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SNS MERCURY TARGET SYSTEM OPERATION AND EVOLUTION

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ABSTRACT

Operating since 2006, the SNS Mercury Target System has reliably provided neutrons through the maturation phase of the facility. Beam power on target has increased to levels above 1 MW. Engineering is ongoing to prepare the system for operation at 1.4 MW and beyond. This paper addresses four aspects of the target system and its engineering;

1. System Operation and Reliability: Early difficulty with the mercury pump has left a desire to limit the rotational speed of the pump so that its useful life may be extended. Therefore, ongoing analysis and adjustment of set points has allowed operation to continue at reduced pump speeds that match reduced power levels.
2. Target Module Design Evolution: The present target module design has not changed significantly from the initial design. However, there have been some minor changes. These changes have been driven by structural analysis at higher powers and by efforts to make the unit easier to manufacture.
3. Target Module Manufacturing and Value Engineering: As a disposable component, a reliable inventory of target modules is required. Without extensive operating history, target lifetime remains an unknown variable. Target lifetime is influenced by radiation induced embrittlement and cavitation damage. Target manufacturing plans and execution are presented.
4. Future Plans: Future plans to address target module leak detection, cavitation damage, and manufacturing are presented.

1. Target System Operation and Reliability

For the purposes of this paper, the SNS Mercury Target System consists of all components directly related to supply target material to the incident beam. This includes the target module, the mercury pump, the mercury to water heat exchanger, the mercury piping, the storage tank, and the target carriage (Figure 1).

This system has provided a reliable target for nearly 4 years, causing minimal interruptions in operations. The lone significant equipment failure was associated with the mercury pump. Within the first 7 months of operation, problems were encountered with both the pump grease seals and the pump shaft seal.

After a few months of operation, grease began leaking from the bearing cavities. Upon investigation, it was determined that the grease seals, which were chosen for their good radiation resistance, were incompatible with the bearing grease. Thus, they deteriorated and began to leak. This problem was addressed by adding graphite packed over-seals beneath the existing bearing seals. Also, accelerometers were added to the bearing housings to more closely monitor bearing vibration in order to detect indications of bearing failure.

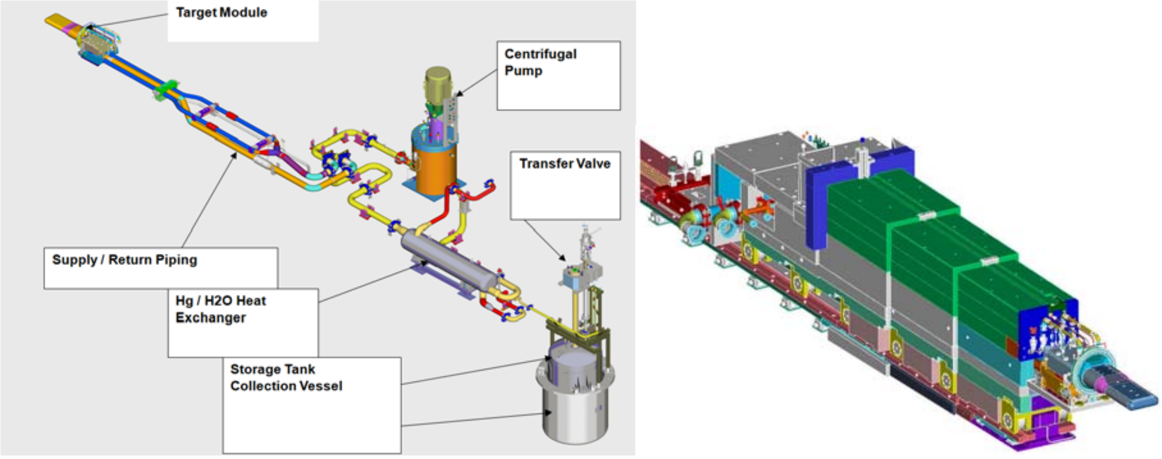

Figure 1 – Mercury Target Piping System and Target Carriage

After about 7 months of operation, the shaft seal on the mercury pump failed. The function of the shaft seal is to prevent highly activated spallation gases from exiting the pump reservoir. Without a functioning shaft seal, the service bay would become unacceptably contaminated. Therefore, this failure was more than a nuisance. A solution was developed in which the lower volume of the pump housing was used as the gas seal. This volume is filled with helium at a pressure slightly higher than the pump reservoir and the surrounding room. Therefore, it leaks helium to the reservoir and the room and prevents gasses from the reservoir from leaking into the surrounding room.

The solutions to these two problems have proven successful over the past 3.5 years and a replacement pump has been procured with redesigned shaft and bearing seals. However, it is recognized that the lifetime of the mercury pump and the applied fixes will be extended if the pump can be operated at a reduced speed. The pump nominal speed is 400 rpm and the flow rate is 1430 litres per minute (lpm). This flow rate was specified to sufficiently remove heat at a beam power of 2 MW. However, early operation was at much lower powers. Therefore, the relevant analysis was reviewed and the pump speed was reduced accordingly. Table 1 shows the pump speeds, flow rates, and corresponding maximum power limits that have been accepted at SNS [5].

Table 1 - Power Levels Corresponding to Flow Rate

Pump Speed	Flow Rate	Maximum Power Level
150 rpm	506 lpm	350 kW
250 rpm	862 lpm	1.0 MW
270 rpm	971 lpm	1.4 MW

2. Target Module Design Evolution

2.1 Target Analysis and Resulting Design Changes

The SNS target module is comprised of a mercury vessel and a water cooled shroud. The mercury target material flows thru the mercury vessel and the water shroud provides a volume to retain mercury in the event that the mercury vessel leaks. However, neither the mercury vessel or water shroud is a safety component. The core vessel is designed to contain mercury if it leaks beyond the water shroud.

SNS has chosen to follow the design and manufacturing guidelines of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC). This serves as a very mature design standard. However, because the module is not a certified pressure vessel, SNS can deviate from the BPVC when appropriate for our unique situation. For example, the BPVC defines material yield strength and safety factors for various types of stress. SNS has chosen to use actual certified material yield strengths to establish stress limits rather than the published minimums. SNS then follows the BPVC guidelines by applying the same safety factors to these actual yield strengths.

2.1.1 Mercury Vessel Analysis

At the start of operation, the mercury vessel had been analyzed to a power level of 1 MW. Therefore, the mercury vessel needed to be analyzed at 1.4 MW and any required changes to reach this power level had to be identified. Due to the operational limits placed on the mercury pump, the mercury vessel was studied with various flow conditions. Four total flow conditions were considered. As shown in Figure 2, there are 3 mercury supplies: 2 bulk flows from either side and a directed window flow from the bottom to the top.

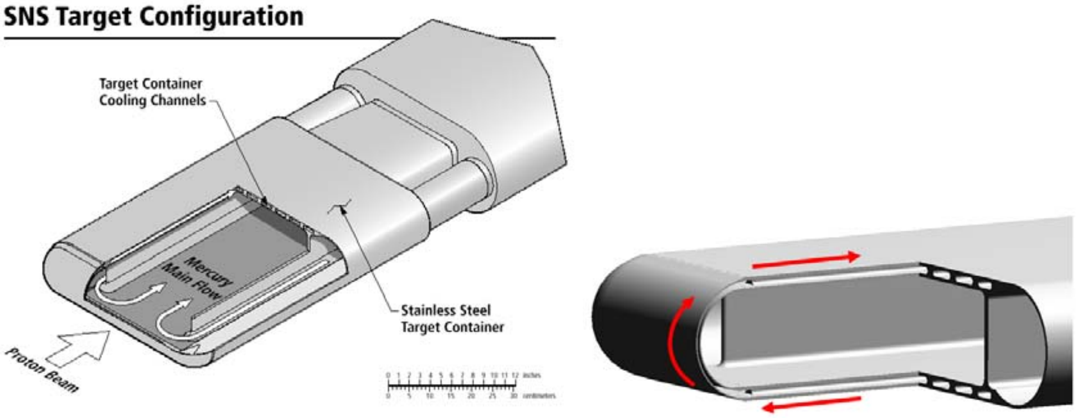

Figure 2 - Mercury Supply Flows

Due to the mercury pump limitations described above, it is desired to operate the pump at 270 rpm rather than 400. Reducing the pump speed reduces heat transfer coefficients in the target. However, there is a removable orifice currently installed which limits the window flow. This provides an additional adjustment parameter. The location of this orifice is shown in Figure 3. Structural analysis was performed for the 4 flow conditions shown in Table 2. The analysis was performed with a beam of 1.54 MW [1].

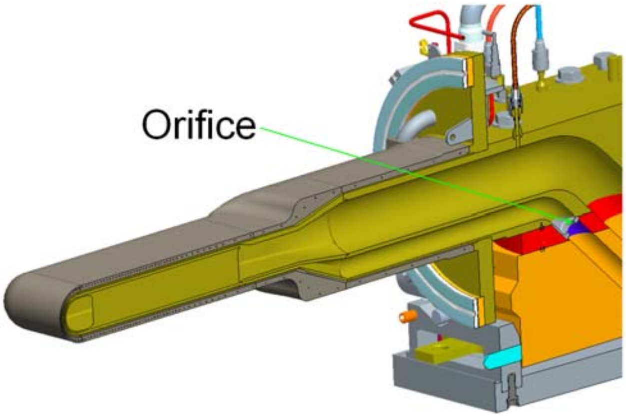

Figure 3 - Window Flow Orifice

Table 2 – Mercury Vessel Analysis Results at 1.54 MW

	Limiting Peak Stress, Secondary (Mpa)	Allowable at limiting location, Secondary, 3*S_m (Mpa)**	Stress/Allowable
270 rpm with orifice	395.2	413.6	0.96
270 rpm without orifice	351.6	413.6	0.85
400 rpm with orifice	371.9	481.1	0.77
400 rpm without orifice	372.1	484.0	0.77

The limiting stresses result from thermal and short lived pressure pulse loads are considered to be secondary stresses by the BPVC. Therefore, they are evaluated against higher allowable stresses. At 270 rpm, removing the window flow orifice lowers the stress by about 11%. As shown, the orifice does not significantly affect the limiting stress condition at 400 rpm. Because of the desire to limit pump speed, the orifice will be removed during the next target replacement and the pump will continue to operate at 270 rpm.

2.1.2 Water Shroud Analysis

The intention of the water shroud is to contain mercury in the event that it leaks from the mercury vessel. The space between the water shroud and mercury vessel is known as the *interstitial*. There are two leak detectors within the interstitial: a continuity probe, which detects the presence of mercury by sensing a reduction in resistance between wires or between wires and the target module shell, and a heated thermocouple junction, which is calibrated to detect the presence of mercury or water. These detectors are located at the bottom of the interstitial, so they should detect a leak before the interstitial becomes filled. However, if the leak detectors do not provide indication of a leak, mercury would fill the interstitial until the helium gas is compressed to a pressure equal to the mercury bulk pressure. The red area in Figure 4 represents the height that the mercury would reach in the interstitial.

The 2 MW analysis of the water cooled shroud did not include a case in which mercury filled the interstitial and the beam continued to operate [2]. In light of the decision to operate the target until 10 displacements per atom (DPA, see section 3.1) is reached or mercury leaks to the interstitial, the water cooled shroud analysis has been extended to include the case in which the interstitial filled with mercury.

The structural loads for this analysis include: dead weight, static mercury bulk pressure, steady state temperature distribution due to a 1 MW beam, and pressure pulse due to a 1 MW beam. The interstitial is assumed to be completely filled with mercury, i.e. the boundary between helium and mercury at the top of the interstitial is ignored. This assumption is likely conservative because the pressure pulse would be dissipated by the helium at the top of the interstitial.

This analysis provided a safety factor (allowable stress / calculated stress) of about 1.37 at 1 MW [3]. Scaling this result yields the conclusion that the water cooled shroud is suitable for close to 1.4 MW operation with undetected mercury in the interstitial. However, this conclusion does not allow for the significant uncertainties in beam profile, heat generation calculation, thermohydraulic analysis, and the structural analysis itself. Therefore, the design requires improvement to gain margin.

The peak stress location is in the center of the water shroud inner window (see Figure 4). This stress is primarily driven by the temperature gradient through the window. This high gradient is caused by the heat deposition in the three layer composite wall composed of the water shroud inner window, the stagnant mercury in the interstitial, and the mercury vessel outer window. Therefore, the peak stress can be reduced by thinning one or more of these layers.

Three parametric analyses have been performed to lower the peak stress in the water shroud inner window:

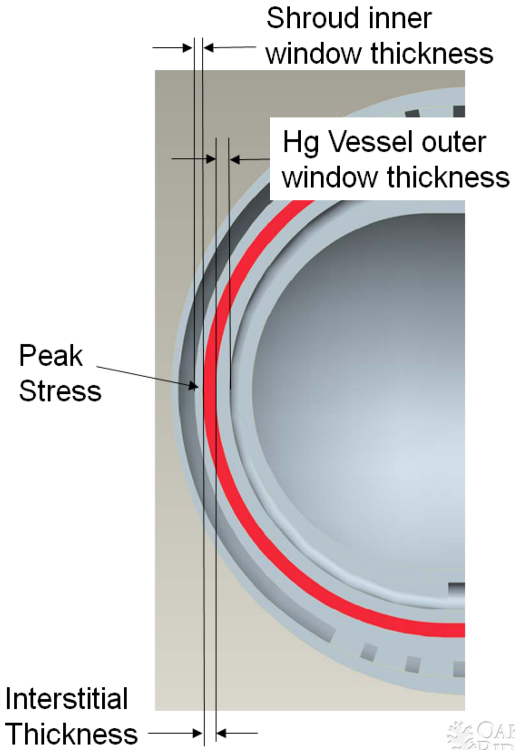

Figure 4 – Water Shroud Peak Stress Location

1. A 2-D model was developed to study the effect of thinning the interstitial thickness. Representative heat generation was applied and the interstitial thickness was allowed to vary. Reducing the interstitial thickness from the initial maximum of 3.05 mm to 1.9 mm, results in a 16% reduction in thermal stress, and about 15% reduction in total stress. This design change has been adopted and applied to future targets.
2. A simplified 3-D model was developed to study the effect of thinning the water shroud inner window. Beam powers of both 1 MW and 1.4 MW were applied. As the window is thinned, the thermal stress is reduced because the temperature gradient falls. However, the membrane stresses caused by static pressure and the pressure pulse increases. The initial window thickness was 1.8 mm, but the optimal thickness is 1.3 mm [4]. Therefore, the design has been changed by thinning this window to 1.3 mm.
3. The 2-D model used in the first parametric study was used to study the effect of reducing the thickness of the mercury vessel outer window. For the mercury in interstitial off normal case, reducing the mercury vessel outer window thickness from the current design thickness of 3 mm to 1.5 mm lowers the thermal stress in the water shroud by over 20%. Coincidentally, this change would also lower the stress in the mercury vessel itself. However, the extra thickness in the mercury vessel provides margin against cavitation erosion. Therefore, this change will not be adopted until the cavitation phenomenon is better understood.

At the time of this writing, a complete 3-D analysis is being performed to analyze the synergistic effects of thinning the interstitial gap and the water shroud inner window.

2.1.3 Applied Power Limits

Based on the analysis summarized above, each actual manufactured target can be assigned an approximate power limit as shown in Table 3. These differences in the scaled limits are caused by variances in material properties and measured interstitial thicknesses.

Table 3 - Scaled Power Limits

Target # 2	1.61 MW
Target # 3	1.53 MW
Target # 4	1.85 MW
Target # 5	1.85 MW

The limits in Table 1 are based on ideal conditions. For the current target (#2), the limit has been reduced to 1.2 MW. This additional margin allows for the uncertainties in the beam profile and in the analysis. When the beam is peaked (higher peak current density than nominal), the thermal stress rises accordingly. The peaking factor is defined as the peak number of protons per unit area in a given run divided by the maximum number of protons per unit area in the nominal beam profile. For example, if the peaking factor is for a production run on target #2 is 1.1; the power limit is reduced to 1.2 MW/1.1, or 1.09 MW.

Setting the power limit at 1.2 MW for the second target provides comfortable margin against a structural failure of the water shroud. This margin is desired because if mercury leaks from the water shroud, the Inner Reflector Plug would likely be irreparably damaged and cleanup would be costly and lengthy. This would have major operational impacts to the facility. However, as the beam profile diagnostics improve and the target design and analysis process progresses, the required margin may be reduced.

2.2 Value Engineering

Due to the complex geometry of the target module, several non-standard manufacturing techniques have been employed. EB welding, EDM, and deep hole drilling are all used on each module. Different manufacturers apply these techniques in unique ways. Having three manufacturers (as discussed below) producing targets simultaneously has provided a surge of *manufacturability* information regarding the present target design. The SNS approach has been to allow each manufacturer to evaluate the design and choose the manufacturing methods with which it is most comfortable, so long as the functional stress and thermohydraulic requirements of the module are maintained.

As such, targets may be slightly unique from each other in one way or another. This is most prevalent in weld joint design. As long as the structure is not compromised and the functional geometry is maintained, weld joints can be shifted to suit the strengths of each vendor.

In some cases, actual geometry has been modified to accommodate specific techniques. For example, the mercury vessel transition part, shown in cross section in figure 5, was modified so the center channel could be machined complete with wire EDM. The previous geometry required additional plunge EDM or conventional milling.

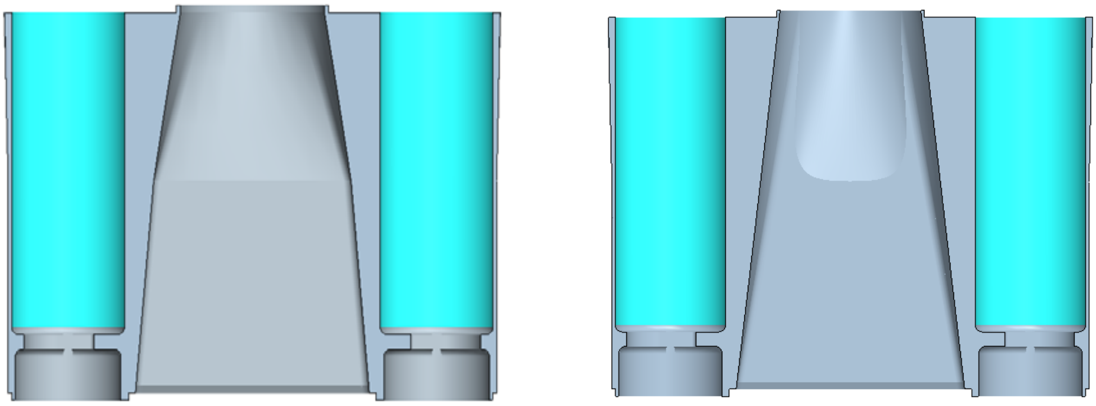

Figure 5 - Mercury Vessel Transition before (left) and after modification to allow center section to be machined complete with wire EDM

3. Target Module Manufacturing

3.1 Target Supply Requirements

The SNS target module, like all Spallation targets, is a consumable item. Lifetime is dictated by a wide range of parameters such as beam power, beam profile, target materials, and target construction. Initially, the lifetime of the SNS mercury target was to be limited by radiation damage to the 316L stainless steel through which the mercury flows. Based on available radiation damage data, a limit of 5 displacements per atom (DPA) was chosen as the limiting parameter for SNS targets. At the eventual 2 MW power level and with the nominal beam profile, 5 DPA is reached after ~1250 operating hours, or ¼ of a year. Therefore, 4 targets per operating year at 2 MW would be required.

When SNS first placed beam on target in 2006, 2 targets had been fabricated (one installed and one spare). Initial beam powers were in the low kW range, and the power ramp up to even 1 MW would take months. Therefore, one might assume that the initial need for additional targets was not strong.

However, experimental studies had shown that cavitation damage was a legitimate potentially life limiting mechanism. Cavitation occurs when each beam pulse causes high pressure gradients in the mercury, which lead to bubbles. When these bubbles form and collapse adjacent to the walls of the vessel, pitting can occur in the stainless steel. Unfortunately, there is no facility in the world that can replicate the beam intensity and rep rate of SNS. Target lifetime events were made based on largely extrapolated data, and there was fear that cavitation could end target life unacceptably soon.

Due to the large uncertainty of target lifetime and the lack of experimental options, SNS had little choice but to accept the possibility that initial targets could reach end of life due to cavitation damage. Target modules will preferably be replaced at scheduled maintenance periods as required based on radiation damage, but the risk of mid cycle change outs is accepted if a leak occurs.

3.2 Target Manufacturing

With only two targets at the start of operation and a usage rate of up to 4 per year, target manufacturing commenced soon after the SNS start-up. The first two targets were produced by a single source. The performance was widely recognized as very good. However, due to the critical need for target modules and the large cost, it was determined that multiple vendors should be able to reliably supply targets.

Three separate contracts were awarded for a total of 10 additional modules. A contract was placed with the initial vendor, as well as two others. The initial manufacturing and funding schedules were designed so that up to 4 targets per year would be available.

3.3 Target Consumption

As time passed, the worst case fear of eroded targets at low powers was not realized. Correspondingly, target manufacturing schedules have slowed so that funding matches the actual needs of the facility. In November 2008, after over 2 years of operation at low powers (up to ~650 KW); the first target was approaching the 5 DPA limit. Based on the most recent radiation damage data, SNS made the decision to raise the radiation damage limit to 10 DPA. This decision would provide more insight into cavitation affects at higher powers.

SNS is currently operating with 2 long maintenance periods per year, during which the accelerator is turned off. The maintenance periods are 6 to 8 weeks long. At the start of the summer 2009 maintenance period, the first target had reached a peak damage level of about 7.5 DPA. The maximum power on the first target was over 800 kW. If this target had been left in operation after the summer 2009 maintenance period, 10 DPA would have been surpassed before the winter 2009 maintenance period. Therefore, the first target was replaced with no indication of leak so that operations would not be interrupted to replace the target due to radiation damage [6].

The second target operated through the fall 2009 run cycle and is currently operating in the winter/spring 2010 cycle. It has reached a damage level of ~3.5 DPA. If the accelerator operates near its planned reliability and power level (above 1 MW), the second target will be replaced during the summer 2010 maintenance period.

4. Current and Future Plans

4.1 Target Design

4.1.1 Water Cooled Shroud

As discussed above, design changes have been made to thin the interstitial gap and the water shroud inner window. These solutions address the steady state case of mercury filling the interstitial. However, if leak detection can be improved, this load case becomes less relevant because there is more confidence that the beam will be shut down before mercury fills the interstitial.

Therefore, design studies are underway to add more leak detection. The current method under investigation is the use of a burst disk on the interstitial. The burst disk acts as a simple go/no-go type of pressure gauge. As the pressure in the interstitial rises due to the leaking mercury, the disk bursts and provides indication of a leak.

4.1.2 Mercury Vessel

Samples from the nose of the first target have been obtained. Figure 6 shows a sample of the mercury vessel inner window. Cavitation damage has eroded through the window separating the mercury bulk flow and the window flow. The damage is heavily biased in the quasi stagnation point in the center of the module where the two side bulk flows meet. The preliminary conclusion is that damage in other regions was mitigated by one directional flow across the surfaces. Therefore, SNS in currently investigating ways to move the stagnation point away from the peak beam intensity location. This could be accomplished adjusting the flow orifices upstream of the two bulk supplies so that one side has a stronger flow. Other options are to connect one of the supplies to the return line so that it becomes a return, or to add an additional baffle which would direct flow across the front window. All of these options require further thermohydraulic and structural analysis.

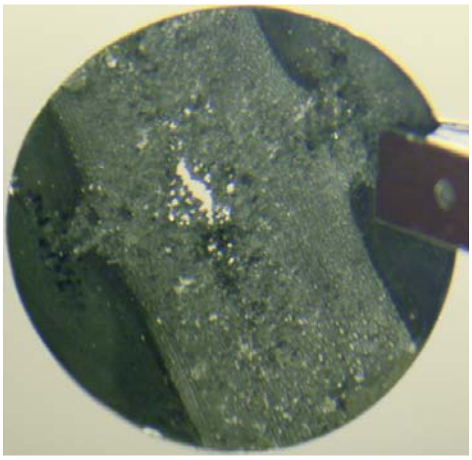
Figure 6 - Cavitation Damage to Inner Window of Mercury Vessel

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