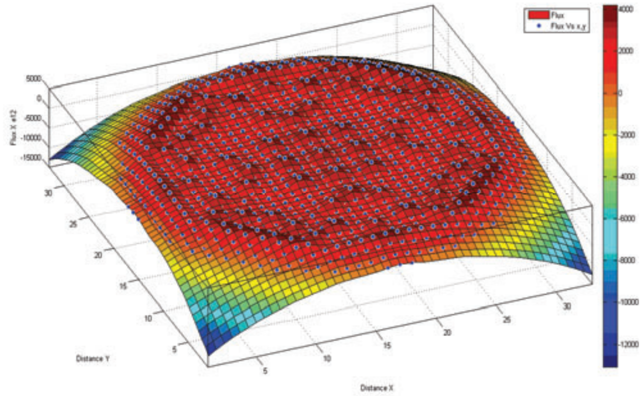


Fig.3 Annular Fuel Rod Core Neutron Flux Profile

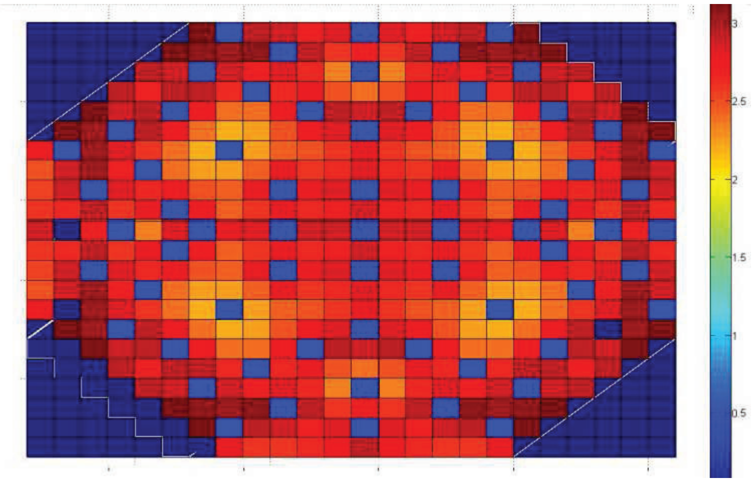
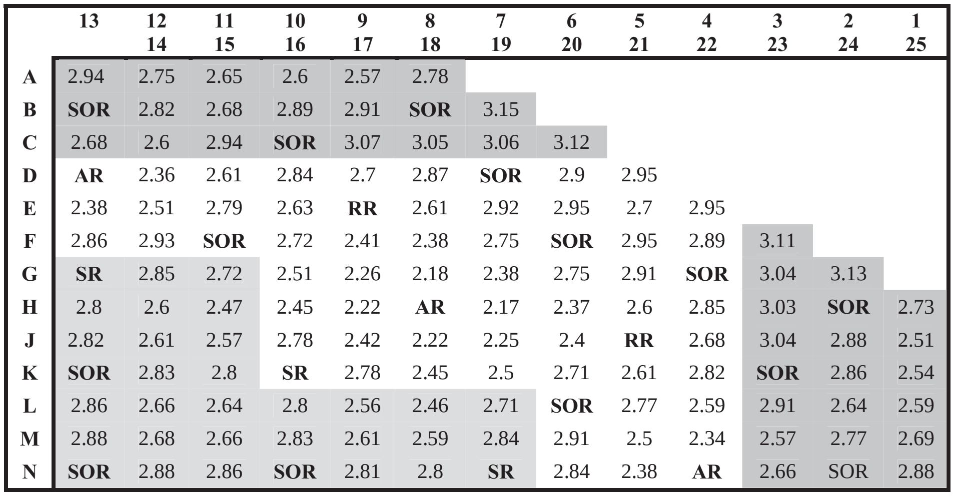


Fig.4 Optimized Annular Fuel Rod Core Power Map



	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	2.94	2.75	2.65	2.6	2.57	2.78							
B	**SOR**	2.82	2.68	2.89	2.91	**SOR**	3.15						
C	2.68	2.6	2.94	**SOR**	3.07	3.05	3.06	3.12					
D	**AR**	2.36	2.61	2.84	2.7	2.87	**SOR**	2.9	2.95				
E	2.38	2.51	2.79	2.63	**RR**	2.61	2.92	2.95	2.7	2.95			
F	2.86	2.93	**SOR**	2.72	2.41	2.38	2.75	**SOR**	2.95	2.89	3.11		
G	**SR**	2.85	2.72	2.51	2.26	2.18	2.38	2.75	2.91	**SOR**	3.04	3.13	
H	2.8	2.6	2.47	2.45	2.22	**AR**	2.17	2.37	2.6	2.85	3.03	**SOR**	2.73
J	2.82	2.61	2.57	2.78	2.42	2.22	2.25	2.4	**RR**	2.68	3.04	2.88	2.51
K	**SOR**	2.83	2.8	**SR**	2.78	2.45	2.5	2.71	2.61	2.82	**SOR**	2.86	2.54
L	2.86	2.66	2.64	2.8	2.56	2.46	2.71	**SOR**	2.77	2.59	2.91	2.64	2.59
M	2.88	2.68	2.66	2.83	2.61	2.59	2.84	2.91	2.5	2.34	2.57	2.77	2.69
N	**SOR**	2.88	2.86	**SOR**	2.81	2.8	**SR**	2.84	2.38	**AR**	2.66	SOR	2.88

Fig.5 Typical Power Distribution before Thermal Hydraulic Iteration

5.0 Summary of Equilibrium Core Reactor Physics and Thermal Hydraulics Calculations

The design parameters with annular fuel rod for equilibrium core calculations are given in table 3.The core power distribution has been optimized for a total power of 1200 MW_{th}. In order to achieve flat flux profile, the equilibrium core has been divided into 3 burn up zones. The burn up zones are 70 GWd/t ,59 GWd/t and 51 GWd/t. Reactor Physics parameters for annular fuel rod core are tabulated in table 3.

Table 3 Physics Parameter of Reactor Equilibrium Core with Annular Fuel Rod for Advanced Heavy Water Reactor

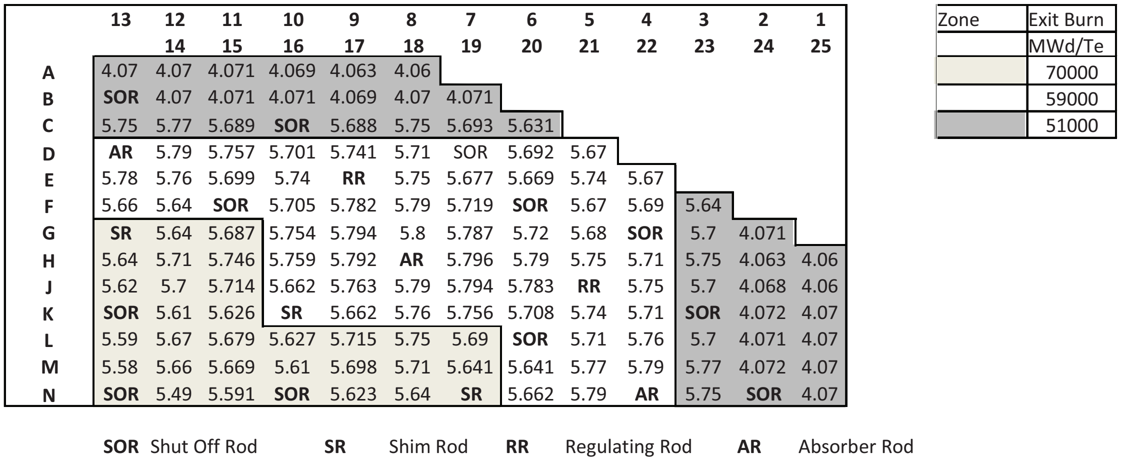
Parameter	**Value**
	Burn up zone
Zone 1	70 GWd/t
Zone 2	59 GWd/t
Zone 3	51 GWd/t
	Peaking Factors (Maximum)
Local	1.17
Radial	1.31
Axial	1.17
Total	1.79
	Reactivity Coefficients , *Δk/k* (ºC)
Fuel Temperature	-2.74×10^{-5}
Channel Temperature	-2.075×10^{-5}
Void Coefficient, *Δk/k (% void)*	-5.5×10^{-5}

Thermal hydraulic design of the annular fuel rod core for AHWR has been carried out with adequate thermal margin. The thermal margin is defined as the difference between operating heat flux and critical heat flux. A brief outline of the thermal hydraulic parameters is tabulated in the table 4.

Table 4 Thermal Hydraulic Parameters of Reactor with Annular Fuel Rod

Parameter	Value
Core Fission Power	1200 MWt
Core Power	1155 MWt
Coolant	Light Water
Heated Fuel Length	3.5 m
Total Core Flow Rate	2237 kg/s
Coolant Outlet Temperature	533.5 K
Feed Water Temperature	403 K
Average Steam Quality	18.2%
Steam Generation Rate	407.6 kg/s
Steam Drum Pressure	7 MPa
MHT Loop Height	39 m
Minimum Critical Heat Flux Ratio	1.10
Maximum Channel Power	3.2 MW

The equilibrium core flow rates are calculated after the iterative procedures between coupled ARTHA, ANUFAN and FEMINA are shown in figure 6. Different enrichment zones in the core are shown by different shades of colour.



	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	4.07	4.07	4.071	4.069	4.063	4.06							
B	**SOR**	4.07	4.071	4.071	4.069	4.07	4.071						
C	5.75	5.77	5.689	**SOR**	5.688	5.75	5.693	5.631					
D	**AR**	5.79	5.757	5.701	5.741	5.71	SOR	5.692	5.67				
E	5.78	5.76	5.699	5.74	**RR**	5.75	5.677	5.669	5.74	5.67			
F	5.66	5.64	**SOR**	5.705	5.782	5.79	5.719	**SOR**	5.67	5.69	5.64		
G	**SR**	5.64	5.687	5.754	5.794	5.8	5.787	5.72	5.68	**SOR**	5.7	4.071	
H	5.64	5.71	5.746	5.759	5.792	**AR**	5.796	5.79	5.75	5.71	5.75	4.063	4.06
J	5.62	5.7	5.714	5.662	5.763	5.79	5.794	5.783	**RR**	5.75	5.7	4.068	4.06
K	**SOR**	5.61	5.626	**SR**	5.662	5.76	5.756	5.708	5.74	5.71	**SOR**	4.072	4.07
L	5.59	5.67	5.679	5.627	5.715	5.75	5.69	**SOR**	5.71	5.76	5.7	4.071	4.07
M	5.58	5.66	5.669	5.61	5.698	5.71	5.641	5.641	5.77	5.79	5.77	4.072	4.07
N	**SOR**	5.49	5.591	**SOR**	5.623	5.64	**SR**	5.662	5.79	**AR**	5.75	**SOR**	4.07

Zone	Exit Burn
	MWd/Te
░	70000
	59000
▨	51000

SOR Shut Off Rod **SR** Shim Rod **RR** Regulating Rod **AR** Absorber Rod

Fig.6. Optimized Core Coolant Mass Flow Rates after Thermal Hydraulic Iterations in Quarter Section
(Numbers indicate mass flow rates in kg/s)

6.0 Conclusion

The 19 rod annular fuel cluster designed for pressure tube type boiling water reactor with (Th, LEU) MOX fuel is capable of enhancing the power rating to 1200 MW_{th}, This increases core electrical output from 300 MWe to 400 MWe. It has also shown that the thermal margin of the reactor is 10%. The LEU content has been optimized so that core has a discharge burnup of about 58 GWd/T and negative coolant void coefficient. The present studies show that use of annular fuel cluster can lead to significant power up rating in a pressure tube type BWR.

References

[1] R.K.Sinha, A.Kakodkar, “Design and development of the AHWR—the Indian thorium fuelled innovative nuclear reactor”, Nuclear Engineering and Design, 236, (2006), PP 683-700

[2] Chandraker, D.K., Maheshwari, N.K., Saha, D., Sinha, R.K., January 2002. “A computer code for the thermal hydraulic analysis of a natural circulation reactor”. In: 16th National Heat and Mass Transfer Conference and 5th ISHMT-ASME Heat and Mass Transfer Conference, Department of Mechanical Engineering, Jadhavpur University, Calcutta, India.

[3]A.P.Deokule, A.K.Vishnoi, K.Umasankari, D.K.Chandraker, P.K.Vijayan, S.Ganesan, “Design of 33 pin annular fuel rod cluster for Advanced Heavy Water Reactor ”,Nuclear Engineering and Design,Vol.254 PP 94-101.

[4]A.P.Deokule, A.K.Vishnoi, A.Dasgupta, K.Umasankari, D.K.Chandraker, P.K.Vijayan, “Design of 19 pin annular fuel rod cluster for Pressure Tube Type Boiling Water Reactor”, Nuclear Engineering and Design,Vol.274,PP 64-73.

[5] Kumar, A., Srivenkatesan, R., 1984. “Nodal Expansion Method for Reactor Core Calculation.” BARC Report. BARC-1249.

[6]A.K.Vishnoi, D.K.Chandraker, P.K.Vijayan “Development of thermal hydraulic analysis code for annular fuel assemblies” Kerntecnik 77(2012) PP 12-17.