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REMOTE HANDLING REPLACEMENT OF MERCURY TARGET AND PROTON BEAM WINDOW AT SNS

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ABSTRACT

After several years of operation, radiation-induced material degradation has necessitated replacement of the initially-installed mercury target and proton beam window modules at SNS. Due to the hazardous nature of these operations, replacement of both modules was performed entirely using remote handling methods. Replacement of the target module was carried out in a hot cell environment utilizing a combination of through-the-wall manipulators and a bridge-mounted servo-manipulator. Proton beam window replacement was accomplished in a high bay environment using casks and specially-designed long-handled tooling to mitigate personnel exposure. The details of these replacement operations will be discussed along with the specialized tooling developed to facilitate remote handling. Dose rates and contamination levels encountered during the replacement activities will be outlined. Lessons learned from the replacement operations will also be discussed.

1. Mercury Target Module Replacement

1.1. First SNS Target Replacement

The replacement of the Spallation Neutron Source (SNS) mercury target module was successfully completed during a scheduled maintenance outage in August 2009. The target module had been installed since facility start-up and had received over 3000 megawatt-hours of accumulated energy resulting in dpa damage levels necessitating replacement. Replacement of the target module was accomplished completely using remote handling tooling and procedures as hands-on operations are precluded due to the high radiation environment and mercury contamination of target module components. While the tooling and procedures utilized enabled a successful replacement, several design and operational concerns were revealed during the process.

1.2. Target Module Description

The SNS mercury target module is a component in the target system mercury process loop designed to be replaced on a periodic basis due to radiation-induced material damage or other end-of-life criteria. The mercury process loop contains 1.4 cubic meters of mercury flowing at 16 liters/second. A 2" all-metal dump valve drains mercury to a shielded storage tank during target replacement operations. The target module is mechanically connected to the Target Carriage. The Target Carriage provides the mercury supply, coolant water supply, helium, vacuum, instrumentation and other utilities required for system operation. The Target Carriage also provides the means to move the target module into and out of the Core Vessel. Figure 1 depicts the target module mounted to forward end of the Target Carriage.

Figure 1: Target Module Installed onto Target Carriage

1.3. Target Replacement Environment

Replacement of the target module is fully accomplished within the Target Service Bay (TSB). The TSB provides enclosure of the mercury process equipment as well as systems and tools for the maintenance of the process equipment (including the target modules) and processing and disposal of spent equipment. The TSB is designed for fully remote operations.

An array of sophisticated, remotely-operable equipment is deployed within the cell with a bridge-mounted servo-manipulator as the key element. The servo-manipulator is a Telerob EMSM 2B unit featuring a dual arm arrangement providing full cell coverage on a four degree-of-freedom bridge and boom system (see Figure 2). The servo-manipulator features master arm position control with force feedback. Remote operation of the servo-manipulator is aided by three on-board CCTV cameras.

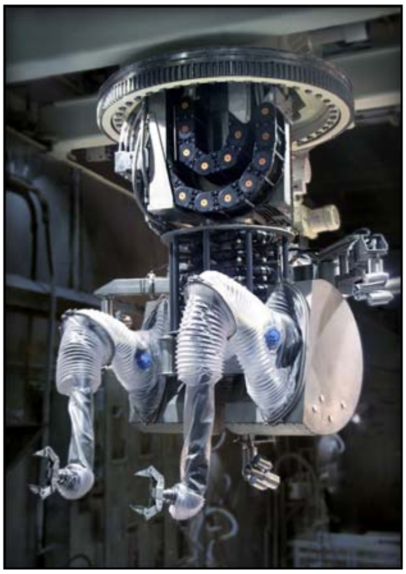

Figure 2: Telerob Servo-Manipulator

Additionally, three master-slave manipulators are located in a manipulator gallery adjacent to the TSB. These manipulators can be used to perform operations such as bolt torquing, tool transport, inspections and precision operations.

1.4. Radiation Environment

During beam-on operations, mercury process equipment can achieve contact radiation levels of approximately 400 gray/hr. Ion chambers placed in the TSB on mercury process equipment provide dose rate information. Steel shielding inside the TSB surrounds components of the mercury process equipment to reduce background radiation to approximately 2 gray/hr.

During maintenance operations mercury is drained from process lines to facilitate component replacement. Residual contamination in these lines results in elevated dose rate levels even after draining of the mercury. An ion chamber mounted directly to a 15.25

cm mercury return line indicated contact radiation levels of 3-5 gray/hr following draining of the mercury.

Irradiation of the nose of the target module is of particular interest as it directly receives the proton beam and a high level of neutrons. Contact dose levels are a function of the beam power delivered prior to shut-down. Beam power prior to target replacement had been in the 400 kW range for weeks preceeding the shutdown. This beam power resulted in dose rates of approximately 14 gray/hr measured 1.1 meters from the target six days after shutdown. Full power targets (2 MW operation) are expected to be approximately 70 gray/hr at 1.1 meters. Further measurements of target nose dose levels made four months after shutdown revealed contact dose rates of about 11 gray/hr at the center of the nose (point of maximum beam intensity) with 6.5 gray/hr seen slightly off-center.

1.5. Contamination Environment

Experience has shown that the isotopic particulate contamination is long-lived and widespread in the Service Bay. At the end of the first target replacement operations, the cell background away from the process area had risen from essentially clean (10,000 disintegrations/minute) to significant levels of contamination. Contamination has also migrated to the Transfer Bay adjacent to the Service Bay due to in-cell ventilation systems and movement of the in-cell crane and servo-manipulator into the Transfer Bay as a part of normal operations. Localized surveys of crane and servo-manipulator components yielded 3,000,000 dpm smears during the target replacement operation.

1.6. Mercury Vapor Environment

Opening of mercury process lines during target replacement results in an expected increase in mercury vapor in the Service Bay. Once exposed to the atmosphere, the mercury forms an oxide layer that greatly inhibits vaporization until disturbed by vibration or movement. As a result, spikes in Service Bay mercury vapors levels occur during portions of the replacement operation involving movement of the Target Carriage or spent target. Opening of the mercury process lines and retraction of the Target Carriage occurred on 7/17 and 7/18/2009. Subsequent spikes in vapor levels reflect Target Carriage insertion and leak testing activities (see Figure 3).

The presence of mercury vapors throughout the Service Bay also manifests itself in the form of droplets of condensation on Service Bay components. Several instances of coalesced mercury droplets were visibly observed on horizontal surfaces of components not physically located near portions of the mercury process system opened during target replacement operations. This phenomenon indicates widespread mercury contamination in all areas of the Service Bay.

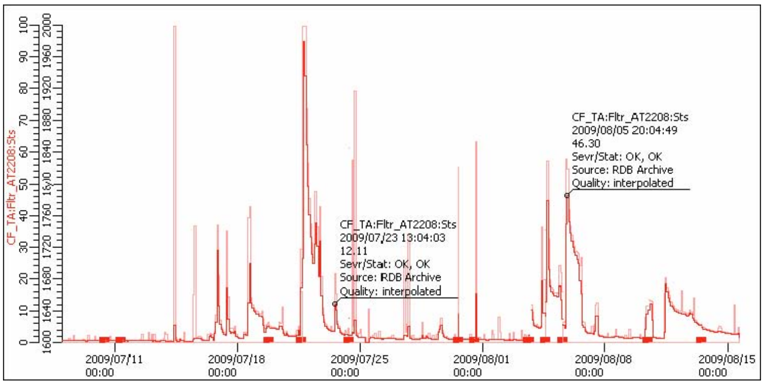

Figure 3: Mercury Level Spikes Observed During Target Change

1.7. Target Replacement Operations

Replacement of the target module is a complex process involving the remote handling of shielding, jumpers and seals in addition to the target itself. The following components are removed and installed during each target change:

- Four pieces of in-cell shielding (12,700 kg of steel)
- Nine process and utility jumpers at the back of the Target Carriage
- Two 2" and two 6" water coolant and mercury process lines
- Seven process and utility jumpers between the Target Carriage and Target Module
- One spent and one new target module (eight 1" tie-down bolts)

Additional operations include movement of the 91,000 kg Target Carriage over a distance of 9 meters and the capture and release of liquid mercury from open process piping. Replacement of the target progressed essentially according to plan with only minor issues and delays. Extensive tooling, procedural development and cold mock up testing efforts enabled target replacement in approximately 90 hours.

Initial reluctance to introduce complexity (and associated risk) into the process drove early decisions to forego redundancy and intermediate testing steps during the replacement operations. Although no in-process testing was planned during the target change, a vacuum was applied to the mercury process loop as a preliminary indication of system integrity. During this test, a susbtantial leak was discovered.

1.8. Target Replacement Issues

Identification of the source of the leak in the mercury process loop proved to be challenging. Due to the fact that the target module is installed onto the target cart and then inserted 9 meters into the Core Vessel shielding, only three of the five mercury process loop connections affected during target replacement are accessible with the Carriage inserted. Retraction of the Carriage to access the remaining connections requires disconnection of the two 6" mercury supply and return lines which then precludes the vacuum test which initially identified the leak due to the now open loop. Identification of the leak point involved isolating the target carriage portion of the mercury loop and then pressurizing the loop to enable leak detection activities. Test fixtures and procedures were developed real-time to develop a method of leak detection. The source of the leak was found to be a Hiltap fitting on one end of the mercury vent jumper that connects the Target Carriage to the Target module. The leak was eliminated by simply re-torquing the fitting.

While the correction of the leak proved to be simple, approximately three weeks of effort was required to develop the capability to identify the source of the leak. Many of the tools and procedures developed during that period will be used in future target replacements.

An additional issue was revealed during the replacement operation. When the Target Carriage is inserted into the Core Vessel it is spring-loaded in the operating position to accommodate thermal expansion and seismic events. To obtain this preload, brake pins are inserted at the aft end of the Carriage and then heavily-preloaded springs act against the brake pins.

In order to retract the brake pins to initiate retraction of the Target Carriage, the preload on the springs must be relieved. During remote operations it was very difficult for the technicians to accurately assess the point at which the preload had been removed prior to initiating retraction of the pins. The initial pin retraction attempt resulted in deformation of the structure that applies the pin retraction force.

The mechanism remains functional but the damage has resulted in further difficulties in ensuring proper pin engagement. This issue highlights the need to design remotely-operated mechanisms in such a way to ensure robustness and mitigate the judgment required by the technicians for successful operation.

1.9. Target Replacement Summary

The first SNS target module was successfully replaced during a planned 45-day facility maintenance period. Planned target replacement operations were accomplished within the design goal period, however unplanned events caused significant delays and highlighted areas in which the tooling, process components and remote operations can be improved.

2. Proton Beam Window Replacement

2.1. First SNS Proton Beam Window Replacement

The first replacement of the Proton Beam Window(PBW) was successfully completed in August 2009 during the planned maintenance shutdown period. This initially-installed window had received just over 3000 megawatt-hours of accumulated energy resulting in an approximate dpa level of 6.5. The new PBW incorporated the optics portion of the Target Imaging System enabling viewing of the coated Target Module along with additional halo thermocouples to aid in beam centering. Following installation, Core Vessel and Ring to Target Beam Transfer(RTBT) flight tube vacuum leak testing indicated excellent PBW inflatable seal function. Figure 4 shows the new Proton Beam Window Module prior to installation.

Figure 4: Proton Beam Window Module

2.2. Proton Beam Window Description

The PBW forms the barrier between the high vacuum of the accelerator beam flight tube and the slightly negative pressure helium atmosphere of the Core Vessel environment. Sealing between these two interfaces is accomplished with a pair of opposing inflatable seals. The PBW assembly is approximately 5.6 meters tall and weighs approximately 2975 kg. Utilities to the PBW include water for window cooling, helium for inflatable seal inflation and vacuum to evacuate the interstitial volume of the inflatable seal.

2.3. Proton Beam Window Replacement Environment

The PBW installed approximately 2.3 meters upstream of the target module and is accessed from above in a high bay area above the Target Monolith. The PBW is installed approximately 6 meters down into a cavity below five shield blocks designed to provide biological protection.

The upper two shield blocks can be accessed and removed hand-on. Removing these two upper shield blocks reveals the PBW jumper cavity where utility connections are made. The shield blocks below this level are activated to a level that require the use of shielded storage casks for removal.

2.4. Proton Beam Window Replacement Operations

Replacement of the PBW involves the following basic operations:

- Removal of five shield blocks (41,000 kg of steel shielding)
- Drying (cooling water removal) of PBW module
- Cutting and removal of activated utility piping
- Withdrawal of spent PBW module from cavity
- Installation of new PBW module
- Connection of utility piping
- Leak testing of inflatable seals and piping connections
- Re-installation of shield blocks

The installed location of the PBW requires relatively long utility piping (see Figure 5). Disposal of the PBW requires removal of this utility piping to reduce the overall package size for shipment. Removal of this utility piping during replacement operations therefore requires the use of a variety of long-handled cutting tools to sever the piping at the lowest point possible.

The inflatable seals are pressurized with helium to expand and press against opposing surfaces of the Proton Beam Window Box. Due to the short operational stroke of the seals, the nominal clearances on either side of the PBW during installation and removal are small (less than 4 mm). This small amount of clearance coupled with the need to prevent damage to the critical sealing surfaces requires additional precautions be taken during installation and removal. To ensure that the maximum clearance possible is achieved during installation and removal, a vacuum is applied to the inflatable seals to ensure full retraction. This vacuum is applied through the line typically used to pressurized the seals with helium.

Figure 5: PBW Hoisted for Installation

Since the helium line has already been severed along with the remainder of the utility piping in preparation for removal, a method of remotely attaching a vacuum line to this severed 3/8" line was devised. Following installation of this vacuum line onto the helium tubing, the seals can be retracted during removal of the PBW. Figure 6 shows the flexible vacuum line installed onto the severed tubing in preparation for PBW removal. During installation of the new PBW module, the process is simplified by simply applying a vacuum to inflatable seal helium supply line.

Due to the activation levels of the module, the PBW is removed into a lead-shielded cask (approximately 25,000 kg of shielding). A special pneumatically-operated chain hoist that utilizes a remotely-operable grapple fixture is used to withdraw the activated PBW into the shielded cask. A lead-filled door in the bottom of the cask reduces the shine from the bottom of the cask during handling operations.

Figure 6: Flexible Vacuum Lines Installed onto PBW Module Prior to Removal

Figure 7 shows the PBW Cask in position over the cavity with the pneumatically-operated hoist (yellow structure) mounted to the cask. Following removal of the spent module, the cavity is inspected to ensure the sealing surfaces have not been damaged. This inspection is accomplished using a radiation-hardened camera mounted onto a long-handled tool. The tool provides tilt and pan capabilities for the camera with focus being controlled using the camera control box.

Installation of the new PBW module is accomplished in essentially the reverse manner as removal. An installation Guide Can is utilized to ensure proper alignment and orientation of the PBW as it is positioned into the PBW Box.

Figure 7: PBW Cask in Position for PBW Removal

Following installation, shield blocks are reinstalled and utility connections made. Once helium and vacuum are restored to the inflatable seals, testing is performed on both the RTBT and Core Vessel interfaces to ensure acceptable leak rates.

2.5. PBW Replacement Radiological Environment

Radiological surveys were done during every aspect of the removal operation. Dose rate measurements and contamination smears were made on each shield block during removal and a dose rate on the PBW module itself was obtained during removal. Due to the nature of the tooling installation, an unshielded path to the module itself was available. The location of the path was not a hazard for technicians, but did enable an unshielded dose rate of the activated PBW to be obtained.

Removal of the PBW utility jumpers was performed "hands on" following radiological surveys indicating minimal activation. The maximum dose rate recorded (2 mrem/hr) was found on an elbow of one of the coolant water pipes. External contamination was not found, however internal contamination of the water piping was found to be 30,000 dpm/100cm^2 Beta and 150,000 dpm/100cm^2 Gamma. 17,000 dpm H3 was found in two small drops of coolant water. Figure 8 outlines dose rates and contamination levels observed during shielding removal.

Item	Dose Rates (1)	Contamination
PBW Top Block	Neglible	None
Shield Block 6	Neglible	None
Shield Block 5	.1 - .2 mR/hr	None
Shield Block 4	1.5 mR/hr	21,000 dpm
Shield Block 3	210 mR/hr	150,000 dpm
Utility Piping	~ 150 mR/hr	None (4)
PBW Module	50 R/hr (2)	(3)
Notes:		
1. Contact dose rates unless otherwise specified.		
2. Dose rate at approximately 4 ft - unshielded.		
3. No measurement taken.		
4. No external contamination.		

Figure 8: PBW Removal Radiological Conditions

2.6. Summary

The first PBW module was successfully replaced along with the target module during a planned maintenance outage. Extensive mock up testing prior to replacement operations enabled a nominal replacement operation with no significant issues identified. Innovative development of remote tooling provided the ability to sever piping, retract seals and remove the PBW module fully remotely. Performance of the inflatable seals, the optics of the Target Imaging System and the halo thermocouples has been exemplary.