Thermal Stress Analysis of a 3 MW Rotating Solid Target

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Abstract. The structural feasibility of a rotating solid target for potential use at the SNS second target station was evaluated for a beam power of 3MW. The solid target concept consists of a water cooled, segmented, and cladded tungsten disc contained within a stainless steel shroud rotated to distribute energy deposition from a long pulse proton beam. Finite element analysis (FEA) was used to simulate temperature distributions caused by different beam profiles and cooling configurations, and again to evaluate the stress fields resulting from the combination of thermal expansion and mechanical constraint of the tungsten segments. If the segments are split both angularly and vertically, cooling on the top, bottom, and center surfaces can maintain temperatures below 155°C. This cooling configuration, combined with a system of spacers and springs to avoid over constraint, results in stresses well below allowable. A detailed shroud design, incorporating a concave window in order to minimize material in the beam path, results in acceptable stresses with respect to both thermal and internal pressure loads. Although further hydrodynamic evaluation is required to analyze the coolant flow system in detail, the rotating solid target concept is structurally feasible for a beam power of 3 MW.

1. Introduction

Producing the brightest long pulse cold neutron source given the existing accelerator facilities and their planned upgrades drives the development of the second target station (STS) at SNS. Target designs were evaluated for a 1.3 GeV proton beam at 20 Hz with a 1 ms pulse length and a 3 MW power level. Two potential beam profiles were considered during this analysis, a double Gaussian profile with a 15 mm vertical sigma and a 45 mm horizontal sigma and a 60mm by 180 mm rectangular flat beam profile created by rastering a small beam spot.

Despite the success of the liquid mercury target in the current SNS target station, a rotating solid target offers many potential advantages, including increased target lifetimes, slightly improved neutronic performance, and reduced remote handling requirements. Based on successful operational and fabrication experience at ISIS and KENS, tungsten clad with a protective tantalum layer was chosen as the target material while heavy water was selected as the coolant [1]. Initial scoping evaluations revealed that an outer diameter of 1.2 m could provide a lifetime of up to 6 years based on a limit of 10 dpa for the target shroud at 3 MW, as well as maintaining a temperature below 700 C for removal of decay heat by conduction through air and thermal radiation to the surrounding structure during a loss of coolant scenario, which mitigates the potential for tungsten vaporization by steam [2]. A target height of 70 mm was used to allow some tolerance for an off center beam. A tungsten zone depth of 0.25 m was used for adequate stopping of the proton beam, resulting in an inner diameter of 0.7m. Rotation rates near 30 and 60 rpm were considered to avoid overlapping of consecutive beam pulses into the same region of the target.

2. Two-Dimensional Steady State Finite Element Analysis

A two-dimensional axisymmetric FEA study was performed to determine the feasibility of two cooling schemes for a rotating solid target with an incident 3 MW Gaussian proton beam. The cooling designs chosen for evaluation were a top, bottom, and outer face scheme and a top, bottom, outer, and additional central cooling channel scheme (*FIG. 1*). The central cooling channel is created by horizontally segmenting each tungsten wedge. Each cooling

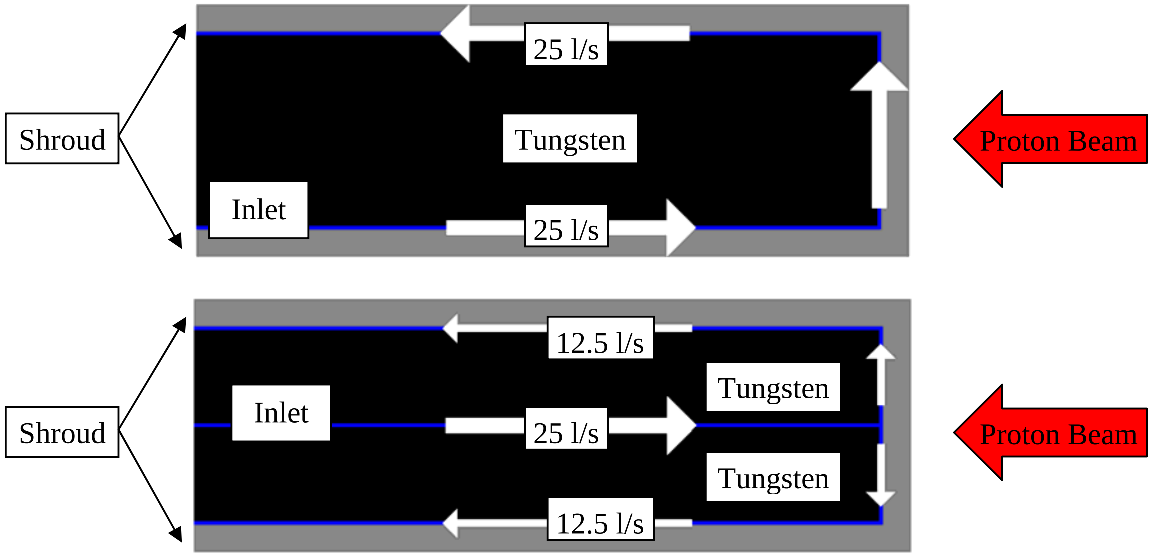

FIG. 1. Cross-section views for coolant flow designs for top, bottom, and outer face only scheme (top) and with additional central cooling channel (bottom).

design features a heavy water flow rate of 25 l/s, selected to obtain heat transfer coefficients on the order of 2 x 10^4 W/m^{2}K with 1.5 mm flow channel heights. Average convection coefficients for each face were calculated from the Dittus-Boelter Correlation, and varied from 1.4 to 3.8 x 10^4 W/m^{2}K depending on the average coolant velocity over the face. A constant coolant temperature of 45 °C was assumed. The tungsten material properties were assumed to be constant with temperature, and the tantalum cladding was neglected. The time averaged energy deposition from the beam was calculated from neutronics simulations and numerically fitted, resulting in the profile

$$E(x,z) = 42.9\frac{W}{cm^3} * e^{\frac{-x^2}{2*(1.52cm+0.0645cm^{-1}*z)^2}} * \tanh\left(1cm^{-1}(z+0.246cm)\right) * e^{-\frac{z}{13.2cm}}$$

where x is target height and z is depth into target.

ANSYS FEA software was used to solve for the resulting temperature profiles, and then again to solve for the resulting thermal stress profiles [3]. Note that because the model is axisymmetric, no angular segmentation of the target is assumed in this simulation. The maximum temperatures in the tungsten were 298 °C and 127 °C, resulting in maximum Von Mises stress levels of 287 MPa and 89 MPa for no central cooling and central cooling, respectively. The much larger resultant temperatures and stresses seen in the scheme without central cooling are a result of a reduced cooling area and an increased distance between cooling surfaces and the region of maximum energy deposition. Although the simulation without central cooling revealed no stress levels above the yield stress of annealed tungsten, 385 MPa at 300 °C, this potential design was not considered for further analysis at 3 MW due to concerns of reduced allowable tensile stress at the high radiation damage levels expected in service [4]. Therefore, only the center cooling channel design will be considered for the remainder of this study.

3. Three-dimensional Transient Finite Element Analysis

A detailed three-dimensional FEA study was performed to investigate the transient effects of the pulsing proton beam and the angular segmentation of the tungsten, which allows for greater thermal expansion and simplified manufacturing. The study also helped to reveal the effects of tantalum cladding, target rotation rate, and adding a step in the central cooling channel to improve neutronic performance and avoid excess radiation damage to the hub. The tantalum is necessary to protect the tungsten from coolant erosion during normal service. Additionally, a 316L stainless steel shroud was added to the model to begin shroud design development. Secondary cooling channels with 3 mm diameter, spaced evenly with 3° separation, were included in the shroud. In the event of a primary cooling failure, the secondary cooling system prevents boiling of stagnant primary cooling water for removal of target decay. An inlet temperature of 30 °C was assumed for primary and secondary coolants and downstream sink temperatures were determined based on heat transfer to the water. For computational efficiency, only 1/20 of the full target, corresponding to two vertically stacked wedges, was included in the model. Heat deposition rate profiles were calculated with neutronics simulations for both Gaussian and flat beam profiles before being interpolated and directly applied to the thermal models. The position of the beam on the target moved each pulse by an amount determined by the rotation rate. Simulations were started with a uniform temperature of 30 °C for all components and were allowed to run until a quasi steady state regime was reached, identified by converged minimum and maximum temperatures of the target segment before and after exposure to a proton pulse, respectively. The thermal simulations required about 15 s of simulated time to reach quasi steady state conditions (*FIG. 2*), where maximum temperatures were as low as 154 °C (*FIG. 3*). Even after quasi steady state conditions are reached, there is some small variation in maximum temperature depending on how each beam pulse is centered in the segment of interest. The before and after pulse temperature and stress extremes in the target and shroud are listed in TABLE I. Note that the difference in temperature before and after the beam has passed in the case of a flat beam profile with a 30 rpm rotation rate is caused by spatial overlapping of two beam pulses. An increase of the rotation rate to about 60 rpm avoids the overlap of consecutive beam pulses, resulting in a temperature ride within a pulse of only about 20 °C.

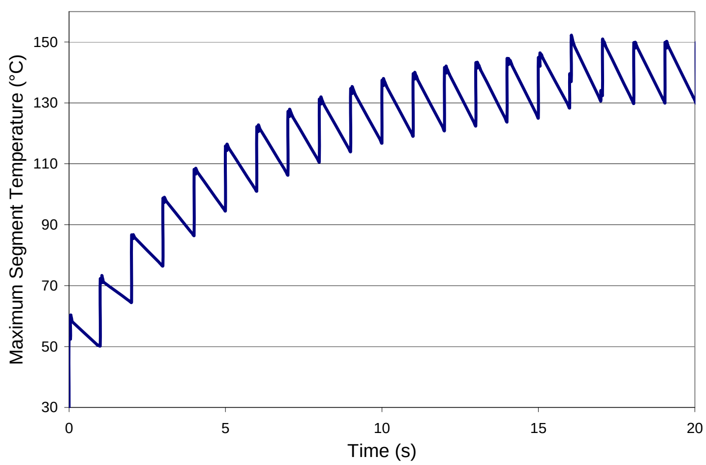

FIG. 2. Maximum segment temperature vs. time for a flat beam profile and 60 rpm.

The resulting temperature profiles just before and after the beam pulse were used as boundary conditions for static structural analyses. Any restraint of the tungsten wedges within the shroud involving bonding resulted in unacceptable stress levels due to thermal expansion differences; therefore, a system of springs and spacers was used to minimize restraint while still locating the wedges within the shroud. Contact modeling was included at all spacer interfaces. Symmetry conditions were imposed at the sides of the shroud to simulate a continuous disc. The resulting stresses were as low as 79 MPa in the tungsten (*FIG. 4*),

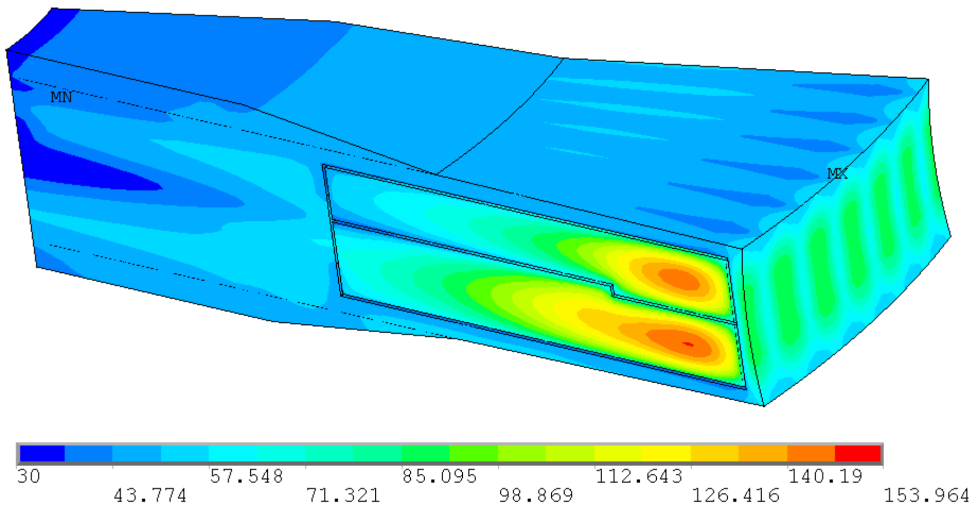

FIG. 3. Temperature profile plot just after the pulse at 16 s for a flat beam profile and 60 rpm.

TABLE I: Summary of maximum temperatures and stresses before and after beam pulses. All stress values are Von Mises stresses except for tungsten, which are 1st principle stresses.

		Temperature (°C)				Stress (MPa)					
	Rotation	Before Pulse		After Pulse		Before Pulse			After Pulse		
Beam Profile	Rate (rpm)	Segment	Shroud	Segment	Shroud	W	Ta	Shroud	W	Ta	Shroud
Gaussian	30	125	100	171	115	66	59	215	84	83	290
Flat	30	128	86	168	95	67	55	165	90	70	201
Flat	60	132	87	154	92	71	68	166	79	66	180

slightly lower than those presented for the 2D analysis, because the angular segmentation of the target allows more freedom for thermal expansion. Note that for tungsten, maximum 1st principle stresses were examined because of the lack of ductility in the material, especially once radiation embrittlement has begun. Tungsten and tantalum have similar coefficients of thermal expansion, which helps to minimize stress levels at the cladding interface and mitigate debonding problems. Acceptable stress levels were found in the bulk tungsten and tantalum cladding for all beam profiles when compared to yield stresses and fatigue data.

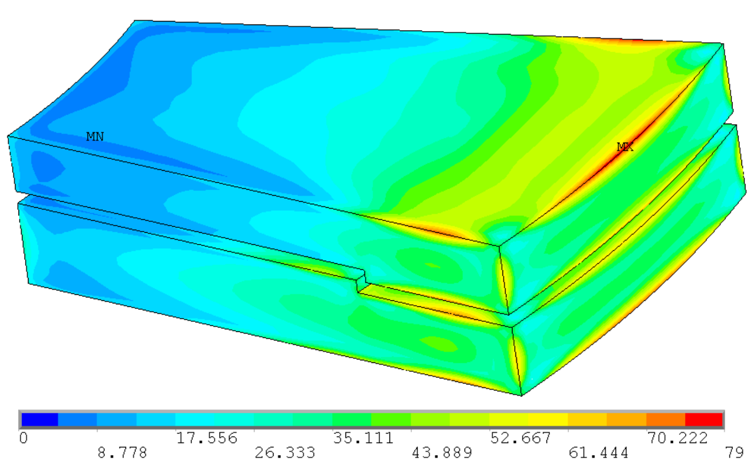

FIG. 4. 1st principle stress contour plot for tungsten with a flat beam profile rotated at 60rpm.

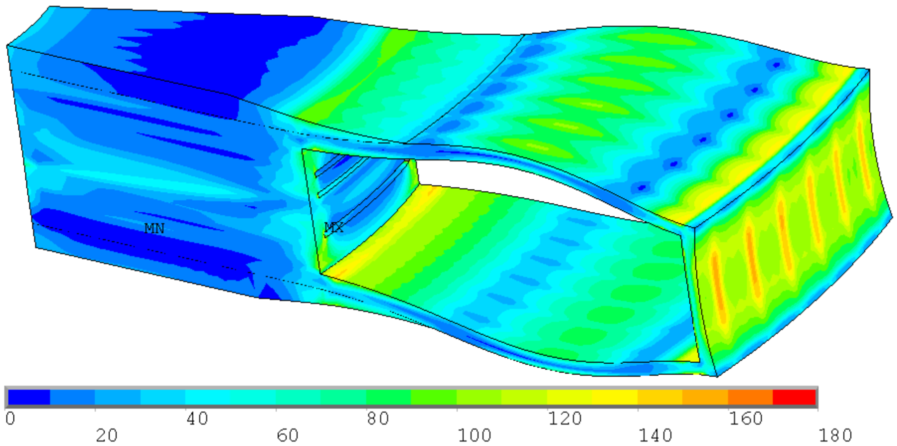

FIG.5. Von Mises stress contour plot for 316L shroud with flat beam profile and 60rpm rotation rate.

An optimized design for the 316L stainless steel shroud was created with a thin window for minimal thermal stresses from proton beam energy deposition and a progressively thicker wall as it approached the hub to accommodate internal coolant pressure. A structural analysis was performed to evaluate the design against the combined loading of thermal expansion, gravity, inertia from rotation, and internal coolant pressure. The results of the analysis show that the maximum stress region is in the target window, which can be as low as 180 MPa for a flat beam profile with 60 rpm rotation rate (*FIG. 5*). The high stresses in this region are a result of the high thermal gradient and stress concentration near the secondary cooling holes. Even for the worst case of 290 MPa for the Gaussian beam, the maximum stress is still below the ASME BPVC allowable for thermal stress in 316L of 345 MPa, and the stress amplitude is below the fatigue limit; however, the fatigue curves do not account for radiation embrittlement [5].

4. Decay Heat Removal

In order to evaluate the effectiveness of the secondary cooling system within the 316L steel shroud, a decay heat model simulation was performed to ensure primary coolant did not boil during a loss of flow scenario. Decay heat profiles after an assumed 10 years of operation at 3MW were predicted by performing activation analyses using the MCNPX and CINDER'90 codes. Immediately after beam shutdown, a decay heat load of 45 kW was obtained for the tungsten target clad with 2 mm tantalum, which could be lowered to 36 kW by reducing the cladding thickness to 1 mm. The decay heat profiles were applied to the target segments and surrounding shroud. The heavy water in the primary flow channels was considered stagnant, while the secondary flow channels were assumed to have 30 °C inlet temperatures and a flowrate of 1.25 m/s. The 1 and 2 mm of tantalum cladding resulted in maximum coolant temperatures of 101 and 117 °C, respectively (*FIG. 6*). Assuming a cooling water supply head of 3.5 m above the target disk, the boiling temperature of heavy water is 111 °C, indicating likely boiling of the primary coolant for a 2 mm cladded target, but no boiling for the case of 1 mm cladding [6]. In order to reduce target decay heat levels so that boiling of coolant does not occur during a loss of primary coolant flow, tantalum cladding should be kept as thin as possible.

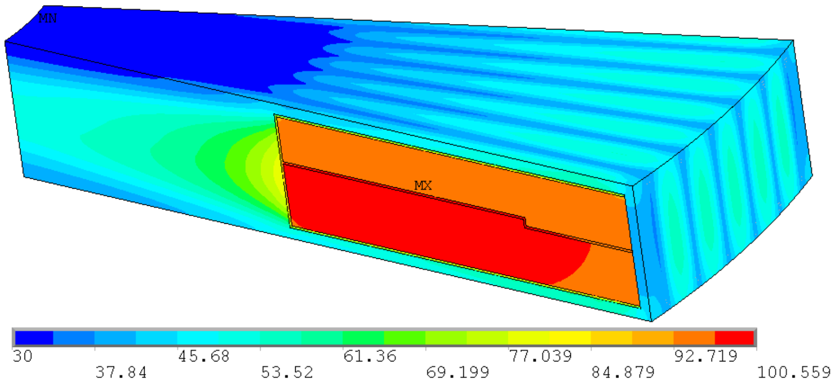

FIG. 6. Temperature profile plot for decay heat removal with 1mm tantalum cladding.

5. Remaining Uncertainties

Some critical assumptions in the preceding analysis require verification to ensure the validity of the conclusions. First, substantial CFD and experimental flow studies will need to be performed to confirm the flow patterns and heat transfer coefficients assumed for the high aspect ratio channels in this study are realistic. Also, a detailed design for sealing angular gaps is still to be completed. Additionally, the correlation between radiation damage and thermal conductivity needs to be investigated in tungsten, as minimal information is currently available on this topic. If the thermal conductivity decreases rapidly as damage increases, thermal stresses much greater than those found in this study could exist, causing premature target failure. Also, the tensile yield and fatigue properties of tungsten at high radiation damage levels are also unknown. Perhaps the best source of information on fatigue properties compared to radiation damage would be a careful examination of operational experience at facilities using tungsten targets, such as ISIS. Finally, concern of radiation damage to springs may require evaluating alternatives for mechanical restraint. If these areas of concern can be elucidated, a rotating solid target could be a viable option for use at up to 3 MW beam power.

6. Conclusions

Through simulations using MCNPX for neutronics analyses and ANSYS for the thermal and structural analyses, the structural viability of a rotating solid target for a Spallation source at powers up to 3 MW has been demonstrated. The use of a central cooling channel and a system of springs and spacers to prevent over constraint mitigates high thermal stresses in the Tantalum clad tungsten segments. The stainless steel shroud has been designed with a concave window in order to minimize material in the highest intensity beam to minimize heat load while providing additional thickness in the corners where stress concentrations from internal pressure are a concern. The resulting design has been analyzed and shows thermal stresses below ASME allowables and stress amplitudes below ASME fatigue limits. The lifetime of the rotating target should be limited by radiation damage level to the shroud window, which is estimated at 6 years for a limit of 10 dpa. Although some assumptions used for this analysis are still awaiting verification, substantial margin exists before the materials utilized in this design are pushed to their limits. A solid rotating target offers the advantages of equal or improved neutronic performance, reduced remote handling requirements, longer target lifetime, and no concern of cavitation erosion compared to a liquid mercury target. Now that the thermo-mechanical feasibility has been shown for beam power up to 3 MW, future spallation sources can realize these benefits.

7. References

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