WWER SAFETY ANALYSIS IN CASE OF SIMULTANEOUS POSITIVE REACTIVITY INTRODUCTION BY CONTROL RODS WITHDRAWAL AND PURE CONDENSATE INJECTION

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ABSTRACT

Results of calculation assessment of positive reactivity insertion rate are presented under condition of simultaneous effect on reactivity of two provided by WWER project reactivity operation systems - extract of regulation group and decrease of boron acid concentration. Showed that maximal positive reactivity insertion rate is achieved at hot zero power and it’s too less than limit value 0.07βeff/sec defined by normative document “Nuclear safety regulation of NPP with pressurized water reactors”. For given reasons concluded that necessity of application of the extended protection PZ-2 actuation time is absent on interval of pure condensate transportation for full exclusion of possibility of positive reactivity insertion simultaneously by two different operation systems.

The work was performed in framework of orders BMU SR 2511 and BMU R0801504 (SR2611). The report describes the opinion and view of the contractor – SSTC N&RS - and does not necessarily represent the opinion of the ordering party - BMU-BfS/GRS and TÜV SÜD.

INTRODUCTION

According to the Ukrainian regulation «Rules of Nuclear Safety for Nuclear Power Plants with Pressurized Water Reactors» [1] an introduction of positive reactivity simultaneously by two or more means of impact on reactivity isn’t permitted. Preventive protection PP-2 upon valve opening on the feed and bleed line is provided for realization of this requirement on Ukrainian NPPs with WWER reactors. It forbids extraction of regulating group CR under pure condensate feed is injected in reactor core. The given action really excludes simultaneous carrying-out by personnel of operations on introduction of positive reactivity by two or more means of impact on reactivity. However possibility of introduction of positive reactivity by two means of impact on reactivity after realization of this action remains, because upon valve closing on a feed and bleed line action of protection PP-2 stops, but transportation of a pure condensate in reactor core proceeds. Transportation time can amount to 15 minutes depending on the flow of the feed and bleed line. Therefore during this time interval the situation is possible when positive reactivity can be introduced simultaneously by pure condensate injection and extraction of regulating group CR due to adjustment of power distribution for compensation of poisoning effect and fuel burning. It is necessary to notice, that the increase of time of PP-2 protection action on an interval of pure condensate transportation in reactor core (about 15 minutes) will lead to difficulties of adjustment of power distribution especially at the end of fuel campaign when great volume of water exchange is required.

At the same time according to [1] rate of increase in positive reactivity should not exceed 0.07βeff/sec by means of impact on reactivity. Each of two systems of reactivity regulation in WWER reactors separately satisfies to the given requirement. Subject of the given research - whether this requirement is fulfilled in a situation of simultaneous input of positive reactivity by two systems of reactivity regulation. Positive results of such analysis can be considered as a substantiation of absence of necessity to develop enough difficult algorithm of increase time of action of PP-2 protection on an interval of pure condensate transportation.

ESTIMATION OF THE MAXIMAL RATE OF POSITIVE REACTIVITY INTRODUCTION BY EXTRACTION OF WWER-1000 REGULATING GROUP OF CR

The analysis of the maximal rate of positive reactivity introduction by only extraction of WWER-1000 regulating group of CR was carried out for three moments of campaign: the beginning, the middle and the end of fuel loading operation. In calculations the stationary block of DYN3D code was used. Conditions of reactor core were considered that correspond to hot zero and full power for each moment of campaign.

Calculated dependences of differential efficiency of working group for reactor core conditions at hot zero and full power at the beginning, the middle and the end of fuel loading operation are given on Fig. 1 and Fig. 2. The given calculations were carried out on the base of steady states reactor core for various positions of regulating group on core height under condition of fixing of Xe^{135} and Sm^{149} nuclide concentration that correspond to a starting position of regulating group. I.e. in calculations was accepted, that Xe^{135} and Sm^{149} nuclide concentration isn't changed at CR moving, and spatial redistribution thermohydraulic parameters at the change of CR position was considered.

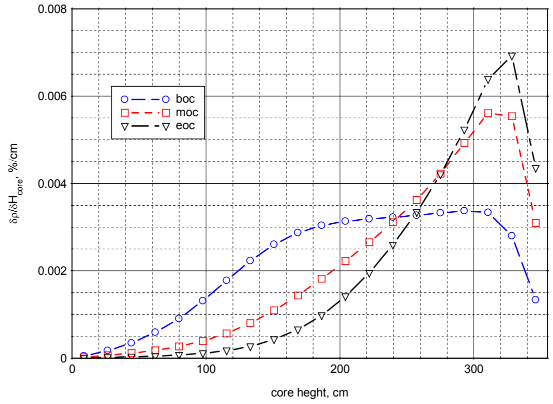

Fig. 1 - Differential efficiency of working group for HZP

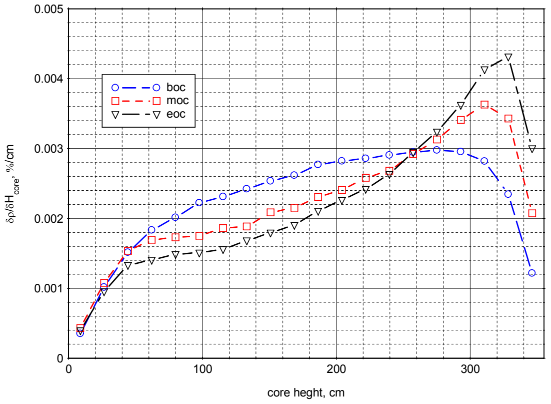

Fig. 2 - Differential efficiency of working group for full power

Received on the base of data at Fig. 1 and Fig. 2 dependences of rate of positive reactivity introduction by extraction of working group with a speed of 2 sm/sec are given on Fig. 3 and Fig. 4. Hereinafter in all calculations values of reactivity are normalized on conservative value of an effective fraction of the delayed neutrons equaled to 0.005.

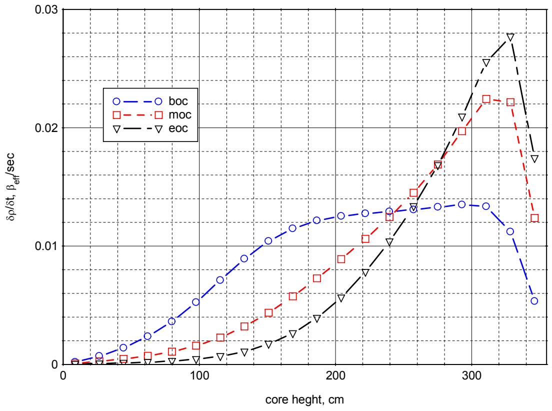

Fig. 3 - Rate of positive reactivity introduction by extraction of working group for HZP

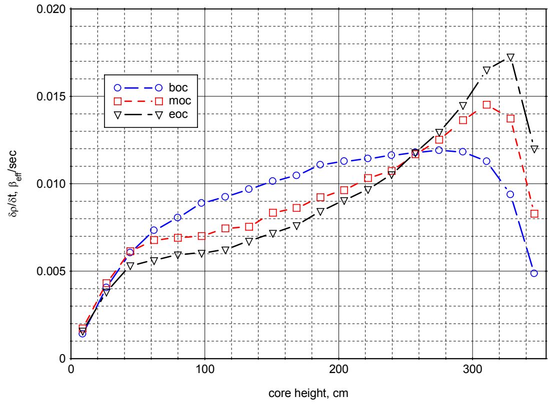

Fig. 4 - Rate of positive reactivity introduction by extraction of working group for full power

As it follows from Fig. 3 and Fig. 4, the maximal rate of positive reactivity introduction by extraction of working is reached during time moments CR pass zones with the greatest efficiency.

ESTIMATION OF THE OF THE MAXIMAL RATE OF POSITIVE REACTIVITY INTRODUCTION BY INJECTION OF A PURE CONDENSATE IN REACTOR CORE

Change of boric acid concentration in the reactor core is carried out by system of boric regulation through the feed and bleed system of the primary circuit. Reduction of boric acid concentration is carried out by injection of a pure condensate on a feed and bleed line by opening of corresponding valve. The maximum flow rate of the coolant (60 t/h) on a feed and bleed line is defined by output of pumps and throughput of the regulating valve [4].

Speed of change of boric acid concentration in the primary circuit by injection of a pure condensate (dC_b/dt) and the flow rate of the injected condensate in the feed and bleed system are connected by the differential equation

$$\frac{dC_b}{dt} = -\frac{q}{M} C_b, \qquad (1)$$

where q — the flow rate of the injected pure condensate; M — mass of coolant in the primary circuit.

The decision of this equation can be written in a following way:

$$C_b(t) = C_b(\text{ini}) \cdot \exp(-\frac{q}{M} t). \qquad (2)$$

The given ratio defines change of boric acid concentration depending on time beginning from C_b (ini).

Proceeding from the equation (1) maximal speed of change of boric acid concentration and, hence, the maximal rate of positive reactivity introduction by boron dilution from feed and bleed system will be realized under following conditions:

- maximal feed of a pure condensate - 60 t/h;
- minimal mass of the coolant in the primary circuit;
- maximal initial boric acid concentration in the primary circuit.

By consideration of short transients in which alignment of boric acid concentration is not provided in whole primary circuit volume, it is necessary to consider mass coolant without mass in the pressuriser, deaerator, auxiliary pipelines etc. In this case the minimum mass of the coolant amounts nearby 200t [4].

In table 3 the calculated values of average positive reactivity introduction on time interval 50sec (changes very slightly) by inject of pure condensate $\frac{d\rho}{dt} = -\frac{q}{M} \cdot C_b(\text{ini}) \cdot \exp(-\frac{q}{M} t) \cdot \alpha_{C_B}$ for three moments of campaign at hot zero and full power are given. At that for calculation of reactivity by boron dilution the reactivity coefficient on boron acid concentration α_{Cb}=–0.0151/(g/kg) was conservatively used. Initial values of critical boric acid concentration for various conditions of a reactor are presented in Table 1. As follows from presented at Table 1 data, the maximal rate of positive reactivity introduction by boron dilution is observed in the beginning of campaign at HZP , and minimal - at full power in the end of campaign. At that the maximal rate of positive reactivity introduction by extraction of working group is much more than rate by boron dilution.

Table 1 - Rate of positive reactivity introduction by inject of pure condensate

Initial level of power	Rate of positive reactivity introduction, β_{eff}/sec		
	beginning of campaign	middle of campaign	end of campaign
HZP	0.00255	0.0018	0.0011
100 % N_{rated}	0.0016	0.0008	$5.7 \cdot 10^{-5}$

On the basis of given data, it should be noted that the maximal speed rate of positive reactivity introduction by simultaneous extraction of working group and inject of pure condensate will be reached, obviously, when working group of CR is passed zones with the greatest efficiency.

ESTIMATION OF THE OF THE MAXIMAL RATE OF POSITIVE REACTIVITY INTRODUCTION BY SIMULTANEOUS INJECTION OF A PURE CONDENSATE IN REACTOR CORE AND EXTRACTION OF WORKING GROUP

Beginning of campaign. The dynamic block of program DYN3D [2, 3] was used for the analysis of the maximal rate of positive reactivity introduction by simultaneous injection of a pure condensate in reactor core and extraction of working group. Real conditions of reactor core were considered in calculations. The full-scale model of core in 360º symmetry was used by axial splitting into 20 uniform layers. It was supposed, that the regulating group is withdrawn from core with speed 2 sm/sec and simultaneously boric acid concentration by inject of a pure condensate according to the equation (2) is decreased. In all conditions of core all four MCP are in work. Extraction of regulating group was considered, beginning from lower allowable by operation regulation position. The next levels of power are considered in the beginning of campaign: HZP, 25%N_{rated}, 50%N_{rated}, 75%N_{rated}, 100% N_{rated}. For HZP condition the initial level of power of a reactor was supposed 0.01MW or 3.3×10^{-4} %N_{rated}. Withdrawn of regulating group from core and reduction of boric acid concentration lead to growth of neutron and thermal reactor power. The increase of neutron power over preventive protection PP-2 setting should lead to actuation of a signal for prohibition to extract of working group. To consider more long interval of time of regulating group withdrawn for definition of the maximal rate of positive reactivity introduction the actuation of protection PP-2 was not considered in the given calculations.

HZP. Results of calculated change of reactivity, speed of introduced reactivity, neutron and thermal power in the transient connected with simultaneous injection of pure condensate and extraction of working group from three different initial positions (71, 200 and 284cm that cover an allowable range of working group position at HZP) are presented at Fig. 5 and Fig. 6. The analysis of results of calculation shows, that maximal rate of positive reactivity introduction is reached at the moment of pass by regulating group of an axial layer with maximal efficiency as it was supposed in above. Therefore in the further calculations for HZP conditions there is no necessity to estimate the maximal rate of positive reactivity introduction for various initial CR positions: it is enough to choose initial CR positions from an allowable range near to its maximal efficiency.

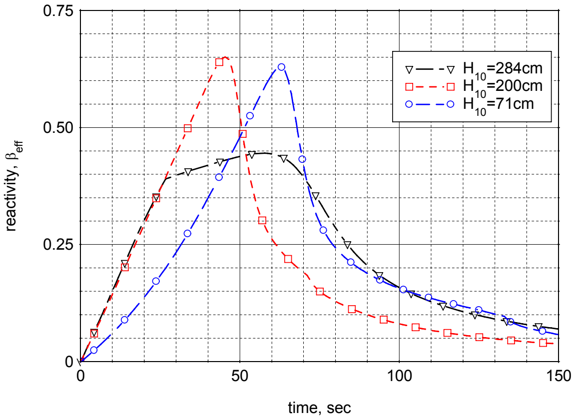

Fig. 5 – Reactivity change at simultaneous injection of pure condensate and extraction of working group at HZP (beginning of campaign)

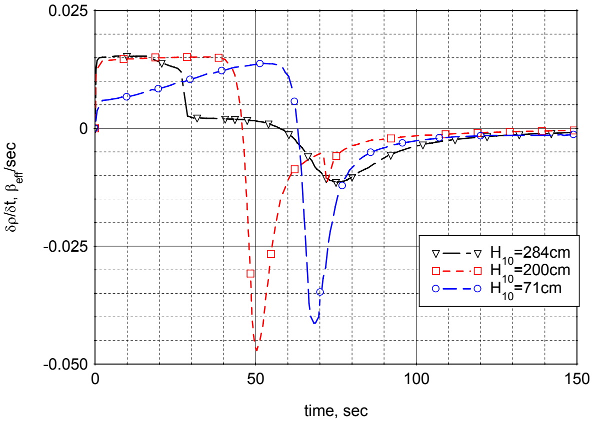

Fig. 6 – Rate of reactivity introduction at simultaneous injection of pure condensate and extraction of working group at HZP (beginning of campaign)

As results of calculations show, the maximal rate of positive reactivity introduction amounts approximately 0.015β_{eff}/sec (Fig. 6). After 40th second of transient the essential increase in neutron and thermal reactor power begins (Fig. 7), that leads to growth of fuel and the coolant temperature. As a result of action of feedback the entered positive reactivity starts to decrease and rate of positive reactivity introduction becomes negative.

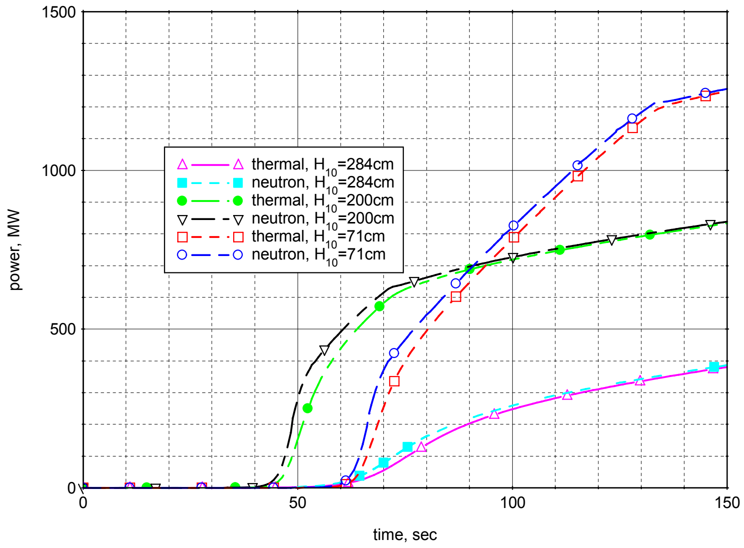

Fig. 7– Neutron and thermal reactor power at simultaneous injection of pure condensate and extraction of working group at HZP (beginning of campaign)

Full power. As at full power the allowable range of working group position makes 70÷95%, the initial position of CR have been chosen 248, 284 and 319cm. Results of calculations are presented on Fig. 8÷Fig. 10. In a condition at full power the value of the introduced reactivity is essentially less that at HZP – $0.023\beta_{eff}$ and $0.65\beta_{eff}$ accordingly (Fig. 5 and Fig. 8). This is explained by the fact that at full power action of feedback begins essentially earlier (practically from the moment of CR movement). It leads to decrease in growth of positive reactivity and, correspondingly, to smaller rate of positive reactivity introduction at full power than at HZP.

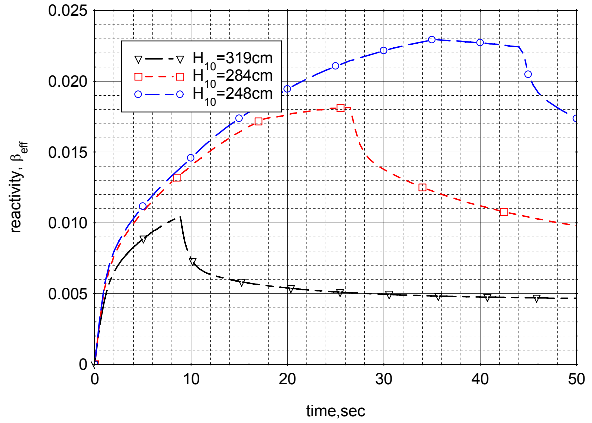

Fig. 8 – Reactivty change at simultaneous injection of pure condensate and extraction of working group at full power (beginning of campaign)

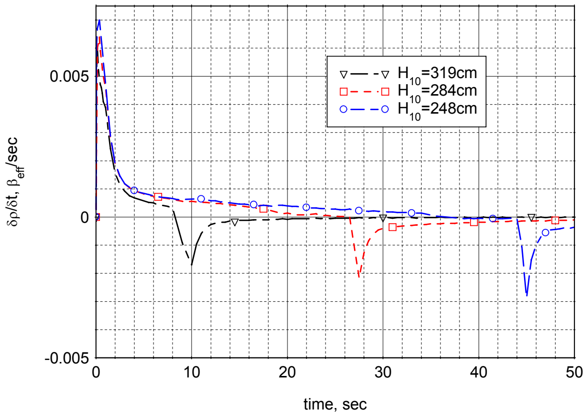

Fig. 9 – Rate of reactivity introduction at simultaneous injection of pure condensate and extraction of working group at full power (beginning of campaign)

From Fig. 9 it's follow that the maximal rate of positive reactivity introduction is observed in calculation with initial CR position at 248cm which is in area of the maximum value of differential efficiency on its ascending branch (Fig. 2) and reaches values 0.007βeff/sec in the beginning of transient.

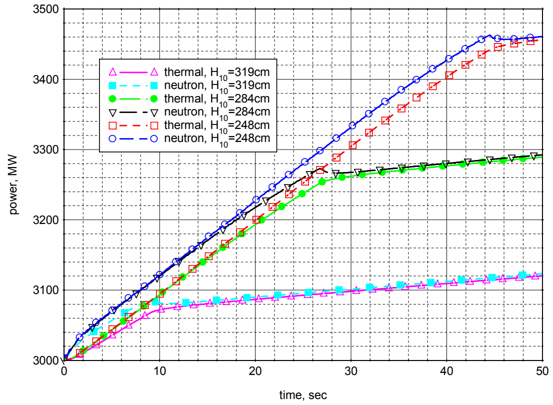

Fig. 10 – Neutron and thermal reactor power at simultaneous injection of pure condensate and extraction of working group at full power (beginning of campaign)

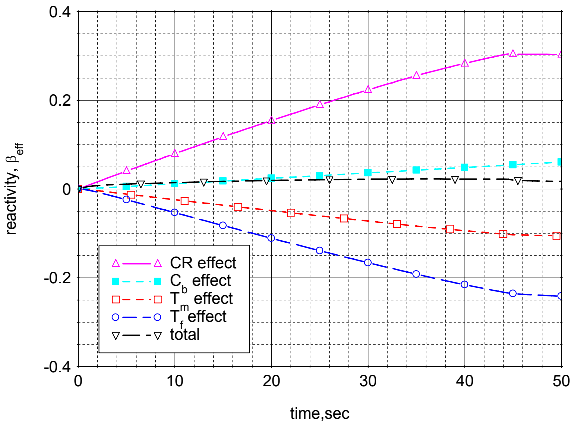

Fig. 11 – Reactivity components at simultaneous injection of pure condensate and extraction of working group at full power and initial CR position 248cm (beginning of campaign)

On Fig. 11 the reactivity components during transient are presented at CR extraction from position 248cm. Given values are calculated by program DYN3D on the basis of perturbation theory. From the shown curves follows, that introduced reactivity by CR extraction is much more then ones by decrease of boron acid concentration. Compensation of introduced positive reactivity occurs mostly by increase of fuel temperature and in less by coolant temperature.

Levels of power 75, 50 and 25 % N_{rated}. Similar results of an estimation of the maximal rate of positive reactivity introduction at levels of power 75, 50 and 25% N_{rated} at the beginning of campaign are presented at Table 2. In all cases three initial CR positions were considered that correspond to an allowable range depending on investigated level of power. In conditions of core at levels of power 75, 50 and 25% N_{rated} the maximal rate of positive reactivity introduction is reached in the beginning of transient from the moment of the starting of CR movement. Due to increase of neutron and thermal power the action of feedback limits reactivity growth therefore rate of reactivity decreases. In all three calculated cases the maximal rate of positive reactivity introduction is observed in a condition of core with initial position of regulating group 284cm.

Table 2 - Results of estimation of the maximal rate of positive reactivity introduction at levels of power 75, 50 and 25% N_{rated} (beginning of campaign)

Level of power, %	Initial position of working group, cm	Maximal rate of positive reactivity introduction, β_{eff}/sec	Time of achievement of maximal rate of reactivity introduction, sec
75	248	0.0085	0.2
	284	0.0088	0.2
	319	0.0080	0.2
50	248	0.0094	0.2
	284	0.0099	0.2
	319	0.0094	0.2
25	160	0.0106	0.2
	284	0.0110	0.2
	319	0.0108	0.2

End of campaign. In this condition the differential efficiency of regulating group in the upper part of core amount approximately 2 times more than at the beginning of campaign (Fig. 1, Fig. 2). Thus the rate of positive reactivity introduction by injection of a pure condensate decreases owing to smaller boron acid concentration at the end of campaign (see the equation 2).

HZP. On Fig. 12 and Fig. 13 change of reactivity and speed of introduced positive reactivity are shown at simultaneous injection of pure condensate and extraction of working group at HZP. Initial positions of working group 284 and 319cm were considered because such range covers a zone with the maximum differential efficiency of group. Extraction of regulating group was considered up to the top of an allowable range of working group position – 95% (337cm). For a case with initial CR position 319cm in the beginning of transient the rate of reactivity is more than for a case with 284cm and maximal value is reached at the moment of a group stop.

For a case with initial CR position 284cm the maximal rate of positive reactivity introduction is reached approximately on 28th second of transient and is limited by action of feedback owing to increase of fuel and coolant temperature. Results of calculations have shown, that the introduced reactivity amounts $0.69\beta_{eff}$ (Fig. 12), and the maximal rate of positive reactivity introduction in both cases – 0.0295 β_{eff}/sec (Fig. 13).

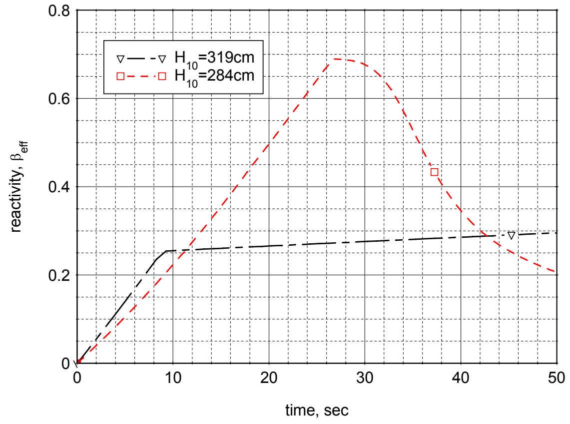

Fig. 12 – Reactivity change at simultaneous injection of pure condensate and extraction of working group at HZP (end of campaign)

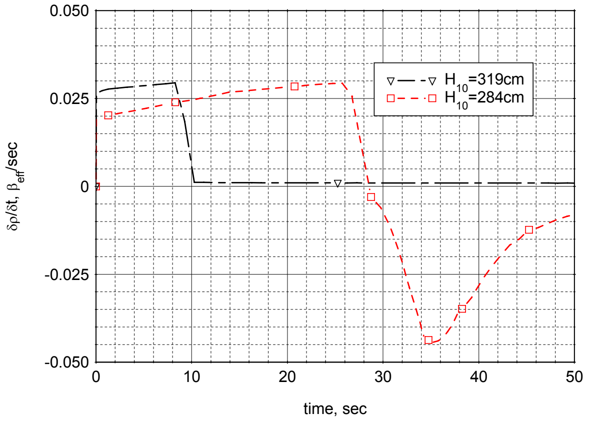

Fig. 13 – Rate of reactivity introduction at simultaneous injection of pure condensate and extraction of working group at HZP (end of campaign)

On Fig. 14 the reactivity components during transient are presented at CR extraction from position 284cm. From the shown figure follows, that main increase of reactivity occurs at the expense of extraction of working group. The contribution to reactivity by reduction of boric acid concentration is very weak.

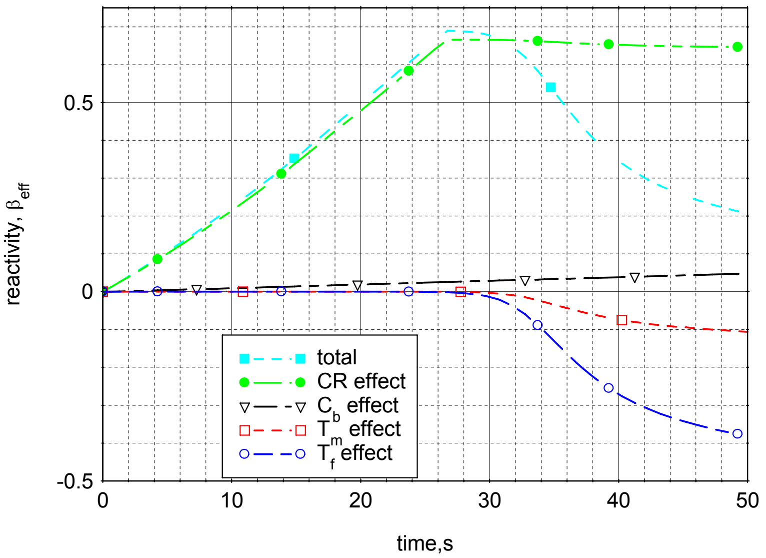

Fig. 14 – Reactivity components at simultaneous injection of pure condensate and extraction of working group at full power and initial CR position 284cm (end of campaign)

Full power and 50% of the rated level. Calculations were carried out for initial positions of regulating group 284 and 319cm. In a full power condition the maximal introduced reactivity amounts $0.020\beta_{eff}$ and has been reached in a case with initial CR position 284cm. This value is essentially less than for a HZP condition ($0.69\beta_{eff}$) owing to action of feedback. The maximal rate of positive reactivity introduction was observed in calculation with initial CR position 319cm and amounted $0.0091\beta_{eff}$/sec in the beginning of transient.

At reactor power 50%N_{rated} the maximal introduced reactivity amounts 0.045β_{eff} and the maximal rate of positive reactivity introduction – 0.0109β_{eff}/sec and 0.0153β_{eff}/sec accordingly for cases with initial CR positions 284 and 319cm.

The middle of campaign. Neutron-physical characteristics of core in the middle of campaign are covered by characteristics of beginning and end of campaign. The maximal values of differential efficiency of working group and speed of distillate injection are also between corresponded values for beginning and end of campaign (Fig. 1-Fig. 4). Therefore it should expect that the rate of positive reactivity introduction at simultaneous injection of pure condensate and extraction of working group will be between values for beginning and end of campaign. In the given calculations the extraction of regulating group was considered from initial position 284 and 319cm (as these positions cover a zone with the maximum differential efficiency of group) to the upper value from an allowable range of CR moving 95% (337cm). Results of these calculations in Table 3 are compared with results of calculations of two previous moments of campaign (at the beginning and the end).

Table 3 - The maximal rate of positive reactivity introduction for different core conditions

Level of power, %	Maximal rate of positive reactivity introduction, β_{eff}/sec		
	BOC	MOC	EOC
HZP	0.015	0.0255	0.030
25 %	0.010	–	–
50 %	0.0099	0.0132	0.0153
75 %	0.0088	–	–
100 %	0.0070	0.0079	0.0091

The maximal rate of positive reactivity introduction is observed at the end of campaign at HZP and amount 0.03 β_{eff}/sec. The given value of reactivity rate is mainly defined by extraction of regulating group (Fig. 11). At the beginning and the middle of fuel campaign for HZP the reactivity rate is less than at the end of campaign.

At increase of reactor power the feedbacks limit reactivity growth that leads to reduction of rate of reactivity introduction for all moments of campaign. The minimal values of introduced positive reactivity are observed at full power and change from 0.0070β_{eff}/sec at the beginning of campaign to 0.0091β_{eff}/sec at the end of campaign.

CONCLUSIONS

1. The maximal rate of positive reactivity introduction forWWER-1000 is observed at the end of campaign for HZP and amount 0.03β_{eff}/sec.

2. For full and intermediate levels of reactor power the maximal rate of positive reactivity introduction by two means of impact on reactivity is less than for HZP owing to the increased action of negative feedback due to increase of fuel and coolant temperature. Thus,

inherent to given reactor type a self-security property provides that the growth reactivity rate decreases with growth of reactor power.

Hence, the modernisation that consist in prohibition for extraction of regulating group during inject of a pure condensate in core, excludes carrying-out by personnel of operations on introduction of positive reactivity by two or more means of impact on reactivity. Since upon valve closing on a pure condensate line the prohibition for extraction of regulating group is taken off but the transportation of a pure condensate still proceeds, the possibility of introduction of positive reactivity by two ways remains during some time, and formally violation of the document [1] requirement takes place. However this situation is safe, as in this case the greatest possible rate of positive reactivity introduction, which was estimated in conservative approach, is considerable below defined by [1] limit value $0.07\beta_{eff}$/sec.

LIST OF NOMENCLATURE

CR - control rod;
HZP - hot zero power;
FA - fuel assembly;
MCP - main circuit pump$
NPP - nuclear power plant;
PP-2 preventive protection 2 (PZ-2)

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