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Innovation in Power Maneuvering Mode for NPP Hanhikivi with WWER-1200 reactor

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ABSTRACT

The possible innovative methods of maneuvering are investigated on the example of NPP Hanhikivi with WWER-1200 reactor in a frame of AES-2006 project. Stationary fuel loading analysis was performed for the for the most significant graph of daily manoeuvring (100-50-100)% Nnom with the rate of power change 1-5 % Nnom per minute, that are the European Utility Requirements. The improvement is ensured by maintaining a constant average coolant temperature in the core "Tav = const" (by changing the pressure in SGs) and a constant boron content in the primary coolant "CB = const". The change of power and Xenon concentration during power manoeuvring is compensated by special movement of the special chosen grey CRs in the core instead of CB change. CB is changed in usual way only for fuel burnup compensation during reactor campaign. The mode "Tav = const" is normally used for the control of power of PWRs in wide diapason and it reduces the amount of radioactive primary water discharges and the mechanical fatigue of the RCS components. Implementation of both – main mode "Tav = const" and auxiliary mode "CB = const" leads to positive effect of synergy. The mode "Tav = const" facilitates the implementation of the mode "CB = const" very much, and they together allow to completely eliminate the production of liquid waste during maneuvering and ensure load following practically for the full length of reactor campaign. Presence of large CRs quantity (121 pieces) in the WWER-1200 allows using part of them as grey CRs without safety violation due to small decrease of EP efficiency. The efficiency of grey CRs is 2-3 times less than of usual black CRs that allows more softly maintain criticality, AO and power peaking factors in their acceptable diapasons at CB = const. Analysis is performed with Russian 3D code BIPR-7 only for neutronics aspects without considering strength cyclic characteristics of the equipment and nuclear fuel.

Key Words: Maneuvering modes, Boron-free control, grey absorbing rods, advantages of WWER-1200.

1 INTRODUCTION

1.1 Two different main modes for power maneuvering can be used in WWER (PWR):

- mode "P_2 = const". The maintenance of constant secondary pressure at the normal operation with power rising or decreasing is traditionally used for WWERs. It naturally spread initially on the conditions with power maneuvering. At this the temperature at the core input tin decreases (increases) with a decrease (increase) in power by about 0.2 °C /% N_{nom}. For example, for the graph (100-50-100) % N_{nom}, the corresponding coolant temperature jumps (affecting the mechanical fatigue) reach 24.8 °C (Table 1), which is considered as disadvantage of this mode. Another disadvantage of this mode is the need to introduce an additional absorber (boron in water and CRs). It is needed to compensate for reactivity due to decrease in the coolant temperature with decrease in power (about 1% Δk/k for 50% N_{nom}) and vice versa, to withdraw an additional absorber for power increase (Table 2). This additional reactivity is substantially greater than the reactivity required to compensate for the power change and current non-stationary Xenon poisoning. This is presented in Table 2 and more clearly in the figures below.

- mode "Tav = const". Maintaining a constant coolant temperature in the core eliminates both of the above mentioned disadvantages of the mode P_2 = const. This can be achieved by increasing the pressure in the SGs. The pressure in the SG should increase (decrease) with a decrease (increase) in power by about 0.020-0.025 MPa /% N_{nom}. For the graph (100-50-100)% N_{nom}, the corresponding jumps in the coolant temperature reach lower values (see Table 1) that should reduce the mechanical fatigue of the RCS components in comparison with mode P_2 = const. An additional absorber is also not required (Table 2). This mode reduces the amount of primary water discharges and less perturbs the power distribution by the movement of the CRs CPS in comparison with mode P_2 = const. Moreover, a need in the small operative reactivity margin makes it possible to use the so-called grey CRs to control power and xenon. Grey absorber has 2-3 times less efficiency than the commonly used black absorber. Grey CRs even less disturb the power distribution and make it easier to implement the auxiliary mode "CB = const" during power maneuvering. Figure 2 shows the number, location and mutual movement of grey CRs in the core which should be most effective in ensuring that the acceptance criteria are met (item 2.3). Grey CRs CPS are installed in the cells instead of a part of the usual black CRs CPS (see item 3.1). The maximum number of 121 CRs was specifically set initially in the AES-2006 project, including possible replacing some part of the black CRs by the grey ones. Therefore, there is some freedom of their reasonable choice.

1.2 Requirements of EUR [1] in relation of power maneuvering and goals, which are achieved in this paper:

1) Load following operation for graph 100-50-100 with rate of power change (1-5) % N_{nom}/minute has to be ensured during as long as possible, but not less than 90% of the whole reactor campaign.

2) This should be achieved in PWRs without adjusting soluble boron concentration during the manoeuvre.

3) The average coolant temperature is normally the parameter of the PWR. Mode Tav = const have to be ensured for the range between 50% and 100% N_{nom} [1]. A constant coolant temperature over a wide range up to 100% load favours Load Following operation. It reduces the amount of the primary water discharges and the mechanical fatigue of the RCS components [1].

Table 1: Temperature changes (jumps) which realized at Power change

Place in the Reactor Plant equipment	Temperature changes (jumps) which realized at Power change from 100 till 50 %N_{nom} (and back) for two modes, °C	
	P_2=const	T_{av}=const
RPV inlet	10	9.2
RPV outlet	**24.8**	**5.6**
SG inlet	**24.8**	**5.6**
SG outlet	10	9.2

1.3 Figure 1 demonstrates the changes of AO and Ro vs. time at free Xenon oscillations after single power maneuvering for different moments (BOC, EOC) of reactor campaign and different core lengths (375 cm (AES-2006), 355 cm (WWER-1000) and 250 cm [2, 3]). A relatively small power change excites Xenon oscillations. They are increased with increasing core height and move from self-attenuation (for BOC) to self-amplification (for EOC) of the amplitude of oscillations.

However, the remarkable intrinsic property of the WWER (PWR) core is the coincidence of the phases of oscillations AO and Ro [7]. It is displayed in the fact that the APC work, while maintaining a constant power (zero reactivity), has addition side effect of suppress "in the bud" amplification of AO oscillations. It is interesting that this coincidence of phases is an indirect consequence of negative TCR - another important intrinsic property of the WWER (PWR) core.

Table 2: Reactivity changes (jumps) which realized at Power change

Rate of power change, $\%N_{nom}$ per minute	Moment of reactor campaign	Power decrease or increase	Average reactivity changes (jumps) which realized at Power change from 100 till 50 $\%N_{nom}$ (and back) for two modes, $\%\Delta k/k$		Reference Figure number
			P_2=const	T_{av}=const	
5	BOC (0FPD)	decrease	1.32	0.46	6
		increase	-1.36	-0.48	
5	EOC*(280 FPD)	decrease	1.71	0.47	4
		increase	-	-0.50	
0.83	EOC*(280 FPD)	decrease	1.62	0.41	5
		increase	-1.58	-0.34	

*280 FPD is about 81% of full reactor campaign lengths (347 FPD). 280 FPD was used for EOC because calculation with 347 FPD (CRs are fixed) is stopped due to very large power nonuniformity Kv.

2 DESIGN MODELING AND ACCEPTANCE CRITERIA

2.1 Initial state. Analysis is carried out only for neutronics aspect without consideration of the strength cyclic characteristics of the equipment and nuclear fuel. As a reference, the calculation of neutronics, developed by Kurchatov Institute - the scientific supervisor of the Hanhikivi project, was used. By the code BIPR-7 was simulated a simplified stationary fuel loading for the symmetry sector 60^o (reference calculation is performed for the full core 360^o due to the lack of strict symmetry 60^o). Satisfactory results for the purposes of this paper were achieved, close to the reference calculation: the duration of the reactor campaign, fuel burn-up, effects and coefficients of reactivity, power peaking factors, etc. Figure 2(a) presents Power distributions (for BOC and EOC) in the core (for symmetry sector 60^o) for stationary loading of Hanhikivi NPP. Initial (before start of power maneuvering) grey RGs heights partially inserted into the core for creation of operation reactivity margin are presented in Table 3.

2.2 The following improvements were modelled in this paper during power maneuvering in the power range (50-100) $\%N_{nom}$:

1) maintaining the constant average coolant temperature in the core "T_{av} = const". This may be achieved by changing the pressure in SGs;

2) maintaining the constant boron content in the primary coolant "CB = const". This may be achieved by movement of the CRs in the core for compensation of reactivity change. Boron concentration is changed as usual only for fuel burn-up compensation during reactor campaign, but not for change of power and Xenon concentration during maneuvering;

3) replace of part of the usual black CRs by grey CRs. Presence of large CRs quantity (121 pieces) in the WWER-1200 allows to use part of them as grey CRs without safety violation. The efficiency of grey absorber is 2-3 times less than of usual black absorber that allows more softly maintain criticality, AO and power peaking factors in their acceptable diapasons at "CB = const" (see item 2.3).

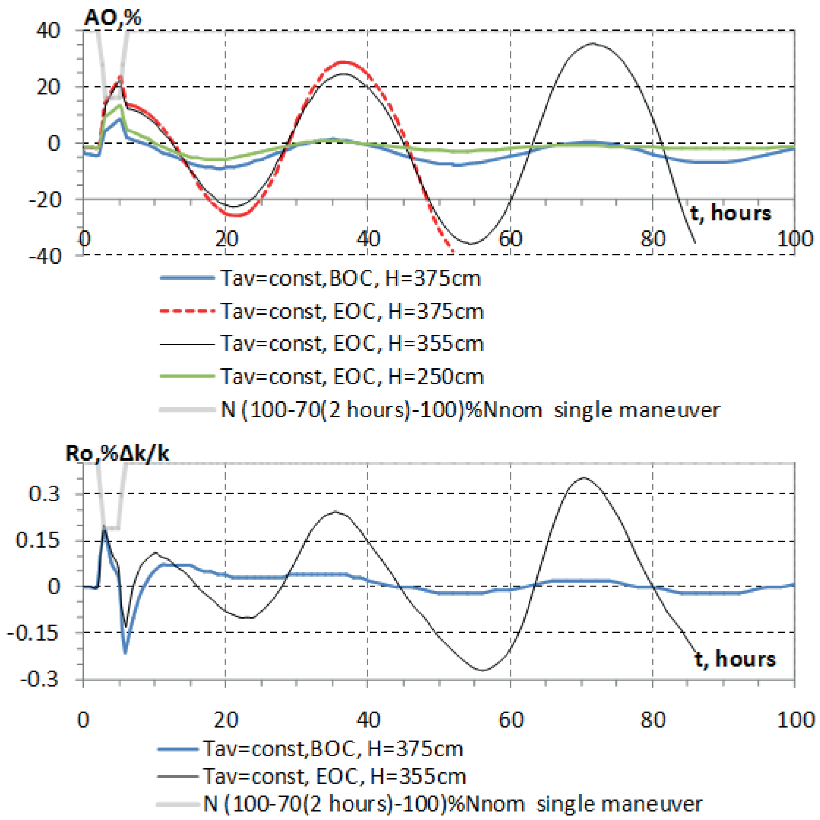

Figure 1: Axial power offset (AO) and reactivity (Ro) vs. time at free Xenon oscillations after single power maneuver *(background grey semitransparent line (N))* for different moments (BOC, EOC) of reactor campaign and different core lengths (375, 355 and 250 cm)

2.3 Acceptance criteria for calculations are maintaining the AO, Kv, Kq, criticality (Ro=0) for CB=const and some specific preliminary data for subsequent safety substantiation in their permissible ranges:

- AO should have as minimal deviation as possible from initial equilibrium value;
- Kv has not to exceed 1.9 for 100% N_{nom} and 2.1 for 50% N_{nom};
- Kq has not to exceed 1.40 for 100% N_{nom} and 1.45 for 50% N_{nom};
- Insertion of reactivity at fall of half-length grey RG has not to exceed 0.23 % Δk/k;
- Decrease of EP efficiency due to replacement of part black CRs by grey ones and after account of partially inserted grey CRs (for creation of operation reactivity margin which is required for maneuvering with CB=const), and due to burn-out of grey CRs, has not to exceed 5-10 % (rel.).

3 RESEARCH RESULTS

3.1 Figure 2(b) presents placement of Black and Grey groups of CRs in the core cells. RG_17&24 (placed in the core periphery) are mutually balanced with RG_3 (placed in the central part of the core) and therefore their movement is approximately the same. When maneuvering, their height remains well above 50% from the core bottom (see Figures 4-6 (d) and 7 (g)). Their bottom parts work as grey absorber during maneuvering. When the EP actuates, their upper parts with a black absorber work more efficiently.

RG_10&19 contains grey CRs of half-length in the bottom part and intended for effective suppression of big negative AO in the core. RG_6 is intended for fine regulation.

As a result we have 18 Grey&Black CRs, which weakly decrease the EP, 6 Grey CRs and 12 Grey CRs of half length. Part of Grey CRs is partially inserted into the core for creating the required operative margin for maneuvering with CB=const. Grey CRs also fall with EP actuation.

The results of calculations show that overall decrease in the EP efficiency due to the replacement of a part of the black CRs by the grey ones and after account of partially inserted the grey CRs, and due to burn-out of grey CRs, does not exceed 10 % (rel.). Small share of the EP efficiency loss is explained by the following: when all 121 CRs are inserted into the core by EP signal, each weakened grey CR is surrounded by powerful black CRs without formation of zones of potential local criticality.

The interesting effect was revealed in the calculations: in the contrary to black CRs the prolonged presence of grey CRs in the core which were chosen for operative reactivity margin weakly distorts the distributions of power and fuel burnup. No need even correct the stationary fuel loading pattern during and after several loadings with inserted grey CRs. It is explained by the rather big quantity of grey CRs uniformly distributed in the core.

Let's compare with some other PWR designs which have significantly less quantity of CRs, that allow to expect the sufficient EP efficiency for WWER-1200 for conditions with rather large quantity of grey CRs (36 ps.), considered in this paper:

- Reactor EPR (http://www.tvo.fi/uploads/julkaisut/tiedostot/ydinvoimalayks_OL3_ENG.pdf).

4300 MW (thermal), 1600 MW (el.). The core contains 241 FAs and totally 89 CRs. 53 CRs of them are black CRs intended for EP. Remaining 36 consist of the grey (12 ps.) and black (24 ps.) CRs, which are intended to control power and AO. However the CB is changed during maneuvering.

- Reactor AP-1000 (https://www.ipen.br/biblioteca/cd/genes4/2003/papers/1030-final.pdf). The core contains 157 FAs and totally 69 CRs. 16 CRs of them are grey CRs intended for control of power and AO. In that paper it is declared that there is possibility to achieve CB=const during maneuvering, but this is raw result obtained on the base of very simplified calculations – one-dimensional diffusion theory.

Also, the big quantity of neutron and thermal sensors in the core of WWERs [4-6], including WWER-1200 of NPP Hanhikivi (much more than in PWRs, including the above mentioned PWRs) facilitates adequate on-line monitoring and control of power distribution by the movement of grey CRs in the core during the power maneuvering with CB=const.

Therefore one can conclude that just the presence of so big numbers of CRs and neutron and thermal in-core detectors in WWER-1200 are the unique cases that makes it possible to realize mode CB=const by the grey CRs. Moreover such big quantities of CRs and sensors in the core is the most reasonable only for this case, whereas the maneuvering with change of CB and less movement of CRs may uses the less quantities of CRs and detectors.

3.2 The following side effect arises. The fall of RG of "half-length" grey CRs from the height of 50% from the core bottom can introduce positive reactivity. For example, when operating at rated power, a large positive AO can sometimes be compensated by such RG_10 at a height of 50%. Its fall to the core bottom will introduce a positive reactivity about 0.2% $\Delta k / k$ during about 1 s, which is comparable to the reactivity inserted during the design basis accident "the ejection of one CR CPS". This RIA should be analyzed within the framework of the further safety justification. It is not expected the safety violation in this event.

```
28
4year
0.258
0.328
26     27
1year 3year
1.153 0.449
1.208 0.550
23     24     25
3year 1year 1year
1.036 1.263 0.926
0.977 1.361 1.041
19     20     21     22
2year 3year 2year 1year
1.218 1.049 1.193 0.927
1.107 1.015 1.185 1.042
14     15     16     17     18
2year 1year 3year 1year 3year
1.135 1.202 1.020 1.266 0.452
1.067 1.240 0.990 1.362 0.554
8      9      10     11     12     13
2year 2year2year 3year 1year 4year
1.248 1.133 1.216 1.066 1.164 0.268
1.164 1.069 1.105 0.998 1.215 0.340
1      2      3      4      5      6      7 - FA's Number
4year 3year 1year 3year 2year 2year 4yearof work
0.685 0.996 1.232 1.029 1.361 1.271 0.522 - BOC Kq
0.719 0.970 1.288 0.946 1.168 1.169 0.586 - EOC Kq
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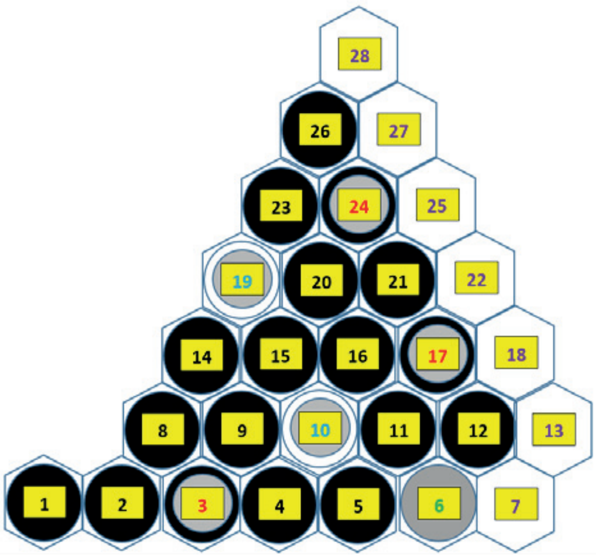
a – Power distribution by FAs (Kq for **BOC** and **EOC**) in the core (symmetry sector 60°). Grey CRs are partially inserted into the core to create operational margin for maneuvering with CB=const



- Grey and Black (G&B) absorbers on the Bottom and Top halves of CRs accordingly (Cells 3, 17,24)

- Grey and Zero (G&Z) absorbers on the Bottom and Top halves of CRs accordingly (Cells 10, 19 without absorber on the Top half)

- Grey (G) absorber on all length (Cell 6)

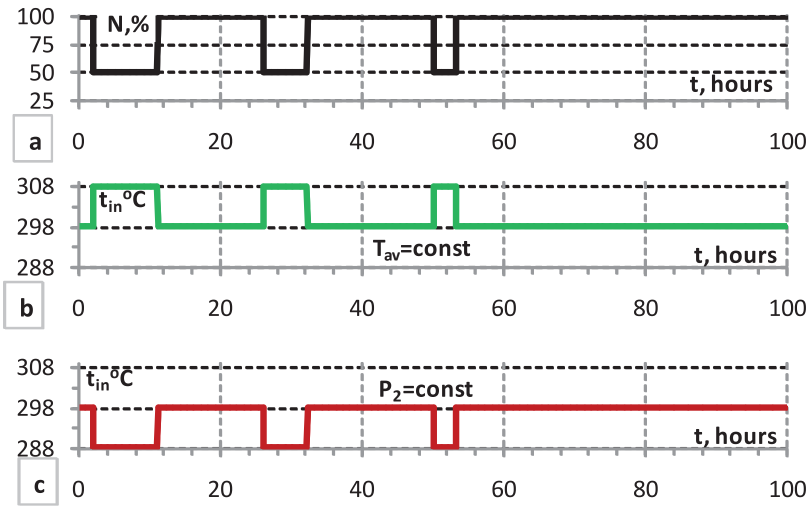
- Black absorber (B) on all length (Cells 1,2,4,5, 8,9,11,12,14,15,16,20,21,23,26)

- No absorber on all length (Cells 7,13,18,22,25,27,28)

b –allocation of Black and Grey absorbers in the core cells. The CR CPS group's number is the same as the cell number (if CR CPS is there in this cell)

Figure 2: Cartogram of the core symmetry sector 60°

3.3 Grey absorbers are simulated in this paper in such a way that their efficiency (in the form of the difference K_{eff} in their absence and in their presence in the FA $\Delta K_{eff} = K_{eff}^{(without\ absorber)} - K_{eff}^{(with\ absorber)}$) is equal to half (1/2) of the efficiency of the commonly used black absorbers. Grey absorbers with a lower efficiency – 1/3 of black absorber, were also examined to evaluate approximately their performance with significant absorber burn-out over several years of operation, and also to have an idea about the sustainability of the results and conclusions in the presence of uncertainty and calculation code accuracy. Grey absorbers can be realized on the basis of some (n-γ) absorbers that remain effective during prolonged burn-out, such as hafnium (Hf) and dysprosium (Dy).



Three daily power decrease for 9, 6 and 3 hours to 50 % N_{nom} and subsequent increase to 100 % N_{nom} occur during 10 minutes and then till 100 hours – the period of stabilization at nominal power

Figure 3: N (a) and t_{in} vs. time for modes T_{av}=const (b) and P_2=const (c) at daily maneuvering (100-50-100) % N_{nom} at rate of power change 5 % N_{nom} per minute

3.4 Figures 4-7 show the maneuvering characteristics of Ro, AO, Kv, Kq, H_RG for different states and conditions.

The common thing for Figures 4-7 is that the main case on them is the mode "Tav = const, CRs are moving" (see the notation in Figure 4-6 (a-c)) in which T_{av} = const and criticality (Ro = 0), AO, K_v, K_q are maintained in their acceptable diapasons by special movement of special selected Grey CRs and partially by black RG_15 (see Figures 4-6(d, e)). Figures 4-6 (a - c) also provide auxiliary additional information for modes T_{av} = const and P_2 = const: Ro, AO, Kv without any compensation by CRs movement. In these conditions, CRs are fixed in the initial position.

This information together with attachment of power changes graph is very demonstrable for comparison with the main case and understanding of proposed strategy. In particular, it is clear from such a comparison that the mode T_{av} = const can be realized with grey CRs without CB changing.

It was also showed that the mode P_2 = const make it hardly achievable or even impossible to realize CB = const because it requires the insertion of black CRs (with big negative reactivity) for power decrease. It greatly distorts the power distributions on the 50 % N_{nom}directly and also (with delay) on the 100 % N_{nom}due to the distortion of the latent Xenon distribution.

Figures 4 and 6 correspond to the maneuvering graph depicted in Figure 3a with a power change of 5% N_{nom} per minute. Figure 4 corresponds to EOC, and Figure 6 – to BOC, where some lower maximum values of K_v (1.8) are achieved than for EOC (1.9) at 100% N_{nom}. At the same time, it should be noted that the CRs movements presented in Figures 4-7 were chosen "in first approximation" and can be considered conservative (suitable as initial data for safety analysis), but in the future they can be optimized with attainment of smaller values of K_v , for example, not more than 1.8-1.85. In addition one can visually note that RGs movement for EOC is simpler and therefore it can be easier controlled than RGs movement for BOC (compare Figure 4(e) with 6(e)). The reason of this simpler movement is more flatten axial distribution of power at the EOC in comparison with sinusoidal axial power distribution at the BOC. It make CRs more effective near the core top and bottom for EOC. The use of axial profiling of BA in the FAs, for example excluding of BA from the 15-20% of the fuel length at the very top and very bottom parts of FAs can ensure more flatten axial distribution of power and facilitate control during the full reactor campaign. Similar axial profiling of the BA and sometimes of the fuel enrichment is used in some PWRs (WWERs) to get small positive effects in improvements of fuel utilization and Kv. But the use of this BA profiling for simplification of control of maneuvering mode "CB = const" by the grey CRs can be a new and more significant its additional application.

Table 3: The positions of the working group (RG_15) and grey RGs in the initial state (before maneuvering) and at the moments of the first, second and third power raises from 50% to 100% N_{nom}

Rate of power change, $\%N_{nom}$ per minute	RG'sNumber	Initial RG's heights, % from the core bottom	RG's heights at the first power raise to 100 % N_{nom}, % from the core bottom		RG's heights at the second power raise to 100 % N_{nom}, % from the core bottom	RG's heights at the third power raise to 100 % N_{nom}, % from the core bottom	Figures' Number (and moments of 100 % N_{nom} achieving)
5	15	90	98		98	96	Fig 4 (11.3, 32.3 and 53.3 hours)
	17&24	96	100		100	100	
	3	96	100		100	100	
	10&19	26	88		82	84	
	6	100	100		100	100	
0.83	15	90	96	98	96	-	Fig 5 (12.0 and 33.0 hours)
	17&24	96	100	100	100	-	
	3	96	100	100	100	-	
	10&19	26	76	100	100	-	
	6	100	100	36	24	-	

3.5 The peculiarity is that when the reactor is returned to 100% N_{nom}, it is required to introduce more positive reactivity (i.e. to achieve greater RG's heights in comparison with the initial RG's heights, see Table 3), than negative reactivity which was introduced before that to reduce the power from 100 to 50 % N_{nom}. This is necessary for compensation of the additional Xenon poisoning accumulated when operating at reduced power during several hours. That is why, for the maneuvering mode with CB = const, it is necessary to create a certain operative reactivity margin by partially inserted grey CRs CPS into the core.

Figure 5 corresponds to a power change 0.83% N_{nom} per minute.

Comparison of Figure 4 and 5 shows that, as expected, a smaller rate of power change requires a slightly smaller introduction of positive reactivity (i.e. lower RG's heights, see Table 3) for the reactor to achieve 100% after 50% N_{nom} and vice versa with a power decrease from 100 to 50% N_{nom}.

Figure 7 simulates daily maneuvering, which differs from Figure 4 in that grey absorbers have a lower efficiency - 1/3 from the black one, in contrast to Figure 4 (with grey absorbers with 1/2 of black efficiency). The maneuvering graph was also slightly changed in comparison with Figure 4. It can be seen that grey absorbers with less efficiency can successfully ensure the maneuvering regimes. As a result, it can be concluded that the grey CRs can maintain their performance in the long-term burn-out of the absorber (over several years of operation) in a maneuverable regime.

3.6 In summary one can conclude that all acceptance criteria (see item 2.3) are met including AO, Kv, Kq and criticality (Ro=0) for CB=const. Safety analyzes have to be fulfilled on the next stage of work for CPS efficiency with grey CRs and for the fall of half-length grey RG_10 or 19.

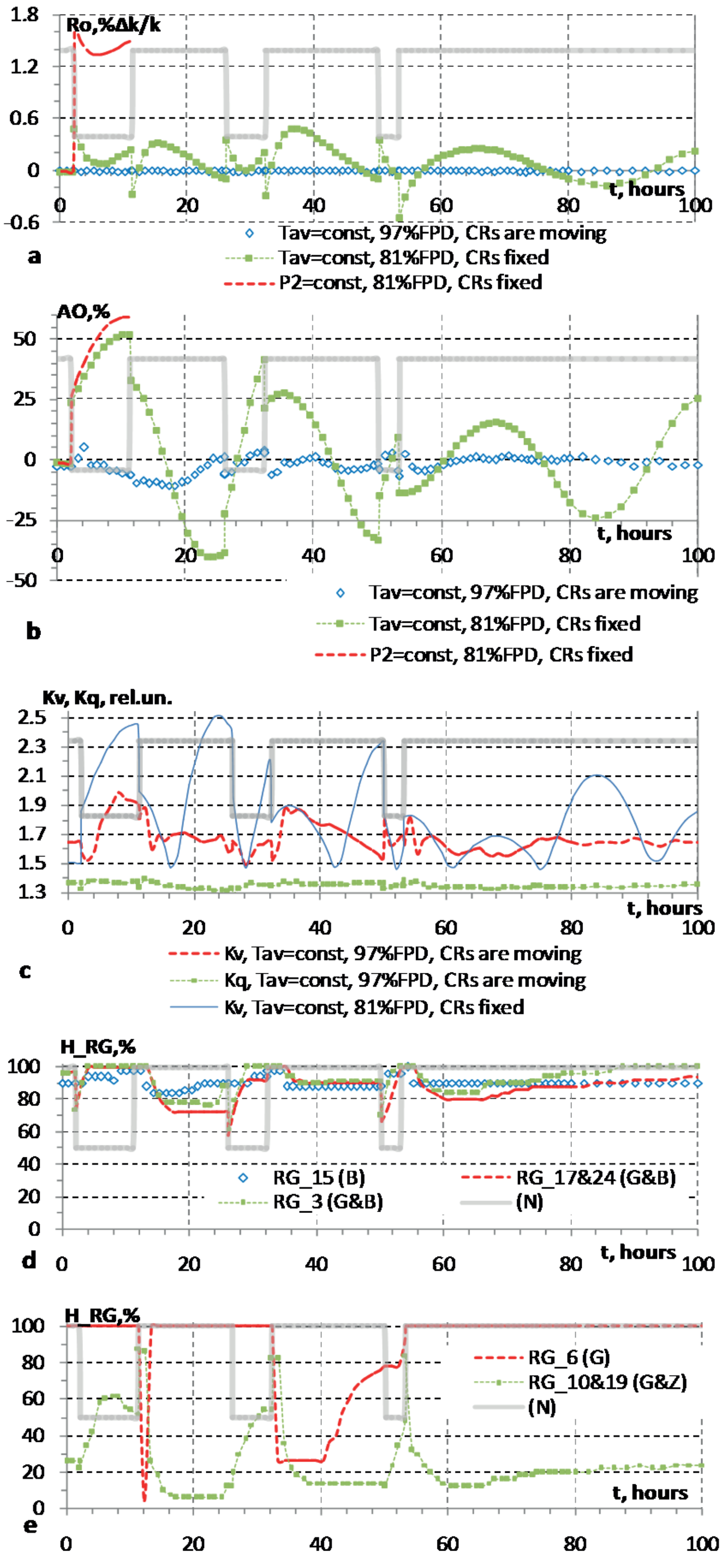


Figure 4: EOC. *5% N_{nom}/min*

a – change of reactivity for:
-**main** mode T_{av}=const and criticality (Ro=0) is ensured mainly by movement of Grey CRs (see below Figures d and e);
-reactivity which should be compensated when CRs are fixed in initial position for modes T_{av}=const and P_2=const (calculation of the last one was stopped due to very large power nonuniformity Kv).

b– change of axial offset due to Xe oscillations for the same modes as on Figure a. Movement of Grey CRs (Figures d and e) smooth Xe oscillations for main mode T_{av}=const;

c – change of power peaking factors Kv, Kq for main mode and Kv for fixed CRs;

d, e – change of heights of RGs 15, 17, 3, 6, 10, 19 for main mode T_{av}=const to ensure criticality and allowable values of AO and power peaking factors.

Note: Background grey semitransparent line (N) facilitate understanding of process due to attachment of power change (100-50-100)%N_{nom}(at rate 5%/min) on all Figures.

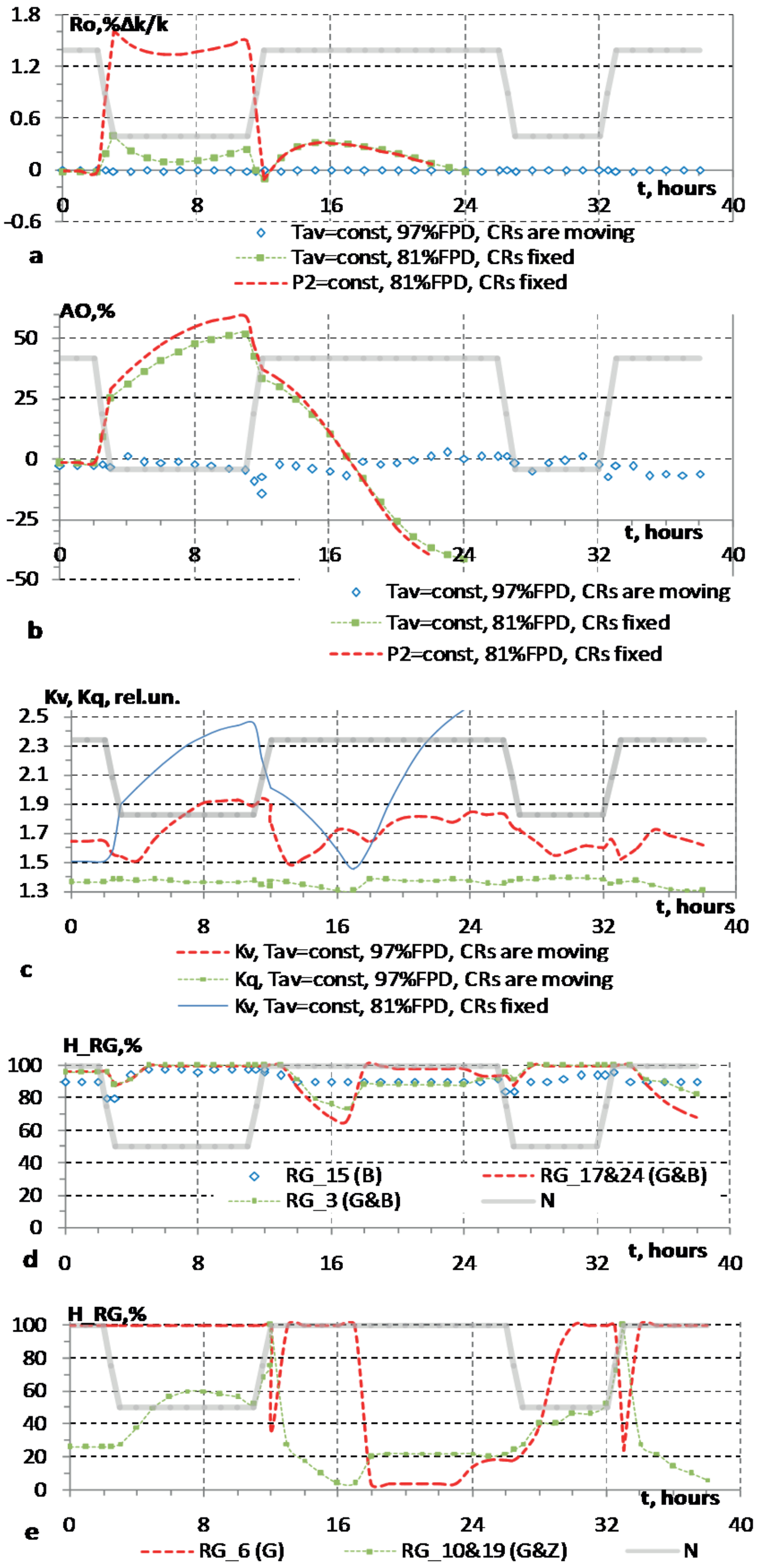


Figure 5:EOC *0.83%* N_{nom} */min*

a – change of reactivity for:
-main mode T_{av}=const and criticality (Ro=0) is ensured mainly by movement of Grey CRs (see below Figures d and e);
-reactivity which should be compensated when CRs are fixed in initial position for modes T_{av}=const and P_2=const.

b – change of axial offset due to Xe oscillations for the same modes as on Figure a. Movement of Grey CRs (Figures d and e) smooth Xe oscillations for main mode T_{av}=const;

c – change of power peaking factors Kv, Kq for main mode and Kv for fixed CRs;

d, e – change of heights of RGs 15, 17, 3, 6, 10, 19 for main mode T_{av}=const to ensure criticality and allowable values of AO and power peaking factors.

Note: Background grey semitransparent line (N) facilitate understanding of process due to attachment of power change (100-50-100)%N_{nom}*(at rate 0.83%/min) on all Figures.*

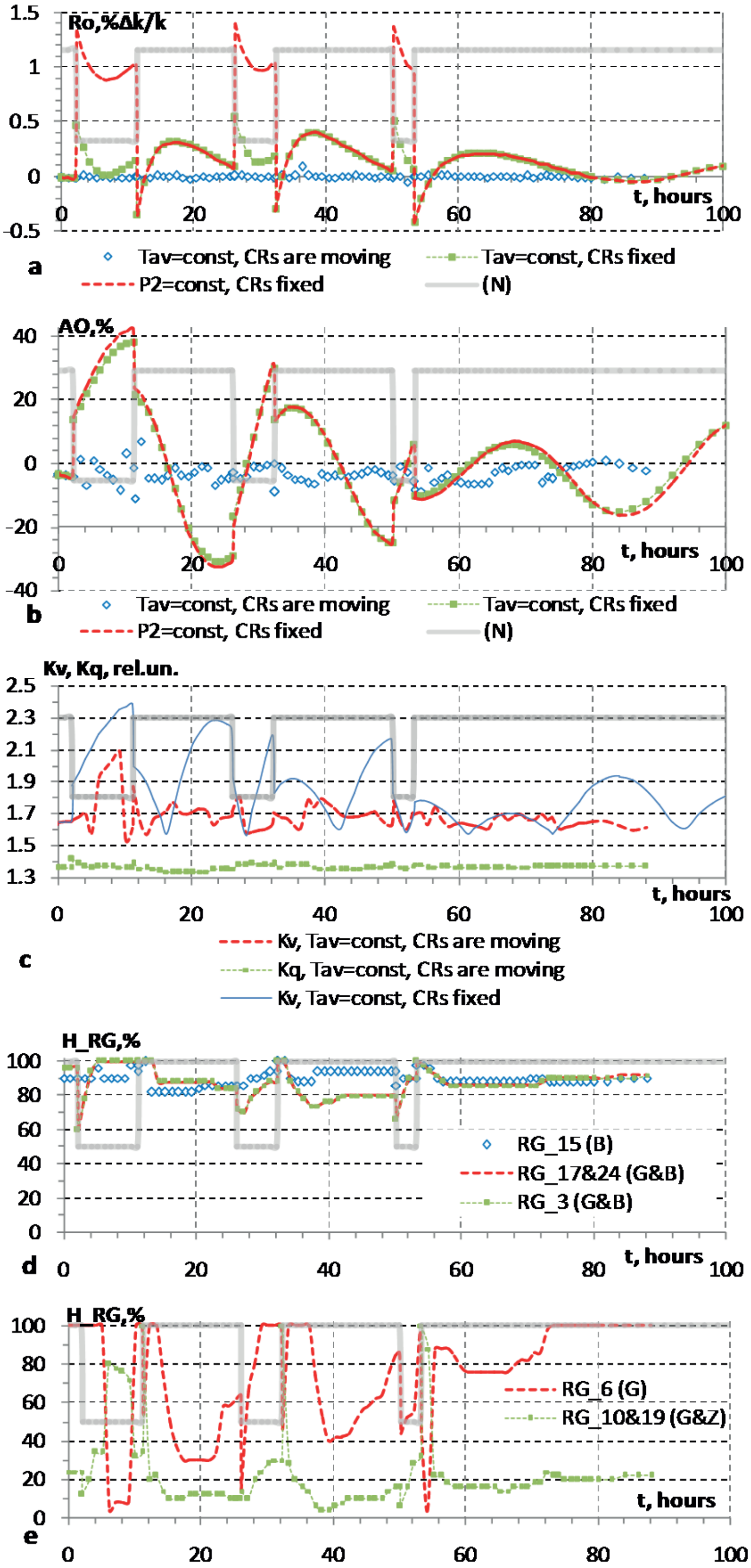


Figure 6: BOC *5% N_{nom}/min*

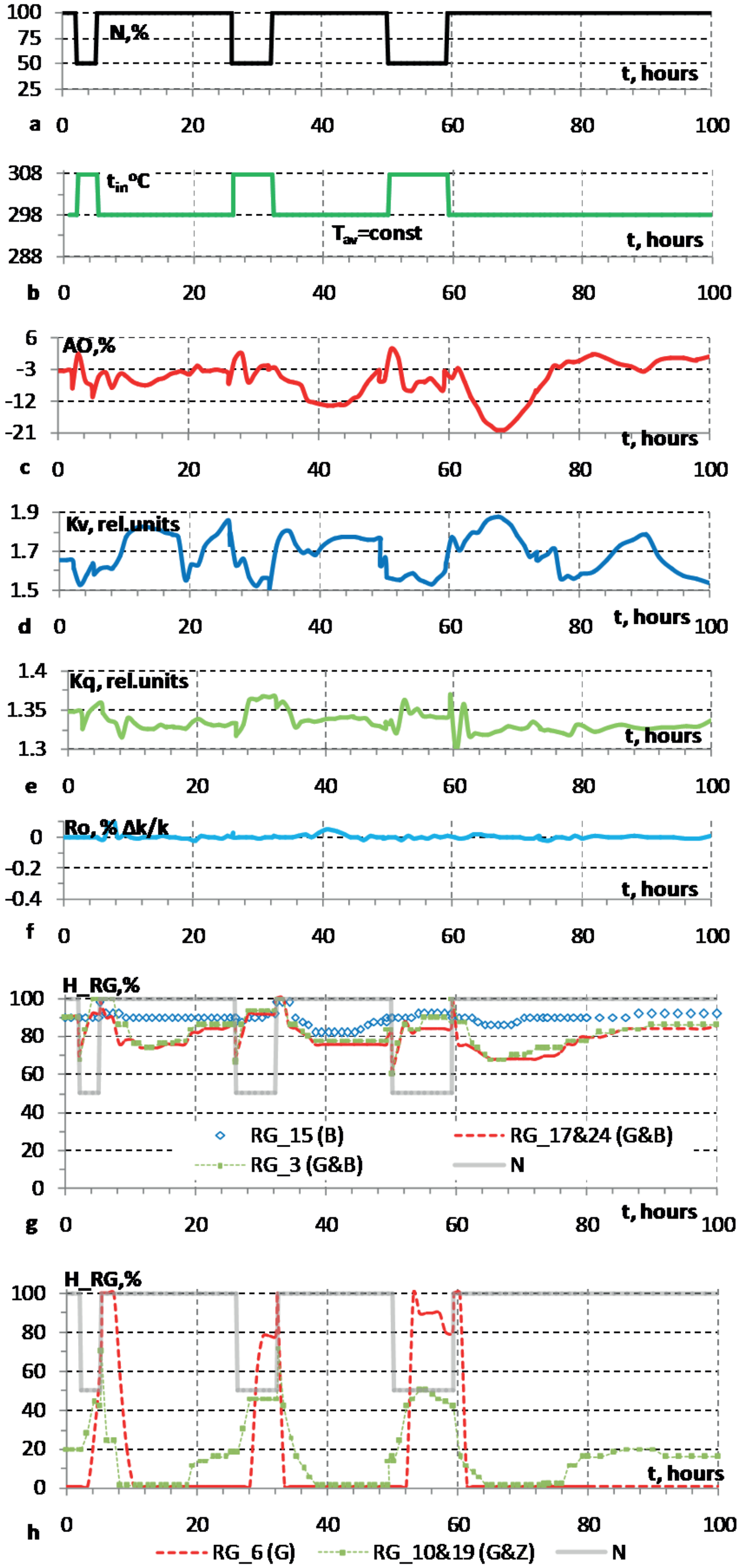
a – change of reactivity for:
-main mode T_{av}=const and criticality (Ro=0) is ensured mainly by movement of Grey CRs (see below Figures d and e);
-reactivity which should be compensated when CRs are fixed in initial position for modes T_{av}=const and P_2=const.

b – change of axial offset due to Xe oscillations for the same modes as on Figure a. Movement of Grey CRs (Figures d and e) smooth Xe oscillations for main mode T_{av}=const;

c – change of power peaking factors Kv, Kq for main mode and Kv for fixed CRs;

d, e – change of heights of RGs 15, 17, 3, 6, 10, 19 for main mode T_{av}=const to ensure criticality and allowable values of AO and power peaking factors.

Note: Background grey semitransparent line (N) facilitate understanding of process due to attachment of power change (100-50-100)%N_{nom}(at rate 5%/min) on all Figures.



a, b – N and t_{in} vs. time for mode T_{av}=const at daily maneuvering (100-50-100) % N_{nom} at the rate of power change 5 % N_{nom} per minute

c – change of axial offset due to Xe oscillations. Movement of Grey CRs (Figures g and h) smooth Xe oscillations for main mode T_{av}=const;

d, e – change of power peaking factors Kv, Kq for main mode;

f– change of reactivity for main mode T_{av}=const and criticality (Ro=0) is ensured mainly by movement of Grey CRs (see below Figures g and h);

g, h – change of heights of RGs 15, 17, 3, 6, 10, 19 for main mode T_{av}=const to ensure criticality and allowable values of AO and power peaking factors.

Figure 7: EOC decreased efficiency of grey absorber (1/3 of the black one) for RG_10&19

4 CONCLUSION

The possibility of satisfying the increased modern requirements of the operators (EUR) to the maneuvering regimes for NPP Hanhikivi was investigated for neutronics aspects. The analysis was fulfilled on the example of the daily maneuvering (100-50-100) % N_{nom} with the rate of power change 1-5 % N_{nom} per minute.

The obtained results demonstrate that maneuvering is possible practically during the full length of reactor campaign without water exchange (at CB=const) in the primary coolant.

For this it is necessary to implement mode of maintaining of the average coolant temperature (T_{av}=const) during power maneuvering and replace part of usual black CRs by the grey ones. In the paper it is described the proposed characteristics of grey absorbers: quantity, effectiveness, placement in the core, approximate algorithms of their mutual movement and is demonstrated the satisfaction of the preliminary acceptance criteria (item 2.3) during maneuvering.In the contrary to black CRs the prolonged presence of grey CRs in the core which were chosen for operative reactivity margin weakly distort the distributions of power and fuel burnup.It is recommended also to use the axial profiling of BA in the FAs, for more flatten power distribution that facilitate control of CRs movement during full reactor campaign.

It was also showed that the mode P_2 = const make it hardly achievable or even impossible to realize mode CB = const, because it requires the insertion of black CRs (with big negative reactivity) for power decrease. It greatly distorts the power distributions on the 50 % N_{nom}directly and also (with delay) on the 100 % N_{nom}due to the distortion of the latent Xenon distribution.

The key conditions of successful solution of the problem of power maneuvering with CB=const is the presence of big quantities of CRs and neutron and thermal sensors in the core of WWER-1200 of NPP Hanhikivi (much more than in the PWRs). This allows to choose the grey CRs, the quantity, placement and movement of which is sufficient and effective to ensure the adequate on-line monitoring of power distribution and safe control of power and Xenon changes.

5 ACRONYMS AND CONVENTIONAL SYMBOLS

APC – automated power controller
BOC – beginning of cycle
BA – burnable absorber
CB – boron concentration
CPS – control and protection system
CR – control rod
EOC – end of cycle
EP – emergency protection
EUR – European Utilities Requirements
FA – fuel assembly
FPD – full power days
FR – fuel rod
NPP – nuclear power plant
PWR – pressurized water reactor
RP – reactor plant
RPV – reactor pressure vessel
TCR – temperature coefficient of reactivity
WWER – water-water energy reactor

AO – axial offset of power in the core, %
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
K_q – power peaking factor by FAs in the core, rel. units
K_v – 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 Xenon transient during power maneuvering, hours
t_{in} – coolant temperature at the core entrance, ^oC
"t_{av}=const" – mode of power maneuvering with maintaining of constant average by the core coolant temperature

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