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Technical note

Simulation of VVER-1000 startup physics tests using the MCU Monte Carlo code

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ABSTRACT

The main objective of this work is to make the quality test and verification of a full-scale computer model of the VVER-1000 reactor with the detailed description of the geometry and material composition. Using the computer model and MCU Monte Carlo code, we simulated the experiments conducted at the stage of physical start-up of the third power unit of Rostov NPP (Russia) in December 2014. The following neutron-physical characteristics were calculated: effective neutron multiplication factor, critical boric acid concentration, efficiency of single control rod cluster, integral and differential efficiency of control rod group, scram system reactivity worth, and reactivity coefficients. The calculated neutron-physical characteristics were compared with the measured ones. The comparison shows agreement with the measured data over the range of the experimental error and statistical uncertainty of the calculation. To reduce the impact of statistical uncertainty on the calculated differential control rod reactivity worth and reactivity coefficients we applied a special approach for the estimation of these parameters.

1. Introduction

In the past several years, there is a stable trend to involve the Monte Carlo codes in calculation of the neutron-physical characteristics of the full-scale reactor cores. The Monte Carlo calculation of the full-scale reactor core is often used to obtain the credible values of the important reactor safety characteristics, for which measurement is difficult or impossible. In addition, Monte Carlo calculation of the full-scale reactor core is used to verify the accuracy of design codes. This is particularly important when developing the physical part of a perspective fuel cycle design for which the operating experience is absent.

A computer model specifying the considered system is a prerequisite for Monte Carlo calculations. The complexity of the full-scale reactor model development leads to the need of a thorough verification of agreement between the computer model (geometry, material composition, etc.) and the real reactor. The purpose of the article is to demonstrate one of the possible ways to make the quality test and verification of the full-scale reactor model.

We developed a full-scale VVER-1000 computer model with a detailed description of the geometry and material composition of the core and its reflectors. Using the computer model and MCU Monte Carlo code, we simulated the experiments conducted at the stage of physical start-up of the third power unit of Rostov NPP (Russia) in December 2014. The following neutron-physical characteristics were calculated: effective neutron multiplication factor, critical boric acid concentration, efficiency of single control rod cluster, integral and differential efficiency of control rod group, scram system reactivity worth, and reactivity coefficients.

In case of coincidence of the measured values and the calculated ones within the limits of calculated and experimental errors, the computer model can be used to calculate the neutron-physical characteristics of a VVER-1000 core.

2. Methods

Simulation of the startup physics tests was carried out using the MCU code and the full-scale computer model of the VVER-1000 reactor. In addition, we applied the polynomial approximation method to calculate the differential efficiency of the control rod group and the least squares method to calculate the reactivity coefficients.

2.1. The MCU code

MCU (Monte Carlo Universal) is designed to address the analog and non-analog Monte Carlo heterogeneous transport equation for neutrons, photons, and charged particles. For neutrons, the code allows solving the homogeneous equation. It uses the evaluated

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nuclear data and the detailed description of the laws of interaction of particles with matter, without simplifications in geometry and taking into account various boundary conditions. The paper (Kalugin et al., 2015) reviews the modern MCU software package. During simulation of startup physics tests, we used the following libraries included in the MCU data bank (Kalugin et al., 2015): ACE/MCU (fast energy region), MULTIC (unresolved resonances region), LIPAR (resolved resonances region), VESTAM (thermalization region).

2.2. The computer model of VVER-1000

The full-scale three-dimensional computer model of VVER-1000 was developed based on the previously existing VVER-1000 computer model (Bikeev, 2015) and using the design documentation of the fuel assemblies and the reactor facility: reports, drawings, explanatory notes, and technical validations. The study of influence of the detail specification of some structural elements of fuel assembly (top nozzle, bottom nozzle, and spacer grids) on the basic neutron-physical characteristics of the reactor core had been preliminarily carried out (Bikeev et al., 2013).

The computer model consists of the geometry and material description of the following elements, beginning from the center: fuel assemblies making the core; a baffle; a reactor pit; a reactor vessel; and some elements of beyond vessel space.

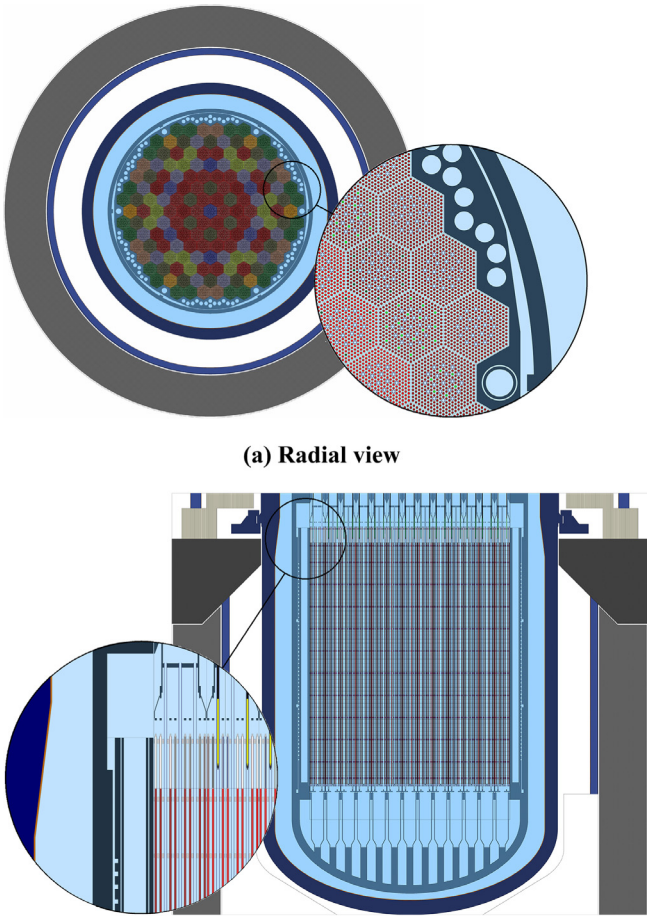
The reactor core was assembled from 163 fuel assemblies with fresh fuel according to the first fuel-loading pattern of the third unit of Rostov NPP. Special attention was paid to the accurate specification of the geometry and material description of fuel and control rods, spacer and mixing grids, guide tubes, bottom and top nozzles of the fuel assembly model. The fuel rod model consists of a cladding, fuel pellets, a spring lock, and top and bottom endpieces.

Fig. 1 shows the 2-D images of the computer model.

The chemical isotopic compositions of all materials used in the computer model are described in detail. The information about the chemical isotopic compositions of steels, alloys and other structural materials is taken from the state standards, technical specifications or design documentation.

The computer model includes the absorbing elements of control rods. The top part of control rods contains boron carbide with a natural content of boron isotopes. The bottom part of control rods contains dysprosium titanate. The control rods are combined into a control rod cluster (18 control rods in the fuel assembly). Control rod clusters are grouped into 10 groups. A group consist of three to nine clusters. An operating group is the group which number is 10. The group's position specifies by the percent of its withdraw from the reactor core. In Fig. 2, the numbers on the core loading pattern are the numbers of control rod groups.

It should be noted that development of the VVER-1000 computer model with the detailed description of geometry and material composition is complex and extremely laborious work. The input data file of the model contains about one million text lines and has the size greater than 100 MB. It is made using the MCU-Constructor interface. The interface (see Fig. 2 is designed for automated development of MCU input files using the interface library and some user-defined data: fuel loading pattern, control rods position, etc. The interface library contains information on the geometry and material composition of fuel assemblies and reactor facilities in the form of prototype files. Additionally, MCU-Constructor includes capability for processing and visualizing the calculation results. It significantly reduces the total time spent on the problem by means of automated creation of input file, processing and visualizing the results.



(a) Radial view

(b) Axial view

Fig. 1. Computer model of VVER-1000.

2.3. The method for estimating integral and differential efficiency

Several stationary reactor states weresimulated. The only difference was the position of the studied group. The integral efficiency was calculated using equation,

$$\Delta\rho_i = \frac{1}{k_{eff,0}} - \frac{1}{k_{eff,i}} \tag{1}$$

where $k_{eff,0}$ and $k_{eff,i}$ are effective neutron multiplication factors for states zero (initial position of the group) and i relatively.

Statistical uncertainty of integral efficiency was defined as,

$$\sigma(\Delta\rho_i) = \sqrt{\frac{\sigma^2(k_{eff,0})}{k^4_{eff,0}} + \frac{\sigma^2(k_{eff,i})}{k^4_{eff,i}}} \tag{2}$$

where $\sigma(k_{eff,0})$ and $\sigma(k_{eff,i})$ are statistical uncertainties (one standard deviation) in estimating of the values of $k_{eff,0}$ and $k_{eff,i}$.

The dependence of the integral efficiency on the group position $\Delta\rho = f(H)$ was approximated by a polynomial of degree 6,

$$\Delta\rho = \sum_{n=0}^{6} \alpha_n H^n \tag{3}$$

where α_n is an approximation coefficient, and H is the position of the studied group.

The differential efficiency can be calculated as the derivative of Eq. (3) with the respect to the argument H