YALINA-Booster Conversion Project

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Abstract. The YALINA Booster subcritical assembly was constructed at the Joint Institute for Power and Nuclear Research (JIPNR)-SOSNY, Belarus to examine the physics of Accelerator Driven Systems (ADS). The assembly has fast and thermal zones to study the coupling between the two zones, the transuranics transmutation, and the ADS kinetics. It is driven by an external neutron source located at the assembly center. The central fast zone (the booster zone) consists of high enriched uranium (HEU) fuel rods loaded in a lead matrix and it is surrounded by the thermal zone. The thermal zone has low enriched uranium (LEU) fuel rods loaded in polyethylene moderator. Between the two zones, there is a thermal neutron absorber. JIPNR-SOSNY has an International Science and Technology Center project in collaboration with Argonne National Laboratory of USA to replace the HEU fuel of YALINA Booster with LEU fuel without penalizing its performance.

In this paper, the analytical models and the obtained results performed for the project are presented including the static and the kinetic results. The experimental and analytical results are compared and discussed. The new assembly configuration with LEU is also presented.

1. Introduction

The YALINA-Booster facility was constructed at the Joint Institute for Power and Nuclear Research SOSNY of Belarus. It is a subcritical assembly driven by an external neutron source [1, 2]. The facility has no active cooling system and it consists of four concentric square zones: a target zone, an inner fast zone, an outer fast zone, and a thermal zone. The inner fast zone utilizes high enriched metallic uranium fuel rods with 90% ^{235}U, the outer fast zone contains uranium oxide fuel rods with 36% ^{235}U, and the thermal zone uses uranium oxide fuel rods with 10% ^{235}U (EK-10 fuel type). In-between the outer fast and the thermal zones, a thermal neutron absorber zone composed of two concentric square shells is used. The first square shell has natural uranium rods and the second one has natural boron carbide rods. These two absorber shells allow fast neutrons to stream from the fast zone to the thermal zone but they reduce the opposite streaming of thermal neutrons. The matrix material of the fast zones is lead, and the thermal zone moderator is polyethylene. The assembly is surrounded by a radial graphite reflector. A stainless steel grid holds the lead and the polyethylene matrix blocks and extends in the axial reflector. At the top and the bottom of all fuels rods, borated polyethylene reflector is used. Along the fuel rods length, half of the target zone has pure lead and the other half accommodates the copper disk, which contains deuterium or tritium for producing Deuterium-Deuterium or Deuterium-Tritium neutrons. The subcritical assembly has ten experimental channels and six measurement channels.

This paper presents some of the analyses performed for the YALINA-Booster conversion project to use low enriched uranium (LEU) instead high enriched uranium (HEU) fuel rods for the booster zone. First the performance of the YALINA Booster subcritical assembly with HEU has been characterized by performing detailed analytical and experimental studies. Then, the booster zone has been configured to use uranium fuel rods with 21% ^{235}U for achieving the original subcriticality level.

The analytical analyses have developed accurate calculational models for performing Monte Carlo and Deterministic calculations. MCNPX, MCB, MONK, and ERANOS computer codes with different nuclear data libraries based on ENDF/VI, JEF3.1, and JEF2.2 have been used for static and kinetic analyses. The geometrical details are included explicitly without approximation or homogenization in the Monte Carlo models. In the experimental program, the subcriticality has been measured as a function of the number of the fuel rods loaded in the subcritical assembly. Different methods have been used to measure the assembly subcriticality. In addition, the spatial neutron flux distribution, spectral indices, and transmutation reactions rates have been measured.
This paper presents the developed analytical models to simulate the YALINA-Booster assembly and the obtained static and kinetic results. The experimental and analytical results are compared and discussed. The new YALINA-Booster configuration with 21% enriched uranium fuel rods is also presented.

2. Calculational Methods

The accurate analysis of YALINA-Booster represents a challenge because of the geometrical nature of the assembly. The assembly dimensions are relatively small and heterogeneous. In addition, it has fast and thermal fuel zones coupled with absorber interface, which results in significant spatial variations in the neutron flux and the neutron spectrum. Deterministic and statistical methods have been used to analyze and characterize the YALINA-Booster subcritical assembly. The deterministic methods provide detail spatial characterization of the neutron flux and the spectrum but require geometrical homogenization. On the other hand, the statistical methods model the assembly without geometrical approximations but they provide limited space dependent results. Different nuclear data files are utilized for both methods to determine the impact on the neutronics parameters. In this section, the utilized computational methods, computer codes, nuclear data files, and geometrical models are described.

2.1. Deterministic Methods

A three dimensional XYZ geometry is used to model the assembly to match its square lattice arrangement. In this model, the geometry is divided into a large number of zones where each zone has one material, simple geometry, or repeated unit cell. A one- or two-dimensional model with explicit details of the geometry is generated for each zone to calculate a homogeneous cross section set for this zone. The generated cross section sets are used for the transport calculation of the full three dimensional model of the assembly.

The ERANOS code package [3] has been used for this deterministic analysis. The zone calculation used the ECCO cell/lattice code of ERANOS with nuclear data generated from JEF3.1 and ENDF/B-VI.8 nuclear data files. ECCO flux calculations for the heterogeneous geometries use the collision probability method in fine group structure. The subgroup method is used in ECCO to treat resonance self-shielding effects. Self-shielded cross sections are condensed and homogenised to provide cross section sets in the defined group structure for the full neutron transport of the assembly calculation. For non-fissile zones, the neutron flux is calculated using a source term given by the neutron leakage from the neighbouring cell. The VARIANT module of ERANOS has been used to calculate the multiplication factor and the neutron flux distribution of the assembly, which uses the nodal variational method The scattering anisotropy is included as P_n moments up to the order N of the Legendre expansion of the VARIANT flux. The ERANOS geometrical model is shown in *FIG. 1*, where some of the zone numbers are displayed on the model. The calculation was performed with 53 energy group structure. Criticality calculation was performed to determine the neutron multiplication factor of the assembly. Static and dynamic source calculations were also performed to define the source multiplication factor and the dynamic parameters of the assembly.

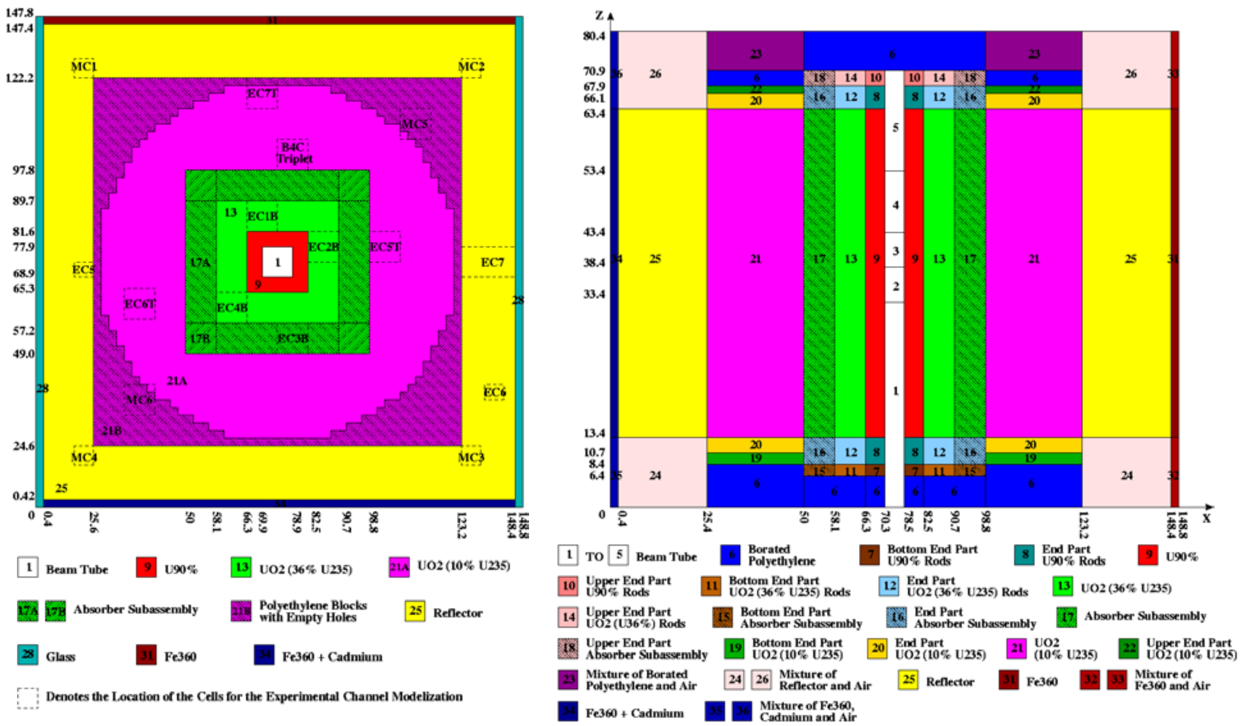

FIG. 1. ERANOS deterministic model of YALINA-Booster subcritical assembly.

2.2. Statistical Methods

Two independent geometrical models have been developed for examining YALINA-Booster assembly using Monte Carlo methods. The first geometrical model [4] was developed using the Monte Carlo code MONK9a [5] computer code. MONK has been developed by SERCO Assurance and British Nuclear Fuel and it is one of the neutron transport codes used for licensing nuclear power plants in United Kingdom. The code uses a continuous energy nuclear data library (BINGO) based on JEF-2.2, a 13193 energy groups library (DICE) based on JEF 2.2, ENDF/B-VI or JENDL-2, or a 172 energy groups WIMS nuclear data library. MONK has the capability to calculate the external source neutron multiplication factor (k_{src}) for a subcritical assembly. The YALINA-Booster assembly was modelled without any geometrical approximations or material homogenization as shown in *FIG. 2*. The model was verified by using interactive visualization software

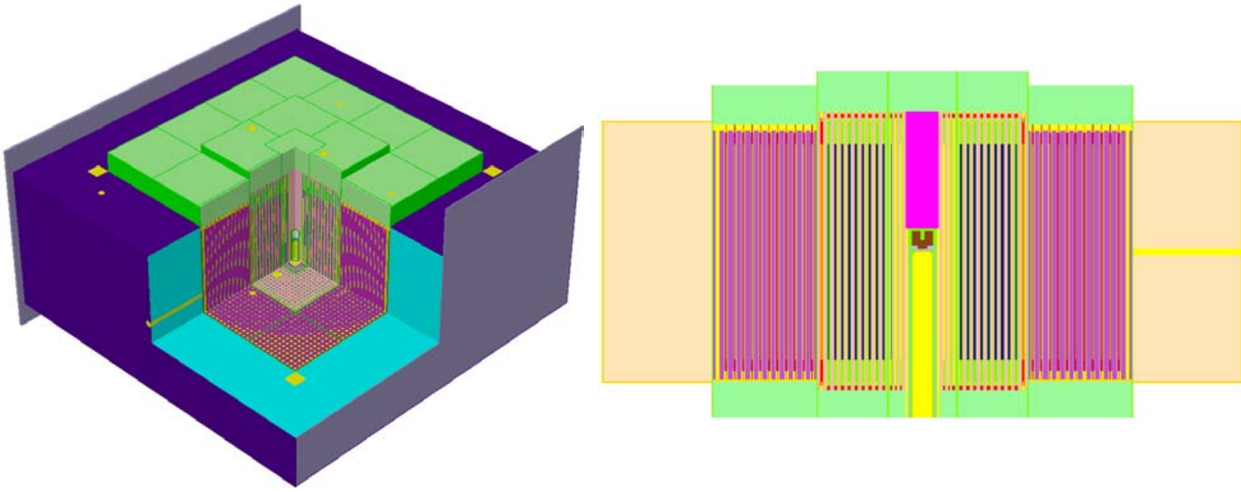

FIG. 2. MONK geometrical model of YALINA-Booster shown as a three dimensional view with a corner cut on the left and a vertical section on the right.

The second geometrical model [4] was developed using the Monte Carlo code MCNPX [6] and the same model was used for the Monte Carlo Continuous Energy Burnup Code MCB [7]. MCB is an extension of the MCNP4c3 code with burnup capability. In the present work, the MCB code has been only used with JEF-2.2 nuclear data library for calculating k_{src} and the prompt neutron lifetime. Again, the geometrical model has explicit presentation of all the details of the YALINA assembly without geometrical approximation or material homogenization. The MCNP model is shown in *FIG. 3*.

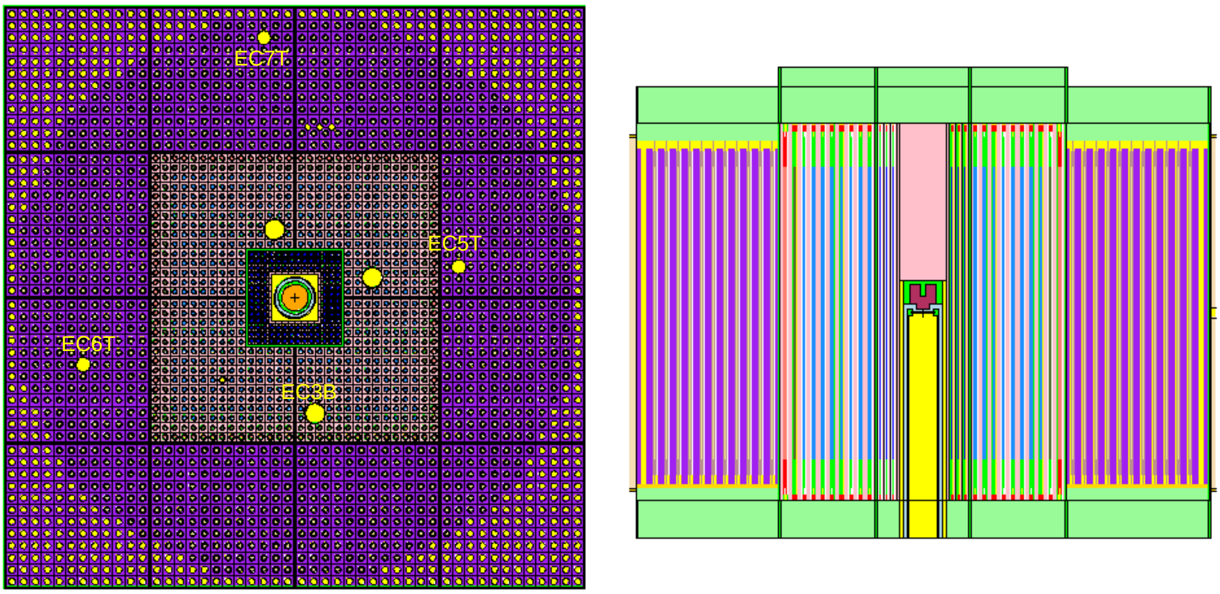

FIG. 3. MCNPX geometrical model of YALINA-Booster shown without the graphite reflector as a horizontal section of the fast and thermal zones of the on the left and vertical section on the right.

3. Results

The analytical and the experimental studies of the YALINA-Booster conversion project have carried out in two steps. The first step has replaced all the 90% enriched fuel rods with 36% enriched fuel rods and extra EK-10 fuel rods have been added in the thermal zone to maintain the same subcriticality level of ~0.98. The analytical and experimental results of the converted assembly show a good agreement. The second step has replaced all the 36%

enriched fuel with 21% enriched fuel rods, which has decreased the assembly subcriticality to ~ 0.95. The lack of extra EK-10 fuel rods necessitate a different approach to adjust the subcriticality level. The parametric study shows that the desired subcriticality level (~0.98) can be achieved by changing the square arrangement of the absorber zone to a circular geometry.

The analyses have been performed for different configurations and fuel enrichments with the deterministic and the statistical models using different nuclear data files. The obtained analytical results have been compared with the experimental results. Samples of the analytical and the experimental results are presented in this section.

3.1. Original Configuration with 90% Enriched Uranium Fuel Rods

The ERANOS analytical results are given and compared with experimental results in Table I for the original configuration with 1141 EK-10 fuel rods in the thermal zone. The calculated multiplication factor with JEF3.1 nuclear data files is 0.9730. The use of ENDF/B-VI.8 instead of JEF3.1 reduces the multiplication factor by 80 pcm. The K_{src} calculation results are higher than the effective multiplication. This is due to the higher average neutron energy of the external neutron source relative to the average energy of the fission neutrons from U-235 and U-238. In addition, the external neutron is located at the assembly center of the fast zone, which results in more neutrons per fission. This effect is clearly observed for the D-T neutron source as shown in Table I.

Time dependent studies with KIN3D module of ERANOS have been performed to calculate the helium detector response from D-D pulsed neutron source to compare with the experimental results. First, an analytical simulation has been performed to calculate and compare the detector response with the experimental data for the different experimental channels. An example is shown in *FIG. 4* for the EC6T experimental channel. The comparison shows an excellent agreement. The area method has been applied to these results to calculate the neutron multiplication factor similar to the experiment. The maximum difference between the analytical and experimental multiplication factors is ~50 pcm as shown in Table I. In addition, the calculated results have been used to eliminate the space dependent from the experimental data using Bell & Glasstone [8] correction factor. The corrected values are shown in Table I. The maximum difference between the calculated K_{eff} value and the correctedd values is 50 pcm, which is less than statistical error of the experimental data as shown in Table I.

Similar Monte Carlo analyses have been performed with MCNPX computer code using JEF3.1 and ENDF/B-VI.6 [4, 9] and a sample of the results is given in Table II. The experimental data used with MCNPX are more recent than the previous data. The maximum difference between the measured and the calculated neutron multiplication is ~360 pcm, which is comparable to the statistical error of the experimental data. The comparison between the experimental measurements and the calculated values of He-3 detector response as a function of the axial position inside the EC6T experimental channel is show in *FIG. 5*. The comparison shows a good agreement.

3.2. New Configuration with 21% Enriched Uranium Fuel

The booster zone of the original YALINA-Booster configuration has 695 fuel rods (132 90% and 563 36%) with high enriched uranium. These 695 fuel rods have been replaced with 651 fuel rods with 21% enriched uranium, which leaves some empty fuel cells in the booster zone. In addition, all the available inventory of EK-10 fuel rods, which is 1185 rods, has been used in the thermal zone of the YALINA-Booster. The resulting configuration has a neutron multiplication of ~0.95. A parametric study has been carried out to reconfigure the absorber zone to achieve a subcriticality level around 0.98 without reconstructing the assembly. The lead, polyethylene, graphite, and steel structure are kept without any change. The obtained configuration is shown in *FIG. 6* with a neutron multiplication factor of ~0.98. The neutron flux calculation shows that the spatial distribution is similar to the distribution of the original configuration. Although the absorber zone has a circular shape instead of square, the lead and polyethylene materials are responsible for maintaining the spatial flux distribution. A minor perturbation can be seen at the corners of the booster zone. FIG. 7 shows the total neutron flux map of the new configuration with 21% enriched uranium fuel rods in the booster zone due to a D-T neutron source at the assembly center. Experimental measurements are underway to confirm and compare these analytical results.

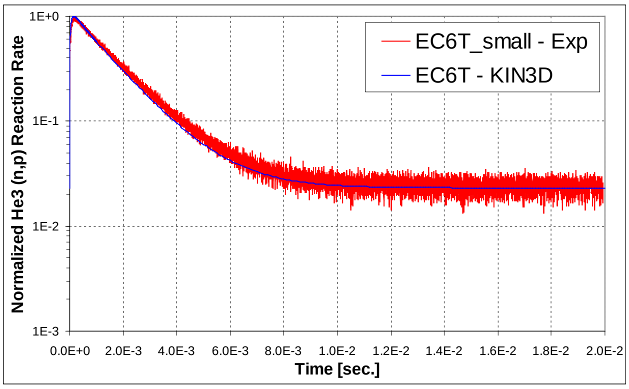

FIG. 4. Experimental measurements and ERANOS analytical simulation results of He-3 detector response comparison located at the center of the EC6T experimental channel of the YALINA-Booster original configuration due to pulsed D-D external neutron source at the assembly center.

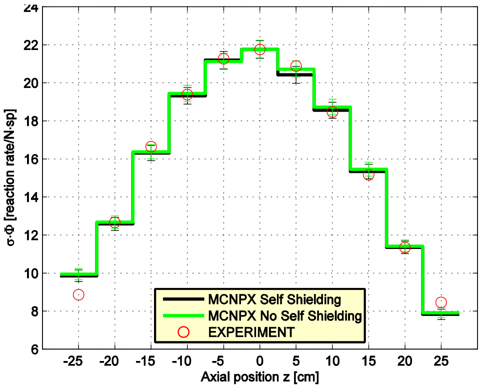

FIG. 5. Experimental measurements and MCNPX analytical simulation results of He-3 detector response comparison along the EC6T experimental channel due to Cf external neutron source located at the assembly center.

4. Conclusions

YALINA-Booster subcritical assembly have been successfully modelled using deterministic and statistical methods. The comparison between the analytical results and the experimental measurements shows excellent agreement. The original assembly has been reconfigured to use low enriched uranium instead of the high enriched uranium without penalizing its performance.

Acknowledgments

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TABLE I: ERANOS DETERMINISTIC RESULTS AND JULY 2006 EXPERIMENTAL DATA FOR YALINA-BOOSTER ORIGINAL CONFIGURATION WITH 1141 EK-10 FUEL RODS

Nuclear Data Files	JEF3.1		ENDF/B-VI.8
Multiplication Factor (K_{eff})	0.97303		0.97223
Source Multiplication Factor (K_{src})			
Cf-252 Neutron Source	0.98083		0.98044
D-D Neutron Source	0.98154		0.98113
D-T Neutron Source	0.98905		0.98881
Effective Delayed Neutron Fraction, pcm	753.3		753.4
Nuclear Data Files	JEF3.1		
Multiplication Factor Using Area Method in Different Experimental Channels with ^{3}He Detector	EC5T	EC6T	EC7T
Calculated Multiplication Factor with Area Method	0.97267	0.97483	0.97565
Measured Multiplication Factor [1] with Area Method	0.97318±220	0.97513±200	0.97535±220
Difference between the Measured and the Calculated Multiplication Factors, pcm	51	30	-30
Corrected Multiplication Factor Measurements to Remove the Space Dependent	0.97353	0.97335	0.97269
Difference between the Corrected Measured and the Reference Multiplication Factors, pcm	50	32	-34

[1] The measured values are only reported with the statistical error.

TABLE II: MCNP MONTE CARLO RESULTS AND DECEMBER 2007 – FEBRUARY 2008 EXPERIMENTAL DATA FOR YALINA-BOOSTER ORIGINAL CONFIGURATION WITH 1141 EK 10 FUEL RODS

Nuclear Data Files	JEF3.1		ENDF/B-VI.6
Multiplication Factor (K_{eff})	0.98008±9		0.97972±4
Source Multiplication Factor (K_{src})			
D-D Neutron Source			0.98690
D-T Neutron Parameter Source			0.99145
Effective Delayed Neutron Fraction, pcm	728±12		760±8
Nuclear Data Files	ENDF/B-VI.6		
Multiplication Factor Using Area Method in Different Experimental Channels with ^{3}He Detector	EC3B	EC6T	EC8R
Calculated Multiplication Factors with Area Method	0.97879	0.97970	0.98049
Measured Multiplication Factors [1] with Area Method	0.97603±160	0.97956±110	0.97701±140
Difference between the Measured and the Calculated Multiplication Factors, pcm	-276	-14	-348
Corrected Multiplication Factor Measurements to Remove the Space Dependent	0.97708	0.97958	0.97611
Difference between the Corrected Measured and the Reference Multiplication Factors, pcm	-264	-14	-361

[1] The measured values are only reported with the statistical error.

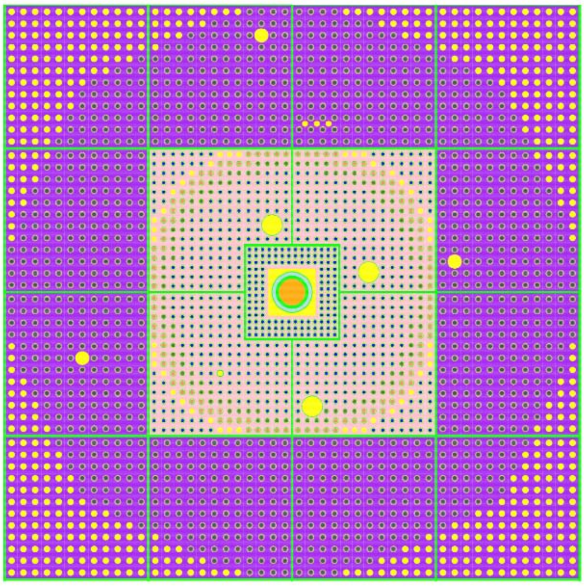

FIG. 6. Horizontal section of MCNPX geometrical model of YALINA-Booster configuration with 21% enriched fuel rods in the booster zone shown without the graphite reflector.

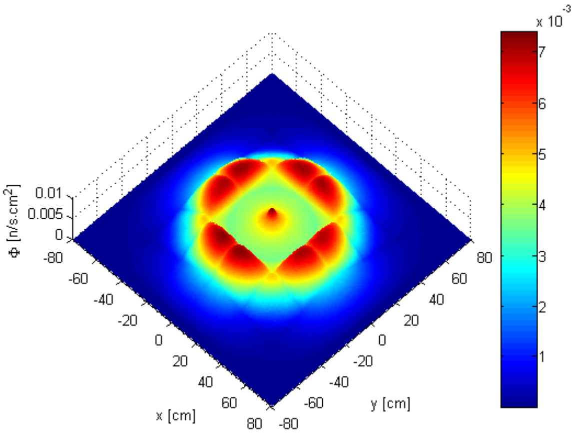

FIG. 7. Total neutron flux map of the YALINA-Booster configuration with 21% enriched fuel rods in the Booster zone due to a D-T neutron source at the assembly center.

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