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“Fuel cycles of WWER-1000 based on assemblies with increased fuel mass”

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Abstract

Modern WWER-1000 fuel cycles are based on FAs with 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 highest possible fuel enrichment has reached its license limit that is 4.95 %.

Research in the field of modernization, safety justification and licensing of equipment for fuel manufacture, storage and transportation are required for further fuel enrichment increase (above 5 %). So in the nearest future an improvement of technical and economic characteristics of fuel cycles is possible if assembly fuel mass is increased. The available technology of the cladding thinning makes it possible. If the fuel rod outer diameter is constant and the clad inner diameter is increased to 7.93 mm, the diameter of the fuel pellet can be increased to 7.8 mm. So the suppression of the pellet central hole allows increasing assembly fuel weight by about 8 %.

In this paper we analyze how technical and economic characteristics of WWER-1000 fuel cycle change when an advanced FA is applied instead of standard one. Comparison is made between FAs with equal time interval between refuelings. This method of comparison makes it possible to eliminate the parameters that constitute the operation component of electricity generation cost, taking into account only the following technical and economic characteristics:

- cycle length;
- average burnup of spent FAs;
- specific natural uranium consumption;
- specific quantity of separative work units;
- specific enriched uranium consumption;
- specific assembly consumption.

Collected data allow estimating the efficiency of assembly fuel weight increase and verifying fuel cycle characteristics that may be obtained in the advanced FAs.

Intoduction

If we take a glance at the history of WWER-1000 fuel cycles development it will become clear that in recent years enhancement of fuel usage efficiency has been reached by increasing the average fuel enrichment. The highest enrichment in uranium-gadolinium fuel cycle with 48 feeding FAs [1] was 4.1 %, a four-year fuel cycle [2, 3] being applied using FA with rigid skeleton with maximum fuel enrichment of 4.4 %. The fuel rod column height of these FAs was 3530 mm, the fuel pellet diameter - 7.57 mm and the central hole 1.4 – 1.5 mm.

The highest fuel enrichment of the TVS-2M [4-5] being used today in Russian WWER-1000 units has been increased to 4.95 %. Additionally the energy potential of such FA was enhanced using increased fuel weight (by about 8 %) that was reached because of the fuel column extension to 3680 mm, an increase of the fuel pellet diameter to 7.6 mm and a decrease of central hole diameter to 1.2 mm. This upgrade, combined with the use of a low leakage arrangement, makes it possible to reduce the number of feeding FAs to 36 units in 12-month fuel cycles and apply 18-month fuel cycle with 66 feeding FAs.

Research in the field of modernization, safety justification and licensing of equipment for fuel manufacture, storage and transportation are required for further fuel enrichment increase (above 5 %). So in the nearest future an improvement of technical and economic characteristics of fuel cycles is possible if assembly fuel mass is increased. The available technology of the cladding thinning makes it possible. If the fuel rod outer diameter is constant and the clad inner diameter is increased to 7.93 mm, the diameter of the fuel pellet can be increased to 7.8 mm. So the suppression of the pellet central hole allows increasing assembly fuel weight by about 8 %.

Fuel rods with such fuel pellets without central hole have operating experience as a part of a TVS-ALFA at the Kalinin NPP. The fuel column height of such FAs, unlike TVS-2M one, was standard: 3530 mm.

Integrated experience of TVS-ALFA and TVS-2M operation makes it possible to suggest an advanced fuel rod design which would have an increased fuel column height (as a TVS-2M) and an increased fuel pellet weight (as a TVS-ALFA). As a result the uranium loading in an advanced FA will be increased by about 8 % as compared with a TVS-2M and by about 4 % as compared with a TVS-ALFA. The suggested increase of fuel weight will be obtained by changing the fuel rod design with other design features unvariable. The differences between FAs designs have only a weak effect on the core neutronics characteristics and practically have no impact on the results that are shown in this paper.

Here we try to assess influence on the technical and economic characteristics of WWER-1000 fuel cycle while transition to the advanced assembly instead of the standard one takes place.

1. Range of change of WWER-1000's fuel cycle characteristics.

We used the data on the characteristics of fuel cycles based on TVS-2M (3680/7.6/1.2), which was pointed out in the paper [6]. A set of stationary fuel cycles that have different number of loaded FAs (from 36 to 78 pcs) and different loaded fuel enrichment (from 3.6 to 4.95 %) was examined. Loading patterns of stationary fuel cycles are presented in Figure 1. Low neutron leakage arrangement of the core has been applied in all loadings. There are 12 fresh FAs on the periphery, and the rest of positions on the periphery are occupied by FAs that have maximum burnup.

Figure 2 illustrates the dependence of stationary cycle length and average burnup of discharged fuel on the number of fresh FAs in the core and on their enrichment. The possible variation interval of these characteristics, while applying fuel with the fuel column height of

3680 mm, the fuel pellet diameter of 7.6 mm and the central hole of 1.2 mm, can be estimated using these correlations. Clear, that the biggest possible cycle length is limited by the value of 585 EFPD. The average discharge burnup, while the operation duration is 320 EFPD (12-month fuel cycle) is limited by the value of 60 MW·days/kgU. The value of the burnup of 18-month fuel cycle (about 510 EFPD) cannot exceed 53 MW·days/kgU. The characteristics of 18-months cycle with feed by 66 FAs and the average fuel enrichment of about 4.8 % are marked with an asterisk in this and the following diagrams.

Assessment of the change of the operation duration and of the fuel burnup of advanced FAs (3680/7.8/0) was carried out using the same set of fuel cycles. Figure 3 illustrates the calculations. Using of FAs with increased fuel weight makes it possible to expand the range of feasible fuel cycles as can be seen in the picture. The biggest possible duration will be limited by the value of 630 EFPD. That is by 45 EFPD longer than while using the standard design of FA. However, the maximum possible operation duration will be about 610 EFPD due to the required reduction of uranium-gadolinium fuel enrichment (the average fuel enrichment of feeding FAs will decrease to 4.8 %). That is not enough to ensure a 24-months fuel cycle.

It becomes clear comparing Figures 2 and 3 that high-capacity uranium FA provides greater operation duration under the same refueling ratio. In practice the operation duration necessary to achieve the selected interval between refuelings (made once a year or a year and a half) is a part of the requirements the fuel cycle should meet. So it is advisable to compare FA design comparing fuel cycles with the same operation duration. This method of comparison makes it possible to avoid the indicators of electricity generation cost, and take into account only the natural characteristics of the fuel usage. The given operation duration can be achieved by less fuel enrichment or less number of loaded FAs.

Let us discuss in detail both methods of operation duration ensuring.

2. Probable reduction of fuel enrichment provided by transfer to high-capacity uranium FA.

As shown in Figure 4, it can be determined how much the value of advanced fuel enrichment (the fuel pellet of diameter 7.8 mm without the central hole) should be reduced to provide the operation duration that would correspond to the standard fuel element design under the same number of feed FAs. The ordinate axis refers to the enrichment of the advanced FA. The legends for the curves shown in the figure characterize the standard FA (the fuel pellet diameter is 7.6 mm, the central hole is 1.2 mm). Clearly that while the refueling ratio being constant, a high-capacity uranium assembly makes it possible to reduce fuel enrichment by about 7 – 8 %, providing the same operation duration as with a standard FA. In addition, relative reduction of fuel enrichment is almost insensitive to the refueling ratio and the operation duration time.

For the purpose of simplifying presentation of the batch of fuel cycles based on the standard FA, the fuel cycles with enrichment of 4.4, 4.8 and 4.95 % and number of loaded assemblies from 36 to 78 pcs, have been chosen. Figure 5 illustrates evolution of average discharge burnup while transferring to the high-capacity uranium FA, under constant operation duration and refueling ratio. Analyzed characteristics as a function of number of loaded FAs are marked with the thick lines. Cuts shown with thin lines illustrate an effect of transferring to the high-capacity uranium FA.

As shown in Figure 5, the average discharge burnup can be decreased by about 3.5 – 4.5 MW·days/kgU while transferring to the advanced FA. The specific natural uranium consumption will be almost insensitive to such method of saving the operation duration (Fig. 6). The reduction of the specific quantity of separative work units will be 1.7 – 2.3 % (Fig. 7). It is important to note that the specific enriched uranium consumption will grow in proportion to fuel weight increase (by about 8 %), and the specific assembly consumption will be insensible while saving the refueling ratio and the operation duration.

Thereby, only specific cost associated with fuel enrichment process and discharged fuel transportation has changed. Naturally, the sign and the value of variation of fuel component in the cost will depend on expenses at each step of technological fuel cycle. This cost is a function of time being different for various types of NPPs. Moreover the discharged fuel transportation cost may be or not be a function of the fuel burnup. So we cannot lead to the uniform conclusion whether it is reasonable to increase the fuel assembly weight and decrease the fuel enrichment at the same time. If the cost of discharged fuel transportation grows rapidly with increasing the fuel burnup, then if you decrease the fuel enrichment, while transferring to the high-capacity uranium FA, the specific cost relating to the discharged fuel handling may reduce.

3. Reduction of the number of loaded FAs while transferring reduction to high-capacity uranium FA.

In point of the fuel component in electricity generation cost the second method of the required operation duration ensuring is preferable. Here the increasing fuel weight is accompanied by decreasing number of loaded FAs.

Figure 8 illustrates how much the number of loaded FAs may be reduced under constant fuel enrichment, while transferring to the advanced FAs, is taken place. The ordinate axis refers to the number of advanced FAs that are loaded during the refueling. The legends for the curves shown in the figure characterize the standard FA (the fuel pellet diameter is 7.6 mm, the central hole is 1.2 mm). Clearly that relative reduction of the number of reloaded fuel is almost insensitive to the fuel enrichment and the fuel cycle duration. To provide the necessary cycle length, during the refueling it will be required to decrease the number of uranium high-capacity FAs by 9-10 rel. % as compared to the standard FAs with the same fuel enrichment. The number of FAs that may be excluded from a 12-month fuel cycle feeding is 3 or 4. As for a 18-month fuel cycle this value is limited by 6 pcs.

It is important to note that the number of loaded FAs is a discrete value. It is defined by the selected loading symmetry and the different type loads in the stationary fuel cycle. Commonly 60 degrees loading symmetry is applied. Naturally, the number of loaded FAs should be multiple 6 (for example, 36, 54, 78). If the stationary fuel cycle consists of several loadings then a fresh assembly may occupy the central cell of one of them. The FA is maintained there during several operation times unless it will reach the end of its service life and will be discharged. In this case the average number of loaded FAs may be a magnitude with a fraction (for example, 54.3, 78.5). For convenience let us assume that the number of loaded FAs is continuous value. Then using Figure 9 the number of advanced and standard loaded FAs, that ensure the same operation duration, can be definitely obtaned.

For the purpose of simplifying presentation of the batch of fuel cycles based on the standard FA (3680/7.6/1.2) the fuel cycles with the average number of loaded FAs of 42, 54.3, 66.5 and 72.5 are chosen. Relative number of uranium high-capacity FAs is 38.5, 49.3, 60.5 and 70.7.

By approximation of the calculated values the average discharge burnup and specific parameters of the fuel usage may be defined for the obtained refueling ratio. Figure 9 illustrates the average burnup evolution, if the fuel enrichment is constant and the number of loaded FAs is decreased, while transferring to the advanced FAs. Analyzed characteristics as a function of FAs enrichment, while the number of feed FAs corresponds to the selected type of assembly, are marked with the thick lines. Cuts shown with the thin lines illustrate an effect of transferring to the uranium high-capacity FA.

Figure 9 shows the increase of the average discharge burnup by about 0.5 – 1.0 MW·days/kgU, while shifting to the uranium high-capacity FA. The specific natural uranium consumption will decrease by about 1.3 – 2.5 % (Fig. 10). The reduction of the specific quantity of separative work units will be 1.2 – 2.2 % (Fig. 11). The specific enriched uranium consumption will decrease by about 1.3 – 2.3 % (Fig. 12). The specific FA consumption will decrease in proportion to number of loaded FAs reduction (by about 9 - 10 %).

Thereby, all summands applied to estimate a fuel component in electricity generation cost will decrease.

4. Application of FAs with increased fuel weight to 12-month and 18-month fuel cycles.

Decrease of the number of FAs in 12-month fuel cycles may lead to negative consequences. First, an increase of the fuel weight makes it possible to reduce the number of loaded FAs not much, by about 3 – 4 pcs; it may cause problems with 60 degree symmetry and complicate the control of power distribution. Secondary, the power distribution irregularity in the core increases, while reducing the number of loaded FAs. It will decrease the operational margins and sometimes makes impossible to fit such cycles. So in the 12–month fuel cycle with the advanced FAs the first method was applied that ensures the required length of the operation duration.

Reduction of feeding by about 6 FAs in 18-month fuel cycle makes possible to decrease the specific fuel cost, conserving constant core symmetry and power distribution irregularity.

Figure 13 illustrates maps of 12-month and 18-month fuel cycles with the standard FA types (TVSA-ALFA and TVS-2M) and the FA with increased fuel weight. Table 1 contains main neutronics characteristics of these cycles.

Conclusion

Summarizing the above it can be noticed that suggested fuel rod cladding thinning, increasing of the fuel pellet diameter and suppressing of the central hole, while the highest-possible fuel enrichment is limited (up to 4.95 %), is one of the perspective directions of WWER-1000 fuel cycles development.

Application of the uranium high-capacity FA to 12-month fuel cycle makes possible to decrease the fuel enrichment and to reduce the discharge burnup.

In 18-month fuel cycle it is reasonable to compensate the extension of the fuel cycle duration caused by using FA with increased UO_2 weight by reduction of the number of loaded FAs (it is desirable to use the average enrichment that is close to the maximum-possible value). In this case reactor power generation is constant, and specific fuel cost decreases.

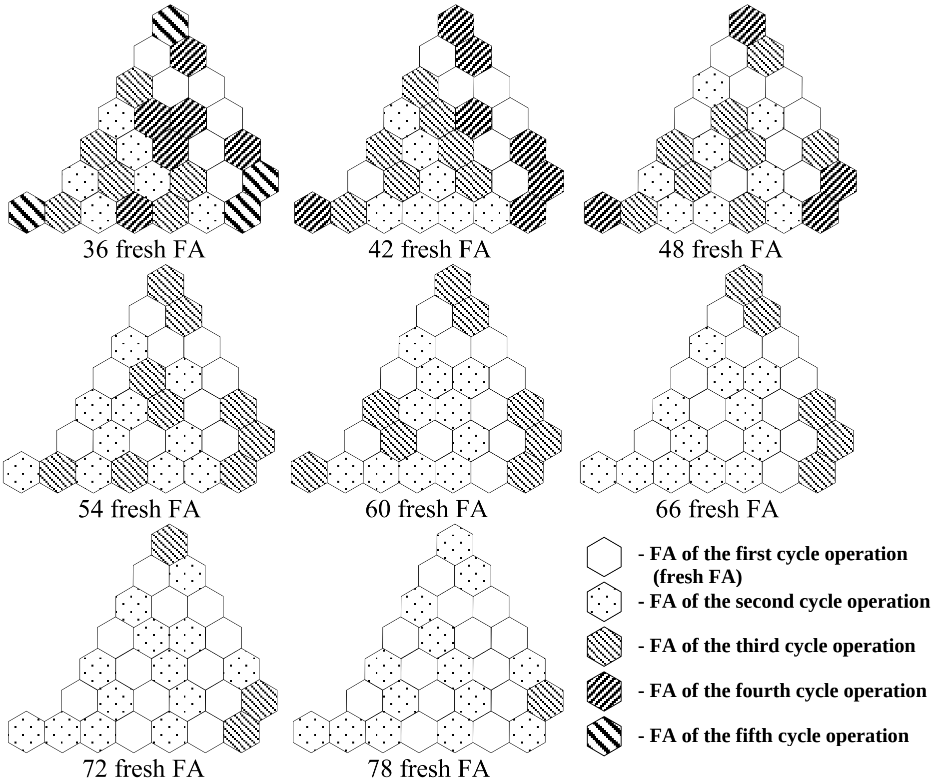


Figure 1. Patterns of equilibrium VVER-1000 core loads (symmetry sector 60^0)

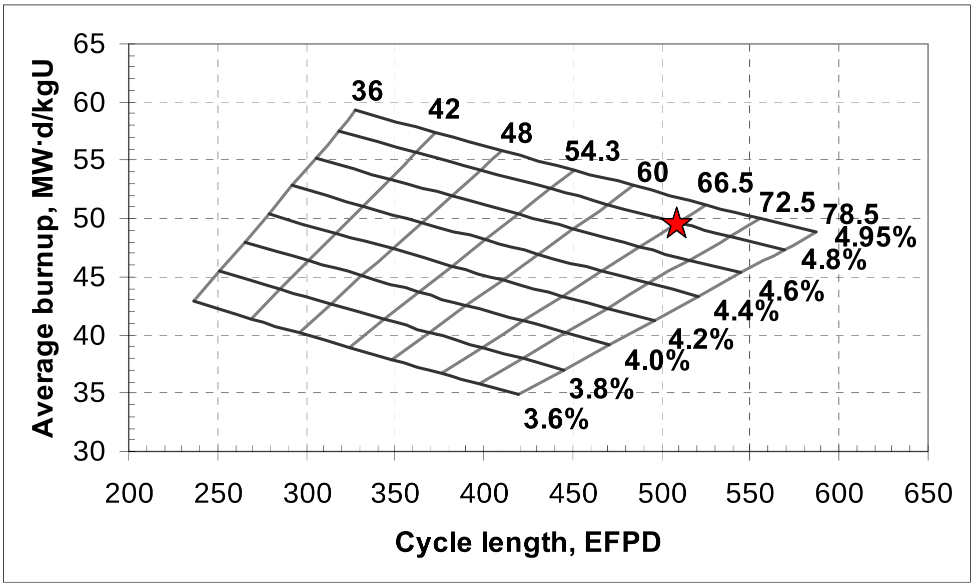


Figure 2. Average burnup as a function of number of loaded FAs, FA enrichment and cycle length (modern design of fuel rods - 3680/7.6/1.2)

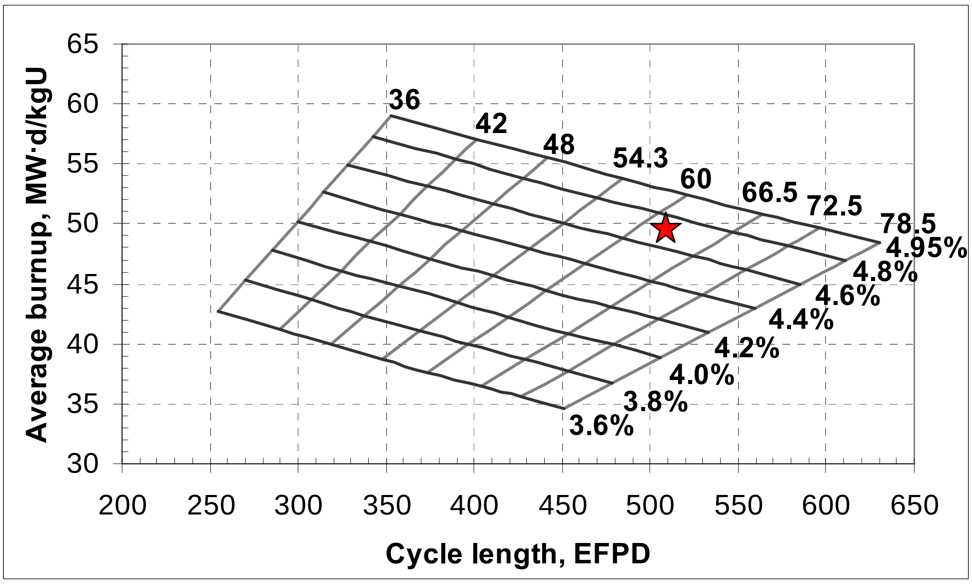


Figure 3. Average burnup as a function of number of loaded FAs, FA enrichment and cycle length (advanced design of fuel rods – 3680/7.8/0)

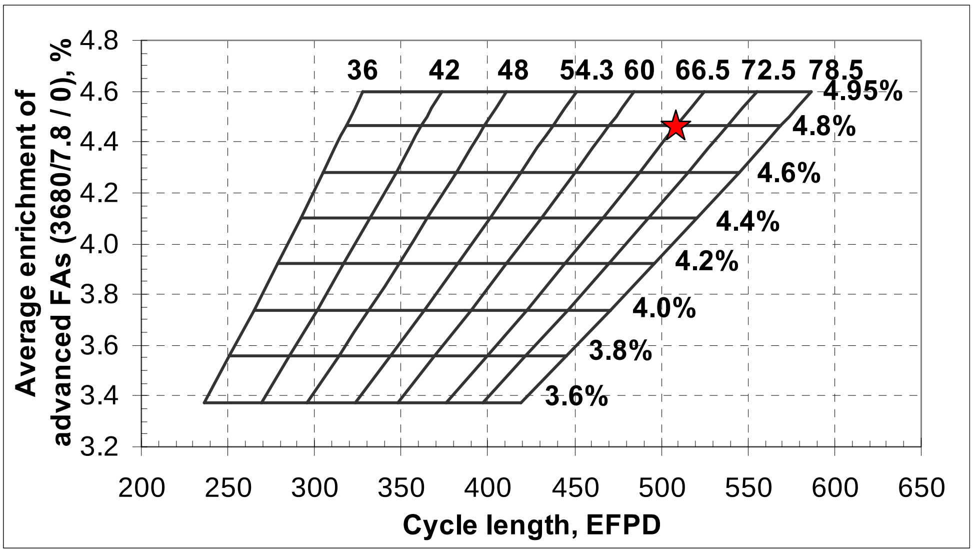


Figure 4. Average enrichment of advanced FAs (3680/7.8/0) providing the same cycle length as modern FAs (3680/7.6/1.2) as a function of number of loaded FAs and average enrichment of modern FAs

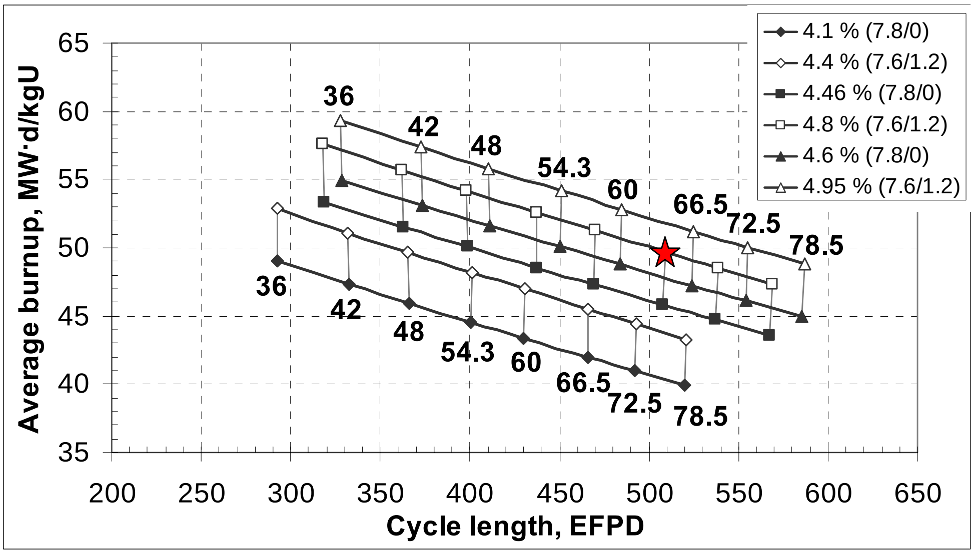


Figure 5. Average burnup for different designs of FA as a function of number of loaded FAs, FAs enrichment and cycle length

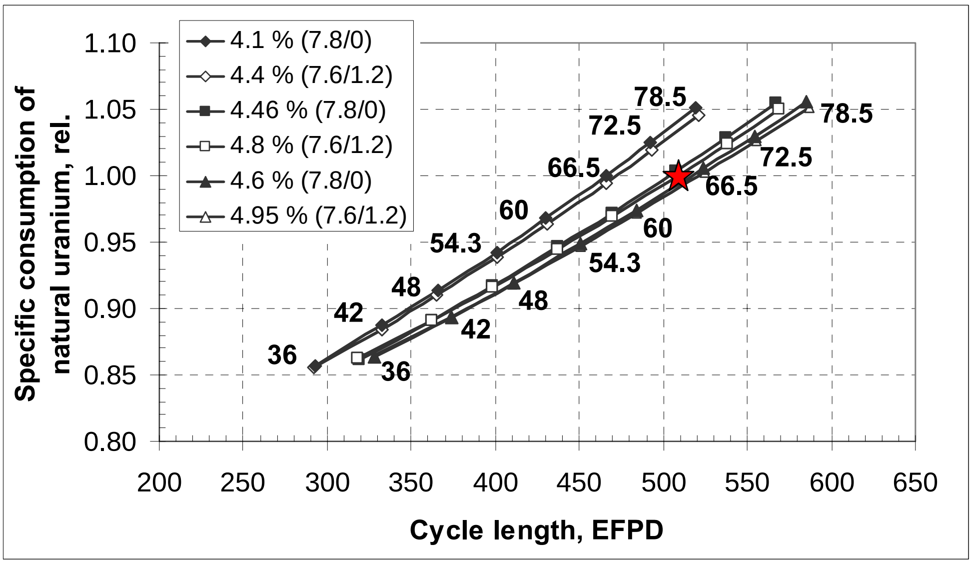


Figure 6. Specific consumption of natural uranium for different designs of FA as a function of number of loaded FAs, FAs enrichment and cycle length

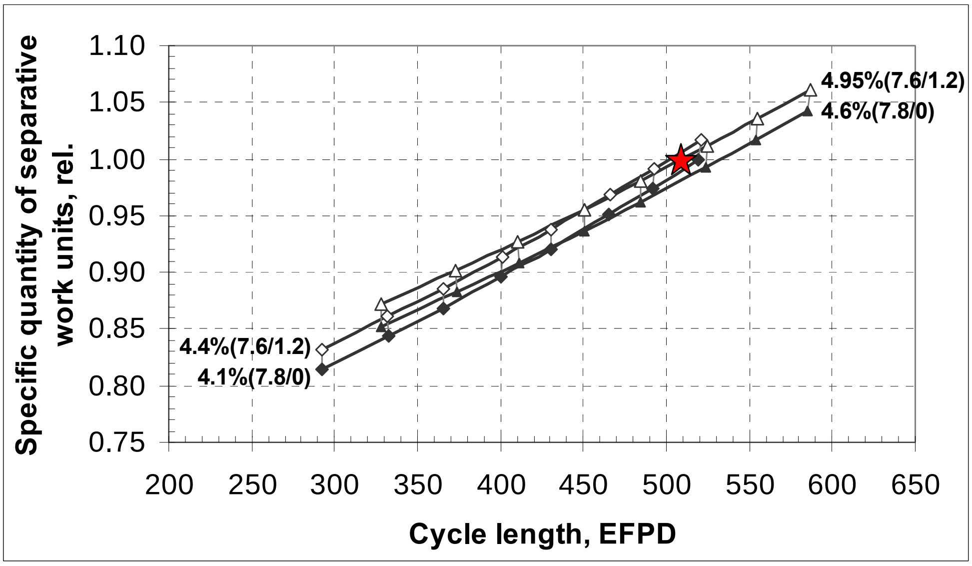


Figure 7. Specific quantity of separative work units for different designs of FA as a function of number of loaded FAs, FA enrichment and cycle length

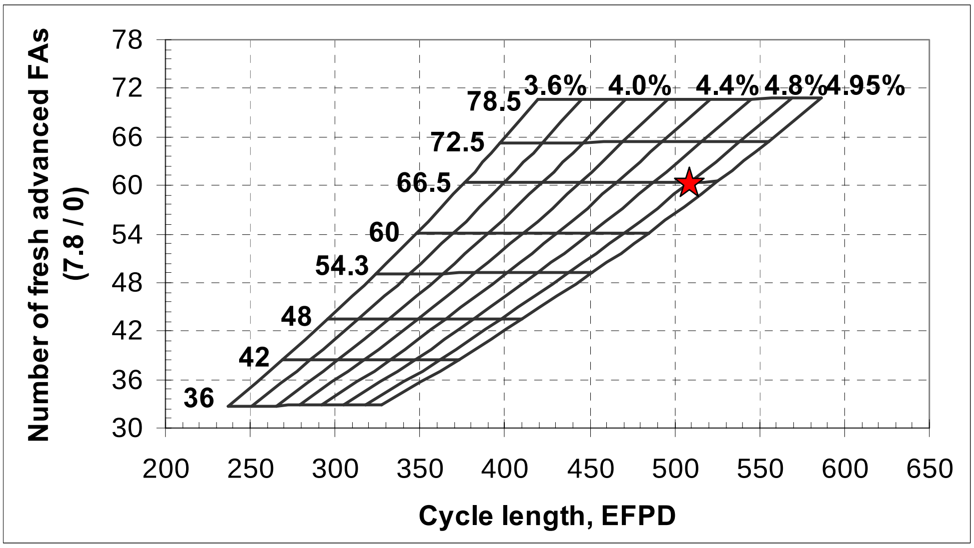


Figure 8. Number of fresh advanced FAs (3680/7.8/0) providing the same cycle length as modern FAs (3680/7.6/1.2) as a function of number of loaded modern FAs and average enrichment of FAs

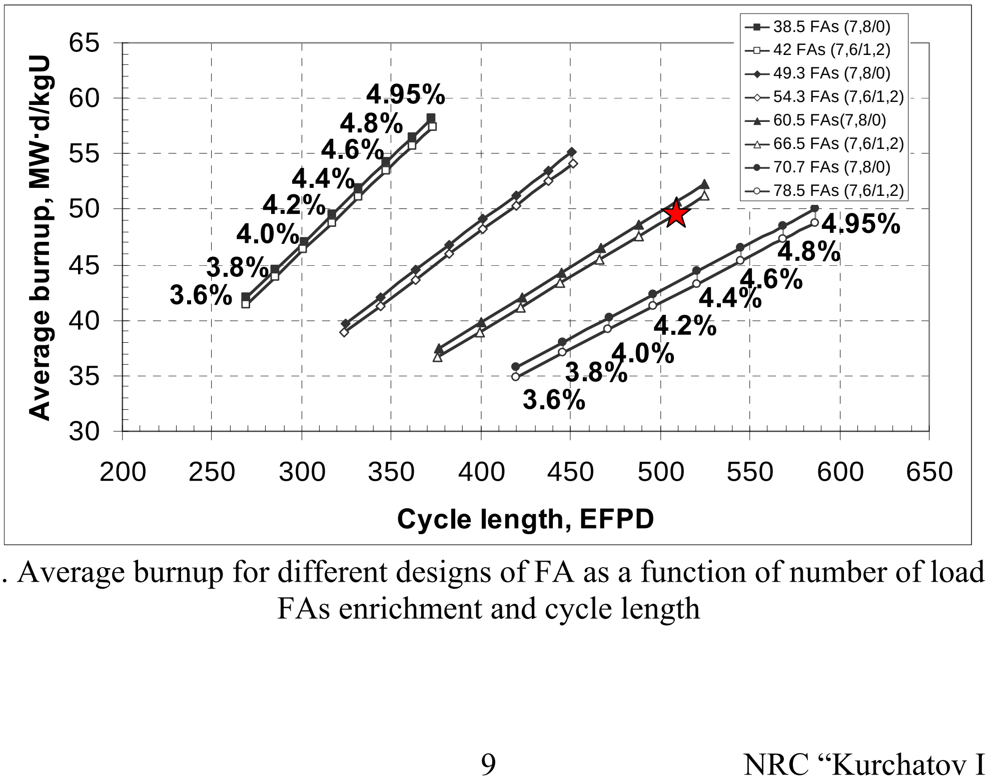


Figure 9. Average burnup for different designs of FA as a function of number of loaded FAs, FAs enrichment and cycle length

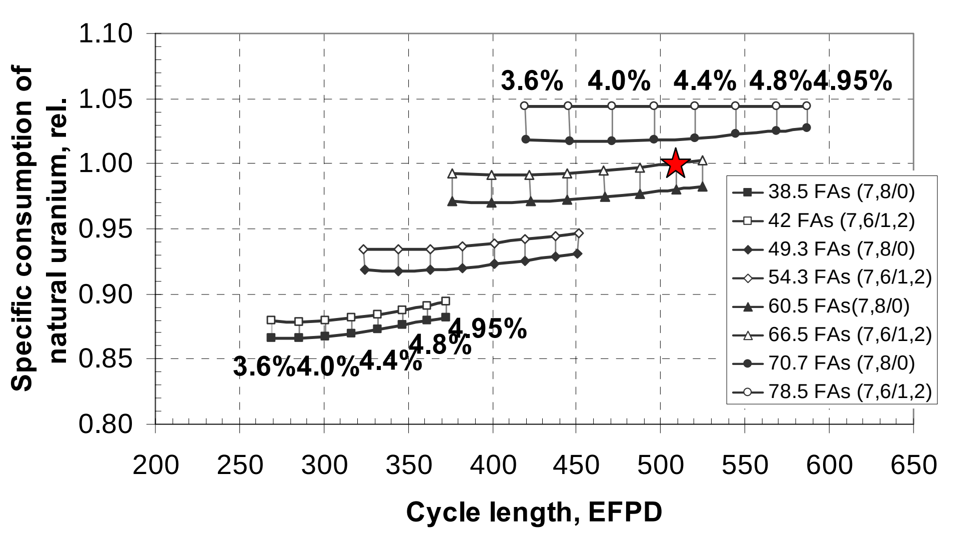


Figure 10. Specific consumption of natural uranium for different designs of FA as a function of number of loaded FAs, FAs enrichment and cycle length

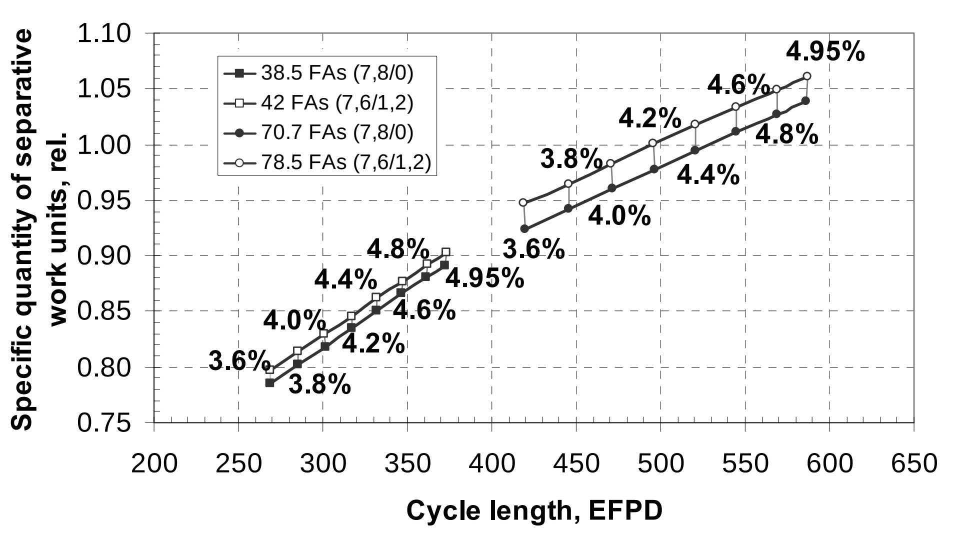


Figure 11. Specific quantity of separative work units for different designs of FA as a function of number of loaded FAs, FA enrichment and cycle length

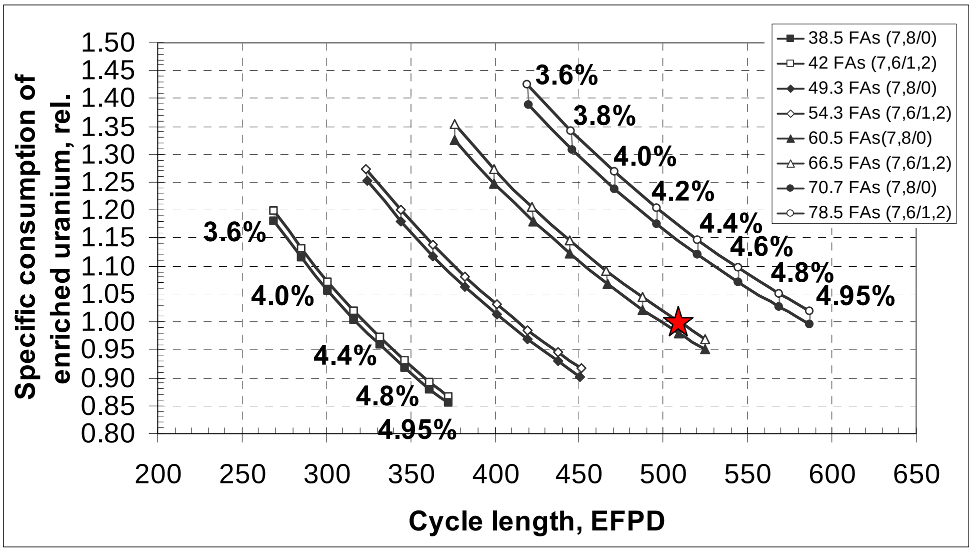
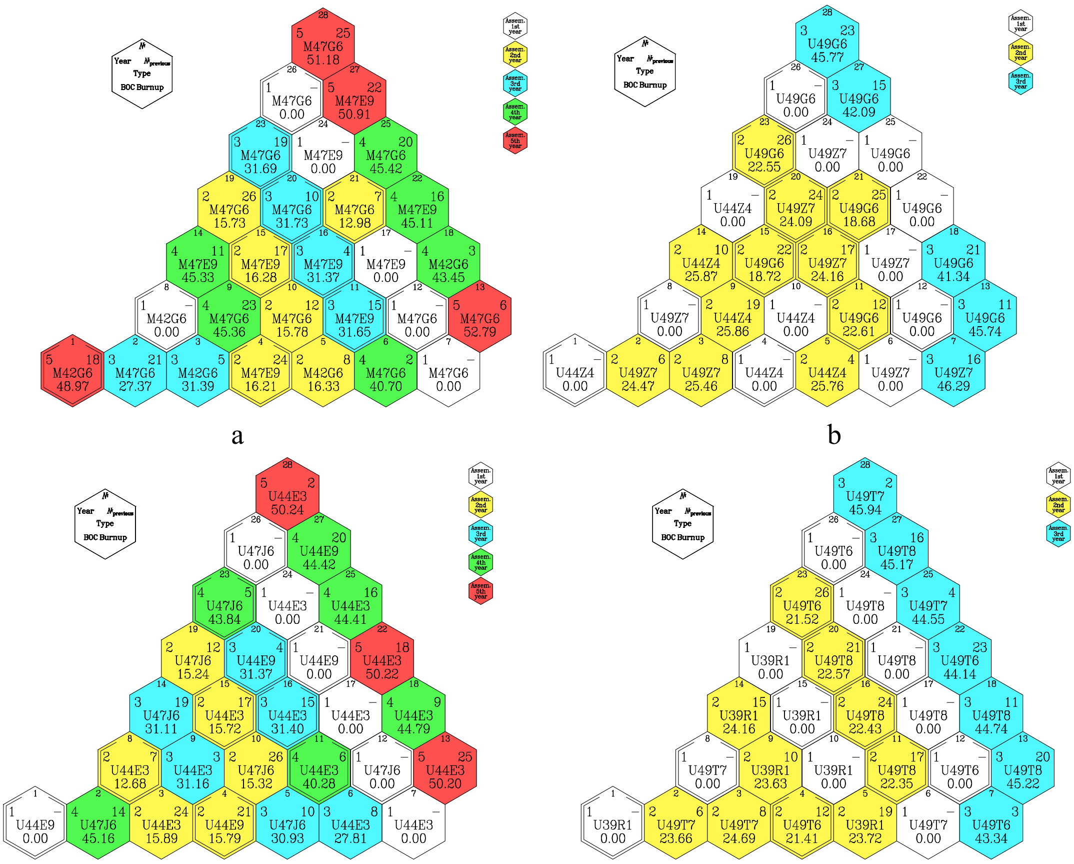


Figure 12. Specific consumption of enriched uranium for different designs of FA as a function of number of loaded FAs, FAs enrichment and cycle length



a b c d

Figure 13. Loading patterns of equilibrium fuel cycles. (a - modern 12-months fuel cycle based on TVSA-ALFA (3530/7.8/0), b - modern 18-months fuel cycle based on TVS-2M (3680/7.6/1.2), c - 12-months fuel cycle based on advanced FA (3680/7.8/0), d - 18-months fuel cycle based on advanced FA (3680/7.8/0))

Table 1. Characteristics of VVER-1000 fuel cycles

Characteristics	Modern		Avanced	
	12-months (TVS-ALFA)	18-months (TVS-2M)	12-months	18-months
Number of fresh loaded FAs	36	66(67)	36(37)	60
Average fuel enrichment, %	4.6	4.7	4.5	4.6
Cycle length, EFPD	320	512	331	505
Average fuel burnup, MW·days/kgU	55	50	55	50
The highest fuel rod power	1.55	1.50	1.52	1.50
Critical concentration of boric acid, g/kg$_{H_2O}$	7.6	8.1	7.2	8.1
Moderator temperature coefficient, pcm/°C	<0	<0	<0	<0
Temperature of against criticality , °C	190	170	190	160

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