Advanced Fuel Cycles of WWER-1000 Reactor

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1. Introduction

On creating the WWER-1000 reactor and basing on the Russian requirements of an annual reloading, a design fuel cycle was developed with a cycle length of about 7000 EFPH [1]. Fuel cycles developed in the recent years, which employed advanced FAs with zirconium structure elements and uranium-gadolinium burnable absorbers were also based on the reloading in 12 months. In particular, in 2002 the project development was completed for a cycle length up to 300 EFPD. This fuel cycle employs advanced FAs that are operated for 4 campaigns and achieve maximum burnup of about 55 MWd/kgHM with regard to possible operation at the reduced parameters at the campaign end [2].

At the present time, changes in the operation of power units with WWER-1000 reactors are planned. The Ministry of Atomic Energy of Russian Federation made a decision to increase generation of electrical energy at NPPs. In accordance with this decision, a set of works has been started at Russian NPPs that must provide the increase in the load factor of power units with WWER-1000 reactors. The extension of the campaign duration is one of the major lines in the solution of the stated problem. Based on the operation conditions of power units, the employment of 12-months fuel cycles with the campaign duration of 300 and more effective days is planned at Kalinin NPP. The introduction of fuel cycles with the campaign duration of about 350 EFPD is in progress now at Balakovo NPP. In future, it is intended to convert reactors of Balakovo NPP to an 18-months fuel cycle with the campaign duration of about 450-470 EFPD.

On the other hand, in Bulgaria and Ukraine the campaign duration for WWER-1000 reactors is about 250-270 EFPD in accordance with local operation conditions of power units.

Thus, to satisfy demands of consumers, the WWER-1000 reactor with advanced FAs must provide for the opportunity to implement fuel cycles with the campaign different duration. This will allow to adapt in the optimal way the electricity production in the power unit for peculiar features of a specific power system and to respond adequately to possible changes in the proportion of components of electric power production cost. It is evident that specific information about mentioned operation conditions of a power unit is lacking or unavailable at the stage of the project development for fuel cycles. Therefore, a consumer must have available a set of cycles from which he will be able to choose the most economically profitable one.

The present paper considers characteristics of fuel cycles for the WWER-1000 reactor satisfying the following conditions:

- Duration of the campaign at the nominal power is extended from 250 EFPD up to 470 and more ones;
- Fuel enrichment does not exceed 5 wt.%;
- FA maximum burnup does not exceed 55 MWd/kgHM.

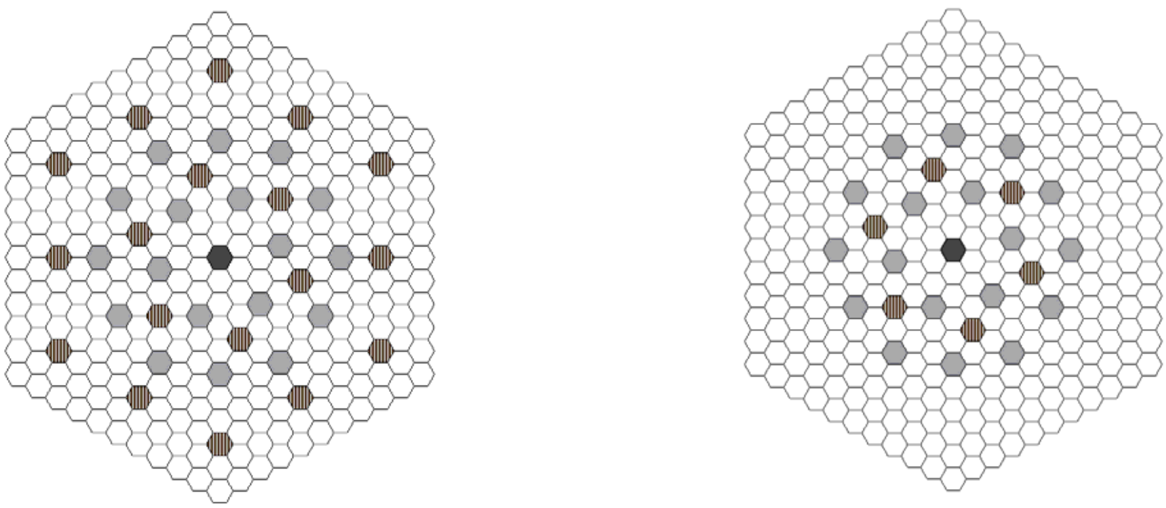


Figure 1. Arrangement of rods within fuel assemblies
⬡ - Fuel rod; ⬢ - Guide tube; ⬢ - UGBA rod; ⬢ - Instrumental tube

Along with uranium fuel, the use of mixed Uranium-Plutonium fuel is considered.

Calculations were conducted by codes TVS-M, BIPR-7A and PERMAK-A [3,4] developed in the RRC Kurchatov Institute, verified for the calculations of uranium fuel and certified by GAN RF.

2. Impact of Fuel Enrichment and of the Quantity of Loaded FAs on Performances of Equilibrium Fuel Cycles

Let us consider dependencies of the campaign duration and unloaded fuel burnup (for equilibrium fuel cycles of the WWER-1000 reactor) on the quantity of reloaded FAs (from 36 up to 81 pcs.) and average enrichment of fresh fuel (from 3.6 up to 5 wt.%). Fuel cycles are arranged from advanced FAs. Uranium-gadolinium burnable absorbers (up to 24 pcs. in one FA) were used to provide for the negative reactivity coefficient over the moderator temperature in hot state and the flattening of power distribution. Figure 1 illustrates patterns for the location of uranium-gadolinium rods in FA. The fresh and burnt-up FAs were placed in a core according to the following principles:

- 18 FAs of the last year of operation were positioned in the core periphery row, the rest of peripheral positions were filled with fresh FAs;
- The least burnt-up FA taken from among unloaded FAs was located in the core central cell;
- The rest of FAs were “scattered” in the core central part so that the maximum value of a fuel rod relative power did not exceed 1.54.

Figure 2 illustrates the campaign duration (thick lines) and fuel burnup (thin lines) versus the quantity of loaded fresh FAs and their average enrichment.

It follows from the stated information that the campaign maximum duration is about 550 EFPD on using the advanced FA during 2 campaigns and with enrichment of about 5%. FA average burnup achieves about 47 MWd/kgHM and the maximum one – about 53 MWd/kgHM (without regard for the central FA burnup). The further extension of the campaign duration is possible at the expense of operation at the reduced parameters at the campaign end. Besides, the opportunity is considered for the future to increase fuel mass in a FA due to the extension of a fuel column length, reduction of the axial hole in a fuel pellet and increase of a fuel pellet diameter on retaining the external diameter of a fuel element cladding.

The campaign duration of about 260 EFPD may be provided on the reloading of 36 FAs with average enrichment of about 4.4%. In this case, average burnup of unloaded FAs achieves about 53 MWd/kgHM (without regard for the central FA burnup).

The information presented in Figure 2 may be used for the choice of a fuel cycle with regard to justified fuel burnup, peculiar features of an NPP operation and specific values of price parameters. In particular, for power units of Kalinin NPP, a 12-months cycle with the campaign duration of about 300 EFPD, fuel enrichment 4.4% (5% for the prospects) and the reloading of 42 (36 for the prospects) FAs was chosen. An 18-months cycle with reloading of 72 FAs (66 FAs for the prospects) and with the maximum fuel enrichment up to 5% is considered as an advanced cycle for Balakovo NPP.

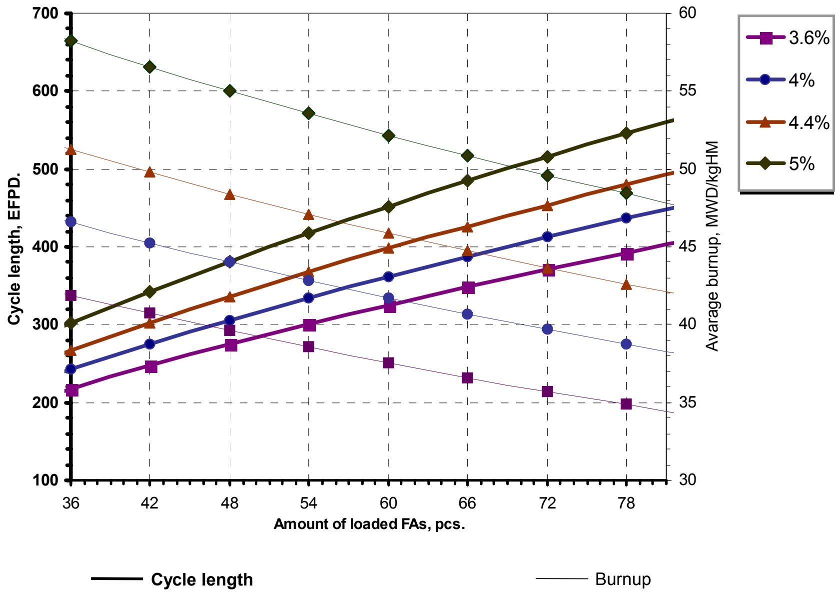


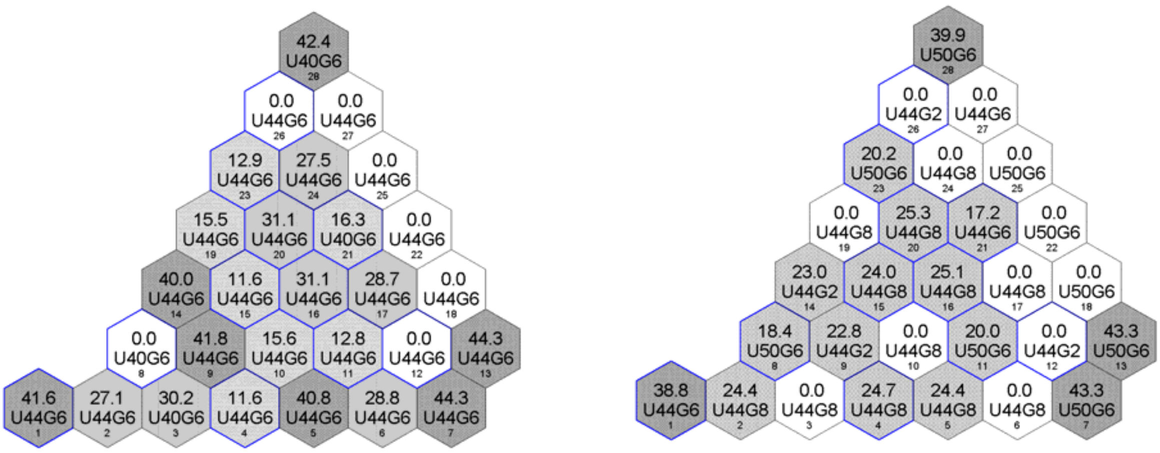
Figure 2. Cycle length and fuel burnup versus fuel enrichment and amount of loaded FAs

3. 12- and 18-months Fuel Cycles

This section presents specific patterns of 12- and 18-months cycles for the WWER-1000 reactor.

The 12-months equilibrium fuel loading is formed of 36 FAs with fuel enrichment 4.4% and of 6 FAs with fuel enrichment 4%. Each of all FAs contains 6 uranium-gadolinium burnable absorbers (UGBA). The core pattern provides for reduced neutron leakage, that is, burnt-up FAs are located in 12 core cells nearest to the reactor vessel as well as in the cell 7 (the symmetry is 60 degree) having one edge common with the reflector. Thus, 7 of 15 edges of FAs (the symmetry is 60 degree) by which the core is contiguous with the reflector belong to burnt-up FAs. This significantly (by 25-30%) reduces the maximum value of neutron flux coming to the reactor vessel as compared to the arrangements in which only fresh FAs are located at the periphery. Figure 3 demonstrates the loading pattern containing burnup of FAs at the beginning of cycle and types of loaded FAs. The following rules for forming identifiers of FA types are employed in the presented paper: the first symbol U designates uranium fuel, P designates mixed uranium-plutonium fuel, the second and third symbols designate a FA average enrichment multiplied by 10, the fourth one is the UGBA indicator, the fifth symbol is the number of UGBA (6, 9, 12, 15, 18, 21, 24, 27 rods are designated by the last numerals, respectively, as 6, 9, 2, 5, 8, 1, 4, 7). Table 1 contains basic neutronics characteristics of fuel loading (version V12).

The 18-months equilibrium fuel loading is formed of 18 FAs with fuel enrichment 4.95% and of 54 FAs with fuel enrichment 4.4%. Each FA contains 6 or 18 UGBA. Figure 3 shows the loading pattern. Table 1 contains basic neutronics characteristics of fuel loading (version V18). On the basis of presented results one can make a conclusion that when passing from the 12-months



12 months cycle **18 months cycle**

Figure 3. Loading patterns of equilibrium cycles with reduced leakage

Table 1. Main neutron physics characteristics of equilibrium cycles

Name of cycle		V12	V18	V12in	V18in
Amount of loaded FAs, [pcs]		42	72	42	72
Average enrichment of feeding fuel in ^{235}U, [wt.%]		4.32	4.49	4.32	4.48
Amount of UGBA rods in loaded FAs, pcs.		252	990	252	1386
Cycle length, EFPD		298	466	306	468
Burnup of unloaded fuel, [MWd/kgHM]	Average	49.5	45.1	50.7	45.3
	Maximum over FAs*	53.0	52.4	52.2	54.4
Maximal relative power of fuel rods in the core (Kr_{max})		1.49	1.43	1.52	1.50
Maximal value of fuel rods linear heat rate, [W/cm]		295	296	306	310
Average relative power of assemblies bordering upon reflector		0.74	0.73	0.51	0.53
Cb_{crit} at BOC, HFP, [ppm]		1170	1500	1280	1350
MTC at BOC, HZP, no Xe, CRs out, [pcm/˚C]		-4	-1	-3	-2
Cb at BOC, CZP, no Xe, ρ=-2%,CRs out, [ppm]		1990	2340	2080	2220
RCT at EOC, Xe and Sm, no boron, [˚C]		185	190	170	155

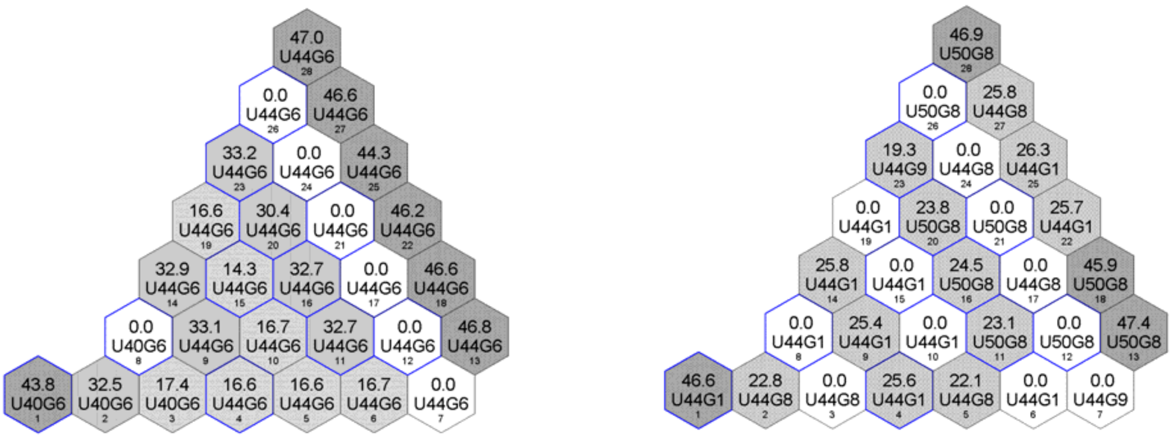
* Central FA not including

cycle to the 18-months one, the critical boron concentration in coolant is significantly increased. The reactivity coefficient over the moderator temperature changes insignificantly due to the increase in the quantity of UGBAs. Burnup of unloaded fuel, power distribution parameters and the repeat criticality temperature vary insignificantly.

The planned increase in the load factor and extension of the design term of operation for Russian NPP make the problem of the further reduction of neutron flux to the reactor vessel quite urgent. Equilibrium fuel cycles with low neutron leakage in which burnt-up FAs are placed into all core periphery cells except for the cell 7 (that is, 14 outer edges of 15 ones belong to burnt-up FAs) are presented below. Figure 4 demonstrates the loading patterns for the 12- and 18-months cycles. Table 1 presents the core basic neutronics characteristics (version V12in and V18in). The increase in the quantity of burnt-up FAs at the core periphery results in the following changes of neutronics characteristics for 12- and 18-months equilibrium loadings:

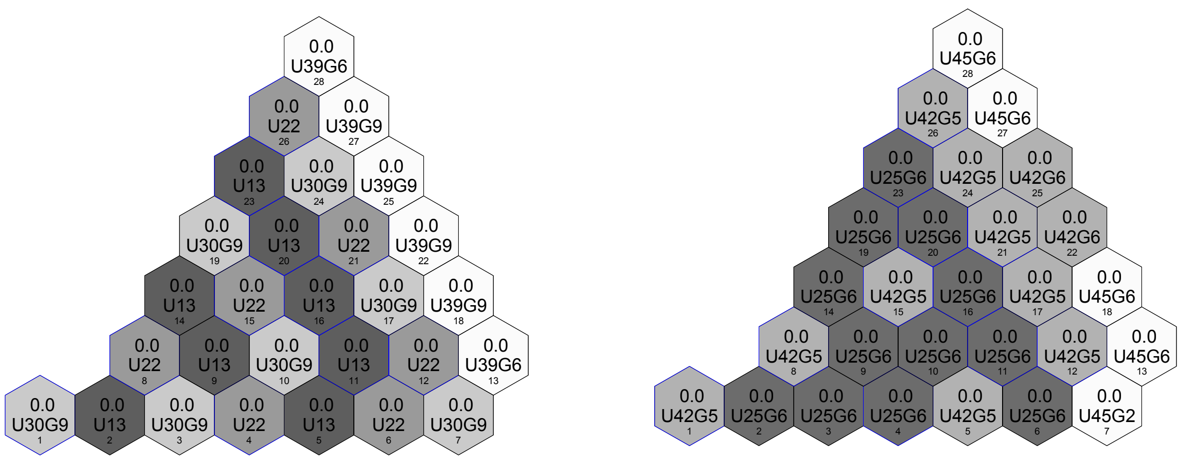
- Relative power of periphery FAs averaged per a campaign is reduced by 30%;
- The campaign duration is increased by 2.5% and 0.5%;
- The repeat criticality temperature is reduced by 15°C and 35˚C;
- Maximal relative power of fuel rod is increased by 2% and 5%;
- Maximal value of fuel rods linear heat rate is increased by 4% and 5%.

Thus, the reduction of the flux to the rector vessel, decrease of the repeat criticality temperature and some extension of the campaign duration are accompanied by the expansion of power distribution non-uniformity. Therefore, the choice of the specific type for the core pattern must be determined by the conditions of a power unit operation.



12 months cycle **18 months cycle**

Figure 4. Loading patterns of equilibrium cycles with low leakage



12 months cycle **18 months cycle**

Figure 5. Loading patterns of first cycles

4. First Fuel Loading

The requirement of the fuel cycle flexibility leads as a whole to the necessity to develop the first fuel loadings with different campaign durations. The peculiar feature of the first fuel loading is associated with the employment of FAs of reduced enrichment that are unloaded after the operation during one, two, and so on campaigns. In this case, the quantity of FAs of different enrichments is determined by the type of an equilibrium cycle in which a power unit operation is planned. Two first fuel loadings for the use in 12- and 18-months cycles are presented below as an illustration. Figure 5 shows loading patterns. Table 2 contains the basic neutronics characteristics. A considerable difference between the campaign durations (296 and 531 EFPD) results in a big difference in critical concentration of boron. In this case, the negativity of the reactivity coefficient over the moderator temperature in hot state is provided due to the increase of the quantity of UGBA from 621 up to 1455 pcs. Parameters of power distribution and repeat criticality temperature weakly depend on the campaign duration.

Table 2. Main neutron physics characteristics of first cycles

Name of cycle		V12	V18
Average enrichment of feeding fuel in ^{235}U, [wt.%]		2.50	3.46
Amount of UGBA rods in loaded FAs, [pcs]		621	1455
Cycle length, EFPD		296	531
Burnup of unloaded fuel, [MWd/kgHM]	Average	10.9	21.6
	Maximum over FAs	11.2	22.2
Maximal relative power of fuel rods in the core (Kr_{max})		1.41	1.45
Maximal value of fuel rods linear heat rate, [W/cm]		327	335
Cb crit at BOC, HFP, [ppm]		770	1470
MTC at BOC, HZP, no Xe, CRs out, [pcm/˚C]		-4	-1
Cb at BOC, CZP, no Xe, ρ=-2%,CRs out, [ppm]		1440	2220
RCT at EOC, Xe и Sm, no boron, [˚C]		180	175

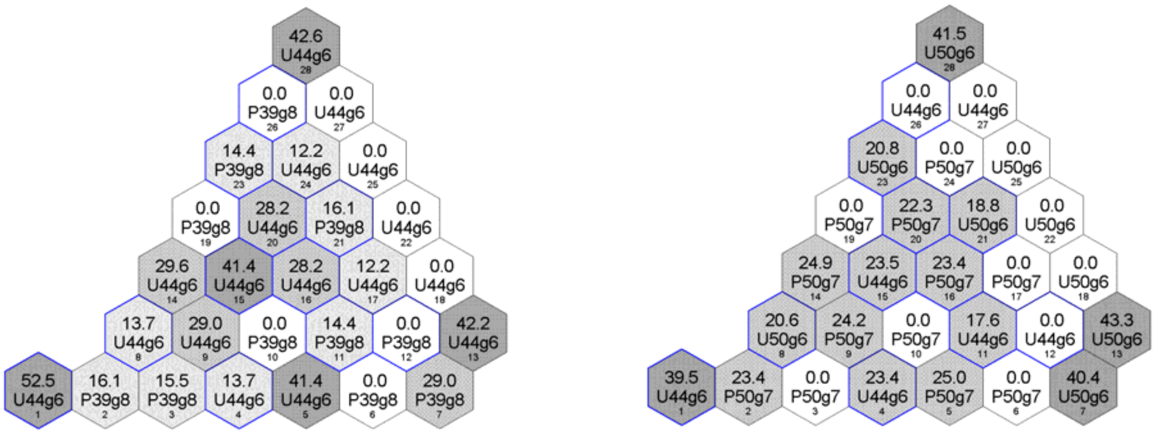
Table 3. Main neutron physics characteristics of equilibrium cycles with MOX FAs

Name of cycle		V12 MOX	V18 MOX
Amount of loaded uranium FAs, [pcs]		24	36
Average enrichment of fresh uranium FAs, [wt.%]		4.38	4.65
Amount of UGBA rods in loaded uranium FAs, [pcs]		144	216
Amount of loaded MOX FAs, [pcs]		30	36
Average content of plutonium in fresh MOX FAs, [%]		3.48	4.23
Amount of UGBA rods in loaded MOX FAs, [pcs]		540	972
MOX fuel rods part in core, [%]		38.2	40.3
Cycle length, EFPD		307	465
Annual plutonium consumption, [kg]		445	450
Burnup of unloaded uranium FAs, [MWd/kgHM]	Average	50.4	46.3
	Maximum over FAs	53.3	52.8
Burnup of unloaded MOX FAs, [MWd/kgHM]	Average	31.1	43.5
	Maximum over FAs	36.9	45.5
Maximal relative power of fuel rods in the core (Kr_{max})		1.41	1.47
Maximal value of fuel rods linear heat rate, [W/cm]		278	306
Cb crit at BOC, HFP, [ppm]		1350	1870
MTC at BOC, HZP, no Xe, CRs out, [pcm/˚C]		-6	-1
Cb at BOC, CZP, no Xe, ρ=-2%,CRs out, [ppm]		2300	2830
RCT at EOC, Xe и Sm, no boron, [˚C]		180*	177*

* Absorber elements with ^{10}B content increased up to 80% are used in fuel cycles with MOX FAs

5. 12- and 18-months Cycles with MOX Fuel

In accordance with current international agreements, Russian specialists in cooperation with specialists of France and USA consider the opportunity to utilize Russian weapon-grade plutonium surplus for the defence purposes in WWER-1000 reactors. Cycles with the campaign duration of about 7000 EFPH were put under consideration within the framework of these studies [5]. According to the strategy of the concern Rosenergoatom, the implementation of the program on the plutonium utilization in WWER-1000 reactors must not lead to the reduction in the annual electric energy generation. Therefore, the necessity arises to develop and study cycles with MOX fuel providing for the campaign duration comparable with those of advanced uranium cycles. In addition to a high load factor, cycles with MOX fuel must provide the Pu consumption of about 450 kg/year per one



12 months cycle **18 months cycle**

Figure 6. Loading patterns of equilibrium cycles with MOX FAs

WWER-1000 reactor. It is evident that developed cycles with MOX fuel must meet the requirements of the operation safety.

At the present time, the concept of a direct replacement of U fuel by MOX fuel is implemented, that is MOX FA design is basically similar to that of the advanced uranium FA. To reduce multiplying properties of MOX FAs, UGBA (from 18 up to 27 pcs.) are employed similar to those used in uranium cycles discussed earlier. Three types of fuel rods with different contents of plutonium are used in MOX FAs. Pu content is within the range 2.5-5 wt.%. Figure 7 demonstrates the pattern of the typical MOX FA. B enriched by the isotope boron-10 up to 80% is used in CR CPS that allows compensate the reduction of boron efficiency in MOX FAs.

Figure 6 shows the patterns of equilibrium loadings for 12- and 18-months fuel cycles with U and MOX FAs. Table 3 presents the basic neutronics characteristics of cycles. Summarizing the presented primary results, the following conclusions may be made about equilibrium cycles with MOX FAs:

- The cycle duration may be varied within the range 300-460 EFPD;
- Annular consumption of Pu is about 450 kg;
- The maximum burnup of MOX FAs dies not exceed 45 MWd/kgHM;
- The values of the basic neutronics characteristics (power distribution, reactivity coefficients, efficiency of CPS CRs, repeat criticality temperature) are close to those of the corresponding U cycles;
- B concentration in coolant is changed more significantly in comparison with that in U cycles.

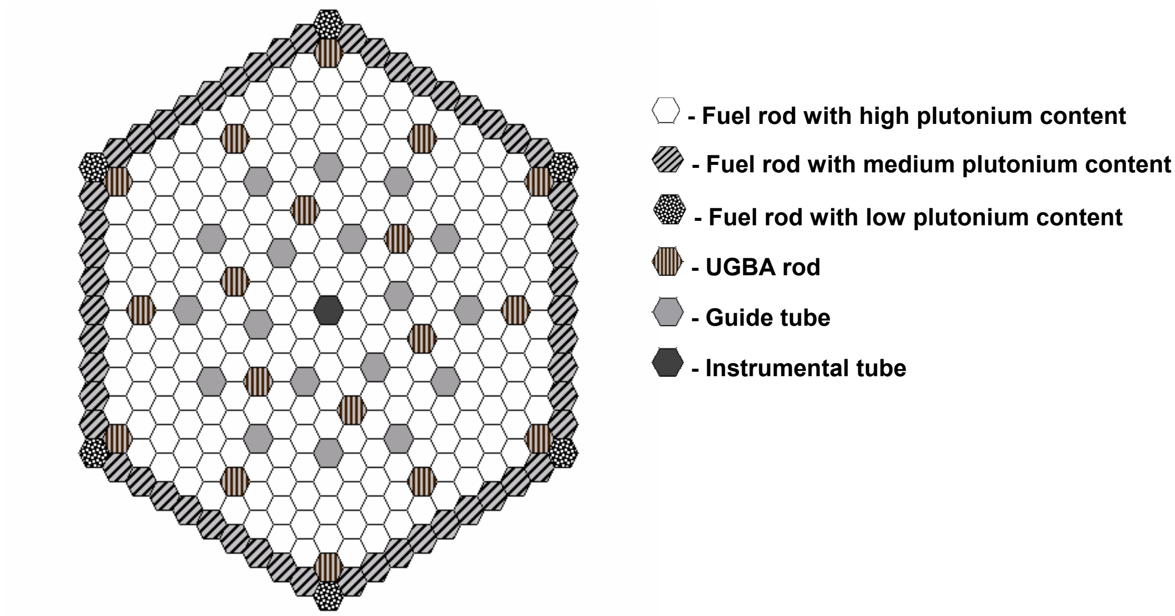


Figure 7. The pattern of the typical MOX FA

6. Conclusions

Different fuel cycles of the WWER-1000 reactor have been considered in the present paper. Basing on the presented results, the following conclusions may be made:

- Improved cycles of the WWER-1000 reactor developed on the basis of advanced FAs with UGBA provide the flexibility of the reactor operation from the viewpoint of the campaign duration starting from the first fuel loading;
- Depending on the operation requirements, the implementation of the different core loadings is possible including loadings with low leakage that provides the reduction of flux to the reactor vessel and the improvement of fuel use efficiency;
- Both in 12- and 18-months cycles, there is an opportunity for the utilization of weapon-grade plutonium with the rate of about 450 kg/year per one WWER-1000 reactor.

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Abbreviations and Designations

BOC	Beginning of Cycle
Cb	Boron Concentration, [ppm]
Cb_{crit}	Critical Boron Concentration, [ppm]
CPS	Reactor Control and Protection System
CR	Control Rod
CZP	Cold Zero Power State
EFPD	Effective Full Power Day
EFPH	Effective Full Power Hours
EOC	End of Cycle
FA	Fuel Assembly
GAN RF	Russian Regulatory Authority
MTS	Moderator Temperature Coefficient
HFP	Hot Full Power State
HM	Heavy Metal
HZP	Hot Zero Power State
Kr_{max}	Peak Value of Fuel Rods Relative Power
MOX	Mixed Oxide
NPP	Nuclear Power Plant
Ql_{max}	Peak Value of Fuel Rods Linear Heat Rate, [W/cm]
RCT	Repeat Criticality Temperature, [°C]
WWER	Russian Water-Water Reactor
UGBA	Uranium-Gadolinium Burnable Absorber
ρ	Reactivity of Core