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«WWER-1000 fuel cycles: current situation and outlook»

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Abstract

Usage mode of nuclear fuel in WWER type reactor has been changed significantly till the moment of the first WWER-1000 commissioning. There are a lot of improvements, having an impact on the fuel cycle, have been implemented for units with WWER-1000. FA design and its constructional materials, FA fuel weight, burnable poison, usage mode of units and etc have been modified. As the result of development it has been designed a modern FA with rigid skeleton. As a whole it allows to use more efficient configurations of the core, to extend range of fuel cycle lengths and to provide good flexibility in the operation.

In recent years there were in progress works on increasing FA uranium capacity. As the result there were developed two designs of the fuel rod:

- the fuel column height of 3680 mm, diameters of the fuel pellet and its central hole of 7.6 and 1.2 mm respectively;
- the fuel column height of 3530 mm, the fuel pellet diameter of 7.8 mm without the central hole.

Such fuel rods have operating experience as a part of different FA designs. Positive operating experience was a base of new FA (TVS-4) development with the fuel column height of 3680 mm and the fuel pellet diameter of 7.8 mm without the central hole.

The paper presents the overview of WWER-1000, AES-2006 and WWER-TOI fuel cycles based on FAs with fuel rod designs described above. There are demonstrated fuel cycle possibilities and its technical and economic characteristics. There are discussed problems of further fuel cycle improvements (fuel enrichment increase above 5 %, use of erbium as alternative burnable poison) and their impact on neutronics characteristics.

Introduction

More than 10 years have passed till the moment of design and introduction of pioneering FAs with a rigid skeleton in NPP with WWER-1000. Development of a FA skeleton structure had two independent from one another trends:

- the skeleton structure consisted of spacer grids welded to guide tubes (development of OKB Gidropress) [1-3];
- the skeleton structure consisted of spacer grids welded to vertical angle bars of FAs (development of Africantov OKBM) [1-2]

The skeleton structure was updated. Design, number and location of spacer grids, design of FA bottom nozzle and its top end fitting, dimensions of FAs angle units and others were improved. Secondary members of FAs, such as antidebris filters and mixing grids, were designed.

Listed engineering solutions improved FAs performance (deformation stability, thermohydraulic characteristics and others). Because of this, FAs life time and the value of allowable fuel burnup were increased. Besides of mentioned differences between skeleton structures and listed engineering solutions, those don’t have a direct impact on a fuel cycle neutronics characteristics, the fuel rod design was improved. The modern fuel rod has increased uranium capacity (on account of increase in the fuel pellet weight and/or the FA height) as compared to pioneering deformation stable FAs.

The main trends that have an impact on neutronics characteristics are considered in the paper. These trends find their way into development of fuel rods, FAs and WWER with high power capacity fuel cycles in recent years. The further ways to improve fuel cycle characteristics are discussed. In the paper was assumed that there are no differences between skeleton structures of FAs because of their insignificant impact on neutronics characteristics of fuel cycles.

1. Fuel cycle with 42 fresh loaded FAs

A fuel cycle with 42 fresh loaded FAs was the first one that was based on deformation stable FAs (TVSA and TVS-2 designs) [4-5] (figure 1). The height of fuel rod was 3530 mm, the fuel pellet diameter was 7.57 mm and its central hole diameter was 1.4-1.5 mm. The operation time of that fuel cycle was 290 EFPD, when the average fuel enrichment of fresh loaded fuel cycles was 4.3 % (the maximal one was equal or less than 4.4 %). The average discharge fuel burnup reached the value of 49 MW·d/kgU, the maximal one was limited by the value of 55 MW·d/kgU.

The equilibrium fuel loading of that fuel cycle was worked in practice at the first generating unit of the Kalinin NPP. The first fuel loading of the four-years fuel cycle was started up in 2004 at the second generating unit of the Khmelnitskaya NPP and at the third generating unit of the Kalinin NPP. Different variations of that fuel cycle were worked in practice at generation units of Ukraine and Bulgaria.

The operating experience confirmed reliability of FAs designed with rigid skeletons. This fact encouraged the further FA upgrading and development of WWER-1000 fuel cycles.

The following trends were chosen as the mainstream of FA design improvement: increase in fuel enrichment; increase in the weight of fuel pellet; increase in the height of FA.

Moreover, changes of nuclear plant operators’ requirement to technical and economic performances have an impact on trend of fuel cycles development. Over the years a number of activities related to increase of energy generation of WWER-1000 units were undertaken. Work to reduce the time of the unit shutdown for the core refueling, work to increase the capacity up to 104 % of rated and others were performed. This led to the necessity of increase in the operating time up to 320 EFPD in 12-month fuel cycles and there was a need to implement an 18-month fuel cycle with the operating time of 490 EFPD.

Considered trends of WWER-1000 fuel cycles development we will discuss in details.

2. Increase in fuel enrichment

The energy potential of the FA increases with fuel enrichment rising. Because of this fact, the operating time can be increased or number of fresh loaded FAs can be reduced, that will improve the fuel usage efficiency.

Figure 2 shows the variation of the cycle length and the average discharge fuel burnup with increasing the average fresh loaded fuel enrichment (for the FA height of 3680 mm with the diameter of fuel pellet of 7.6 mm and the central hole of 1.2 mm). The curve is plotted for equilibrium fuel loadings with different number of fresh loaded FAs. The figure shows that the cycle length can be increased by about 10 % with increasing fuel enrichment from 4.4 to 5 %. Moreover, the number of fresh loaded FAs can be reduced by 6-12 pcs. without the losses in the cycle length. As the result, the average discharge fuel burnup will increase. Because of this fact the specific fuel cost will be reduced in OTFC [7-8].

This trend finds its way into development of all modern fuel cycles where the average fuel enrichment is close to its limit (4.95 %) and its value is 4.7 – 4.8 %.

3. Increase in fuel weight

Because of increase in fuel weight the energy potential of the FA also rises. It allows increasing the fuel cycle length or reducing the number of fresh loaded FAs. Uranium capacity growth is achieved by change in dimensions of the fuel pellet and/or increase in the FA height. At the present time the operating experience as parts of different FAs have fuel rods with the following characteristics:

- the fuel rod column height is 3530 mm, the fuel pellet diameter is 7.8 mm without the central hole (use as a part of advanced FA design with rigid skeleton – TVSA-12);
- the fuel rod column height is 3680 mm, the fuel pellet diameter is 7.6 mm with the central hole of 1.2 mm (use as parts of advanced FA designs with rigid skeleton – TVS-2M and TVSA-PLUS).

There is the final stage of development of the fourth generation FA design, where fuel rods with the fuel rod column height of 3680 mm, the fuel pellet diameter of 7.8 mm without the central hole are used.

Figure 3 shows the variation of the cycle length and the average fuel burnup for described above fuel rods characteristics in equilibrium fuel cycles with different number of fresh loaded FAs. Fuel enrichment is constant at 5.0 %.

The figure shows that because of the increase in FA weight, the fuel cycle length can be increased by about 10 %. Moreover, the number of fresh loaded FAs can be reduced by about 10 % without the losses in the cycle length. Evaluations have showed that the use of the potential associated with the increase in fuel weight by the reduction of the fresh loaded FAs number is more effective [6]. The specific fuel cost can be reduced by 2-4 %, when passing from the standard, at the present time, fuel rod design of 7.6 / 1.2 / 3680 to the one of 7.8 / 0 / 3680.

4. WWER-1000 modern fuel cycles

Described above fuel rods were applied in different NPPs as parts of different FAs designs at different times.

A fuel rod with the fuel column height of 3680 mm, the fuel pellet diameter of 7.6 mm with its central hole of 1.2 mm was used in the TVS-2M design. Each of 12-month fuel cycle with 36 fresh loaded FAs (the cycle length was 320 EFPD, the average fuel enrichment was 4.8 %, the average burnup was 58.5 MW·d/kgU) and 18-month fuel cycle with 60 fresh loaded FAs (the cycle length was 480 EFPD, the average fuel enrichment was 4.9 %, the average burnup was 52 MW·d/kgU) were developed for that design.

Those FAs were worked in practice at the Balakovo NPP. It was at the same time with switching to 18-month fuel cycles and increasing the capacity up to 104 % of rated. At the present time fuel loadings of Balakovo NPP are close to the equilibrium one [9], developed for those operation conditions, with respect to the cycle length, the nomenclature and the loading pattern. Figure 4a shows the loading pattern of the equilibrium fuel cycle. Table 1 presents the main neutronics characteristics of that fuel cycle.

A fuel rod with the fuel column height of 3530 mm, the fuel pellet diameter of 7.8 mm without the central hole was used in the TVS-ALFA (TVSA-12) design. The 12-month fuel cycle with 36 fresh loaded FAs (the cycle length was 310-325 EFPD, the average fuel enrichment was 4.6 %, the average burnup was 58.5 MW·d/kgU) was developed for that design. That fuel cycle was worked in practice at Kalinin NPP [9]. Figure 4b shows the loading pattern of the equilibrium fuel loading. Table 1 presents the main neutronics characteristics of that fuel cycle.

The positive operating experience of described fuel rods designs was the basis for the development of the fourth generation FA design (TVS-4). The skeleton structure of that FA can be implemented as a version with vertical angle bars (Afrikantov OKBM design) and without them (OKB Gidropress design).

A fuel rod with increased fuel column height of 3680 mm, the fuel pellet diameter of 7.8 mm without the central hole is used. That fuel rod has the maximum possible uranium capacity for today. The 12-month and the 18-month fuel cycles, designed for operation mode of 104 % the rated power, have been developed on the basis of the TVS-4. Figure 5 shows loading patterns of those fuel cycles. Table 1 presents the main neutronics characteristics of them.

The further increase in fuel weight is difficult. Evidently, today, an improvement of neutronics characteristic of a fuel cycle will be possible only when fuel enrichment above 5 % is used.

5. Use of uranium-erbium fuel with fuel enrichment above 5 %

Traditionally, the highest fuel enrichment is limited by 5 % for Russian and foreign light water reactors. Fuel manufacture and transportation equipment has been designed and licensed for this value of fuel enrichment. Most of safety assessments for modern NPPs with light water reactors are based on this enrichment.

Figure 6 shows advantages of a fuel cycle when fuel enrichment above 5 % is used. Presented curves are plotted for a new reactor project “AES-2006”. The fuel column height of 3720 mm, the fuel pellet diameter of 7.6 mm and its central hole of 1.2 mm are used in that project. At figure 6 X-axis presents the cycle length and Y-axis – the average discharge fuel burnup. Cross points of these lines correspond to the equilibrium fuel cycle with the selected number of FAs and their enrichment. The region of hatching shows fuel cycles with average enrichment above 5 %. Cross-hatching demonstrates the region, where the average FA burnup is higher than maximum possible for today. Vertical regions present cycle lengths corresponding to 12-month, 18-month and 24-month fuel cycles.

Analyzing the data presented it can be noticed that the average discharge fuel burnup is quite lower than its limit in 18-month fuel cycle with enrichment of 5 %. The enrichment increase and the reduction of fresh loaded FAs number will allow increasing the average discharge fuel burnup. As the result the specific fuel cost will significant decrease. Moreover, to develop the fuel loading with shut down the reactor once in 24 month for refueling will be possible when use of enrichment above 5 %.

Research in the field of modernization, safety justification and licensing of equipment for fuel manufacture, storage and transportation will be required for switching to fuel enrichment above 5 %.

The task can be significant simplified by use of a burnable poison homogeneously mixed in all fuel rods of a FA. The burnable poison reduces multiplication properties to a large degree and can significantly improve nuclear safety during all stages from the transportation to the loading in the core of FAs with fuel enrichment above 5%.

At the present day gadolinium is used as burnable poison for WWER type reactors. The absorption cross sections of gadolinium isotopes are large. Thus, to reduce the intensity of the burnable poison burnup, it is distributed in limited number of fuel rods (from 6 to 27) and its content is relatively high (from 3 to 8 wt %). Very intensive burnup of the gadolinium oxide will be the result of the burnable poison homogeneous distribution. It leads to substantial power density redistribution and input of the positive reactivity during the fuel burnout. Increasing the concentration of boric acid in the coolant will be required to compensate it. Therefore, another type of burnable poison with less absorption cross sections, which can be homogeneously distributed in a FA, is worth to consider for use in high enriched fuel.

Erbium applied today as the burnable poison in RBMK type reactors [10] is worth to consider.

To understand how much the fuel enrichment can be increased when erbium is distributed in each fuel rod, the multiplication ratio of the FA with erbium (the erbium oxide content was from 0.3 to 0.9 wt %) was calculated and the fuel enrichment of the FA without the burnable poison with the same multiplication ratio was determined. Calculation was carried out in cold condition with boric acid concentration of 0 and 16 g/kg. An infinite grid of FAs was considered. Figure 7 demonstrates the results. It shows that the fuel enrichment can be increased to about 6.0 %, while the multiplication ratio is less than in a FA with the fuel enrichment of 5 %, if the erbium oxide content is equal to 0.3 %. With increasing the burnable poison content the fuel enrichment can be further increased.

The relatively low erbium absorption properties can result in the residual burnable poison reactivity worth at the end of the operation time that decreases the multiplication ratio of the FA. It leads to some loss in the fuel cycle length (so called under-burnup effect). To avoid some loss in the fuel cycle length it is reasonable to increase the fuel enrichment in a way to compensate the under-burnup effect.

Figure 8 shows how much the enrichment of a uranium-erbium FA must be increased to compensate the presence of erbium isotopes in different moments of the fuel life. Oval regions correspond to a FA burnup at the end of the first and the second fuel loadings operation time in 18-month fuel cycle. You can see that the under-burnup effect can be compensated by increase the fuel enrichment by about 0.2 – 0.3 %.

Figure 9 shows the effect of uranium-erbium fuel on the axial power density distribution. Calculations have been conducted with use of KASKAD program system developed at NRC Kurchatov Institute [11, 12] for infinite radial and axial grid of FAs. The figure demonstrates axial power density profiles of a FA without burnable poison, with uranium-gadolinium (27 U-Gd fuel rods) and uranium-erbium fuel for selected moments of operation time. As you can see, use of erbium instead of gadolinium will allow significantly decreasing the axial power peaking factor that is issue of the day for fuel cycles with high cycle length (for example, 18-month fuel cycles).

In summary, it can be noticed that use of high enriched uranium-erbium fuel in 18-month fuel cycles will allow significantly improving the power density distribution and the fuel usage efficiency. Fuel cycles with shut down the reactor once in 24 month for refueling become feasible. Use of high enriched uranium-erbium fuel in 12-month fuel cycles is debatable because economic advantages will be insignificant for close to fuel burnup limit.

To demonstrate the application of high enriched uranium-erbium fuel equilibrium fuel loadings of 18- and 24-month fuel cycles have been developed (figure 10). For comparison, the loading pattern of equilibrium fuel loading of uranium-gadolinium fuel cycle with enrichment below 5 % is presented in the figure. The table 2 presents neutronics characteristics of fuel cycles.

Based on the results obtained the following may be concluded:

- the average burnup of discharged FAs increases by approximately 20% (up to the typical value to 12-month fuel cycles) and, relatively, the number of fresh FAs decreases by 17 %;
- owing to the low leakage configuration of the core, the maximum peripheral FAs power decreases by 40 %;
- even as the configuration is different and fewer fresh FAs are needed, the maximum fuel rods power is approximately the same and the maximum linear thermal power in the upper part of the core decreases by 10 %;
- specific consumption of natural uranium and specific FAs consumption decrease by 2% and 19 %, respectively;
- the concentration of boric acid required for the reactor to be subcritical (5%) in the cold condition increases from 16 to 20 g/kg$_{H2O}$.

Conclusions

In summary, it can be noticed that modern fuel cycles are able to satisfy the main requirements of Russian and foreign customers.

In the short term characteristics of fuel cycles can be improved by use of new uranium high-capacity FA of the fourth generation.

In the long run the high enriched fuel with the erbium oxide integrated in each fuel rod of a FA is reasonable to use. It will further improve the fuel usage efficiency of an 18-month fuel cycle and unapproachable 24-month fuel cycles become feasible.

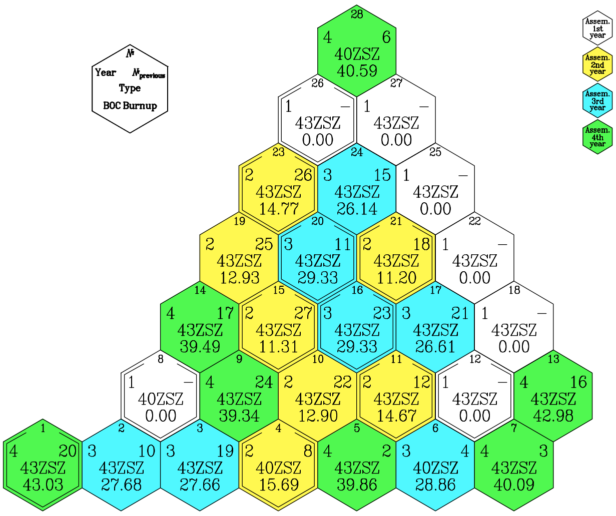


Fig.1. Loading pattern of equilibrium fuel cycle (42 fresh FAs, fuel rod 7,57 / 1,4 / 3530)

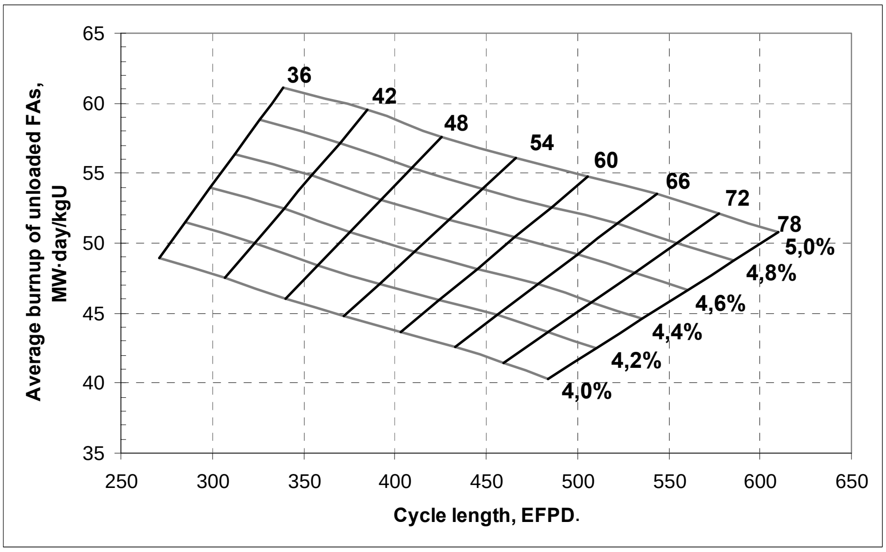


Fig. 2. Average burnup of unload FAs and cycle length as a functions of fresh FAs number and average enrichment

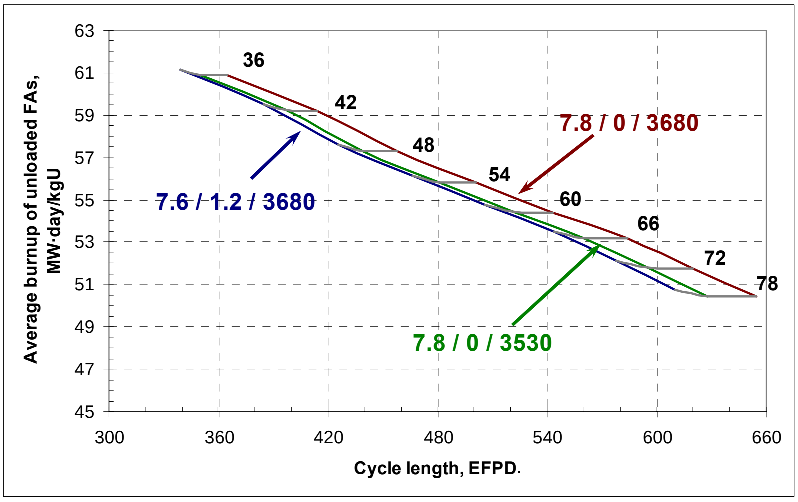
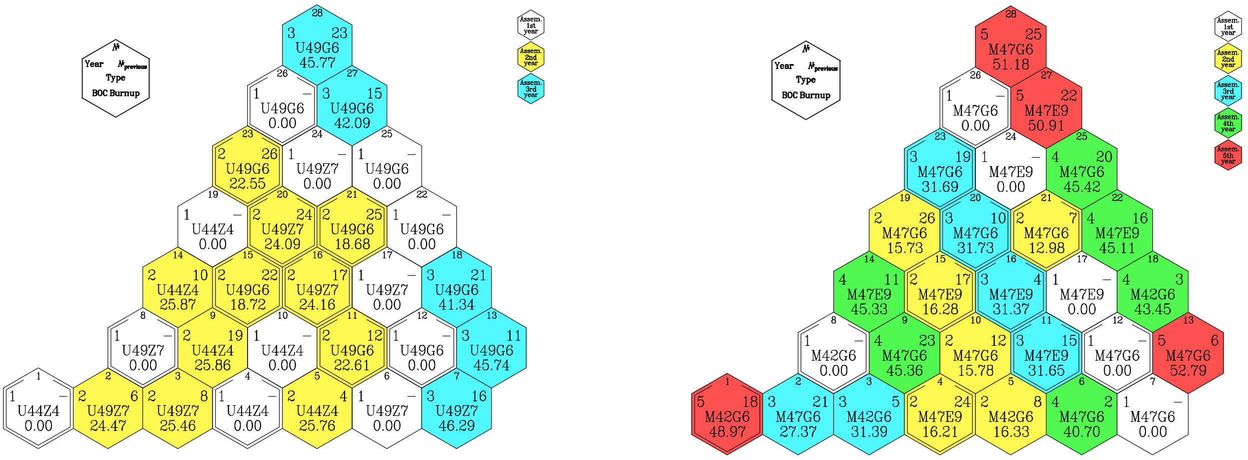
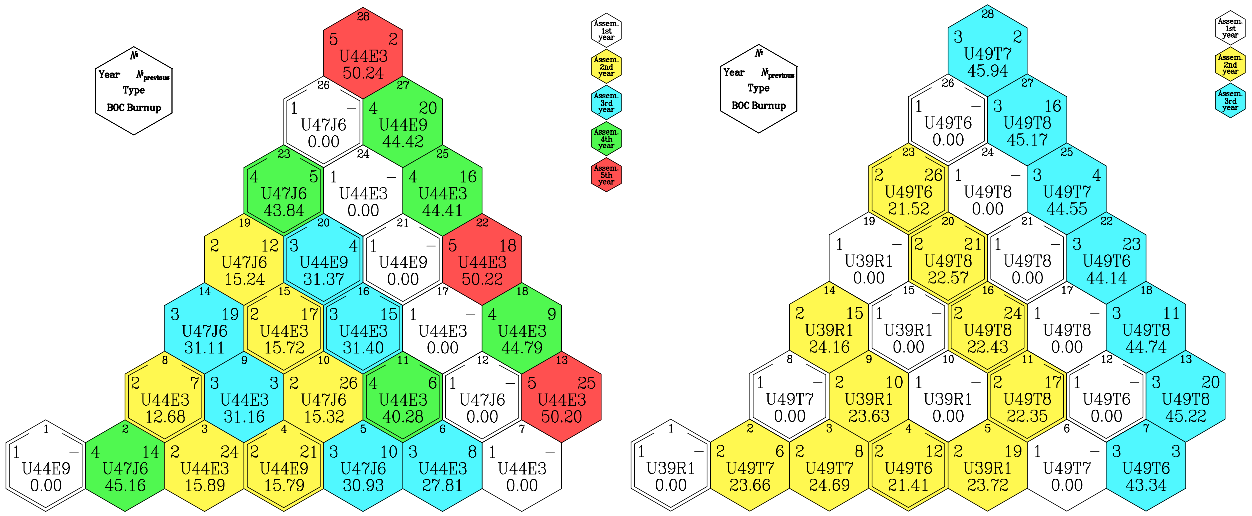


Fig 3. Average burnup of unload FAs and cycle length as a functions of fresh FAs number and fuel mass



a b

Fig. 4. Loading patterns of equilibrium fuel cycles (a – 18-month fuel cycle, 66 fresh FAs, fuel rod 7,6 / 1,2 / 3680; b - 12-month fuel cycle, 36 fresh FAs, fuel rod 7,8 / 0 / 3530)



a b

Рис. 5. Loading patterns of equilibrium fuel cycles designed on TVS-4 (fuel rod 7,8 / 0 / 3680)

Tabl. 1. Basic neutronic characteristics of VVER-1000 fuel cycles

Characteristics	Modern fuel cycles			Advanced fuel cycles	
	12-month (TVSA, TVS-2)	12-month (TVSA-12)	18-months (TVS-2M, TVSA-PLUS)	12-months (TVS-4)	18-months (TVS-4)
Thermal power, MW	3000	3000	3120	3120	3120
Fuel tablet dimensions, mm	7,57 / 1,4	7,8 / 0	7,6 / 1,2	7,8 / 0	7,8 / 0
Fuel column height, mm	3530	3530	3680	3680	3680
Number of fresh FAs, psc.	42	36	66	36	60
Average enrichment, %	4,3	4.6	4.7	4.5	4.6
Cycle length, EFPD	297	320	487	318	485
Average burnup, MW·day/kgU	49	55	50	55	50
Peak power of fuel rod	1,47	1.55	1.50	1.52	1.50
Critical concentration of boric acid, g/kg$_{H_2O}$	6,2	7.6	8.1	7.2	8.1
Moderator temperature reactivity coefficient, pcm/°C	<0	<0	<0	<0	<0
Temperature of against criticality, °C	190	190	170	190	160
Specific consumption of natural uranium, rel.	1.00	0.92	1.10	0.95	1.05

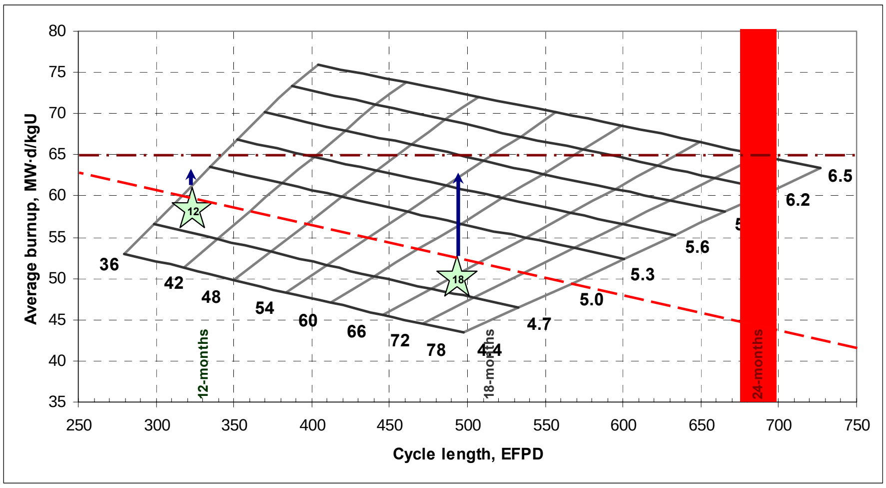


Fig. 6 Average burnup of unload FAs and cycle length as a functions of fresh FAs number and average enrichment

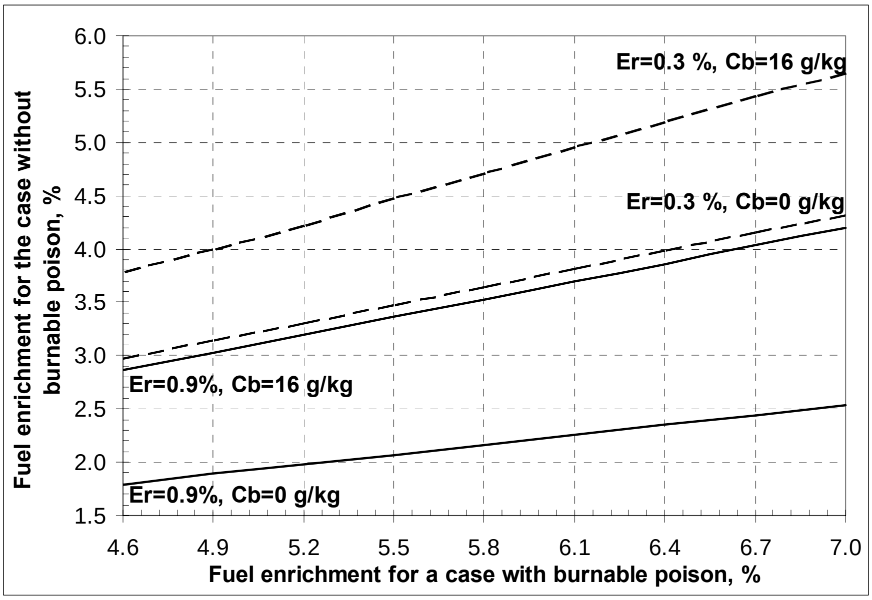


Fig. 7. Fuel enrichment of FA without erbium (E_0) as a function of fuel enrichment of FA with erbium (E_{Er}) as per equation $K_\infty(E_0) = K_\infty(E_{Er})$ in the cold condition with boric acid concentration of 0 and 16 g/kg

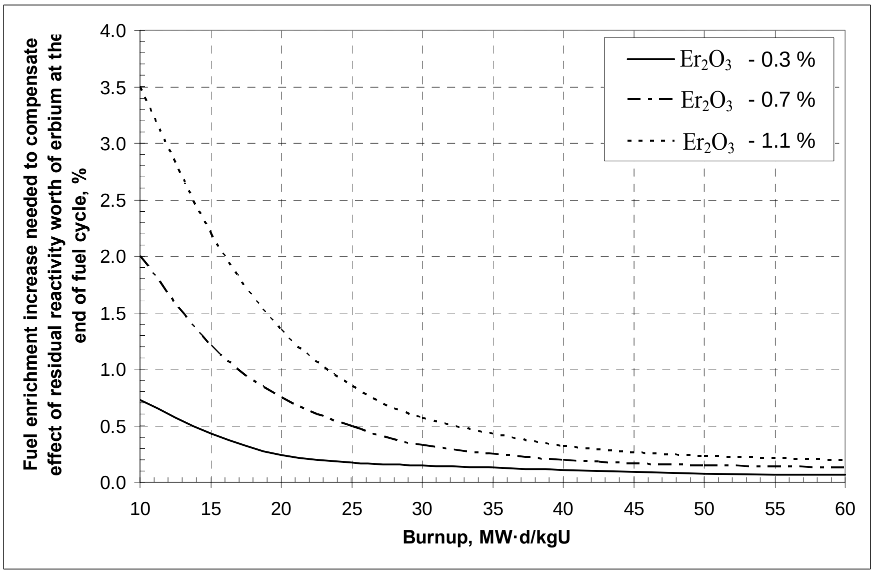


Fig. 8. Fuel enrichment increase (ΔE) in FA with burnable poison A (gadolinium or erbium) as a function of fuel burnup (ρ) satisfying the condition $K_\infty(5\ \% + \Delta E, A, \rho)=K_\infty(5\ \%$, without burnable poison, $\rho)$ when the reactor operates at nominal power

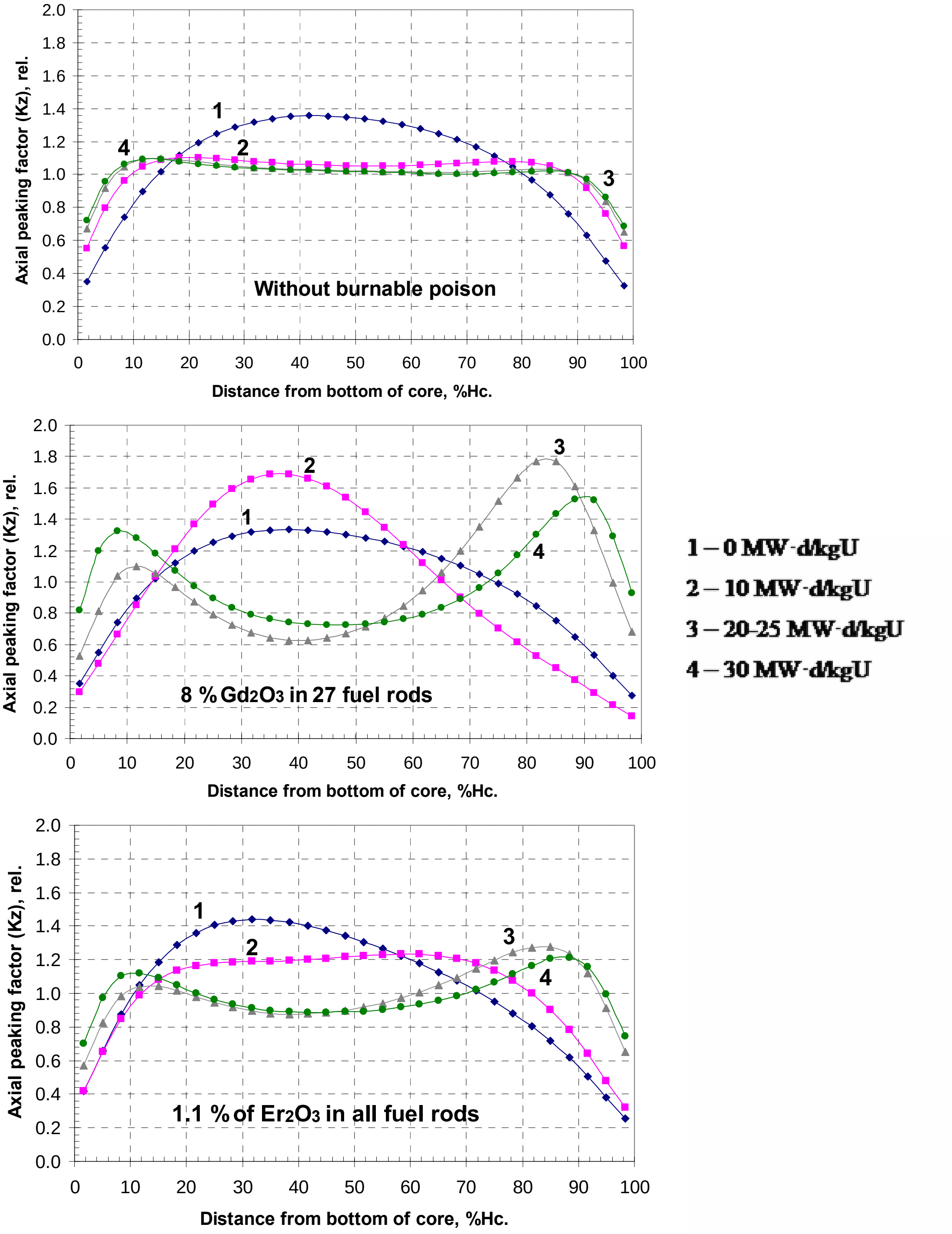


Fig. 9. Axial power distribution as a function of fuel burnup for different types of burnable poisons

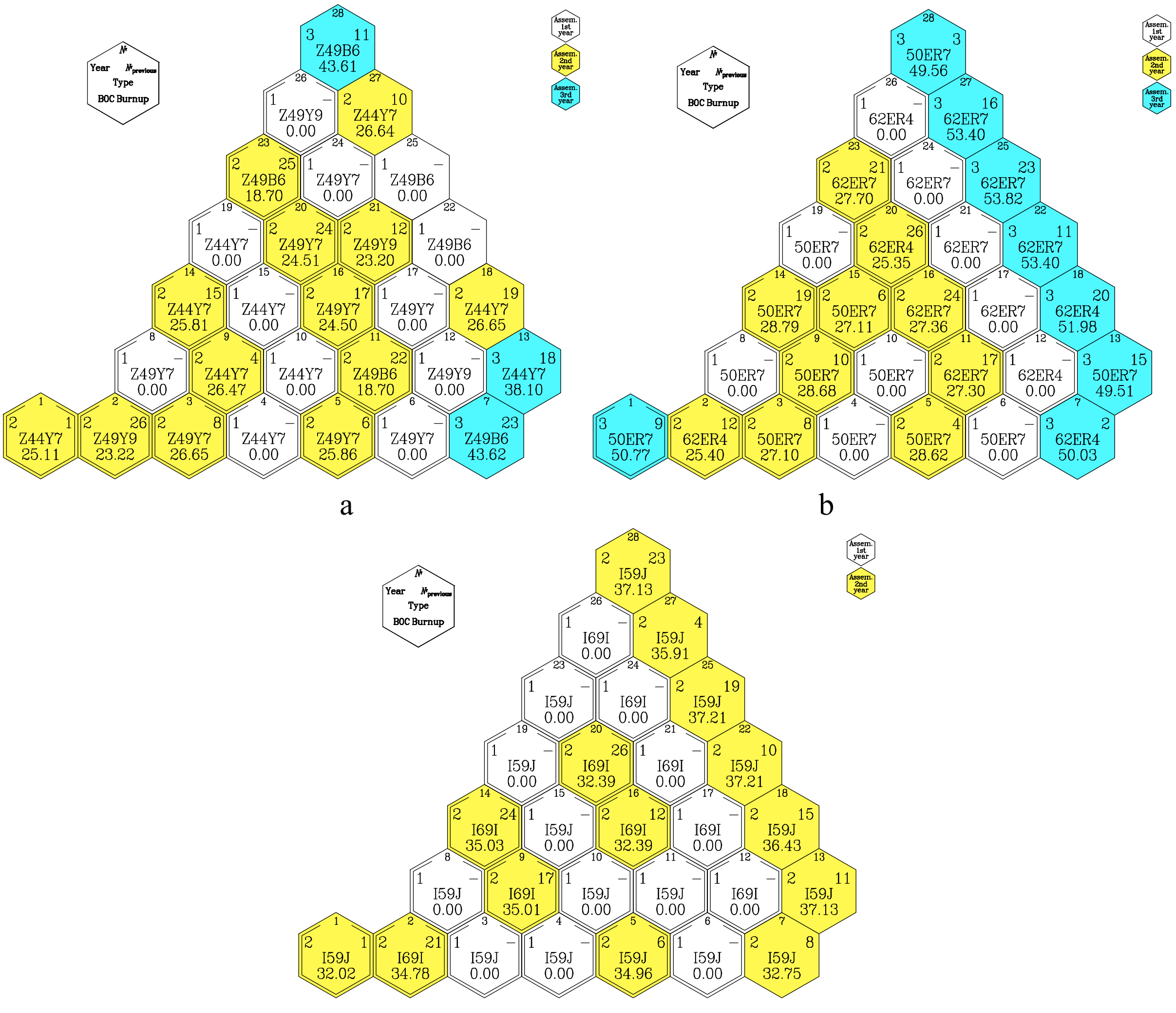


Fig. 10. Loading patterns of equilibrium fuel cycles (a – 18-month fuel cycle, 72 fresh FAs, enrichment below 5 %; b - 18-month fuel cycle, 60 fresh FAs, enrichment above 5 %; c - 24-month fuel cycle, 82 fresh FAs, enrichment above 5 %)

Tabl. 2. Basic neutronic characteristics of fuel cycles

Characteristics	18-month <5%	18-month >5%	24-month >5%
Number of fresh loaded FAs	72 / 73	60	79 / 84
Average / maximum fuel enrichment,%	4.69 / 4.95	5.60 / 6.2	6.27 / 6.9
Type of burnable poison	Gd	Er	Er
Er_2O_3 content in FA, %	-	0.4 or 0.7	0.9 or 1.2
Average number of fuel rods with Gd_2O_3 / Gd_2O_3 content in FA, %	21 / 5 or 8	-	-
Fuel cycle length, EFPD	502	510	689
Average / maximum FA burnup, MW·d/kgU	47 / 55	58 / 68	58 / 68
Maximum radial fuel rod power, rel.un.	1.50	1.51	1.51
Maximum axial fuel rod power at the distance from the bottom of core, W/c:			
33%	313	322	328
85%	287	259	271
Re-criticality temperature, C	35	< 27	31
Critical concentration of boric acid when control rods ↑ and $\Delta\rho/\rho$=-0.05, g/kg	16.0	20.2	21.2
Specific consumption of natural uranium, rel. ($kgU_{nat}/MW \cdot d_{th}$)	1.00	0.98	1.10

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