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Scoping Study for Irradiation of LEU Circular Involute Plates in the BR2 Reactor

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ABSTRACT

Circular involute fuel plates with HEU are used nowadays in several high flux nuclear research reactors which are still waiting for the qualification of high-density LEU fuel providing minimum reduction of the reactor performance. The design demonstration experiment for irradiation of full size high density LEU involute curved plates requires a large available space for the irradiated plates in the driving reactor core and high neutron fluxes. One of the potential reactors for qualification irradiation of full size involute curved plates is the BR2 high flux materials testing reactor. A neutronic study has been performed to determine the provisional irradiation conditions for LEU circular involute curved fuel plates with grading dimensions of the monolithic uranium fuel zones during design demonstration experiment in the BR2 reactor. The involute curved MCNP model of the fuel plates has been used to generate the geometry of eight involute plates containing monolithic LEU with grading dimensions of the fuel zones of the HFIR inner and the outer fuel element. The irradiation will take place in the large central channel inside the BR2 core. The numerical calculations of the power density evolution distributions in the eight involute plates and the fuel burnup calculation were performed using the MCNP & SCALE codes and remain an additional post-processing procedure to calculate a correlation between the power and the fuel burn-up in fuel plates. The power peaking distributions and the distributions of fission events in the involute curved plates were calculated using non-uniform meshes in the involute curved shape of the grading fuel zones in 378 different fuel cells in each IFE plate and in 297 fuel cells in each OFE plate. The calculated profile of the power density and the maximum of fission events in each fuel plate during irradiation experiment are compared with the preliminary design of LEU core specifications of the HFIR reactor.

1. Introduction

In the framework of reducing uranium enrichment in the research reactors, the development of a high-density and low-enriched uranium (LEU) fuel remains a top priority for the high flux nuclear research reactors. Several high flux research reactors are still waiting to receive a qualified high-density LEU fuel, which should provide minimum reduction of the reactor performance.

In order to qualify the new fuel for the existing reactor the irradiation experiments are executed in the same reactor or in another driving reactor core. In several high flux reactors the reactor core consists of a single fuel element or of two fuel elements, each of which assembles large number of high enriched uranium (HEU) curved fuel plates of the circular involute shape. There are several high flux reactors which deploy HEU circular involute plates: the High Flux Isotope Reactor HFIR, the FRM-II reactor (Research Neutron Source Heinz Maier-Leibnitz) and the ILL High-Flux reactor. The core of the HFIR reactor has two fuel elements: inner and outer fuel elements containing involute plates. The large geometrical dimension of these fuel plates and the necessity to reach high power density reduces the number of available candidate reactors where the qualification irradiation of LEU high-density fuel can be performed.

One of the potential reactors for qualification irradiation of the full size circular involute LEU plates is the Belgium Reactor -2 (BR2) high flux materials testing reactor. The scoping study of the irradiation experiments in the BR2 reactor for eight involute fuel plates with LEU fuel has been performed using a preliminary design of LEU HFIR-types fuel plates of the inner and of the outer fuel elements.

2. Fuel Element with Circular Involute plates containing LEU

The geometry of circular involute plates (the involute of the circle) in the fuel elements of HFIR, ILL, FRM-II can not be processed directly in the existing neutron transport codes. In the meantime, an azimuthal homogenization of fuel plates and of the cooling water significantly simplifies the calculation model of the whole fuel element without considering individually the involute plates. However, it is necessary to have information about power distributions in each plate during the qualification irradiation of several involute plates. The involute shape of the fuel plates and of fuel zone can be approximated using a system of linear planes. In this approximation linear planes pass through the nodes which belong both to the circular involute curves of the cladding and to the graded fuel zone in the HFIR plates. An example of approximation of two fuel elements with involute fuel plates was prepared using the developed MCNP model and is given in Figure 1. A quarter part of the whole fuel elements is shown in order to give a better view on the approximation of the involute plates. The plates of the outer fuel element (OFE) are rotated in the same way that they are in the core of the HFIR.

The geometrical dimensions of the inner (IFE) and outer fuel element LEU plates is based on the preliminary design of the low-enriched core performed for the HFIR reactor and is shown in Figure 2. The general specifications of the fresh LEU fuel plates are included in Table 1. The fuel zone thicknesses in IFE and OFE involute plates are profiled along the plate width as shown in Figure 2, but in the axial direction of the plate the fuel thicknesses are not profiled and remain constant. No burnable absorbers were included into the fuel plates. The thickness of fuel zone in the IFE plates is lower than the thickness of the OFE plates. The representative irradiation conditions in the LEU IFE and OFE involute plates are presented in Table 2.

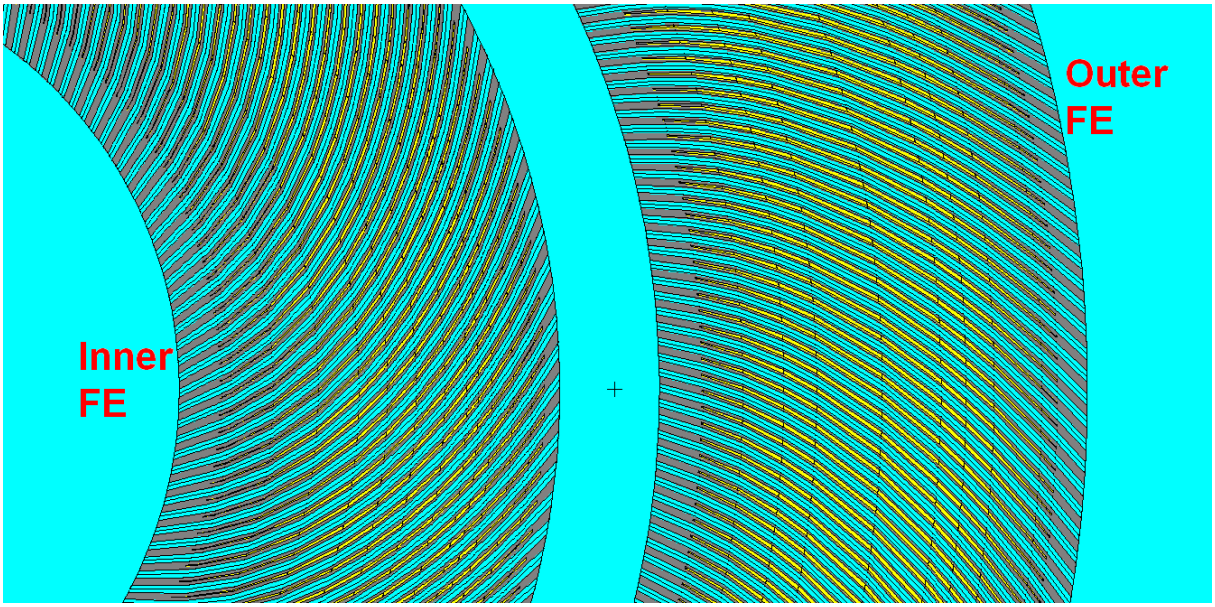

Figure 1 Approximation MCNP model of the inner and of the outer fuel element consisting of circular involute fuel plates with grading fuel zones.

Table 1. Geometry specification and fuel composition for the fresh LEU HFIR-type fuel plates [1]

Thickness of the fuel plate, cm	0.127
Mean height of the fuel zone,cm	50.8
Mean length of the IFE fuel phase zone, cm	7.7953
Mean length of the OFE fuel phase zone , cm	7.0891
Water gap between the fuel plates, cm	0.127
U_{total} density, g/cm3	15.3
U10Mo density, g/cm3	17.0
^{235}U , %	19.75
^{236}U , %	0.24

Table 2. Requested representative irradiation conditions for the LEU HFIR-type involute fuel plates [1].

Inner Fuel Element (IFE)			Outer Fuel Element (OFE)		
Region	Peak power kW/cm^3	Peak burnup, fis/cm^3, 10^{21}	Region	Peak power kW/cm^3	Peak burnup, fis/cm^3, 10^{21}
I1	72	4.75	O1	34	2.66
I2	40	3.14	O2	32	2.51
I3	34	2.7	O3	28	2.25
I4	31	2.47	O4	26	2.01
I5	30	2.38	O5	25	1.84
I6	31	2.45	O6	24	1.70
I7	34	2.65	O7	25	1.59
I8	36	2.70	O8	33	2.47
			O9	44	3.22

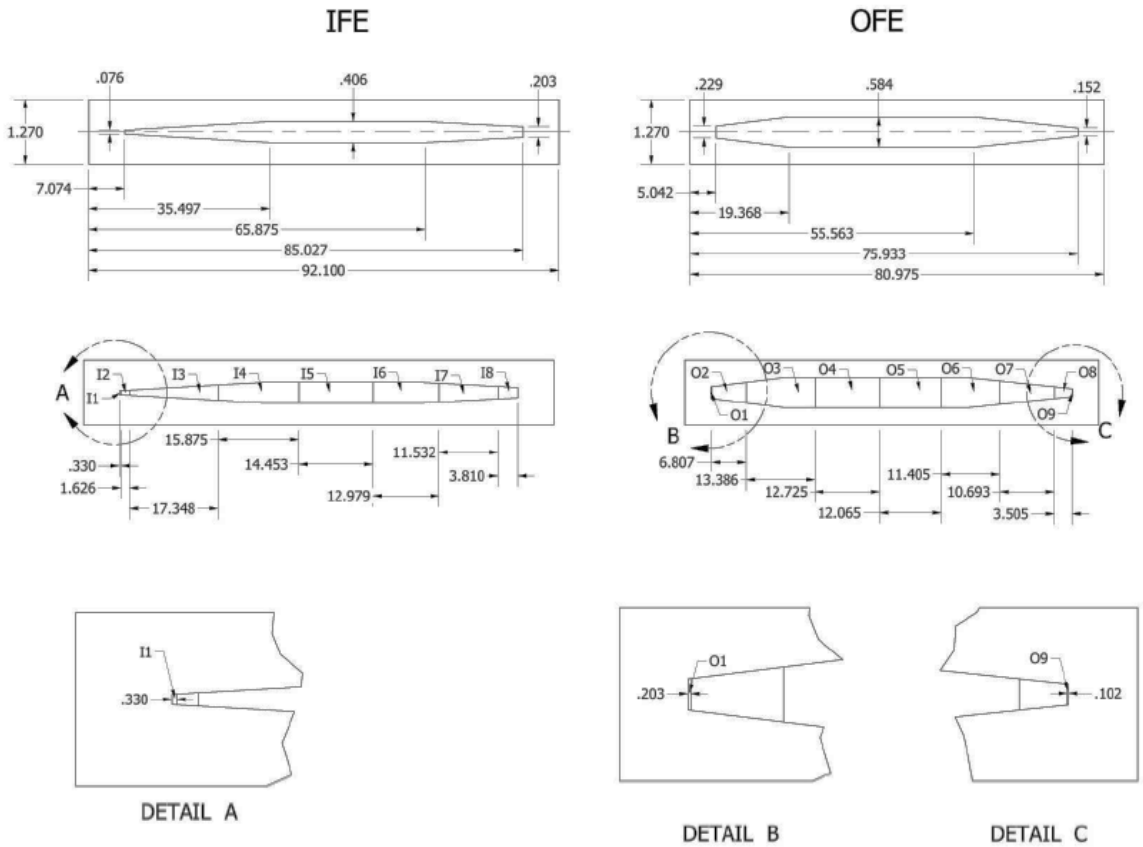

Figure 2 Preliminary design of the LEU fuel zone grading dimension (mm) and the calculation mesh in the plates.

3. MCNP model of the HFIR-type involute fuel plates

The core of the HFIR reactor contains two fuel elements with large number of circular involute plates: the Inner fuel element has N_{IFE}=171 involute fuel plates and the Outer fuel element contains N_{OFE}=369 involute fuel plates. The thickness of the plates and the water gap between the plates is equal to δ=0.127 cm. The number of plates and the parameter δ define the unique values of the radii of the base circles for the involute plates in the inner and in the outer fuel element of the HFIR core: R_{IFE}=6.9127358 cm and R_{OFE}=14.916956 cm.

The MCNP code [2] does not include possibility to process circular involute surfaces. Only the surfaces described by linear or quadratic equations can be processed using the set of MCNP surface cards. Because of the complexity of the circular involute plates, the preparation of the MCNP model of involute plates can be based on an approximation approach, which keeps the general involute shape and the volume of fuel in the plates and repeats the grading dimensions of the fuel zones.

The set of equations for the circular involute curves can be written in the parametric form containing several parameters:

$$x_i = R_i\left[\cos(\theta+\varphi_n)+(\theta-h)\sin(\theta+\varphi_n)\right]$$
$$y_i = R_i\left[\sin(\theta+\varphi_n)-(\theta-h)\cos(\theta+\varphi_n)\right],$$

where $$\theta=\left[0\div\theta_{\max}\right],\quad \varphi_n=\frac{\pi}{N_i}(n-1),\quad n=\left[1,\ldots,N_i\right],\quad h=\frac{\Delta y_m}{R_i}$$

Here R_i, $i=1,2$ are the radii of the base circles for the inner and for the outer fuel element, N_i

is the number of fuel plates in the corresponding fuel element, and the angle θ is measured in radians. The angle θ defines the circle involute for the base circle radius R_i. The angle φ_n describes the set of N_i circle involutes. The set of circle involutes was generated to approximate the cladding surfaces of involute plates. In order to approximate the fuel zone of variable thickness inside the involute plate, the set of involute curves passing through the defined mesh points in the plane fuel zones is generated using parameter Δy, which is used to shift the involute curve along y-axis by Δy cm. In this model, all mesh nodes in the plates belong to the involute curves.

An example of the MCNP model of four involute plates of the IFE is shown on the left side of Figure 3. On the right side of the Figure 3 is shown the MCNP model of four involute plates from the OFE of the HFIR-type core. The calculation mesh in the fuel zone is defined separately in each involute plate and is shown partly in Figure 4 and in Figure 5. The neutron flux distributions, the deposited energy and the fuel burn-up distributions are calculated individually in each involute plate.

The error of the geometry approximation is calculated by comparing the volumes and the masses of uranium in each part of the calculation mesh in the plane and in the circular involute fuel zones. The total volume of the fuel zones in the involute IFE and OFE plates differs from the plane fuel plates by 0.29% for the IFE plate and differs by 0.004% for the OFE plate. The differences in the accuracy of approximation of the involute IFE and OFE plates are caused by the curvature of the involute plates. The achieved accuracy permits to use the approximation models of involute HFIR-type plates in the scoping study of the HFIR design demonstration experiment using the MCNP model of the BR2 reactor. The fuel masses in the involute models of the fuel zones in the Inner and in the Outer fuel element are practically the same as in the plane models of the fuel plates. The mass of ^{235}U is equal to 38.4 g in the IFE involute plate and 52.894 g in the OFE involute plate.

The model of the Design Demonstration Experiment includes four IFE plates and four OFE plates. The mass of ^{235}U in four IFE plates is equal to 154.0 g, and to 211.58 g in four OFE plates: The total weight of ^{235}U in eight plates is equal to 365.58 g, i.e. it is comparable with the weight of ^{235}U in the fresh BR2 fuel element.

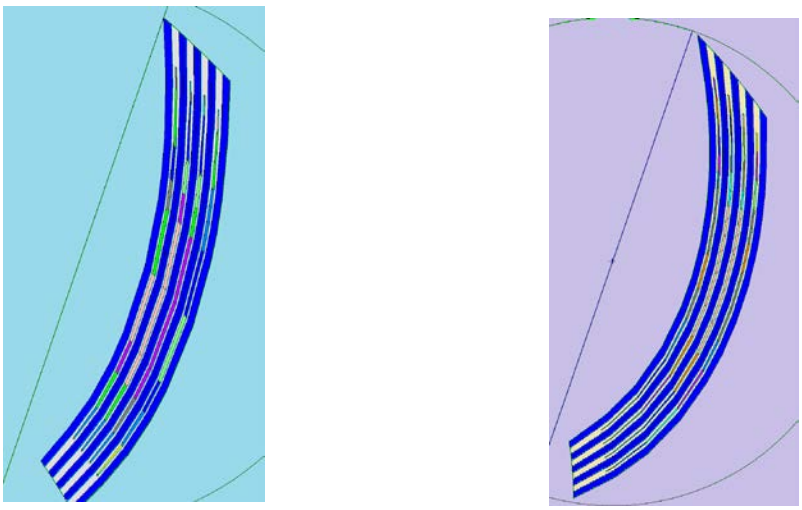

Figure 3 MCNP approximation models of the HFIR-type involute plates of the IFE (right) and of the OFE (left) generated for the scoping study of the design demonstration irradiation experiment.

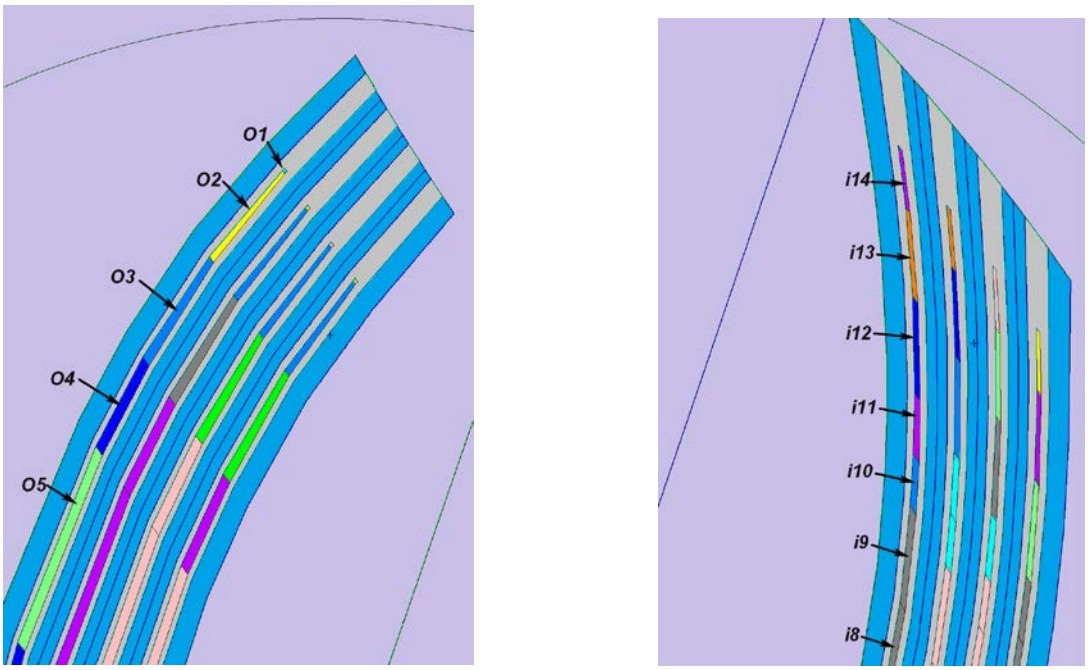

Figure 4 Calculation meshes in the fuel zones of the involute plates of the Outer Fuel Element (left side of Figure) and of the IFE (right side).

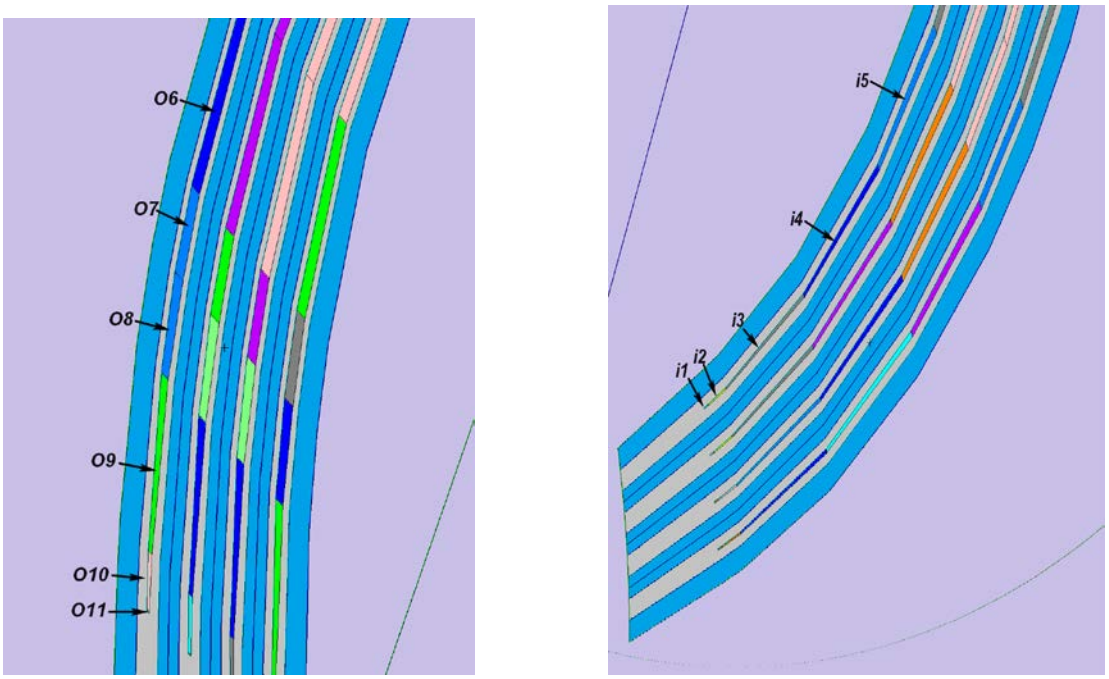

Figure 5 Calculation meshes in the fuel zones of the involute plates of the Outer fuel element (on the left side of figure) and of the IFE (on the right side).

4. Power distribution in the HFIR type involute plates during irradiation in BR2

The performance of eight involute HFIR plates with high-density low-enriched monolithic fuel during irradiation in the BR2 core have been calculated using the MCNP model of the BR2 reactor. The calculation model of the refurbished BR2 core contains low poisoned Be matrix. The inner Be plug in the channel H1 (200 mm) has larger diameter than the standard diameter of the BR2 plug (84 mm) and includes involute holders in order to arrange the HFIR-type involute plates. The six smaller periphery channels in the H1 channel are the same as in the actual BR2 design. They are loaded with neutron absorbing capsules at different axial positions. The mass of the neutron absorbers in each channel is not a constant value and has to be re-evaluated for each case depending on the number of involute plates and on the actual load of the BR2 core.

Neutronic calculations of the power released in eight HFIR plates were performed using the MCNP code. The so-called F6 and F7 tally in the MCNP code calculate the thermal power in the registration zones. The tally F7 uses the Q_{fiss}=180.88 MeV/fission, and the tally F6 calculates the energy deposited by the neutrons, and only by prompt photons (delayed photons and β^- are not included). Fuel burn-up calculations in the IFE and in the OFE plates were performed on non-regular mesh consisting of 2700 fuel zones of different burnup compositions. The mesh along the plate's widths is defined according to the description given in the previous chapter. The height of each mesh cells is equal to 2 cm, except the height of the first and the last axial cells in the plate, which have height of 0.4 cm.

The distribution of the power density in the plates is optimized by changing the orientation and the axial position of the plates and by changing the amount of neutron absorbers in the periphery channels. The fuel thickness in the axial direction of HFIR plates is not profiled. The fuel zone grading dimension along with the width of the IFE and OFE plates were defined in the above chapter. No burnable absorbers were included into the involute fuel plates. An absence of a neutron absorber at the bottom of the HFIR fuel plate provokes an increase of the power density at the bottom of the fuel plate.

The reactor is operated at the power providing the maximum power density of 72 kW/cm^3 in the hot spot in IFE. The graphs of the power density (kW/cm^3) distribution at BOC in two IFE and two OFE HFIR-type involute plates are presented in Figure 7.

The final distributions of the fission events density (fiss/cm^3) in the fuel zones in plates after 28 days of irradiation are presented in Figure 8.

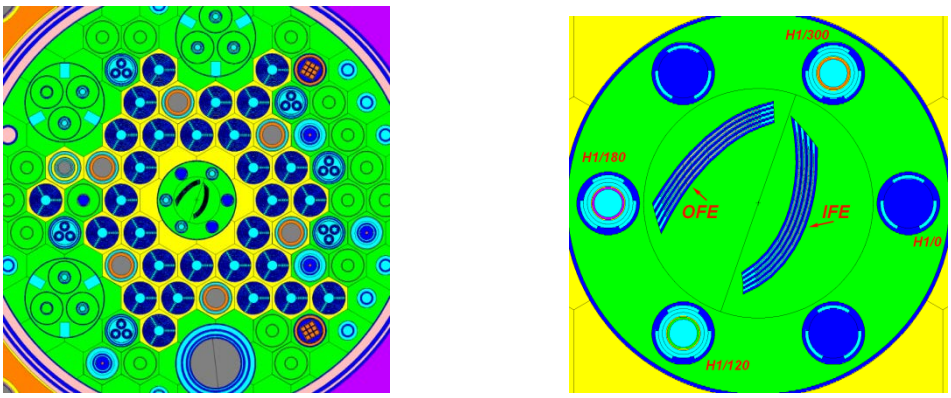

Figure 6 BR2 core with involute plates in the H1 channel. The right figure shows the H1 channel containing HFIR-type involute plates and the periphery channels containing neutron absorbers.

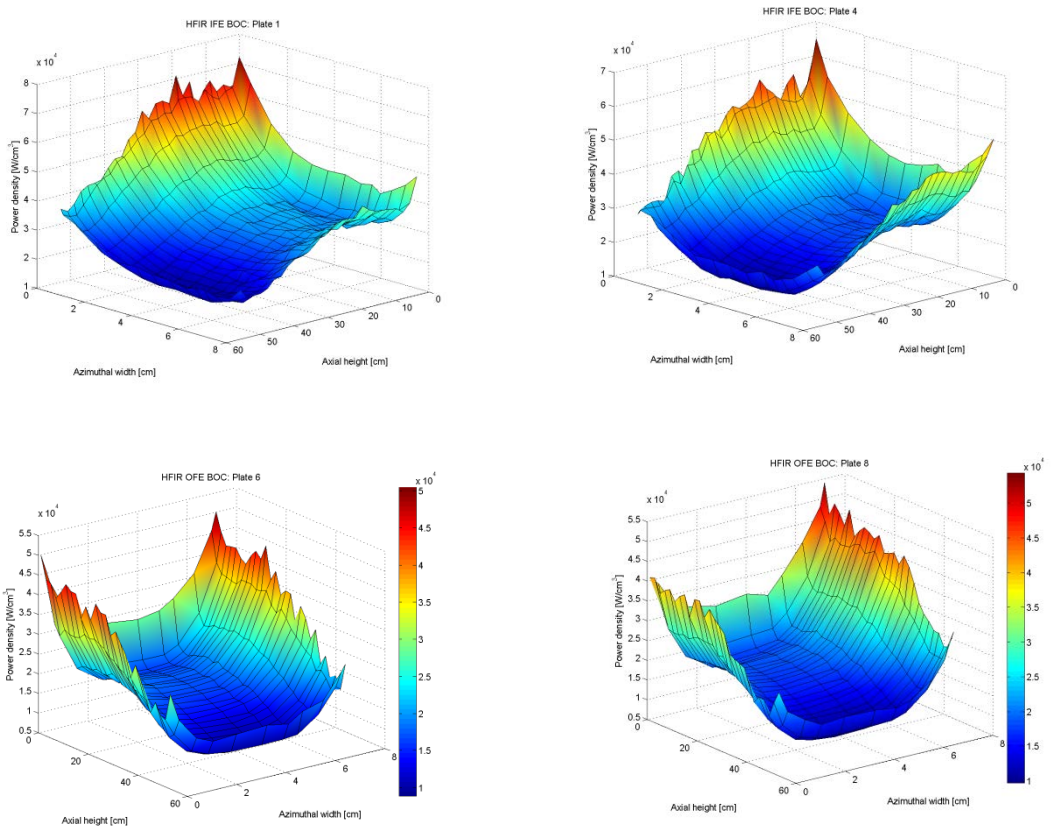

Figure 7 Power density (kW/cm^3) distributions in two IFE (upper figures) and two OFE (lower figures) involute fuel plates at BOC.

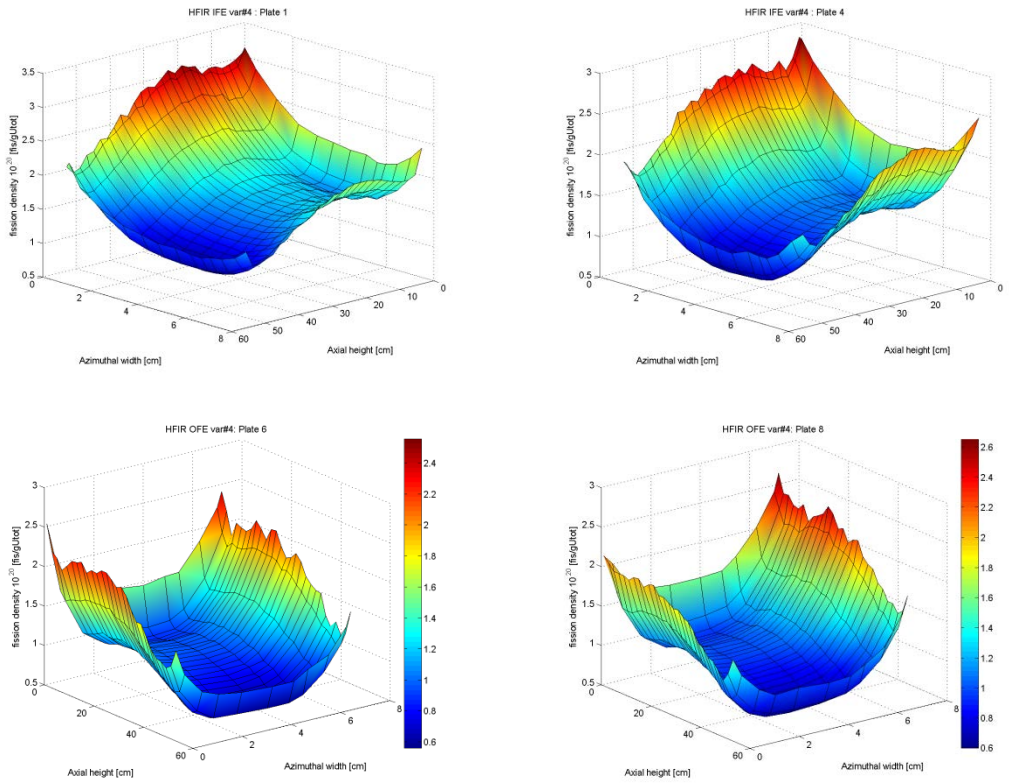

Figure 8 Distributions of fission events density (fiss/cm^3) in two IFE (two upper figures) and two OFE (two lower figures) involute fuel plates at EOC.

5. Discussion

The general form of the calculated power density distribution in the plates is similar to the targeted distribution in the LEU fuel plates given in Table 2. In the presented study the centers of the involute plates were located in the middle plane of the BR2 core. However, the hot spot in the BR2 core is located below the middle plane of the reactor core. For this reason the calculated axial distributions in the involute plates are not symmetrical. The axial power distributions become more symmetrical in the case of shifting the center of plates toward the bottom of the BR2 core. In absence of burnable absorbers, the power density has a peak at the bottom of the fuel plates. To simulate the evolution of the power distribution during the irradiation in the BR2 reactor the fuel burnup distributions in all eight involute plates have been re-calculated after each time step of 7 days. The targeted maximum power density of 72 kW/cm^3 in the IFE plate was maintained during each time step by changing the power of BR2 reactor. The performed calculations show a collective difference of 15%-20% in the maximum of the power distributions in plates. The observed nonequivalence of the irradiation conditions in the plates depends on the orientation of the basket in the H1 channel and on the content in the periphery channels. Using optimized amount of neutron absorbers in the periphery channels and a proper positioning of the involute plates in the H1 channel the power distributions can be fitted better to the targeted distributions.

The spread of the deviation of the calculated power density and of the total number of fissions at the end of irradiation from the targeted parameters are presented in two summary tables which include the calculated deviations in four variants of the plates positioning in H1 channel. The deviations of the maximum power density in the arc zones of the fuel plates are presented in Table 3. The spread of the calculated deviations for the maximum number of fissions are presented in Table 4.

The comparison of the calculated results with the specified target irradiation conditions demonstrates that the target peak power and the target fission density can be accomplished during irradiation in the BR2 reactor. Nevertheless, additional optimizations are necessary to be performed for the design of the involute HFIR-type plates and for the refurbished core of the BR2 reactor.

Table 3. Collective calculated deviations of the peaking power density in fuel zones of eight involute plates obtained during the scoping study for the BR2 reactor at BOC relatively to the targeted values of the preliminary design of the LEU plates IFE&OFE. The maximum statistical error of the calculations is equal to 5% (1σ) and the minimum is about 1 %(1σ).

IFE zones	Evaluation/request
I1	0.75 ± 1.00
I2	1.25± 1.58
I3	1.06 ± 1.38
I4	0.81 ± 1.13
I5	0.73 ± 1.07
I6	0.74 ± 1.00
I7	1.00 ± 1.12
I8	1.08 ± 1.25

OFE zones	Evaluation/request
O1	1.18 ± 1.47
O2	0.91 ± 1.16
O3	0.70 ± 0.96
O4	0.62 ± 0.88
O5	0.64 ± 0.88
O6	0.75 ± 0.92
O7	1.00 ± 1.20
O8	1.00 ± 1.27
O9	0.95 ± 1.05

Table 4. Collective calculated deviations of the number of fissions in fuel zones of eight involute plates obtained in the scoping study for BR2 reactor relatively to the targeted values of the preliminary design of the LEU plates IFE&OFE. The maximum statistical error of calculations is equal to 5% (1σ) and the minimum is about 1%(1σ).

IFE zones	Evaluation / request
I1	0.85± 1.00
I2	1.25± 1.47
I3	1.07 ± 1.36
I4	0.82 ± 1.15
I5	0.77 ± 1.08
I6	0.79 ± 1.04
I7	0.93 ± 1.06
I8	1.16 ± 1.29

OFE zones	Evaluation / request
O1	1.16 ± 1.47
O2	0.97 ± 1.26
O3	0.71 ± 1.04
O4	0.67 ± 1.02
O5	0.72 ± 1.06
O6	0.84 ± 1.16
O7	1.32 ± 1.50
O8	1.16 ± 1.36
O9	1.00 ± 1.13

6. Conclusion

The paper contains results of the neutronic scoping study for the irradiation of eight HFIR-type involute plates containing low-enriched high-density monolithic uranium fuel in the BR2 reactor. The developed high-fidelity MCNP model of the involute plates with grading dimensions of the fuel zones in the Inner and in the Outer fuel element has been applied for the computer simulation of the irradiation experiment HFIR-type involute plates containing high-density monolithic LEU fuel. Several scenarios for positioning of the involute plates in the H1 channel have been analyzed. Two baskets with different involute curvature are placed in the H1 channel simultaneously. Each of the baskets includes involute plates from the IFE and from the OFE. The calculated distributions of the power density and of the number of fission events show good correlations with the targeted distributions of the preliminary design of the LEU core of HFIR-type reactor.

7. Acknowledgements

The present work on the scoping study for Irradiation of high-density monolithic LEU involute plates in the BR2 reactor has been performed in the framework of the contract No. 00156694 between the INL and the SCK•CEN.

8. References

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[2] X-5 Monte Carlo Team, MCNP — A General Monte Carlo N-Particle Transport Code, Version 5, LA-UR-03-1987, April 24, 2003.