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Peculiarities of Neutronics Characteristics of Integral Reactor WWER of Small Capacity

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ABSTRACT

In the present paper are analyzed the neutronic characteristics of the stationary fuel loading of the core of integral reactor WWER with a small power 600 MW (th.) and about 200 MW (el.) calculated with Russian code BIPR-7. The core and the FAs, and also the technological parameters are basically analogous to serial reactor WWER-1000; however, there are essential differences in comparison with the WWER-1000:

- in the core are placed 85 FAs (163 in WWER-1000) with an active length 250 cm (355 cm in WWER-1000);
- it is used the reactor campaign of 24 months length and the fuel campaign of 48 months (in WWER -1000 is used 12-18 months the reactor campaign and 36-48 months the fuel campaign);
- for reduction in the neutron leakage on the core periphery are placed burnt out FAs with the smallest multiplication properties, and also FAs have axial blankets with the smaller enrichment (in WWER-1000 they are used to a lesser degree or they are not used);
- there are 18 Guiding Tubes placed in FAs for reactor control and EP provision for the arrangement in them the Black and Grey CRs CPS (in WWER-1000 they are used only Black CRs CPS for EP provision);
- for compensating of the reactivity margin for fuel burn-up and for subcriticality provision of reactor in shut-down conditions are widely used the IFBA in FAs – 18-30 FRs with 8% of natural Gd (tvegs), and also Grey and Black CRs CPS and is not used the dissolved boron in the coolant (in WWER-1000 in essence it is used dissolved boron in the coolant and to a lesser degree the tvegs);
- under the conditions for boron-free control, for guaranteeing the minimum power peaking factors in the core it is fitted the optimum axial enrichment profiling of FAs and axial profiling of concentration of BA in tvegs, and also the axial profiling of concentration of absorber in CRs CPS (in WWER-1000 it is not used).

The neutronic characteristics were investigated in the process of burning out of fuel in the base operating mode at the nominal power for variant of boron-free control. They are compared with analogous characteristics for usual variant of boron control.

The mode of the daily manoeuvring in a wide range of power change 100-30-100% of nominal power is also analyzed for variant of boron-free control and with use of additional regulation by various primary coolant temperatures (modes "P_2=const", "t_{in}=const", "t_{av}=const").

The positive results were obtained, which make it possible to make a conclusion about the relatively simple feasibility of WWER technology in the neutronic aspect in the integral small-power reactor.

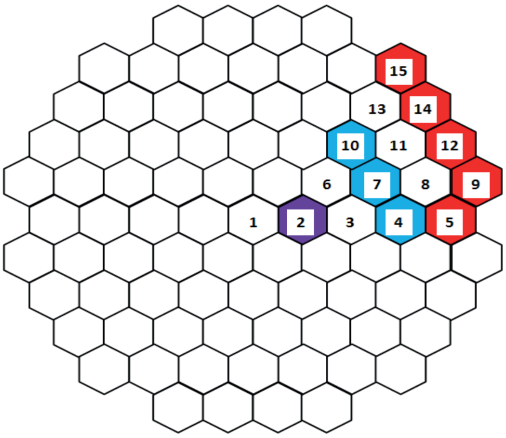
Keywords: *Neutronics, Boron-free control, WWER technology for small capacity, Base and maneuvering modes*

1 INTRODUCTION

Unit of small power with reactor WWER-I of integral arrangement supposes the usage of innovative solutions and acquisition of advantageous effects from their realization.

In the part of shortening volumes and periods of construction of NPP:

- decrease of sizes of the reactor compartment building;
- reduction of a quantity of units of basic RP's equipment;
- reduction of equipment and pipelines of safety system;
- decrease of specific quantity of metal of RP (tons/MW);
- shortening the periods of building and assembly of equipment.



Cartogram of the core of 85 cells of FAs. Cells of the symmetry sector 60° are numbered (if CR CPS presences in the cell, the number of the CR CPS group coincides with the number of cell). 1+9·6=55 CRs CPS are in all cells of FAs, except of 5·6=30 of peripheral cells (5, 9, 12, 14, 15 and symmetrical to them). From them 1+5·6=31 "black" CRs CPS in the cells 1, 3, 6, 8, 11, 13 and symmetrical cells. 3·6=18 "grey" CRs (with less absorption of neutrons than "black" CRs) in the cells 4, 7, 10 and symmetrical cells. 1·6=6 composite "black & grey" CRs CPS in the cell 2 and symmetrical cells.

Figure 1: Cartogram of the core of 85 cells of FAs

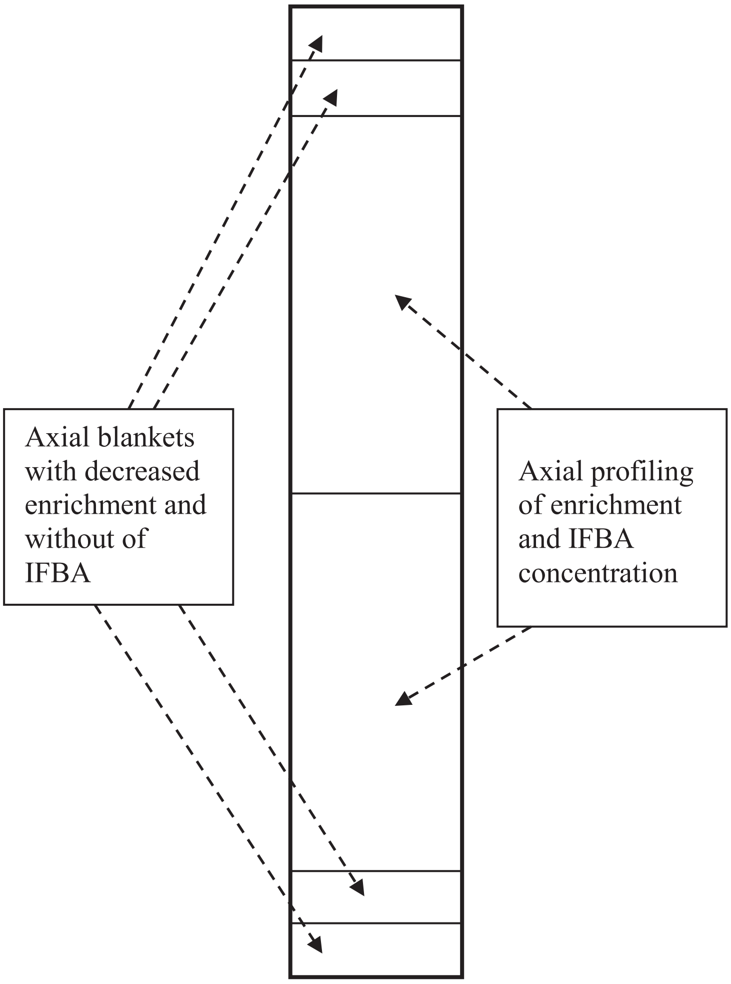


Figure 2: Typical scheme of FA's axial profiling

In the part of the readiness of production and construction:

- complete factory readiness of RP;
- the small duration of arrangement and commissioning;
- high operational reliability.

In the part of the electro-generation:

- the possibility of incorporation into the low capacity power system;
- the possibility of construction near the consumer.

In the part of the safety support:

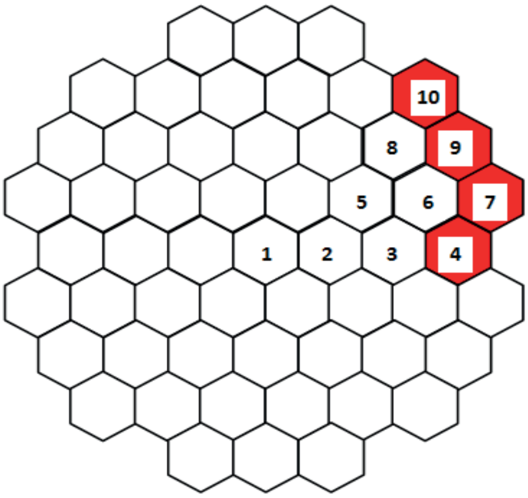
- the possibility of different placement of radioactive waste (ground-based, deepened, underground);
- the exception of LBLOCA emergency;
- the possibility of more widely use of passive safety systems.

FA's geometrical parameters in plan are the same as FAs of WWER-1000. In all cells of FAs, except the peripheral cells adjoining with the baffler, are located black and grey CRs CPS (see

Figure 1). Force framework of FA consists of 18 guiding tubes and welding to them spacing grids. Channel of in-reactor diagnostics is placed in the one of guiding tubes. There are 313 FRs with diameter of fuel pellets 7.6 mm in FA. Part of these FRs (up to 30-42 pcs.) are so called tvegs in each FA. Tvegs contain IFBA in the form of Gadolinium Oxide (Gd_2O_3) with concentration up to 8-12 weight %. Axial profiling of fuel enrichment and IFBA concentration are used in FAs (see Figure 2).

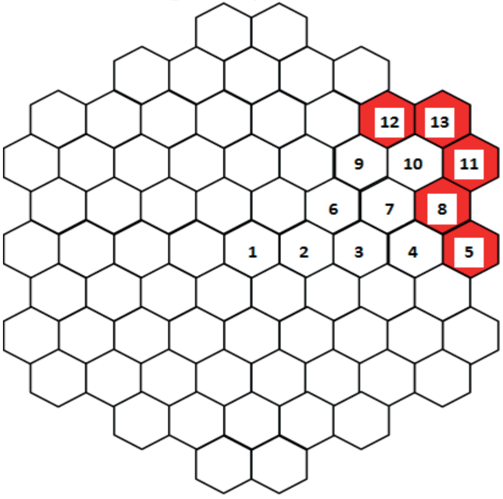
In principle there are different possible combinations of the following variations and diapasons of parameters of integral reactor of WWER type of low or middle power:

- Reactor power: (300-900) MW(th.);
- Number of FAs in the core: 55, 73 or 85 pcs. (see Figures 1, 3, 4);
- The height of the fuel column in the core: (140-270) cm;
- Average fuel enrichment: (3.5-5)% ^{235}U;
- Duration of reactor operation between the refueling: (500-1000) eff.days;
- Duration of fuel operation before unloading from the core: (1000-2000) eff.days;
- Variants of reactor control: usual for WWER and PWR "high" boron control or recommended by EUR option of low boron control (with increased quantity of IFBA) or supposed in this paper boron-free control (with use of CRs CPS and increased quantity of IFBA).



Cells of the symmetry sector 60° are numbered. 1+5·6=31 CRs CPS are in all cells of FAs, except of 4·6=24 of peripheral cells (4, 7, 9, 10 and symmetrical to them)

Figure 3: Cartogram of the core of 55 cells of FAs



Cells of the symmetry sector 60° are numbered. 1+7·6=43 CRs CPS are in all cells of FAs, except of 5·6=30 of peripheral cells (5, 8, 11, 12, 13 and symmetrical to them)

Figure 4: Cartogram of the core of 73 cells of FAs

This paper presents the description and characteristics of the specific combination of parameters:

- Reactor power: 600 MW(th.) and ~200 MW(el.);
- Number of FAs in the core: 85 pcs. (see Figure 1);
- The height of the fuel column in the core: 250 cm;
- Average fuel enrichment: 3.5% ^{235}U;
- Duration of reactor work between the refueling: 700 eff.days;
- Duration of fuel work before unloading: 1400 eff.days;
- Two variants of reactor control – usual boron control and boron free control are compared for this combination of parameters.

The main aim of this paper is the checking and demonstration of the principle ability of realization and achievement of advantages of boron-free control in the basic and maneuvering operational modes with the use of the different methods of additional temperature control.

2 RESULTS OF RESEARCHES

Basic operational mode. The neutron characteristics were analyzed and compared for two variants of reactor control – the compensation of the reactivity margin for fuel burn-up and also for heating-up and reactor power raise.

```
                    15
                   21.6
                  0.488
                13     14
                0.0   19.7
              1.066 0.664
             10     11     12
            18.8    0.0   21.7
           1.219 1.154 0.661
          6      7      8      9
         0.0   16.2    0.0   19.4
       1.263 1.257 1.192 0.550
    1      2      3      4      5
  30.1   19.8    0.0    0.0    0.0
 1.104 1.138 1.267 1.130 0.935
```

```
                    15
                   29.4
                  0.446
                13     14
               18.9   30.1
              1.165 0.565
             10     11     12
            37.3   19.7   31.8
           1.151 1.160 0.538
          6      7      8      9
        21.5   35.1   19.9   27.9
       1.354 1.183 1.154 0.466
    1      2      3      4      5
  44.3   36.1   21.7   19.4   16.2
 0.897 1.094 1.387 1.361 0.993
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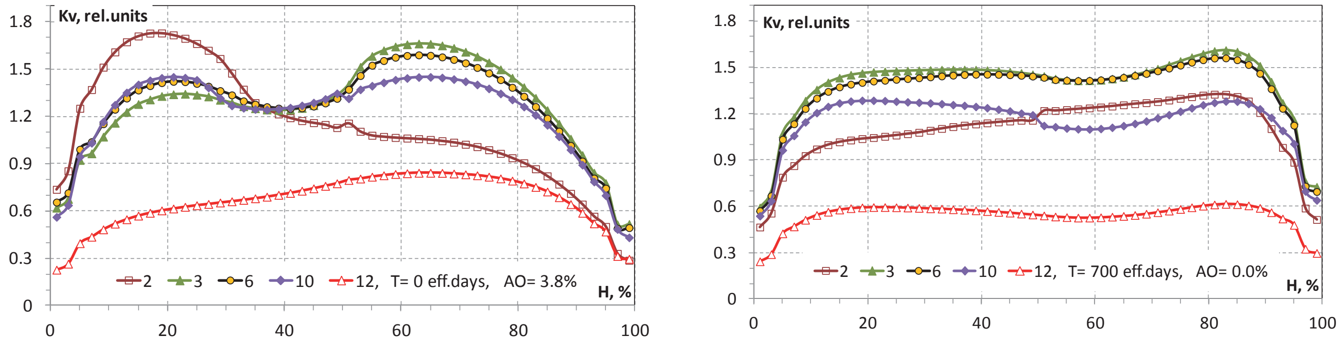

BOC 0 eff.days EOC 700 eff.days

Figure 5: Typical radial and axial power (burn-up) distributions in the core for variant of the **boron-free** control

The **first variant**, the so-called variant of boron-free control is characterized by the application of the increased IFBA quantity, integrated with the fuel in the separate FRs with Gd_2O_3 (so called tvegs), by introduction/withdrawing of CRs CPS in/from the core, and also by a change in the coolant temperature at the core entrance. This makes it possible to manage without the use of a boric acid in the coolant both in the base operating mode at the nominal power and in the mode of power maneuvering.

However the complete exclusion of boron system from WWER technology is technically hardly feasible and contradicts with safety requirements. The variant of completely boron-free control can be realized not in all states and modes. Reason is that safety provision and normative regulation document require the presence of the second shut-down system (besides mechanical EP system), based on other operating principle. Furthermore, the rule of WWER technology and operation during the PPR and the fuel reloading is the provision of subcriticality only with boron in the water without the account of inserted mechanical CRs CPS.

Therefore in the first variant the boron system is simplified and is used only for guaranteeing the subcriticality with the failures of mechanical EP system, and also in the cold (less than 200°C) depoisoning state of reactor, which is realized during the PPRs and fuel reloadings. During start-up of reactor, up to the moment of reaching MCL (at a temperature more than 200°C) boron is completely removed from the coolant. Similar variants of boron-free control are assumed also in the designs of integral type foreign reactors, for example in IMR (Mitsubishi Heavy Industries, Japan 350 MW(e) and 1000 MW(th)). European Utility Requirements EUR [1] recommends considering the option of so called *low boron* control capability for PWRs in the basic operational mode and notes its advantages above the usual "high" boron control. EUR [1] also recommends the regulation without adjusting soluble boron concentration for load following and maneuvering.

```
                15
               18.1
              0.435
            13    14
            0.0   0.0
           1.225 0.672
         10    11    12
        11.7   0.0  20.5
        1.285 1.251 0.518
      6     7     8     9
     20.2  20.1   0.0  21.2
     1.222 1.238 1.102 0.385
  1     2     3     4     5
 25.8  15.2   0.0   0.0   0.0
0.932 1.126 1.341 1.320 0.892
```

```
                15
               25.8
              0.544
            13    14
           20.1  11.7
           1.291 0.824
         10    11    12
        31.0  20.2  29.5
        1.147 1.286 0.624
      6     7     8     9
     37.8  38.6  18.1  28.1
     1.038 1.108 1.167 0.489
  1     2     3     4     5
 39.2  31.3  20.5  21.2  15.2
0.823 0.960 1.225 1.306 1.020
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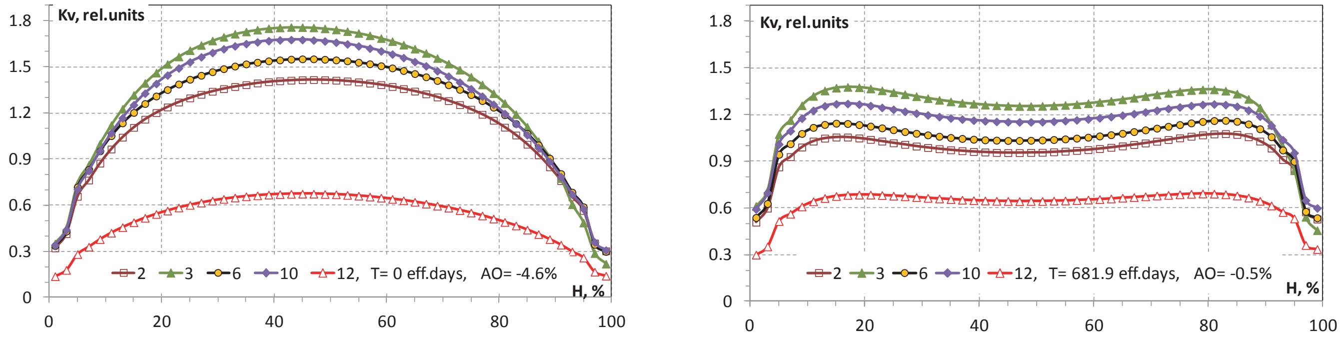

BOC 0 eff.days

EOC 681.9 eff.days

Figure 6: Typical radial and axial power (burn-up) distributions in the core for variant of the **boron** control

The **second variant** relates to the traditional for WWERs and PWRs boron control and is characterized by the compensation for temperature, power and burning-out effects mainly due to the boric acid in the coolant and partially due to IFBA (in less extent than in the first variant).

As it is demonstrated further, there are following **advantages** on safety and economy of the taken variant of boron-free control as compared to the variant with the boron control:

- the course of ATWS modes (with EP failure) is more safe since TCR is strongly negative during the entire reactor operating period and in any power level. On the contrary, in the boron control variant the TCR is near to zero at the beginning of operating period in the low power conditions;
- TCR remains negative at the criticality accident in the cold depoisoning condition, in contrast to the boron control variant. On this reason the complete removal (dilution) of boron from the coolant introduces substantially smaller positive reactivity. Thus, the course of DEC modes is also safer;
- the absence of boron in the coolant at the power operation removes the radioactive tritium generation and improves the radiological index ALARA;
- the smaller boron concentration in the reactor and in the HAs the less probability of dangerous boron crystallizing during the LOCA;
- strongly negative TCR provides the possibility of the safe early achievement of MCL power (at 200°C) and further reactor heating-up due to the nuclear reaction instead of heating-up due to pumps (economic effect);
- simplification of the boric system and reduction in liquid radioactive wastes (economic effect);
- the possibility of the more effective fuel utilization due to the more flexible regulation by CRs and the smaller radial neutron leakage from the core (economic effect).

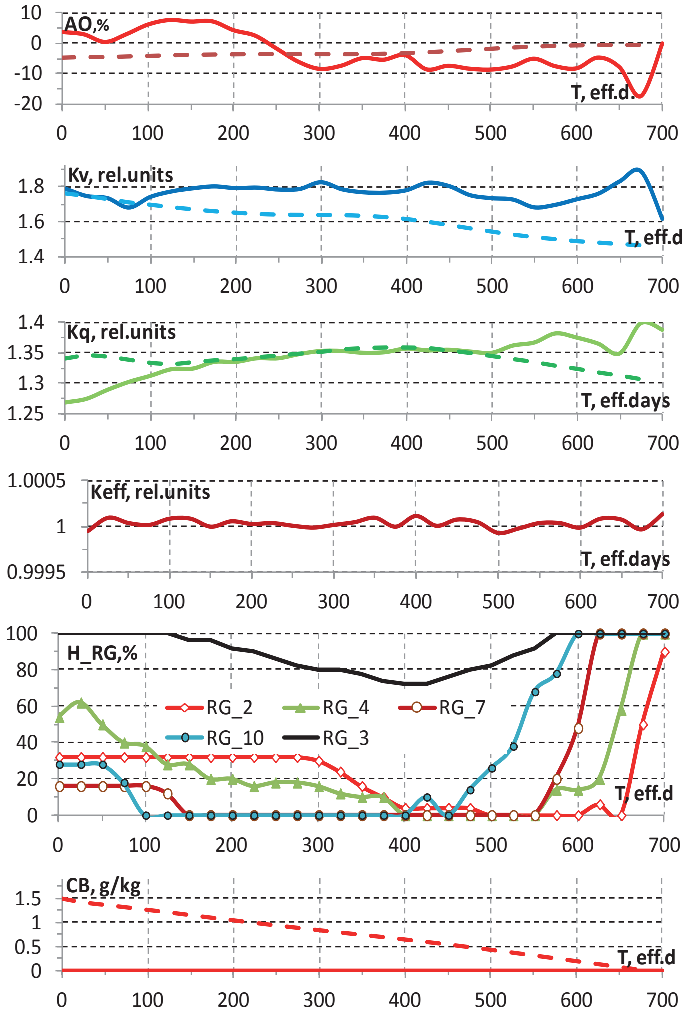

Figure 7: Change of characteristics vs. burn-out time in stationary fuel loading for variants of boron (dashed lines) and boron-free (solid lines) control

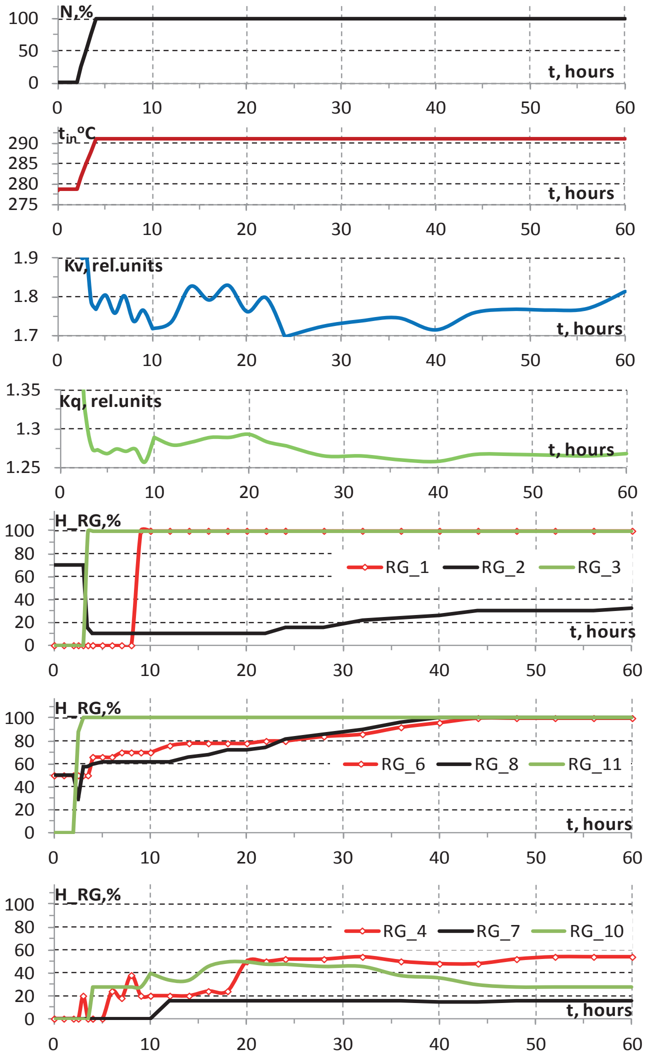

Figure 8: Change of characteristics vs. time at power increase by the CRs moving from MCL till nominal power for the BOC of stationary fuel loading for variant of boron-free control

A **deficiency** of the variant of boron-free control as compared to the variant with boron control is more complicated regulation by the control rods moving and caused by it certain (not very large) increase of power peaking factors Kq and Kv in the core. However just this deficiency makes it possible to obtain some benefit in fuel utilization. And this deficiency itself is not principal thing, since the power peaking factors are within the permissible limits. Taking into account remaining advantages (see above) the variant of boron-free control seems as more preferable. Therefore mainly this variant is analyzed in this paper. At the same time, both variants have right to be realized and in principle can be used as the options taking into account the customer's desire.

Typical power and burn-up distributions in the core at the beginning (BOC) and the end (EOC) of the stationary fuel loadings for variants of boron-free and boron control respectively are presented on Figures 5, 6. These are the relative power and burn-up distributions by FAs in the core symmetry sector 60^{o} and axial relative power distributions on separate typical FAs.

Change of main characteristics (AO, Kv, Kq, H_RG, CB) vs. burn-out time in stationary fuel loading for variants of boron (dashed lines) and boron-free (solid lines) control is shown on the Figure 7. One can see rather small increase of power peaking factors (about 3 % by maximal Kq and 7 % by maximal Kv) in the core for variant of boron-free control as compared to the variant with boron control. It was achieved by means of the grey CRs usage (RG_4, RG_7, RG_10) and proper algorithm of CRs moving for compensation of different burn-up rate of fuel and BA. During first 400 eff. days the BA's burn-up rate is more intensive than for the fuel. It requires insertion of several RGs. After 400 eff. days the BA is burnt out almost entirely and fuel burn-up requires the step-by-step withdrawn of all inserted CRs CPS until EOC.

Figure 8 shows the change of characteristics vs. time at power increase by CRs moving from MCL till nominal power for the BOC of stationary fuel loading for variant of boron-free control.

Power maneuvering. Figures 9-13 present the characteristics vs. time at daily power maneuvering in wide diapason (100-30-100% of nominal power) in the modes "P_2=const" and "t_{av} =const" for the BOC, near middle (450 eff.days) and EOC of stationary fuel loading for variant of boron-free control.

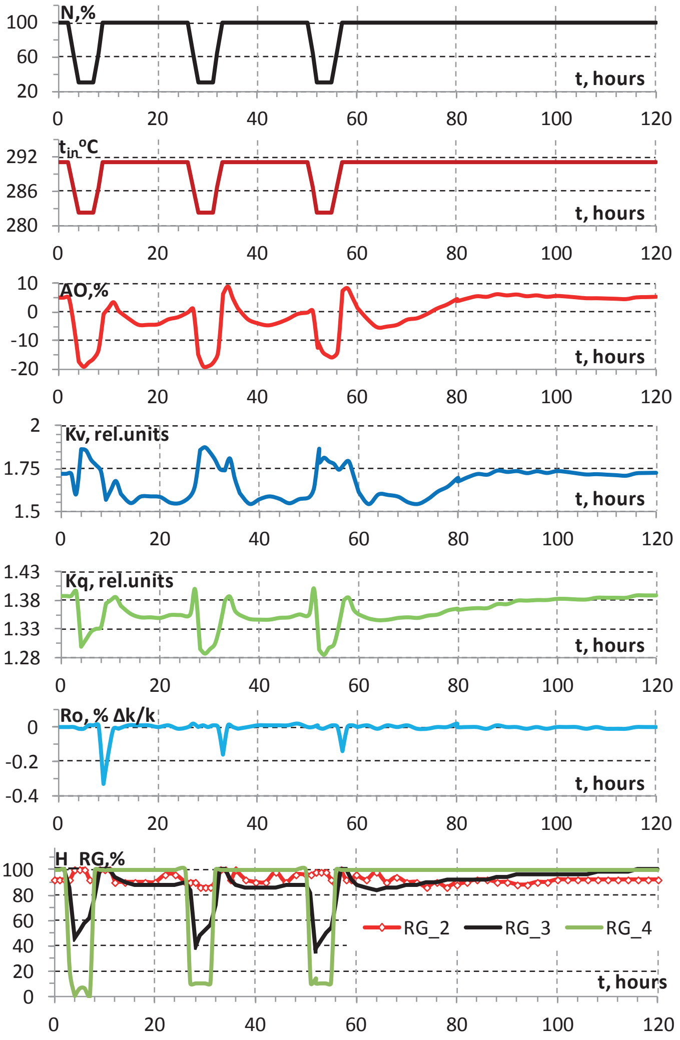

Figure 9: Power maneuvering at EOC.
Mode "P_2=const"

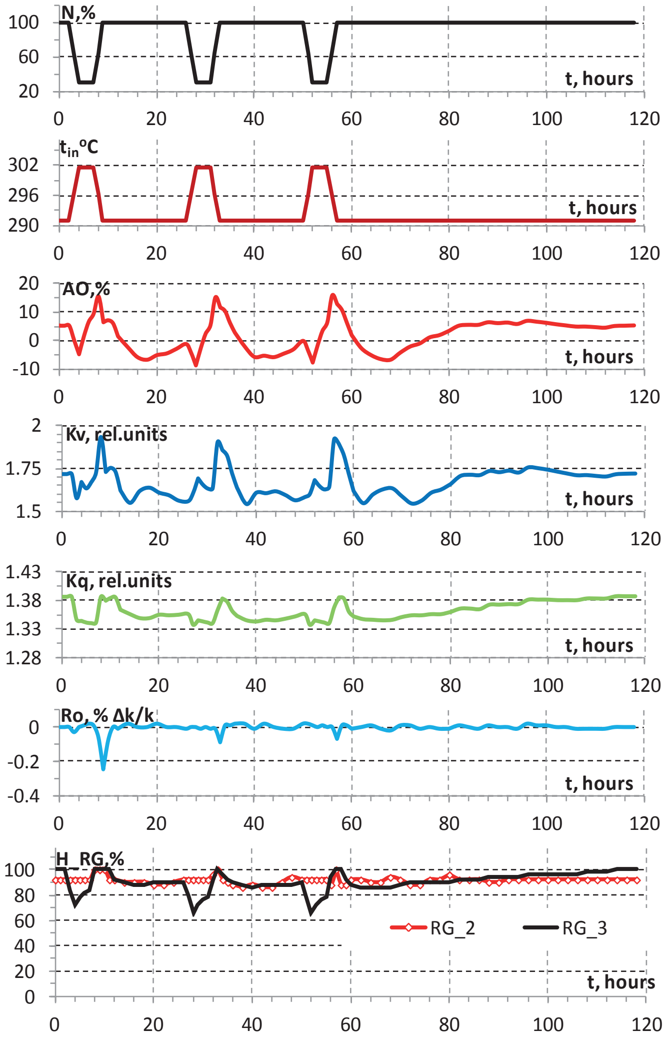

Figure 10: Power maneuvering at EOC.
Mode "t_{av} =const"

Daily work at power level 30% is continued during 3 hours and at power level 100% is continued during 17 hours. Decrease down to 30% and increase up to 100% power levels are continued during two hours. Three daily cycles of power maneuvering from 0 till 72 hours were modeled, last of them may be considered as stationary daily cycle. Further from 72 till 120 hours modeling was continued with the constant nominal power. The analysis of period from 72 till 120 hours is intended for the test whether the axial Xenon instability occur in the core. Such instability may occur as a result of previous deep change of power and CRs movement and is typical for big core of WWER-1000 type. However it was obtained that similar instability does not occur in the considered rather small and short core. I.e. there is big negative stability index, because of all significant characteristics, presented on Figures 9-13 are smoothly returned to their initial (at zero hours) values in 16-18 hours (at the moment 88-90 hours).

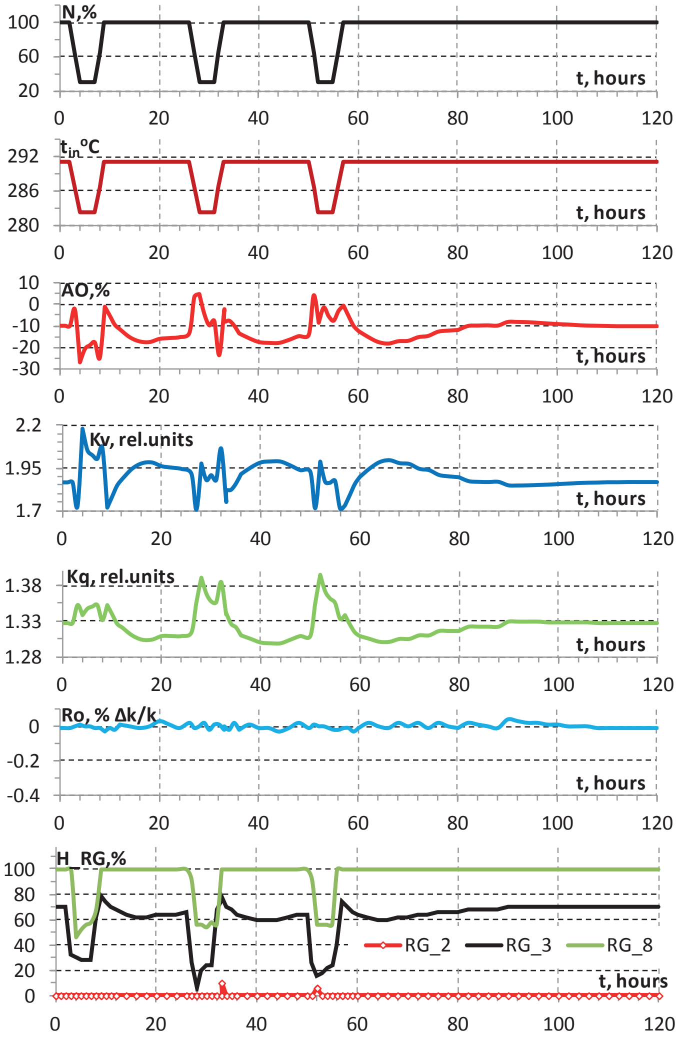

Figure 11: Power maneuvering at burn-up time 450 eff.d. Mode "P_2=const"

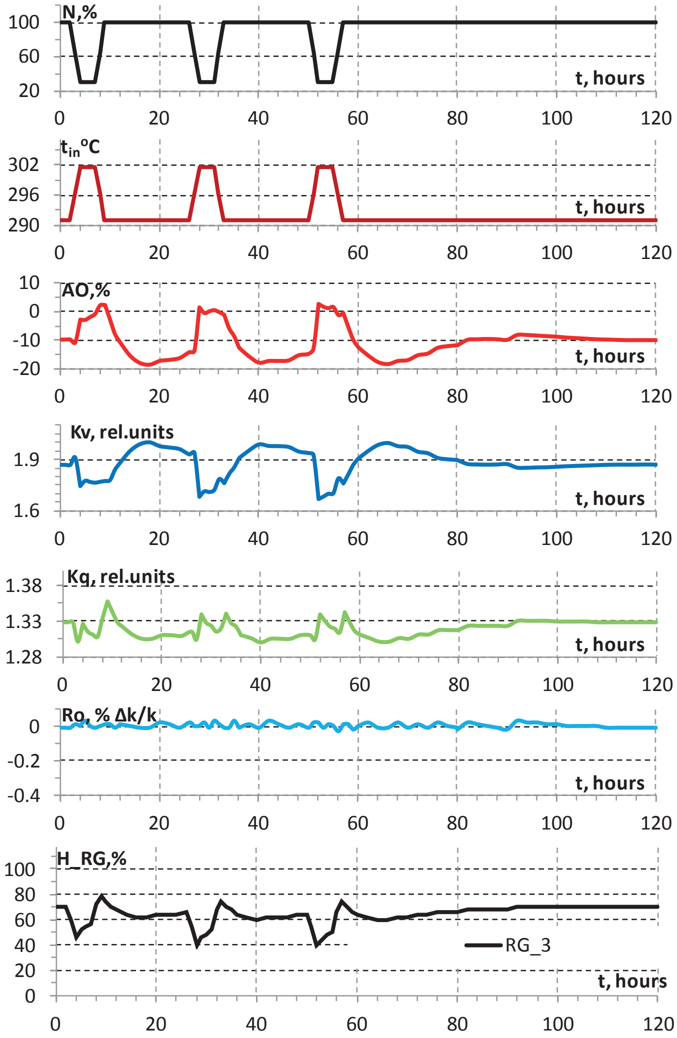

Figure 12: Power maneuvering at burn-up time 450 eff.d. Mode "t_{av} =const"

The mode of regulation "t_{av} =const" is differed from the mode "P_2=const" by less diapasons of CRs moving that one can see from the comparison of Figure 9 with Figure 10 and Figure 11 with Figure 12. Explanation is that in the mode "t_{av} =const" the change of t_{in} inserts the same sign of reactivity as CRs, but in the mode "P_2=const" – on the contrary – reactivity inserted by the change of t_{in} has the opposite sign. The mode "t_{in}=const" was considered also and it is placed in an intermediate position between two above-mentioned modes "P_2=const" and "t_{av} =const".

On the Figure 9 is presented the mode "P_2=const" for the EOC. In contrast to other moments of reactor campaign, presented on Figures 11-13, the power rise up to 100% at the very end of campaign may require more time approximately by one hour due to the so called effect of *iodine pit* and exhausting of possibility to insert the positive reactivity by the CRs withdrawal. This effect is presented in the form of small short-term peaks of negative reactivity Ro(t) on the Figures 9 and 10. This additional one hour should be enough for burning-out of excessive ^{135}Xe at power level near 90% and gradual power rise up to 100%.

Reactivity effects and coefficients. The following values of TCR are realized during the Hot Full Power, t_{in}=279 °C and the stationary ^{135}Xe and ^{149}Sm poisoning:

- for variant of the boron-free control: $-61.2\cdot10^{-5}$, $-58.2\cdot10^{-5}$, $-60.6\cdot10^{-5}$ 1/°C for the BOC (0 eff.d), 450 eff.d and EOC (700 eff.d) respectively;

- for variant of the boron control: $-24.9\cdot10^{-5}$, $-49.4\cdot10^{-5}$, $-64.5\cdot10^{-5}$ 1/°C for the BOC (0 of eff.s), 450 eff.s and EOC (681.9 of eff.s) respectively.

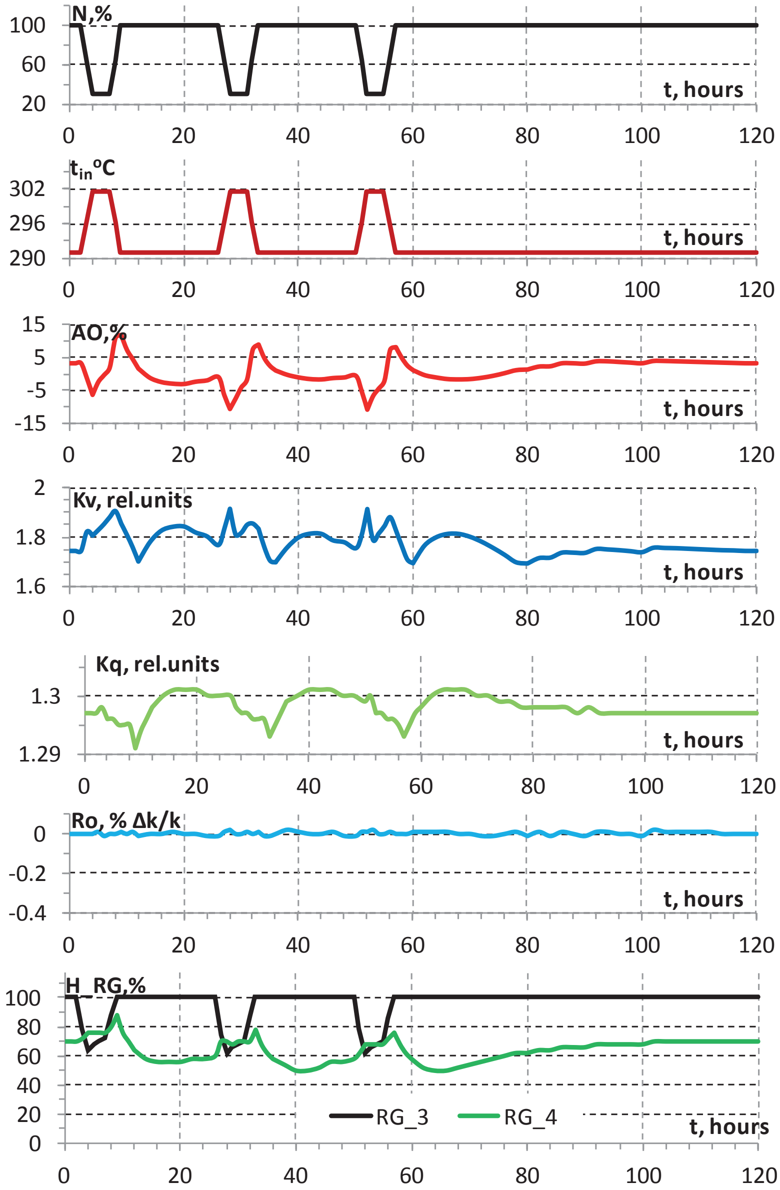

Figure 13: Power maneuvering at BOC. Mode "t_{av} =const"

So boron-free control is characterized by the well negative TCR which is practically constant during the fuel burn-up that is preferable in contrast to the variant of boron control where TCR is significantly changed during burn-up.

K_{eff} and TCR are compared in the Table 1 in some conditions for two variants with the following deductions:

- for variant of the boron-free control it is possible to achieve MCL at 200 °C and further heating-up up to 279 °C accomplish by the nuclear reaction instead of by RCPs(as usual), that gives an economical advantage. Safety in diapason 200-279 °C is ensured by the strongly negative TCR in contrast to the variant of boron control that one can see from comparison of TCR in the states 6, 7 with 13, 14 in Table 1;

- negative TCR for variant of the boron-free control is realized even for DEC, for example at achievement of critical state at the depoisoning Cold Zero Power in contrast to the variant of boron control with positive TCR (compare states 5 and 11 in Table 1).

Table 1 Comparison of K_{eff} and TCR in certain conditions for variants of Boron-free Control and Boron Control. BOC, Cold Zero Power, Xenon depoisoning, Sm stationary)

Boron-free Control						Boron Control					
Numb.	CRs inserted	t_{in}, °C	CB, g/kg	K_{eff}	TCR, 10^{-5} 1/°C	Numb.	CRs inserted	t_{in}, °C	CB, g/kg	K_{eff}	TCR, 10^{-5} 1/°C
1	No	50	0	1.169	-	8	No	50	0	1.239	-
2	All	50	0	1.055	-	9	No	50	1.000	1.116	-
3	All without **one CR**[*]	50	0	1.074	-	10	No	50	2.000	1.020	-
4	No	50	2.000	0.960	-	11	No	50	2.233	1.000	4.8
5	No	50	1.531	1.000	-0.3	12	No	50	3.000	0.948	-
6	All, but H_RG_6=58%	200	0.092	1.000	-30.8	13	No	220	2.287	1.000	5.0
7	All, but H_RG_6=58%	220	0	1.000	-36.2	14	No	279	2.277	1.000	-0.7

[*] All CRs inserted without one the most effective CR of RG_8 which stuck in the extreme top position

Burn-up and efficiency of fuel utilization. The specific natural uranium consumption has complicated dependence on different factors and it is equal to 0.236 kg U/MW·d (th.) for considered variant with 24-months reactor campaign and 2 fuel reloadings. This is only 3.6% higher than for WWER-1300 with 18-months campaign and 3 fuel reloadings. But this is already 16% higher than for serial WWER-1000 with 12-months campaign and 4 fuel reloadings. This situation reflects the following well-known fact: the shorter reactor campaign and the more fuel reloadings the better fuel utilization but the worse *use factor of installed capacity*. Besides, the less neutron leakage from the core (due to core dimensions and fuel arrangement) and the less average fuel power rating (due to bigger core volume and less installed capacity) the better fuel utilization.

Average burn-up is equal to 32.9 MWd/kg U which is achieved during 700 eff. days for variant of boron-free control (see Figure 5) and 32.0 MWd/kg U which is achieved during 681.9 eff. days for variant of boron control (see Figure 6) at the same average enrichment 3.48% ^{235}U.

I.e. fuel utilization for boron-free variant is better by 2.6% that is explained by the more flexible regulation by CRs and the smaller radial neutron leakage from the core for concrete realizations of fuel arrangements in considered two variants.

3 CONCLUSION

Neutronic characteristics of the core of integral WWER reactor with a small power 600 MW (th.) were analyzed. Variant of boron-free control was compared with usual variant of boron control in the process of burning out of fuel in the base operating mode. Variant of boron-free control uses simplified boron system which is used only for guaranteeing the subcriticality with the failures of mechanical EP system, and also in the cold depoisoning state of reactor, which is realized during the PPRs and fuel reloadings. Some advantages on safety and economy of variant with boron-free control as compared to the variant with boron control were obtained. Nevertheless both variants have right to be realized and in principle can be used as the options taking into account the customer's desire.

The mode of the daily manoeuvring was also analyzed for variant of boron-free control and with use of additional regulation by various primary coolant temperatures (modes "P_2=const", "t_{in}=const", "t_{av}=const").

The positive results were obtained, with conclusion about the relatively simple feasibility of WWER technology in the integral small-power reactor.

ACRONYMS AND CONVENTIONAL SYMBOLS

ALARA – as low as reasonably achievable
ATWS – anticipated transient without scram
BOC – beginning of cycle
BA – burnable absorber
CPS – control and protection system
CR – control rod
DEC – design extension condition
EOC – end of cycle
EP – emergency protection
EUR – European Utilities Requirements
FA – fuel assembly
FR – fuel rod
HA – hydro-accumulator
IFBA – integrated with fuel burnable absorber
LBLOCA – large break loss of coolant accident
LOCA – loss of coolant accident
MCL – minimally controlled level
NPP – nuclear power plant
PPR – planned preventive repair
PWR – pressurized water reactor
RCP – reactor coolant pump
RP – reactor plant
TCR – temperature coefficient of reactivity
WWER – water-water energy reactor
eff.d. – effective days

AO – axial offset of power in the core, %
CB – concentration of natural boron in the coolant, g/kg
H – height of the core, % from the bottom
H_RG – height of RG in the core, % from the bottom
K_{eff} – effective multiplication factor, rel. units
Kq – power peaking factor by FAs in the core, rel. units
Kv – power peaking factor by the nodes in the core, rel. units
N – neutron power of reactor, % of nominal power
"P_2=const" – mode of power maneuvering with maintaining of constant secondary pressure
RG_*i* – regulative group of CRs CPS with number *i*
Ro – reactivity, %Δk/k
T – time of reactor campaign, eff. d.
t – time of Xenon transient during power manoeuvring, hours
t_{in} – coolant temperature at the core entrance, ^{o}C
"t_{av}=const" – mode of power maneuvering with maintaining of constant average by the core coolant temperature
"t_{in}=const" – mode of power maneuvering with maintaining of constant coolant temperature at the core entrance

REFERENCES

[1] EUR. European Utility Requirements for LWR Nuclear Power Plants. Volumes 1&2 Revision D October 2012.