Lattice Burnup Calculation for a PWR Assembly

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1 author:

Mohga Hassan
Egyptian Nuclear and Radiological Regulatory Authority

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Mohga Hassan
Nuclear and Radiological Regulatory Authority, 3 Ahmed Alzomer Str. Nasr City, Cairo, Egypt

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ABSTRACT

A computer model was designed to simulate a pressurized water reactor assembly. Three types of assemblies were considered in the study, the first without burnable poison rods, the second has 12 burnable rods and the last has 20 burnable rods. The multiplication factor calculated by the model was compared with previous studies and found to be in good agreement. The model was used to estimate pin by pin power distribution in the assembly as well as axial power distribution. The position of the maximum power pin was identified in each case. The effect of burnup on radial and axial power distribution was discussed.

Key words: PWR, Radial Power, Axial power, Burnable Poison, Burnup.

INTRODUCTION

Both pin power distribution calculation in the fuel assembly modeling and fuel assembly power distribution calculation are very important for PWR core design, radial reflector design, and pressure vessel fluence calculation [1,2]. Power distribution within fuel pins is also required as they account for the possibility of fuel densification [3]. Fuel densification, causes the fuel pellets to shrink both axially and radially, as a result, gaps can occur in the fuel column. The gaps, which are random and vary in length and location, result in decreased neutron absorption in the vicinity of the gap. This produces power peaking in the adjacent fuel rods, resulting in an increased power peaking factor for the core. Thus, defining hot spots within a fuel assembly is very important to determine possible location of defects.

This work aims to identify the location of a hot spot in PWR fuel assembly. A regular 17×17 PWR assembly was chosen for the study, which was the subject of a benchmark problem [4]. Pin by pin power distribution is calculated and analyzed for three types of fuel assemblies, with different burnable poison rods (BPRs) loading. The effect of burnable poison distribution, as well as burn up, on radial and axial power distribution was also assessed.

MODEL DESCRIPTION

MCNPX code [5] was used to develop a model for a PWR assembly. Three types of assembly were investigated, no burnable poison rods (BPRs) (Fig 1-a), and with 12 (Fig1-b) or 20 (Fig 1-c) BPRs. Typical dimensions and details of the fuel assembly were used in the model, and reflective boundaries were assumed at the outer surfaces of the assembly. Table (1) states the parameters used in the model. Neutrons are divided into five energy groups, with boundaries 0.625 eV, 50 keV, 500 keV, 2 MeV and 20 MeV.

The tallies representing power were normalized to 17.1 MW [6,7] (average power per assembly) which corresponds to total thermal power of 2686 MW in 157 assemblies [4].

The burnup lattice calculations were performed at hot full power (HFP) for the following conditions: $T_{moderator}$=309.9 C^o, T_{clad}=340 ^{o}C, T_{fuel}=640 ^{o}C [4], and for a cycle length of 18 months [8].

Table (1): Assembly Design Parameters

Assembly	
Arrangement	17×17
Number of fuel rods per assembly	264
Fuel	
Material	UO_2
Density	95 % of theoretical density
Enrichment	2.6%
Pellet Radius (cm)	0.4096
Active fuel length (cm)	365.76
Cladding	
Materials	Zircalloy -4
Density (g/cm^3)	6.55
Inner radius (cm)	0.4179
Outer radius (cm)	0.4750
Fill gas material	Helium
Burnable Poison	
Material	B_2O_3 in Pyrex Glass
Fraction of boron in material	12.5 w/o
Active length (cm)	359.562
Outside radius (cm)	0.48387
Clad thickness (cm)	0.04699
Clad material	SS-304
Inner tube material	SS-304
Inner tube outside radius (cm)	0.2305
Inner tube thickness (cm)	0.01651

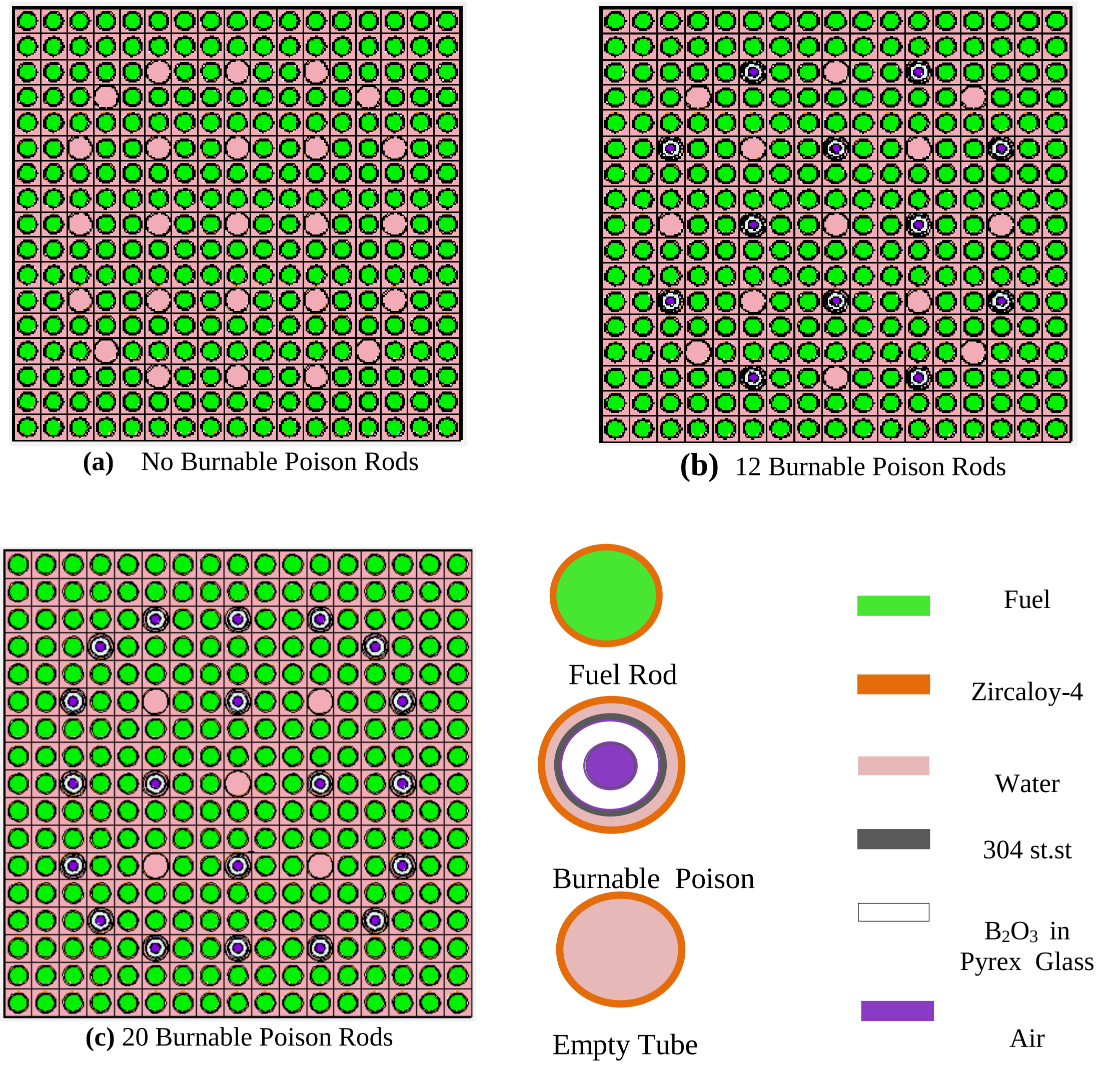


Fig (1): MCNPX Model for PWR Assembly

RESULTS AND DISCUSSIONS

1- Model validation:

The infinite multiplication factor calculated by this study was compared to that of the benchmark in the three assemblies for two cases: no soluble boron; and 1000 ppm soluble boron added to the coolant. Table (2) illustrates the results which show a very good agreement.

Table (2): Multiplication Factor Comparison

BPRs	Soluble Boron (ppm)	Present Study	Reference (4)
Non	0	1.3558±0.00036	1.35929
Non	1000	1.15731±0.00277	1.15480
12	0	1.21858±0.00063	1.22020
12	1000	1.06151±0.00063	1.06018
20	0	1.13802± 0.00180	1.13789
20	1000	0.99581± 0.00069	0.99987

2- Radial Power Distribution:

Pin by pin power distribution for the three assemblies is shown in Figures (2-4) for half assembly, the values shown are relative to the average.

For the assembly with no burnable poison rods the power tends to be lower at the edges and increases towards the interior, that is due to the presence of the moderating medium at the water holes and the neutron leakage at the edges. In this case the fuel rod with maximum power is located near the center of assembly as shown in figure 2. As a result of burnup the the maximum power is shifted but still in the assembly interior. The average power produced in the fresh fuel rod was estimated to be 68.38 kW, reduced to 57.37 kW as a result of burnup,while the maximum power was 73.77 kW and reached 69.89 kW after one cycle.

Assemblies with burnable poison rods tend to have their maximum power rod at the edges, due to the higher neutron absorption near these rods. For 12BP assembly the position of maximum power is located at the corner of the assembly at BOC (Fig. 3). As aresult of burnup it was shifted towards the assembly interior. The assembly average rod power at BOC was 61.72 kW and the maximum was 69.17, while at EOC the average was 51.87 kWand the maximum was 56.33 kW.

The assembly with 20 BP (fig. 4) had an average rod power of 57.85 kW, and a maximum of 64.28 kW at BOC. At EOC the average and maximum power were 46.63 kWand 52.32 kW respectively. The location of maximum power is located at the corner of the assmbly and burn up had no effect on the maximum power.

3- Axial Power Distribution:

To determine the axial power distribution, the assembly was divided into 30 axial zones, each zone is approximately 12 cm. The average power in each zone was calculated using the same normalization method illustrated above. The axial power distribution for each assembly at BOC and EOC are shown in figure (5). At BOC the maximum power for the assembly without burnable poison, (Fig. 5-a), occurs slightly above the middle of the core active height, with a value of about 920 kW, while at EOC the maximum is slightly shifted downs with a value of about 863 kW. The values for the assemblies with 12 and 20 BPRs at BOC were 870 kW and 850 kW respectively, while at EOC the maximum values were both approximately equal to 750 kW. The results show that the burnup causes the maximum power to be shifted towards the lower part of the assembly; this is due the xenon buildup which is concentrated mainly in the upper region of the assembly which increases absorption in the upper region [9].

0.9025 0.9383																
0.9247 0.8970	0.9530 0.9290															
0.9558 0.9192	0.9621 0.9383	0.9425 0.9660														
0.9585 0.9371	0.9601 0.9459	1.0276 1.0014														
0.9555 0.9373	0.9715 1.0007	1.0016 1.0904	1.0262 1.0649	1.0073 1.0789												
0.9442 0.9431	1.0084 1.0008		1.0547 1.0805	1.0677 1.1077												
0.9467 0.9735	0.9541 1.0074	1.0285 1.0283	1.0176 1.0183	0.9931 1.0255	1.0549 1.1420	1.0144 1.0312										
0.9556 0.9793	0.9486 0.0017	1.0499 1.0418	0.9890 1.0299	0.9767 0.9989	1.0573 1.0382	1.0289 1.0292	1.0095 1.0567									
0.9558 0.9758	1.0715 1.0241		1.0351 1.0462	1.0519 1.0729		1.0786 1.0386	1.0666 1.0872									
0.9720 0.9314	1.0277 1.0081	1.0549 1.0398	1.0422 1.0322	0.9639 1.0132	1.0373 1.0728	1.0159 1.0571	1.0013 1.0062	1.0328 1.0203	0.9776 1.0270							
0.9773 0.9457	0.9832 0.9894	1.0243 0.9990	1.0234 1.0617	1.0412 1.0621	1.0443 1.0883	1.0202 1.0140	0.9637 1.0204	1.0153 1.0436	0.9876 1.0192	0.9973 1.0657						
0.9337 0.9807	0.9784 1.0411		1.0708 1.0473	1.0105 1.0657		1.0669 1.0310	1.0453 1.0572		1.0252 1.0764	1.0192 1.0587						
0.9404 1.0081	1.0084 1.0204	1.0569 1.0780	1.0638 1.0887	0.9996 1.0803	1.0480 1.0616	1.0583 1.0569	1.0183 0.9856	1.0697 1.0496	1.0308 1.0246	1.0484 1.0428	1.1200 1.1006	1.0418 1.0574				
0.9121 0.9404	0.9463 1.0421	0.9975 1.0522		1.0735 1.0649	1.0440 1.1074	0.9974 1.0274	1.0050 0.9890	1.0433 1.0730	0.9927 0.9796	1.0258 1.0098	1.0149 1.0556	1.0996 1.0700				
0.9500 0.9457	0.9264 0.9689	0.9504 0.9959	1.0130 1.0710	1.0551 1.0696		1.0282 0.9851	1.0165 1.0810		1.0228 1.0243	1.0167 1.0390		1.0501 0.9976	1.0103 0.9712	0.9595 0.9158		
0.9514 0.9663	0.9818 0.9462	0.9454 0.9636	0.9792 0.9650	0.9983 0.9378	1.0075 1.0181	0.9832 1.0025	1.0000 0.9764	1.0123 1.0228	0.9719 1.0131	0.9903 0.9884	0.9891 1.0023	1.0252 0.9589	0.9525 0.9463	0.9324 0.9243	0.9172 0.8941	
0.9567 0.9244	0.9686 0.9672	0.9971 0.9807	1.0026 0.9966	0.9928 0.9572	0.9423 0.9784	0.9617 0.9992	0.9476 1.0325	0.9733 0.9715	0.9591 0.9741	0.9661 0.9648	0.9919 0.9416	1.0002 0.8986	0.9572 0.9587	0.9140 0.9131	0.9490 0.9132	0.9461 0.9151

Fig. (2): Relative Radial Power Distribution (NO BPRs)
(Upper values for BOC and lower for EOC)

Average Pin Power
BOC= 68.38 kW
EOC = 57.37 kW

Maximum Power (BOC)

Maximum Power (EOC)

1.0778 1.0634																
1.0366 1.0079	1.0420 1.0366															
1.0263 1.0456	1.0146 1.0225	1.0118 1.0194														
0.9715 0.9915	0.9976 0.9987	1.0199 1.0307														
1.0081 0.9754	0.9607 0.9211	0.9364 0.9573	0.9980 0.9700	1.0057 1.0353												
1.0060 0.9840	0.9208 0.9099		0.9483 0.9041	1.0358 1.0083												
0.9872 1.0028	0.9913 0.9861	0.9214 0.9451	1.0067 0.9843	0.9930 1.0373	1.0173 1.0277	0.9813 1.0041										
1.0211 1.0316	1.0420 1.0541	1.0455 1.0550	1.0633 1.0088	0.9895 0.9399	0.8903 0.8469	0.9166 0.9714	0.9423 0.9830									
1.0805 1.0223	1.0617 1.0629		1.0889 1.0712	0.9158 0.9448		0.9100 0.8822	1.0066 1.0189									
1.0580 0.9630	1.0466 1.0083	1.0331 1.0271	0.9986 0.9936	1.0089 0.9280	0.9196 0.8759	0.9531 0.9388	0.9759 0.9999	0.9970 1.0537	0.9911 1.0201							
1.0580 0.9766	0.9456 1.0052	0.9420 0.9655	0.9886 0.9450	1.0336 0.9727	1.0449 0.9661	0.9663 1.0058	0.9729 0.9588	0.9076 0.9459	0.9038 1.0254	0.9911 1.0612						
1.0063 0.9887	0.9033 0.8991		0.9111 0.9767	1.0257 1.0743		1.0776 1.0683	0.9269 0.8776		0.9083 0.9412	1.0261 1.0234						
1.0328 0.9758	0.9333 0.9286	0.9352 0.9706	1.0290 1.0639	1.0254 1.0474	1.0503 1.0248	1.0599 0.9688	0.9677 0.9359	0.9278 0.8733	0.9504 0.9872	0.9913 0.9807	1.0436 1.0322	1.0605 1.0839				
1.0029 0.9935	1.0259 0.9886	1.0881 1.0164		1.0326 1.0517	0.9408 0.9248	1.0135 0.9293	0.9979 1.0180	1.0400 1.0182	1.0123 0.9984	0.9969 0.9630	0.9745 0.9524	0.9784 1.0355				
1.0463 0.9741	1.0573 1.0254	1.0768 1.0576	1.0495 1.0875	0.9328 0.9697		0.9576 0.9578	1.0870 1.0589		1.0736 1.0093	0.9469 0.9038		0.9393 0.9834	1.1029 1.0748	1.0408 1.0132		
1.0510 1.0198	1.0507 1.0029	1.0328 1.0021	1.0455 1.0174	0.9773 1.0044	0.9212 0.9111	0.9763 0.9944	1.0722 0.9691	1.0857 1.0609	1.0467 1.0067	0.9683 0.9638	0.9617 0.9292	0.9762 1.0198	1.0579 1.0129	1.0611 1.0337	1.0636 1.0429	
1.1211 1.0745	1.0445 1.0827	1.0249 1.0081	1.0250 1.0297	1.0160 1.0560	0.9858 0.9990	1.0171 1.0440	1.0488 1.0262	1.0611 1.0518	1.0744 1.0234	1.0363 1.0617	0.9829 1.0071	1.0181 1.0378	1.0203 0.9646	1.0499 1.0297	1.0593 1.0438	1.0784 1.0295

Fig. (3): Relative Radial Power Distribution (12 BPRs)
(Upper values for BOC and lower for EOC)

Average Pin Power
BOC= 61.72 kW
EOC = 51.78 kW

Maximum Power (BOC)

Maximum Power (EOC)

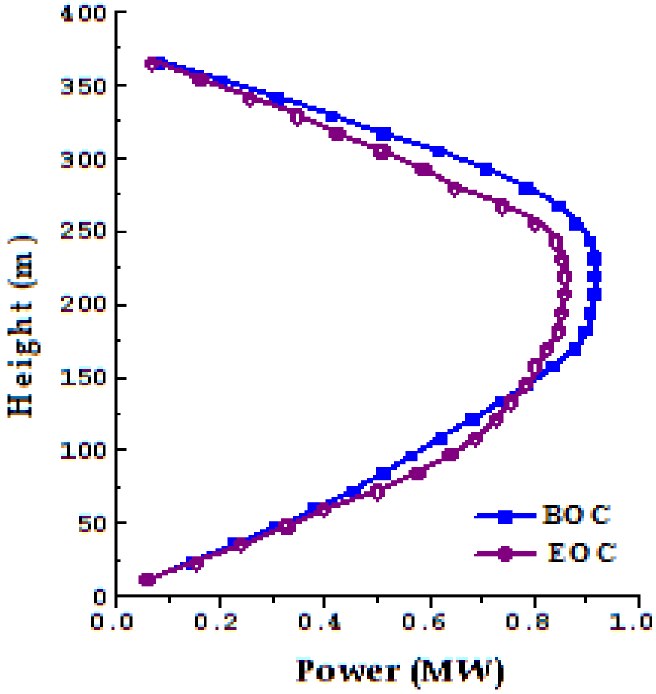
1.1101 1.1228																
1.0987 1.0841	1.0688 1.0510															
1.0704 1.0599	1.0234 0.9889	1.0032 1.0044														
1.0632 1.0618	1.0098 0.9905	0.9247 0.9378														
1.0239 1.0322	0.9726 0.9401	0.9091 0.9176	0.9065 0.9274	1.0162 0.9902												
1.0319 1.0140	0.9470 0.9452		0.9323 0.9357	1.0613 1.0607												
1.0187 1.0081	0.9952 0.9628	0.9056 0.8980	0.9567 0.9799	1.0322 1.0545	1.0887 1.1186	1.0645 1.0530										
1.0264 0.9711	0.9943 0.9531	0.9128 0.8793	0.9648 0.9534	0.9743 0.9691	0.9668 1.0048	1.0252 1.0213	1.0769 1.0658									
1.0300 0.9913	0.9317 0.9234		0.9216 0.8985	0.9228 0.9212		0.9739 0.9753	1.0940 1.1148									
1.0353 1.0242	0.9783 0.9901	0.9192 0.9062	0.9508 0.9434	0.9737 0.9750	0.9522 0.9944	1.0318 1.0329	1.0617 1.0494	1.1096 1.0892	1.0531 1.0554							
1.0305 1.0069	0.9867 0.9270	0.9122 0.8988	0.9448 0.9628	1.0392 1.0357	1.0635 1.0623	1.0435 1.0622	1.0243 1.0106	0.9798 0.9585	0.9990 1.0313	1.0173 1.0541						
1.0279 1.0082	0.9445 0.9461		0.9153 0.9432	1.0538 1.0780		1.0733 1.0800	0.9637 0.9454		0.9605 0.9912	1.0785 1.0744						
1.0303 1.0334	0.9690 0.9983	0.8946 0.9045	0.8948 0.9515	0.9763 1.0306	1.0411 1.0930	1.0164 1.0453	0.9694 1.0054	0.9237 0.9149	0.9566 0.9808	09937 1.0392	1.0663 1.0767	0.9952 1.0122				
1.0834 1.0343	1.0455 1.0118	0.9335 0.9322		0.8811 0.9048	0.9354 0.9542	0.9361 0.9751	0.9437 0.9934	0.9018 0.9238	0.9424 0.9477	0.9747 0.9952	0.9225 0.9416	0.8933 0.8893				
1.0900 1.0901	1.0305 1.0348	0.9821 0.9849	0.9337 0.9409	0.8991 0.9187		0.8920 0.9221	0.9113 0.9362		0.9245 0.8956	0.9343 0.9052		0.9132 0.8902	0.9308 0.9305	0.9970 0.9861		
1.0997 1.1007	1.0714 1.0644	1.0489 1.0211	1.0139 1.0231	0.9865 0.9748	0.9356 0.9761	0.9705 0.9594	0.9598 0.9656	0.9222 0.9337	0.9822 0.9824	0.9627 0.9514	0.9586 0.9500	0.9877 0.9754	1.0489 0.9642	1.0534 1.0268	1.0780 1.0719	
1.1095 1.1017	1.0812 1.0653	1.0704 1.1103	1.0322 1.0620	1.0497 1.0064	1.0502 1.0180	1.0367 1.0012	1.0299 1.0067	1.0415 1.0109	1.0437 1.0489	1.0362 1.0402	1.0389 1.0149	1.0406 1.0594	1.0741 1.0450	1.0831 1.0613	1.1018 1.0316	1.1101 1.1188

Fig. (4) Relative Radial Power Distribution (20 BPRs)
(Upper values for BOC and lower for EOC)

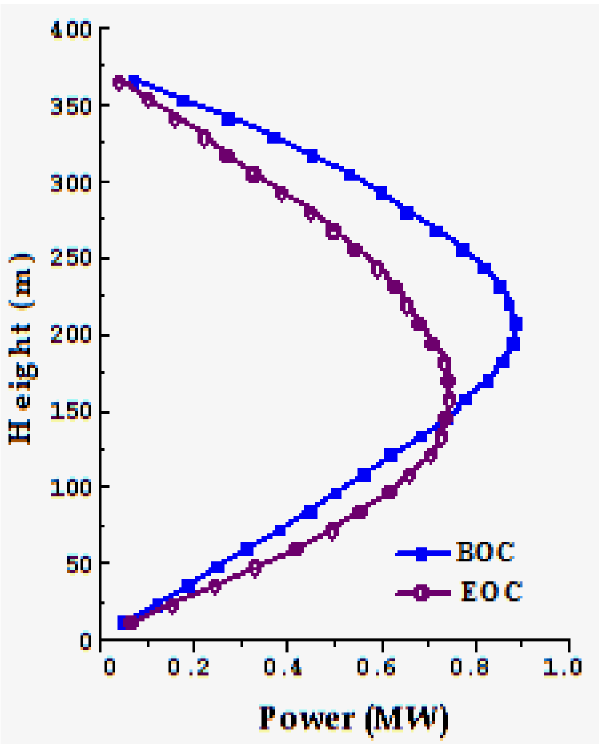
Average Pin Power
BOC= 57.85 kW
EOC = 46.63 kW

Maximum Power (BOC)

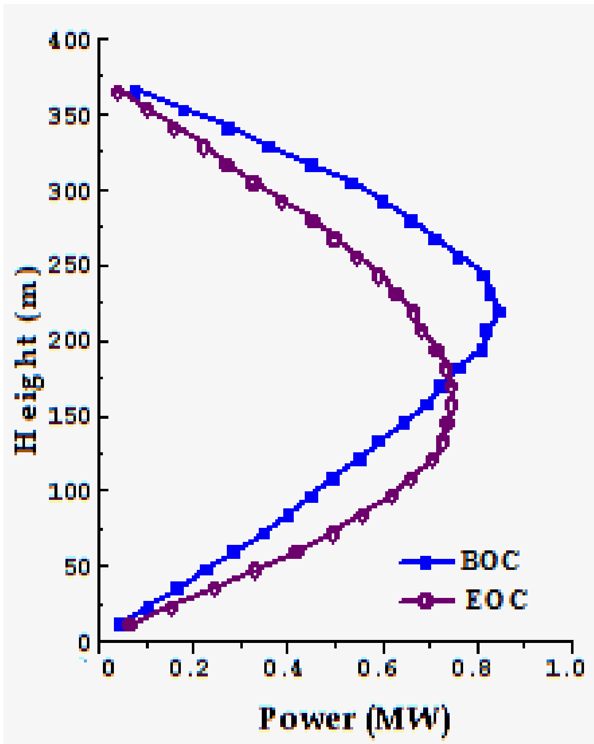
Maximum Power (EOC)



(a) No BPRs



(b) 12 BPRs



(C) 20 BPRs

Fig.(5): Axial Power Distribution

CONCLUSION

- The presence of BPRs affects the position of hot spot in a PWR fuel assembly.
- The maximum pin power for the assembly with no BPRs was located near the center of the assembly while for assemblies with BPRs the maximum power was located at the peripheries due to the absorbing effect of BPRs.
- The less the number of burnable of BPRs the more the position of maximum pin power is affected by burnup.
- The maximum axial power is shifted towards the bottom of the assembly mainly as a result of xenon buildup in the upper region of the assembly.
- The larger the number of BPRs the more is this shift towards the bottom of the assembly. This last conclusion requires further investigation which involves the analysis of axial isotope distribution as a result of burnup with the presence of BPRs.

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