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Inclusion of specific geometry of the beryllium blocks in the computational model of the MARIA reactor

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Abstract

The aim of this study is to analyze the accuracy of neutron-physical calculations made using the existing and alternative computational model of the basic cell component of the MARIA reactor core. For this purpose, an analysis of the accuracy of the calculation of the neutron flux and the effective multiplication factor by an alternative and existing computational model was performed. The results were compared with the exact model of the core primary cell prepared using the MCNP computational code.

Keywords: Nuclear reactor, Beryllium blocks, MARIA reactor, Computational model of reactor

1. Beryllium blocks

The MARIA reactor core consists of fuel elements arranged within a matrix consisting of beryllium and graphite blocks, with neutron-absorbing control rods ensuring the stability of the reactor. Beryllium and graphite blocks are in the shape of truncated pyramids with a square base and cylindrically recessed corners. Fuel elements are placed in these cylindrical grooves. Control rods are placed in the central channels of the beryllium blocks. These pyramids narrow downwardly, so that all the walls of the reactor matrix are slanted. This conical arrangement allows for the installing of much larger reactor components (moving fuel elements and control rod drives) and experimental equipment above the core. A typical beryllium block is shown in Fig. 1. The size of the block (to be precise, the aluminum cap) at the top is 140 mm, and at the bottom 120 mm. In order to manipulate the blocks and place them in an appropriate position in the core, aluminum caps are attached to the top and bottom of the blocks. The lower cap has been equipped with a leg and the upper cap with the head of the handle. These caps cause a 1.5 mm thick gap to form over the entire height of the block, which ensures the flow of the coolant between the blocks.

2. Main characteristics of a real basic cell

A basic core cell (shown in Figs 2 and 3) is comprised of a tubular fuel section with 6 fuel pipes located in the fuel channel, filled with water and surrounded by beryllium blocks. In the corners of the cell there are Ø28 mm or Ø35 mm channels, filled with water, used for control rods. These channels contain aluminum Ø25 × 1 mm leading pipes. The gaps between the beryllium blocks (1.5 mm thick) are also filled with water. The volume of the cell

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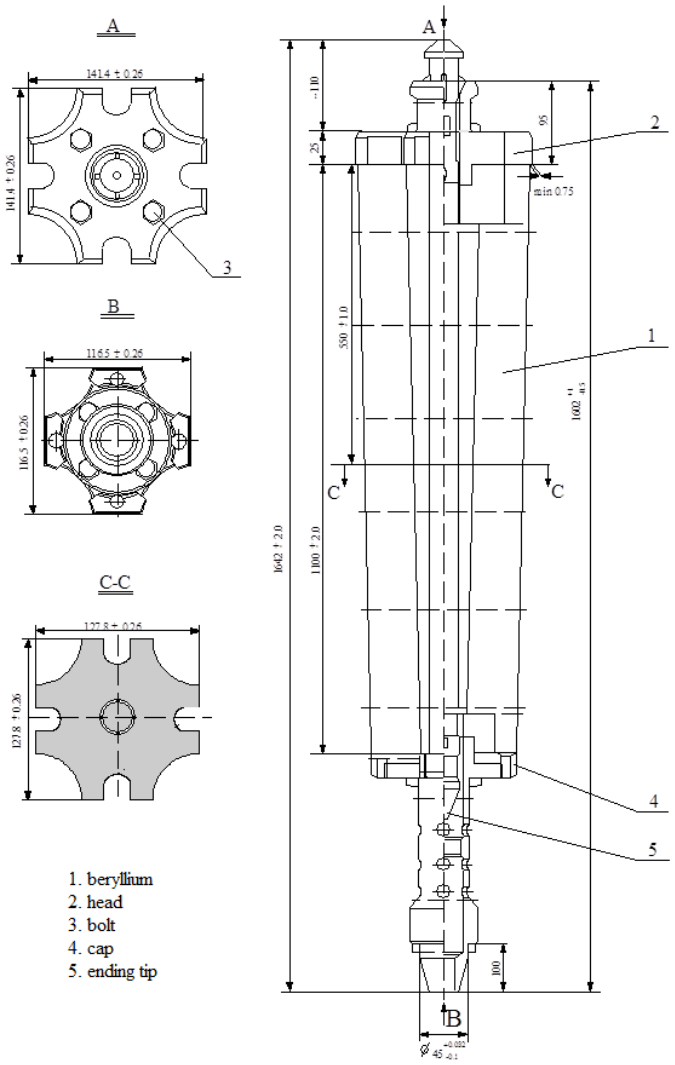
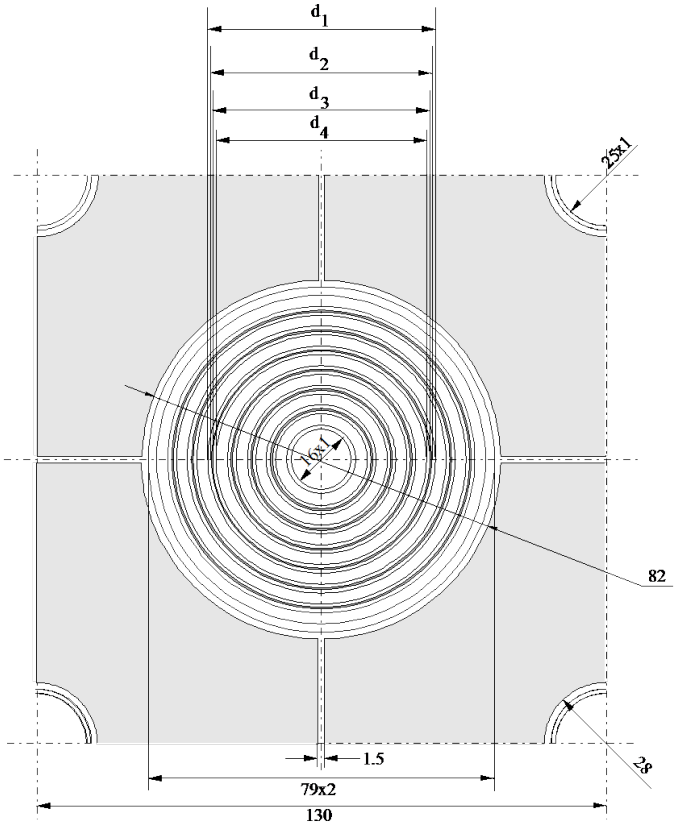


Figure 1: Standard beryllium block [1]



№ of fuel pipe	d_1	d_2	d_3	d_4
1	25	23.5	22.5	21
2	34	32.5	31.5	30
3	43	41.5	40.5	39
4	52	50.5	49.5	48
5	61	59.5	58.5	57
6	70	68.5	67.5	66

Figure 2: MARIA reactor core basic cell [1]

is 16.95 dm^3. The cell is a truncated pyramid, with a cross-section at mid-height of 130 × 130 mm [1].

Table 3: Beryllium weight composition [1]

Element	Weight fraction, %	Element	Weight fraction, %
Be	97.8	O	1.8
C	0.15	Al	0.04
Mn	0.02	Fe	0.1
Cu	0.015	Si	0.02
Ni	0.01	Mg	0.005
Cr	0.03		

The characteristics of individual areas of the cell, including specification of the materials, densities, weight composition and volume fractions are summarized in Tables 1÷3. The densities of materials are given for a temperature of 20°C. Beryllium weight composition (Table 3) also includes various impurities, as they play an important role in determining the nuclear properties of beryllium, which is a dominant (volumetric) component of the cell.

In the basic cell there are also water gaps between the blocks and central water channels in the beryllium. In Table 1 water areas are isolated, as separate, external layers. Possible regulatory or isotope channel pipes, as well as absorbers and target materials used for irradiation are not included.

Fig. 2 shows the reactor core basic cell with fuel element dimensions, whereas in Fig. 3 the location of the basic cell against a beryllium matrix is shown. This cell consists of a fuel channel, four quarters of

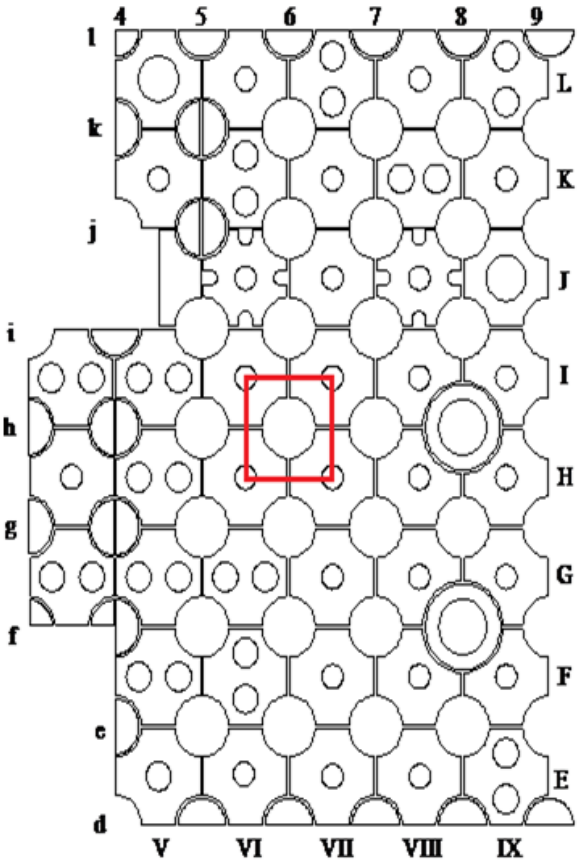


Figure 3: MARIA reactor core layout with basic cell marked

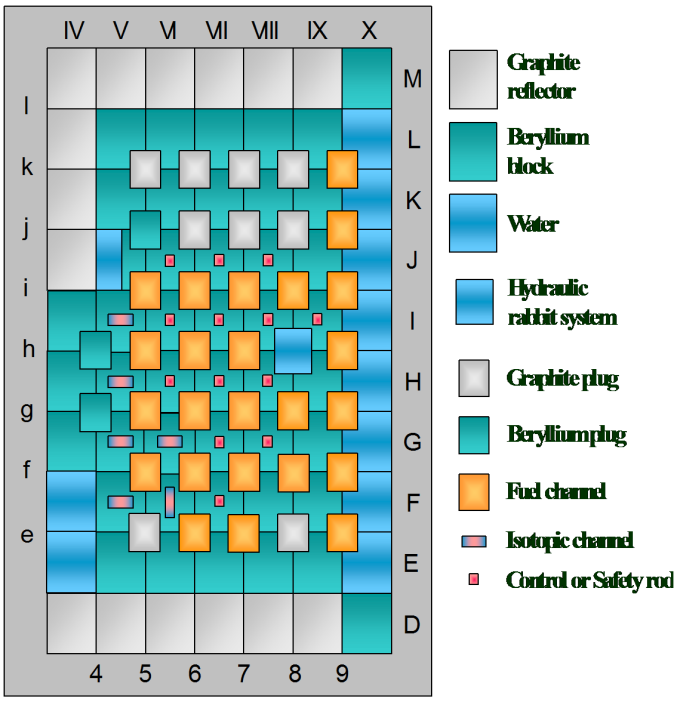


Figure 4: MARIA reactor core diffusion model cross-section from REBUS code [2]

beryllium blocks and water gaps between the blocks.

3. Calculation models used in comparative analysis

As mentioned earlier, a special feature of a real beryllium matrix is its conicity, i.e. beryllium blocks, which make up the reactor matrix, are in the form of truncated pyramids tapered downwards. Modeling such geometry is not possible in REBUS code, used in NCNR for full core neutronic calculations, as it solves differential equations of diffusion in a rectangular grid. Therefore, the geometry of the beryllium matrix block is simplified to a simple cuboid with the length of the sides equal to the average of the length of the upper and lower ends of the block. As a result, the volume of the block remains the same. A disadvantage of this model is the symmetry of vertical distributions of neutrons in the core, when in fact this distribution is asymmetric. Fuel elements are homogenized (Fig. 4), which means that in a given volume fuel, water and cladding are mixed in appropriate proportions. The advantage of REBUS code is the short calculation time [3].

A simplified model is used to represent the basic cell of the REBUS model for the purposes of this comparison. This model consists of a tubular fuel element and four quarters of beryllium blocks, whose walls are perpendicular. For the purpose of the calculations the beryllium blocks are divided along the vertical axis into five equal layers called nodes. The amount of beryllium is identical in each node. The length of the side wall of the modeled beryllium block is the average length of the side of the real block of beryllium, i.e., 12.825 cm (average of 11.65 and 14 cm per an engineering drawing of the beryllium block in [1]). The beryllium blocks and fuel element have a height of 110 cm, but the active height (where the fuel is located) is 1 m. The model also includes a water gap between the quarters of beryllium blocks. From the bottom and top the beryllium is covered with a 2.5 cm thick layer of aluminum, aimed to represent the aluminum caps and accessories from the actual blocks. Above and below the caps there is a 10 cm thick layer of water.

Fig. 5 shows a longitudinal section through the ba-

Figure 5: Longitudinal section of the model representing a simplified REBUS basic cell

sic cell geometry model. It shows individual nodes and the fuel element in the center of the model. The walls of this model are not slanted.

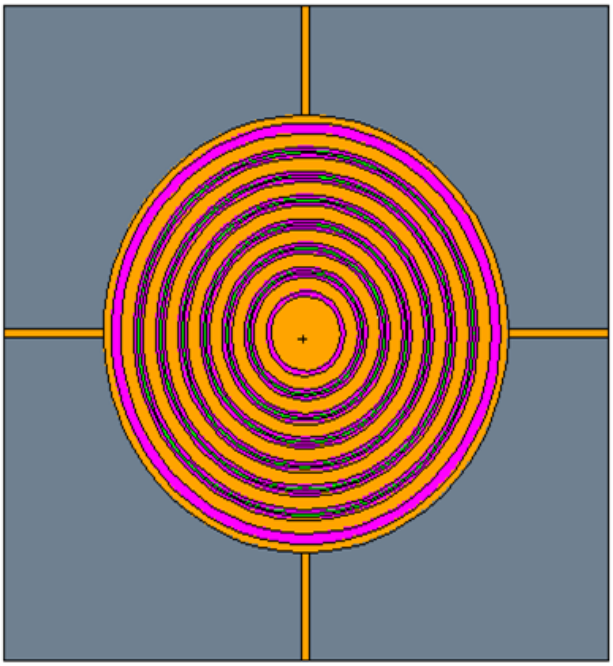


Figure 6: Cross-section of the basic cell model

The macrocell geometry model prepared for calculations in MCNP code reproduces the MARIA reactor beryllium matrix basic cell more precisely, because it can reproduce the conical shape of the beryllium blocks. Thus, the beryllium blocks surrounding the tubular fuel element are modeled as truncated square-based pyramids. In this study central channels for control rods and irradiation are neglected, so the cross-section of the block is a square, whose side length varies with height. This length varies from 11.65 cm at the lowest point of the beryllium block to 14 cm at the highest. The height of the beryllium block and the fuel element is 110 cm, and the height of the active portion of the fuel element is 1 m. Therefore, five centimeter layers with no fuel element are modeled. Fig. 6 shows the cross-section of the cell used for calculations; it was obtained using MCNPX Visual Editor. It shows the concentric geometry of the fuel element and beryllium blocks layout.

The tubular fuel element is surrounded by beryllium quarters in such a way that water gaps are left between the fuel element and the beryllium, as well as between the blocks themselves. For the purpose of calculations they are divided vertically into five layers (nodes) of equal height, but because the side walls of the macrocell are slanted, the volume of each layer is different. This division occurs at the length of one meter, which is the height of the active part of the fuel element. Separate cells are five centimeter extensions of the fuel element and the beryllium blocks at the top and bottom of the macrocell. 2.5 cm aluminum caps are located on the ends of the block, both upper and lower. They represent real aluminum caps and hardware present in MARIA reactor. There is a 10 cm water layer above and below the caps; it also fills the space above and below the fuel channel.

Beryllium blocks in this model (and also in the other two) contain pure beryllium, without admixtures or impurities. The mass of beryllium in individual nodes of the accurate model is different, but the density is constant.

On the side walls a white boundary condition was given, corresponding to neutron reflection. In the vertical axis direction a black boundary condition was given, i.e., the possibility of neutron leaking. In the course of calculations it could be observed that the 17.5 cm of material that divides the end of the active height of the fuel from the end of the macrocell model is a large enough layer, so that changing the white boundary condition at the ends does not affect the results of the calculations. However, to reflect the actual conditions it was decided to apply the conditions corresponding to the escape of neutrons.

Figure 7: Longitudinal section of the MCNP basic cell model

Fig. 7 shows the longitudinal section of geometry used in the MCNP calculations. It shows the slope of the beryllium blocks, the division of the active zone into five separate parts, aluminum cap plates and the layer of water above and below the fuel element.

The last of the models considered in calculations

is the alternative model, which is a kind of fusion of representations of diffusion and Monte Carlo models. The geometry of this model is identical to the simple model (simulating the REBUS model). A proposed improvement is to put different beryllium and water gap masses from individual layers of the conical model into this one. For this purpose, in the geometry and material cards of the MCNP input, different atomic densities were put for all of the five beryllium blocks and water gap layers (for accuracy, the atomic densities in the five centimeter layers without fuel was also changed).

To reflect the differences of masses of materials in the individual layers of the geometric model it was necessary to modify the atomic densities of beryllium and water in water gaps. As a result, in spite of the rectangular construction of the model, in each layer a different quantity of materials (beryllium and water) equal to the mass of materials from the conical model is represented.

4. Changes of the k_{eff} coefficient according to reactor basic grid pitch

Table 4: k_{eff} coefficient changes according to basic grid pitch

Node No	Block thickness, cm	k_{eff}	uncertainty
1	15	1.50632	0.00017
2	14	1.52084	0.00016
3	13	1.53310	0.00016
4	12	1.54203	0.00016
5	11	1.54740	0.00016

To examine the physical effects occurring in MARIA reactor grid, k_{eff} coefficient values were compared in a single node of the simple model with variable pitch of basic reactor core grid. Pitch was changing from 11 to 15 cm. The size of fuel element remains unchanged. k_{eff} coefficient values depending on the thickness of the block have been collected in Table 4.

5. Changes of k_{eff} coefficient according to beryllium block density

Subsequent calculations were related to changes in the value of the k_{eff} coefficient according to the density of the beryllium blocks. Calculations were performed for densities corresponding to individual nodes from the variable density model. Model geometry is similar to the previous calculations, which is a single node from a simple model with beryllium thickness of 12.825 cm. In each of the following calculations the nuclear density of beryllium in the node was changed. The results are summarized in Table 5.

6. k_{eff} coefficient comparison

The basic value obtained from Monte Carlo (MCNP code) calculations is k_{eff}. It is also the primary factor taken into account in the comparison between the computational models discussed earlier. The table below summarizes the results of calculations of k_{eff} and the size of the relative error which affects the results. The following names for different models are used: the model reproducing the characteristics of the REBUS model is called simple, the MCNP model reproducing the conicality of the basic cell is called accurate, and the model with proposed improvements is called alternative. The computational models used for these calculations were described earlier.

Table 6: Comparison of k_{eff} coefficient in individual computational models

Model	k_{eff}	error
simple	1.46928	0.019%
accurate	1.46956	-
alternative	1.46899	0.039%

7. Comparison of relative axial flux of thermal and fast neutrons

Another quantity serving to compare the previously discussed computational models is the relative axial flux of neutrons. For comparison, thermal neutron flux from the water channel in the center of the fuel element was selected. The channel was divided

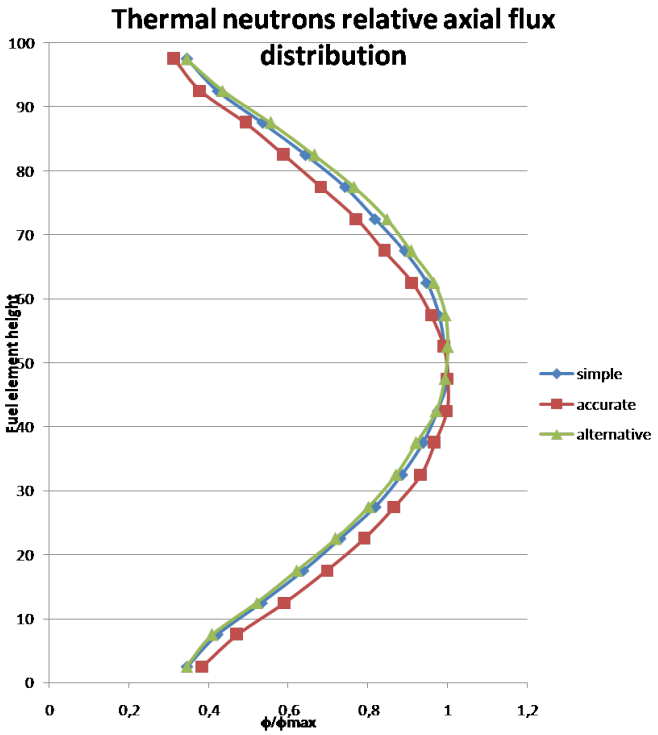


Figure 8: Relative axial flux of thermal neutrons

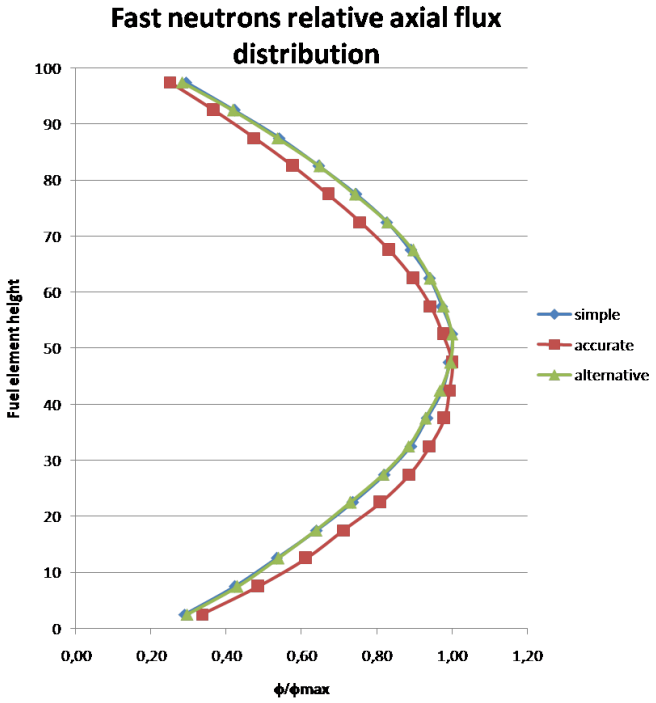


Figure 9: Relative axial flux distribution of fast neutrons

into 20 layers to get a larger number of measurement points. The division into groups of neutron energy spectrum was done according to the distribution of groups used in the calculations with REBUS diffusion code. The boundaries of the energy groups given in MeV are as follows: 0 to 5.8 E-8, then to 2.5 e-7, 6.25 E-7, 4.0 E-6, E-3, 5.53, 0.821, and finally 10 MeV. In Fig. 8 the distribution of the relative axial flux of thermal neutrons is presented. One can see that the accurate MCNP model faithfully captures the actual distribution of flux, i.e., the maximum is shifted to the lower half of the fuel element's active height and it is not symmetrical. The simple and alternative models do not reflect the true nature of neutron flux distribution, i.e., they are symmetrical with respect to fuel element height and the maximum falls at exactly half of the active fuel height.

The results look very similar with the fast neutron spectrum. The flux from the accurate model reflects very well the nature of the actual axial flux measured in the reactor (with its maximum shifted to the bottom part of the reactor). The flux from the alternative model is close to the symmetrical distribution from the simple model. The distribution of fast neutron flux is shown in Fig. 9. The model used for the calculations and energy groups are the same as in the case of the thermal neutron flux distribution.

8. Summary

From the comparison of the neutron multiplication factor it can be observed that the simple model used previously for diffusion calculations in REBUS code reproduces k_{eff} of the system in a good manner. The alternative model is slightly worse here.

Axial neutron fluxes from the simple and alternative models are close to each other and symmetrical to the center of the fuel element, thus they deviate from the actual distribution of neutron flux. This flux is better reflected by the accurate model. The difference between the values obtained from the accurate and alternative models are on average 5.43%.

The results are much less sensitive to changes in beryllium density than to change in basic reactor grid pitch. This can be seen when comparing the change in the neutron multiplication factor in these two cases (see Tables 4 and 5).

The properties which the alternative model with simple geometry and altered nuclear densities exhibits do not reflect the accurate geometry model

properties well enough to usefully replace the existing model used in calculations performed with REBUS and WIMS codes.

At a sufficiently great distance from the fuel, the type of boundary condition (the possibility of / no possibility of neutron escape) has no influence at the upper and lower model end.

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Table 1: Basic core cell individual areas characteristics [1]

Cell area	Out. diam., mm	Material	Density, g/cm^3	Weight comp, %	Vol. fract., %
Filler central channel	14	H_2O	0.998	H-11.1 O-88.9	0.91
Filler—Al pipe	16	Al	2.7	Al.-100	0.28
Water gap between filler and fuel element	21	H_2O	0.998	H-11.1 O-88.9	0.86
Fuel element	70		See Table 2		20.72
Water gap between fuel element and channel pipe	75	H_2O	0.998	H-11.1 O-88.9	3.37
Fuel channel pipe	79	Al	2.7	Al.-100	2.86
Water gap between channel and beryllium	82	H_2O	0.998	H-11.1 O-88.9	2.25
Beryllium block*	142.9**	Be	1.82	Table 3	63.69
Water in gaps and block central channel*	146.7**	H_2O	0.998	H-11.1 O-88.9	5.06

* Standard beryllium block (see Fig. 1)

** Equivalent diameter for the calculations in cylindrical geometry

Table 2: Fuel element characteristics [1]

Fuel area	Thickness, mm	Material	Density, g/cm^3	Weight comp, %	Vol. fract, %
Water in gaps between fuel pipes	2.5	H_2O	0.998	H-11.1 O-88.9	10.573
Fuel element inner cladding	0.75	Al	2.7	Al-100	3.001
Fuel layers	0.50	UO_2 in Al	4.8	U-52.2 Al-40.1 O-7.7	3.778
Fuel element outer cladding	0.75	Al	2.7	Al-100	3.370

Table 5: k_{eff} changes according to beryllium block density

Node No	Beryllium atom density, atom/barn·cm	k_{eff}	uncertainty
1	1.48646E-1	1.52570	0.00017
2	1.35899E-1	1.53010	0.00016
3	1.23561E-1	1.53382	0.00016
4	1.11632E-1	1.53703	0.00016
5	1.00112E-1	1.53961	0.00016