ACCELERATOR-DRIVEN SUBCRITICAL ASSEMBLY: CONCEPT DEVELOPMENT AND ANALYSES

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ABSTRACT

A conceptual design activity has been started to develop an accelerator-driven subcritical assembly using the existing electron accelerators at Kharkov Institute of Physics and Technology (KIPT) in Ukraine. The main functions of the subcritical assembly are the production of medical isotopes and the support of the Ukraine nuclear power industry. Reactor physics experiments and material performance characterization will be carried out utilizing the capabilities of the subcritical assembly. The neutron source of the subcritical assembly is generated from the interaction of 100 KW electron beam with a tungsten or uranium target. The electron beam has a uniform spatial distribution and the electron energy is in the range of 150 to 200 MeV. The subcritical assembly is planned to use high enriched uranium (HEU). This activity is evaluating the possibility of converting the assembly to use low enriched uranium (LEU) without penalizing its performance. Different fuel forms are under consideration with water coolant including the LEU fuel of the Kiev research reactor. Beryllium or water is utilized for the reflector of the subcritical assembly. In the design process, the neutron flux is maximized to enhance the capabilities of the subcritical assembly. The conceptual design and the design analyses will be presented in this paper. The analyses include nuclear physics, neutronics, heat transfer, hydraulics, and material issues.

1. Introduction

Kharkov Institute of Physics and Technology (KIPT) in Ukraine has a plan to construct an accelerator driven subcritical assembly using high enriched uranium (HEU). An existing electron accelerator will be utilized with high atomic number target material to generate neutrons for driving the subcritical assembly. The electron beam power is about 100 KW with a uniform spatial distribution. Deuteron beam with beryllium target is an option under consideration. The main functions of the subcritical assembly are the medical isotope production and the support of the Ukraine nuclear industry. Reactor physics experiments and material research will be carried out utilizing the subcritical assembly. Argonne National Laboratory (ANL) is studying the possibility of utilizing low enriched uranium (LEU) instead of HEU without penalizing the subcritical assembly performance. This paper describes the ANL work performed for this study in preparation for a joint conceptual design activity between ANL and KIPT.

In the course of this work, several studies have been carried out to investigate the main choices and the system parameters for a satisfactory operating performance. The neutron source intensity and spectrum have been characterized as function of the electron energy for two target materials. The main focus is to maximize the neutron production for the 100 KW beam power. The spatial energy deposition in the target material, spatial neutron generation, and neutron utilization fraction have been studied to define the main target parameters. A conceptual design for the target has been developed based on these parameters and the engineering aspects including heat transfer, thermal hydraulics, structure, and material requirements. The target geometrical configuration has been designed to maximize the neutron utilization in the subcritical assembly and to provide irradiation channels at the highest flux level. The subcritical assembly design with LEU fuel has been iterated to maximize the neutron flux. The main objective is to obtain a neutron flux level comparable to the corresponding flux level with HEU fuel. The paper presents the key results from these analyses and the conceptual design for the target and the subcritical assembly.

2. Neutron Source

In a subcritical system, the neutron source strength defines the neutron flux level and the fission power of the subcritical assembly. This requires a special attention to maximize the neutron yield from the available beam power, the neutron fraction delivered to the subcritical assembly, and the neutron utilization in the subcritical assembly. High atomic number target materials are required to enhance the neutron production from the electron interactions. In addition, high melting point, high thermal conductivity, chemical inertness, high radiation damage resistance, and low neutron absorption cross section are the desirable properties for the target materials. Previous physics studies[1] showed that uranium, tungsten, lead, and tantalum materials produce the highest neutron yield per incident electron. Based on all these issues and the operating experience from different accelerator facilities, tungsten and uranium have been selected for this application. The neutron yield from the two materials has been studied as a function of the electron energy using MCNPX[2] computer code. MCNPX is a Monte Carlo radiation transport computer code that transports 34 particle types over a wide energy range for modeling nuclear and non-nuclear systems.

The performance of tungsten and uranium target materials has been analyzed as a function of the electron energy for the 100 KW total beam power. The spatial energy deposition density per incident electron in tungsten is shown in Figure 1 as a function of the target length for different electron energies. The peak value occurs few millimeters away from the electron beam window. This peak increases and shifts further from the electron beam window as the electron energy increases. The spatial energy deposition normalized to beam power density of 2 KW/cm^2 on the beam window is plotted in Figure 2. The heat removal of the energy deposition requires the use of thin layers of the target material to avoid high temperature and thermal stresses. This results in a large number of coolant channels, which reduces the target performance. The water coolant slows down and absorbs electrons without generating neutrons. This requires the use of a low beam power density less than 2 KW/cm^2 or electron energy above 150 MeV. Reducing the beam power density increases the target cross section area that reduces the neutron flux in the subcritical multiplier. This leads to the consideration of electron energy above 150 MeV.

The neutron yield per electron is shown in Figures 3, which increases as the electron energy increases. However, the neutron source production per second from the 100 KW beam reaches a saturation value as the electron beam energy increases above 150 MeV as shown in Figure 4. Therefore, the 100 KW electron beam with the electron energy above 150 MeV produces about the maximum neutron yield.

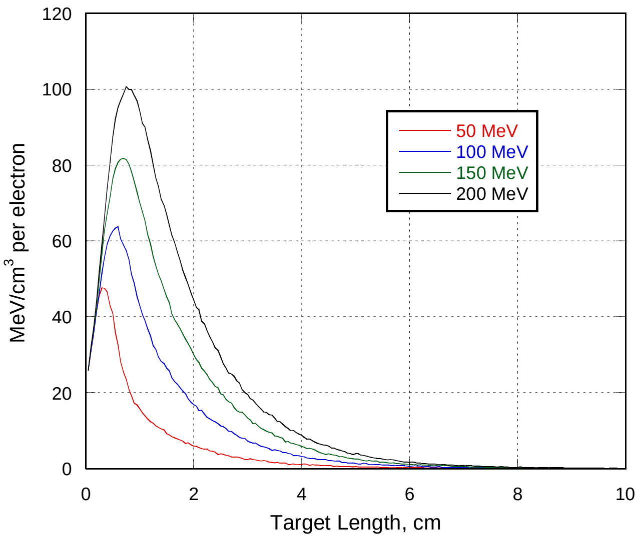

Figure 1. Spatial energy deposition per electron in tungsten target material for different electron energies

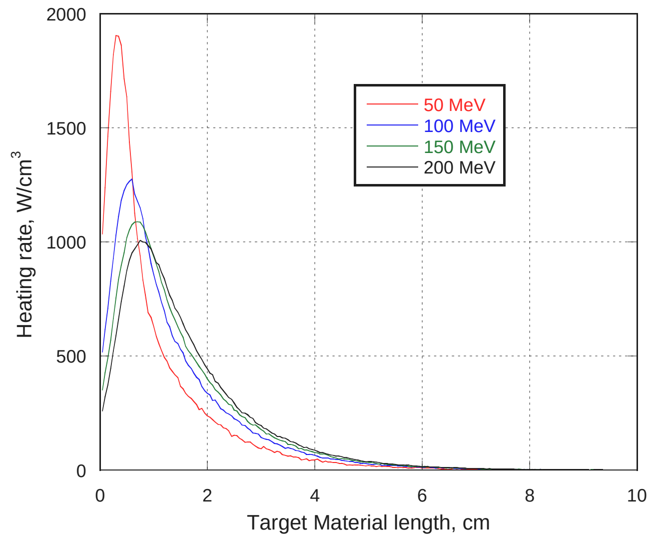

Figure 2. Spatial energy deposition normalized to beam power density of 2 KW/cm^2 on the beam window for different electron energies

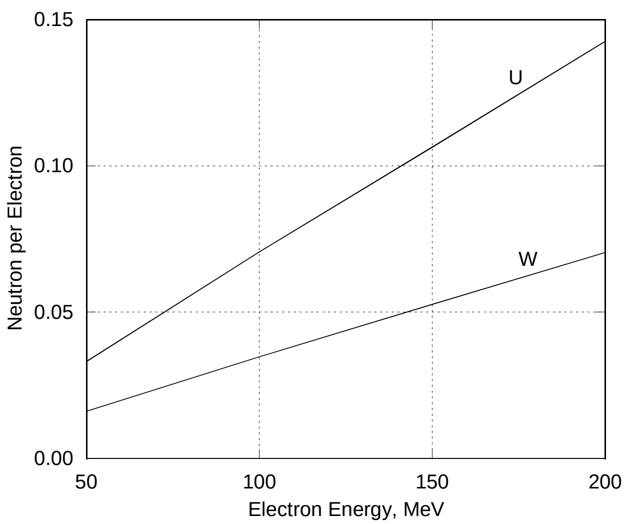

Figure 3. Neutron yield per electron as a function of the electron energy for uranium and tungsten target materials

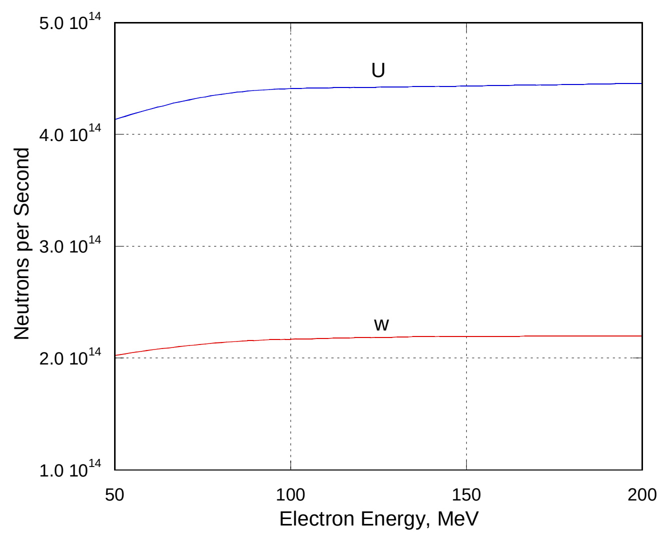

Figure 4. Neutron source strength as a function of the electron energy for 100 KW beam energy from uranium and tungsten target materials

The spatial distribution of the generated neutrons is analyzed to maximize their utilization in the subcritical assembly. The neutron fraction that leaves the target along the beam axis has the potential of disappearing without utilization. A large fraction of the neutrons leaving from the electron beam window (top fraction) exits the system through the vacuum beam tube or interacts with the beam tube structure. A fraction of these neutrons reaches the subcritical assembly by leaking from the beam tube. Also, the neutrons leaving the target in the beam direction (bottom fraction) interact with the water coolant and the beryllium reflector under the target, which reduce their chances for reaching the subcritical assembly. Figure 5 shows the neutron fraction distribution from the tungsten target as a function of the electron energy. Again, the use of high electron energy enhances the neutron fraction that leaves in the direction of the subcritical assembly, side fraction. It should be noted that the top neutron fraction is comparable to the side fraction, which calls for locating the target under the subcritical center to increase the chance for the neutrons leaving the top target surface for reaching the subcritical assembly. All the results show that the use of high energy electrons in the range of 150 to 200 MeV is beneficial for improving the system performance. The neutron spectrum from the target was analyzed to quantify the high energy component as a function of the electron energy. The calculated neutron spectra are shown in Figure 6. The peak value of the neutron spectrum is above 1 MeV similar to the fission spectrum. The high energy component of the spectrum is not sensitive to the electron energy and its magnitude is very small as shown in Figure 6.

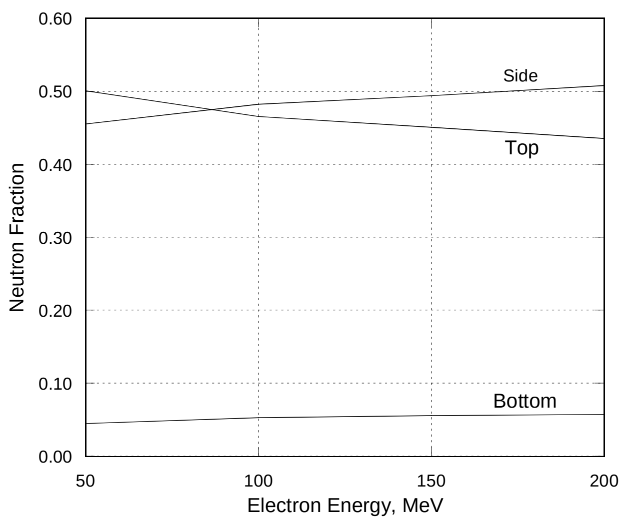

Figure 5. Neutron fraction distribution from the tungsten target as a function of the electron energy

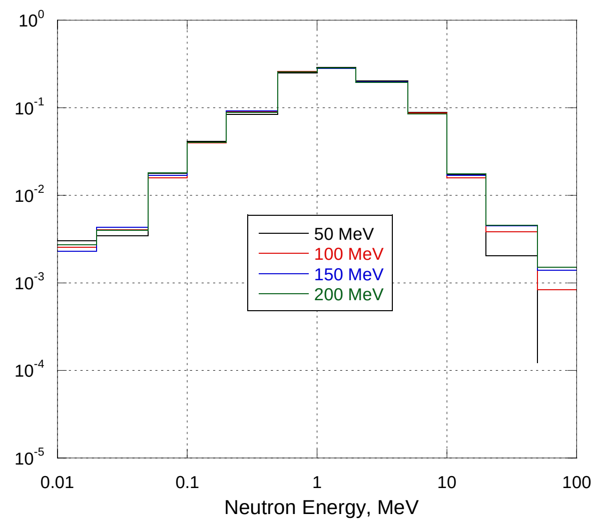

Figure 6. Normalized neutron spectra from tungsten target as a function of the electron energy

The target length in the previous analyses is 0.10 m to insure an adequate target material for stopping the electron beam and generating gamma rays. However, extra target material will interact with the generated neutrons that leave the target bottom surface. A study was performed to define the required target length. Figure 7 shows the generated number of neutrons per electron as a function of the tungsten target length. The number of neutrons per electron increases as the target length increases to reach a maximum value at about 0.069 m. Extra tungsten target length acts as a neutron absorber, which reduces the neutron yield. The neutron loss rate is very small because the neutron fraction leaving the bottom surface is only about 0.07. The balance of the generated neutrons is not sensitive to the extra tungsten target length. Uranium target has a different performance with respect to the target length because of the fission reactions caused by the generated neutrons as shown in Figure 8. In the first part of the target length, most of the neutrons are generated from the electron and neutron interactions. As the electron beam vanishes inside the target material, the fission reactions caused by the bottom neutron fraction slightly increase the neutron yield as shown in Figure 8. Therefore, a 0.08-m target length is utilized for the uranium target to get these extra fission interactions to occur in the fuel material of the subcritical assembly.

Heat transfer and thermal-hydraulics parametric studies were performed to define the target mechanical configuration, the size of the water coolant channels, and the temperature distribution in the target materials. A 100 KW electron beam with a 2-KW/cm^{2}uniform beam power density, a 7-m/s water coolant velocity, and a 4-atm coolant pressure are used for the studies. The target material has a cylindrical geometry and its axis coincide with beam tube axis. The water coolant flow direction is perpendicular to the target axis. This arrangement results in a stack of disks forming the target design. The water coolant channels between the target disks have a constant thickness of 1.75 mm based on a maximum water temperature increase of less than 5 °C. Each target disk is cooled from both sides to minimize its thermal deformation. The water coolant channels are connected in parallel to the input and output manifolds. The parametric study defined the thickness of the different target disks assuming a maximum surface temperature of 80 or 100 °C for the electron energy of 150 and 200 MeV. These temperatures were selected to provide a margin of 65 or 45 °C away from boiling temperature. Then the studies were iterated to define the disk thicknesses that can operate with electron energy of 150 and 200 MeV for a maximum surface temperature of less than 80 °C. Table 1 shows the disk thicknesses for tungsten and uranium target materials. A clad material is utilized for the uranium disks to avoid water coolant contamination with fission products. Figure 9 shows an exploded view of the tungsten target disks and the configuration for the coolant manifolds.

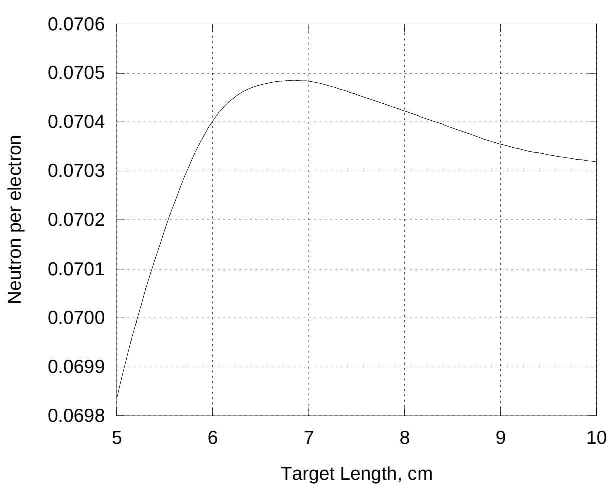

Figure 7. Number of neutrons per electron as a function of the tungsten target length

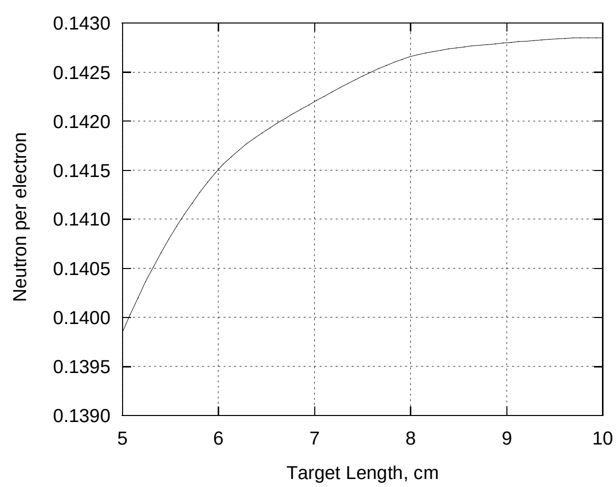

Figure 8. Number of neutrons per electron as a function of the uranium target length

Table 1. Disk thicknesses for tungsten and uranium target materials

Target Material	Disk Thickness, mm							
Tungsten	4.5	3.0	3.5	5.0	8.0	20.0	25.0	---
Uranium	4.2	3.0	3.0	4.2	6.0	12.0	24.0	24.0

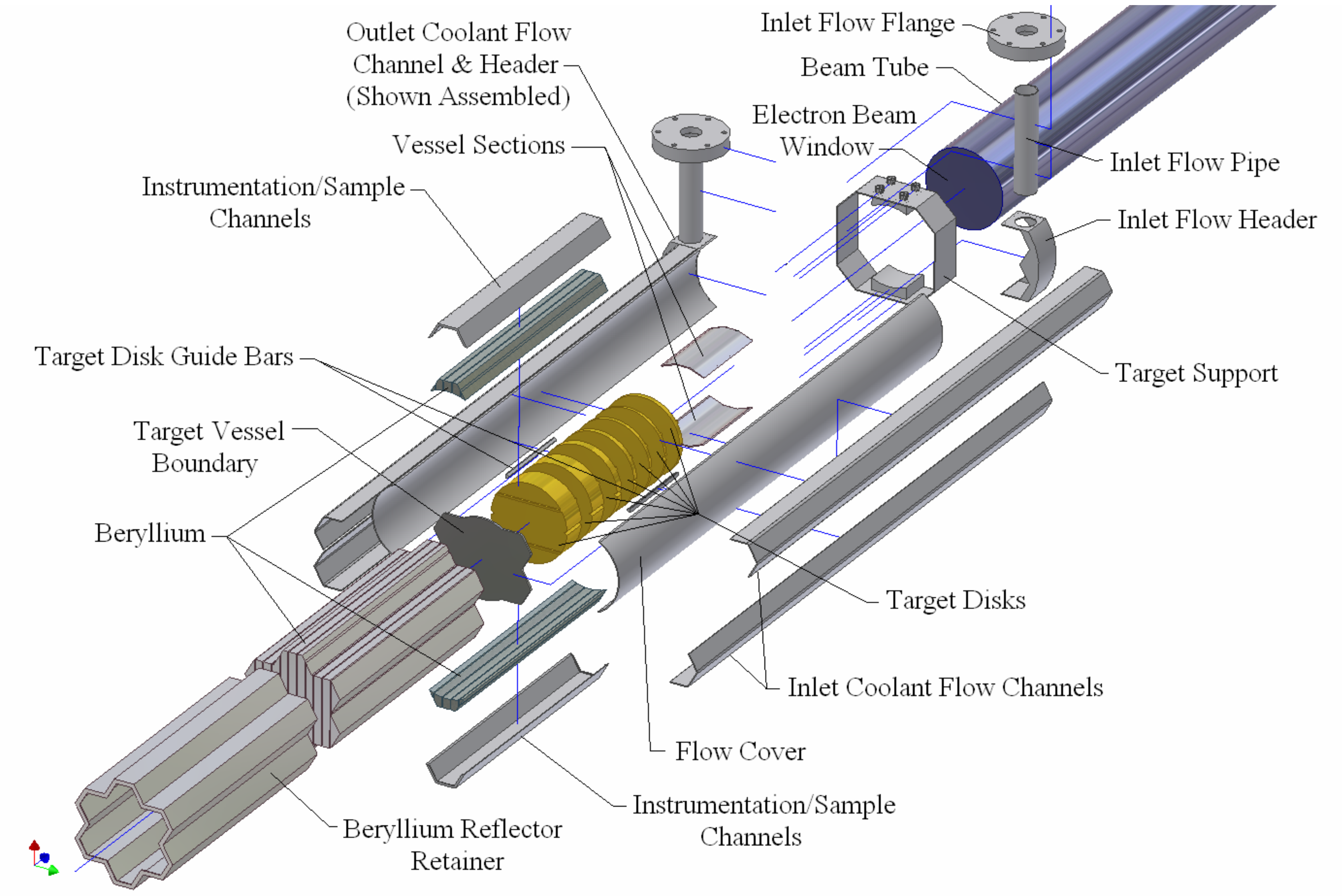

Figure 9. Exploded view of the tungsten target

3. Subcritical Assembly

The subcritical assembly is configured to maximize the neutron flux and the utilization of the generated neutrons. Research reactor fuel assemblies with water coolant are used for the subcritical assembly. The electron beam axis is aligned with the centerline of the subcritical assembly to deliver the generated neutrons uniformly around the critical assembly centerline. The neutron source current from the electron beam window is much higher than the neutron current from the bottom target surface. This leads to locate the target midplane under the geometrical center of the subcritical assembly to utilize the neutron current from the electron beam window as much as possible. Kiev research reactor fuel design (WWR-M2 type fuel) is utilized for the subcritical assembly. The fuel material is uranium oxide in aluminum matrix with aluminum clad. The target disks are configured in hexagonal canister to match the fuel geometry. The active fuel length is 0.5 m. Beryllium reflector is utilized to minimize the number of fuel assemblies, which increases the flux level. An isometric view of the subcritical assembly is shown in Figure 10.

A three dimensional model for the subcritical assembly including the target was developed for MCNPX analyses. The target and fuel designs are modeled explicitly without any approximation or homogenization to get an accurate prediction for the subcritical performance. Figure 11 shows a horizontal cross section of the subcritical assembly calculational model with 24 fuel assemblies through the tungsten target material. MCNPX computer code with continuous energy data libraries and S(α,β) thermal data was used for the analyses. Several configurations with different number of fuel assemblies and uranium enrichment were analyzed to define the subcritical assembly reactivity and flux levels. Table 2 shows a sample of the obtained results with Kiev research reactor fuel design.

The subcritical assembly requires 24 to 26 LEU fuel assemblies to operate with K_{eff} in the range of 0.96 to 0.98. Such number of fuel assembly produces about two fuel rings around the target. The use of HEU requires 17 fuel assemblies to operate with K_{eff} of 0.98. Such small number of fuel assemblies limits the subcritical assembly flexibility to study different geometrical configurations. Also, the worth of the HEU fuel assembly is about 1.5 times the LEU, which constraints the ability to compensate for small reactivity losses from experimental hardware.

Table 2. Key neutronics parameters of the subcritical assembly

Fuel Enrichment	LEU	LEU	LEU	LEU	HEU
Number of fuel Assemblies	24	27	30	26	17
K_{eff}	0.9612	0.9913	1.0216	0.9810	0.9811
Neutron Flux, n/cm^{2}s					
Total	7.648 10^{12}	1.978 10^{13}	-	1.288 10^{13}	1.463 10^{13}
E < 0.1 MeV	4.673 10^{12}	1.213 10^{13}	-	7.860 10^{12}	8.711 10^{12}
E = 0.1 to 20 MeV	2.975 10^{12}	7.647 10^{12}	-	5.018 10^{12}	5.921 10^{12}
E > 20 MeV	6.197 10^{08}	7.621 10^{08}	-	5.468 10^{08}	6.557 10^{08}

The average flux values were calculated over the fuel core length in the beryllium channels next to the target, the two red channels in figure 11. These two channels provide good neutron environment for material irradiation and experimental measurements. The neutron flux has a good fraction of fast neutrons as shown in Table 2. The beryllium in these channels can be replaced with water for enhancing the thermal neutron flux. Also, the results of Table 2 show that the LEU fuel produces about the same flux level as of the HEU. Design analyses are underway to enhance further the subcritical assembly performance by utilizing electron beam with uranium target, deuteron beam with beryllium target, different fuel design, and different reflector materials.

4. Conclusions

The conceptual design activity has developed an accelerator-driven subcritical assembly with 100 KW electron beam. The target design analyses defined the electron beam parameters and the target performance. Tungsten and uranium are the target materials under consideration for the electron beam. Electron energy in the range of 150 to 200 MeV provides an optimum performance for this application. A low pressure water coolant is used for the target and the subcritical assembly, which facilitates the system design and satisfies its functions. A beam power density of 2 KW/cm^2 is selected based on the target analyses to satisfy the engineering requirements and to minimize the target cross section area. The target material length is 69 and 80 mm for tungsten and uranium, respectively.

A three dimensional geometrical model was developed for the subcritical assembly including the target design to carry out the analyses and define its performance. LEU and HEU fuels have been utilized to compare the obtained performance. Kiev research reactor fuel design is employed for the subcritical assembly. The analyses defined the required number of fuel assembly to achieve K_{eff} in the range of 0.96 to 0.98. The LEU subcritical assembly utilizes more fuel assemblies, which provides more experimental flexibility relative to HEU. Also, the obtained neutron flux levels from LEU and HEU are comparable. This shows the possibility of using LEU fuel instead of HEU without penalizing the subcritical performance. Further activities are underway to analyze the use of the electron beam with uranium target, deuteron beam with beryllium target, different fuel design, and different reflector materials; and to complete the conceptual design.

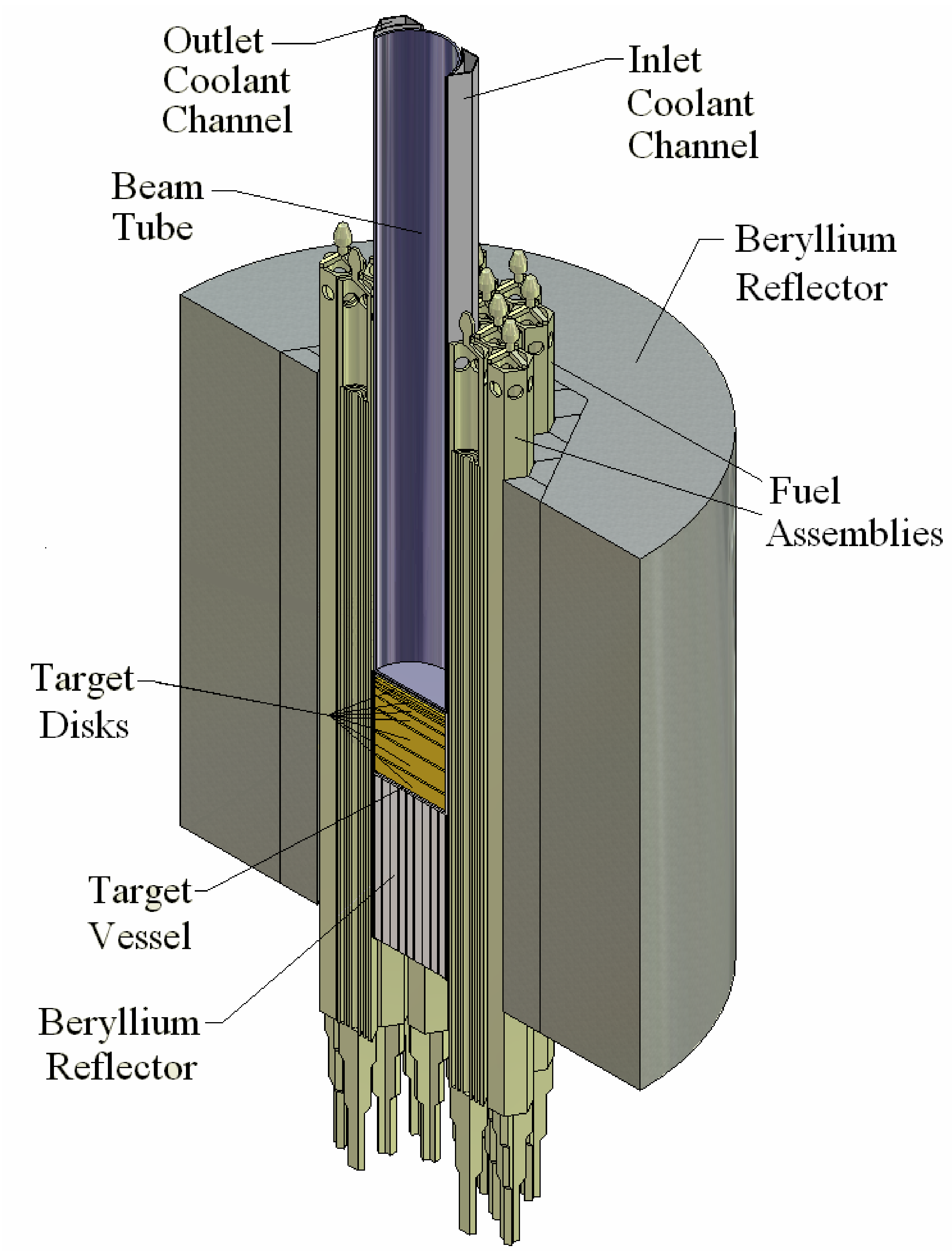

Figure 10. Subcritical assembly isometric view

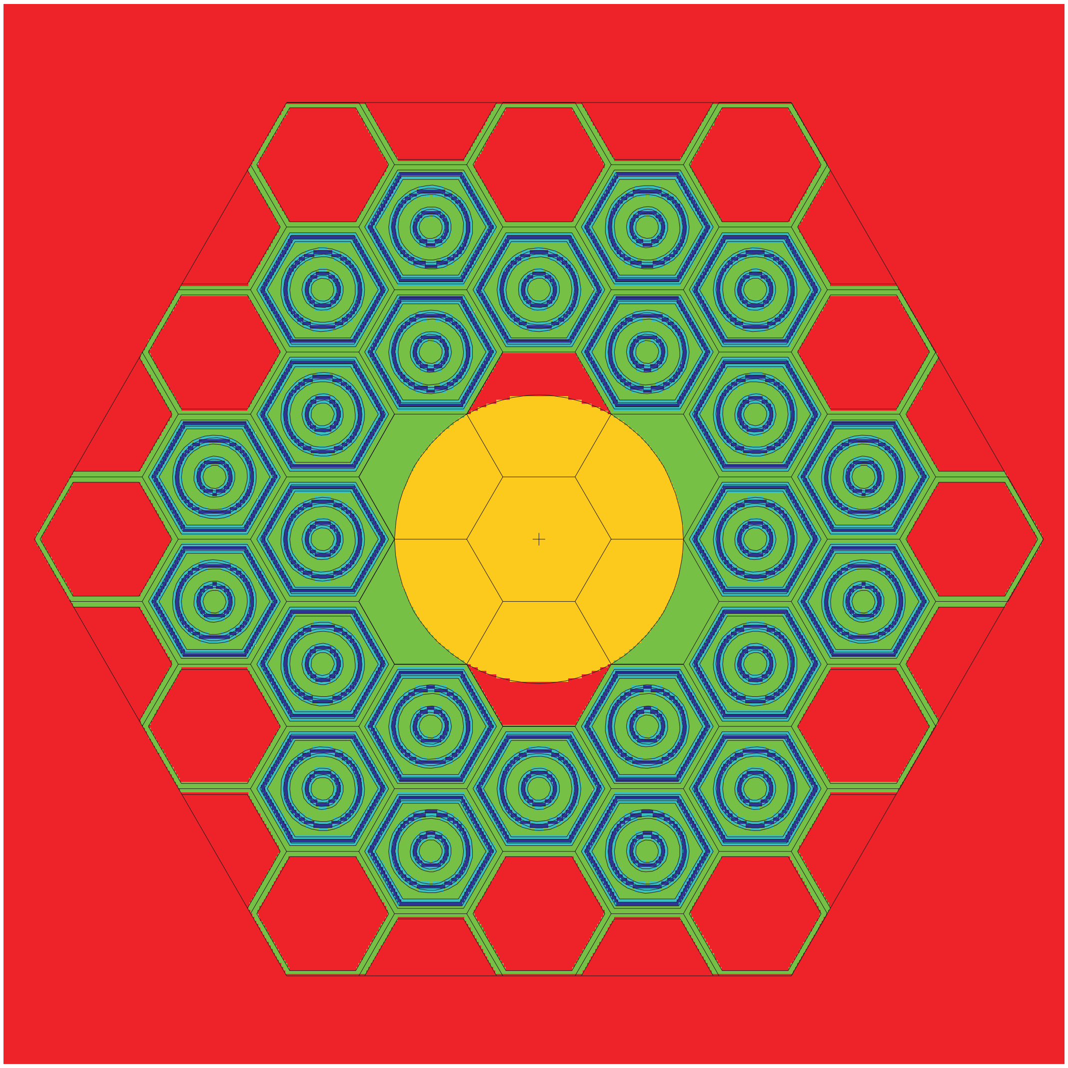

Figure 11. Horizontal cross section of the subcritical assembly calculational model with 24 fuel assemblies through the target material

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