SciEn

Proceedings of 7th International Conference on Mechanical, Industrial and Energy Engineering-Part I
22-24 December, 2022, Khulna, BANGLADESH

SciEn Conference Series: Engineering Vol. 1, 2025, pp 81-85 https://doi.org/10.38032/scse.2025.1.15

Effect of the burnable absorber on the efficiency of nuclear fuel cycle in VVER-1200 reactor

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ABSTRACT

The significant impacts of burnable absorbers (UO_2+Gd_2O_3) on reactivity, neutron multiplication factor (K_{eff}), burnup, neutron flux distribution, power peaking factor, as well as safety criterions of the VVER-1200 reactor are discussed in this paper. Fuel economics have improved, resulting in increased enrichment of fuel & the need for better neutron flux distribution as well as reactivity controls. In order to achieve these enhancements in neutron flux distribution, burnable absorbers must be incorporated into the fuel matrix. To compute the 3D (three-dimensional) model for VVER-1200 fuel assembly, the Monte Carlo Serpent code was used. There are different processes for loading 8.0% Gd_2O_3 as integral burnable absorbers (IBAs) on the VVER-1200 assembly. In the first fuel cycle, the calculations were carried out under normal operating conditions. The fuel assemblies of VVER-1200 reactor with (Gd_2O_3) and without gadolinium oxide (Gd_2O_3) are compared in terms of neutron multiplication factor (K_{eff}) and neutron flux distribution in this research. The inclusion of gadolinium oxide significantly improves reactor safety by greatly flattening the neutron flow and so reducing power peaks, especially at the reactor core. Finding their impacts on the behavior of the reactor core is therefore an important factor in each reactor core plan, construction and safely functioning. The inclusion of gadolinium oxide (Gd_2O_3) significantly improves reactor safety by greatly flattening the neutron flux and reducing power peaks, particularly near the center of the core. The analysis of the current work is crucial for improving the reactor core design, arrangement of fuel rod, fabrication of fuel pallet, placement of control rod and the safety of reactor operation.

Keywords: Burnable Absorber (BA), Multiplication Factor (Keff), Neutron flux, VVER-1200, Power Peaking Factor (PPE)

1. Introduction

Extending the duration of the fuel burnup is one of the primary objectives of scientific and technological improvements connected to the nuclear fuel cycle of power reactors. Typically, it is accomplished by providing partial overloads and increasing the initial enrichment. To accommodate for high reactivity, a "liquid" method based on adding a boric acid absorber to the fluids and using several kinds of burnable absorbers is used.

Burnable absorbers (BA) or burnable poisons (BP) serve a crucial role in nuclear fuels. Substances with a strong tendency for neutron particles absorption include boron, gadolinium, dysprosium, hafnium, and erbium when they are exposed to radiation. When these substances absorb a neutron, they change into substances that absorb relatively less. The neutron multiplication factor in the reactor may be controlled in this way over the course of the fuel with less dependency on the placement of neutron absorbing control rods or other control devices. From the perspectives of safety and operation, these absorbers (Gd_2O_3) have a number of limitations, criteria, benefits, as well as drawbacks; these features rely on the concentration and distribution of the aforementioned toxins in the reactor core.

Burnable absorber (Gd_3O_2) are substances with a neutron absorption cross section that, as a function of neutrons absorption, change into substances with a fairly low cross-section of absorption. The negative reactivity of the burnable absorber reduces during the course of the core life as a result of the absorber's (Gd_3O_2) burnup. Gadolinium is often used in the nuclear industry as a neutron absorber because two of its isotopes, ^{155}Gd and ^{157}Gd, have a comparatively large absorption cross-section. They have the strongest absorption tendency of any stable isotope. For thermal neutrons (for 0.025 eV neutrons), ^{155}Gd has 61000 barns, while ^{157}Gd even has 254000 barns. As a result of ^{155}Gd becoming ^{156}Gd and ^{157}Gd becoming ^{158}Gd both of which do not undergo further isotope conversion, it displays residual reactivity suppression. The fuel's excess positive reactivity should be eliminated when these absorbers (Gd_3O_2) reduce their negative reactivity. [1-6].

Table 1 The main chemical elements used as burnable absorbers [7]

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
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

For Gadolinium is therefore frequently utilized in fresh fuel as a burnable absorber to make up for the reactor core's

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excessive reactivity. Gadolinium behaves as a fully black substance in compared to other burnable absorbers. Gadolinium is therefore particularly efficient in offsetting the excess reactivity. On the other hand, an uneven neutron-flux density in the reactor core may result from an incorrect distribution of Gd-burnable absorbers.

2. The aim of work

The aim of the simulation works (Neutronics Analysis) are given below:

- Computational analysis of neutron flux of fuel assembly (VVER-1200 reactor) with burnable absorber (BA) and without BA.
- Comparison of multiplication factor (K_{eff}) of reactor core with burnable absorber (BA) and without BA.
- Calculation of burnup of fuel assembly with burnable absorber (BA) and without BA.
- Evaluation of power peaking factor (PPE) within the VVER-1200's reactor core.
- Comparison of the boric acid content in nuclear reactors working both with and without burnable absorbers

3. Simulation Software

3.1 Monte Carlo Code (Serpent)

Serpent is a versatile, three (3D) dimensional Monte Carlo particle transport code for continuous energy. Since 2004, it has been under research at the Finnish VTT Technical Research Center. Between 2004 and 2008, Serpent was initially known as the Probabilistic Scattering Game (PSG), until the first prerelease of Serpent 1 in October 2008. Serpent 2's development was underway in 2010. Serpent 2.2.0, the most recent stable version, was published in May 2022. Serpent was originally developed as a compact neutron transport method for reactor physics issues. Its primary objective was to generate group constants using two-dimensional lattice computations. Early on, the ability to calculate burnup was implemented. Serpent is utilized nowadays for a variety of purposes, including the creation of group constants, linked multiphysics applications, fusion neutronics, and radiation protection. Serpent may carry photons in addition to the initial ability to transport neutrons [11].

3.2 COMSOL Multiphysics

The COMSOL Multiphysics tool is used by engineers and research scientists to analysis designs, devices, and methods in a variety of expert's people, industrial, and experimental fields. Fully integrated single-physics and multiphysics modeling is possible with the help of a simulation platform called COMSOL Multiphysics. The Model Builder handles the whole designing process, from specific geometry, material characteristics, and the physical characterizing specific fact to answering and finishing models to provide proper results. Modeling capabilities for both single-physics and fully integrated multiphysics are available through the simulation software COMSOL Multiphysics. [12].

4. Research Methodology

In this work, neutronics calculation were made for (UO_2 and UO_2+Gd_2O_3) assembly of the VVER-1200 reactor's fuel. Research model of fuel assembly of VVER-1200 s 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 Russian nuclear power plants. The Fuel Assembly (in figure 4.1) consists of:

- 300 Fuel Elements (Fuel Pin with 4% UO2)
- 12 U/Gd Fuel Elements (Fuel Pin with 4% UO2 + 8% Gd_2O_3)
- 18 Guide tubes
- 1 Central tube

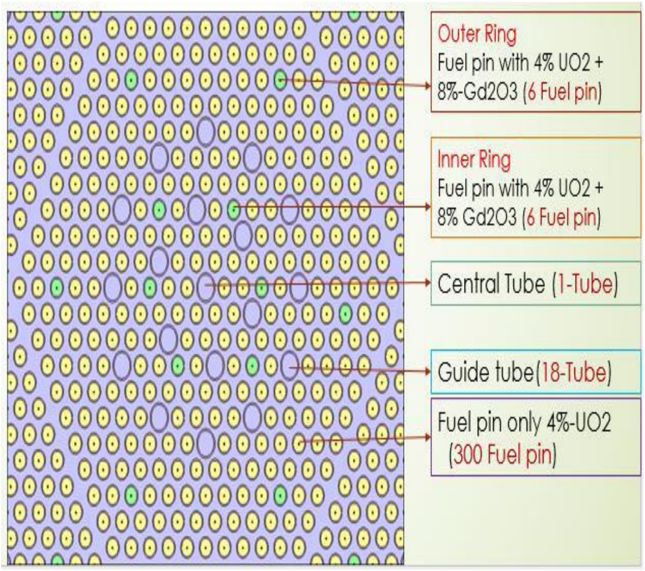

Fig.1 Research Model Fuel Assembly (VVER-1200)

The radius of fuel for FE and U/Gd FE: R_1 = 0.386 cm, the outer radius of clad ding for FE and U/Gd FE: R_2 = 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

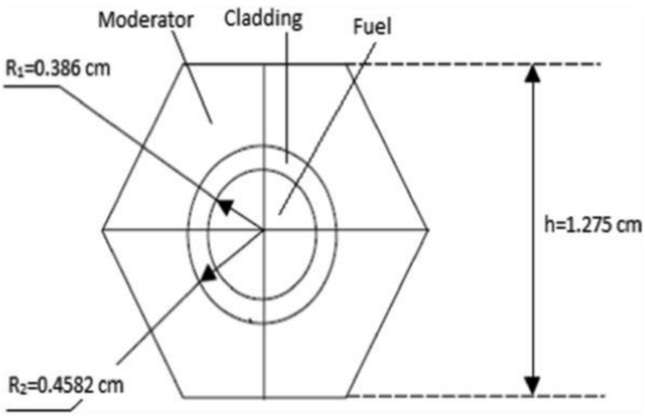

Fig.2 The configuration of the elementary fuel cell

Lattice type of FA (VVER-1200)

- Hexagonal lattice grid
- Main lattice is focused at (0,0)
- 23 x 23 matrix of lattice elements
- Length of pitch of the Lattice 1.275 centimeter

Table 2 Reactor core specification of VVER-1200 [6-9]

Parameters	VVER-1200
Number of FA, pcs	163
Number of FA with control rods, pcs	121
Thermal power (nominal), MW	3200
Outlet coolant pressure, absolute (nominal), MPa	16.2
Inlet coolant temp. [Cold leg temp.], nominal, °C	298.2
Outlet coolant temp. [Hot leg temp.], nominal, °C	328.6
FA pitch, m	0.236
Coolant flow-rate, (at inlet temp.), m^3/hr., nominal	85000
Core flow area, m^2	4.15
Active length (cold), m, nominal	3.73
Maximum permissible fuel burnup in FA, MW·day /kg U	60.0

Table 3 Geometrical dimension and Main input parameter of Serpent Code [5-10]

Parameters	Value
No. of Fuel Assembly, pcs	163
No. of FA with control rods, pcs	121
Fuel Pin(UO_2)	300
Hole radius (cm)	0.06000
Fuel UO_2 radius (centimeter)	0.38000
Cladding radius : Zircaloy4, centimeter	0.45500
Water	
Fuel Pin with (Gd_2O_3+UO_2)	12
Hole radius (cm)	0.06000
Fuel (Gd_2O_3+UO_2) radius (centimeter)	0.38000
Cladding radius : Zircaloy4, centimeter Water	0.45500
Guide Tube	18
Water Radius (centimeter)	0.54500
Cladding radius : Zircaloy4, centimeter	0.63000
Central Tube	1
Water Radius (centimeter)	0.54500
Cladding radius : Zircaloy4, centimeter	0.63000
Lattice Type	Hexagonal
Lattice dimension	23 x 23
Lattice pitch (centimeter)	1.275
Assembly Pitch (centimeter)	23.51

With few approximations, Assessed nuclear data can be used with Monte-Carlo programs. They may change the nuclear data since they are adaptable. The precision of the Monte-Carlo computations is determined by the number of simulated particles, and it was chosen to depict the impact of altering the nuclear data from the standard ENDF/BVII.1 database to ENDF/B-VI.8 or JEFF-3.2. There are 500000 neutrons in each cycle in this scenario, and there are 2000 calculation cycles total. Water containing 650 ppm soluble boric acid is used as coolant. Water has a temperature of 583 K. A pressure of 15.5 MPa is used in the calculation of density. Serpent will be instructed to use two bounds libraries for interpolation:

- lwj3.11t (H-1 in light water at 574 K)
- lwj3.13t (H-1 in light water at 624 K)

Table 4 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. Result and Discussion

5.1 Multiplication factor and Burnup

In **Fig.3**, blue color line represents the assembly of fresh fuel's (4% enrichment of UO_2) results and red color line represents the assembly of mixed fuel's (4% UO_2 + 8% Gd_2O_3) results. At the time of startup of reactor, multiplication factor (K_{eff}) is higher than unity due to large amount of fresh fuel in reactor core. Fresh fuel assembly has a larger multiplication factor (Keff) than fuel assembly with BA at the starting state. Therefore, new fuel assemblies have stronger positive reactivity than fuel assemblies that had BA at the beginning of the cycle (BOC).

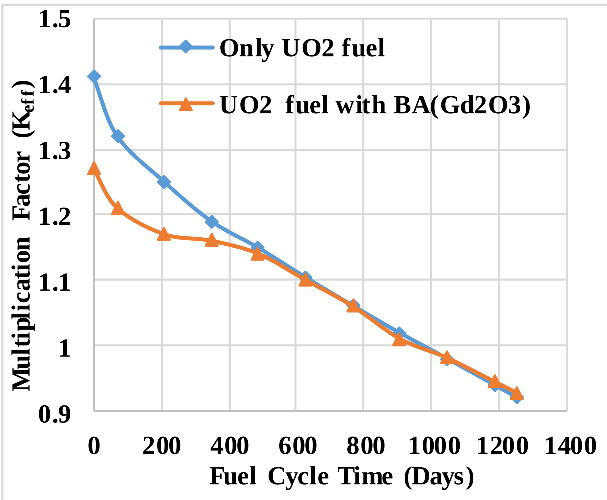

Fig.3 Comparison of the multiplication Factor (K_{eff}) between fresh fuel and fuel with BA

At ending of cycle (EOC) of reactor, multiplication factor (K_{eff}) is lower than unity due to less amount of fresh fuel in reactor core. Fresh fuel assembly's multiplication factor (Keff) is smaller than fuel assembly with BA's multiplication factor (Keff). So positive reactivity of fresh fuel assembly is lower than fuel assembly with BA in ending of cycle(EOC).Initially positive reactivity is very dangerous for reactor operation (reason for explosion) but ending of the cycle positive reactivity is useful to increase the nuclear fuel cycle.

Since the beginning of commercial nuclear power generation, there has been a desire to improve reactor performance through longer cycle periods or better fuel economy. The resultant changes include increasing the initial fuel enrichment among other things.

The use of dissolved absorber in the fluid was permissible in reactors of the VVER type. Boric acid in the moderator has therefore been used regularly to meet the needs of increased reactivity compensation. But at a certain concentration, thermal expansion of water during starting lowers the quantity of boron in the core, eventually resulting in a favorable moderator temperature reactivity coefficient. Therefore, raising the concentration of boric acid cannot totally compensate for the rise in initial fuel enrichment. To avoid this undesirable situation the introduction of solid burnable absorbers in the fuel is considered.

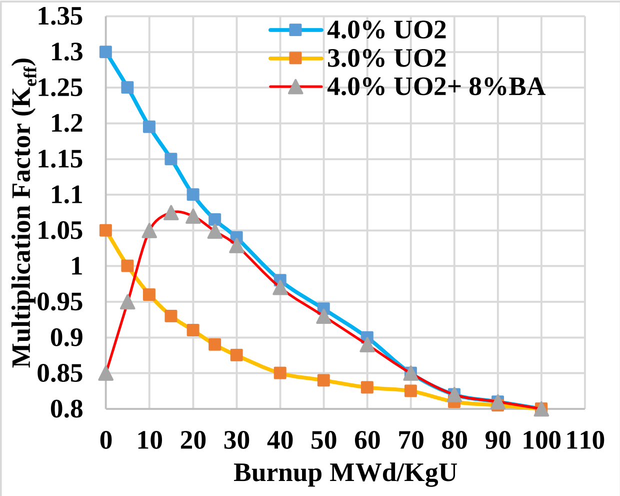

Fig.4 Result of reactivity behaviour of VVER-1200

The reactivity of VVER fuels without BAs rods reduces in a nearly linear manner against burnup. On the other side, as fuel burnup progresses, reactivity rises in VVER fuel assembly designs that make substantial use of BAs. In Fig.4, This reactivity peaks at a burnup when the BA is almost completely consumed, and it then rapidly declines as burnup progresses. When BAs are used sparingly in fuel assembly designs, reactivity either remains mostly constant or progressively drops with burnup until the BA is almost completely used, at which point it drops with burnup in a roughly straight way. The first third of the assembly life basically results in the burnable absorber being exhausted due to the assemblies' design, which causes the reactivity to peak during this time of burnup.

In **Fig.4**, blue color line represents the assembly of fresh fuel's (4% enrichment of UO_2) results , yellow color line represents the assembly of fresh fuel's (3% enrichment of UO_2) results and red color line represents the assembly of mixed fuel's (4%UO_2+8%Gd_2O_3) results. At the time of startup of reactor, multiplication factor (K_{eff}) is higher than unity due to large amount of fresh fuel in reactor core. If K_{eff} is greater then unity then it will provide the positive reactivity in the reactor core. It is the supercritical condition of reactor core. If K_{eff} is equal to unity then it will the provide zero reactivity in the reactor core. It is the critical condition of reactor core. At ending of cycle (EOC) of reactor, multiplication factor (K_{eff}) is lower than unity due to less amount of fresh fuel in reactor core. Keff will produce negative reactivity in the reactor core if it is less than unity. It is the reactor core's subcritical state.

5.2 Neutron flux distribution

By modeling a 3D model of the core in COMSOL Multiphysics, the flux distribution was performed. From Serpent code we get the three group macro cross-sections for determining the flux distribution in COMSOL.

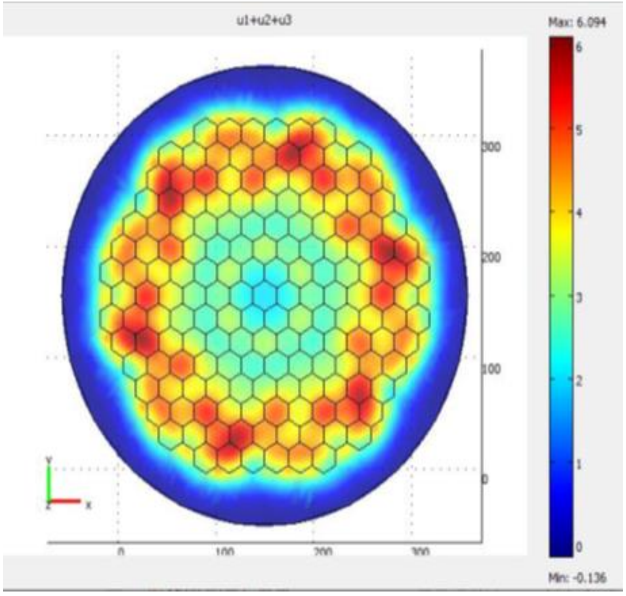

Fig.5 Neutron Flux distribution without burnable absorber (4% enrichment of UO_2)

The energy groups range from 10.5 MeV to 1 MeV, 1 MeV to 2.15 eV and 2.15 eV to 0 eV. Data that were used to put as constants in COMSOL are given in the software. From **Fig.5** & **Fig.6**, it is noted that neutron flux is uniform distribution for mixed fuel assembly (4%UO_2+8%Gd_2O_3) and not uniform distribution for fresh fuel assembly (4% enrichment of UO_2).

5.3 Boric acid concentration & Power peaking factor

Gadolinum plays an important role in conducting safe reactor operation at the beginning of the campaign. It lessens the VVER-1200 reactor core's excessive reactivity. Furthermore, from **table 5** we can see that using Gd resulted in reduction of boron concentration.

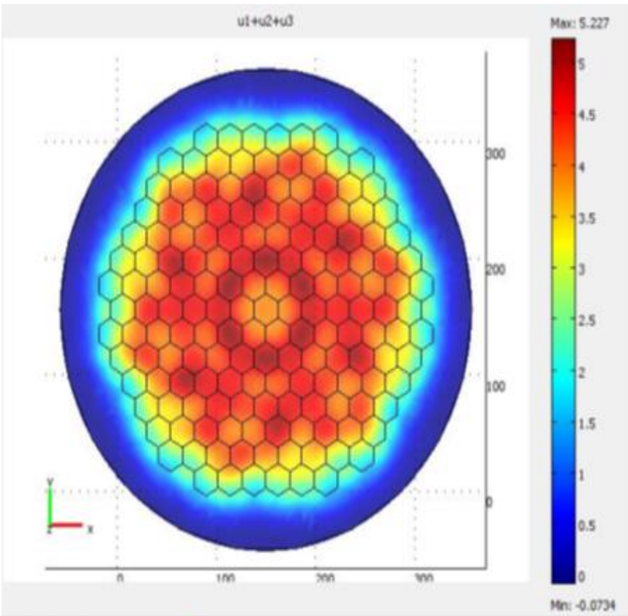

Fig.6 Neutron Flux distribution with burnable absorber (4%UO_2+8%Gd_2O_3)

Table 5 Effect of BA on Boron concentration

Variant	Boron concentration (g/cm^3)
Fuel Assembly Without BA (4% enrichment of UO2)	0.16 x 10^{20}
Fuel Assembly With BA ($4\%UO_2+8\%Gd_2O_3$)	0.12 x 10^{20}

The ratio of the greatest local power density to the average power density of the reactor core is known as the power peaking factor (PPF). We have to organize the fuel assemblies and U-Gd rods in order for the BA to reduce the power peaking and determine the power peaking factor. There are two reasons why BA is used in fuel assembly: to lower the level of boron acid and to lower PPF in the core (named as macro PPF). We need to be aware about the BA implementation will not make things worse in micro PPF.

Table 6 Power peaking factor with and without BA

Variant	Power peaking Factor
Fuel Assembly Without BA (4% enrichment of UO2)	1.6
Fuel Assembly With BA ($4\%UO_2+8\%Gd_2O_3$)	1.09

The micro PPF is non-uniformity of energy release in fuel pins. From references the micro PPF seems not to be high than 1.12. To prevent a boiling crisis and to remove the circumstances that might lead to fuel pellet melt, power peaking limitations are imposed on the reacor core. PPE is the measurement of unevenness of power distribution throughout the core. From **table 6** we can observe that using (4%UO2+8%Gd2O3) PPF is reduced significantly.

6. Conclusion

Both good and negative impacts are brought about by the usage of BAs as nuclear fuel. These effects depend on the type of burnable absorbers employed, the amount of BAs in the fuel, how many fuel elements contain BAs, and where those BAs are located in the fuel elements. The impact of burnable absorbers on the reactor's fuel life cycle was explored in this paper.

Reactor core reactivity is influenced by the fuel assembly's multiplication factor. On the other hand multiplication factor is influenced by burnable absorber of fuel assembly. Optimal amount of BA, proper location of BA and exact number of fuel rods with BA provide positive impact on reactor operation and also increase the safety of VVER reactors. Shown in **Fig.4** multiplication factor Keff of fuel with BA is more stable than multiplication factor K_{eff} of fuel without BA. Stable Keff provide stable reactor operation. From **Fig.5** & **Fig.6** it is noted that neutron flux distribution of fuel assembly with BA is more uniform than neutron flux distribution of fuel assembly without BA. Power peaking factor (PPE) of fuel assembly with BA is lower than Power peaking factor (PPE) of fuel assembly without BA due to uniform flux distribution in reactor core. Boric acid concentration in reactor is influenced by burnable absorber (Gd_2O_3).

7. Acknowledgement

At the beginning, I would like to thank almighty for giving me the strength and health to let this work see the light. I wish to express my deepest gratitude to my scientific supervisor, Kolesov V.V, Associate Professor, Obninsk Institute for Nuclear Power Engineering, MEPhI (Russia), for his kind help and sincere guidance. This work was supported by Aklima Khanam Lima, Department of Physics (University of Dhaka).

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NOMENCLATURE

BA : Burnable Absorber
VVER: Vodo Vodyanoi Energetichesky Reaktor
K_{eff} : Effective Multiplication Factor
PPE : Power Peaking Factor
FE : Fuel Elément
FA : Fuel Assembly
BOC : Beginning of cycle
EOC : Ending of cycle