Decision support system for WWER-1000 reactivity management

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Abstract. The article describes the developed software for automating operational calculations of reactivity changes of the water-water energetic reactor (WWER-1000). The main calculation dependencies, screen forms and test results on the Rostov nuclear power plant (Rostov NPP) are given. The calculation accuracy increase is shown.

1. Introduction

Reactivity is a dimensionless value that shows the dynamics of chain fission reaction in a nuclear reactor. According to the World Association of Nuclear Operators (WANO) recommendations [1], the safe operation of a WWER reactor facility assumes that operating staff have a clear understanding of the final state of the reactor and the transient process when planning the reactivity insertion. According to the working procedure of safe operation, two ways of the reactivity insertion [2] are provided:

- relocation of the control and protection system absorbing rods (CPS AR);
- change of boric acid concentration in the primary circuit by influence on the chemical and volume control system.

Assessment of the final state of the reactor should be performed taking into account the actual neutron-physical characteristics (NPC) of the fuel load. Operational personnel can use two main methods:

- calculation of the reactivity balance by reference NPC of the fuel loading determined using three-dimensional neutron-physical codes (in case of operation of WWER-1000 and WWER-1200 – BIPR-7A code with group constants provided by TVS-M code [3,4]);
- direct usage of three-dimensional neutron-physical codes (in case of operation of WWER-1000 and WWER-1200 it is the "Imitator of the reactor" code (IR) [5] installed at the reactor shift engineer workplace.

Thus, the decision on the reactivity insertion should be made by the operator based on the neutron-physical calculation of the final state of the reactor. The developed program solves this issue using the calculation of the reactivity balance according to reference NPC.

As part of the measures to improve the operational safety of the Rostov NPP reactors, the Album of Neutron-physical Fuel loading Characteristics-interactive program «ANFC-i» was developed and implemented for testing in the training department of the NPP [3]. The «ANFC-i» software allows

operators to reduce the time of the calculations and minimize errors in the manual account. The software is developed on C# programming language.

«ANFC-i» calculates the final state of the reactor using the reactivity balance. The algorithms of the developed program are based on the procedures and reference data regulated by the operating document of the WWER reactor (fuel load NPC album). The method of comparison with the results of numerical simulation on a full-scale simulator, which is currently used at Russian NPPs for similar purpose programs, has been chosen for testing.

2. Existing operator support methods

The advantage of the reactivity balance method is that it can be performed manually using a standardized procedure. This procedure at Rostov NPP is also provided by operational documentation (fuel load NPC album). Usually, when training NPP personnel, the leading reactor plant engineer and the reactor shift supervisor have to calculate manually the reactor power change or the starting boron concentration. Thus, the ability to understand and use in practice the basic physical features of the WWER-1000 reactor is demonstrated.

The staff training experience has shown the following:

- operating the control panel, the calculation and verification takes a lot of time (not less than 10-15 minutes) and makes the personnel lose focus on the current technological process;

- there is a risk of error when a large number of factors distract the personnel from the calculation.

Calculation and analytical support of WWER-1000 reactor operation is provided by NPC album, which is intended for use by operational personnel during operation of the reactor plant. The NPC album is based on software calculations:

- BIPR-7A as the basic neutron physical 3D diffusion code;
- TVS-M for group constants calculations.

The data given in the NPC album allows to evaluate the final state of the WWER-1000 reactor transient. Calculated changes of reactivity as a result of xenon transients by any effective day for arbitrary change of power level are requested in Nuclear Safety and Reliability Department (NSRD) of the Rostov NPP.

In the absence of the possibility to obtain the calculated values of the reactivity change, the operational personnel can make a rough estimation manually. However, such procedures are inevitably associated with the problems mentioned above. The proposed software is designed to solve this problem by providing reactor plant personnel with the decision support system for rapid, automated calculation of reactivity changes based on the NPC album data.

Workstations at the WWER-1000 and WWER-1200 power units, with rare exceptions, are equipped with the IR program, a three-dimensional neutron-physical code designed to predict the state of the reactor. IR program is developed by the SRC "Kurchatov Institute" (Scientific Chief of WWER-1000 operation). It includes a mathematical model corresponding to the model used for fuel loading NPC assessment in the BIPR-7A software. The IR calculation methodology is based on solving the two-group neutron diffusion equation on a wide grid.

The operation of the IR program requires precise information from the in-core instrumentation system -layered burnup of fuel assemblies based on the measured energy release distribution.

The software is designed for the following neutron-physical calculations of stationary and non-stationary (xenon and samarium transients) operating modes of the reactor plant:

- calculation of individual reactor states, as well as the processes of fuel load burnup and changes in the concentration of Xe-135 and Sm-149 nuclei;
- calculation of criticality parameters;
- calculation of the efficiency of regulatory bodies;
- calculation of the power distribution in the core volume.

The downside of the extensive capabilities of the IR program is a certain complexity in its development, due to the complexity of the mathematical model of the reactor. Using the IR program implies that the operator has perfect knowledge of the physical properties of the WWER fuel loading.

3. Evaluation of the error of manual calculation of the reactivity changes

The manual calculation of reactivity changes according to the procedure described in the NPC album has an inherent error, which is mainly based on:

- definition of reference data on NPC album graphs;
- the error in determining the initial and final state of the reactor plant.

Thus, for example, the following formula is used to calculate the volume of boron concentrate when the reactor plant capacity changes:

$$V = \frac{V_{1K}}{1.04} \cdot ln\left(\frac{C_m - C_0}{C_m - C_{fin}}\right) \cdot 60 \tag{1}$$

where $V_{1K} = 320\ m^3$ – is the volume of one circuit;

$C_m, C_0, C_{fin}\ (\frac{g}{kg})$ – make-up, initial and final concentration of boric acid.

Error in determining the volume of water exchange can be calculated by the formula:

$$\varepsilon_V = \frac{\left(\left|\frac{C_0 - C_{fin}}{(C_m - C_0)\cdot(C_m - C_{fin})}\right|\cdot\Delta C_m + \left|\frac{-1}{C_m - C_0}\right|\cdot\Delta C_0 + \left|\frac{1}{C_m - C_{fin}}\right|\cdot\Delta C_{fin}\right)\frac{V_{1K}}{1.04}\cdot 60}{\frac{V_{1K}}{1.04}\cdot ln\left(\frac{C_m - C_0}{C_m - C_{fin}}\right)\cdot 60} \tag{2}$$

where $\Delta C_m = \Delta C_0 = \Delta C_{fin} = \Delta C = 0.01\frac{g}{kg}$ – errors of measurement of boric acid concentrations.

After transformations using decomposition into Maclaurin Series:

$$\varepsilon_V \approx \frac{2\cdot\Delta C}{\delta C} \tag{3}$$

where δC – is a module of change in the concentration of boric acid in the first circuit.

The following formula is used to calculate the reactivity change at the reactor power change:

$$\Delta\rho = \left(W^{fin} - W^{in}\right)\cdot\left(\frac{\delta\rho}{\delta N} + \frac{8}{3000}\cdot\frac{\delta\rho}{\delta T}\right) \tag{4}$$

where W^{fin} – is a final value of heat power level, *MW;*

W^{in} – is an initial value of heat power level, *MW;*

$\frac{\delta\rho}{\delta N}$ – is a power factor of reactivity taking into account the heating of the coolant at the same temperature at the inlet to the core, $\frac{\%}{MW}$;

$\frac{\delta\rho}{\delta T}$ – is a coefficient of reactivity by temperature of the coolant, $\frac{\%}{°C}$.

The error of determining the reactivity change can be found by the formula:

$$\varepsilon_{\Delta\rho} = \frac{2\cdot\Delta W}{W^{fin} - W^{in}} + \frac{\Delta\left(\frac{\delta\rho}{\delta N}\right) + \frac{8}{3000}\Delta\left(\frac{\delta\rho}{\delta T}\right)}{\frac{\delta\rho}{\delta N} + \frac{8}{3000}\cdot\frac{\delta\rho}{\delta T}} \approx \frac{2\cdot\Delta W}{W^{fin} - W^{in}} + \frac{\varepsilon_N + \varepsilon_T}{2} \tag{5}$$

where $\Delta\left(W^{fin}\right) = \Delta\left(W^{in}\right) = \Delta W$ – is an absolute power measurement error;

ε_N and ε_T – are the relative errors of determining the power and temperature coefficients, respectively.

Similar calculations can be made to calculate the concentration of boric acid, the final power, the volume of distillate for the insertion of positive reactivity, the final position of the CPS AR groups, etc. At the same time, the error of determining the temperature coefficient of reactivity according to the graphs similar to that shown in Figure 1 is approximately 3.5%, the power coefficient approximately -4.2%, the coefficient of reactivity of boric acid approximately - 5%.

Initial and final power, based on the known characteristics of the in-coreinstrumentation system (ICS) [6], can not be determined more precisely than $\Delta W = 60\ MW$. It follows that the result of the calculation will have a noticeable error, the greater the smaller the change in the state of the reactor plant. Figures 1 and 2 show the function of the relative error in the calculation of the reactor plant characteristics.
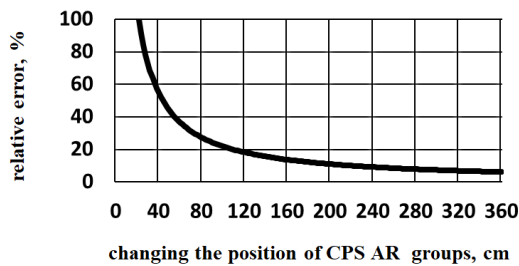
Figure 1. Relative error as a function of the CPS AR group position change.
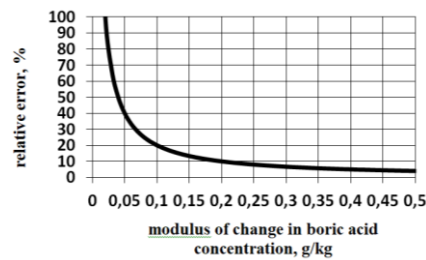

Figure 2. Relative error as a function of changes in boric acid concentration.

Taking into account the small curvature of the calculated graphs, double linear interpolation allows to increase the accuracy by two orders of magnitude [7]. The error of linear interpolation on some segment can be estimated by the formula:

$$\Delta_L \leq \frac{M_2 \cdot h^2}{8} \qquad (6)$$

where M_2 – the maximum of the absolute value of the second derivative function on the segment;
h – the width of the segment.

Thus, the error of calculating the temperature coefficient of reactivity by interpolation does not exceed $2 \cdot 10^{-5}$ in the units of the coefficient of reactivity, which results in a relative error of no more than $0.5 \cdot 10^{-2} = 0.5\%$. The relative error in interpolation of other values from the NPC album graphs do not exceed 0.5 %. Thus, the software implementing the calculation of the reactivity change with the use of double linear interpolation can reduce the error of determining the final state of the reactor plant by 8-12 times. Taking into account these factors, it is necessary to consider software implementation into the lead reactor plant engineer work.

4. Description of development

To eliminate these disadvantages, the authors developed a program to predict the state of the reactor using reactivity balance. The developed program provides information support when the operator of the reactor makes a decision on the impact on reactivity.

The «ANFC-i» software provides an opportunity to carry out calculations of transients associated with changes in reactivity in the entire range of power determined by the maximum allowable thermal power of the reactor depending on the number of operating loops. The maximum allowable heat capacity of the reactor is 104% (3120 MW) of the nominal capacity at four operating main circulation pumps and 40% (1200 MW) of the nominal capacity at two operating main circulation pumps. Figure 3 shows an example of the «ANFC-i» screen form designed to predict the new position of the control and protection system controls when the reactor power changes.
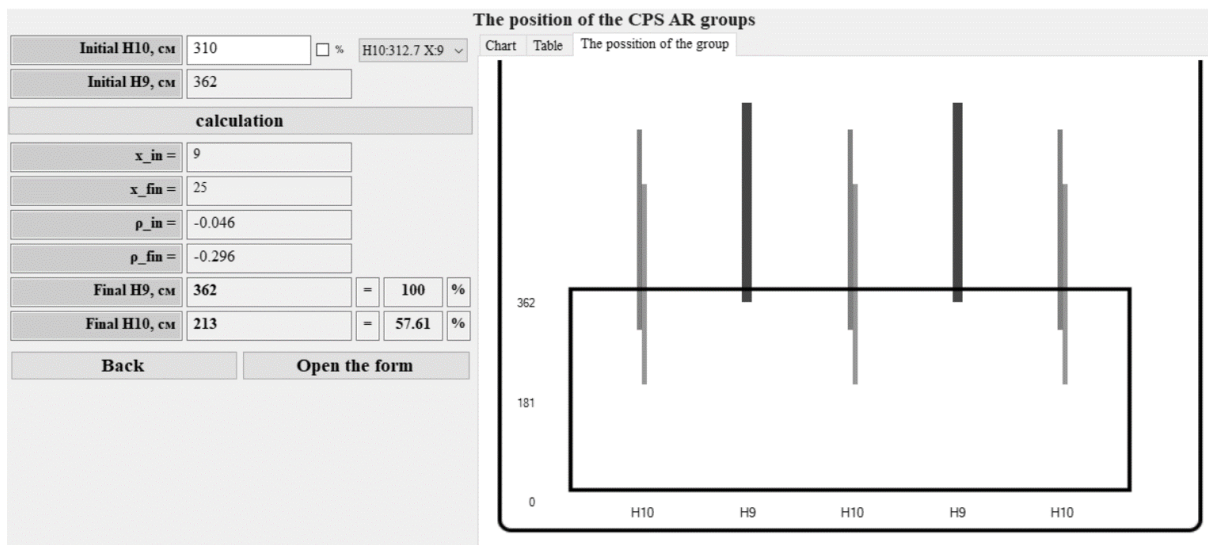
Figure 3. Screen form for calculating the position of the CPS AR groups.

The developed program implements the following types of calculations:

1) calculation of changes in the position of the CPS AR groups when the reactor power changes;
2) calculation of change in concentration of boric acid at reactor power change;
3) calculation of change of critical concentration of boric acid at change of position of CPS AR groups at invariable reactor power;
4) calculation of time and volume of water exchange at feeding the primary circuit with pure distillate or boric acid solution;
5) search of critical configuration of the reactor (the configuration means a combination of power, position of CPS groups and concentration of boric acid) after changing the state of the reactor plant taking into account the change of xenon-135 concentration;
6) calculation of starting concentration of boric acid lot after the reactor unit is switched to the "hot shutdown" state.

Calculations are made on the basis of reference data from the NPC album, read by the program in xml format. Data conversion to the required format was performed during the development process. In order for the calculations to be performed correctly and for the user to enter data within the specified limits, the program provides error messages.

5. Experimental operation of «ANFC-i»

Currently, the developed program is being tested in the training department of Rostov NPP. It is possible to draw preliminary conclusions:

- the developed program implements the declared set of functions in full;
- mastering the interface and operation of the program takes no more than 15-30 minutes for qualified personnel of the reactor shop;
- in the process of training on a full-scale simulator, the staff spends no more than 1-1.5 minutes calculating reactivity changes under the conditions of distractions.

According to users' comments, additional features were added to the program:

- input of initial data and output of results concerning CPS AR position both in centimeters from the bottom of the core and in percentage of stroke;
- input of initial data and output of results in terms of power unit capacity, both thermal and electrical;
- prediction of boric acid concentration a day ahead taking into account xenon processes;
- calculation of the required water exchange time, taking into account the supply of make-up pumps, both for the supply of distillate and boron concentrate.

Comparison of «ANFC-i» calculations with the results of full-scale simulator was conducted mainly in the process of raising and reducing the power unit capacity. The relative difference between the «ANFC-i» calculation and the simulation results was chosen as a comparison indicator. For example, if calculating change of group positions while modifying the capacity there has been received by ANFC that the position of the 10th group should be changed on $\Delta H10_{(ANFC)}$, and by the simulator - on $\Delta H10_{(FSS)}$, the relative difference is defined by the formula:

$$d_1 = \left| \frac{\Delta H_{10(ANFC)} - \Delta H_{10(FSS)}}{0,5 \cdot \left(\Delta H_{10(ANFC)} + \Delta H_{10(FSS)} \right)} \right| \qquad (7)$$

Similarly, for the concentration of boric acid C_B is determined:

$$d_1 = \left| \frac{\Delta C_{B(ANFC)} - \Delta C_{B(FSS)}}{0,5 \cdot \left(\Delta C_{B(ANFC)} + \Delta C_{B(FSS)} \right)} \right| \qquad (8)$$

Calculating boron overcompensation at constant power the calculated and simulated displacement of the 10th group moved to the regulatory position by increasing the concentration of boric acid in the primary circuit are compared, similarly to the formula (7). The results of comparison are given in Table 1.

Table 1. The «``ANFC-i»» software testing

Type of calculation	Number of performed calculations	Relative difference in physical units d1, %
Calculation of group position changes in case of power changes	12	1.4-14.2
Calculation of the change in the concentration of boron acid at power change	9	1.2-5.2
Calculation of boron overcompensation at constant power	12	1.5-11.4

The reason for the increased error in calculating the position of groups may be a large number of assumptions used in calculating their effectiveness. Thus, according to the NPC album, the relative error of the group's full stroke efficiency calculation is ±10% (in reactivity units). The authors have shown in [3] that the relative error increases in the calculation of partial group movements. Thus, it is not possible to significantly improve the accuracy of this calculation within the existing system of engineering and computational support for the operation of PWR reactors, which implies the use of the "KASKAD" software.

6. Conclusion
The software calculation of reactivity balance allows increasing the safety of operation of the PWR reactor plant by increasing the accuracy and speed of evaluation of the final state of the reactor when making a decision on the impact on the reactivity, compared to the traditional use of the NPC album.

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