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Simulation of BEAVRS Benchmark at Hot Zero Power Using MCNP6

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ABSTRACT

The BEAVRS benchmark provides detailed design data and in core flux measurements for a standard PWR. In this work the BEAVRS benchmark is simulated at hot zero power using the Monte Carlo code MCNP6. The effective multiplication factors estimated at various control banks insertions and boron concentrations. Calculations also include control rod banks worth, and isothermal temperature coefficient. Axially integrated Thermal flux in 58 assemblies, resembling detector positions in the core, are also evaluated and compared to the actual data provided by the benchmark. The axial thermal flux calculated for selected assemblies was compared to the results produced by detector signals located at 61 axial positions. Radial power distribution in the whole core is also evaluated, and compared to a previous study. The accuracy of the thermal flux and radial power calculations were evaluated using two methods; the absolute relative difference and the root mean square deviation. The model was capable of simulating the benchmark with a good degree of accuracy.

1- INTRODUCTION

Recent development in computer codes that utilizes parallel computing leads to the development of high-fidelity tools for the design and analysis of nuclear reactor cores, and such tools require extensive verification and validation. The BEAVRS benchmark (Benchmark for Evaluation and Validation of Reactor Simulations) provides the most detailed specifications, to allow a challenging comparison of a whole core model for neutronics calculation. It was published in 2013 by the Massachusetts Institute of Technology (MIT) Computational Reactor Physics Group (CRPG), and it was updated several times [1-3].

This benchmark provides a detailed description of a four loop Westing house PWR loaded with 193 fuel assemblies of 17×17 lattice for the rated reactor power of 3411 MWth. The details include all geometrical data and material compositions for the major core constituents including the assemblies, baffle and the barrel, neutron shield, burnable absorbers (BA), control rods (CR), core loading patterns, and numerous in-vessel components such as spacer grids, plenum regions, end plugs, an upper and lower nozzles and support plates. Moreover, the benchmark provides measured reactor data for Hot Zero Power (HZP) physics tests, including control rod worth and isothermal temperature coefficient (ITC). Detector readings, in the form of three-dimensional in-core flux maps from fifty-eight instrumented assemblies, are provided. These in-core detector signals are axial thermal neutron flux distributions measured by fission chambers inserted into the instrumentation tube of the 58 assemblies in the core. Both the axially-integrated and axial distributions of the thermal neutron flux are reported. A presentation of core arrangement including^{235}U enrichment, number and location of BAs and CR banks distribution in the core, as well as location of detectors are illustrated in Figure (1), and the main specifications for the core are listed in Table (1). Details of data concerning design and material composition can be referred to in previous MIT publications [1-3].

Many Research studies have been performed using the BEAVRS benchmark .J. Leppänen et al. [4] modeled the HZP condition of the initial core using the ARES nodal diffusion code[5] with Serpent-generated group constants[6]. Flux and power distributions were compared to full-scale heterogeneous Serpent calculations and experimental data .D.J. Kelly etal.[7] compared the results of MC21[8] and Open MC[9] Monte Carlo codes with BEAVRS HZP measurements using a quarter core model. Included in this comparison are axially-integrated full core detector measurements and axial detector profiles.

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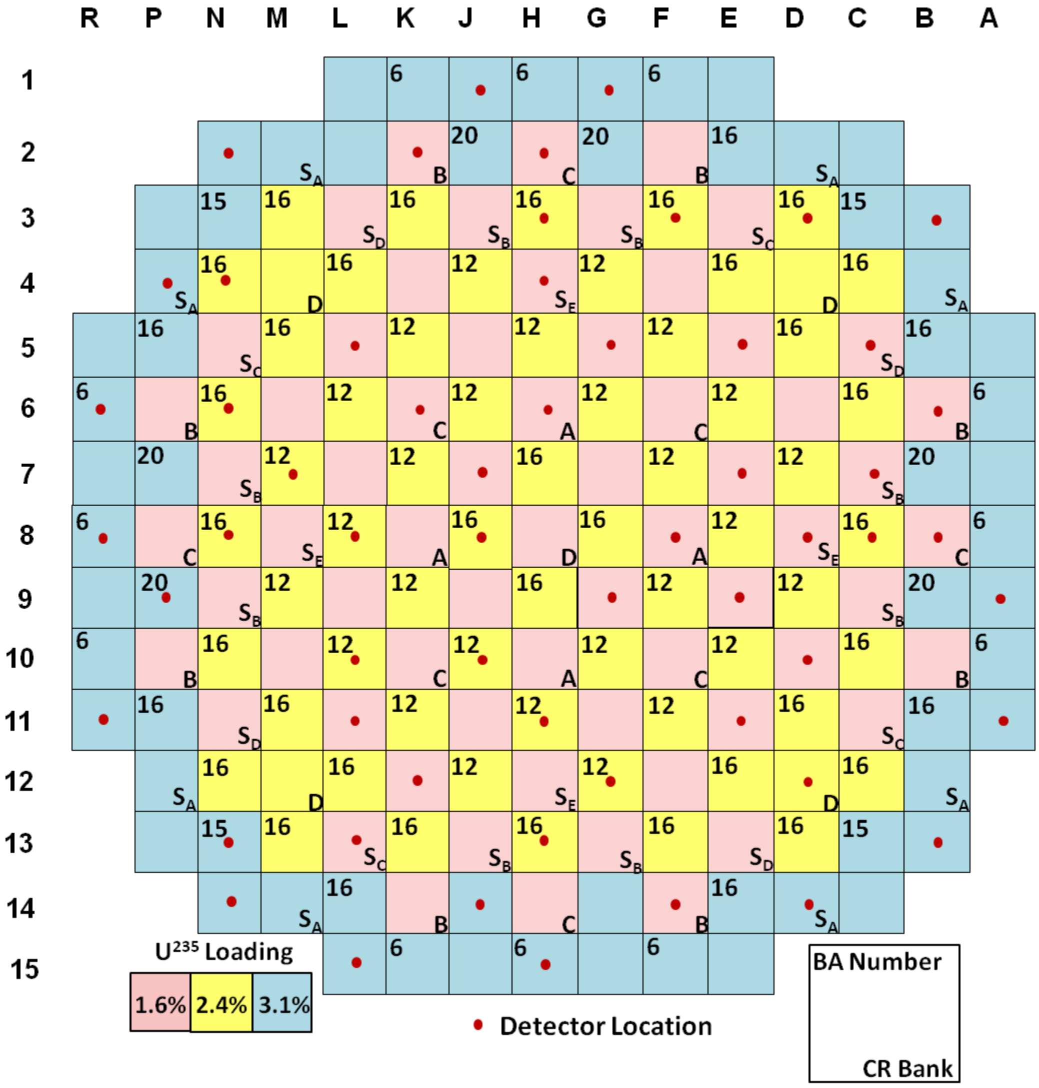


Fig. (1): Core Arrangement for BEAVRS Benchmark

Min Ryu et al. [10] solved the BEAVRS benchmark by the nTRACER code [11] employing direct whole core calculation code to assess its accuracy and to examine the solution dependence on modeling parameters. The resulting solutions for several HZP states are compared first with the corresponding Monte Carlo solutions and then with the measured data which includes the control rod worth as well as the critical boron concentration. Li Gang Deng et al. [12] compared the JMCT Code [13]results with HZP measurements of BEAVRS benchmark. Included in the comparisons are the Eigen values, control rod bank worth, isothermal temperature coefficients, axially integrated full core detector measurements, and axial detector profiles. Zhiyan Wang etal. [14] Applied the Super MC code [15] to calculate the HZP condition of BEAVRS. In this study, effective multiplication factor, control rod bank worth, temperature coefficient, U-235 fission rate and pin-by-pin relative power distribution are calculated and discussed. Bykov, V., et al.[16] assessed the capabilities of the SIMULATE-5 [17] code using the BEAVRS benchmark. In this work the power distribution was compared at BOC (beginning of cycle), MOC (middle of cycle), and EOC (end of cycle) against the provided fission detector measurement data. The calculation results of the criticality, the control rod bank worth, ITC and the in-core detector signals that correspond to the thermal neutron flux distribution are discussed. Darnowski, and Pawluczyk[18] performed tests and assessments of the SCALE-PARCS [19] two-step methodology for BEAVRS benchmark as a part of the training and experience-gathering process to enhance reactor safety competencies.

Table (1): BEAVRS Main Core Specification

Core	
Thermal power	3411 MW
Operating pressure	2250 psia
Fuel assembly	
Number	193
Lattice	17×17
Assembly pitch	21.50364 cm
Active fuel length	365.76 cm
Fuel rod pitch	1.25984 cm
No. of fuel rods	264
Fuel Rod	
Pellet material	UO2
Cladding material	Zircaloy
U-235 enrichment	1.6, 2.4, 3.1 wt %
Pellet radius	0.39218 cm
Cladding material	Zircaloy
Inner clad radius	0.40005 cm
Outer clad radius	0.45720
Control material	
Control Rods (upper region)	B_4C
Control Rods (Lower region)	Ag-In-Cd
Burnable absorber	Borosilicate glass
Spacer grid	
Number	8
Material for fuel rod	Inconel718, Zircaloy
Material for assembly	SS.304, Zircaloy
Structure Material	
Baffle	SS.304
Core Barrel	SS.304
Neutron shield	SS.304
Pressure vessel	Carbon Steel 508

In the present work, the latest version of the benchmark[3] is simulated using MCNP6 Monte Carlo Code [20], at HZP. The model is used to calculate the multiplication factor (estimated at different control banks insertions and boron concentrations), control bank worth, and ITC. Axially -integrated thermal flux for 58 assemblies resembling detector positions in the core, are also evaluated and compared to the actual results provided by the benchmark. Axial relative flux for selected assemblies is estimated and compared to the actual data located at 61 axial positions of assemblies with detectors. Moreover, radial power of the core is calculated and compared to a previous simulation of the benchmark.

2- MODEL DESCRIPTION

A detailed full core of the benchmark design was simulated using MCNP6 Code [20],and the Evaluated Neutron Data File library, ENDF/B-VII.1 [21]. The MCNP6 model is illustrated in Figure (2). The model was prepared to include all the details such as spacer grids neutron shield, upper and lower nozzles and upper plenum. There are nine types of fuel assemblies in the initial core, according to fuel enrichment, presence of burnable absorbers and control rods (Figure 1).

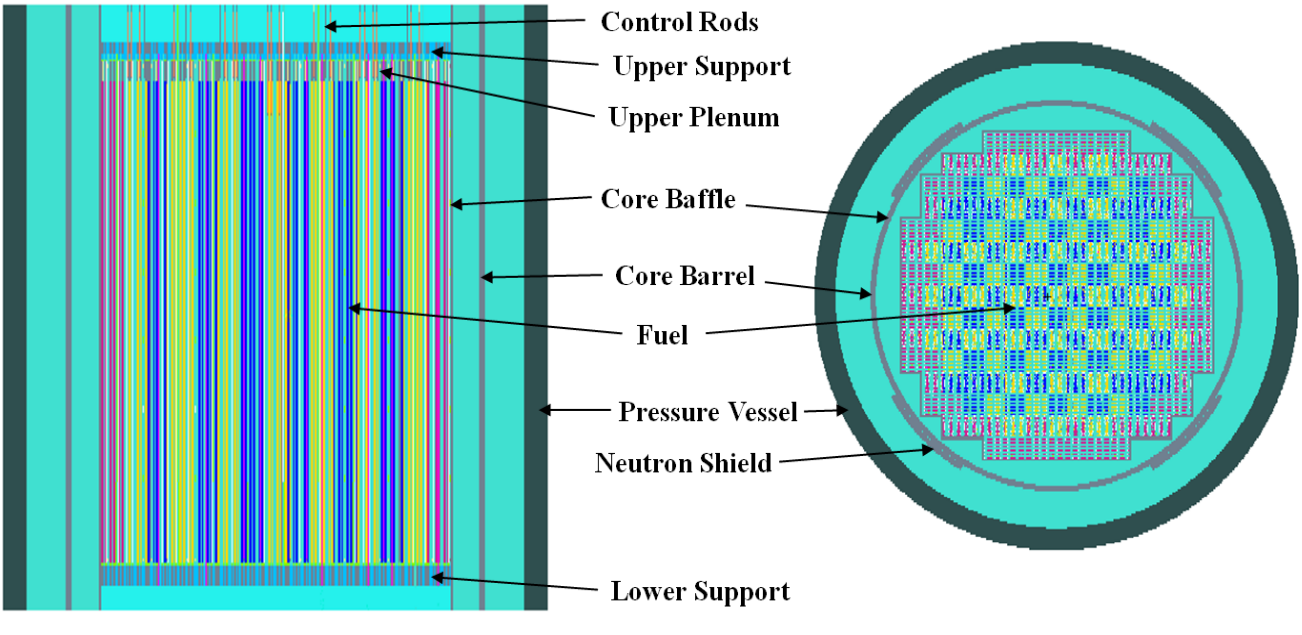


Fig. (2): MCNP Model of BEAVRS Benchmark

175 million neutron histories (500,000 neutron per cycle, 150 skipped cycles, and 350 active cycles) were used to determine the multiplication factor and flux distribution. The standard deviation of the criticality calculation was 0.00006.

The reactivity change, due to the change of temperature, density, or control bank insertion, is calculated from the following relation [22]:

$$\delta\rho = \frac{K_2 - K_1}{K_2 \times K_1} \quad \textbf{(1)}$$

Where $\delta\rho$ is the change in reactivity, K_1 is the multiplication factor before change and K_2 is the multiplication factor after change.

The ITC is the sum of moderator temperature coefficient (MTC) and fuel temperature coefficient (FTC)[23]. The MTC or FTC are calculated by using the following equation[22]:

$$MTCorFTC = \frac{\delta\rho}{T_2 - T_1} \quad \textbf{(2)}$$

Where $\delta\rho$ is estimated using equation 1with K_1 is the multiplication factor at original temperature and K_2 is the multiplication factor after temperature raise. T_2 is the elevated temperature and T_1 is the original temperature.

The accuracy of the calculation of thermal flux and power distribution was evaluated by two factors; the first is the absolute relative difference (ARD) given by [24]:

$$ARD = \frac{|calculatedvalue - referencevalue|}{referencevalue}$$

And the other is the root mean square (RMS) given by[25]:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}(calculatedvalue - referencevalue)^2}{N}}$$

Where N is the number of calculated values.

3- RESULTS AND DISCUSSION

3-1 Effective multiplication factor

Effective multiplication factors were calculated for different control banks insertions and corresponding boron concentration provided in the benchmark for each case[3]. The results are shown in Table (2). It is clear that the MCNP6 model is capable of predicting the multiplication factor for each case with an acceptable accuracy.

Table (2): Results of Criticality for Provided Conditions

Configuration	Boron Concentration (pcm)	MCNP6	BEAVRS	Difference (pcm)
ARO (All Rods Out)	975	0.9996	1.0	-40
D in	902	1.00123	1.0	123
C,D in	810	1.00037	1.0	37
A, B, C, D in	686	0.99927	1.0	-73
A,B,C,D,SE, SD,SC in	508	0.99798	1.0	-202

3-2 Control bank worth

The control banks worth were calculated by considering the difference in criticality with all rods out and that with all control rod bank (or banks) in. Table (3) shows that the resulting control banks worth agree to a large extent with actual values, the largest difference is for banks (A, B, C, D) insertion, 47 pcm, is less than 4%.

Table (3): Comparison of Control Rod Bank Worth Between Calculation Results and Benchmark Data

Configuration	MCNP6 (pcm)	BEAVRS (pcm)	Difference (pcm)
D in	775	778	3
C,D in	1250	1203	47
A, B, C, D in	558	548	10
A,B,C,D,SE, SD,SC in	1110	1099	11

3-3 Isothermal temperature coefficient

In order to estimate the ITC, multiple runs were performed where the moderator temperature and the fuel temperature were raised by 5 ^{o}K, Calculations were all performed at a boron concentration of 975ppm.The results are shown in Table (4), all the ITC calculations compare very wellwith the measured value, even for different control rod configurations.

Table (4): Comparison of ITC between Calculation Results and Benchmark Data

Configuration	MCNP6 (pcm/^{o}K)			BEAVRS (pcm/^{o}K)	Difference (pcm/^{o}K)
	MTC	FTC	ITC	ITC	
ARO	-1.85	-1.92	-3.77	-3.15	0.62
D in	-3.57	-1.75	-5.32	-4.95	0.37
C,D in	-13.46	-1.5	-14.96	-14.42	0.54

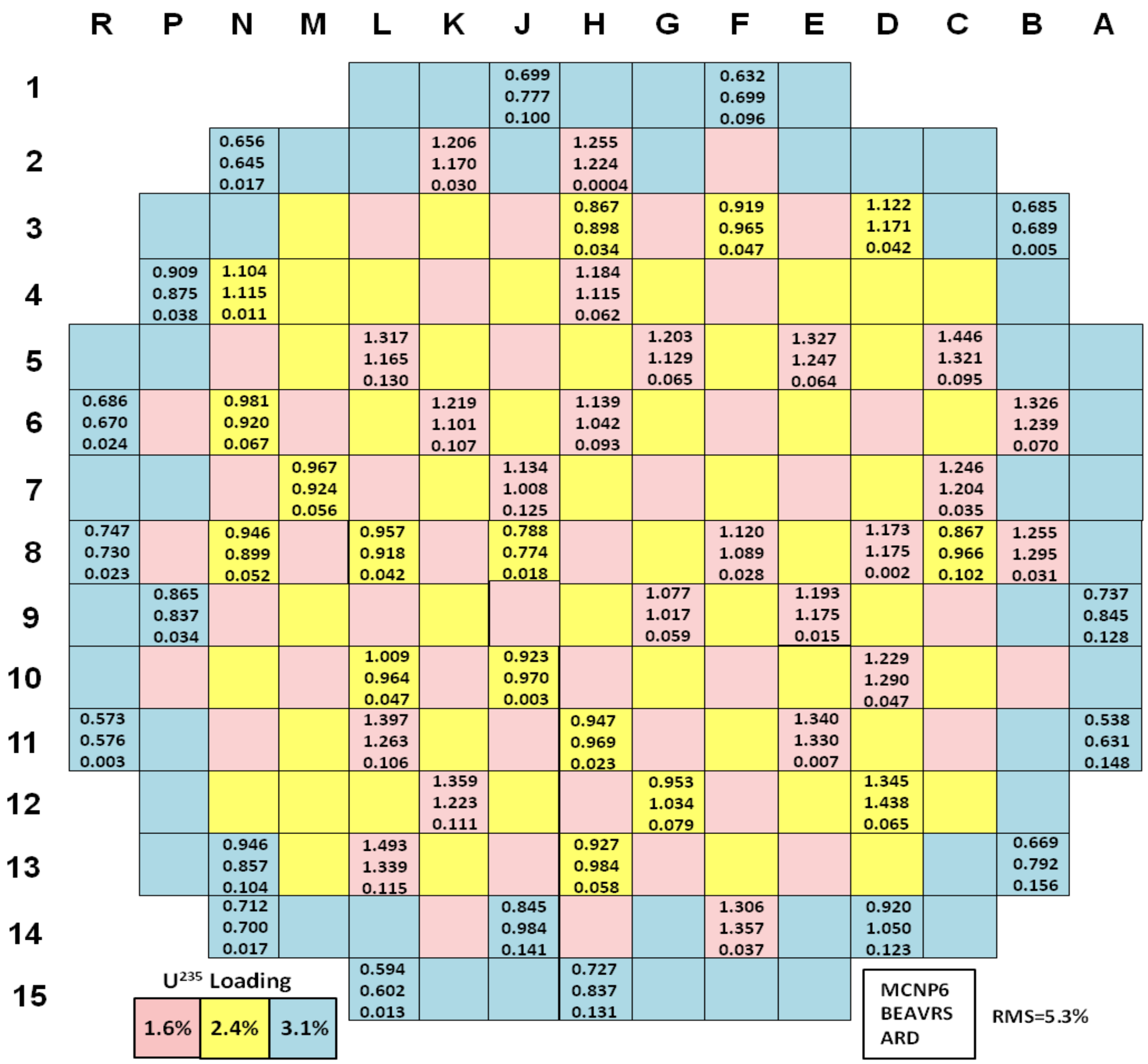
3-4 Thermal flux

In order to estimate the thermal flux in the 58 assemblies, where the detectors are positioned, the assemblies were divided into 61 axial divisions, corresponding to the number of detector positions in the benchmark. The resulting thermal flux was calculated for each division, and then averaged over the whole assembly readings. The flux was then normalized to the average flux in 58 assemblies which was 1.44×10^{14} neutron/cm^2.sec.

According to benchmark specifications, these measurements were performed with all control rod banks out except for bank D which was kept at bite position; at step 213 or an elevation of 376.909 cm from the bottom of the core. These calculations, as well as radial power calculations, were also performed with a boron concentration of 975 ppm.

The results of the calculations are shown in Figure (3). The maximum ARD occurred at assembly B13 (0.156), and RMS is 5.3%. The results are in agreement with the measured results as well as most of other codes results, where in some cases the difference between calculated and measured results reached 0.165 and RMS 6.89% [16].

Another means to verify the simulation is by comparing the axial relative thermal flux to the measured values. Figure (4) illustrates the relative axial flux for six assemblies distributed in the core; N2, H2, G9, L10, E11, and B13. These assemblies were chosen to have different positions, different relative flux and different ARD values, and included assembly B13 with the maximum ARD. The flux is normalized by dividing each segment flux by the average of all 58 assemblies. It can be seen that there is a reasonable agreement between the calculated and measured distributions.



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							0.699 0.777 0.100			0.632 0.699 0.096					
2			0.656 0.645 0.017			1.206 1.170 0.030		1.255 1.224 0.0004							
3								0.867 0.898 0.034		0.919 0.965 0.047		1.122 1.171 0.042		0.685 0.689 0.005	
4		0.909 0.875 0.038	1.104 1.115 0.011					1.184 1.115 0.062							
5					1.317 1.165 0.130				1.203 1.129 0.065		1.327 1.247 0.064		1.446 1.321 0.095		
6	0.686 0.670 0.024		0.981 0.920 0.067			1.219 1.101 0.107		1.139 1.042 0.093						1.326 1.239 0.070	
7				0.967 0.924 0.056			1.134 1.008 0.125						1.246 1.204 0.035		
8	0.747 0.730 0.023		0.946 0.899 0.052		0.957 0.918 0.042		0.788 0.774 0.018			1.120 1.089 0.028		1.173 1.175 0.002	0.867 0.966 0.102	1.255 1.295 0.031	
9		0.865 0.837 0.034							1.077 1.017 0.059		1.193 1.175 0.015				0.737 0.845 0.128
10					1.009 0.964 0.047		0.923 0.970 0.003					1.229 1.290 0.047			
11	0.573 0.576 0.003				1.397 1.263 0.106			0.947 0.969 0.023			1.340 1.330 0.007				0.538 0.631 0.148
12						1.359 1.223 0.111			0.953 1.034 0.079			1.345 1.438 0.065			
13			0.946 0.857 0.104		1.493 1.339 0.115			0.927 0.984 0.058						0.669 0.792 0.156	
14			0.712 0.700 0.017				0.845 0.984 0.141			1.306 1.357 0.037		0.920 1.050 0.123			
15					0.594 0.602 0.013			0.727 0.837 0.131							

Fig. (3): Normalized Thermal Flux

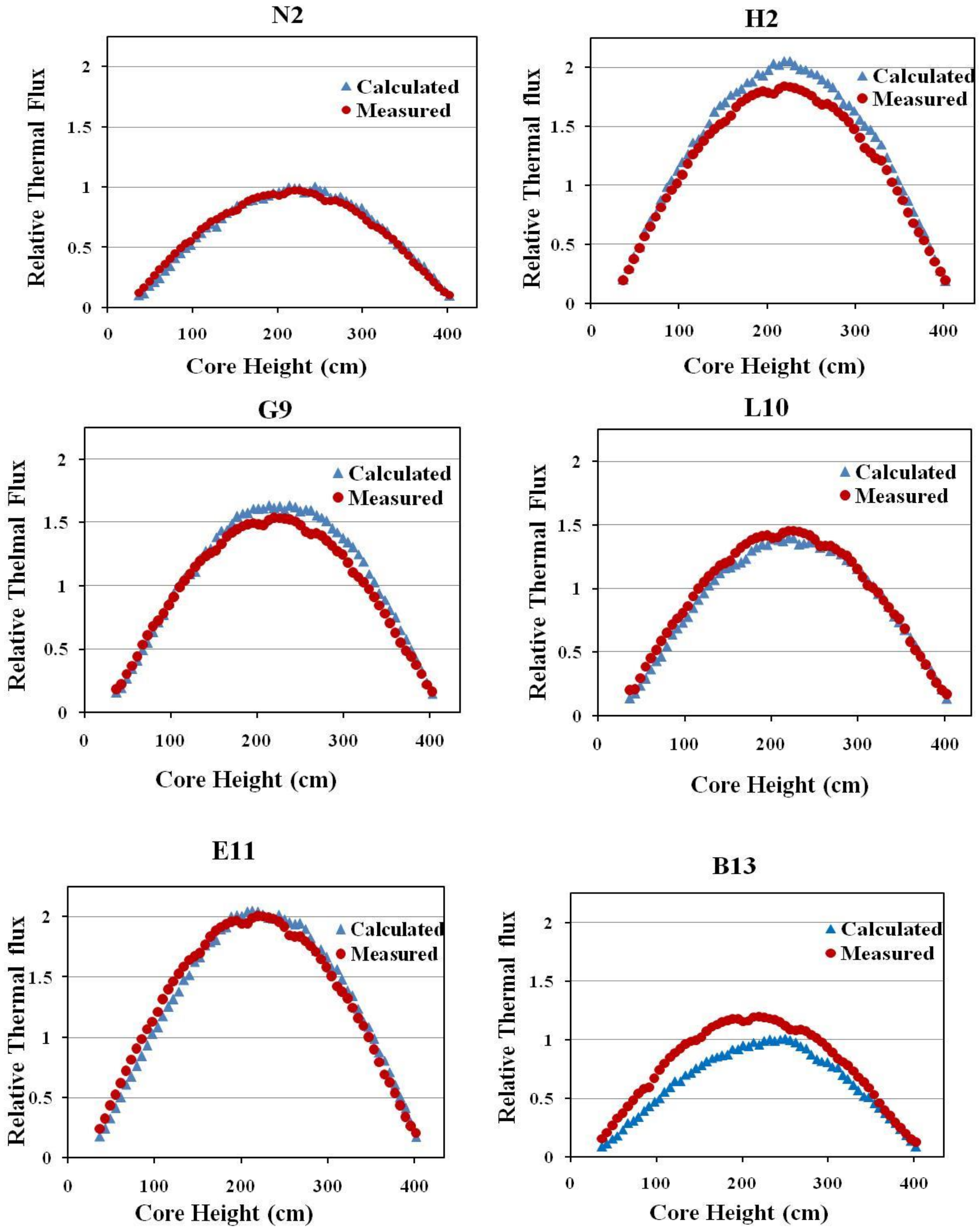
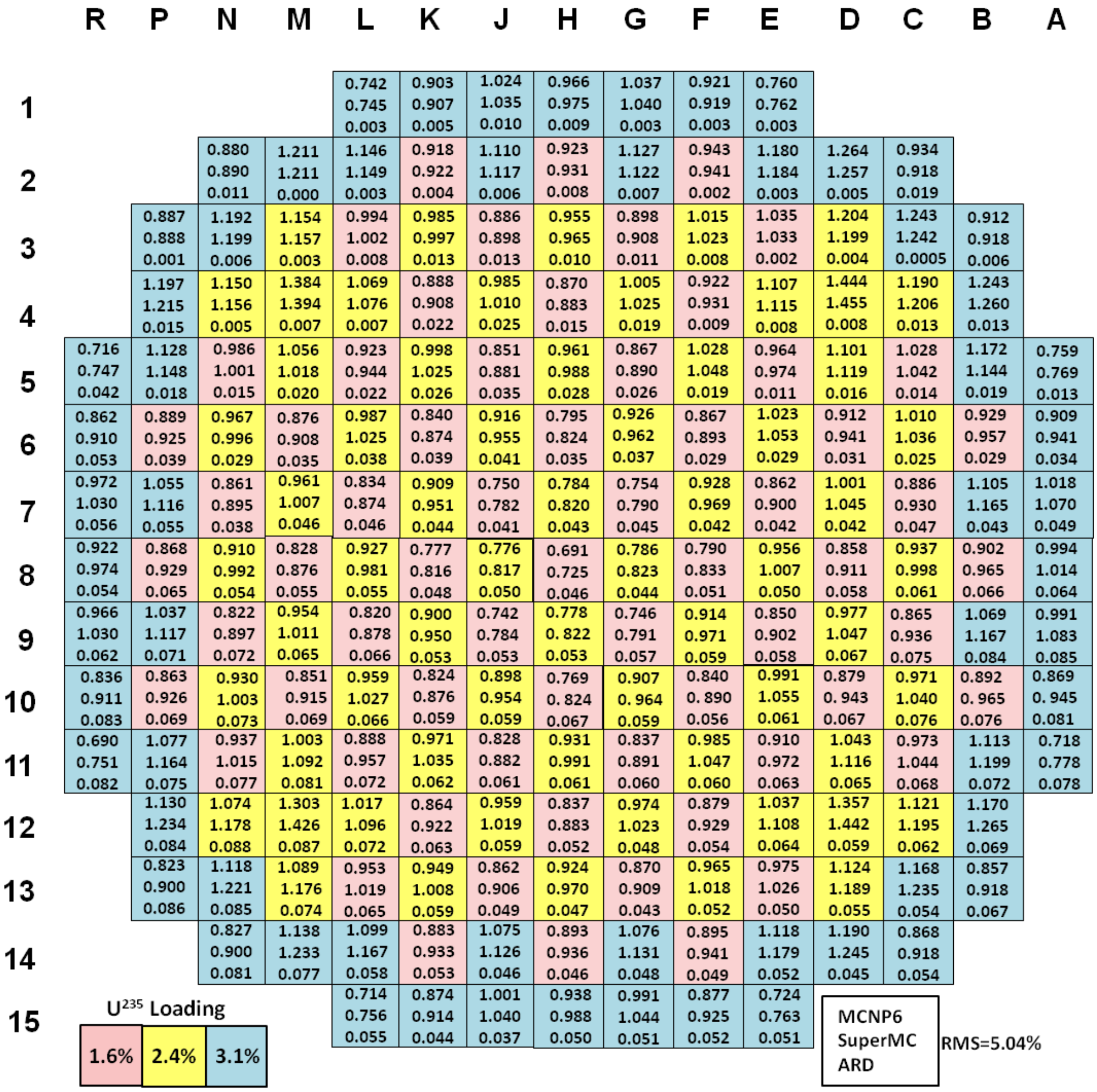


Fig. (4): Normalized Axial Flux for Selected Assemblies in Comparison to Experimental Fission Chamber Measurements

3-5 Radial power distribution

The radial power for each assembly was calculated and the relative radial power was compared to a previous study [14]. The results are shown in Figure (5). As illustrated, the model was able to predict that the power distribution is comparable to the previous study which was based on a fine mesh tally superimposed on the core geometry. The same procedure for estimating deviation that was used in calculating thermal flux was used here, considering the previous study as the basis of comparison. The resultant maximum ARD is 0.088 and the root mean square error is 5.04%.



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1					0.742 0.745 0.003	0.903 0.907 0.005	1.024 1.035 0.010	0.966 0.975 0.009	1.037 1.040 0.003	0.921 0.919 0.003	0.760 0.762 0.003				
2			0.880 0.890 0.011	1.211 1.211 0.000	1.146 1.149 0.003	0.918 0.922 0.004	1.110 1.117 0.006	0.923 0.931 0.008	1.127 1.122 0.007	0.943 0.941 0.002	1.180 1.184 0.003	1.264 1.257 0.005	0.934 0.918 0.019		
3		0.887 0.888 0.001	1.192 1.199 0.006	1.154 1.157 0.003	0.994 1.002 0.008	0.985 0.997 0.013	0.886 0.898 0.013	0.955 0.965 0.010	0.898 0.908 0.011	1.015 1.023 0.008	1.035 1.033 0.002	1.204 1.199 0.004	1.243 1.242 0.0005	0.912 0.918 0.006	
4		1.197 1.215 0.015	1.150 1.156 0.005	1.384 1.394 0.007	1.069 1.076 0.007	0.888 0.908 0.022	0.985 1.010 0.025	0.870 0.883 0.015	1.005 1.025 0.019	0.922 0.931 0.009	1.107 1.115 0.008	1.444 1.455 0.008	1.190 1.206 0.013	1.243 1.260 0.013	
5	0.716 0.747 0.042	1.128 1.148 0.018	0.986 1.001 0.015	1.056 1.018 0.020	0.923 0.944 0.022	0.998 1.025 0.026	0.851 0.881 0.035	0.961 0.988 0.028	0.867 0.890 0.026	1.028 1.048 0.019	0.964 0.974 0.011	1.101 1.119 0.016	1.028 1.042 0.014	1.172 1.144 0.019	0.759 0.769 0.013
6	0.862 0.910 0.053	0.889 0.925 0.039	0.967 0.996 0.029	0.876 0.908 0.035	0.987 1.025 0.038	0.840 0.874 0.039	0.916 0.955 0.041	0.795 0.824 0.035	0.926 0.962 0.037	0.867 0.893 0.029	1.023 1.053 0.029	0.912 0.941 0.031	1.010 1.036 0.025	0.929 0.957 0.029	0.909 0.941 0.034
7	0.972 1.030 0.056	1.055 1.116 0.055	0.861 0.895 0.038	0.961 1.007 0.046	0.834 0.874 0.046	0.909 0.951 0.044	0.750 0.782 0.041	0.784 0.820 0.043	0.754 0.790 0.045	0.928 0.969 0.042	0.862 0.900 0.042	1.001 1.045 0.042	0.886 0.930 0.047	1.105 1.165 0.043	1.018 1.070 0.049
8	0.922 0.974 0.054	0.868 0.929 0.065	0.910 0.992 0.054	0.828 0.876 0.055	0.927 0.981 0.055	0.777 0.816 0.048	0.776 0.817 0.050	0.691 0.725 0.046	0.786 0.823 0.044	0.790 0.833 0.051	0.956 1.007 0.050	0.858 0.911 0.058	0.937 0.998 0.061	0.902 0.965 0.066	0.994 1.014 0.064
9	0.966 1.030 0.062	1.037 1.117 0.071	0.822 0.897 0.072	0.954 1.011 0.065	0.820 0.878 0.066	0.900 0.950 0.053	0.742 0.784 0.053	0.778 0. 822 0.053	0.746 0.791 0.057	0.914 0.971 0.059	0.850 0.902 0.058	0.977 1.047 0.067	0.865 0.936 0.075	1.069 1.167 0.084	0.991 1.083 0.085
10	0.836 0.911 0.083	0.863 0.926 0.069	0.930 1.003 0.073	0.851 0.915 0.069	0.959 1.027 0.066	0.824 0.876 0.059	0.898 0.954 0.059	0.769 0. 824 0.067	0.907 0. 964 0.059	0.840 0. 890 0.056	0.991 1.055 0.061	0.879 0. 943 0.067	0.971 1.040 0.076	0.892 0. 965 0.076	0.869 0. 945 0.081
11	0.690 0.751 0.082	1.077 1.164 0.075	0.937 1.015 0.077	1.003 1.092 0.081	0.888 0.957 0.072	0.971 1.035 0.062	0.828 0.882 0.061	0.931 0.991 0.061	0.837 0.891 0.060	0.985 1.047 0.060	0.910 0.972 0.063	1.043 1.116 0.065	0.973 1.044 0.068	1.113 1.199 0.072	0.718 0.778 0.078
12		1.130 1.234 0.084	1.074 1.178 0.088	1.303 1.426 0.087	1.017 1.096 0.072	0.864 0.922 0.063	0.959 1.019 0.059	0.837 0.883 0.052	0.974 1.023 0.048	0.879 0.929 0.054	1.037 1.108 0.064	1.357 1.442 0.059	1.121 1.195 0.062	1.170 1.265 0.069	
13		0.823 0.900 0.086	1.118 1.221 0.085	1.089 1.176 0.074	0.953 1.019 0.065	0.949 1.008 0.059	0.862 0.906 0.049	0.924 0.970 0.047	0.870 0.909 0.043	0.965 1.018 0.052	0.975 1.026 0.050	1.124 1.189 0.055	1.168 1.235 0.054	0.857 0.918 0.067	
14			0.827 0.900 0.081	1.138 1.233 0.077	1.099 1.167 0.058	0.883 0.933 0.053	1.075 1.126 0.046	0.893 0.936 0.046	1.076 1.131 0.048	0.895 0.941 0.049	1.118 1.179 0.052	1.190 1.245 0.045	0.868 0.918 0.054		
15					0.714 0.756 0.055	0.874 0.914 0.044	1.001 1.040 0.037	0.938 0.988 0.050	0.991 1.044 0.051	0.877 0.925 0.052	0.724 0.763 0.051				

Fig. (5): Relative Assembly power distribution

4- CONCLUSIONS

- In the present work, the BEAVRS benchmark was simulated using MCNP6 Monte Carlo code. The simulation included a comprehensive description of fuel assemblies, as well as design details including baffle and barrel, upper and lower nozzles, upper plenum and also spacer grids.
- The results included the multiplication factor, at various control banks insertions, and boron concentrations. The resulting differences from benchmark values were within acceptable range.
- The maximum difference between the calculated values and benchmark values for control rod worth was less than 4%.
- The isothermal temperature coefficient was calculated by adding the MTC and FTC. The comparison between calculation and actual results was satisfactory.
- Fifty eight assemblies containing detectors were divided into 61 axial divisions where thermal flux was estimated, integrated, and compared to the actual data. The RMS for these results was 5.3%

which indicates a good agreement with the actual data, the maximum ARD was 0.156.

- The axial relative thermal flux was compared to the real data resulting from 61 axial detector positions, for six assemblies distributed in the core including the one with the highest ARD.
- The normalized radial power was compared to a previous study and the maximum difference was 0.088, and RMS was 5.04%.
- The model was able to simulate the real data effectively.

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