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Temperature coefficients calculation for the first fuel loading of NPP Mochovce 3–4

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ABSTRACT

Due to the planned first criticality start-up of the Nuclear Power Plant (NPP) Mochovce units 3 and 4 in the near future, detailed analyses of core parameters are required to support safe operation of the nuclear facility. Since the previous calculations were performed by the deterministic nuclear codes, the stochastic approach was used to produce the independent results. The paper introduces determination of temperature feedback reactivity coefficients, especially summary (isothermal) and moderator (density) reactivity coefficients between 200 °C and 260 °C with step of 2 °C. The evaluation of the critical boron acid (H_3BO_3) concentrations for different positions of the 6th control assembly group was performed for the given coolant temperatures as a precondition of the thermal coefficients calculation. All calculations were performed by computational code MCNP5 1.60 supported by NJOY99.364 microscopic cross sections processing system and our control scripts. For the validation of the criticality calculations (critical boron acid concentration), the experimental data based on the first critical conditions of the NPP Mochovce 2 start-up were used.

1. Introduction

The completion of last two units of Nuclear Power Plant (NPP) Mochovce has been restarted in Slovakia in the year 2008. Originally the construction started in 1985, but in1992 was interrupted and NPP was conserved. The licensed design included also definition of the first loading pattern which was based on the 1st generation fuel. Unfortunately this fuel generation is not manufactured in the present, hence the first criticality start-up of the new 3rd and 4th unit of the Slovak NPP Mochovce, which is planned in near future, will be based on the first core loading pattern with 2nd generation fuel. In addition, to preserve ability reached nominal power, the original first loading pattern from the basic design has to be also maintained. Normally, the VVER-440 reactor is initially started up from a precondition stage by placing control rods to the working positions, by withdrawing the safety rods (5 groups), and by decreasing the boron acid concentration (from the shutdown level) in primary circuit coolant until the reactor is slightly supercritical, thus producing an exponentially increasing neutron population on a very long period. In general, as the neutron population increases, the fission heating and thus the reactor temperature increases, but the difference between temperature of water and fuel is significant. In the case of first start-up process, temperature changes of the reactor core in the Cold Zero Power (CZP) are driven only by the work of circulation pumps. Energy released from fission is negligible in this case, so the temperature of fuel is based on the temperature of coolant. The VVER-440 reactors reaches CZP at 200 °C and the core heating process, which is relatively slow, is carried out till 260 °C. Therefore we can assume that the temperature is changing in all parts of the reactor core during this process uniformly. The purpose of this procedure is to decrease the necessary boron acid concentration and to mitigate the positive temperature effect in the core. In terms of the increased moderator and fuel temperature, it will cause a change in the local fuel–moderator properties as well as change in both the moderator absorption and the flux disadvantage factor which are defined and measured as a temperature reactivity coefficients. In addition, a decrease in moderator density will reduce the moderating effectiveness and produce a hardening (shift to higher energies) in the neutron energy distribution. This will have an effect on the effective energy-averaged absorption cross sections for the fuel. The reduction in moderator/coolant density increases the diffusion length of neutrons, which will cause of the increased leakage from the system and also reduces the parasitic absorption in water and boron diluted in the coolant (Stacey, 2001). The change of k_{eff}

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during this process is caused by temperature feedback only and this change is compensated by boron acid concentration or by movement of safety rods. Generally, core loading patterns are designed in such way that temperature reactivity effect should already be negative at the CZP. Meeting this requirement could be problematic, particularly for the first core loading, when all fuel assemblies are fresh and water–uranium ration will be changed. For this reason the detailed analyses of start-up temperature reactivity feedback coefficients should be performed to support licensing process and verify feasibility of this stage of commissioning.

2. Material and methods

Considering the whole core effects of the VVER-440 reactor during the first start-up, reliable neutron transport calculation can only be performed using a technique enabling the treatment of complex three-dimensional geometry. Therefore the MCNP5 1.60 code (Monte Carlo Team, 2003) based on transport Monte Carlo method was chosen and applied. Regarding the objective to determine the temperature coefficients of reactivity with high accuracy and reliability, the geometric and material part of the reactor model was created in the finest possible details. In the same way, determination of temperature reactivity coefficients in the range between 200 °C and 260 °C were performed. To register all eventual fluctuations of a reactivity change caused by the increased temperature, calculation was performed with 2 °C step. As was mentioned above, the first start-up of new units will be the unique critical experiments due to usage of second generation fuel. Based on the lack of experimental data, the criticality calculation of CZP during the first start-up of NPP Mochovce 2 was carried out to evaluate the computational bias and uncertainty coming from the input parameters. The first loading pattern of NPP Mochovce 2 was based on the first generation fuel which is more under moderated in comparison with the second generation. In this context, the temperature reactivity coefficients for units 3 and 4 with first generation fuel design were also investigated.

2.1. Cross section processing

Libraries of the microscopic effective cross sections and probability tables entering the calculation code MCNP5 1.60 were prepared using NJOY99.364 code system (MacFarlane and Kahler, 2010). The code system NJOY is a modular calculation system where each module is intended for solving a specific assignment. The verified library of microscopic effective cross sections ENDF/B-VII distributed by OECD NEA Data Bank consisting of 381 materials was used as an input for the NJOY99.364 calculation (ENDF library, 2011). The whole library preparation process was verified (Lüley et al., 2012) using benchmark tasks based on the International Handbook of Evaluated Criticality Safety Benchmark Experiments (Handbook of Evaluated Criticality Safety Benchmark Experiments, 2007). Special cases were selected to cover basic parameters describing VVER reactors like low enriched UO_2 fuel, water as a moderator and coolant, H_3BO_3 and structural materials. In addition the comparison of different source of nuclear data were carried out (Lüley et al., 2012). Processing of the microscopic effective cross sections by NJOY99.364 is schematically illustrated in the Fig. 1. The individual modules are well described in MacFarlane and Kahler, 2010. For each desired temperature and by using mentioned methods, new cross section data sets were prepared.

MCNP uses two different methods to account for the scattering of neutrons. For the most materials it attempts to construct a free-gas scattering model based on the constant elastic cross-section. For important moderator materials, like hydrogen bound in water in our case, it takes the binding of the material in the solid, liquid or gas into account (Brown, 2006). The binding of the scattering nucleus affects the cross-section, the angular and energy distribution of secondary neutrons, as the neutron can give up energy to excitation in the material or it can gain energy. For these reasons the basic nuclear data files are complemented by scattering law $S(\alpha,\beta)$ files which describe the thermal scattering of bound moderators (Mattes and Keinert, 2005). $S(\alpha,\beta)$ light water law files were prepared for each computational step by *makxsf* code. The main functions performed by *makxsf* include Doppler broadening and for our purpose most important feature, interpolation of $S(\alpha,\beta)$ thermal scattering kernel data to required temperatures. (Brown, 2006).

2.2. Critical boron acid estimation

The MCNP5 1.60 code used to calculate the critical boron acid (H_3BO_3) concentration, does not have the direct output of this value. The critical boron acid concentration corresponds to the value, at which the calculated k_{eff}^{MCNP} is equal to 1 with the defined accuracy. The result can be obtained in at least two ways: simulation of the critical experiment or using the iteration method. Taking into account the computation time to evaluate the critical boron acid concentration, the iteration method was chosen for the analyses. This approach is capable of shortening the calculation time due to no need to analyze the partial calculation results and decreasing the amount of necessary iteration steps. This shortening was also achieved by automating the processing of results and preparing new input files. Moreover, the applied method allows automatic termination of the computation when the specified result's accuracy is reached. The numerical iteration procedure used for evaluation of the critical boron acid concentration uses the bisection method and the Newton's iteration method. The control Unix shell script in the scripting language C shell was developed.

2.3. Validation

For the validation of the criticality calculations (critical boron acid concentration), the first critical conditions of the NPP Mochovce 2 start-up were used (Pre-Operational Safety Report, 2005). The stabilized critical parameters are presented in Table 1.

In order to validate the calculation of the critical boron acid concentration, experimental values obtained by three more independent measurement methods were considered. The values coming from the different experimental methods are:

- Potentiometric method, c_{Bcrit1} = 8.12 g/kg.
- Coulometry method, c_{Bcrit2} = 8.14 g/kg.
- Titration method used in NPP Mochovce, c_{B3crit} = 8.08 g/kg.
- 716 DMS Titrino method, used in NPP Mochovce as well, c_{B4crit} = 8.11 g/kg.

The experimental data have been provided by VUJE Trnava a.s and by SE a.s during the first start up of NPP Mochovce 2. These boron acid concentration measurement methods provide the values with uncertainty of +0.05 g/kg. In relation to the above described conditions, the MCNP5 input file was created, taking into account all the materials and geometric arrangement of the first fuel loading of the NPP Mochovce 2.

The critical H_3BO_3 concentration for the first fuel loading of the Unit 2 was calculated for the described conditions by means of the iteration method. During the calculation, the accuracy of the k_{eff}^{MCNP} calculation was adjusted to the value better than ξ_N = 0.00005, due to the boron acid concentration changes smaller than the experimentally measured. The calculated critical H_3BO_3 concentration $c_{Bkrit}^{MCNP} = 8.45$ g/kg differs from the experimentally obtained value of $c_{Bkrit}^{\exp} = 8.11$ g/kg. This deviation is considered to be a systematic error and an additive penalty of the calculations, which