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Approaches to optimization of core reactivity coefficirnts for the "MASTER" heat supply reactor

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Abstract

After increasing the power output of heat supply reactor «MASTER» by insertion of the annular channel with coolant, feedback coefficients are deteriorated. Thereby, there was need to find ways for changing reactivity coefficients in new reactor design and at the same time to save natural circulation, low core pressure and outlet core temperature of coolant. Reactivity coefficients have been calculated depending on width and locations radius of annular coolant channel at once to fuel enrichment. Neutron-physical code WIMS-D4 was used as calculation tool. The results showed that the feedback coefficients optimum can be achieved by reducing of annular channel width and increasing of fuel enrichment. At the same time reactivity coefficients are insensitive to location of annular coolant channel radius changes. Restrictions for fuel enrichment (IAEA requirements) coupled with geometry restrictions of annular channel listed above (impossible to remove the thermal power or significant increasing of heat exchangers height) have shown that prospect of feedbacks improving via width and location of annular channel is used up. Possible improvements can be achieved by changing type of burnable poison and neutron spectrum.

Keywords: Reactor physics; Burnable poison; Small reactors; Reactivity coefficients.

Introduction

Application of nuclear power includes the use of small nuclear reactors with a thermal power of up to 300 MW. The development status of small power units, including very small units with a thermal power of below 30 MW can be seen from [1] and from proceedings of periodic conferences on small-scale power generation, e.g. [2]. In publications, the number of the designs not implemented exceeds to a great extent the number of those brought into life. In the USA in the 1950s, about a dozen small reactors were built for energy saving applications at military sites far off district power grids. No further evolution of these units followed because of little emphasis placed on economic issues in such designs [3]. There were a number of later designs developed largely as rivals to units of a comparable power fired by conventional fossil fuel. Some of the designs have been implemented [4,5].

This study is a continuation of [6,7] and focuses on the development of the 300 kW MASTER heat supply reactor. As opposed to other small and very small reactor designs, this reactor features natural coolant circulation, low pressure in the primary circuit (0.16 MPa) and a concept of a fuel-coolant heat conduction matrix which forms an additional safety barrier.

In the course of the design, a 1 MWth reactor modification of an improved performance [8] was achieved as the result of the following improvements:

- the reactor's thermal power was increased to 1 MW through adding an annular cooling channel to the reactor core design;
- the uranium enrichment was reduced to below 20%;
- the content of Be was reduced through the use of the Al-Be alloy;
- dysprosium (Dy) was used as the burnable absorber (BA) for the passive compensation of the reactivity variation due to the fuel burn-up.

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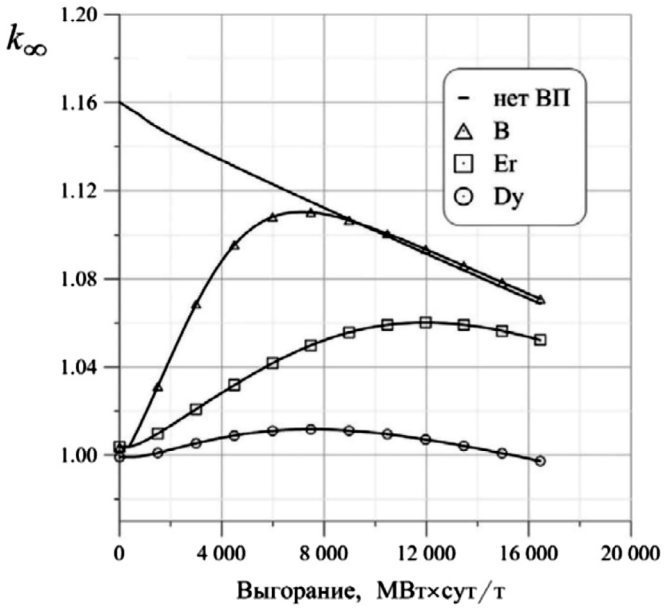

Fig. 1. k_∞ as a function of fuel burn-up for various types of burnable absorbers.

The use of dysprosium contained inside of the steel cladding of the annular cooling channel has been advantageous from the point of view of the reactivity overshoot during the reactor lifetime. Fig. 1 shows k_∞ as a function of the fuel burn-up for various types of burnable absorber [9].

Calculations in this study were performed using WIMS-D4 (Winfrith Improved MuLtigroup Scheme), a transport code [10] generally used for neutronic calculations of the lattice cells in reactors of different types. The WIMS-D4 code developed in Winfrith, UK, is one of the most well-known codes in its class, and uses its own 69-group constant library and the ENDF/B-VII library [11] prepared for various materials and temperatures based on the ENDF (Evaluated Nuclear Data File) format.

Temperature reactivity coefficients were calculated as follows. The effective reactivity coefficients were determined for two coolant (or fuel) temperatures: the initial temperature at 300 K, and the temperature at the rated reactor power. Reactivity increments were normalized to 1 K, and so the average coolant (fuel) reactivity coefficient was calculated for a range of zero-power to rated-power temperatures.

The power reactivity coefficient was calculated for two states. In one of these states, the core temperature of 300 K was assumed for the case of zero power. In the other state, the following temperatures were assumed for the 100% reactor power: 800 K for the fuel, 600 K for the fuel cladding, 400 K for the core cladding, 500 K for the Al-Be moderator, 360 K for the coolant (with a density of 0.967 g/cm^3), and 360 K for the shell material. The effective multiplication factor for these temperatures was calculated by the formula $\alpha_w = (k_1–k_2)\cdot 10^5/100$, where k_2 is the effective multiplication factor for the 100% power, and k_1 is the effective multiplication factor for zero power. In this case, the average value of the power reactivity coefficient was determined for a power range of 0–100%.

Table 1
Reactivity coefficients for 1 MWth MASTER reactor core.

Coefficient	WIMS-D4 (no Dy)	WIMS-D4 (with Dy)
α_{H2O}, pcm/K	7.0	14.7
α_f, pcm/K	−2.1	−2.0
α_w, pcm/%	−5.1	−1.2

α_{H2O} – coolant temperature reactivity coefficient;
α_f – fuel temperature reactivity coefficient;
α_w – power reactivity coefficient

An improvement in the self-regulation characteristics thanks to the use the dysprosium burnable absorber has had a negative effect on the reactivity coefficients with the positive coolant temperature reactivity coefficient nearly doubled. Table 1 presents the updated reactivity coefficient estimates for two cases: with dysprosium being inside of the steel channel cladding and with no dysprosium. The temperature reactivity coefficient calculations had either the fuel temperature or the coolant temperature varying, which resulted in variations in the macroscopic cross-sections of the neutron interaction with the fuel or coolant nuclei.

The purpose of this work is to find ways to decrease the coolant temperature reactivity coefficient, and, ideally, to make this coefficient negative by optimizing the performance of the 1MWth MASTER reactor core.

Reactivity coefficients as a function of the reactor core parameters and fuel enrichment

An annular cooling channel was introduced into the MASTER reactor core to improve heat removal and, therefore, to provide for an increase in the reactor facility thermal power. The following designs have been used to find ways to optimize the reactivity coefficients: the radius of the annular cooling channel location within the core has been changed; and the channel thickness and fuel enrichment have also been changed.

Temperature coefficients were calculated as a function of the channel location radius for several values in a range of 10–25 cm, where the channel thickness for each case varied in a range of 1–2.5 cm. The ^{235}U enrichment was kept invariable at 17%, and all dependences were calculated for the case with no BA. The calculations show that the variation in the reactivity coefficients becomes linear both for the case with the burnable absorber (dysprosium) being inside of the annular cooling channel and for the case with no BA (Fig. 2). For this reason, the dependences were calculated with no BA.

Then, a three-dimensional plane was constructed. The coolant temperature reactivity coefficient reactivity (in pcm/K) was plotted along the Z axis, and the radius of the annular channel location (in cm) and the coolant channel thickness (in cm) were plotted along the X axis and the Y axis, respectively.

As can be seen from the results shown in Figs. 3 and 4, the coolant temperature reactivity coefficient is positive and assumes the minimum value at the maximum fuel enrichment of 20% and when the channel thickness is 1–1.5 cm. The channel location radius has no effect on the value of this coolant temperature reactivity coefficient component.