TARGET DESIGN OPTIMIZATION OF KIPT NEUTRON SOURCE FACILITY

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ABSTRACT

Argonne National Laboratory (ANL) of the United States developed and designed a neutron source facility for Kharkov Institute of Physics and Technology (KIPT) of Ukraine. The facility was constructed at Kharkov, Ukraine and its commissioning process has been started. The facility has an electron accelerator driving a subcritical assembly. The electron beam power is 100 kW using 100 MeV electrons. The subcritical assembly has WWR-M2 fuel assemblies with U-235 enrichment of 19.7 wt%. The facility will be utilized to perform basic and applied nuclear research, to produce medical isotopes, and to train young nuclear specialists. Solid target design with stacked disks is selected and each target disk is cooled by water from both sides. Tungsten or natural uranium is the target material. This paper presents the target design optimization to maximize the neutron yield and the neutron flux level of the facility while satisfying the thermal-hydraulic design criteria. Monte Carlo computer code MCNPX is utilized for the neutron yield analyses with ENDF/B-VII.0 nuclear data libraries, as a function of target thickness using a simplified target model without cladding or coolant channels. It's found that the neutron yield saturates at target thickness ~ 60 mm for both tungsten and uranium materials. For the final target design with cladding and coolant channels, the total uranium thickness is 56.5 mm, and the total tungsten thickness is only 33.0 mm. The tungsten material has a large absorption cross section for thermal neutrons. If the tungsten thickness is increased, the neutron yield gain is offset by the neutron absorption reaction. The paper presents the design optimization analyses for both target materials.

KEYWORDS

electron accelerator, target, neutron yield, MCNPX

1. INTRODUCTION

National and international research institutions are considering accelerator driven systems (ADS) in their fuel cycle scenarios for transmuting actinides and long-lived fission products, and performing other missions. Therefore, several studies and experiments have been conducted using accelerator driven sub-critical systems. As a part of the collaboration activity between the United States of America and Ukraine, Argonne National Laboratory (ANL) and the National Science Center-Kharkov Institute of Physics and Technology (NSC-KIPT) have been collaborating on developing a neutron source facility based on the use of an electron accelerator driven sub-critical system [1]. The main functions of this facility are the medical isotope production and the support of the Ukraine nuclear industry. Physics experiments and material research will also be carried out utilizing this facility. This facility has been constructed at Kharkov, Ukraine and its commissioning process has been started.

The facility uses 100 kW electron beam delivered with 100 MeV electrons. Tungsten or natural uranium is selected as the target material. The electron interactions with the target material produce high energy photons, which generate neutrons through photonuclear reactions with the target material for driving the subcritical system. The WWR-M2 fuel assemblies, with U-235 enrichment of 19.7 wt% is the fuel for...
the subcritical assembly. The WWR-M2 type fuel is used in the Kiev research reactor [2] and in other test reactors with water coolant around the world.

The target design plays an important role for the whole system, the neutron yield from the target should be maximized while the thermal-hydraulic design criteria should also be satisfied. Square electron beam and target design are utilized. The electron beam is deemed to have a uniform spatial distribution. The target design consists of the stacked tungsten or uranium disks separated by the water cooling channels. The stack of disks is surrounded by the target cooling manifolds of the target assembly. The uranium target disks are cladded by aluminum alloy to avoid water coolant contamination with fission products, while the tungsten target disks are coated with tantalum to avoid tungsten corrosion issues. A schematic of the target geometry is shown in Fig.1. The water coolant channels between the target disks have a constant thickness of 1.75 mm. Each target disk is cooled from both sides to minimize its thermal deformation.

![Figure 1. The stacked disk geometry of the target for tungsten or uranium materials](image)

2. NEUTRON YIELD OF TARGET

The neutron yields of uranium and tungsten target material from 100 MeV electron particles were first studied. The electron beam is deemed to have a uniform spatial distribution over a 64 mm × 64 mm surface. First, a simplified target model was used to study the neutron yield, without clad material or coolant channels. The target disk dimensions are 66 mm × 66 mm, which is consistent with the real target design. Different target thickness was selected, and the neutron yield per electron was calculated by MCNPX [3] using ENDF/B-VII.0 [4] nuclear data libraries, as a function of target thickness. The obtained neutron yields of tungsten and natural uranium target material are plotted in Fig. 2 and Fig. 3. The neutron yield is calculated by tallying the net neutron current on the six surfaces of target. The statistical error of each tallied results is also plotted as error bars.

For the natural uranium target, the neutron fissions were turned off during the MCNPX calculations to eliminate the neutrons generated from fission reactions. The tallied neutrons are only generated thorough
photonuclear reactions caused by electrons. The tungsten neutron yield saturates as the target thickness reaches ~70 mm. The corresponding thickness for the natural uranium is ~60 mm.

The saturated neutron yields from tungsten and uranium for 100 MeV electrons are ~0.0318 and ~0.0573 neutrons per electron, respectively. Tungsten maximum neutron yield is ~55% of the uranium. In addition, tungsten has higher absorption cross section for thermal neutrons, which impacts the neutron economy of the system. However the operation life of the natural metal uranium target is shorter than the tungsten target due to the swelling caused by fission gases generated during the operation.

![Figure 2. Tungsten neutron yield per 100 MeV electron from 100 MeV as a function of the target thickness](image2.png)

![Figure 3. Uranium neutron yield per 100 MeV electron from 100 MeV as a function of the target thickness](image3.png)
It should be noted that the neutron yields shown in Figs. 2 - 3 are the theoretical values since the cladding materials and the coolant channels are not included in these calculations. In the target design analyses, cladding materials and coolant channels are explicitly modeled, which reduce the neutron yield values for both materials.

3. TARGET ASSEMBLY DESIGN

The target design consists of tungsten or uranium disks separated by water cooling channels. Heat transfer and thermal-hydraulics parametric studies have been performed to define the target mechanical configuration, the size of the water coolant channels, and the temperature distribution of the target assembly. The water coolant channels between the target disks have a constant thickness of 1.75 mm. Each target disk is cooled from both sides to minimize its thermal deformation. Square target plates are utilized, with side length of 66 mm to match the square electron beam profile. The uranium disk size is 64.6 mm with 0.7 mm aluminum alloy clad and the tungsten disk size is 65.5 mm with 0.25 mm tantalum coating.

The tungsten and uranium target parameters are shown in Table 1. Aluminum alloy clad is utilized for the uranium disks to avoid water coolant contamination with fission products, and tantalum coating is utilized for tungsten disks to protect against water interaction. The thickness of coolant channel and cladding is also shown in Table I. The thickness of the target plates and the coolant channels were obtained from the iterated MCNPX and thermal-hydraulic calculations. The radial and axial configuration of the target assemblies are plotted in Figs. 4 - 5.

The uranium target has eleven disks, with the total uranium thickness of 56.5 mm, which is very close to the saturated uranium thickness as shown in Fig. 3 to maximize the neutron yield. The tungsten target consists of seven-plate, with the total tungsten thickness of 33.0 mm including the tantalum coating, which is much less than the saturated tungsten thickness as shown in Fig. 2. The use of extra tungsten increases the neutron yield as well as the thermal neutron absorption.

The TALLYX user subroutine of MCNPX was modified and utilized to calculate the neutron yield per electron. For these two target design, the neutron yields is ~0.0477 and ~0.0290 for uranium and tungsten materials, respectively. These neutron yields are lower than the saturation values shown in Fig.2 and Fig.3 due to the impact of the clad and the coolant materials.

The earlier target analysis [4] used eight tungsten disks with a total target thickness of 70 mm for 200 MeV electrons. The final facility design limited the electron energy to 100 MeV to reduce the accelerator cost and the biological shield thickness. For the 100 MeV electrons, the eighth disk thickness of the earlier configuration is 37 mm and it has only a small contribution to the neutron yield. In addition the neutron absorption in this disk is much more than its neutron production and it reduces the neutron multiplication factor of the subcritical assembly. Analyses were performed to quantify the impact of this disk on the neutron source facility without changing the first seven disks. The thickness of this disk was changed and the fuel loading of the subcritical assembly was also changed to maintain the same effective multiplication factor of ~0.98 as shown in Fig. 6. For each configuration, the energy deposition in the target assembly and the neutron flux in the target coolant channels were calculated with MCNPX and the results are shown in Table II. The results show that when the eighth tungsten disk is removed, two fuel assemblies can be removed without penalizing the neutron flux level. The reactivity worth of each fuel assembly is ~500 pcm and the reactivity worth of the eighth disk is ~1200 pcm.
Table I. Tungsten and uranium target dimensions

<table>
<thead>
<tr>
<th>Channel number</th>
<th>Tungsten Target</th>
<th>Uranium Target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water channel thickness, mm</td>
<td>Target thickness*, mm</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>1.75</td>
<td>3.0</td>
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<td>2</td>
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<td>10</td>
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<td>1.75</td>
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<tr>
<td>11</td>
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<td>1.0</td>
</tr>
<tr>
<td>Total</td>
<td>12.5</td>
<td>33.0</td>
</tr>
</tbody>
</table>

* include the tantalum coating

Based on the results shown in Fig. 2, if the total target thickness is below 30 mm the neutron yield would drop quickly. Therefore the seven-plate tungsten target design, with 33-mm total tungsten thickness is used for the final design, as shown in Table I.

The energy deposition profiles within the target was calculated using the mesh tally capability of MCNPX, and it is plotted in Figs. 7 - 8. These profiles are used for thermal-hydraulic analyses [5, 6], which show that the target design meet the primary design goals and allowed the target plates to be cooled effectively.

![Figure 4. Radial configuration of the target assembly](image-url)
Table II. Comparison of neutron flux for the cases using tungsten target, with different target thickness

<table>
<thead>
<tr>
<th>Number of target disks</th>
<th>Total tungsten thickness (cm)</th>
<th>Number of fuel assemblies</th>
<th>k-eff</th>
<th>Target energy deposited (kW)</th>
<th>Target neutron yield per electron</th>
<th>Neutron flux along the core*</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7</td>
<td>44</td>
<td>0.97665 (±0.00012)</td>
<td>88.680 (± 0.01 %)</td>
<td>0.0304</td>
<td>1.038e+13 (±0.0033)</td>
</tr>
<tr>
<td></td>
<td>4.4</td>
<td>43</td>
<td>0.97881 (±0.00012)</td>
<td>87.077 (± 0.01 %)</td>
<td>0.0299</td>
<td>1.152e+13 (±0.0036)</td>
</tr>
<tr>
<td>7</td>
<td>3.3</td>
<td>42</td>
<td>0.97855 (±0.00012)</td>
<td>84.194 (± 0.01 %)</td>
<td>0.0290</td>
<td>1.162e+13 (±0.0036)</td>
</tr>
</tbody>
</table>

*the neutron flux is tallied within the vertical coolant channel of target
Figure 7. Energy Deposition Profile in the tungsten target ($\text{w/cm}^3$), with 100 kW electron beam using 100 MeV electrons driving subcritical assembly with 38-fuel assemblies

Figure 8. Energy Deposition Profile in the uranium target ($\text{w/cm}^3$), with 100 kW electron beam using 100 MeV electrons driving subcritical assembly with 37-fuel assemblies
4. SUMMARY AND CONCLUSION

Target design configurations were analyzed for the KIPT neutron source facility. Both tungsten and uranium target designs were optimized to maximize their neutron yields as well as the total neutron flux in the facility while satisfying the thermal hydraulics design criteria. The target design has solid stacked disks with water from both sides. The thickness of target disks and coolant channels were defined based on coupling MCNPX calculation and the thermal-hydraulic analyses.

The tungsten target has seven disks and the total tungsten material thickness is 33 mm. This thickness is less than the required thickness for the maximum neutron yield per electron. The use of extra tungsten thickness results in a significant neutron loss in the facility. The target is used to drive the subcritical assembly, which has thermal neutron spectrum. The thermal neutron absorption in the extra target length exceeds its neutron production from the electron interactions. Therefore, the optimum tungsten length for this facility is less than the required 70 mm thickness for the maximum neutron yield per electron.

The uranium target thickness has eleven disks and the total target thickness is 56.5 mm. This thickness produces the maximum neutron yield per electron. In addition, some the thermal neutron losses in the target results in fission reactions, which increases the neutron production. This is different from the tungsten target due to the parasitic neutron interactions.

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REFERENCES