NEUTRONIC, THERMAL-HYDRAULIC, AND STRUCTURAL ANALYSES OF THE ELECTRON TARGET FOR AN ACCELERATOR-DRIVEN SUBCRITICAL SYSTEM

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As part of the design effort for an accelerator-driven subcritical facility, the high-fidelity analyses of various target options are performed with formulations to reflect the realistic 3-D geometry of each concept. The tungsten and uranium targets are considered for generating neutron from electron interactions using electron beams with either circular or square cross-sections. The optimization of target configurations is performed via sequential neutronic, thermal-hydraulic, and structural analyses for a comprehensive assessment of multi-physics phenomena affecting each design. In addition to geometric modifications to streamline the flow field and avoid hotspots, the target analyses included evaluation of inlet/outlet configurations, target plate and coolant channel partitioning, flow rate manipulations, beam profile variations, and cladding material alternatives.

I. INTRODUCTION

An accelerator-driven subcritical facility is planned at the Kharkov Institute of Physics and Technology (KIPT) in Ukraine for medical isotope production, basic research, staff training, and education. The conceptual design of the facility is being pursued through collaborations between Argonne National Laboratory (ANL) and KIPT.

The facility is intended to use a 100 kW electron accelerator to drive a subcritical pile that consists of an array of 50 cm long hexagonal fuel elements with low- or highly-enriched uranium oxide in aluminum matrix. The 10 cm long electron target assembly is placed vertically in the middle of the subcritical pile replacing seven fuel assemblies at the center as shown in Fig. 1. Initially, an electron beam with circular cross-section is considered (shown as the yellow area in Fig. 1) leaving six roughly half-fuel-assembly spaces around the beam tube and tungsten/uranium disks (shown in light green in Fig. 1) for target coolant inlet and outlet channels and optionally for instrumentation.

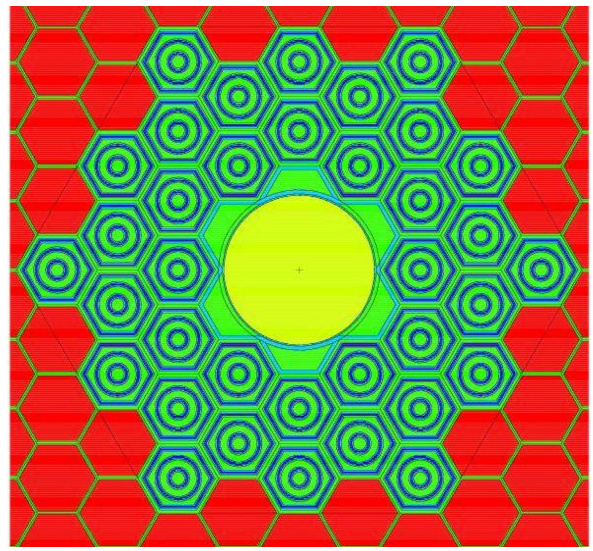

Fig. 1. Schematic of the subcritical pile with the electron target assembly at the center.

In each target configuration studied, the coolant (water at room temperature) is assumed to flow down parallel to the electron beam on one side of the target assembly, split among narrow gaps between the target disks to cool them, and return in opposite direction to the beam on other side of the disks. Such a configuration with two inlet and two outlet channels is shown in Fig. 2 for the electron beam with circular cross-section. During the second phase of the project, an electron beam with a square cross-section is also considered, replacing the circular target disks with square target plates.

The target optimization studies included development of a base CAD model with proper emphasis on manufacturability to provide a basis for separate but consistent models for subsequent neutronic, thermal-hydraulic, and structural analyses. The electron beam interactions with the target material and the neutronic response of the subcritical assembly are evaluated using the MCNPX code to provide spatial energy deposition in the target assembly. The computational fluid dynamics

(CFD) software Star-CD is used for the thermal-hydraulic analyses to evaluate the impact of recirculation and stagnation zones and resulting hotspots. The structural analyses are performed with NASTRAN using the temperatures calculated with CFD model.

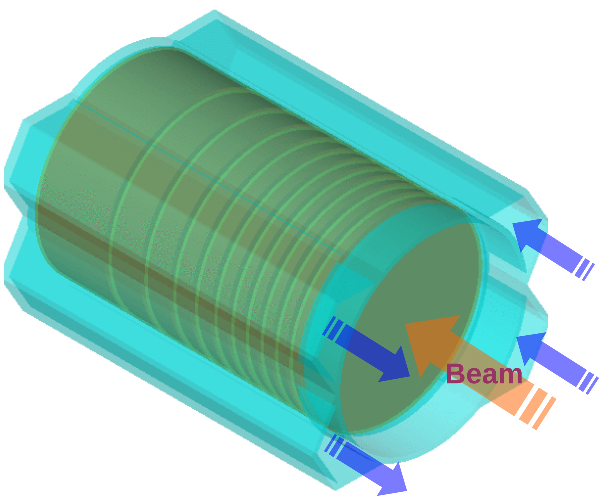

Fig. 2. Schematic of target assembly for circular electron beam (configuration with two inlet and outlet channels).

The optimizations are pursued for maximizing the neutron yield, streamlining the flow field to avoid hotspots, and minimizing the thermal stresses to increase the durability. In addition to general geometric modifications, the design optimizations included evaluation of inlet/outlet channel configurations, target plate partitioning, flow rate manipulations, beam diameter options, and cladding material alternatives.

II. NEUTRONIC ANALYSIS

The electron beam interactions with the target assembly and the neutronic response of the subcritical system are calculated using the MCNPX code.[2] The neutron source intensity and spectrum as well as the spatial neutron generation and energy deposition in the target material have been evaluated for various beam parameters and target materials. The neutron flux of the subcritical assembly has been examined as a function of the uranium fuel enrichment and density, the reflector material and thickness, and the target material selection for k_{eff} of ~0.98.

When the electrons hit the target plates, they generate neutrons that drive the subcritical assembly, yielding a neutron flux with typical axial and radial (mid-plane) profiles as shown in Fig. 3. Due to the dissipation of the electron beam as well as the resulting neutron yield in the subcritical assembly, the power density is significantly higher in target assembly in comparison to neighboring fuel assemblies as shown in Fig. 4. This in turn requires a separate cooling system for the target assembly to meet the set of thermo-mechanical design criteria.

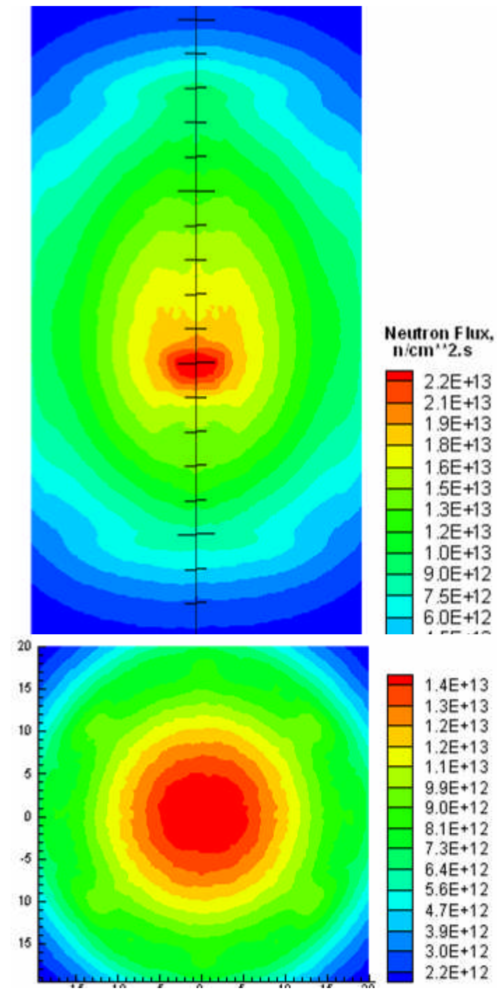

Fig. 3. Typical axial (top) and radial (bottom) neutron flux profiles for a subcritical pile with 74 low-enriched U fuel (3-g/cm^3 density), water reflector and U target.

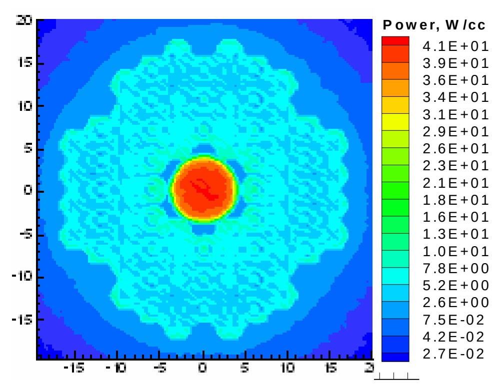

Fig. 4. Power density distribution for the subcritical pile shown in Fig. 3.

For the scoping calculations, initially only axially-varying power density distributions are considered, and only in the target material. The more detailed assessments are based on

- axisymmetric models with r,z-dependent power density profile for target disks and electron beam with circular cross section,
- full 3-D models with x,y,z-dependent power density profile for target plates and electron beam with square cross section.

These detailed power density distributions are obtained including the effects of the electron beam dissipation in the coolant and in the Al-clad for U-target. An example of each case is shown in Fig. 5.

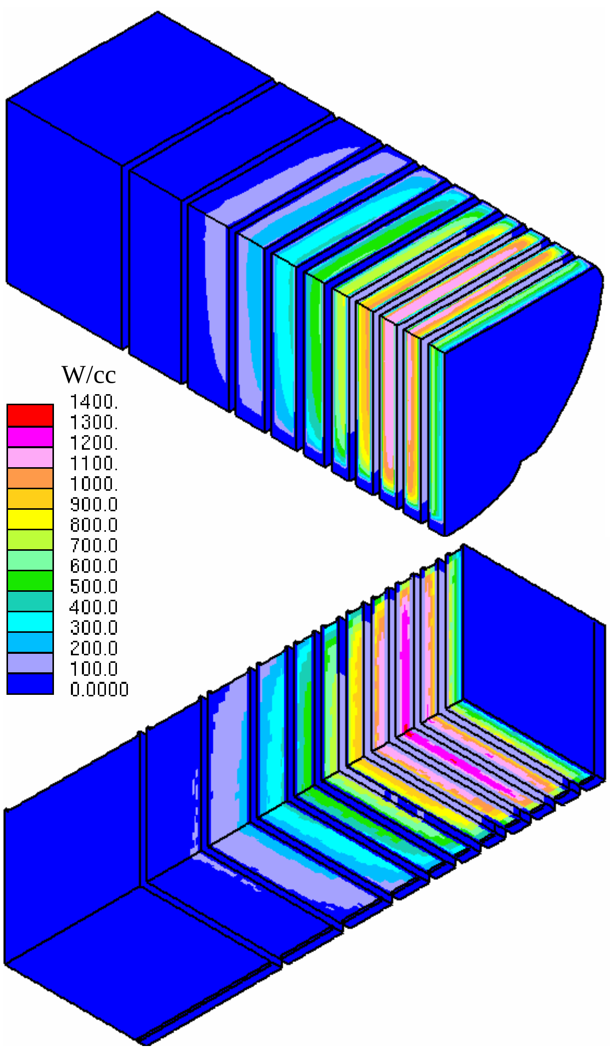

Fig. 5. Power density distributions (W/cc) in U-target disks with circular electron beam (top) and U-target plates with square electron beam (bottom). Only ¼ target segment is shown for 200 MeV electrons.

Both tungsten and uranium target materials are considered for 100 and 200 MeV electrons. In that energy range, the greatest deposition takes place near the beam window requiring thin partitioning of the first several target plates to balance the heat load in each one. Various target plate and coolant channel thickness are evaluated and optimal neutron yield is obtained with 1.75 mm narrow coolant channels between target plates. Consequently, the subsequent thermal-hydraulic optimizations are based on 1.75 mm thick coolant channels between target plates.

Although the neutron spectra from tungsten and uranium are found to be similar allowing the use of either material in the subcritical assembly without changing its characteristics, the higher neutron yield from uranium target is found to increase the neutron flux in the subcritical assembly. Therefore, a greater emphasis is placed on the optimization of the uranium target. The uranium plates are considered to be covered with 0.7-0.95 mm thick Al-alloy cladding to avoid coolant contamination with fission products.

III. THERMAL-HYDRAULIC ANALYSIS

The results for the electron beam energy deposition, neutron generation and utilization in the subcritical pile are used to characterize the axisymmetric (for circular beam) and 3-D (for square beam) heat generation profiles in the target assembly with discrete values for the beam tube, coolant, cladding, and target material as shown in Fig. 5. Based on the provided dimensions and heat generation profile, the commercial CFD software Star-CD[3] is used for thermal-hydraulic analysis of each target design to verify that it satisfies the thermal criteria. The limiting factor is to maintain the water temperature 50ºC below the boiling point (150ºC at 4 atm) and the peak target material temperature much lower than the melting point.[4]

Due to high speed flow (on average 7-12 m/s), a fully developed turbulent flow is established in the inlet and outlet coolant channels of the target assembly. However, the turbulence in the flow field quickly dissipates in the narrow gaps between the target plates resulting in generally laminar heat transfer to cool the target plates. In all configurations studied, on average the temperature difference between the inlet and outlet channels is less than 5ºC. However, the poor heat transfer in laminar regime results in significantly higher target plate temperatures at shown in Fig. 6.

Despite the uniform 1.75 mm thick gap between the target plates, the flow redistribution between the coolant channels between the plates is calculated to be substantially different, highest flow rate being closest to the beam tube. This unevenness of the flow rate in the gaps between the target plates actually helps improve the thermal-hydraulic design since it results in better cooling for the first set of target disks that are exposed to much higher heat loads.

On average, 3-D CFD analyses of target assembly are found to agree well with 1-D subchannel approximations used in RELAP for a set of target configurations (RELAP calculations are performed at KIPT). However, the recirculation and stagnation zones predicted with CFD model prove to be important causing local variations in temperatures as shown in Fig. 7 for the third target disk in Fig. 6. Consequently, the major thermal-hydraulic design challenge has been to avoid the resulting hotspots.

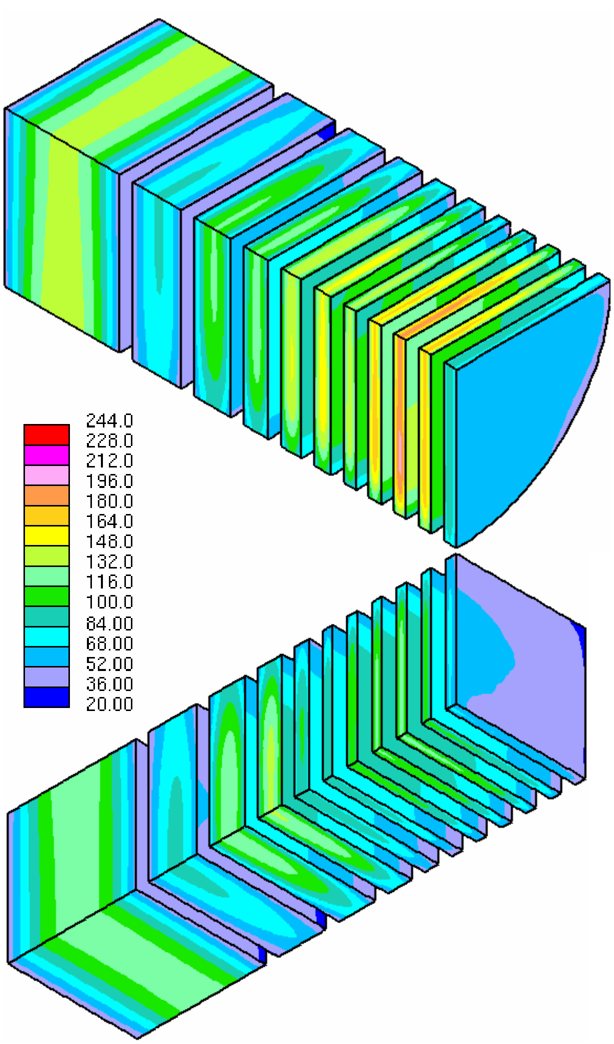

Fig. 6. Temperature distributions (°C) in Al-clad U-target disks with circular electron beam (top) and plates with square electron beam (bottom). Only ¼ target segment is shown. The results correspond to Fig. 5.

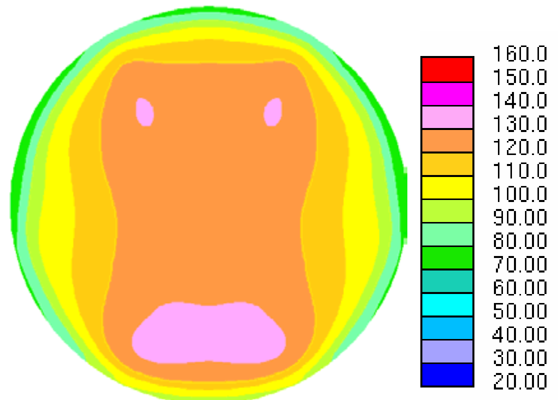

Fig. 7. Mid-plane temperatures (°C) in third disk of the Al-clad U-target assembly shown in Figs. 5 and 6 with three inlet and three outlet channels.

IV. STRUCTURAL ANALYSIS

The calculated temperatures are used for the structural analysis of each target configuration to satisfy the engineering design requirements. The main structural performance criterion has been to keep peak thermal stresses well below the yield point of the corresponding material, ~200 MPa for uranium target. The thermo-structural calculations are performed mostly with NASTRAN and the results occasionally verified with MARC, both commercially available structural-mechanics analysis software.[5]

Due to its high thermal conductivity, temperatures and thermal stresses in tungsten target disks are significantly lower than uranium target disks. In order to keep the thermal stress below the design limit, the Al-clad uranium target plates have to be cooled more aggressively with 70% more flow rate relative to the value for tungsten plates.

Although a significant thermal gradient exists in thin target plates along the beam direction, the limiting thermal stresses are generally observed peripherally around the edge of target disks as shown in Fig. 8. In order to keep the thermal stresses below 200 MPa limit, the U-target assembly design for the electron beam with circular cross section has to be cooled through three inlet and three outlet channels with 12 m/s average coolant velocity. The U-target assembly design for the electron beam with square cross section requires only two inlet and two outlet channels with 10 m/s average coolant velocity.

Additionally, to reduce the peripheral strain in the target plates, a thin insulating gap along the edge of uranium target material and surrounding Al clad is included in the design for both circular disks and square U-target plates. This insulating gap is found to reduce the temperature difference between the plate center and near the edges, reducing the thermal gradients. The gap is also considered to be beneficial to collect the gaseous fission products, avoiding the swelling.

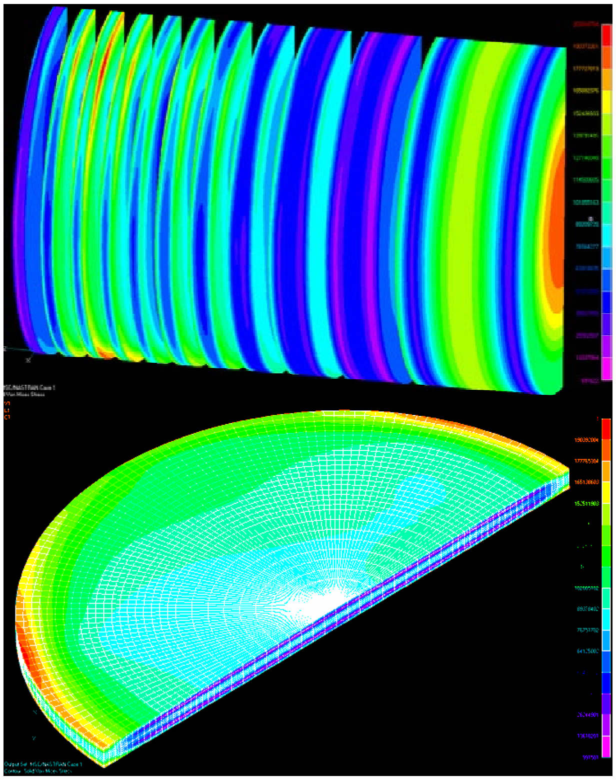

Fig. 8. VonMisses stresses (Pa) in Al-clad U-target assembly for circular electron beam (top) and in third target disk (bottom) for the configuration shown in Figs. 5-7. The maximum stress in red color is about 200 MPa.

At the end, keeping the thermal stress below the limit, the thickness of the first four plates had to be limited to only 3 mm for tungsten and 2.5 mm for uranium target. The thickness of the Al-clad for the thin uranium target plates is considered to be 0.95 mm on each side to provide additional structural support.

V. CONCLUSIONS

A 100 kW beam power is considered with electron energies varying from 100 to 200 MeV. The 100 MeV electrons deposit their energy closer to the beam window, and electrons with higher energies spread deposition slightly further along the beam direction. But in both cases, the energy deposition near the beam window is significantly greater than further downstream, requiring minimal thickness for the first five target plates to limit the maximum temperatures and the resulting thermal stresses.

It is found that the turbulence in the inlet channels dissipates quickly in narrow gaps between the target plates and, as a result, the heat transfer is limited to laminar flow. On average, the results of CFD calculations agree well with 1-D subchannel approximations; however, the recirculation and stagnation zones predicted with the CFD models emphasize the importance of a 3-D analysis to avoid the resulting hotspots.

Although the thermal gradients are more significant along the beam direction in the thin target plates, the limiting thermal stresses are observed peripherally around the edge of the plates. Also, the deformations of the target disks are found to be insignificant, eliminating the concerns for blockages in narrow coolant channels.

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