ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-THP065

RADIOISOTOPE PRODUCTION AT THE SPALLATION NEUTRON SOURCE: DESIGN CONCEPT OF EXPERIMENTAL TARGET STATION *

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Abstract

Completion of the Proton Power Upgrade Project for the Spallation Neutron Source (SNS) accelerator at Oak Ridge National Laboratory opens an opportunity to utilize reserve beam power of more than 100 kW for applications beyond neutron production. One of these applications is the production of critical radionuclides. To demonstrate the feasibility of using the reserve beam power to produce radioisotope at SNS, a design concept of a small-scale experimental target station in the Linac Dump area has been developed. This experimental facility will provide isotope yield benchmarking data using protons in the GeV range. It will also enable additional research and development in isotope handling and radiochemical separation. The target station consists of a target module enclosed in a vessel and concrete shielding. Particle transport calculations and thermo-mechanical simulations are used to determine beam parameters, decay time, isotope yield, shielding dimensions, and target design parameters. Calculations verified that the irradiated capsule can be handled manually using hands-off tools and transported to a hot cell in a shielded container for post-irradiation characterizations.

INTRODUCTION

The Spallation Neutron Source (SNS) accelerator at Oak Ridge National Laboratory will be able to deliver beam power beyond what is required for operating two neutron sources, the first and second target stations. The surplus beam power can be utilized for other applications such as medical isotope production. Computational analyses showed the technical feasibility of a medical isotope production target that receives 250 kW beam power from the SNS accelerator [1]. Particle transport analyses showed that the 1.3 GeV proton beam at SNS has a high potential to produce a large amount of medical isotopes thanks to its long stopping range in target materials. To validate the calculated isotopes yields, there is a need to perform a small scale proof-of-concept experiment using the SNS proton beam. The purpose of the experiment would be to provide benchmarking data to validate concepts and computational results, and to acquire basic demonstration for the isotope production, handling, and separation processes. This will allow early identification in gaps of knowledge or processes that need to be addressed to consider a full-scale concept for radioisotope production. In this paper, we present a design concept of a small-scale experimental target station at SNS. The design focuses on maximizing potential for learning while maintaining a low-cost, "minimal demonstration" philosophy. The design includes particle transport calculations to estimate isotopes yields and shielding, engineering of a target insertion device, and choice of pathways for isotope separation. A critical consideration for the design configuration is that it does not affect the primary neutron production mission in any way.

LOCATION AND BEAM PARAMETERS

The area directly upstream of the SNS linac dump is chosen for the installation of a test target irradiation stand. Figure 1 shows the area where test target is foreseen. There are two 6-way crosses with 6" flanges unoccupied. One of these flanges can be used for the installation of an irradiation port.

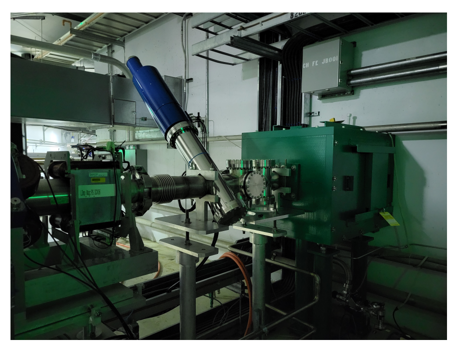

Figure 1: The area where test target is chosen to be stationed.

Protons are routinely transported to the SNS linac dump for beam studies. By deactivating the last quadrupole magnet pairs, the beam profile on the target has a Gaussian shape with σ_x =8 mm and σ_y =3 mm at the potential test target location which is about 14 meters upstream from the SNS linac dump surface. The proton energy can be varied comfortably between 800 MeV and 1.3 GeV. For the beam study, the time averaged beam power is limited below 7 kW with the maximum allowed beam pulse energy of 33 kJ. The beam on the linac dump has a pulsed structure with repetition rates up to 60 Hz, which can vary upon experimental needs. The pulse length is 1 ms. The actual beam conditions on the test target should be determined by the how much beam power the test target assembly can endure and the required shielding to

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allow personnel to access the test port after the experiment and handle the target material.

For the study presented, we used 1.3 GeV proton beam energy with 1 kW beam power. This beam power is chosen such that the target assembly containing medical isotope producing material can be cooled passively by natural convection, surface radiation, and heat conduction. This simplifies the design of the irradiation stand. In order to reduce dynamic stresses in the target, the beam pulse repetition rate is set to be 60 Hz with a pulse energy of 16.7 J·pulse^{-1}.

IRRADIATION STAND DESIGN

The target assembly will be installed in the central horizontal port as shown in Fig. 2. It consists of a target capsule, a target vessel, bellows with linear motion stage, and a target holder assembly.

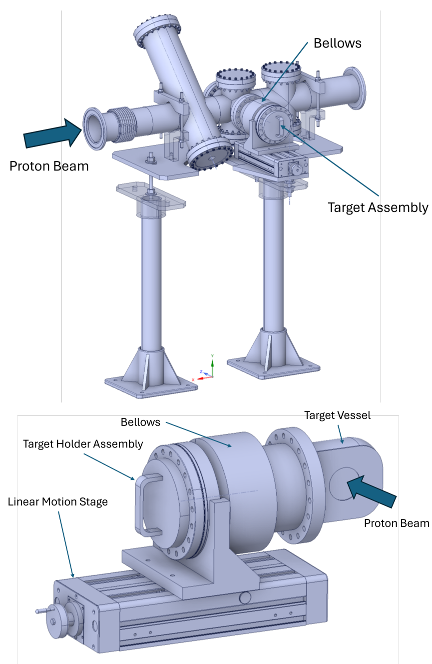

Figure 2: Engineering model of the target assembly as installed in the central horizontal port (top) and its close view (bottom).

The target capsule houses the 0.25 mm thick target disc with a diameter of 5.0 cm, where thorium is chosen for the target material for the production of Ra-225 and Ac-225. It is made of stainless steel 316L, which is widely used beam intercepting structural material. There are two 0.125 mm thin gaps between the target disc and the beam windows of the capsule, which is filled with thin flexible graphite discs. The flexible graphite sheets remove heat deposited by the proton beam in the target disc. The atmospheric air pressure in the target vessel presses the thin capsule windows, the flexible graphite layers, and the target disc together resulting in low contact heat resistances at the capsule-graphite and graphite-target interfaces. Figure 3 (left) shows the engineering model of the target capsule assembly.

The target vessel separates atmospheric air volume surrounding the target capsule from the high accelerator vacuum. It is made of aluminum alloy 6061-T6, which is widely used as proton beam window material. It also activates less than 316L which is commonly used pressure vessel material. The vessel is enclosed in bellows where the gaps between the two are kept in accelerator vacuum. When the target is not being irradiated, the vessel is retracted together with the bellows which are attached to a linear motion stage. This enables linac beam studies to continue without breaking the accelerator vacuum and activating the linac dump area unnecessarily. Figure 3 (right) shows the engineering model of the target holder assembly.

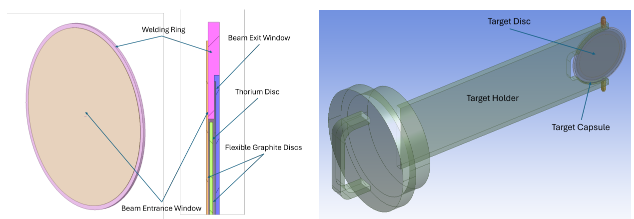

Figure 3: Engineering models of the target capsule assembly (left) and target holder assembly (right).

TEMPERATURE AND STRESS

The heat deposition in the target assembly has been calculated with FLUKA [2–4]. The 1.3 GeV beam loses about 1% of its energy while passing through the beam intercepting parts of the target assembly. The energy loss configuration in the target assembly was imported to ANSYS-CFX [5] to calculate the temperature in the target assembly. A buoyancy model was used to calculate the heat removal via natural convection. A discrete ordinate method (DOM) with 36 rays was used for surface-to-surface radiative heat transfer. Conductive heat transfer in air and solids were also calculated. The calculated steady maximum temperatures in the target assembly and vessel are 69 °C and 41 °C respectively. ANSYS structural simulations show that the peak steady maximum principal stresses in the target disc and stainless steel capsule are 3 MPa and 12 MPa respectively. These are far less than half of yield stress (YS) and one-third of ultimate tensile stress (UTS) of the thorium and 316L, which are acceptable by the ASME BPVC thermal stress limit. Transient simulations showed that the maximum temperature rise in the target assembly during a single pulse is 0.14 °C causing negligible dynamic stresses compared to the steady stress background. Figure 4 shows the calculated temperature and stress profiles of the target capsule.

SHIELDING AND DOSE RATE

The beam power on the target is constrained by the post irradiation residual dose level in the SNS linac dump area and the beam induced thermo-mechanical stress on the target assembly. The dose rate to workers is advised to be limited

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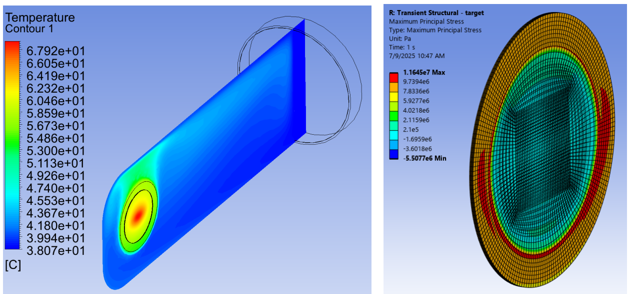

Figure 4: Calculated temperature profile of the target assembly (left) and the stress profile of the target capsule (right).

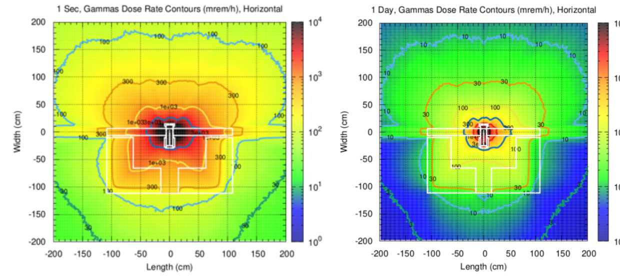

Figure 6: Top view of the the decay dose at the end of bombardment (EOB) and after 24 hours of cool-down time (right).

to 10 mrem·hr^{-1} at 0.3 m distance from the outside shielding surfaces after a day of cool down time.

Figure 5 shows the irradiation port surrounded by 46-cm thick portable concrete shielding. There is a horizontal opening with a slide door made of 316L, which will be used for hands-off handling of irradiated target capsules.

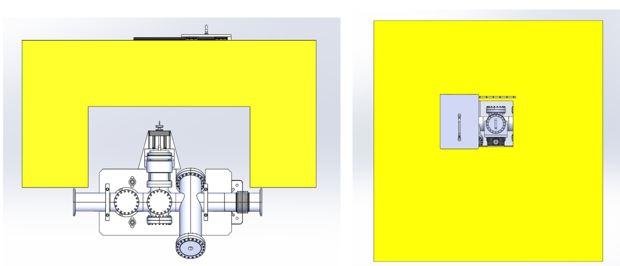

Figure 5: Top view (left) and side view (right) of the irradiation port surrounded by portable concrete shielding (yellow).

The radiation transport code MCNP6.2 [6] is used to simulate the radiation environment near the target, and to calculate isotope production rates due to spallation reactions and the below-20-MeV neutron fluxes, which are fed into the CINDER2008 code [7] using the standardized activation script AARE (Activation in Accelerator Radiation Environments) [8] to calculate the residual source terms, when beam is off for several decay times. The irradiation profile is defined with a proton rate of $4.802 \cdot 10^{12}$ protons·s^{-1} on the target for 48 hours of irradiation time. Dose rates result from weighting the energy-dependent fluxes with flux-to-dose conversion coefficients [9].

During beam-on, the prompt dose at 2 m distance from the target is calculated to be well above 1 rem·hr^{-1}, which does not allow personnel access to the linac dump area during irradiation. Figure 6 shows a top views of the decay dose at the end of bombardment (EOB) and after 24 hours of cool-down time. At EOB, the dose rate at 0.3 m distance from the outer shielding area is about 100 mrem·hr^{-1} making personnel access to the target station area not advised. After a day of cool-down time, the contact dose on the outer shielding surface drops to about 10 mrem·hr^{-1}. This dose level allows personnel to access the area to extract the target. The dose rate from the target capsule at 0.3 m distance after 24 hours of decay time is calculated to be about 100 mrem·hr^{-1}. This does not allow hands-on maintenance of the target capsule. However, target handling with a hands-off tools and a light portable shielding between the worker and the target should be manageable. Independent dose calculations made with FLUKA based on ICRP-116 [10] for the same irradiation profile confirmed the MCNP6.2/CINDER2008 calculations. The target capsule extracted using hands-off tools should be transported in a cask with appropriate shielding. The details of the hands-off tools to be used and the specifications of the transport cask will be determined in future works. The target capsule will be transported to a hot lab for target material extraction and post irradiation characterizations.

ISOTOPES YIELDS

The EOB activities of Ra-225 and Ac-225 in the thorium target calculated by MCNP6.2/CINDER2008 are 0.4 MBq and 6.1 MBq respectively. These compare well with the values calculated with FLUKA, which are given by 0.8 MBq and 5.7 MBq respectively for Ra-225 and Ac-225. The masses of Ra-225 and Ac-225 are minute in a nano-gram range. The studies on codes comparison and simulation validations will be reported in future publications.

CONCLUSIONS

A design concept of a test target station at the SNS linac dump area is presented. The target station will demonstrate the feasibility of applying 1.3 GeV proton beam for efficient medical isotope production. Irradiation of a thorium target with a 1 kW beam for 48 hours was considered. Thermal and structural analyses showed that the target assembly can withstand the beam power without requiring active cooling. Particle transport analyses showed that the target can be extracted and transported for post irradiation examinations without requiring remote handling. The presented study showed that the experiment will provide benchmarking data to validate computationally calculated isotopes yields, and basic demonstrations for the isotope production, handling, and separation processes. Upon successful run of proof-of-concept experiments at the SNS linac dump station, an opportunity will be open for a dedicated > 100 kW class medical isotopes production target station at SNS.

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