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ROTATING TARGET DEVELOPMENT FOR SNS SECOND TARGET STATION

T. McMANAMY
Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN, 37831, USA

and

K. Crawford, P. Geoghegan, J. Janney,
M. Rennich,
Oak Ridge National Laboratory, Bethel Valley Road, Oak Ridge, TN, 37831, USA

ABSTRACT

A rotating target for the second target station (STS) at SNS has been identified as an option along with a mercury target. Evaluation of the rotating target alternative for STS has started at 1.5 MW which is considered an upper bound for the power. Previous preconceptual design work for a 3 MW rotating target is being modified for the lower power level. Transient thermal analysis for a total loss of active water cooling has been done for a simplified 2D model of the target and shielding monolith which shows that peak temperatures are well below the level at which tungsten vaporization by steam could exceed site boundary dose limits. Design analysis and integration configuration studies have been done for the target-moderator-reflector assembly which maximizes the number of neutron beam lines and provides for replacement of the target and moderators. Target building hot cell arrangement for this option will be described. An option for operation in rough vacuum without a proton beam window using Ferro fluid seals on a vertical shaft is being developed. A full scale prototypic drive module based on the 3 MW preconceptual design has been fabricated and successfully tested with a shaft and mock up target supplied by the ESS-Bilbao team. Overall planning leading to decision between mercury and the rotating target in 2011 will be discussed

1. Introduction

Initial technology development studies at ORNL in 2008 led to the development of a 3 MW rotating target design [1]. In 2009 conceptual design for the Second Target Station at SNS was authorized and an integrated evaluation started which showed that 1.5 MW was a likely upper power bound for reasonable costs. The previous designs were modified for the lower power. The activities include target design with structural and thermal hydraulic analysis, neutronic analysis [2], safety and overall facility configuration studies including remote handling and integration of neutron scattering instrument requirements. Conceptual target design for the SNS Second Target Station (STS) has been based on optimizing cold neutron brightness. Target design has been based on 1.5 MW beam power at 1.3 GeV, 20 Hz and long pulse operation (10^{-3} s) with 2 large para-hydrogen moderators in wing position. Design optimization studies are in progress and the status of results to date will be given below. Neutronic analysis has shown the rotating solid target to give equivalent or slightly improved moderator performance compared to a mercury target [2].

2. Target Design

2.1. Configuration

The target disk (Figure 1) is based on a water-cooled, tantalum-clad tungsten block assembly. Good fabrication and operational experience with these materials in fixed solid targets has been observed at ISIS target stations 1 and 2 and KENS. A 1 mm tantalum clad thickness was assumed for analysis. The target blocks are contained in a stainless steel housing 1.2 meters in diameter, 8 cm high and approximately 12 mm thick above and below the target block region (0.35m to 0.6m radius and 5.4 cm thick). Stainless steel was selected for the shroud because of the good neutronic damage data base and also the ability to maintain structural integrity at elevated temperatures which could occur under loss of cooling accidents. The height was minimized to improve neutronic performance. Water cooling of the clad blocks and shroud is routed through the target hub. Flow is across the top, front and bottom surfaces in nominally 1.5 mm high flow channels. The primary life limiting factor is assumed to be radiation damage to the shroud face. Assuming a relatively flat beam profile (4.4 x 12 cm^2) the target will have an operating life of approximately 10 years for 10 dpa on the window at 1.5 MW.

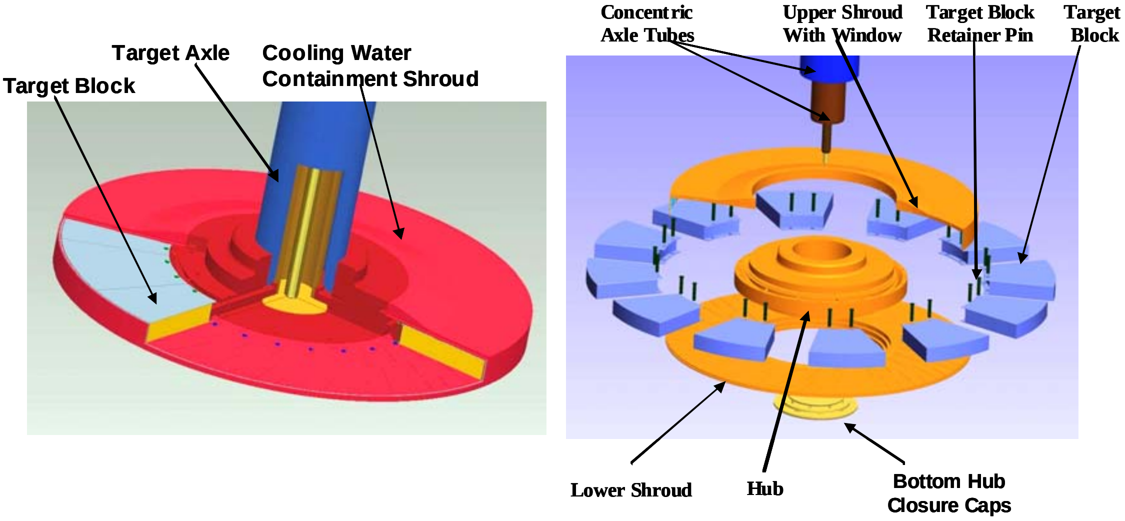

Figure 1. 1.2 m diameter target disk and Exploded view of the assembly

The rotational speed is selected to keep pulses from overlapping at 20 Hz. For beam widths of 12 to 18 cm the range would be on the order of 30 to 60 rpm. The target blocks are pinned to the hub on the inside to restrain radial motion.

2.2 Initial Design Analysis

Before detailed design could begin, a scoping analysis was performed using ANSYS 11.0 finite element analysis software for heat transfer and structural analyses. The goals of the analyses were to gain an understanding of the effect of cooling scheme and beam width on the resulting temperatures and stresses in the target. The study used a 1.5 MW proton beam power with an assumed 25 l/s coolant flow rate, 35 C constant sink temperature, and 2.4 – 4.2 W/cm^{2}K convection coefficients (Dittus-Boelter correlation). The results of the study are summarized in Table I. Peak stresses are 1st Principal for tungsten and Von Mises for tantalum. Changing the beam width from 12 to 18 cm results in a stress reduction of about 20%, but requires a 50% increase in rotational speed to prevent pulse overlapping.

Despite the near 50% reduction in stress levels for a center cooled target, the stress level without center cooling is only 122 MPa, and the improvement is outweighed by the additional complexity and reduced neutronic performance of a target including a center cooling channel. Therefore, detailed studies were performed without a central cooling channel and with a 12 cm width for the proton beam profile.

Table I. Summary of initial design analysis.

Block Configuration	Cooling Configuration	Beam Width (cm)	Max. Temp. (W) (°C)	Peak W 1st Prin. Stress (MPa)	Peak Ta V.M. Stress (MPa)	Optimal Rotation Speed (rpm)
Full Block	Outer	12	154	122	72	40-49
Full Block	Outer	15	147	107	61	50-60
Full Block	Outer	18	144	100	55	61-74
Split Block	Outer + Center	12	96	63	36	40-49

2.3 Thermal Hydraulic Analysis

In order to implement a more detailed analysis, ANSYS CFX 12.0 Turbo machinery was employed to simulate the flow and heat transfer under steady state conditions. To minimize peak flow velocity and to increase the Reynolds number with decreased flow rate, the detailed design included 432 flow spacers milled into the stainless steel shroud, forming 18 channels 1.0 cm wide above and below each tungsten segment. The channel height was tapered from 3.0 mm at the inner tungsten radius to 1.5 mm at 45 cm radius and 1.5 mm outwards. The tungsten segments rest directly on the bottom flow spacers, with a small gap (0.25 mm) on top. Total flow rates of 11, 15, and 20 l/s were considered with a rotational speed of 30 rpm. Periodic boundaries reduced the domain to 1/12th of the full target and the standard k-ε and k-ω models turbulence were investigated with no discernable difference in results. 30 ^{0}C was the inlet temperature of the water, while a time averaged heat generation rate from MCNPX calculations represented the proton beam energy. After a steady state solution was achieved, a single beam pulse was applied, corresponding to the maximum temperature state just after a proton beam pulse. The results of the detailed analysis were promising, as seen in Table II and Figures 2 and 3, with peak tungsten temperatures reaching only 172 ^{0}C for 15 l/s coolant flow. Flow distribution was nearly as desired, although not yet fully optimized. The low rotational speed and presence of the spacers resulted in negligible coriolis affect. One concern is that the flow in the gaps between the angular segments was low and gave the highest water temperatures in Table II. These are just below boiling for operation at 4 bar. Although optimization could provide improvement, structural analysis was performed based on these CFD results.

Table II. Summary of Detailed CFD and Structural Analysis.

Water Flow Rate (l/s)	Max. Speed (m/s)	Water ΔTemp. (°C)	Water Peak T(°C)	Peak W Temp. after pulse (°C)	Peak W 1st Prin. Stress (MPa)	Peak Ta V.M. Stress (MPa)
11	4.4	17.2	134.1	187	168	85
15	5.5	12.7	116.9	172	158	85
20	7.4	9.4	103.3	162	151	84

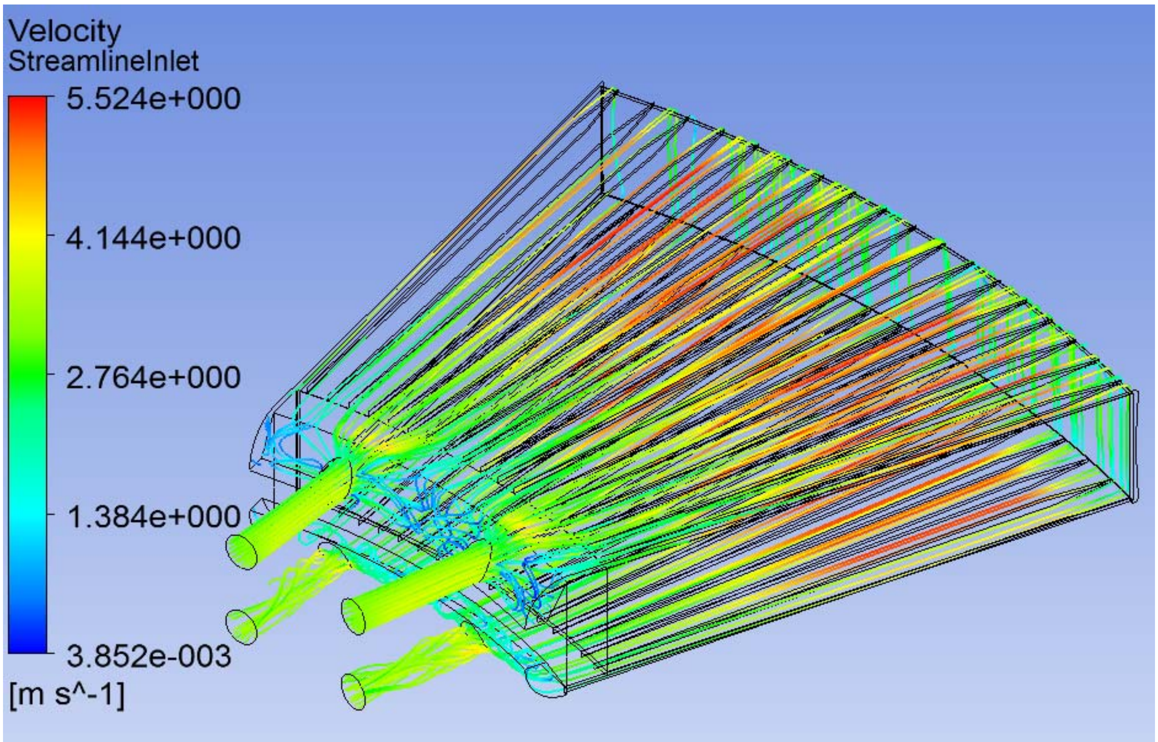

Figure 2. Contour streamline plot of water velocities (15 l/s flow rate).

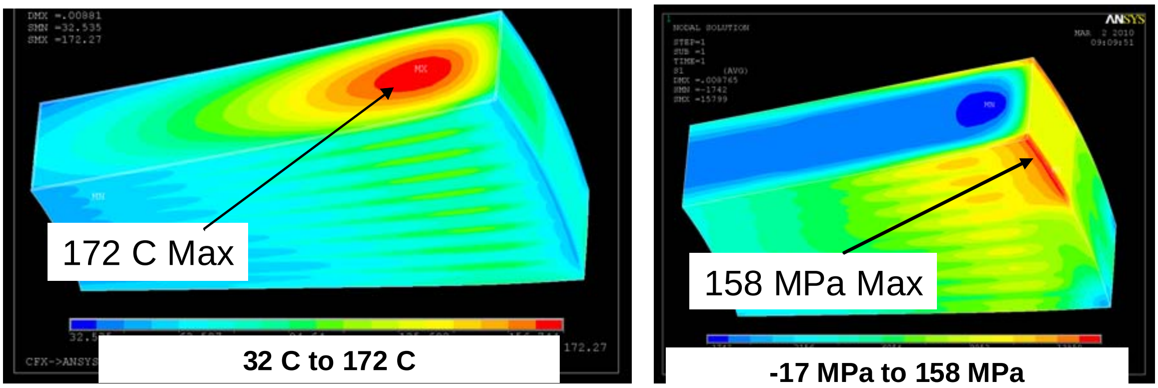

Figure 3.Tungsten Temperature and 1st Principal Stress just after beam pulse (split on centerline for clarity)

2.4 Structural Analysis

The thermal results from the CFD analysis representing the peak temperature condition were applied as temperatures to the tungsten wedge for an ANSYS simulation of the thermal stress. The segment was pinned at the inner radius for mechanical constraint. As can be seen in table II, resulting stresses, are slightly higher than expected from the initial analyses, even when accounting for decreased flow rates. The main cause for this increase seems to be overcooling of the outer top and bottom edges of the segments, due to the high recirculation noted in the hydraulic analysis. A wider beam (15 cm), optimization of flow distribution and reduction of flow spacer size could also reduce maximum stress levels with little neutronic effect. Although the structural analysis reveals no stresses near the yield stress of 517 MPa at 150 C, concerns of reduced ductility and thermal conductivity with expected radiation damage levels require further optimization of the thermal hydraulic design to reduce resulting stress levels.

3. Target Station layout Studies

3.1 Target Module Design

The current design is based on using an extended vertical shaft with a drive module approximately 4 m above the target disk. It is divided into two subassemblies; the target module including the disk and axle, and the drive module which includes all the active mechanical and electrical components. The two modules are coupled with a static joint located outside the vessel. Contact maintenance of all the drive module components subject to radiation damage or operating wear will be possible either in-situ or in a dedicated maintenance bay. This arrangement also allows personnel to directly make and break the water and other utility fittings, thus insuring testable and reliable sealing. This enables the facility to quickly recover from a majority of failures without removing the highly activated target module. Other advantages of this arrangement include the use of proven, commercially available components, conventional speed control, reliable monitoring of temperature and vibration, and the use of a remote bearing lubrication system. The target module would be part of a single plug assembly which would include the moderators, reflector and shielding. The option of handling the relatively high burn-up components in the moderator/reflector in a dedicated, horizontal cell located near the proton beam region was considered. Cost and the loss of a significant amount of useful instrument space were judged to out weigh the benefits of possibly more efficient, independent change-outs which would be expected to only occur 8 to 12 times over the life of the facility. Figure 3 shows the proposed assembly.

The drive module combines four primary components; a drive motor, two rotary couplings, shaft support bearings and a structural support frame. By grouping the drive, seal and structural components in one place it is possible to build them into a single module which can be exchanged independently of the target and shaft module. Alignment of the target disk with respect to the moderator containers is a critical requirement. Neutron production has been shown to decline if the gap between the two assemblies exceeds 1 cm. This challenges the proposed extended shaft rotating target since it requires precision alignment of several components starting with the mounting face on top of the core vessel, passing through the drive frame, bearings, upper axle, axle coupling and finally, the extended drive axle. In-situ adjustment of the drive module can be used to compensate for some misalignment of the target assembly; however, excellent internal tolerances must also be achieved in manufacturing to achieve the needed system alignment. Long-term alignment stability is based on a rigid structural frame rather than internal adjustment capability. Conventional machining capabilities can reasonably provide the necessary alignment to position the target disk within the monolith. The rigidity of the system is further enhanced by the large diameter, hollow drive shaft which requires the use of over-size bearings, 400mm and 480mm in diameter. In addition to providing excellent alignment and stiffness, the low operating speed of the large bearings will significantly improve the durability of the system. The heavy-duty bearing arrangement can also be expected to withstand small, pulse or harmonic up-sets during start-ups, shut-downs or off-normal events.

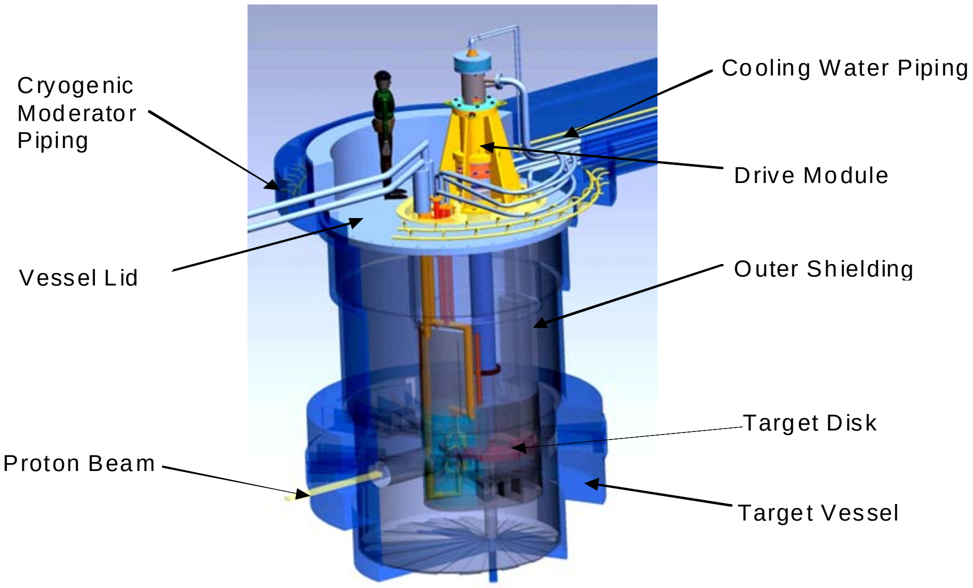

Figure 3. Target Module Assembly and Target Vessel

Sealing the primary cooling water flow (15-25 l/s) in the transition between the static piping and the rotating axle is critical. A review of possible dynamic seals led to the selection of a high integrity, bellows face seal. The slow rotational velocity will significantly extend the life of the wear face. However, the large shaft diameter (220 mm) required to accommodate the water flow to the target disk limited the selection of available seal possibilities. The seals used in the prototype drive [3] use stellite-on-graphite faces and were originally designed for use by NASA in high integrity systems.

Sealing between the feed and discharge channels inside the water couplings is accomplished with a passive, close-fitting ring. Precision tolerancing throughout the drive module allows for a seal gap of less than 0.025 mm. A bypass leak rate of less than 2% of the total flow is expected.

3.2 Target Remote Handling and hot cell configuration

In order to limit the size of the high bay bridge crane and the corresponding building structure, the large target plug will be handled with a dedicated shielded transfer container mounted on rails. Rail mounting will improve positioning, shielding and safety. The container will also be used to handle smaller activated components requiring transfer along the centerline of the high bay. The maintenance cells will be built primarily to handling and process the target plug assembly. Other activated components generally require limited handling prior to loading in a shipping container and therefore should be easily accommodated. Three cells are planned to take advantage of a “ready-spare” target change-out maintenance plan. In this arrangement a fully assembled and tested target plug will be held in a small cell near the monolith. This complete plug or possibly only the drive will be available for immediate loading after the removal and transport of a target plug or drive module. Figure 4 shows the transfer container and Hot Cell configuration. The overall size is similar to what is required for the mercury target system, but slightly smaller.

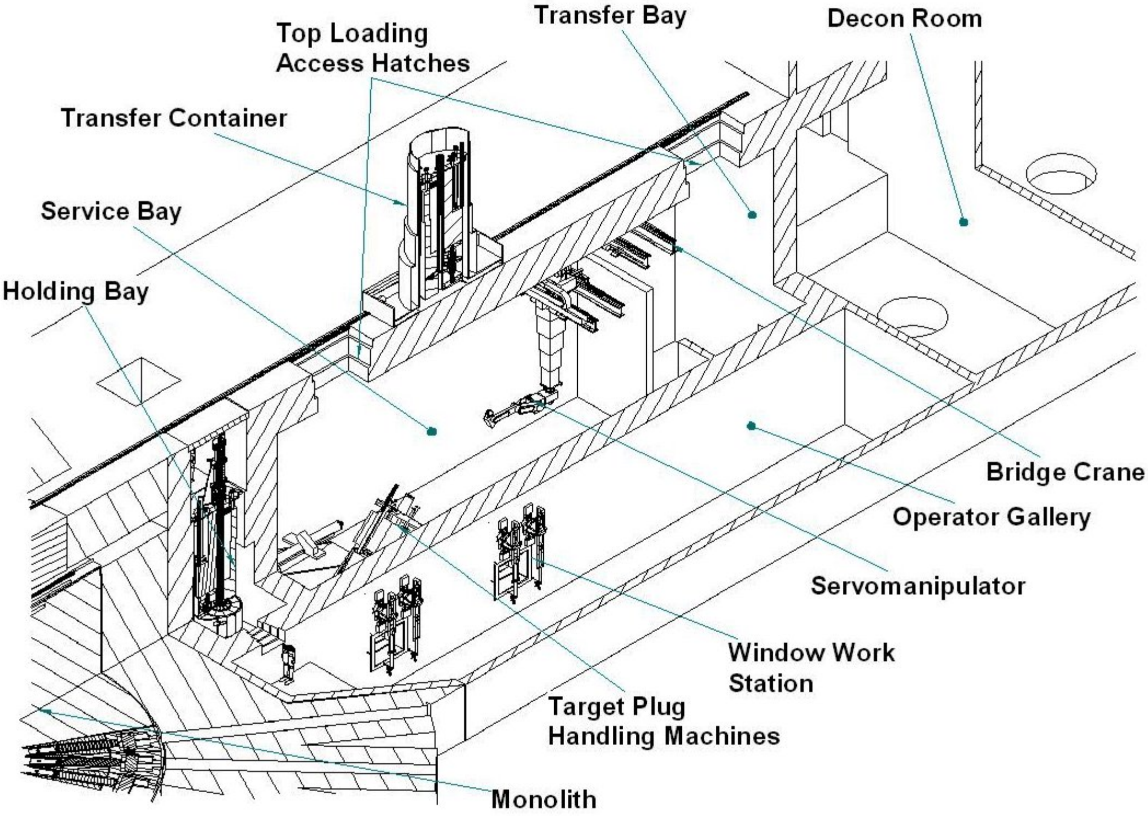

Figure 4. Target transfer container and Hot Cell

3.3 Monolith and beam line layout

Figure 5 shows a section through a typical neutron beam line and the shielded personnel access room for the drive module. 20 neutron beam lines are planned.

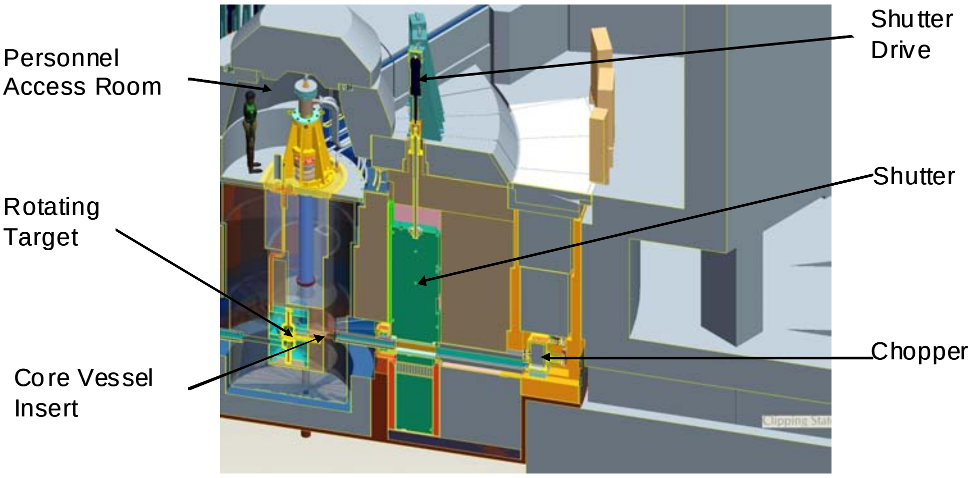

Figure 5. Monolith Section View through typical neutron beam line

4. Preliminary Safety Evaluations

Chemical reactions of tungsten with steam form hydrated tungsten-oxide which has a high vapor pressure and is readily convected in flowing atmospheres.[4] The fraction of the total radionuclide inventory which would give a 1 rem dose at the site boundary assuming

5 years of operation at 1.5 MW and release of all gases was estimated. The result was 0.15%. A peak allowable temperature of 790 C was then estimated for the 1.2 m diameter target assuming the tungsten was exposed to steam on the entire top and bottom surfaces for 10^6 seconds. The mass loss rate was assumed to be given by the expression developed by testing at Brookhaven National Laboratory [4] with 15% air and a 30% release fraction. The target decay heat at shutdown from 1.5 MW with 1mm tantalum clad is 18 kW. Any active cooling system (shroud, reflector system or low flow primary cooling) can keep the target well below 800 C. A preliminary transient analysis was done assuming no functioning active systems beside a beam trip. Decay heat was removed by gas conduction through a 5 mm water vapor gap to the reflector assemblies and by thermal radiation across the gap in a simplified 2D model of the target and monolith. The very large mass of carbon steel shielding above and below the target acted as a good heat sink and the peak temperatures of the tungsten peaked at about 500 C after 10 hours and continued to decrease for 11 days as the shielding heated by conduction. A more detail calculation with natural convection, larger gaps and contact thermal resistances is planned.

5. Mockup Testing

The drive module from the 2008 design for the rotating target containing the seals and bearing was fabricated and tested by itself and then with a full scale mockup of a 1.2 m diameter target and 4 m long shaft [3]. The shaft and target were supplied by the ESS-Bilbao team. Initial results from full scale mockup testing of the drive module and target module has shown that fabrication tolerances can be held to give very good alignment without bearings in the high radiation area. In addition the rotating water seals have been operated for over 1600 hours at 30 to 60 rpm with no leak indications. Full results are given in a companion paper at this conference [3].

6. Summary

The solid rotating target appears to be a good option for STS offering a long life and good performance with conservative mechanical design. Further evaluations of fabrication methods, radiation damage effects on tungsten and independent safety studies are still needed.

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6. References

1. T. McManamy, et al, *Journal of Nuclear Materials* 398 (2010), pp. 35-42 DOI information: 10.1016/j.jnucmat.2009.10.007

2. F. Gallmeier, et al, “NEUTRONIC ANALYSES IN SUPPORT OF ROTATING TARGET DEVELOPMENTS AT SNS”, *Proceedings, ICANS XIX, 2010*

3. M. Rennich, et al,”Design and Testing of a Prototype Spallation Neutron Source Rotating Target Assembly”, *Proceedings, ICANS XIX, 2010*

4. G. Greene, et al, “Generation, Transport and Deposition of Tungsten-Oxide Aerosols at 1000 ^{0}C In Flowing Air-Steam Mixtures”, Brookhaven National Laboratory Report BNL-52645, October 2001