# Equalization of energy density in boiling water reactors (as exemplified by WB-50). Development and testing of WB -50 computational model on the basis of MCU-RR code

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**Abstract**. Within the framework of research in possibility and prospects of power density equalization in boiling water reactors (as exemplified by WB-50) a work was undertaken to improve prior computational model of the WB-50 reactor implemented in MCU-RR software. Analysis of prior works showed that critical state calculations have deviation of calculated reactivity exceeding ±0.3 % (ΔKef/Kef) for minimum concentrations of boric acid in the reactor water and reaching 2 % for maximum concentration values. Axial coefficient of nonuniform burnup distribution reaches high values in the WB-50 reactor. Thus, the computational model needed refinement to take into account burnup inhomogeneity along the fuel assembly height. At this stage, computational results with mean square deviation of less than 0.7 % (ΔKef/Kef) and dispersion of design values of ±1 % (ΔK/K) shall be deemed acceptable. Further lowering of these parameters apparently requires root cause analysis of such large values and paying more attention to experimental measurement techniques.

## 1. Influence of raw data uncertainty on the dispersion of results

Uncertainties in the raw data are determined by deviations of parameters describing material composition and geometry of the reactor core from their nominal values and by positioning allowance values for the reactor's elements, as well as by measurement errors.

The following uncertainties were analyzed for their influence over dispersion of the calculation results:

- non-uniform distribution of uranium (burnup) over the volume of fuel assembly;
- uncertainty of concentration and distribution of boron in wrapper tubes;
- uncertainty of thickness and composition of deposits on the fuel elements;
- uncertainty of chemical composition of boric acid water solution;
- uncertainty in manual regulator position and gap position between absorbing and fuel parts of the regulator;
- uncertainty in distribution of $^{10}B$ along the height of absorbing parts of the manual regulators (during the most of the run the manual regulators are partially submerged into the reactor core).

Non-uniform distribution along the hight of fuel assemblies is defined by two causes: non-uniformity of initial distribution of uranium along the height of fresh fuel elements and fuel assemblies

(non-uniform size and density of uranium dioxide pellets) and non-uniform $^{235}U$ burnup along the height and radius of the assemblies.

According to [3] production of fuel elements for water-cooled reactors, the same as used in the VK-50 reactor, provides the following allowance values:

- deviation of ±0.055mm is allowed for fuel elements with average outside diameter of 9.135mm;
- deviation of ±0.045mm is allowed for pellets of uranium dioxide with average outside diameter of 7.755mm;
- while average density of uranium dioxide in pellets is 10.6 g/cm$^3$, allowable minimum is 10.3 g/cm$^3$ and allowable maximum is 10.8 g/cm$^3$.

The last two parameters help estimate non-uniformity coefficient of uranium mass distribution (not accounting for enrichment tolerance) along the height and section of a fresh fuel assembly with the value of ~1.03. Dispersion of calculated reactivity due to dispersion in fuel with such non-uniformity coefficient may reach (depending on reactor loading) ±0.1 % (ΔKef/Kef).

While the average outside diameter of fuel elements is 9.135 mm, maximum diameter may reach 9.19 mm (as per specifications). Deposits increase the outside diameter of the element and thus decrease the flow passage for reactor coolant. According to [3], registered outside diameter does not exceed 9.173 mm; while with deposits the outside diameter of the fuel element may reach 9.19 mm. Dispersion in calculated reactivity due to change in wrapper tube outer diameter in the range of 9.08 - 9.19 mm does not exceed ±0.1 % (ΔKef/Kef).

At boron reactivity coefficient equal to 4 %/(g/l) the error of ±0.01 g/l in its concentration leads to reactivity error of ±0.04 % (ΔKef/Kef).

Change of distance between the absorbing and fuel parts of the manual regulator in the range from 20 to 34 cm leads to changes in reactivity not exceeding ±0.02 % (ΔKef/Kef).

Change in manual regulator suspension height with respect to reactor core by ±5 cm leads to changes in reactivity not exceeding ±0.01 % (ΔKef/Kef).

Lowering concentration of $^{10}B$ in absorbing parts of manual regulator by 10% leads to increase in reactivity by 0.04 % (ΔKef/Kef).

Non-uniform distribution of $^{235}U$ in irradiated fuel assembly is largely determined by non-uniform burnup distribution along the height and radius of the assemblies, which is determined in calculations with the help of software packages BIPR-K and MCU. Estimation of error in fuel distribution along height and radius of a fuel assembly due to inaccuracy of burnup description is a complex task. In general, if the material distribution calculation accuracy along the height and radius is 5 %, then dispersion of calculated reactivity may reach (depending on reactor loading) ±0.2 % (ΔKef/Kef) due to non-uniform fuel distribution.

Analysis of these results shows:

- the most important are effects linked to geometric characteristics, fuel concentrations and fuel distribution calculation accuracy; joint inaccuracy in calculated reactivity due to these factors comprises up to 0.5 % (ΔKef/Kef);
- in the reactor core loaded with fresh fuel assemblies the uncertainties of fuel content may reach ±0.3 % (ΔKef/Kef); but these errors lead to systematic error in calculated values for critical assembly experiments and on 12th run of the reactor; they cannot explain random variation of calculated values; however, during modeling of such experiments the standard mean-square deviation between calculated and experimental values is on average 0.65 % (ΔKef/Kef);
- in the reactor core loaded with irradiated and fresh fuel assemblies the calculated accuracy values due to fuel composition reach up to ±0.5 % (ΔKef/Kef).

Projected boron content in wrapper tubes of the fresh fuel assemblies is (0.07-0.10) per cent by weight. If we select the average boron content (0.085 % wt), as a basic value, then its changes within the stated range lead to dispersion of calculated reactivity of ±0.6 % (ΔKef/Kef).

Changes in boron content within the design range (0.07 - 0.10) % wt lead to changes in reactivity from +0.8 % (ΔKef/Kef) to -0.35 % (ΔKef/Kef). For the experiments described above the average calculated reactivity values were within the range from -0.21 % (ΔKef/Kef) to +0.74 % (ΔKef/Kef). That is, in the same range.

New fuel loading scheme for a run with partial overloads contains another disturbing factor: fresh fuel assemblies are typically loaded in the third and fourth rows of reactor core; at that, power (and, consequently, thermal neutron flux density) of surrounding fuel assemblies relative to its power may vary from being approximately 1.5 times higher to being 2-3 times lower. Such wide range of power variation in surroundings shall lead to high non-uniformity of boron burnup in the wrapper tubes and shall be accounted for (especially orientation!) during rearrangements of fuel assemblies in the reactor core in overload.

## 2. Refinement of computational model of WB-50 reactor by increasing the number of material zones for fuel along the reactor's height

The first variant of the WB-50 reactor computational model [1] allowed describing each of the reactor's fuel assemblies with a single material zone, while energy release was calculated for each fuel element separately.

### *2.1. The first variant of the WB-50 reactor computational model*

The first variant of the WB-50 reactor computational model [1] allowed describing each of the reactor's fuel assemblies with a single material zone, while energy release was calculated for each fuel element separately. Boron burnup in all the wrapper tubes was described as three zones:

- boron in a fresh fuel assembly;
- boron in an irradiated fuel assembly after the first run;
- boron in a fuel assembly that underwent more than 2 runs ($^{10}$B burnt up).

### *2.2. The second variant of the computational model*

The second variant of the computational model allowed determining changes in burnup within a single fuel assembly (20 material zones along the assembly height). For other assemblies the fuel was described with one individual zone. Boron burnup in all the wrapper tubes was described as three zones as well. Such computational model allows calculating changes in material composition of an assembly and element-wise calculation of power density as they are changing through the run.

The second variant of the computational model was used to obtain dependency of energy density distribution of $^{235}$U in one of the central operating fuel assemblies on its average burnup at constant material content of other assemblies of the reactor. At that, dependencies were obtained between the energy density distribution along the assembly's height and density of principal fissile isotopes ($^{235}$U + $^{239}$Pu) and average burnup.

The previous computational model was refined to take account of detailed calculation of $^{10}$B burnup and its distribution along the fuel assembly height depending on the duration of reactor's operation: SA wrapper tube was divided into 20 material zones along its height and $^{10}$B burnup was calculated separately for different zones.

Accounting for obtained dependency of $^{10}$B distribution along the height of assembly on time, as well as (factory) non-uniformity, significantly influences the results of computational modeling of experimental critical conditions. Additionally a perturbation shall be mentioned that is introduced into the computational modeling of reactor overload due to lack of accounting for orientation of rearranged fuel assemblies with different $^{10}$B content in different flanks of the wrapper tubes in their new position in the reactor core.

### *2.3. The third variant of the computational model*

The third variant of the computational model was created to describe each of the reactor's fuel assemblies by 2 material zones (top and bottom halves of the assembly). Burning boron in all wrapper

tubes was still described with three zones, however there are plans for future modifications with several material zones describing boron content in the wrapper tubes (from 5 to 10 along the height). This variant will allow more accurate consideration of boron burnup along the fuel assembly height and will hopefully increase accuracy of reactivity calculations for high concentrations of boric acid in the reactor water. From this perspective, it is hard to expect that mean-square deviation of reactivity calculations for critical states will be less than 0.7 % (ΔKef/Kef), and dispersion of calculated values will be less than ±1 % (ΔKef/Kef).

## 3. Conclusion

In conclusion, the following should be noted:

- uncertainty of raw data determined by characteristics of fuel elements and fuel assemblies with fresh fuel may explain only relatively small deviations of calculated values from experimental ones, such deviations (±0.4 % (ΔKef/Kef)) are typical in calculations for other reactor units;
- a single factory non-uniform distribution of boron along the wrapper tubes can explain deviations of calculated values from experimental results on critical assembly and fresh reactor core in the 12th run;
- during calculations for WB-50 reactor it is necessary to describe $^{10}B$ along the height and azimuth of the assembly in more detail; when describing wrapper tubes with a single material zone their burnup time is unjustifiably lowered two- or three-fold;
- to create a more accurate computational model of the WB-50 reactor it seems sufficient to introduce at least 2 material zones for description of fuel burnup along the height and at least 5 material zones to cover $^{10}B$ distribution in the wrapper tubes.

All these issues were largely considered while preparing the third variant of the WB-50 computational model.

## References

[1] Yescherkin V, Starkov V, Chertkov Yu et al 2005 Estimation of possibility to use 3.6 % enriched fuel in WB-50 reactor *Research report* Registry no. O-5682

[2] Vaneev Yu, Antonov S, Bulycheva L et al 2004 Development and verification of MCU-based models of the VK-50 reactor active zone at its loading with fresh fuel assemblies *Research report Control* no. O-5542

[3] Scheglov A, Proselkov V, Enin A 1991 Results of statistical treatment of design and technological parameters of WWER-1000 fuel element *Preprint* of Kurchatov Atomic Energy Institute reg. no. IAE-5334/4