SNS Target Test Facility: Prototype Hg Operations and Remote Handling Tests

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ABSTRACT - *The Spallation Neutron Source, Target Test Facility is a full-scale replica of the mercury-target flow loop and the target hot cell, used to study flow the characteristics of a large scale mercury system, and develop remote handling techniques and tools for replacing target system components. During the past year, prototypic equipment was added to the loop to simulate actual flow conditions and to compare empirical and analytical data. These included a welded-tube heat exchanger, an electromagnetic flow meter, a hydraulically prototypic target, and numerous pressure sensors. Outside of the loop enclosure, tests were done on a new seal configuration to assess leak tightness and remote handling features. In addition, testing of remotely operated tools and lift fixtures, remote replacement of utility pipes, and remote handling of the target module were performed.*

I. INTRODUCTION

The Target Test Facility (TTF) is a full-scale replica of the Spallation Neutron Source (SNS) target station.[1] It is being used to investigate and assess the thermal-hydraulic characteristics of the mercury-target flow loop, gain experience operating the full-size mercury system, and develop and demonstrate remote-handling operations on key target system components. The TTF contains 1400 liters of mercury for flow testing and has a containment enclosure to meet environmental, safety, and health requirements. The enclosure was designed to match the size of the actual SNS target cell. Figure 1 is a photo of the TTF enclosure and target assembly installed in a high bay test facility at Oak Ridge National Laboratory (ORNL).

Figure 1. Target Test Facility.

II. FLOW TESTS

The Target Test Facility (TTF) provides a full-scale test bed for confirmatory hydraulic tests using Hg as the working fluid. Because of the very high energy deposition rates in the SNS target, it is important to understand the thermal hydraulic characteristics in the Hg flow region of the target. A target test assembly with prototypic internal geometry for the main (bulk) Hg flow in the SNS target, as shown in Figure 1, has been tested in the TTF. Pressure, flow and velocity distribution measurements have been made over a range of flows including the nominal SNS target flow rate of 380 gpm. The feed and return pipes in this assembly included two 90º miter bends as part of the seal design geometry at the target replacement interface. The feed pipe miter bends were found to cause significant Hg cavitation problems at the nominal flow rate. Problems with cavitation include high-pressure oscillations and potential erosion of the piping. An SNS design change was made to replace the 90º sections with 45º elbows, and larger diameter piping in this region. These changes were recently incorporated and tested in the TTF and were shown to eliminate the cavitation. Testing of target thermal hydraulics with the new configuration is now in progress.

II.1. EM Flow Meter

An electromagnetic (EM) flow meter supplied by the European Spallation Source Program was tested in the TTF. Figure 2 shows the flow meter mounted on one of the supply pipes. It is a commercial product of the type used on sodium cooled reactors and consists of a saddle-shaped permanent magnet that mounts over the flow pipe. Liquid metal that passes though the pipe produces a voltage that is measured with electrical terminals attached to the pipe. The flow meter was mounted on one of the 4-inch bulk feed lines; the electrical terminals consist of studs welded to the pipe wall.

In this configuration the output voltage at nominal flow rates of 178 gpm was only 12 microvolts, significantly less than the 6 millivolts (mV) expected. Poor electrical conductivity between the flowing Hg and pipe wall, along with the current-shorting effect of the pipe wall between the 2 electrical terminals, was suspected to be the problem. To test this hypothesis the flow meter was configured with electrically insulated stainless steel electrodes in direct contact with the Hg. In this case the voltage output was in good agreement with the theoretical voltage, with a nominal flow rate producing 5.9 mV. Data was collected over a range of flow and the output was shown to be linear, repeatable, and steady, and showed good tolerance to flow turbulence.

Figure 2. EM flow meter installed on a 4-inch supply line.

Because of concerns regarding the long-term reliability of electrically insulated electrodes in the SNS loop, uninsulated SST electrodes with machined surfaces (to remove chromium oxide layers) were tested. In this case a nominal flow rate produced an output voltage of 1.2 mV, orders of magnitude better than the initial configuration, and potentially satisfactory. However, the output voltage with uninsulated electrodes was shown to be unsteady with fluctuations of 5% or greater. This is likely due to small, micro-ohm level variations in the Hg-to-electrode contact resistance. The flow meter configured with insulated electrodes remains installed on the supply line to test its long term performance and stability. Acceptable methods of using insulated electrodes in SNS are being investigated. The current baseline design uses flow venturis.

II.2. Heat Exchanger

A heat exchanger was added to the flow loop to remove heat added by the main circulation pump and test performance of the SNS system design. The TTF heat exchanger is smaller than the SNS system with 19 tubes instead of 330, but is prototypic in most respects. It uses double-wall tubes and tube sheets to provide a double barrier between the Hg and coolant medium (water), and the tube diameter and flow velocities are equivalent. Based on projections of the double-wall tube heat transfer efficiency, the nominal heat transfer rate of the TTF system is 55 kBTU/hr (16.1 kW). The actual heat transfer rate was found to be 15.8 kW, 98% of design. In this test, the interstitial space between the tubes was filled with atmospheric-pressure air. The system was also tested with the interstitial volume at 100 psig He gas which is the SNS system's baseline gas and pressure. This improved the heat transfer rate to 17.1 kW, an 8% improvement. The heat transfer rate with the interstitial space at vacuum (0.1 torr) was also tested and found to be 14.4 kW, a 9% reduction. Table I summarizes the results of the heat exchanger tests.

Table I. Heat Exchanger Test Results

Interstitial Space	Pressure (psig)	Heat Transfer Rate (kW)	Design (% of 16.1 kW)
Air	0	15.8	98
He (baseline)	100	17.1	106
Vacuum	0.1 torr	14.4	89

III. REMOTE HANDLING TESTS

A pair of Central Research Laboratory (CRL) Model F manipulators mounted to a movable platform is the basis for remote-handling tests.[2] The platform includes a simulated 1-m thick shield window and target cell wall for remote maintenance tests. The tests are being done to ensure that the design of key components in the target cell can be remotely handled.

A number of remote handling tests with small tools and pipe connectors have already been completed.[3] These tests focused primarily on manipulator handling of hydraulic and air-driven tools, use of the tools on components in the target cell, cable management, and preliminary remote viewing studies with wall-mounted cameras.

III.1. Cutting Tools

Remotely operated cutting tools are being developed for target cell operations. A commercial hydraulic shear is being modified for cutting the proton beam window coolant lines, and a rebar cutter is being modified for cutting 2-inch water pipes. A water-hydraulic pump will be used to power the shear tool.

The fluid for the hydraulic pump is pure water with only trace amounts of a biocide. Initial tests of the system revealed the necessity for adding the biocide. When the pump was initially placed into service it was filled with tap water and within two months, the tap water was fouled. A quarterly water change and addition of the biocide eliminated the problem.

The pump, fabricated by Marshalsea Hydraulics Ltd, is commercially available and specifically designed for water-hydraulic use. The hydraulic power supply will provide pressure at either 5000 or 3000 psig, with a maximum flow rate of 3.75 gpm.

The hydraulic shear is a Mega-Tech CC1.5 which has been adapted to a long handled tool. The lines to be cut with the shear are at the bottom of a pit. The operation involves lowering the tool to the bottom of the pit using a crane. The operator maneuvers the tool into cutting position by means of a T-handle on the tool support pole. The tool remains supported by the crane during the entire cutting operation. The shear is intended for cutting the proton beam window module service lines. These are thin-walled stainless steel tubes up to 1.5-inches OD, plus a conduit containing 50 signal wires. The operating pressure for the shear is 5000 psig and modifications will not be made to the tool for operating with water as the hydraulic fluid.

The rebar cutter will be used for cutting tubing and small pipes. It is a Multiquip HBC-19N which has been modified into a long handled tool. The cutter is electrically powered with 110-volt AC power. The operational procedure is similar to that of the hydraulic shear. The crane is used to lower the tool into a pit area, and maneuvered into cutting position by the operator. Test fixtures to demonstrate both of these operations are being fabricated.

III.2. Connector Testing

In its current configuration, the SNS replaceable target incorporates a water cooling shroud and an inflatable seal. Several utility lines are connected to the target module through removable, rigid tubing jumpers. These jumpers provide water supply and return, target vacuum, helium supply and vacuum, and Hg vapor venting functions. To facilitate the remote handling of these six jumpers, piping connectors manufactured by Hiltap, Inc. were chosen because of their provision of double seals, their compact size, and their ability to be reused. Hiltap modified their standard connector with features to facilitate remote handling operations. The connectors can be loosened and tightened by mechanical master-slave manipulators using a manual, click-type torque wrench. Sealing ability of the connectors has been tested using various ferrule materials, including SS 316, Al 6061-T6, and Ni 201; leak rates of 10^{-5} atm-cc He/sec have been observed. Figure 3 is a photo of the test stand for the Hiltap connectors.

III.3. Metal-Cutting Tests

The target modules used in SNS are currently designed to be replaced every three months. Because of the expected high fabrication and disposal costs, any reduction in the frequency of target replacements would be very cost-effective for SNS Operations. The primary reason for changing the target is structural degradation of the stainless steel shroud caused by the 60 Hz proton beam. A Target Surveillance Program is being planned whereby material samples extracted from the first few spent targets will be analyzed to determine the metallurgical damage caused by the proton beam. The samples will be extracted from the nose, side, and top of the target module, which is shown in Figure 4. The target module is comprised of multiple layers of SS 316 sheet steel 0.060-inch and 0.120-inch that create flow paths for the mercury and water. Each layer would be extracted and analyzed separately.

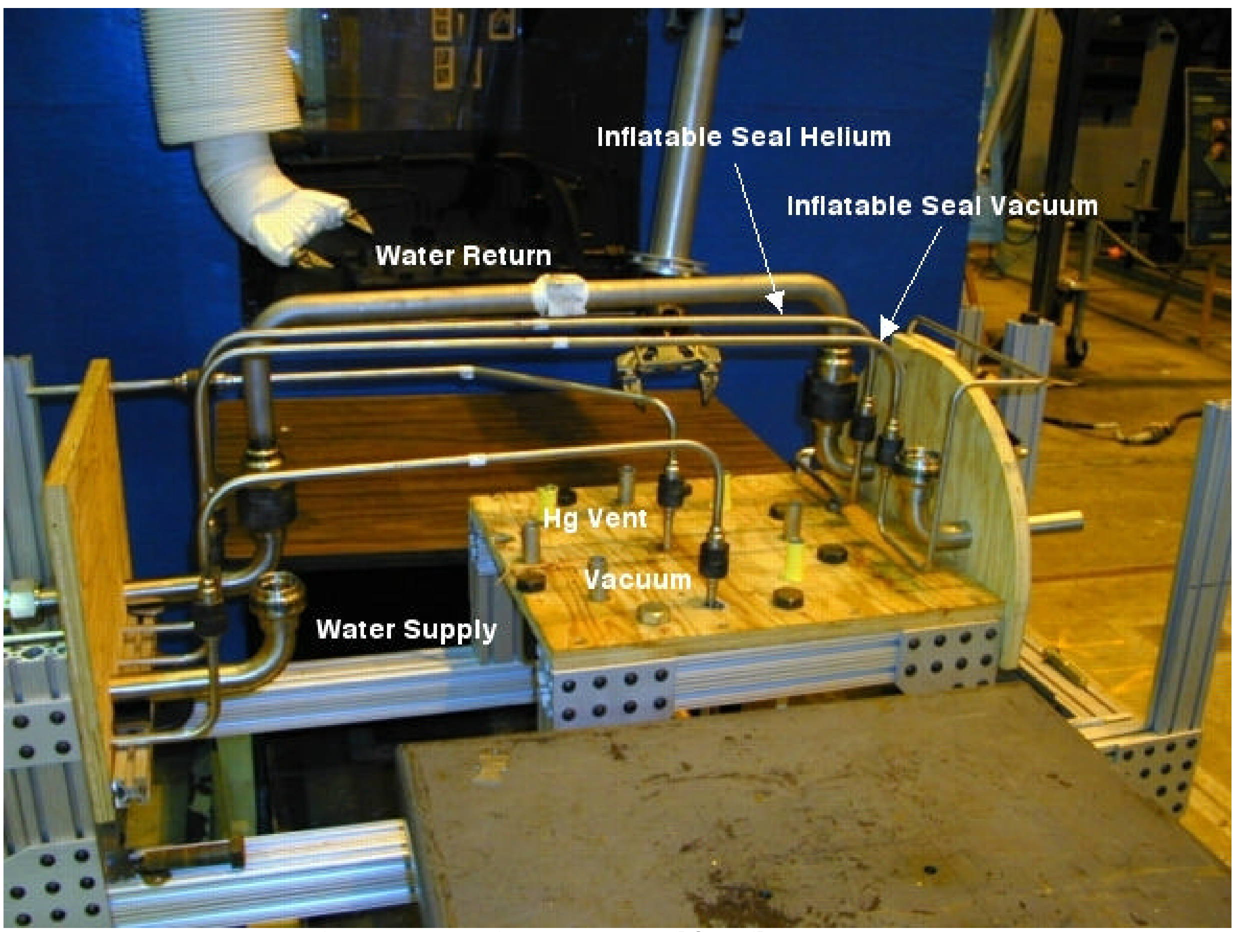

Figure 3. Target jumper test stand for Hiltap connectors.

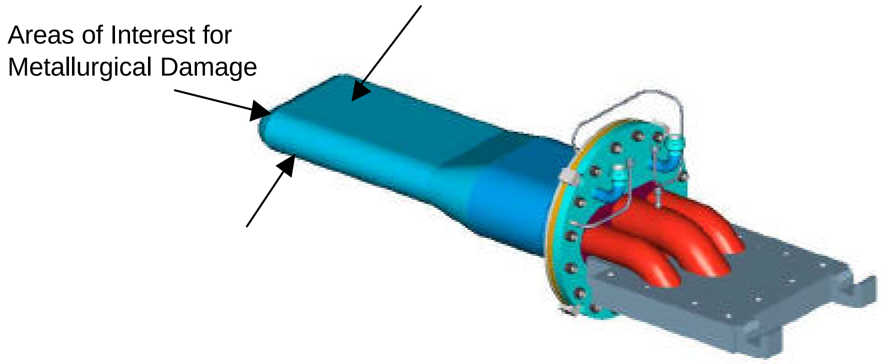

Figure 4. Target module assembly.

Because the spent targets will be activated to mega-rad levels, all cutting operations must be performed in the SNS Target Cell using remotely operated tools. Various methods of cutting the targets and extracting metallurgical samples are under consideration. These include conventional machining operations such as shearing, sawing, and milling, as well as non-mechanical cutting methods such as plasma arc and laser cutting. Debris-generation and containment are being considered, in addition to how conducive the method is to remote handling operations.

Other components in the Target Cell that will be replaced will also need to be cut up to fit into appropriate waste containers. Methods that may not be applicable for target sampling operations may still be preferred for general cutting within the cell. Preliminary tests for several methods are underway and those that show promise will be further tested for cutting efficacy and any necessary remote handling characteristics will be developed.

IV. TARGET SEAL TESTING

The target seal interface was redesigned to be horizontal, and the seals were configured to be small circular diameters.[3] The tests for the new design included assessing bolt-torque values and leak testing using nitrogen gas pressurization and helium leakage tests. Figure 5 is a photo of the fixture for these tests.

IV.1. Bolt Load Tests

The purpose of the tests was to correlate bolt torque to bolt tension using unlubricated, instrumented 3/4-inch and 1-inch diameter bolts, and to investigate the pressure distribution on the top and bottom of the seal plate using pressure-sensitive film. The film that was used had a sensitivity range of 10-50 Mpa (1400–7000 psi).

For the initial test, eight 3/4-inch (inner) bolts were loaded to 500 ft-lbs which corresponded to approximately 30,000 lbs of bolt tension. (It was previously estimated that 450 ft-lbs would develop 34,000 lbs.) The test data showed that actual friction was greater than originally estimated. The washers under the bolt heads showed significant compression and galling, and the seal plate surface under the washers was also galled. Grade 8 washers were installed and found to significantly reduce friction and eliminate galling. Testing continued using pressure sensitive film mounted underneath and above the seal plate. Twenty-four 3/4-inch (outer) bolts were torqued to 500 ft-lbs in the proper sequence before the top target plate was mounted.

Eight 1-inch diameter bolts were installed and torqued according to procedure. It was originally estimated that about 950 ft-lbs would achieve the desired bolt load of 57,000 lbs. However, it was noted that at 900 ft-lbs of torque the bolt loads ranged from 37,000 lbs to 24,000 lbs. The test was stopped since it appeared that friction under the bolt heads and in the threads was becoming excessive. The friction factor was calculated to be 0.32, and since these bolts are 18.25-inches long, they would simply twist without adding to the bolt tension.

Figure 6 is a photo of the pressure-sensitive film used to measure the clamping stress between the plates. The film on the top surface of the plate shows a pressure distribution pattern that is not uniform around the outer 1-inch bolt pattern, or on the inner surface of the plate-to-plate interface. The 1-inch bolts could not develop the 57,000 lb design load.

Figure 7 shows the film that was mounted under the seal plate. The intensity of the pressure was higher than that of Figure 6, and there was more distribution of plate stress, but the stress was lower than what was expected.

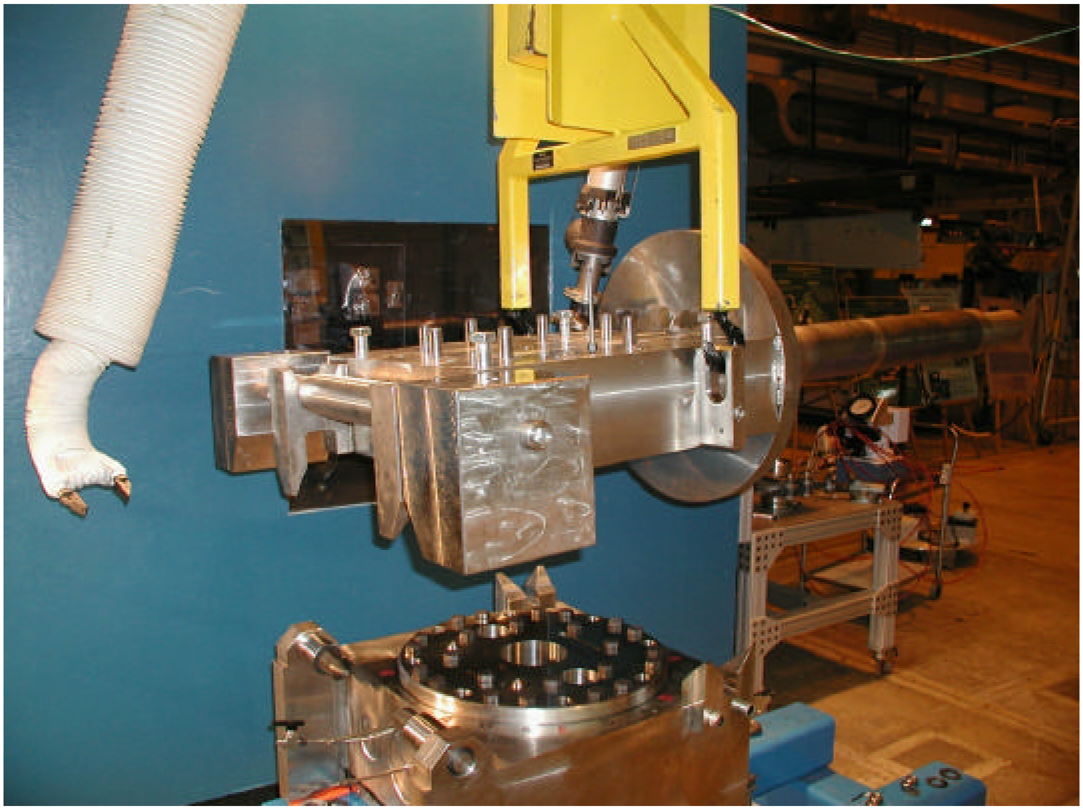

Figure 5. Test fixture for the modified target seal design.

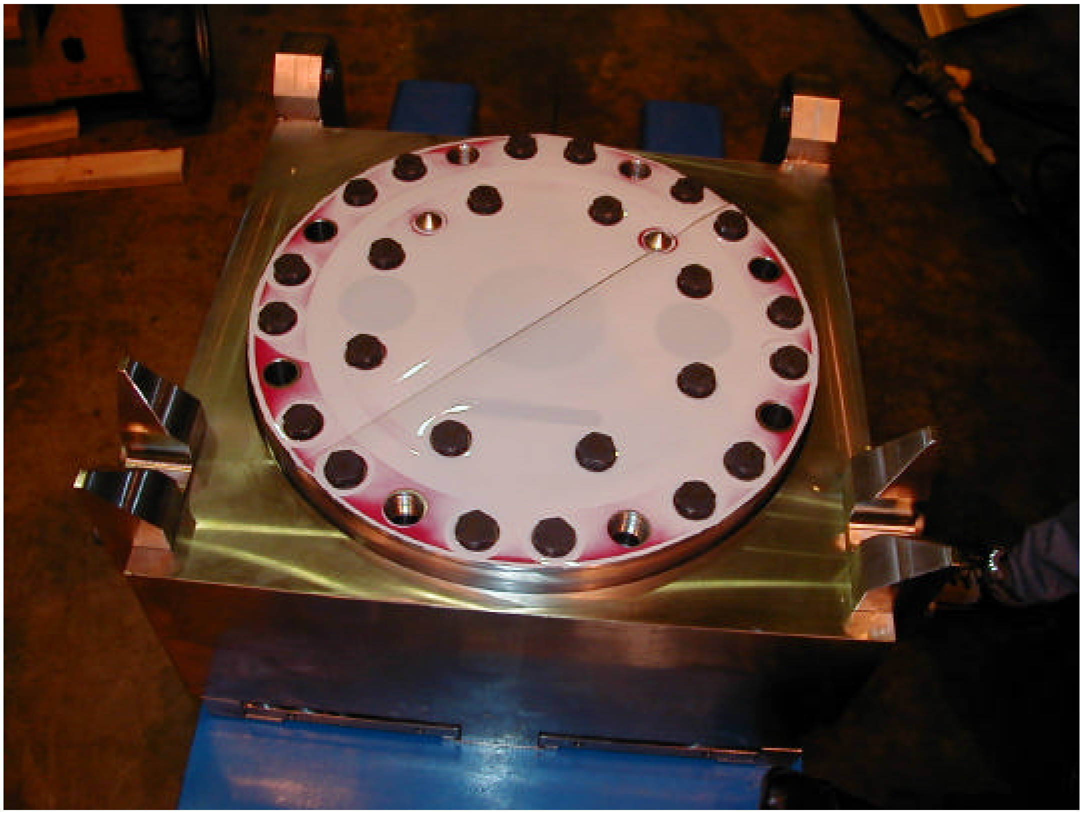

Figure 6. Pressure sensitive film stress distribution on the top seal plate.

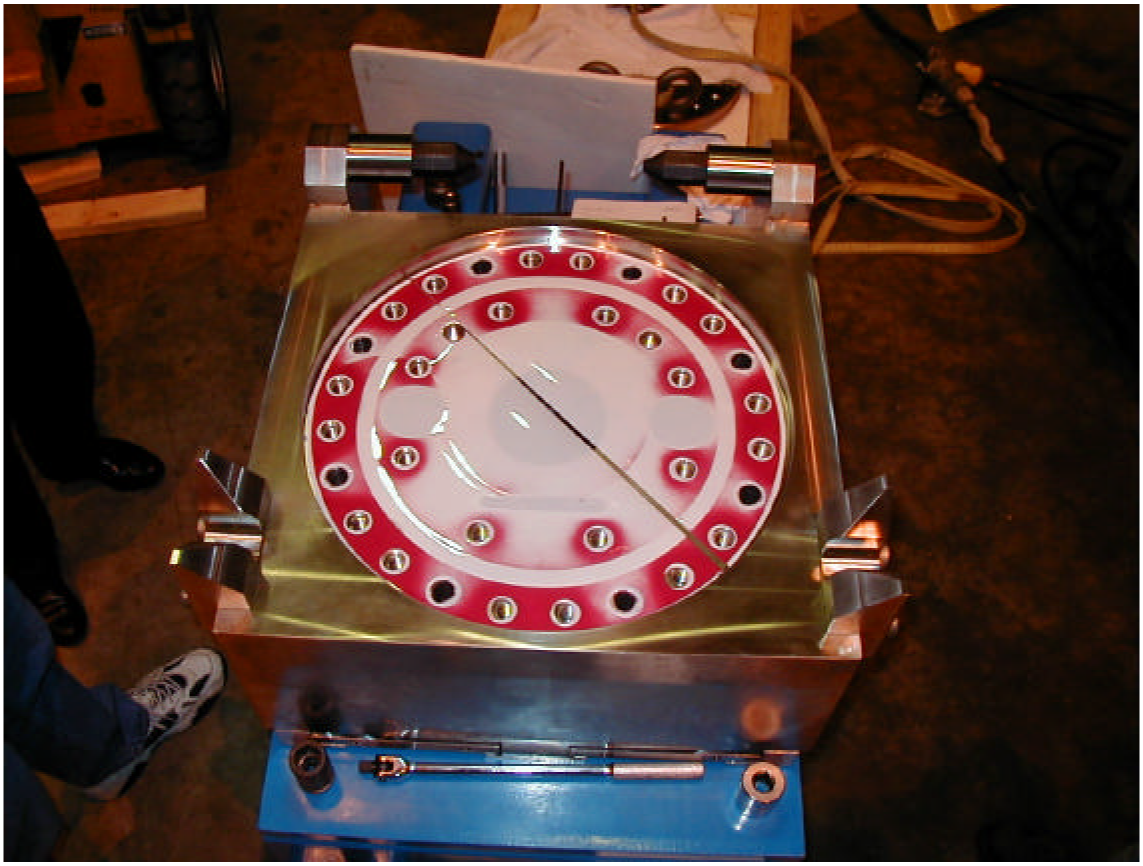

Figure 7. Pressure sensitive film stress distribution on the bottom seal plate.

IV.2. Time Trials

A series of target handling tests were done to determine the time required to remotely install and remove a target module. The test demonstrated remote operations using an end-effector tool (a standard socket torque wrench was used for this test), lifting and positioning with the crane hook fixture, and operator viewing through the mock up shield window. Figure 5 shows the assembled target module in near-perfect balance under the lift fixture. The target is being lowered onto the base plate; the alignment-guide features will position the target to precisely engage two alignment pins. Installing the target took 110 minutes; removal took 22 minutes. If higher bolt torque is needed, it is likely that the installation will take longer because of the use of a hydraulic torque wrench that will add 1-3 minutes per bolt.

IV.3. Torque Wrench Tests

Additional remote handling tests were performed using the Sweeney RSL2 hydraulic torque wrench capable of developing 1400 ft-lbs. Testing was done with the master-slave manipulator to remotely position the wrench onto each of the target fasteners. This differed from previous tests because the hydraulic umbilical lines that came with the tool were replaced with smaller, 5/32-inch ID lines, and swivel connectors were added to the wrench head to increase flexibility of the lines and make them less of a hindrance during target replacement operations.

The smaller diameter lines were beneficial to remote operations and did not affect the mechanical/hydraulic performance of the wrench. They are more flexible than the original 3/8-inch lines, and the decreased weight of hydraulic fluid was noticeable for remotely handling the tool. There was no performance difference due to the smaller diameter lines. The smaller, more flexible lines will be used for all hydraulic tools unless other requirements prevail. Figure 8 shows the hydraulic torque wrench fitted with smaller lines.

The hydraulic swivel connectors did not enhance remote operations, and in some instances hindered cable management. Since the swivels are rated for 10,000 psi, they were too stiff to rotate as the tool was moved to new positions. The operator had to remotely move the swivels thereby increasing operation time, and in some orientations the swivels obstructed use of the tool. The swivels did not provide any benefit for remote operations and will not be used.

Prior to these tests, it was believed that attaching the hydraulic lines to an overhead support to keep the hoses pointing upward, suspended off the target, would enhance remote handling tasks. Manipulator operations determined that this was not the case for these thinner flexible lines. They easily “dragged” over and around the target appurtenances. Furthermore, the manipulator operators believe that arranging the lines so they point up will make it difficult to maneuver the wrench. Therefore, hydraulic tool lines will not be supported from overhead unless the heavier, less flexible hoses are needed.

Quick-disconnect (QD) couplings were mounted on the hydraulic lines to accommodate the short tether that came with the torque wrench. It was originally believed that having a common umbilical connection in the Target Cell for numerous tools instead of an umbilical for each tool would be efficient for remotely changing tools. However, the QD fittings were observed to drag over edges and objects and generally hinder tool placement. Therefore, each tool will have its own full-length umbilical connected directly to the tool. A quick-disconnect will be installed on the cable-end that attaches to the cell wall connector.

V. CONCLUSIONS

A full-scale replica of the SNS mercury target station is being used to study thermal-hydraulic characteristics of the flow loop, verify engineering design with empirical data, and develop and demonstrate remote handling operations for replacing target system components. Additional tests are being completed to characterize the newly installed EM flow meter and heat exchanger in the Target Test Facility. Equipment is being prepared/modified for tube and pipe cutting tests, and for sheet metal cutting of the target enclosure. Fluid connector tests for target pipe jumpers have been successfully completed and are the basis for modifying the connectors. Target seal tests were completed and were instrumental in modifying the seal design. Remote handling time-tests for target replacement showed that the target can be replaced in a matter of hours, and torque tool tests resulted in modifications that enhance remote handling operations.

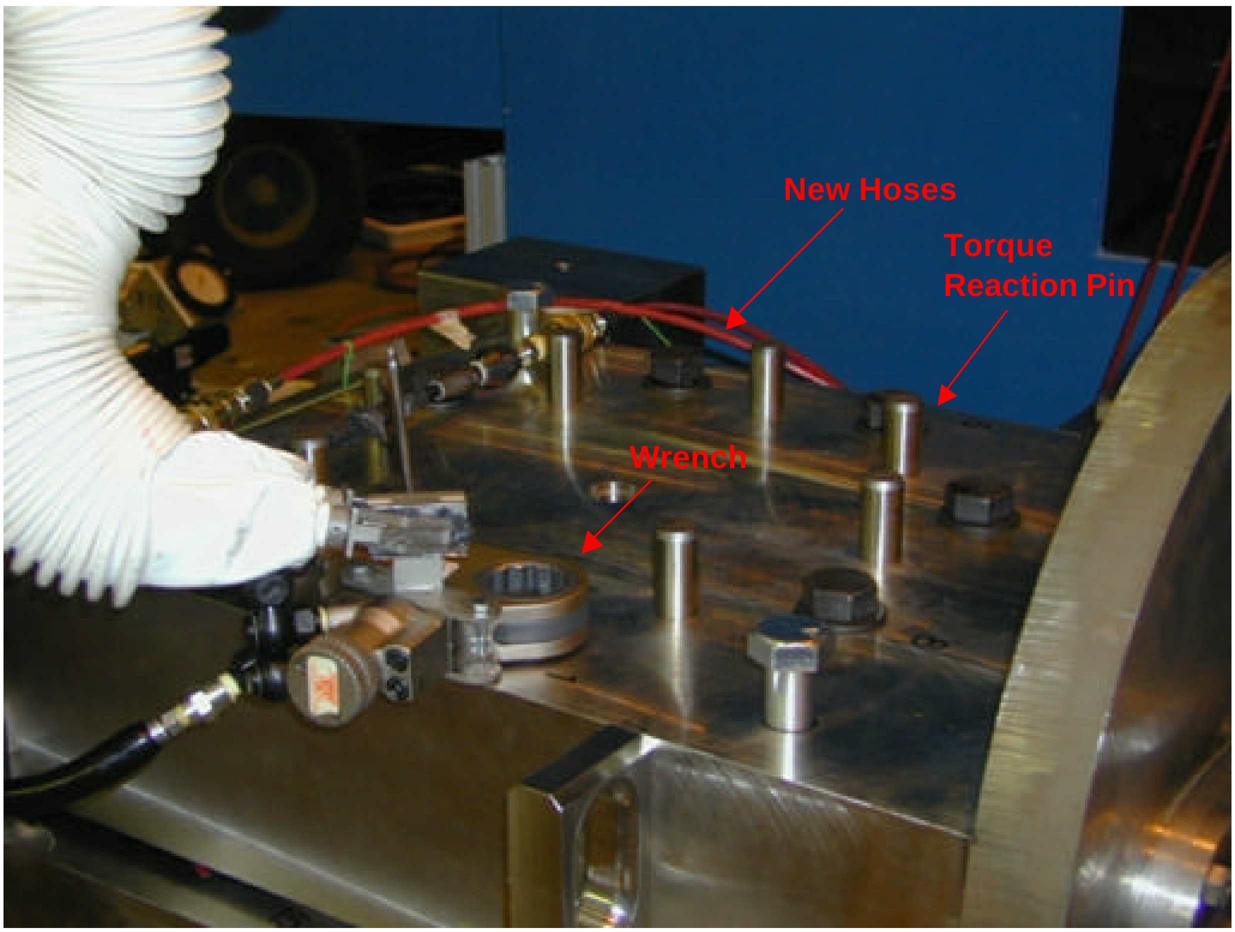

Figure 8. Hydraulic torque wrench with smaller, more flexible lines.

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