PAPER • **OPEN ACCESS**

Determining the critical concentration of boric acid and the time of its onset when reaching to minimum controllable power for VVER

To cite this article: A I Al-Shamayleh *et al* 2020 *J. Phys.: Conf. Ser.* **1689** 012041

Determining the critical concentration of boric acid and the time of its onset when reaching to minimum controllable power for VVER

A I Al-Shamayleh, D A Solovyov, A A Semyonov, N V Shcukin, B Djaroum, H A Tanash and I A Molev

Institute of nuclear physics and engineering, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse, 31, Moscow, 115409, Russian Federation

asema7078@gmail.com, vulture@inbox.ru

Abstract. Startup to minimum controllable power level (criticality approach) is one of the most hazardous nuclear operations during operation. In particular, the spontaneous and unauthorized startup to minimum controllable power is very dangerous, and it occurs as a result of some technological operations or changes in technological regimes. Currently, there are codes for neutron-physical calculations at NPPs with VVER, such as reactor simulator (IR) and BIPR-7A. These codes calculate the boric acid critical concentration without relying on ex-core ionization detectors data, which may result in inaccuracies in determining the critical concentration. In addition, feeding the primary circuit with clean condensate must be stopped at least 15 minutes before is reached, and these codes do not calculate the time to reach the critical state. As a result, the idea arose to develop a code that would predict the time to reach the critical state and the critical concentration of boric acid only using the measuring equipment readings without reliance on additional calculations.

1. Introduction

The development of nuclear power requires the solution of a number of important scientific and engineering problems, first of all, improving the safety, reliability, efficiency and economy of the newly created and already used NPP equipment, including those with VVER reactors, since among the huge variety in principle possible and a much smaller number of economically profitable and technically developed types of reactors for nuclear power plants, they occupy a very important place.

One of such responsible and important tasks reactor start-up. Reactor start-up is a separate complex nuclear-hazardous procedure, therefore, it receives increased attention, it is regulated by special instructions. In management practice, the procedures of physical and energy starts are distinguished. In this article, an algorithm is considered that allows one to reduce the psychological load on the operator when switching from a mode with a minimum change in power to a mode with a rapid increase in power during one of the most important and dangerous stages of the power start-up, called Startup to minimum controllable power level (MCL).

2. VVER-1000 reactor start-up and its driving to MCL

Driving VVER reactors to the MCL is carried out after refueling and is carried out approximately once every one and a half years, in addition to that, during the campaign, for various reasons, several shutdowns are carried out, after which the reactor is also withdrawn - first to the MCL, and to power levels.

Before proceeding with driving the reactor to the MCL, the critical concentration of boric acid is calculated using the standard BIPR-7A operation support program [1].

Startup to the MCL is carried out in the following order:

- boric acid is removed from the primary circuit (distillate is introduced) to a concentration of about 1 g / kg more than the critical one;
- entering distillate is stopped to ensure uniform mixing of the coolant in the primary circuit, pressure compensator and deaerator;
- boric acid removal continues at a low rate until a small supercriticality is reached. At the same time, the reactor power grows up to the MCL (from 10-8 to 10-3% of the nominal power value in a few hours). When carrying out this operation, it is necessary to stop the distillate injection in a timely manner (10-15 minutes), since the reaction to the closing of the feed valves with pure condensate (PC) occurs with a delay for tens of minutes due to the large volume of supply lines. If, in the process of bringing the reactor to the ISU, the acceleration period is less than 60 s, then the emergency protection will operate and the reactor will have to be restarted, and for this it will be necessary to bring all the systems of the power unit to the hot state again. This may take from one day or more, which will lead to losses in power generation;
- boric acid removal stops, the power begins to be maintained by the movement of the control rods.

From the above it follows that the determination of the critical concentration of boric acid and the remaining time before reaching the MCU is an important practical task.

3. Current situation during driving the reactor to the MCL

Currently, nuclear power plants with VVER use neutron-physical calculation programs such as a reactor simulator (IR) [2] and BIPR-7A. Unlike the BIPR-7A program, which performs static calculations, the IR program calculates the dynamics of xenon processes and is focused on providing information support to the NPP operator in real time. Both of these programs calculate the critical boric acid concentration using fuel load data without relying on ex-core ionization detectors data, as a result there may be an error in determining the critical concentration of boric acid. In addition, the feeding of the first circuit of the PC must be stopped at least 10-15 minutes before reaching the MCL, and these programs do not calculate the time before reaching the critical state. As a result, the idea arose of developing a program that would predict the time to reaching the critical state and the critical concentration of boric acid, relying only on the readings of the measuring equipment, without using the load data.

This idea was implemented in the MKU01 program [3], which is used during the start-ups of all four power units of the Kalinin NPP. This program allows you to update in real time the value of the critical concentration of boric acid and the time before reaching the MCL, using the power obtained from the ex-core ionization detectors data and the readings of the boron meters in the primary circuit. The developed program allows solving the following tasks:

- to reduce the psychological load on the operator when switching from a mode with an almost imperceptible change in power to a mode with its rapid growth, since for various reasons the value of the calculated starting concentration of boric acid can have a noticeable error;
- in a timely manner (not less than 15 minutes) to stop the withdrawal of boric acid from the primary circuit;
- to ensure the performance check of measurement system of currents ex-core ionization detectors and boron meters by comparing the readings of various sensors.

In the MKU01 program, the algorithm has established itself as a reliable mean of processing experimental data to determine the value of the starting concentration of boric acid at NPPs with VVER-1000 [4].

However, the algorithm has a number of disadvantages, for example, using of linear regression for approximation of data on boric acid concentration, which provides a predicted time before the reactor reaches a critical state of the order of 15–40 minutes. I would like to increase this time, passing from linear regression to logarithmic, which is more consistent with the real change in the concentration of boric acid in the first loop. Possibly, such a transition will also lead to an increase in the accuracy of determining the starting concentration of boric acid.

4. Mathematical model

When developing an improved algorithm for predicting critical parameters, the following processes were considered:

- multiplication of background source neutrons with considering the change in the shape of the neutron field with an increase in the integral power;
- change in the concentration of iodine and xenon due to radioactive decay;
- change in the concentration of delayed neutron emitters;
- dynamics of mixing of the coolant and distillate when changing the position of the corresponding valves;
- generation of boron meters signals, including consideration of the noise of this device;
- generation of ex-core ionization detector signals, including consideration of random noise and limitation of the current signal;
- transfer of radiation from the active core to the location of the ex-core ionization detectors.

Consideration of these processes showed that it is possible to use a simplified model, which neglected:

- kinetics on prompt and delayed neutrons;
- isotopic kinetics of iodine and xenon;
- changes in the background neutron source in time;
- changes in the spatial distribution of the neutron field in the process of start up to the MCL;
- nonlinearity of the dependence of reactivity on the concentration of boric acid;
- nonlinearity of the dependence of the current of ex-core ionization detectors on the neutron flux density, except for the hardware limitation of the detectors current;
- the randomness of the noise in the readings of the boron meter (its amplitude does not change when it reaches a critical state);
- the constancy of the current noise of the ionization detectors (for a given detector).

5. New algorithm of the MKU program

The change in the concentration of boric acid in the primary loop is described by the following equations:

$$M\frac{dCb(t)}{dt} = (C_{\text{p}} - Cb(t))G; \quad (1)$$

$$Cb(0) = Cb_0, \quad (2)$$

where M — is the mass of the primary coolant; G — feed / flushing mass flow rate; *Cb(t)* — current concentration of boric acid in the primary circuit; C_p — feed concentration — either PC or concentrated boric acid; *Cb*(0) — concentration of boric acid in the primary circuit at the start of the feed / flushing process.

The technological process of feeding is carried out either by PC or by a boric acid solution. In both cases, the feed concentration is constant. The boric acid concentration in the primary circuit at the time of completion of the feeding is calculated from equations (1) and (2) and has the form

$$Cb(t) = \exp\left(-\frac{G}{M}t\right)\left[-C_{\mathrm{p}} + Cb(0) + C_{\mathrm{p}}\ \exp\left(\frac{G}{M}t\right)\right]. \quad (3)$$

Since in our case the concentration of the feeding is $C_{\mathrm{p}} = 0$, then from equation (3) we obtain $C_{\mathrm{p}} = 0$,

$$Cb(t) = Cb(0)\ \exp\left(-\frac{G}{M}t\right) \quad (4)$$

or, by changing variables:

$$Cb(t) = Cb(0)\ \exp(-\omega t), \quad (5)$$

where ω — estimated constant of change in boric acid concentration.

Making the logarithm, we transform equation (5) to the form

$$\ln[Cb(t)] = \ln[Cb(0)] - \omega t. \quad (6)$$

After using regression analysis to process the data on the start up to the MCL, we will find the coefficients *Cb*(0) and ω, which will be used in the future to assess the critical concentration of boric acid.

Now let us consider the relationship between the power obtained from ex-core ionization detectors readings and the concentration of boric acid in the primary circuit. For this, we use the stationary equations of the point kinetics of the reactor with feedback on the concentration of boric acid in the coolant in the subcritical state

$$0 = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^{m} \lambda_i C_i + S; \quad (7)$$

$$0 = \frac{\beta_i}{\Lambda} n - \lambda_i C_i;$$

$$\beta = \sum_{i=1}^{m} \beta_i,$$

$$\rho \neq 0,$$

where n — the neutron power of the reactor; C_i — the concentration of delayed neutron emitters (group I); ρ — reactivity; Λ — the lifetime of prompt neutrons; β_i — the effective fraction of the output of group *i* emitters i; λ_i — the time constant of emitters of group i; *S* — background source.

If we supplement system (7) with the equation for the dependence of the detectors current on the neutron power and the equation for the dependence of the reactivity on the concentration of boric acid

$$n = KI;$$
$$\rho = (Cb(t) - Cb_k)\alpha; \quad (8)$$
$$\alpha = \frac{\partial \rho}{\partial Cb(t)},$$

Where I — measured current of ex-core ionization detectors; K — sensitivity of ex-core ionization detectors to neutron flux; Cb_k — the critical concentration of boric acid in the primary loop, then equation (7) will take the form

$$I = -\frac{S\Lambda}{K\alpha(Cb(t) - Cb_k)}, \quad (9)$$

or, grouping constants:

$$F = \frac{S\Lambda}{K\alpha};$$
$$I = -\frac{F}{Cb(t) - Cb_k}. \quad (10)$$

Since when approaching the critical state, the power of ex-core ionization detectors increases strongly (figure 1), then it will be more convenient to use the reverse currents of ex-core ionization detectors.

$$\frac{1}{I} = -\frac{Cb(t) - Cb_k}{F}, \quad (11)$$

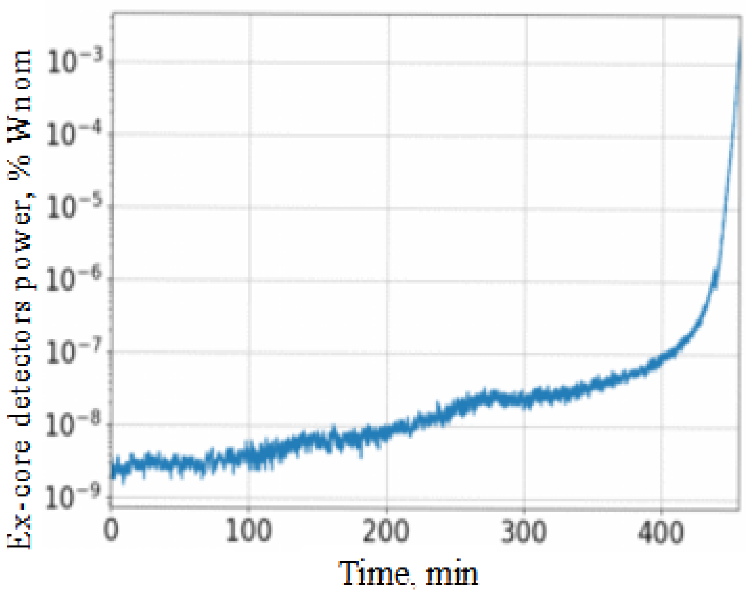

Figure 1. Dependence of power according to ex-core ionization detectors data on time in the process of start up the MCL.

or, grouping the constants again:

$$\frac{1}{I} = A + BCb(t). \quad (12)$$

The coefficients A и B in equation (12) are found by doing regression analysis of the data on the start up to the MCL (figure 2). Since we use a quasi-static approximation, we will assume that the criticism is realized when the power of ex-core ionization detectors tends to infinity. From equation (12) we can find the critical concentration of boric acid

$$I \to \infty \Rightarrow \frac{1}{I} = 0; \quad (13)$$

$$A + BCb_{\text{k}} = 0; \quad (14)$$

$$Cb_{\text{k}} = -\frac{A}{B}. \quad (15)$$

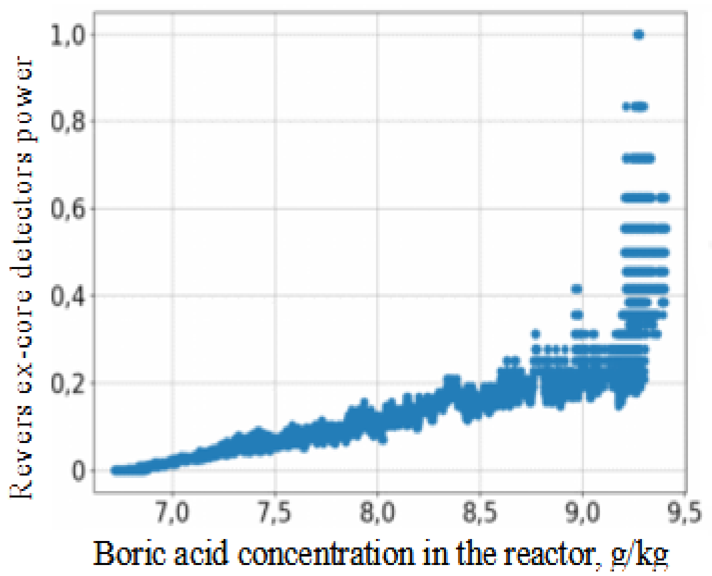

Figure 2. Dependence of the reverse power according to ex-core ionization detectors data on the concentration of boric acid in the reactor during the process of start up to the MCL.

Knowing the critical concentration in the primary circuit and using Eq. (5), you can get the time of the onset of criticism

$$Cb_k = Cb(0)\ \exp(-\omega t); \quad (16)$$

$$t_{\text{k}} = -\frac{\ln[-\frac{A}{BCb(0)}]}{\omega}. \quad (17)$$

It should be noted that the developed algorithm is applicable with unchanged positions of the control elements, constant coolant temperature at the inlet to the core, constant availability of experimental data, and such a rate of start up to the MCL so that transient processes on delayed neutrons can be neglected; it is also necessary that the reactor be in xenon poisoned state.

6. Conclusion

The developed algorithm was tested on the operational data of the NPP. The check has shown that taking into account the exponential dependence of the change in the concentration of boric acid in the first loop makes it possible to accelerate the time of the appearance of the forecast for the critical concentration of boric acid by 20–30% compared to a similar linear approximation (figure 3) [5].

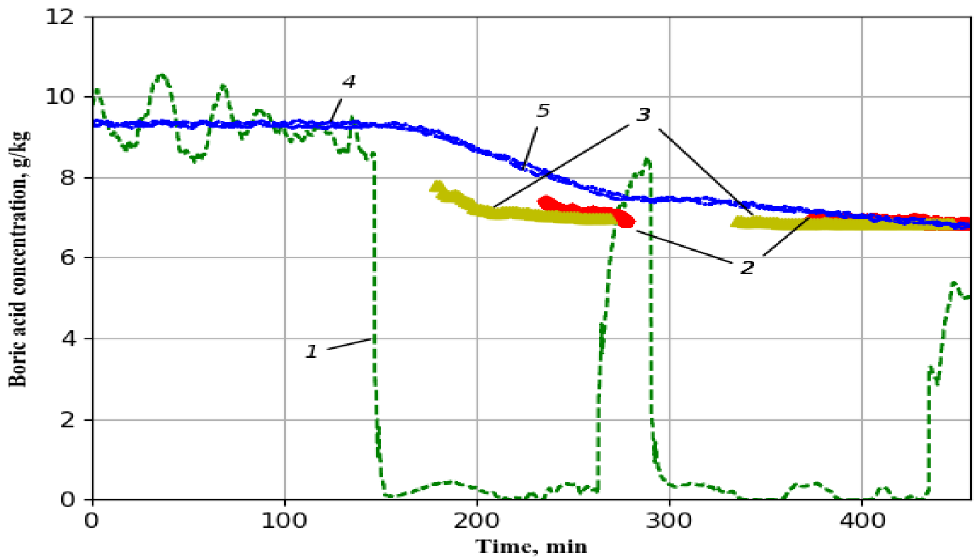

Figure 3. Measured and calculated concentrations of boric acid at the time of start up to the MCU: 1 – boric acid concentration in the make-up node; 2 – the predicted value of the critical concentration of boric acid in the reactor, obtained using the MKU01 program; 3 – the predicted value of the critical concentration of boric acid in the reactor, obtained by the new algorithm; 4 and 5 – current values of boric acid concentration in the reactor according to the readings of boron meters.

Acknowledgments
The authors are deeply grateful to V.M. Chapaev for his help in preparing the article.

References
[1] Federal supervision of Russia on nuclear and radiation safety 2008 Attestation certificate of the software tool. BIPR-7A program. Version 1.5. Registration number of the software in the electronic digital signature No. 613 of 31.07.2008. Registration number of the passport of attestation of the software tool No. 214 of 23.09.2008. —M.
[2] Federal supervision of Russia on nuclear and radiation safety 2002 Attestation certificate of the software tool. IR program. Version 1.2. Registration number of the software in digital electronic signature No. 516 dated 02.21.2002. Registration number of the passport of attestation of the software tool No. 138 dated 02.21.2002. —M .
[3] Aksenov V I, Bogachek L N, Grubman V Ya, Lupishko A N, Kiselev S I, Semenov A A, Chapaev V M 2003 in the collection: Materials of the 14th annual conference of the Russian nuclear society “Scientific support for the safe use of nuclear energy technologies” Development and implementation of methods for monitoring the subcritical state of the reactor during driving the reactor facility to the MCL at units 1 and 2 of the Kalinin NPP (Udomlya) p 21-36.
[4] Semyonov A A, Chapaev V M 2003 In collection: Materials of the 13th seminar "Neutronika-2003" Algorithm for estimating the critical concentration of boric acid when starting up to the minimum controlled power level (Obninsk).
[5] Al-Shamayleh A I, Solovyov D A, Semyonov A A, Shcukin N V, Djaroum B, Tanash H A 2020 Methodology for determining the time before reaching to the MCL for VVER *PAST* **1** p 56-60