SOME REACTOR PROPERTIES OF THE NEW DESIGNED NUCLEAR FUELS AFTER NEUTRON IRRADIATION

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Abstract
The main topic of this paper is the optimisation of the fuel assemblies of reactor VVER-440. The aim of the optimisation is to design fuel assemblies with low power peaking factor but with sufficient enrichment for six year fuel cycle. All designs as well as the shroudless type of the fuel assembly RK-3 were modelled using computer code HELIOS 1.10.

1. INTRODUCTION

Likewise in other branches of industry also in the power engineering in the development of the fuels for pressurized water reactors the effectiveness and economic efficiency are the main indicators. These lead in the context of technical parameters to the efforts to increase of burn-up together with the reactor power. This can be achieved by fuel optimisation and modernization which is based on the design changes introduction and the increasing of the enrichment. Therefore is the amount of the ^{235}U in the new fuel assemblies increasing (from the use of first fuel types). However, the power uprate has also limit which is determined by the fuel operational characteristics. The limiting factor is the power of each fuel pin. This can limit the total reactor power. Thus it is important to assess the coefficient describing the power peaking factor of the fuel pins (k_k) in the fuel assembly during the burn-up in the active zone. In this paper, the brief description of the fuel assemblies development and the influence of changes on the power peaking factor of the fuel pins are presented. Based on the selected fuel assemblies used in the past as well as on the perspective shroudless proposal the optimisation process of profiling was carried out [1].

2. The comparison of selected existing fuel assemblies

The goal was to carry out the optimisation changes of the fuel assemblies from the perspective of fuel assembly profiling and the level of enrichment to achieve the lowest power peaking factor of the fuel pins in the fuel assembly while the reactivity reserve could be sufficient for the 6-years fuel cycle. The limit of the maximal fuel pins enrichment was increased to 6% of ^{235}U (5.95%) in order to ensure the sufficient reactivity reserve. This is inadmissible in the present because the maximal allowed limit for the fuel pins enrichment in the power reactors is 5% of the ^{235}U. However, this limit was created artificially and has no physical meaning. Its relevance is based on the determination of some maximal limit of fuel pins enrichment to ensure that they will never be used in connection with the nuclear weapons (Non-Proliferation Treaty). In the present this is only the limitation without any physical or technical justifications which limits the fuel manufacturers in the design of the fuel assemblies with higher reactivity reserve. In the calculations is the limit 5% of the ^{235}U increased with only 1% of the ^{235}U, which in any case cannot influence the security from the perspective of the nuclear weapons. On the other hand, this could be sufficient enrichment value to achieve the 6-years fuel cycle.

The fact if the fuel assembly has sufficient reactivity reserve could not be proven directly, because additional calculations and simulations are necessary. Therefore the fuel assemblies were modelled with the highest level of average enrichment possible. It can be said that the overall task was to design certain optimal fuel assembly with the power peaking factor in the fuel pins as low as possible but with regard to the highest average enrichment of the fuel assembly.

For the burn-up modelling and simulation the computer code HELIOS 1.10 was used. All designed fuel assemblies with shroud tube have one common construction – they are modelled according to the Gd-2 fuel assembly. In the paper, the calculation and comparison of the fuel assemblies from the point of view of coefficient describing power peaking factor of the fuel pins (k_k) in the fuel assemblies and the average enrichment are carried out. First of all the fuel assemblies with profiling according to the fuel assemblies are shown in Fig. 1 were modelled. These fuel assemblies were used in the past (non-profiled 3.6% of the ^{235}U, profiled 3.82% of the ^{235}U, Gd-2 4.25% of the ^{235}U) or are currently used in Hungarian nuclear power plant (Gd-2n 4.2% of the ^{235}U) or in Czech nuclear power plants (Gd-2CZ 4.86% of the ^{235}U). Also the fuel assembly Gd-2R (4.87% of the ^{235}U) currently used in Slovak nuclear power plants was modelled. For better illustration is also the fuel assembly with average enrichment 4.25% of the ^{235}U (but without burnable absorber) shown in the graph in Fig. 6. It can be seen that the fuel assembly without profiling has very large power peaking factor of the fuel pins. This irregularity decreases progressively with increasing fuel burn-up. On the other hand, from the selected assemblies the profiling fuel assembly has the lowest power irregularity of the fuel pins which emphasises the necessity of profiling fuel introduction.

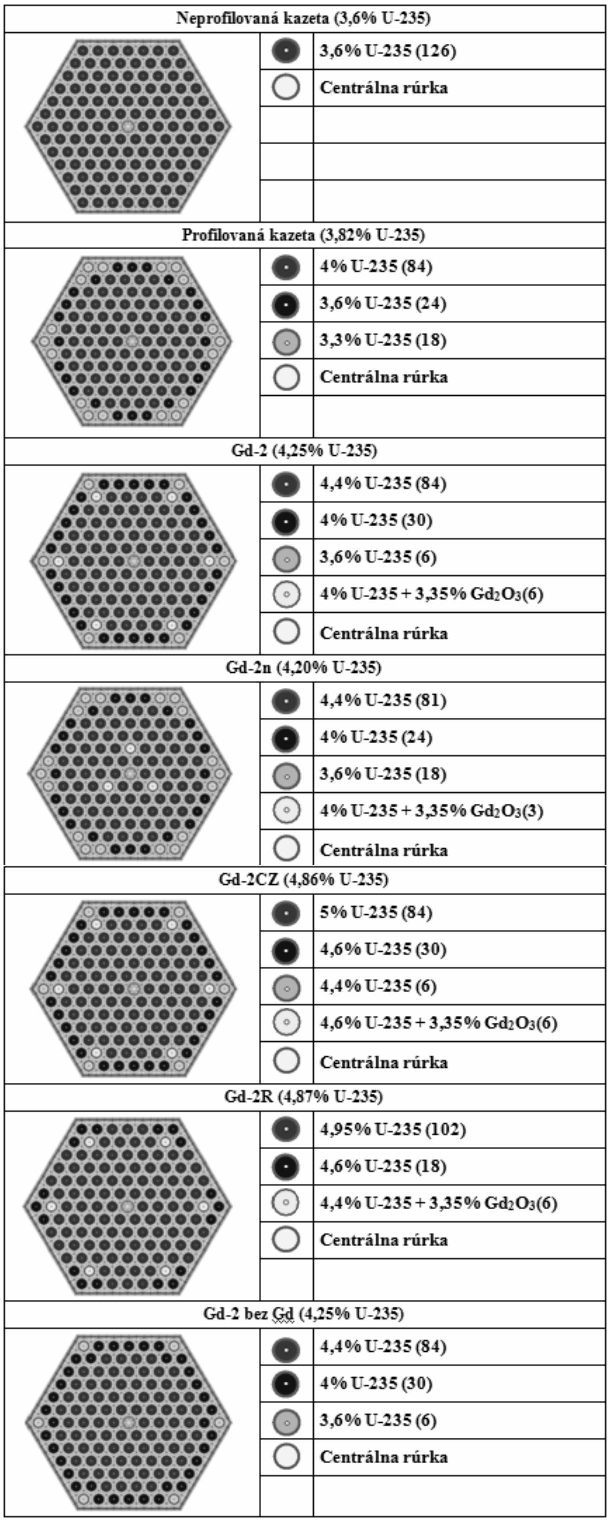


Fig.1: *The distribution of fuel pins in selected fuel assemblies used in VVER-440 reactor.*

Also due to use of fuel pins with gadolinium burnable absorber the cycle of the fuel in active zone became more effective because the fuel with higher enrichment could be used and the negative reactivity worth of gadolinium was lowered.
To emphasise this fact, on the graph in Fig. 6 also the fuel assembly was included whose profiling is the same as in Gd-2 assembly, but contains no gadolinium. If also kinf would be included in the graph, the first 10 000MWd/tHM (thus after the gadolinium burn-up) has the fuel assembly the same behaviour as the fuel assembly without gadolinium. The difference between kinf values is determined by different value of average enrichment. The same applies also for the behaviour of the power irregularity of the fuel pins. After gadolinium burn-up has the power irregularity similar behaviour as for the fuel assembly without gadolinium. But during the process of gadolinium burn-up this causes considerable power irregularity. The rapid decrease of k_k and the local extreme creation in gadolinium assemblies can be characterised as follows: during the process of gadolinium burn-up its negative reactivity worth decreases together with the power peaking factor. This is realising until released reactivity starts again to influence the behaviour of the power peaking factor such that the k_k increases until the process of gadolinium burn-up is finished. After that is the behaviour of k_k similar as in the fuel assembly without gadolinium.
On the graph in Fig. 6 it can be also seen that the Gd-2R fuel assembly which is currently used in the Slovak Republic has very unfavourable trend of power peaking factor of the fuel pins. This fuel assembly has the highest values of k_k compared to the selected fuel assemblies. The Czech design Gd-2CZ has approximately the same enrichment but because of better profiling has significantly better behaviour of k_k. Also the Hungarian design (Gd-2n) has better values of k_k which decrease during the whole process of burn-up. This specific behaviour is caused by using 3 gadolinium pins closer to the central tube.

3. The optimisation of selected types of fuel assemblies

The optimisation process was carried out on several types of fuel assemblies. Also the new profiling types were proposed. In total more than 250 of different designs were proposed, modelled and evaluated, but in this paper the 4 most perspective fuel assemblies from the selected types of fuel assemblies are stated.
Before creating of the new designs the fuel assembly with one type of enrichment and the assembly Gd-2 were modelled. In both cases the fuel pins with gadolinium absorber were shifted from the assembly corner up to the central part. After this procedure it was obvious that the perspective gadolinium pins positions (from the perspective of the power peaking factor of fuel pins) are the position in the assembly corner and in second row.
The optimisation process can be divided into 4 parts. In the first part the optimisation of fuel assemblies with gadolinium pins on the edge (in the corner of assembly) is carried out. In the second part are the optimised fuel assemblies with gadolinium pins shifted in one position closer to the central part (in the second row from the edge of assembly). In the next part the design Gd-2n (3 gadolinium pins in the central part of the assembly) was optimised. In the last part the optimisation of the shroudless assembly was carried out.

3.1 Gadolinium in the central part of the fuel assembly

Several profiling types were proposed, where the gadolinium pins had stable position in the corner of the fuel assembly. One from the designs is the assembly marked as 32m_16_MB (5,73%). This design of the fuel assembly is characterized by maximal enrichment (5,95%) of

90 pins, 6 pins with gadolinium burnable absorber in the corners of assembly and variable enrichment of side pins.

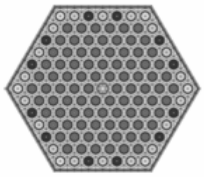
32m_16_MB (5,73%)	
	5,95% U-235 (90)
	5,3% U-235 (12)
	5,25% U-235 (18)
	4,8% U-235+3,35% Gd_2O_3(6)
	Centrálna rúrka

Fig. 2: *Fuel pins configuration in the fuel assembly design marked as 32m_16_MB (5,73% of ^{235}U).*

3.2 Gadolinium in the second row from the edge of assembly

The basic position of fuel pin with burnable gadolinium absorber is in the second row from the corner of fuel assembly. Almost all Russian-type fuel assemblies have such position of burnable gadolinium absorber pin except the Hungarian type fuel assembly Gd-2n, which have only 3 gadolinium pins placed near the central tube.
Design of the fuel assemblies marked as “Gd2o” is based on the distribution of four types os fuel pins according to Gd-2 fuel assembly. Fuel pins with lowest enrichment are placed in the corners of the fuel assembly and pins on the edge of assembly have quite higher enrichment. The reason why the fuel pins have different enrichment is that on these places in the fuel assembly is the power peaking factor unsteady. In the centre of the assembly is placed 84 fuel pins with the highest enrichment (5,95%) of isotope ^{235}U.

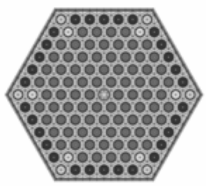
Gd2o_14_MB (5,7%)	
	5,95% U-235 (84)
	5,2% U-235 (30)
	4,8% U-235 (6)
	5,6% U-235 + 3,35% Gd_2O_3(6)
	Centrálna rúrka

Fig. 3: *Fuel pins configuration in the fuel assembly design marked as Gd2o_14_MB (5,7%^{235}U).*

The design marked as “Gd2o_14MB” achieves the best values and also the behaviour of power in the pins of such fuel type. With its behaviour the assembly lies down well below the values of the Gd-2 reference fuel assembly. The average enrichment with isotope ^{235}U was 5.7 % and taking into the account also the power distribution in the assembly, fuel assembly with such enrichment is perspective for 6-year fuel cycle.

3.3 Optimisation according to Gd-2n fuel assembly

As was mentioned in the chapter 3, the perspective position of fuel pin containing burnable gadolinium absorber is in the first or second row of the assembly. However the optimisation process, whose aim was the extended fuel cycle with minimal power peaking factor unsteadiness in fuel pin, lead to the Hungarian fuel assembly type Gd-2n containing only three fuel pin with gadolinium absorber placed in the second row from the central tube. Therefore the further optimisation was done using fuel assembly Gd-2n.

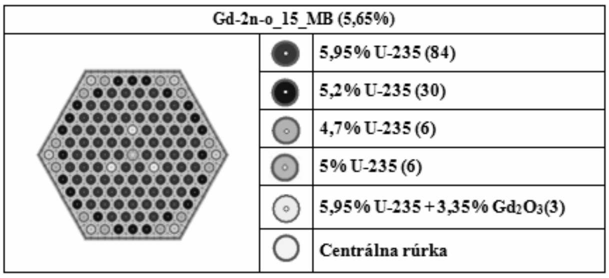


Fig. 4: *Fuel pins configuration in the fuel assembly design marked as Gd-2n-o_15_MB (5,65%^{235}U).*

Gd-2n-o_MB fuel assembly is design-optimised with similar profiling like Gd-2n assembly, but there is different enrichment of fuel pin in the corner of the assembly. This change is based on the fact that the most unsteadiness of power peaking in the fuel pins is on the edge and in the corners of the assembly, because here is a better moderation of neutrons and thus more power is generated. In the Fig. 4 can be seen the different enrichment in individual fuel pins. The lowest enriched pins are placed in the corners of the assembly, followed by pins on the edge, central edge and pins in the corners in the second row of assembly and the rest are gadolinium pins with central pins.
In optimised design Gd-2n-o was confirmed the assumption about enrichment in the pin in the corner of assembly. The most perspective power peaking factor has Gd-2n-o_15_MB design (5.65%), which achieves better results than the assembly Gd-2n during burn-up of 28 000 MWd/tHM and also achieves better or approximately the same results as the reference assembly Gd-2.

3.4 Optimisation of shroudless design RK-3

The next ambitious step to modernization of fuel assemblies with gadolinium burnable absorber is research and development of third generation fuel assemblies, which has started in 2005. Since then many research works has been done and several designs of third generation fuel assembly has been proposed. Detailed design was developed in 2007. This design was based on the second generation fuel assemblies of VVER-1000 reactors. On the basis of these designs fuel assembly marked as “RK-3”, respectively RK-3 Karkas’s assembly or shroudless assembly was developed [2].The shroudless fuel assembly contains several structural changes [2]:

- Shroud tube of fuel assembly was replaced by six corner frames,
- Fuel cladding was slightly decreased,
- Fuel pellet diameter was enlarged
- No central tube is in the fuel pellet,
- The fuel pins step was enlarged,
- Three fuel pins were replaced by zirconium support tubes (12.6x1).

In the following optimisation process the most perspective profiling from the previous designs was used.
In addition to the new designs the influence of shroud on the power peaking factor in individual pins was assessed in such a way that fuel assembly RK-3_TVEL was modelled with the same profiling, but the assembly has construction as second generation. It was obvious from obtained results that the worst power peaking factor in individual fuel pins is in the design Gd-2, as well as profiling as RK-3_TVEL. Its comparing design RK-3_TVEL has

the values k_k lower. Based on the results, it can be concluded, that structural changes have significant influence on the power peaking factor in the individual pins. But the design RK-3_TVEL still shows significant power peaking factor unsteadiness in pins caused by profiling, which have the pins with enrichment of 4.95% ^{235}U on the edge of fuel assembly. Such fuel enrichment of pins increased the average enrichment of assembly, but on the other hand power peaking factor unsteadiness in individual pins was reached. Therefore the optimisation process of profiling of RK-3 fuel assembly was performed again.

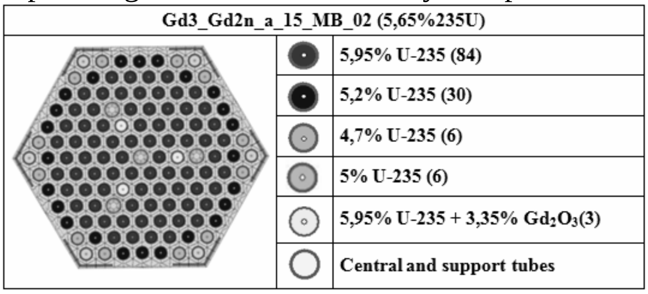


Fig. 5: *Fuel pins configuration in the fuel assembly design marked as Gd3_Gd2n_a_15_MB_02 (5,65%^{235}U).*

The best power peaking factor reaches the fuel assembly Gd3_Gd2n_a_15_MB_02. The k_k starts on the value approx. 1.07 and the small decrease of k_k occur in the first 10 000 MWd/tHM. The power peaking factor is steady and the k_k is slightly decreasing without local extremes. But the line has lowers values as in the reference fuel assembly Gd-2. Suitable optimisation of profiling the power peaking unsteadiness leads to the better results while the enrichment was increased.

Optimisation process of profiling in combination with modernization of the construction of the fuel assembly leads to very good power peaking factor, whose evolution is perspective while the enrichment is quite high. So in the conclusion, it can be said that the optimisation of fuel assemblies is very perspective.

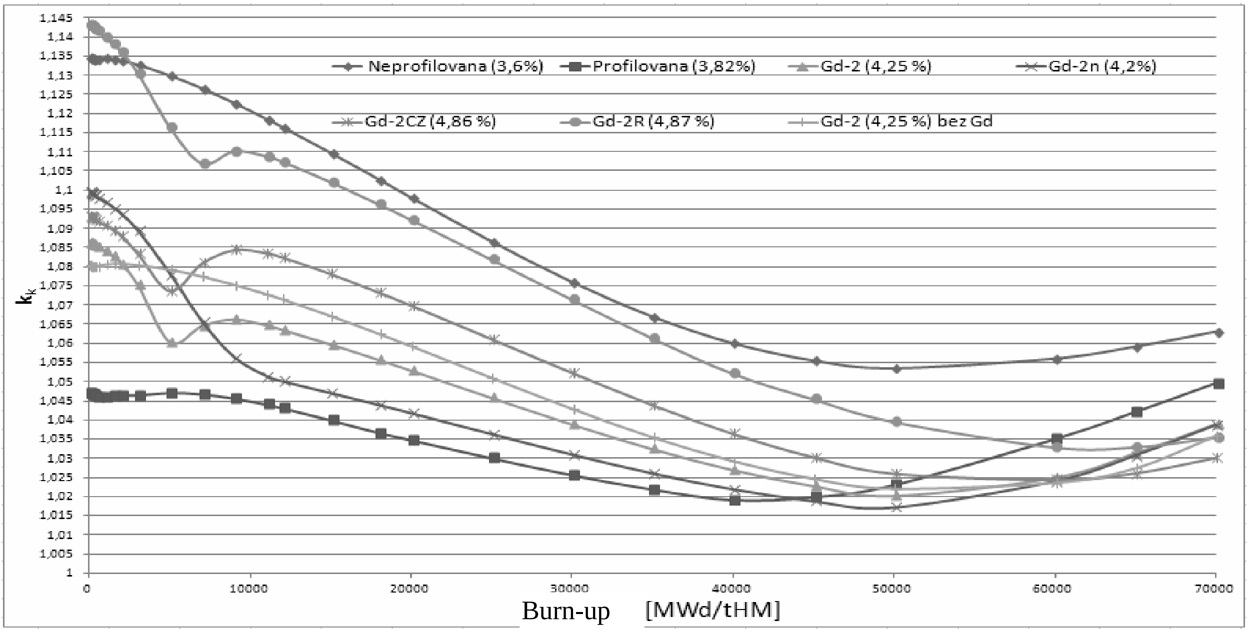


Fig. 6: *Development of power peaking factor depending on burn-up for selected existing assemblies.*

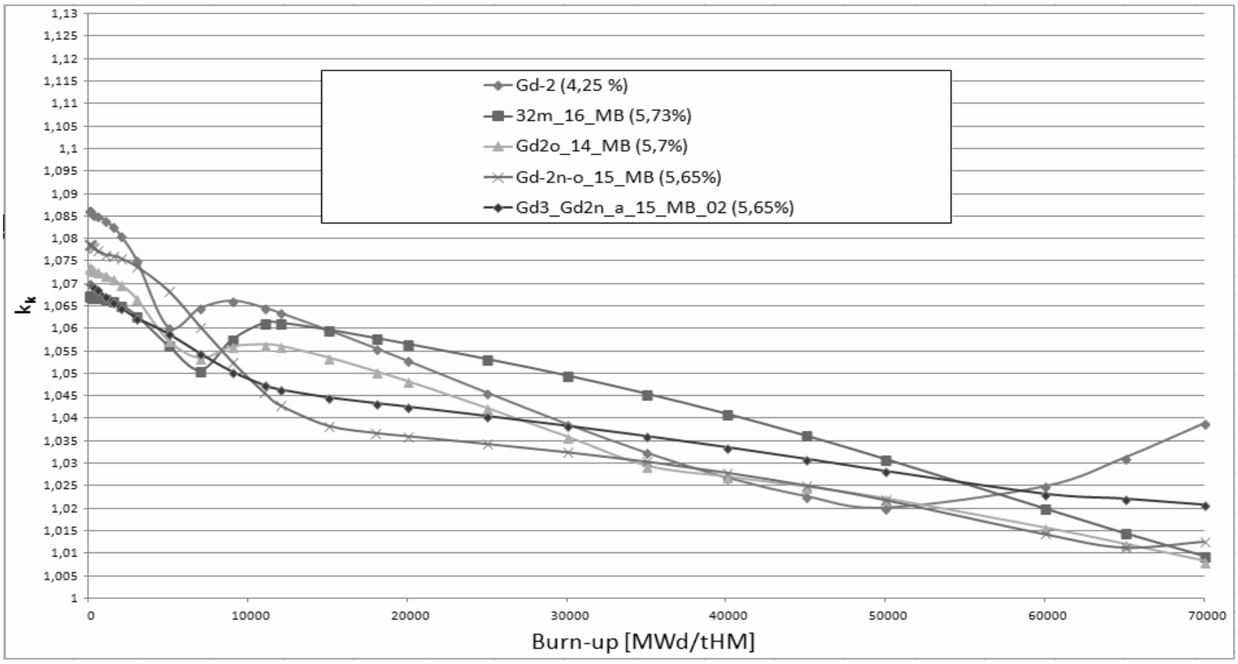


Fig. 7: *Development of power peaking factor depending on burn-up for selected optimised assemblies.*

4. Conclusion

The main goal of this paper was perform the optimisation of the fuel assemblies from the profiling point of view as well as the enrichment of individual rods in such a way that the power peaking factor is steady as possible and also the stock of reactivity for six year fuel cycle. For this reason the limit for maximum fuel rod enrichment was increased to 5.95%. The power in the individual rods is the factor, which can limit the total reactor's power, it is very important to minimise the power peaking factor as possible. At the first the power peaking factor of selected fuel assemblies used in VVER-440 reactor were investigated and from results was based perspective designs which was divided into four parts according to the position of pins with gadolinium burnable absorber and according to the shroudless design. From every part the most perspective fuel assembly was chosen. The results are shown in the Fig. 7. The best result is using the shroudless design. As the second best design is fuel assembly with three gadolinium rods in the middle of the assembly. The power peaking factor unsteadiness is much lower as the reference fuel assembly Gd-2. Also it was demonstrate that the increase of enrichment to 5.95% is perspective, because in several designs the difference in enrichment in individual pins was 1% ^{235}U. Considering only the present allowed value (max 5%) it would not be possible to reach such good power peaking factor and the reactivity sufficient for 6-years fuel cycle.

Profiling optimisation together with modernization of structural changes of assembly was achieved the low power peaking factor unsteadiness in individual pins and higher average enrichment of ^{235}U. So the optimisation can be summarized as very prosperous and perspective.

5. Acknowledgement

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