Burnup Analysis for BN-600 Reactor Core Fuelled with MOX Fuel and Minor Actinides

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Abstract. MCNPX computer code has been used to model the reactor core of the BN-600 fast reactor which is fuelled with MOX fuel with Minor actinides. The MOX fuel is recycled from spent LWR fuel which is burnt up up to 60 GWd/T, and cooled up to 50 years. The BN-600 core consists of three main zones, Low enrichment (LEZ), Medium enrichment (MEZ) and High Enrichment (HEZ). The reactor multiplication factor, control rod worth, Fuel burnup and isotopic transmutation are calculated. Power distribution also is evaluated inside the reactor core. The present results are also compared with that of other previous models.

KeyWords: BN-600 reactor , MCNPX code, Fuel Burnup , Minor Actinides

1. Introduction

The BN-600 reactor is a sodium- cooled fast breeder reactor, built in Russia, designed to generate electrical power of 600 MW in total. IAEA has considered the reactor for many phases of benchmark problems. The coordinated research project activities were started in 1999 and included studies for a so-called hybrid BN-600-reactor-type core model [1], partially fuelled with highly enriched uranium and MOX fuel ,Phases 1 to 3 [2], a full-MOX core model with weapons-grade plutonium (Phase 4), a model of the BFS-62-3A experimental critical configuration [3] , a mockup of the hybrid core (Phase 5) and, finally, a full-MOX core model with plutonium and Minor Actinides coming from spent fuel of Light water reactor (Phase 6).

Benchmark analyses for a BN-600 reactor core model with MOX fuel containing ‘‘Minor Actinides (MAs)’’ were performed in the framework of the IAEA-sponsored ‘‘Coordinated Research Project (CRP)’’ on ‘‘Updated Codes and Methods to Reduce the Calculational Uncertainties of the LMFR Reactivity Effects’’ [4,5]. The general objective of the CRP was to validate, verify, and improve methodologies and computer codes used for the calculation of reactivity coefficients in fast reactors, with the aim of enhancing the utilization of plutonium and minor actinides.

2. BN- 600 Model of Reactor Core with Minor Actinides

In principle, the core layout is the same as that of the MOX core of BN-600. The core consists of a low enrichment MOX inner zone (LEZ), a middle enrichment MOX zone (MEZ), and a high enrichment MOX zone (HEZ). In addition, there is an internal breeding zone (IBZ) in the central 5.1 cm of the LEZ region. For this benchmark configuration, each enriched zone has a burnup of 2–3%, while the internal breeding zone, which contains relatively more ^{238}U, has a burnup of 1.7%. All control rods are located inside the LEZ region Figure 1 , there are nineteen shim control rods (SHR) and Six scram control rods (SCR).All control rods are composed of boron carbide (B_4C), the composition , geometry and data of control rods can be found at reference [5]. Radially , beyond the HEZ outer zone are two steel shielding zones (SSA1 and SSA2) followed by a radial reflector zone (REF). In the control rod zone, the bottom of the absorber is parked 2.55 cm above the core mid-plane, whereas, in the scram rod zone the absorber is parked at the bottom of the upper boron shield region [5].

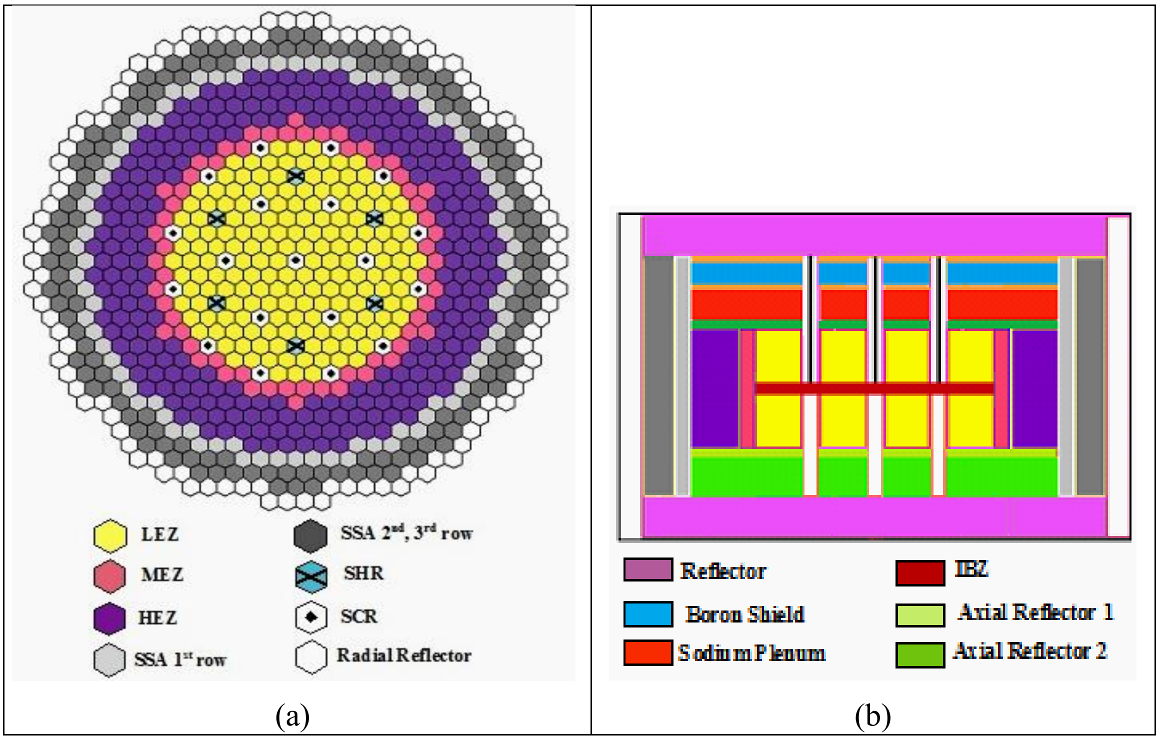

FIG. 1Typical Layout of BN-600 Full MOX Computer Model:(a)radial layout and (b) axial layout.

To establish an envelope case for MOX fuel with addition of Minor Actinides (MA),it is considered that a 60 GWd/t reprocessed LWR uranium fuel and allowing for a fuel storage cooling time period of 50 years before reuse. For a 25% TRU content in the fuel, the MA content there would amount to more than about 6% and may pose a quite challenging issue for the core transient behaviour. The compositions of different fuel zones are calculated at references [5, 6, 7] which are considered at this paper.

MCNPX code, [8] based on Monte Carlo method, is used to design a three dimensional and typical computer model to the reactor core , all core zones radially and axially are represented in the model, and are shown at figure 1. A core cycle of 140 days is considered for the analysis. Fuel temperature is 1200 K and steel, clad and structure material temperature is 600 K, these temperatures have been incorporated by assigning neutron cross section library at these temperature.

Two million neutron histories were used to simulate the neutron interaction and transport inside the reactor core and accumulate the results and tallies. The results include the reactor multiplication factor, flux and power distributions. Safety parameters of the reactor core, also incineration and burn up of minor actinides at EOC are evaluated.

3. *Results and Discussions*

3.1 Core Reactivity and control rod worth

The Reactor core multiplication factor k_{eff} is calculated at beginning of cycle (BOC) when control Rod SHR at middle position and SCR out using the present model it is found that k_{eff} equals 1.00464 , the results are compared with other reference [5,7] , which are given in Table 1. The reactivity loss due to fuel burn up at end of cycle i.e after 140 days of full power operation was found to be 751 pcm which are compared with other results at Table 2, the difference is 157 pcm. The total worth of control rod SHR and SCR are 4929.1 and 2939.5 pcm respectively, the total worth when both SHR and SCR are full inserted in the core together is 4719.1 pcm. Control rod results are given at table 3 and compared with other results. Comparing the results of the present model with other results indicate that good agreement with other methods which includes results performed with diffusion and Transport computer codes.

TABLE 1: K_{eff} AT BOC COMPARISON WITH DIFFERENT ORGANIZATIONS [5,7]

Keff	**Present Model**	**KAERI**
BOC	1.00464	1.00658

TABLE 2:REACTIVITY LOSS - COMPARISON WITH DIFFERENT CALCULATIONS

	Present model	**KIT**
Reactivity loss (pcm)	751	594

TABLE 3:CONTROL ROD WORTH (pcm)

SHR worth	**SCR Worth**	**Total worth present model**	**Total worth Reference (6)**
4729.1	2939.5	7419.3	7448

Fuel Temperature Coefficient of Reactivity

Fuel Doppler coefficient has been calculated for the present core model at BOC for a change in fuel temperature from 1200 K (T_1) to 3000 K (T_2) which is the available processed fuel isotope cross section at MCNPX library , the fuel Doppler coefficient is defined as :

$$K_D = \frac{K_2 - k_1}{k_1 . k_2} \frac{1}{\ln(\frac{T_2}{T_1})}$$

The Doppler reactivity coefficient is given by

$$\alpha_D = \frac{K_D}{T_2}$$

The predicated value for the fuel Doppler coefficient at BOC and EOC are given at table 4 The Doppler coefficient decreases from BOC (- 334.1 pcm) to (-77.99 pcm) at EOC due to increase the concentration of Minor Actinides at EOC as illustrated in Figure 6.

Table 4 Doppler reactivity coefficient

	BOC	**EOC**
K_D	**-334.1 (pcm)**	**-77.99 (pcm)**
α_D	**-0.1114 (pcm/K)**	**-0.02599 (pcm/K)**

3.2 Burnup and Isotopic Transmutation

During Reactor operation fuel atoms interact with neutrons causing fissions , scattering and radiative capture , so atoms concentration change with time. Figures 3 to 6 illustrate the fuel evolution versus time for LEZ zone. Figure 3 shows ^{235}U concentration versus operation time (day), the figure indicates ^{235}U decreases with time. , and 13.8 % are consumed at the end of 140 days of full power operation.

Figure 4 illustrates the concentration of both ^{241}Am and ^{237}Np (atom/barn.cm) versus operation time (days) , both are decreasing with time the consumed ratio for both ^{241}Am and ^{237}Np are -12.3 % and -10.44 % respectively.

Figure 5 illustrates Plutonium isotopes concentration with operation time (days) the results indicates that for ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu and ^{242}Pu the fraction change (increasing or decreasing) are +13.52 , -3.77 , -0.198 , +40.87 and +79.2 respectively.

Figure 6 illustrates the evolution of corium (Cm) isotopes with time (days), corium isotopes are ^{242}Cm , ^{243}Cm , ^{244}Cm , ^{245}Cm , ^{246}Cm and ^{247}Cm. The indicates that al Cm isotopes increases with time the fraction change are +62.78 , 79.84 , 98.28 , 2.51 , 7.22 , and 34.2 % respectively.

Table 5 illustrate the initial concentration, concentration after 140 full power operation days and the fraction change for each isotope of LEZ zone materials .

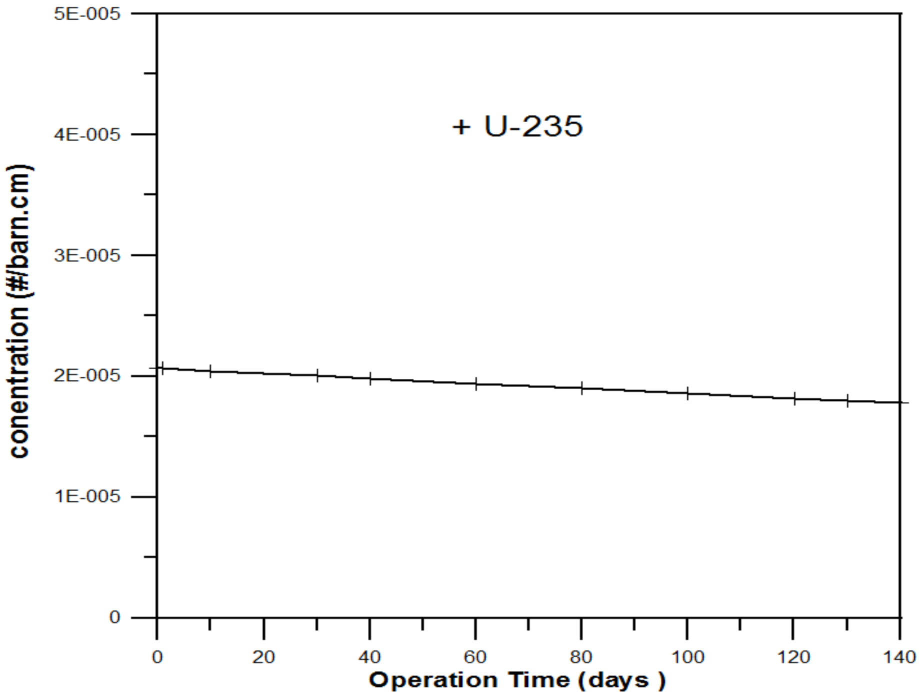

FIG. 3 ^{235}U isotopes (#/b.cm) versus operation time (day) at LEZ zone.

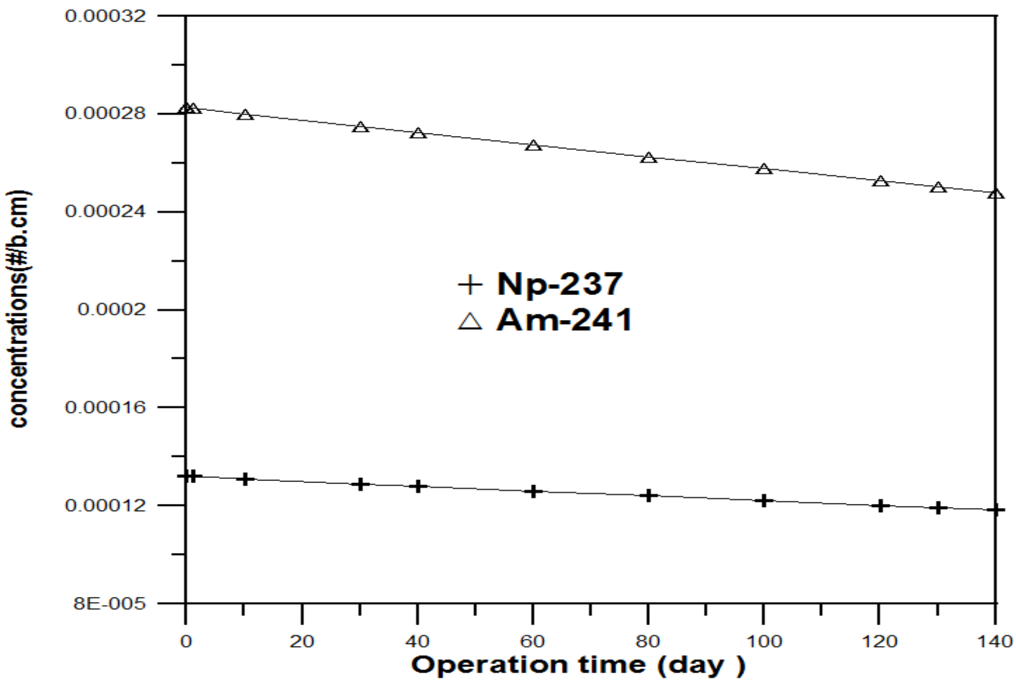

FIG.4 ^{237}Np and ^{241}Am isotopes (#/b.cm) versus operation time (day) at LEZ zone.

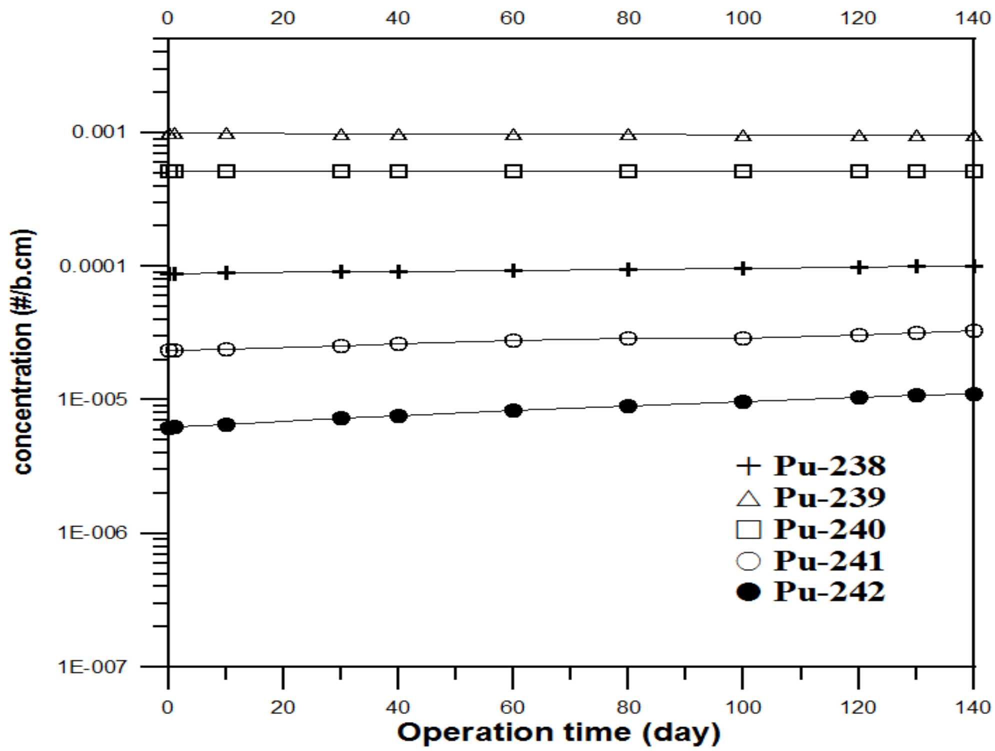

FIG. 5 Pu-isotopes (#/b.cm) versus operation time (day) at LEZ zone.

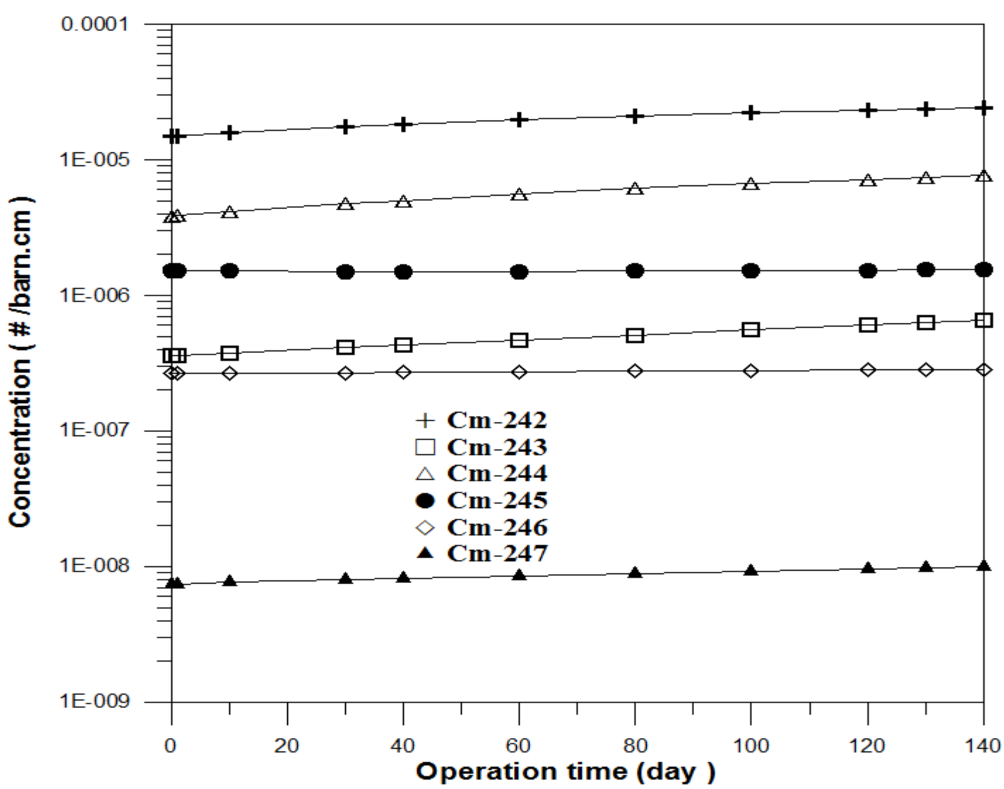

FIG. 6 Cm isotopes (#/b.cm) versus operation time (day) at LEZ zone.

TABLE 5 ATOM CONCENTRATIONS (ATOM/BARN.CM) FOR LEZ AT THE BEGINNING AND END OF CYCLE

Isotope	BOC Atom/barn.cm	EOC Atom/barn.cm	Fraction change %
U-234	0.0	2.775E-07	
U-235	2.068E-05	1.782E-05	-13.83
U-236	6.692E-07	1.274E-06	+90.37
U-238	5.823E-03	5.705E-03	-2.02
Np-237	1.321E-04	1.183E-04	-10.44
Pu-238	8.871E-05	1.007E-04	+13.52
Pu-239	9.959E-04	9.583E-04	-3.77
Pu-240	5.179E-04	5.169E-04	-0.193
Pu-241	2.341E-05	3.298E-05	+40.87
Pu-242	6.243E-06	1.119E-05	+79.2
Am-241	2.827E-04	2.480E-04	-12.27
Am-242	4.353E-06	4.925E-06	+13.14
Am-243	4.118E-05	3.649E-05	-11.38
Cm-242	1.494E-05	2.432E-05	+62.78
Cm-243	3.617E-07	6.505E-07	+79.84
Cm-244	3.859E-06	7.652E-06	+98.28
Cm-245	1.511E-06	1.549E-06	+2.51
Cm246	2.645E-07	2.836E-07	+7.22
Cm-247	7.442E-09	9.990E-09	+34.2

3.3 Core Power Distributions

Table 6 illustrates the power distributions through different zones of the reactor core , the results show power fraction in each zone and power in (Mw), the power (Mw) as compared with other reference (5) , and the fuel burnup (Mwd/T) after 140 full power operation day (discharge burn up). The results show that most of the power is produced in high enrichment zone (HEZ) (0.4432) , Low enrichment zone LEZ with fraction (0.3856) , medium enrichment zone MEZ (0.1368). Blanket zones and IBZ zone produce only small fractions. The results also indicate good agreement between present model and the reference values.

Figure 7 illustrates the total flux map distributions (n/cm^2.s) through the reactor core at BOC of cycle through 1/6 of the core with control rod SHR inserted up mid of the reactor core , and SCR totally out. The results indicates that the total flux increases near the core centre and decreases near periphery of the core towards the outer assembly while the total flux perturbs around the control rod SHR where it is in level mid core.

Figure 8 illustrates the Radial power map distributions (MW/assembly) through the reactor core at BOC (Upper values) and EOC (lower values through 1/6 of the core with control rod SHR inserted up mid of the reactor core , and SCR totally out. The results illustrate that power per assembly slightly change through core cycle from beginning to end of cycle and the power maximize near core center.

TABLE 6 POWER DISTRIBUTION THROUGH DIFFERENT ZONE IN BN-600 REACTOR

Zone number	Power fraction	Power (Mw)	Power (reference 5)	Discharge Burnup MWd/T
LEZ	0.3856	566	559	20050
MEZ	0.1368	201.1	198.507	20080
HEZ	0.4432	651.5	680.11	16280
AB 2 (LEZ)	6.741E-3	9.909	11.815	925
AB 2 (MEZ)	1.858E-3	2.731	3.278	724.1
AB 2 (HEZ)	4.509E-3	6.628	8.444	433.7
AB 1 (LEZ)	3.735E-3	5.491	4.374	2737
AB 1 (MEZ)	1.084E-3	1.594	1.315	2277
AB 1(HEZ)	2.739E-3	4.026	3.646	1412
IBZ	1.368E-2	20.1096	19.61	11320
total	1.0			

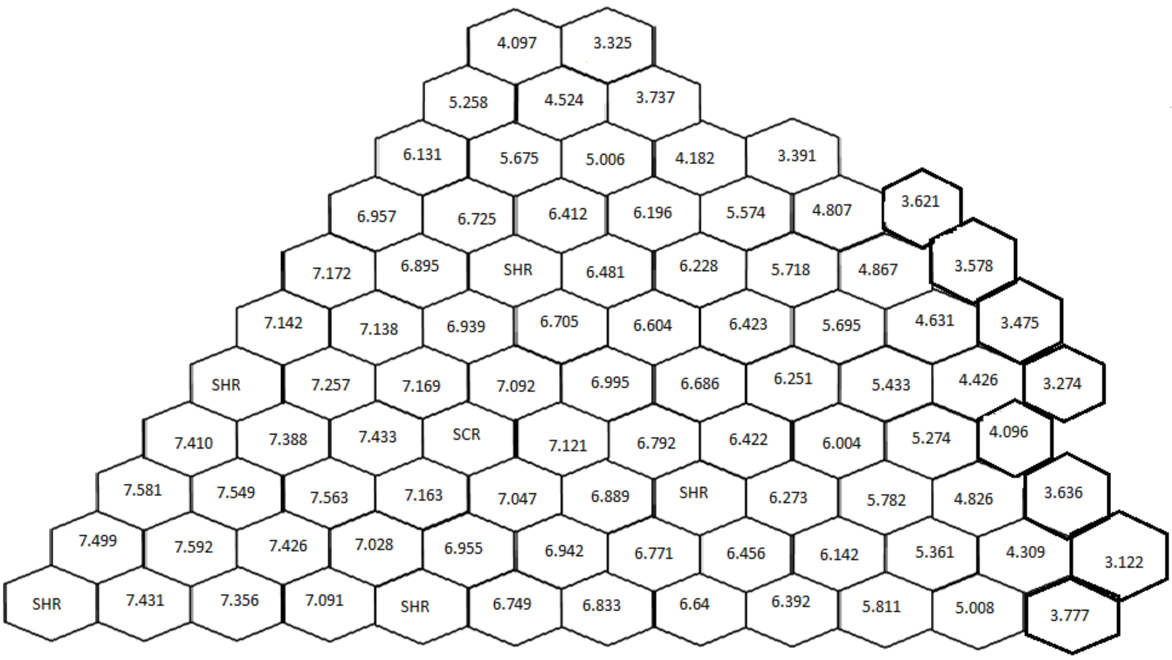

FIG. 7 Radial total flux map distributions (n/cm^2 .s) through the reactor core at BOC cycle

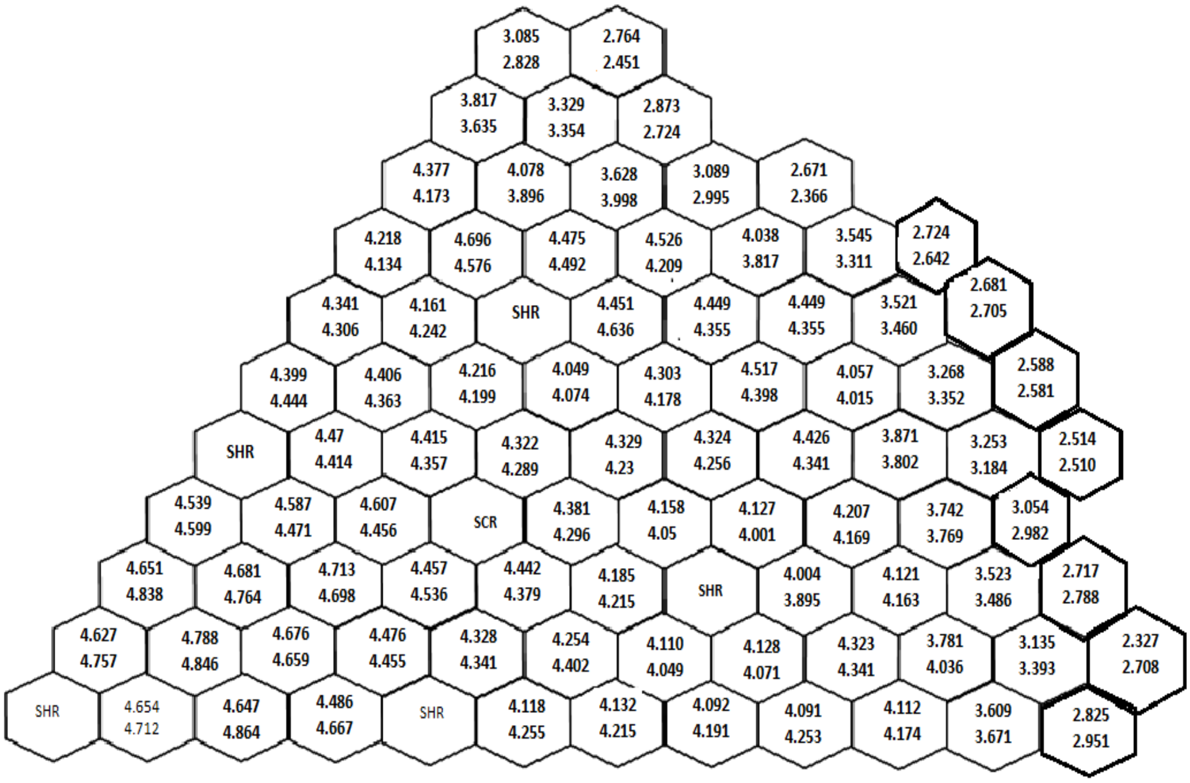

FIG.8 Radial power map distributions (MW/assembly) through the reactor core at
BOC upper values
EOC lower values

4. *Conclusions*

- MCNPX computer code package is used to design a computer model to simulate the burnup of the core for a 140 full operation cycle which is fueled with recycled plutonium from LWR spent fuel with minor actinides .
- The multiplication factor of the core and the control rod worth are calculated and showed compared with other published results.
- Fissile isotopes ^{235}U and ^{239}Pu decreases due to consumption and fission
- ^{241}Am decreases by 12 % due to neutron absorption and decays. All corium isotopes increases with burnup due to buildup from lower isotopes.
- During core operation power fraction are produced in LEZ , MEZ , HEZ and IBZ zones with fractions 0.38 , 0.13 , 0.44 and 0.013 respectively
- Fuel Doppler temperature coefficient of reactivity decreases at the end of cycle EOC due to increases the concentration of minor actinides.

5. References

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