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The Influences of the Burnable Absorber (UO_2+Gd_2O_3) on VVER-1200 Fuel Assembly

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ABSTRACT

Burnable absorber rods (UO_2+Gd_2O_3) and chemical shim are the main control poisons that are used in the core for improving the reactor behavior and satisfying the safety criteria during the core life time. These absorbers (Gd_2O_3) have several constraints, criteria, and advantages and also disadvantages from the safety and operation points of view; and these characteristics depend on the concentration and distribution of mentioned poisons in the reactor core. In this study, the influences of the burnable absorbers (Gd_2O_3) on the main parameters of the reactor such as multiplication factor (K_{eff}), neutron flux and burnup over the reactor life time are investigated. Monte Carlo Serpent code is used to design a three dimensional model for VVER-1200 assembly. The VVER-1200 assembly is loaded in different operation process with 8.0% Gd_2O_3 as integral burnable absorbers (IBAs). Burnable absorber rods (UO_2+Gd_2O_3) are used in two rings in reactor core, one is central rings with low percentage of absorber (Gd_2O_3) due to low neutron flux in central part of core, and another is peripheral ring with high percentage of absorber (Gd_2O_3) because of high neutron flux in peripheral part of core. In this article, optimal position of absorbers (Gd_2O_3) and optimal amount of absorbers (Gd_2O_3) in VVER-1200 core are calculated. The strong influence of the burnable absorbers (BAs) composition and their location in the fuel elements on the dependence of the multiplication factor on fuel burnup is shown.

Keywords: Burnable absorber rods, Multiplication factor (K_{eff}), VVER-1200, Burnup, Neutron flux

1. Introduction

The main sources of energy for the nuclear power plants (NPP), which are operated and constructed in the present, are light water reactors (such as VVER-1200). Similar plants are planned to be used in the future of the construction of the nuclear power plants in different countries, regardless of the specifics of the national plans for the development of the nuclear energy. One of the main goals of the scientific and technical developments related to the fuel cycle of power reactors is increasing the depth of the fuel burnup. Usually it is achieved by increasing the initial enrichment and applying partial overloads. To compensate for excess reactivity, a "liquid" system is used, based on the addition of a boric absorber to the coolant and, in addition, burnable absorbers of various types [1].

Burnable absorbers (also known as burnable poisons) are materials with a high neutron absorption cross section, which, as a result of radioactive capture, are converted to materials with a relatively low absorption cross section. Due to burnout of the absorbing material, the negative reactivity of the burnable absorber decreases over the life of the core. Ideally, these absorbers should reduce their negative reactivity at the same rate that the excess positive reactivity of the fuel is depleted. In PWR, burnable absorbers are used to reduce the initial concentration of boric acid and to reduce the relative power of fresh fuel assemblies [2].

Only two gadolinium isotopes have the largest thermal neutron absorption cross-section among other isotopes (Gd-155 and Gd-157 have 60,000b and 200,000b respectively). Inside PWR assembly fuel rods, Gadolinium produces a shift in the thermal neutron spectrum preventing them from penetrating the material block (Self-Shielding) [3]. It exhibits residual reactivity suppression due to the conversion of Gd155 into Gd156 and Gd157into Gd158 which both don’t convert into further isotopes. When used as integral neutron absorber, gadolinium needs to be concentrated in small number of fuel rods to avoid too fast depletion. Oxide gadolinium Gd2O3 is used in this case because gadolinium reacts quickly with hot water. Gadolinia displaces uranium from the fuel matrix, results in reduced heavy metal loading and shorter cycle. Nevertheless, residual negative reactivity remains due to the presence of other gadolinium isotopes that are not completely destroyed (155Gd and 157Gd) [4]. Compared to other burnable absorbers, gadolinium behaves like a completely black material. Therefore, gadolinium is very effective for compensating for excess reactivity, but, on the other hand, the incorrect distribution of absorbers that burn on the basis of Gd can lead to uneven neutron flux density in the reactor core.

Table 1 The main chemical elements used as burnable absorbers [5]

Elements	Atomic weight	Melting temperature [ºC]	Density [g / cm^3]	σ_a [barn]
Boron(B10)	10	2300	2.40	3840
Boron(eating)	10.82	2300	2.45	755
Europium	153.0	900	5.22	4300

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Samarium	150.35	1052	7.75	5600
Dysprosium	162.51	1400	8.56	950
Gadolinium	157.26	1350	7.95	46000
Erbium	167.27	1550	9.10	173
Cadmium	112.41	321	8.65	2450
Hafnium	178.50	2222	13.1	105

2. Objectives of the study

Objectives of the study of the simulation are given below:

- The position and number of fuel rod with Gd_2O_3 seriously affects the behavior of the reactivity margin during a reactor campaign.
- Find their optimal position and quantity.

The object of study in this work is a VVER-1200 water-water reactor with fuel in the form of uranium dioxide (UO_2). The subject of the study is the determination of the effect of a burnable absorber (Gd_2O_3) on the burnup depth of nuclear fuel cycle [6].

3. Analyzing Software (Serpent Code)

Serpent is a multipurpose three-dimensional continuous energy particle Monte Carlo code developed at VTT Technical Research Center in Finland, Ltd. Development began in 2004, and this code has been publicly distributed by the OECD / NEA and RSICC Databank since 2009. The Serpent began as a simplified physical code for the reactor, but the capabilities of the current development version, Serpent 2, go far beyond modeling the reactor [9]. Applications can be divided into three categories:

- Traditional reactor physics applications, including spatial homogenization, criticality calculations, fuel cycle studies, research reactor modeling, validation of deterministic transport codes, etc.
- Multi-physics simulations, i.e. coupled calculations with thermal hydraulics, CFD and fuel performance codes.
- Neutron and photon transport simulations for radiation dose rate calculations, shielding, fusion research and medical physics

4. Research model description

Within the scope of the present work, calculations were made for U/Gd FA of a VVER-1200 reactor. The configuration of such U/Gd FA is shown in **fig.1**. This FA consists of the fuel element (FE) of the main fuel and the mixed uranium-gadolinium fuel with oxide Gd_2O_3 (U/Gd FE). Fuel assemblies of the presented configuration are in use in all current Ukrainian nuclear power plants. The Fuel Assembly (in fig.1**)** consists of:

- 300 Fuel Elements (Fuel Pin with 4% UO_2)
- 12 U/Gd Fuel Elements (Fuel Pin with 4% UO_2 + 8% Gd_2O_3)
- 18 Guide tubes
- 1 Central tube

The radius of fuel for FE and U/Gd FE: R1 = 0.386 cm, the outer radius of clad ding for FE and U/Gd FE: R2 = 0.4582 cm (see **Fig.2**). In the preparation of such characteristics, campaign values of the fuel temperature averaged by the reactor, the cooling temperature and the concentration of boric acid are commonly used for the calculation of the change in isotopic composition with burn-up, as well as the base states and derived states.

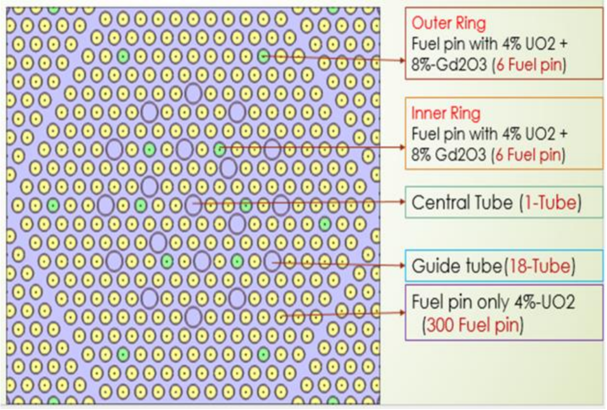

Fig.1 Research Model Fuel Assembly

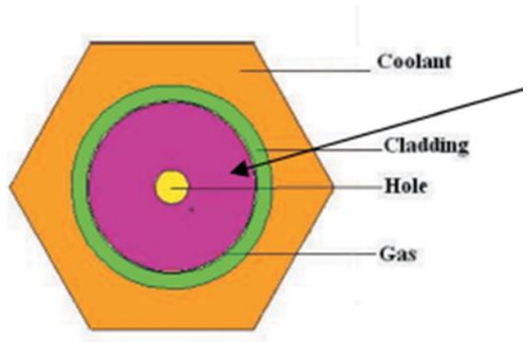

Fig.2 The configuration of the elementary fuel cell [7]

Table 2 Geometrical dimension and Main input parameter of Serpent Code [8, 9]

Parameter	Value
Number of Fuel Assembly, pcs	163
Number of FA with control rods, pcs	121
Fuel Pin(UO_2)	300
Hole radius (cm)	0.06000
Fuel UO_2 radius (cm)	0.38000
Cladding radius : Zircaloy-4, cm	0.45500
Water	
Fuel Pin with (Gd_2O_3+UO_2)	12
Hole radius (cm)	0.06000
Fuel (Gd_2O_3+UO_2) radius (cm)	0.38000
Cladding radius : Zircaloy-4, cm	0.45500
Water	
Guide Tube	18
Water Radius (cm)	0.54500
Cladding radius : Zircaloy-4, cm	0.63000
Central Tube	1
Water Radius (cm)	0.54500
Cladding radius : Zircaloy-4, cm	0.63000

Lattice Type	Hexagonal
Lattice dimension	23 x 23
Lattice pitch (cm)	1.275
Assembly Pitch (cm)	23.51

Table 3 Material properties and Main input parameter of Serpent Code [5-10]

Parameter	Value
Material Properties	
Mass Density of UO2, (g/cm^3)	10.5
Mass Density of (Gd_2O_3+UO_2), (g/cm^3)	10.3
Mass Density of Cladding, (g/cm^3)	6.56
Density of Water with boric acid, (g/cm^3)	0.70602
Amount of boric acid in water, (ppm)	650
Enrichment	
Fuel pin, UO_2	4.0%
Fuel Pin with (8.0% Gd_2O_3 + 4.0% UO_2)	4.0%
Amount of Gd_2O_3 in UO_2	8.0%
Boundary Condition	Reflective

5. Results and discussions

5.1 Results of standard variant

In standard variant, there have 300 UO_2 fuel pin, 18 guide tube, 12 burnable absorber fuel pin with (UO_2+ Gd_2O_3) and 1 central tube. 4.0% enrichment is used in UO_2 fuel pin. 8.0% Gd_2O_3 and 4.0% UO_2 are used in the burnable absorber fuel pin. Zircaloy-4 (Composition -15870) is used in central tube and guide tube. Burnable absorber fuel pins are divided into two rings. One is outer ring another is inner ring. Inner ring is located near the central tube of the fuel assembly and outer ring is located near the periphery of the fuel assembly. Each ring has 6 number of absorber fuel pin. Equal enrichment of UO_2 and equal mass fraction of Gd_2O_3 are used in both rings. Moderator composition represents water with 650ppm of boric acid with density corresponding to temperature 583K. The standard model fuel assembly is shown in **Fig.3**.

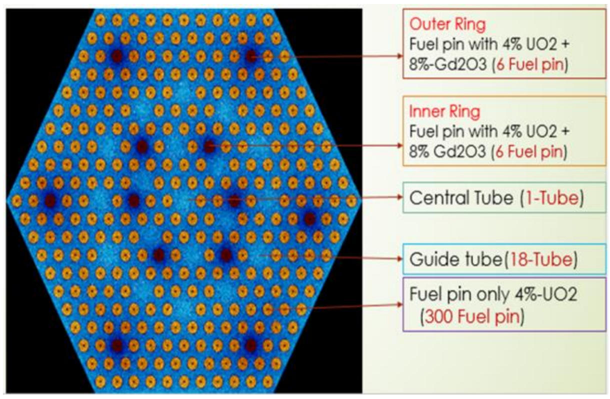

Fig.3 Structure of fuel assembly model for standard variant

From **Fig.4** it is noted that neutron flux of outer ring of fuel assembly is higher and neutron flux of central ring is very lower because neutrons flux enters in fuel assembly from outer ring to inner rings. Neutron flux is gradually decreasing according to number of fuel rings. In peripheral part of assembly, neutron flux is higher than the central part of the assembly. Flux of ring number 8 is little bit low due to burnable absorber fuel pin. Flux of ring 3 is slightly lower than previous and post ring because of using burnable absorber fuel pin.

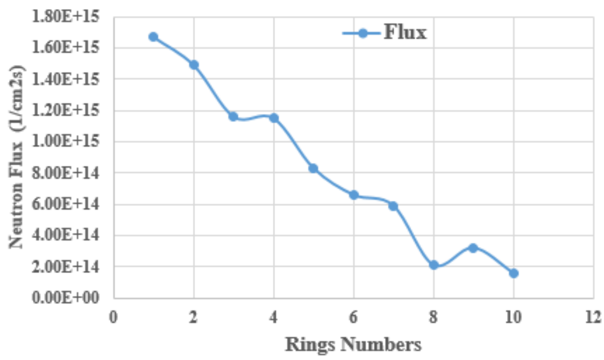

Fig.4 The Result of Neutron Flux Corresponding to Rings number

From **Fig.5** it is seen that K_{eff} is very high at the initial time or starting time. K_{eff} is gradually decreasing according to increasing number of reactor running day. From initial day to 1500 days, K_{eff} is decreasing very slowly because of fresh fuel pin and small burnup in that time. When burnup is increased then K_{eff} is decreased. After 1500 days, the result of K_{eff} is decreasing very sharply due to low burnup and long days running of reactor. If burnable absorber fuel pin is used in fuel assembly then it provides more burn up in the assembly and it increases the fuel cycle life time.

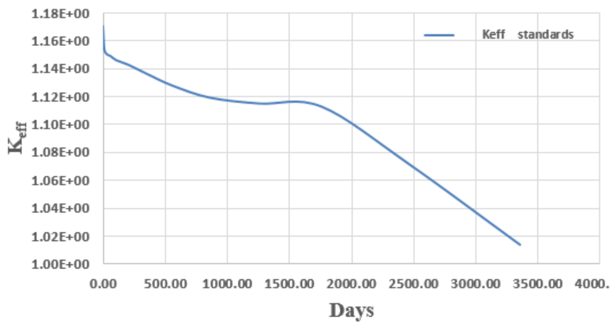

Fig.5 The Result of K_{eff} of standard model fuel assembly

5.2 Results of 4&9 rings variant

In standard variant has been discussed in section 5.1. In 4&9 rings variant, there have 300 UO_2 fuel pin, 18 guide tube, 12 burnable absorber fuel pin with (UO_2+ Gd_2O_3) and 1 central tube. 4.0% enrichment is used in UO_2 fuel pin. Zircaloy-4 (Composition -15870) is used in central tube and guide tube. Burnable absorber fuel pins are placed into two rings. One is ring 4 counting from central tube another is ring 9 counting from central tube. Ring 4 is located near the central tube of the fuel assembly and ring 9 is located near the periphery of the fuel assembly. 6.28% Gd_2O_3 and 4.0% UO_2 are used in the burnable absorber fuel pin for ring 9 of fuel assembly. 1.72% Gd_2O_3 and 4.0% UO_2 are used in the burnable absorber fuel pin for ring 4 of fuel assembly. Both ring 4 and ring 9 have 6 numbers of burnable absorber fuel pin. Amount of percentage of % Gd_2O_3 in ring 9 is higher than Amount of percentage of % Gd_2O_3 in ring 4. Because, amount of neutron flux in ring 9 is higher than amount of neutron flux in ring 4. Sum of the percentage of % Gd_2O_3 in ring 4 and ring 9 is 8% of Gd_2O_3. That means amount of % Gd_2O_3 and number of burnable absorber fuel pin is fixed in 4&9 rings variant. Only changes the location and amount of % Gd_2O_3 in 4&9 rings variant. Moderator composition represents water with 650ppm of boric acid with density corresponding to temperature 583K. The 4&9 rings variant model fuel assembly is shown in **Fig.6**. The results of standards and 4&9 rings variant fuel assembly are calculated by using Monte Carlo Serpent software.

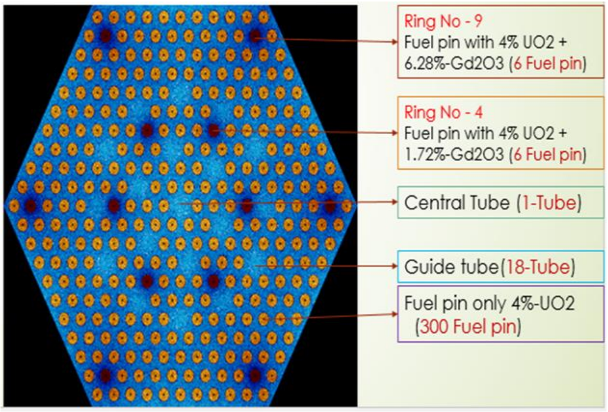

Fig.6 Structure of fuel assembly model for 4&9 rings variant

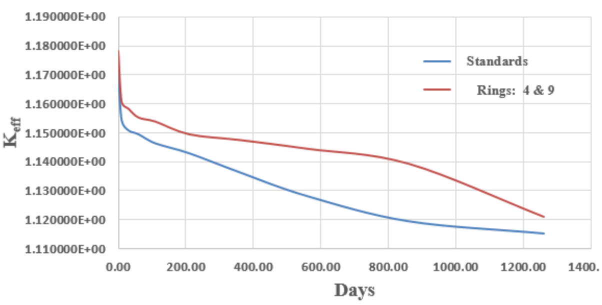

Fig.7 Result Comparison between Standard rings and 4&9 Rings variant

In **Fig.7**, Red color graph represents the 4&9 rings variant result and blue color graph represents the standard variant result. From **Fig.7** it is noted that K_{eff} is very high at the initial time or starting time of reactor for both variants. K_{eff} is gradually decreased according to increasing number of reactor running day. After few day, K_{eff} of standard variant is declined very rapidly than K_{eff} of 4&9 rings variant. From initial day to 1200 days, K_{eff} of standard variant is decreased moderately. From initial day to 1200 days, K_{eff} of 4&9 rings variant is decreased very slowly. When burnup is increased then K_{eff} is decreased. After 1200 days, the result of both variants K_{eff} is decreased very sharply due to long days running of reactor. If burnable absorber fuel pin is used in fuel assembly then it provides more burn up in the assembly and it increases the fuel cycle life time. Equal amount (8.0% Gd_2O_3) of burnable absorber Gd_2O_3 is used in standard variant for both inner and outer rings. That means equal amount of Gd_2O_3 is used for each fuel pin. 12 burnable fuel pin are same. But different amount (6.28% Gd_2O_3 for ring 9 and 1.72% Gd_2O_3 for ring 4) of burnable absorber is used in 4&9 rings variant. That means 6 burnable absorber fuel pin are high mass fraction of Gd_2O_3 and 6 burnable absorber fuel pin are low mass fraction of Gd_2O_3. 4&9 Rings variant maintains high K_{eff} in long days in reactor campaign than standard variant. So 4&9 Rings variant provides the better result than standard variant. It is shown in **Fig.7.**

5.3 Results of 3&8 rings variant

In standard variant has been discussed in section 5.1. In 3&8 rings variant, there have 300 UO_2 fuel pin, 18 guide tube, 12 burnable absorber fuel pin with (UO_2+ Gd_2O_3) and 1 central tube. 4.0% enrichment is used in UO_2 fuel pin. Zircaloy-4 (Composition -15870) is used in central tube and guide tube. Burnable absorber fuel pins are placed into two rings. One is ring 3 counting from central tube another is ring 8 counting from central tube. Ring 3 is located near the central tube of the fuel assembly and ring 8 is located near the periphery of the fuel assembly.

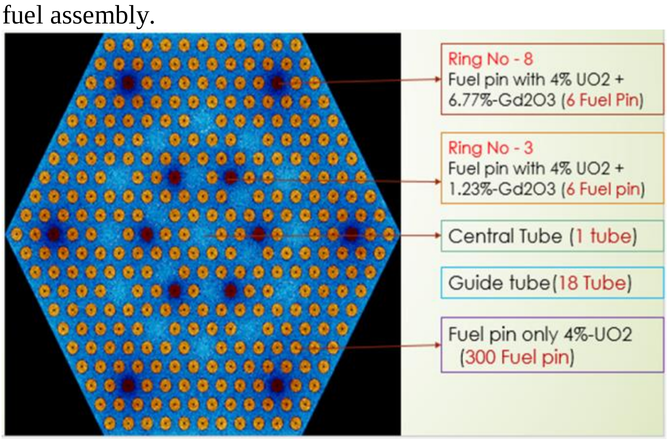

Fig.8 Structure of fuel assembly model for 3&8 rings variant

6.77% Gd_2O_3 and 4.0% UO_2 are used in the burnable absorber fuel pin for ring 8 of fuel assembly. 1.23% Gd_2O_3 and 4.0% UO_2 are used in the burnable absorber fuel pin for ring 3 of fuel assembly. Both ring 3 and ring 8 have 6 numbers of burnable absorber fuel pin. Amount of percentage of % Gd_2O_3 in ring 8 is higher than Amount of percentage of % Gd_2O_3 in ring 3. Because, amount of neutron flux in ring 8 is higher than amount of neutron flux in ring 3. Sum of the percentage of % Gd_2O_3 in ring 3 and ring 8 is 8% of Gd_2O_3. That means amount of % Gd_2O_3 and number of burnable absorber fuel pin is fixed in 3&8 rings variant. Only changes the location and amount of % Gd_2O_3 in 3&8 rings variant. Moderator composition represents water with 650ppm of boric acid with density corresponding to temperature 583K. The 3&8 rings variant model fuel assembly is shown in **Fig.8**.The results of standards and 3&8 rings variant fuel assembly are calculated by using Monte Carlo Serpent software**.**

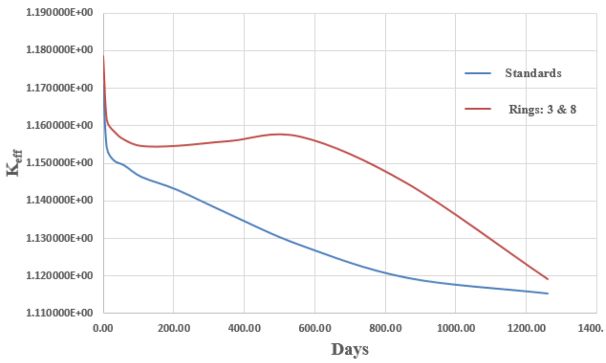

Fig.9 Result Comparison between Standard rings and 3&8 Rings variant

In **Fig.9**, Red color graph represents the 3&8 rings variant result and blue color graph represents the standard variant result. From **Fig.9** it is noted that K_{eff} is very high at the initial time or starting time of reactor for both variants. K_{eff} is gradually decreased according to increasing number of reactor running day. After few day, K_{eff} of standard variant is declined very rapidly than K_{eff} of 3&8 rings variant. In **Fig.9**, from startup time to 100 days, K_{eff} of 3&8 rings variant is decreased very rapidly because of high percentage of burnable absorber (Gd_2O_3). Between 100 days and 500 days, K_{eff} of 3&8 rings is approximately constant due to constant neutron flux in reactor during that period. After 500 days, K_{eff} of 3&8 rings variant is declined gradually because neutron flux is decreased in the reactor due to long reactor running time. From initial day to 1200 days, K_{eff} of standard variant is decreased moderately. From initial day to 1200 days, K_{eff} of 3&8 rings variant is decreased very slowly. When burnup is increased then K_{eff} is decreased. After 1200 days, the result of both variants K_{eff} is decreased very sharply due to long days running of reactor. If burnable absorber fuel pin is used in fuel assembly then it provides more burn up in the assembly and it increases the fuel cycle life time. Equal amount (8.0% Gd_2O_3) of burnable absorber Gd_2O_3 is used in standard variant for both inner and outer rings. That means equal amount of Gd_2O_3 is used for each fuel pin. 12 burnable fuel pin are same. But different amount (6.77% Gd_2O_3 for ring 8 and 1.23% Gd_2O_3 for ring 3) of burnable absorber is used in 3&8 rings variant. That means 6 burnable absorber fuel pin are high mass fraction of Gd_2O_3 and 6 burnable absorber fuel pin are low mass fraction of Gd_2O_3. 3&8 Rings variant maintains high K_{eff} in long days in reactor campaign than standard variant. So 3&8 Rings variant provides the better result than standard variant. It is shown in **Fig.9.**

5.4 Results comparison among three variants

Standard variant, 4&9 Rings variant and 3&8 Rings variant have been discussed in section 5.1, section 5.2 and section 5.3. In this section, results comparison among standard ,4&9 rings and 3&8 rings variant will be discussed

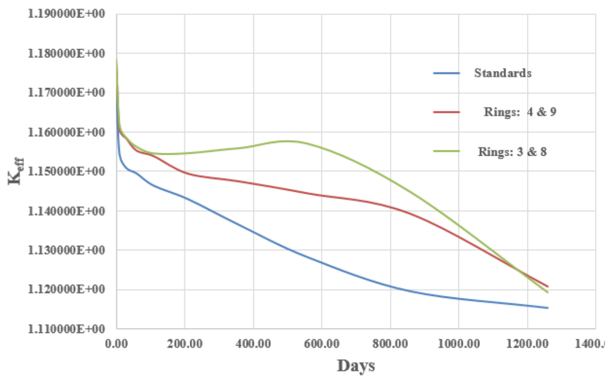

Fig.10 Result Comparison among Standard rings, 4&9 Rings and 3&8 Rings

In **Fig.10**, blue color line represents the standard variant's results and red color line represents the 4&9 rings variant's results and green line represents the 3&8 rings variant's results.At the time of startup of reactor, multiplication factor (Ke_{ff}) is higher than unity due to large amount of fresh fuel in reactor core at initial condition. Multiplication factor (Ke_{ff}) of standard variant is declined gradually from beginning of cycle (BOC) to end of cycle (EOC) due to non-uniform neutron flux in reactor. Multiplication factor (Ke_{ff}) of 4&9 rings variant is decreased very slowly from initial day to 800 days then it is declined gradually after 800 days. In this variant, neutron flux is approximately uniform, as a result it maintains approximately stable condition of reactor campaign. Multiplication factor (Ke_{ff}) of 3&8 rings variant is nearly constant from initial day to 500 days of reactor running. After 500 days of reactor running time, Keff is decreased gradually because of decreasing amount of uranium fuel. In this variant, neutron flux is uniform in whole reactor as a result this variant maintains the stable running condition of reactor. Among this thee results of three variants (standard, 4&9 rings and 3&9rings), 4&9 rings variant is better than standard variant. Because burnable absorber fuel pins are placed in proper position of the reactor in 3&9 rings variant. 3&8 rings variant is the best combination of other two variants. Because burnable absorber fuel pins are placed in exact position of the reactor core. More amount of absorber (Gd_3O_2) is used where flux is higher and less amount of absorber (Gd_3O_2) is used where flux is lower. As a result the reactor core maintains more stable operation due to uniform neutron flux distribution. This variant increases the fuel cycle life time and it maintains the unity multiplication factor (Ke_{ff}) in reactor core for long time. So, 3&8 variant provides the best stable operation parameter and safe condition of the reactor core. Therefore, 3&8 rings variant is the best combination of fuel pins and absorber pins in the reactor core among other two variants in this thesis.

6. Conclusion

Burnable absorber (Gd_3O_2) are materials that have a high neutron absorption cross section that are converted into materials of relatively low absorption cross section as the result of neutron absorption. Due to the burnup of the absorber (Gd_3O_2), the negative reactivity of the burnable absorber decreases over core life. Only two gadolinium isotopes have the largest thermal neutron absorption cross-section among other isotopes (Gd-155 and Gd-157 have 60,000b and 200,000b, respectively). It exhibits residual reactivity suppression due to the conversion of Gd-155 into Gd-156 and Gd-157 into Gd-158 which both don't convert into further isotopes. The importance of using burnable absorbers in reactor operation is significant. In this study we have tried to establish ways to use burnable absorbers for efficient reactor operation. We have incorporated Gd2O3 to VVER-1200 fuel assembly and observed the effects of U-Gd fuel in reactor operation. We have simulated VVER-1200 reactor core in Serpent Code and using 12 U-Gd fuel rods per fresh fuel assembly. In this work, optimal number of fuel rod with absorber (Gd_3O_2) and optimal position of absorber rod (Gd_3O_2) were calculated in reactor core VVER-1200. Three types of variants (Standard variant, 3&8 rings variant and 4&9 rings variant) were used to find the optimal amount of absorber (Gd_3O_2) rod and find the optimal position of absorber rod (Gd_3O_2) in reactor core VVER-1200. All variants results were calculated by using Monte Carlo Serpent Code. The 3&8 rings variant (6.77% Gd_2O_3+4.0%UO_2 materials are used for ring- 8, 1.23% Gd_2O_3+4.0%UO_2 materials are used for ring- 3) provided better result among other two variants (standard variant and 4&9 rings variant). In this work, it is also shown that the multiplication factor also substantially depends on the location of burnable absorbers in the fuel assemblies and the fraction of burnable absorber in each Ping. In conclusion, the nature of the dependence of the multiplication factor (K_{eff}) of fuel assemblies on fuel burnup is mainly determined by three factors. These are the value of the average cross section for the absorption of the burnup absorber, the amount of absorber in the fuel elements and the fuel assemblies, and the ratio of the number of fuel rods per Pings or Pines (fuel elements with Gd are "Pings" or with Eu are "Pines").

7. Acknowledgement

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NOMENCLATURE

NPP	: Nuclear Power Plant
VVER	: Vodo Vodyanoi Energetichesky Reaktor
WWER	: Water -Water Energetic Reactor
BA	: Burnable Absorbers
FA	: Fuel Assembly
K_{eff}	: Effective Multiplication Factor
K_{in}	: Multiplication Factor in infinite medium