A new approach of spectral regulation in the pressurized water reactors using Zr rods

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Abstract. The elongation of the fuel cycle period and the reactor reactivity control are crucial for all reactor suppliers. The traditional methods of boric acid, burnable absorbers, and control rods to control the reactor reactivity have their defects. A new method of the neutron spectral shift is studied to perform the reactor reactivity control and maintain the length of the fuel cycle. The neutron spectrum regulation can be achieved with different methods, including the Zr rods insertion in the fuel assemblies as water displacers. In this work, SERPENT2 version 2.1.30 was used to investigate a new fuel assembly design in the basics of Sierpinski carpet geometry to utilize the Zr rods as water displacers. The study of different fuel pitches of the Sierpinski fuel assembly is investigated to choose the reference fuel of the new design. The effect of boric acid concentration increasing and defining the maximum boric acid concentration in the Sierpinski fuel assembly are studied. The primary safety parameters of the Doppler effect and moderator temperature reactivity coefficients calculations approved the safety of the new Sierpinski fuel assembly design. The infinite multiplication factor at different steps of burnup showed the efficiency of the Sierpinski fuel assembly model to control the reactor reactivity. The average breeding factor to the burnup limit of 65 GWd/T is 0.68 in the Sierpinski fuel assembly with the presence of Zr rods.

1. Introduction
The reactor fuel cycle length and the control of reactor reactivity during the cycle take a large interest in the nuclear reactor research. The extension of the reactor fuel cycle provides the longer fuel discharge time and the better fuel utilization inside the core. The fuel enrichment and the control of the neutron spectrum during the cycle can maintain the longer reactor fuel cycle. The neutron spectrum regulation is known as the spectral shift control. A large fraction of the neutron spectrum is located in the epithermal region (resonance energy region). The spectral shift depends on the shifting of the neutron spectrum from the epithermal region at the beginning of the cycle to the thermal region in the last stages of the cycle. The neutron spectrum regulation provides more accumulation of plutonium in the result of neutron capture in U-238. The accumulated plutonium contributes to the burnup and the produced energy and increases the plutonium ratio in the reactor inventory at the end of the cycle. The control of reactor reactivity during the cycle conserve the reactor safety operating process. The control rods, burnable absorbers and the diluted boron in the moderator are the most used means to control the reactor reactivity. All the prementioned approaches to control the reactor reactivity consume the neutron...
population through the absorption of thermal neutrons. Also, each of them has their defects during the fuel cycle. The burnable absorbers last for a short time in the first stages of the fuel cycle to reduce the reactor excess reactivity [1–5]. The working time of the burnable absorbers depends on the element types and their volume in the reactor core [6–8]. The burnable absorbers remarked with the advantage of control the reactor reactivity without the variation in the moderator temperature or the boric acid concentration [9]. The boric acid performs a homogenous control of the reactor reactivity through absorbing the thermal neutrons. The absorbing of thermal neutrons by diluted boron in the moderator decreases the thermal utilization factor and consequently, the reactor multiplication factor. The use of boric acid inside the reactor core produces a large amount of tritium in the moderator and at too high concentrations of diluted boron induces the hazardous positive effect of moderator temperature effect [10,11].

A new approach of using the concept of spectral regulation to do both tasks (elongation of the reactor fuel cycle and the reactor reactivity control) at the same time. The spectral shift concept is applied in 1960 in different experiments concerned with using a mixture of heavy and light water as moderator-coolant in heterogeneous reactors (the first core contained 484 fuel rods with 4% UO2 fuel in light water while the second core contained 2188 fuel rods with 93% enriched UO2-ThO2 fuel in a moderator mixture of heavy and light water) [12]. The experiments are performed with the Babcock & Wilcox Company under a contract with U.S. Atomic Energy Commission. In this work [12] assured the accuracy of achieved results for the studied cores. In the form of using the Zirconium rods as a moderator displacer in VVER-1000, the spectral shift is studied [13]. The Zr rods were placed in some of the guide tubes and led to a more extended reactor fuel cycle with 4.1 effective operating days. Spectral regulation using the Zr rods in the modernized reactor core VVER-S for uranium and MOX fuel [14]. The use of Zr rods as water displacers changes the water-uranium ratio with a mechanical method. The VVER-S reactor consists of a significant number of fuel assemblies (126 FAs with Zr rod as water displacers and 61 FAs with control rods). The massive number of fuel assemblies and the lower power density allow us to refuse the reactivity regulation with boric acid and give the possibility of enlarging the fuel cycle to six years with average burnup of 50 MWd/kg [14].

In our previous work, the Zr rods are used as water displacers in the fuel assembly of VVER-1000, where the Zr rods are placed between the fuel rods [15]. The U-235 consumption decreased with the presence of Zr rods inside the fuel assembly, and the concentration of Pu isotopes increased. The drawback of the previous work s the massive number of Zr rods compared with fuel rods. Therefore, in the present work, a new design of fuel assembly is investigated. The new design is based on the geometry of the Sierpinski carpet shape. The Sierpinski fuel assembly fuel pitch is investigated to choose the most comparable with the boric acid effect on the reactor reactivity. The burnup, breeding ratio and the primary safety parameter are investigated.

2. Benchmark Model and Calculation Code
The dimensions of the fuel rod and the clad diameter are the same parameters of the PWR reactor [16]. The Sierpinski fuel assembly design will be explained in the next section. The calculations were fulfilled by the three-dimensional continuous energy Monte Carlo neutron transport and burnup code SERPENT2 version 2.1.30. SERPENT developed at VTT Technical Research Centre of Finland [17]. SERPENT2 now is used for several purposes, such as simulated traditional reactor physics applications, validation of deterministic transport codes, multi-physics simulations, neutron and photon transport simulations for radiation dose rate calculations, and others.

3. Results and discussions
The increasing interest in the use of the Zr rods as a water displacer to control the neutron spectrum and the excess reactivity inside the nuclear reactor. The basic operating principle of Zr rods is that after a time from the beginning of the cycle of the fully-loaded Zr rods reactor and the reactor reached the lower reactivity limit, the gradual withdrawal of Zr rods leads to the gradual increase of water amount inside the core. The increase of the water amount in the reactor core increases the moderation rate and the core
reactivity. The use of water displacer (Zr rods) in the neutron spectrum regulation and excess reactivity control in the pressurized water reactor (VVER-1000) from the neutronic point of view is studied [15]. Also, a measure of the reliability of the water displacer in the VVER-1000 reactor through comparing between its effect and the effect of maximum concentration of boric acid in the moderator is studied. The results in our previous work [15] showed a good behaviour of excess activity control using Zr rods as a water displacer. Figure 1 shows the fuel assembly of VVER-1000 with Zr rods as water displacers where the Zr rods are inserted between the fuel rods. The drawback in the previous study is the considerable big number of Zr rods in the fuel assembly inside the TVS. In the present work, the Sierpinski geometry model is investigated as a TVS model to overcome the prementioned drawback.

The Sierpinski carpet starts with a solid square, which is divided into nine compatible squares. The central square will be removed. Every one of the remaining eight small squares will be treated in the same procedure. The repetition of the previous procedure leads to obtain a decreasing sequence of sets [18]. The first, the second, and the third iteration create a set of a 3-by-3 grid, a 9-by-9 grid, and a 21-by-21 grid respectively and so on. Figure 2 shows the Sierpinski carpet to the fourth iteration.

Figure 1. Horizontal cross-section SERPENT computer model of the VVER-1000 assembly with Zr rods as a water displacer.

Figure 2. The Sierpinski carpet to the fourth iteration [19].
In the current work, the removed square is replaced with the Zr rod to work as a water displacer in the proposed design. Figure 3 shows a horizontal cross-section of the SERPENT model of the proposed Sierpinski fuel assembly with and without Zr rods. The selected model of a set of a 9-by-9 grid. The fuel rod dimensions and clad thickness is provided from the PWR reactor [16]. The investigation of the Sierpinski fuel assembly is started with the study of the fuel pitch to define the best fuel pitch to show a reasonable difference in the reactor reactivity. The study of the Sierpinski fuel assembly fuel pitch is started from the fuel pitch equal to 10 mm to 18 mm in the cold and hot states. Figure 4 depicts the variation of an infinite multiplication factor ($k_{\infty}$) as a function of fuel pitch for two cold and hot states of the Sierpinski fuel assembly without any neutron absorbers either in the fuel rod or in the moderator. As demonstrated in Figure 4 the peaks in the cold and hot states curves are located at 12.65 mm and 14.5 mm respectively. As stated in [20] the peak of the hot state curve separates between the over-moderated region and the under-moderated region. The selected fuel pitch should be located in the under-moderated region in the hot state for the pressurized water reactors. The nuclear reactor with a fuel pitch under the peak of the hot state curve has a negative reactivity coefficient for fuel and moderator; therefore, it is a safer and more reliable reactor. Thus, the fuel pitch of the proposed Sierpinski fuel assembly can be expanded to 12.65 mm.

![Figure 3. The Sierpinski fuel assembly model of a 9-by-9 grid with (a) and without (b) Zr rods as a water displacer.](image)
Figure 4. The variation of $k_\infty$ as a function of fuel pitch in the cold and hot states.

The difference between the Sierpinski fuel assembly with and without Zr rods at different fuel pitches is investigated to define the reasonable fuel pitch of the proposed design. Figure 5 show the variation of $k_\infty$ as a function of fuel pitch in the Sierpinski fuel assembly with and without Zr rods. As illustrated in Figure 5 $\Delta k_\infty$ for fuel pitches 10, 12, and 12.65 are 0.215, 0.115, and 0.095 respectively. From the result, the fuel pitch which can perform a comparable difference in $k_\infty$ with the effect of boric acid is 12 mm. In the practical case the fuel pitch of 12.65 mm is used in the operating PWR reactors, but the difference in $k_\infty$ for is less than 0.1.
In the pressurized water reactors, the soluble boron in the moderator is used beside the control rods to perform a partial control in the reactor reactivity. Different concentrations of boric acid from 0 ppm to 10130 ppm are inserted in the Sierpinski fuel assembly moderator. Figure 6 shows the variation of the $k_{\infty}$ as a function of fuel pitch in the HZP state at different boric acid concentrations in the Sierpinski fuel assembly. The results show that the maximum value of the $k_{\infty}$ for every concentration decreases with the increase of the boric acid concentration. The increase of boric acid concentration in the reactor moderator decreases the reactor reactivity by absorbing the thermal neutron and decreasing the thermal utilization factor. At the same time, the maximum fuel pitch at 0 ppm of boric acid is decreased from 14.5 mm to 11 mm at 10130 ppm of boric acid in the Sierpinski fuel assembly model. The fuel pitch of 12 mm which decreases from the operating fuel pitch in the PWR gives more capacity of boric acid concentration in the reactor moderator. The proposed Sierpinski fuel assembly model can safely reach to 5750 ppm of boric acid concentration.

**Figure 5.** Infinite multiplication factor as a function of fuel pitch in the Sierpinski fuel assembly with and without Zr rods.
Figure 6. Infinite multiplication factor versus fuel pitch in HZP state for various boric acid concentrations in the Sierpinski fuel assembly.

Figure 7 shows the variation of the $k_{\infty}$ with burnup for the proposed Sierpinski fuel assembly with and without the Zr rods. The insertion of Zr rods in the Sierpinski fuel assembly displaces an amount of the moderator volume. The decrease of moderator volume in the fuel assembly decreases the thermalization process of the fast neutrons resulting from the fission reaction. The neutron spectrum inside the reactor is shifted to the hard region and the thermal neutron flux is decreased. The thermal neutrons inside the core responsible for causing fission reaction so the fission reaction rate of U-235 decreases. Therefore, the values of the $k_{\infty}$ decrease in the presence of Zr rods. Figure 8 depicts the effect of Zr rods presence in the Sierpinski fuel assembly. The breeding factor in the Sierpinski fuel assembly with Zr rods is higher than without Zr rods. The average breeding factor to the burnup limit of 65 GWd/T is 0.68 in the Sierpinski fuel assembly with the presence of Zr rods. The neutron spectrum shift to higher energy leads to the increase of the neutron absorption rate in U-238, which converts to the plutonium isotopes.
**Figure 7.** The variation of the $K_\infty$ values with burnup (gigawatt-days per ton) for The Sierpinski fuel assembly with and without Zr rods.

**Figure 8.** The variation of the breeding factor with burnup (gigawatt-days per ton) for The Sierpinski fuel assembly with and without Zr rods.
The safety parameters of the Doppler effect reactivity coefficient (DRC) and moderator temperature reactivity coefficient (MRC) are the primary safety parameters in thermal reactors. DRC in the pressurized water reactors where a large amount of U-238 should be negative and in the range of 10^-5 [21]. The increase in fuel temperature decreases the resonance escape probability. Table 1 shows the DRC in the Sierpinski fuel assembly with and without Zr rods. The DRC values are calculated from temperature 900 K to 1200 K with an increment of 50 K. In Table 1 it is clearly shown that the DRC values of Sierpinski fuel assembly with and without Zr rods are negative and in the safe range (-2<DRC<-5)*10^-5. The moderator temperature reactivity coefficient (MRC) is considered in the second order after the DRC. The increase in water temperature leads to a decrease in its density and decreases its moderation properties. Consequently, the reactor reactivity decreases with the increase of moderator temperature. The MRC in general should be negative with the increase of water temperature to realize the safety of the reactor design. Table 2 depicts the effect of the increase of water temperature through the MRC values. As it is illustrated in Table 2 the MRC has negative values and its values increase in the negative direction with the increase of water temperature.

Table 1. Doppler effect reactivity coefficient (DRC) of the Sierpinski fuel assembly with and without Zr rods.

| Fuel temperature | Without Zr | With Zr |
|-----------------|-----------|---------|
|                 | DRC (pcm/T⁰) | DRC (pcm/T⁰) |
| 900 - 950       | -1.103     | -1.951     |
| 950 - 1000      | -1.553     | -2.534     |
| 1000 - 1050     | -2.126     | -1.856     |
| 1050 - 1100     | -1.111     | -2.418     |
| 1100 - 1150     | -1.042     | -1.105     |
| 1150 - 1200     | -1.034     | -1.154     |

Table 2. The moderator temperature reactivity coefficient (MTC) of the Sierpinski fuel assembly with and without Zr rods.

| Water temperature | Without Zr | With Zr |
|-------------------|------------|---------|
|                   | MTC (pcm/T⁰) | MTC (pcm/T⁰) |
| 581 - 656         | -10.45     | -21.42   |
| 656 - 731         | -13.19     | -23.70   |
| 731 - 806         | -18.99     | -35.96   |
| 806 - 881         | -25.68     | -42.95   |

4. Conclusion
A new design of a pressurized water reactor fuel assembly to use water displacer rods in the control of the neutron spectrum and the reactor reactivity in the nuclear reactor is investigated. The new design preferred to have a minimum number of water displacers compared to the fuel rods number. Therefore, new pressurized water reactor fuel assembly in the basics of Sierpinski carpet geometry design. The suggested fuel pitch of the Sierpinski fuel assembly is 12 mm, which realizes a big difference in the values of the infinite multiplication factor. The new design performed reasonable control in the reactor reactivity through the burnup process. The breeding factor with the Zr rods inside the Sierpinski fuel assembly showed higher values. The safety parameters approved the safety of the new design. It is
recommended to study the thermal-hydraulic properties of the Sierpinski fuel assembly as a new design of a pressurized water reactor fuel assembly.

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