Remote Handling Systems Development for the Spallation Neutron Source Target System

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Abstract – *The remote handling system for the Spallation Neutron Source Target System, an accelerator-based neutron scattering facility being constructed at Oak Ridge National Laboratory, has been under development for the past three years. The remote handling system consists of a 7-1/2 ton bridge crane, a separate bridge-mounted servomanipulator system, through-the-wall manipulators, shield windows, remotely operated cameras and lights, and miscellaneous tools and lifting fixtures. The basis for development has been to provide full target cell coverage and use commercially available equipment wherever possible with minimal modifications.*

I. INTRODUCTION

The Spallation Neutron Source (SNS) is an accelerator-based neutron scattering facility that will provide neutron beams with up to ten times more intensity than is available at any similar facility in the world. It is based on a 1-MW, 1-GeV proton beam interacting with a flowing mercury target, at 60 Hz. Basic research conducted at the SNS will lead to technological breakthroughs in the fields of materials science, magnetic materials, polymers, complex fluids, chemistry, and biology. Figure 1 is a rendering of the facility shown on the 80-acre construction site at Oak Ridge National Laboratory (ORNL). The first beam-on-target is scheduled for 2006.

Fig. 1. The Spallation Neutron Source Neutron Scattering Research Facility.

The Remote Systems Group (RSG) in ORNL's Nuclear Science and Technology Division specializes in R&D and design for robotics, remote handling, and process equipment for use in hazardous environments, and is developing the SNS remote handling equipment. In addition to having experienced engineers and technicians, RSG has extensive facilities and equipment for technology development and demonstration. Many of these resources are presently being used to support the remote handling design and testing for the SNS Target System. RSG is engaged in operating the full-scale SNS mercury flow loop located in its high bay facility; developing remotely operated tools, special connectors, and lift fixtures for use in the SNS target system building; testing special seals; and operating a mechanical test stand for the neutron shutters using a full-scale mock-up of the target region.

II. REMOTE HANDLING TEST PROGRAM

A development and testing program has been under way for several years to verify that key SNS equipment and tools can be remotely handled, maintained, and used effectively. The testing is done under simulated (but nonhazardous) SNS conditions, generally using full-scale mock-ups and prototypic equipment.

II.A. Hoist Rings

The purpose of the hoist ring test was to verify the procedure for remotely installing and removing swivel lifting eyes inside the SNS hot cell (target cell). Swivel lifting eyes will be used for many elements inside the hot cell but primarily for lifting shield blocks. Testing was performed in the SNS shield window-manipulator test stand. The equipment used for this test was the following: 1) a swivel hoist ring, part no. SHR-23106, American Hoist Rings, with a rated load of 10,000 lb and modified for remote operation; 2) an Ingersol-Rand electric impact wrench, model IR-8055, purchased for use inside the SNS hot cell and modified for remote operation; 3) a foot-operated power switch for impact wrench power; 4) a manipulator test stand with two CRL Model F through-the-wall master-slave manipulators, identical to those to be used in SNS; and 5) a shield block mock-up, 2-in.-thick steel plate with 1-in. threaded hole. A pair of mast-mounted Telerob EMSM-2B servomanipulators will be used to perform actual hoist ring handling operations, but since this system is not yet available, Model Fs were used that provide the same functions as the servomanipulators.

The hoist ring was modified to improve remote handling by chamfering the end of the bolt, removing two full threads on the bolt, and adding a clamp-on collar to the lift ring. The chamfer and thread removal make it easier to install the bolt and engage the threads. The clamp-on collar makes it easier to position the manipulator gripper under the lift ring after it is installed. A drawing of the swivel hoist ring remote modifications is shown in Figure 2.

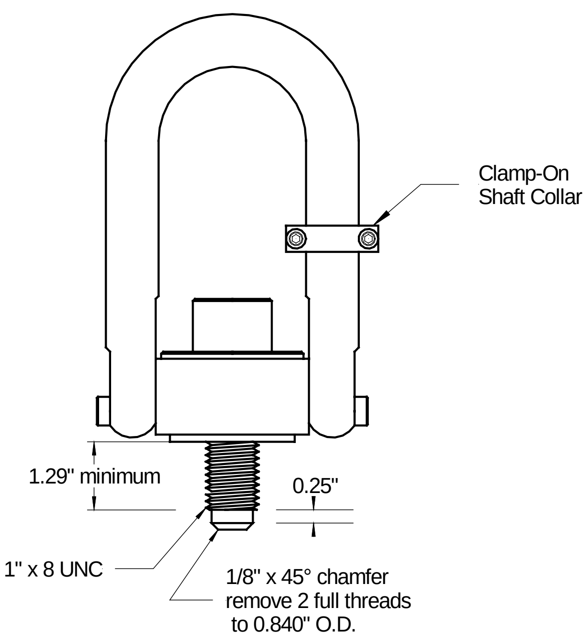

Fig. 2. Modified swivel hoist ring.

The commercially available Ingersol-Rand wrench that will be used in SNS was used in the testing. The wrench was modified to allow remote handling by adding a bracket with manipulator grips and vibration mounts, adding a lever bracket to change motor direction, and clamping the power switch to the “on” position so that power is controlled from a foot-operated switch. Figure 3 is a photo of the modified electric impact wrench.

Fig. 3. Swivel remote testing.

The manipulator was able to lift the swivel hoist ring using the bail; however, the bolt did not remain oriented vertically because it is top-heavy. Hence, the weight of the bolt head rotated the bolt downward. This was overcome by handling the hoist ring at the bolt head. Enough of the lead threads were machined away to insert the bolt into the hole and allow it to stand upright. The 22.5-lb impact wrench was handled using one manipulator and positioned over the socket head bolt. The operator was able to align and insert the Allen wrench into the socket head bolt, and the bolt was spun down and tightened using the impact wrench without any problems. The operator changed the motor direction of the impact wrench by holding the wrench with one manipulator arm while rotating the lever device with the other arm. Removal of the swivel hoist ring was performed without any problems. Figure 3 shows the hoist ring and the pneumatic impact wrench.

II.A. Remote Grapple

A new type of remote lifting device based on the patented Zipnut technology has been developed for use in the SNS Target Facility. A unique characteristic of this “ZipLift” is that it provides a high-weight-carrying capacity in a relatively small fixture. The grapple interfaces to the lifted component through a 1-1/4 in. stud permanently mounted to the component. A pneumatically actuated prototype ZipLift designed for handling the proton beam window was procured; it underwent a performance/endurance test of 700 lifts near its rated capacity of 15,000 lb. Testing revealed some areas for improvement in the design of the ZipLift, but no major issues were observed that would affect usability for SNS operations.

An electrically actuated ZipLift for use in the hot cell was developed by replacing the pneumatic cylinders with 48-volt DC solenoids.

One of the many remote handling issues facing the SNS design team is safe handling of replaceable components in the target region, such as the proton beam window module and the "inner plug." These are located approximately 15 ft below the high bay floor and are accessible only after removal of several large shield blocks. The expected activation level of these components is in the range of 10^3 rad/h.

The procedure to remove these components is to position a bottom-loading shielded transfer container over the component after the shield blocks have been removed. A pneumatic chain hoist and its support frame are then mounted on top of the transfer container. Multiple hoist/frame systems are expected to be required because of the range of component weights involved. The container top has a removable plug that allows the lifting grapple to descend through the container and connect to the component. The hoist then lifts the component into the container. After the component is secured within the container, the grapple releases the component and the container plug is replaced. The container is then lifted using the remotely actuated grapple attached to a 50-ton crane. Figure 4 shows the grapple undergoing a 5-ton lift test.

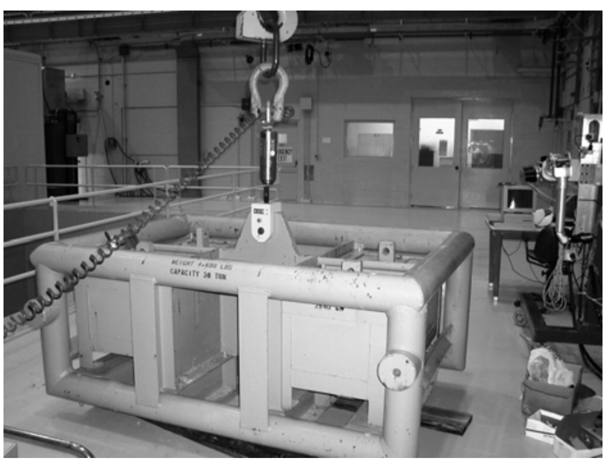

Fig. 4. Grapple lift fixture testing.

The ZipNut device consists of a female thread cut into three pieces along the axis of the nut. The pieces are held in position with a circumferential spring housed in a hexagonal body that conforms to standard nut dimensions. The spring allows the thread segments to expand, increasing the effective diameter and allowing the nut to be directly pushed onto a bolt. Removal of the ZipNut is accomplished using a normal unthreading operation. A modified concept based on the ZipNut was configured for high capacity and compact size; and a fabricator licensed to manufacture ZipNut-based products was engaged to manufacture a prototype for testing.

II.C. Pneumatic Torque Wrench

A pneumatic torque wrench will be used as a general-purpose tool in the SNS hot cell and is preferred over using an hydraulic wrench. The imparted torque is controlled by air pressure within a range of 200 to 900 ft-lb for the chosen tool, with 750 ft-lb typically required for target module bolts. For SNS applications this tool has several advantages over the hydraulic wrench: speed of operation, ease of remote handling, ability to rotate untightened bolts, and ease in reversing its direction. Figure 5 is a photo of a commercially available wrench showing the standard modifications for remote handling.

Fig. 5. Modified commercial torque wrench.

II.D. Nut Runner/Stud Tensioner

The nut runner/stud tensioner is a "long-handled" tool that was designed for remote manipulation of structural nuts that hold large, heavy core vessel "inserts" in place. The inserts, which guide spalled neutrons along beam lines to experimental instruments, are located approximately 15 ft below the high bay floor. Figure 6 is a photo of the full-scale prototype tool.

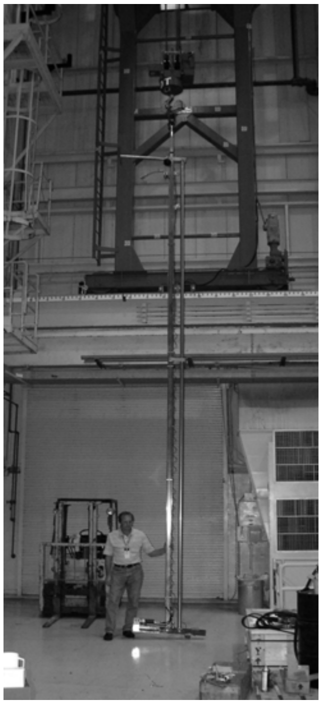

Fig. 6. Long-handled stud tensioner tool.

The tool head is hydraulically operated and consists of a socket for turning nuts and a stud tensioner for applying the required 25,000 lb of tension on 1.25-in. studs. Tool-mounted cameras aid the operator in positioning the tool. Two versions of the tool are required, one for the upper studs and one for lower studs. Figure 7 shows the nut runner/tensioner with three CCTV cameras.

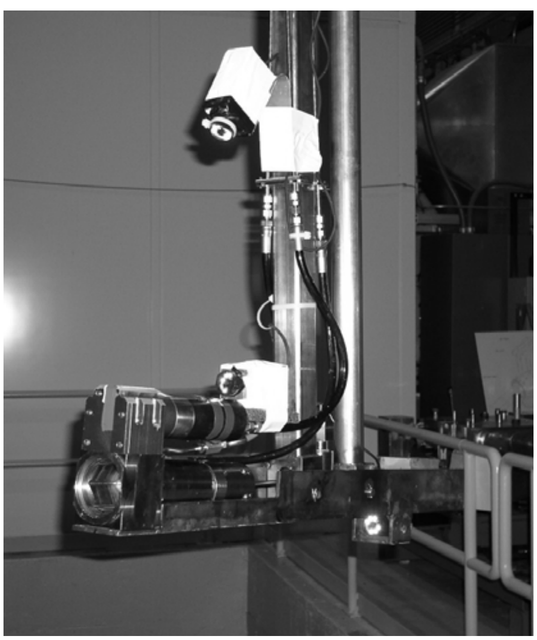

Fig. 7. Stud tensioner with remote cameras.

II.E. Shield Window Workstation

In-cell tools require utility services (120-volt AC, pressurized air, or hydraulic fluid, to name a few) delivered from outside the hot cell. The connections are made at the shield window workstations using bulkhead-type fittings on trays like those shown in Figure 8. Umbilical lines are inserted through wall penetrations near the windows that connect below the trays; tools are connected at the junctions on top of the trays. The arrangement for tool utilities is designed to simultaneously accommodate up to four electric tools, two hydraulic tools, two pneumatic tools, and one radiation-resistant portable inspection camera. The connectors are designed to be covered during a cell washdown and to be replaced remotely if required.

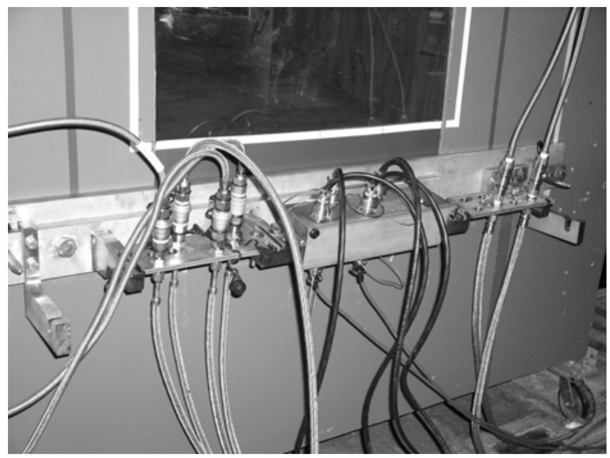

Fig. 8. Shield window utility connection station.

III. REMOTE HANDLING EQUIPMENT

III.A. Bridge Crane

The overhead remote bridge crane is used to install and remove large components in the hot cell. The remotely operated crane (and the servomanipulator system) is shown in Figure 9. The primary components of the bridge crane are the bridge-pair, the trolley, the hoist, and the electrical cable management system.

The crane load capacity is based on the heaviest component that needs lifting plus the added weight of lift fixtures. The main hoist hook includes a hook-rotate feature to allow orienting the hook to lifting-features on the components being lifted. The main hook hoist consists of two hoist drives, each with enough cable capacity to lift the load if one drive fails. This ensures operation of the crane in the event of a primary-drive failure. The bridge spans the 14-ft cell width.

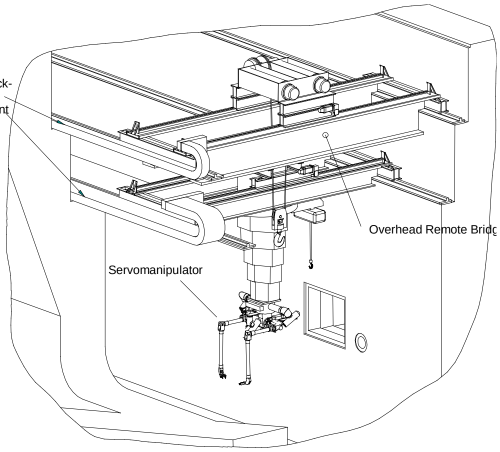

Fig. 9. Bridge crane and servomanipulator system.

The crane hook covers the entire hot cell and can be positioned 18 in. from the side walls and about 45 in. from the end walls, and extends from the bridge to floor level. The bridge crane is radiation-hardened and will have an expected lifetime dose of 10^8 rads. The operating environment is HVAC-controlled, and the crane system is expected to remain operable after a design-basis earthquake. The system includes lighting and CCTV cameras mounted on the bridge to provide remote viewing.

The bridge, trolley, and hoist have redundant drives to recover from the failure of a motor while the crane is operating in the hot cell. The drives ensure that the bridge can be brought to a crane maintenance area after decon for hands-on repair of the failed unit. All special tooling required for maintenance is included in the crane design. Special tooling includes lifting frames for safe handling of the trolley and support stands for the trolley and other assemblies requiring maintenance when removed from the crane.

The crane components are designed for liquid spray decontamination of external surfaces. Surfaces that are likely to collect dust and other airborne contamination are designed to be accessible by the decon equipment. Motors, junction boxes, connectors, and limit switches are totally enclosed and weatherproof. Surfaces that are difficult to access or otherwise unsuitable for liquid decontamination are covered and sealed. All surfaces and enclosed spaces are sloped and channeled for drainage. All instrument and controls connections are sealed to avoid water penetration during decon.

Hollow structural members are also sealed and, where required, have open drain points to ensure that water and contamination cannot become trapped during decon operations.

III.B. Overhead Servomanipulator

The overhead servomanipulator (SM) system is the primary means of accomplishing remote maintenance on components in all areas of the hot cell. An illustration of the overhead SM is shown in Figure 9. The overhead SM system shares many requirements in common with the overhead remote bridge crane. The primary components of the SM system are the bridge, the telescoping tubeset, the interface package, the SM, the trolley, cable management, and an auxiliary hoist.

The SM will be radiation-hardened for the total lifetime dose of 10^8 rads. The operating environment for the SM is an HVAC-controlled environment, and the system will be resistant to washdown sprays used for decontamination. The SM is designed to remain operable after a design-basis earthquake.

The SM bridge has lights and cameras mounted to provide remote viewing. Capabilities for the overhead SM subsystems are outlined below.

<u>Servomanipulator</u>

The SM system consists of Telerob EMSM-2B force-reflecting, dual-arm electromechanical manipulators with the following features per arm:

- Six degrees-of-freedom, parallel jaw gripper
- Continuous load capacity of 55 lb, peak capacity of 100 lbs
- Overall reach of approximately 80 in.
- End-effector tip (gripper) velocity of >39.4 in/sec to support real-time control during teleoperation (master arm control)
- Booting to prevent contamination and allow water solution washdown for decontamination purposes; the booting will be gas-pressurized to ensure out-leakage in case of breach and to assist in cooling the servo drive motors
- Brushless servomotor drives
- Drives with integral brakes and absolute position feedback
- Drive brakes that engage when not actively being controlled by the master arm, and under a loss of power conditions
- Drive motor housings with motor over-temperature protection
- Master control arms and digital control system
- Camera deployment arms to provide close-up viewing

<u>Telescoping Tubeset</u>

The telescoping tubeset is configured to support the positioning and operation of the SM. The tubeset has redundant drives to allow retraction of the tubeset in the event of a tubeset-drive failure. The tubeset has variable travel speed from near zero to 30 ft/min. All cabling to the SM and the interface package is enclosed. The tubeset has a total travel length of 141 in. and a retracted length of approximately 60 in.

Interface Package

The tubeset base has a detachable mechanical interface package for mounting the SM arms, lights, and cameras. The interface includes features that allow independent mounting and removal of each slave arm, the camera-positioning arms, a drive for ±190^{o} of rotation of the SM and the cameras, a remote pin-style connector for tool power (120-VAC), and a camera connector for close-inspection tasks.

Auxiliary Hoist

A 500-lb capacity hoist is located under the trolley, mounted to the interface package. The hoist is capable of rotating ±215° to keep the hook positioned between the manipulator arms. The hoist will have an operating speed of approximately 8 ft/min and has sufficient cable length to reach the cell floor.

III.C. Mechanical Master-Slave Manipulators

Master-slave manipulators (MSMs), also referred to as through-the-wall manipulators, serve as direct extensions of the human operator because they provide direct links between the operator and the tools or components being manipulated. These manipulators consist of a master arm and a slave arm connected by a through-tube mechanism mounted in a shield wall. The human operator on the cold side of the cell wall physically manipulates the master arm.

The “master-slave” terminology originated from earlier mechanical and electrical technologies in which a device that is responsive to another device is termed a “slave,” and the controlling device is termed a “master.” The slave arm has six degrees of freedom, three for translation and three for rotation to position the tong-squeeze gripper. The motion of the slave arm is coupled to the master arm so that the position and direction of the two correspond.

The coupling between the two arms is bilateral, which means that forces at the slave end are reflected back to the master, and displacements at the slave end produce a displacement at the master arm. The slave arm mimics all motions of the master arm through a series of steel tapes, pulleys, and gears. The coupling of the master and slave arms provides no mechanical advantage; therefore, if the operator lifts a 10-lb load in the cell, he feels approximately 10 lb of force on the master arm. The master and slave arms consist of extendible boom tubes that allow the arm lengths to change, depending on the task being performed. Figure 10 shows an operator using master arms in front of a shield window.

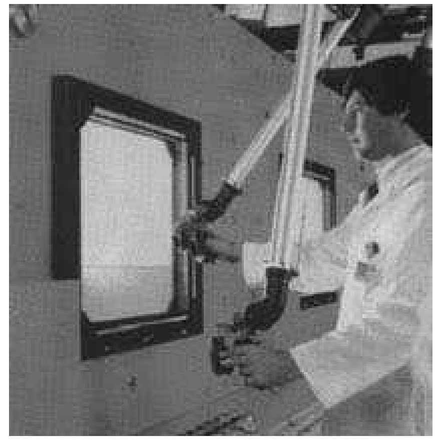

Fig. 10. Remote operation using master-slave manipulators.

A pair of MSMs is located at each workstation along the SNS target hot cell. Central Research Laboratory Model F manipulators were chosen because they are heavy-duty, robust systems rated for 100-lb load capacity, and have been in service for decades. The wall penetrations for each pair of manipulator arms are located 120 in. above the operator’s walking surface, 40 in. apart.

The MSMs incorporate features to increase efficiency and reduce operator fatigue. These include counter-weights, axis-indexing motors, and motion locks. Because of the counterweights on the master arm, the system is nearly balanced, so that most of the arm weight is removed from the operator, and unloaded arms will stay in position or slowly return to their resting position. Indexing motors on the master arms allow the length and position of the slave arm to change without moving the masters. This allows the operator to keep the master arms in a comfortable position even though the slave arms may be near the limit of their reach. Motion locks also aid in operations. They lock the master arms in position even while under load. This allows the operator to hold an object in a fixed location with the slave arm while using a second manipulator to perform tasks on the object. The operator can choose the three mechanical locks that control each axis independently or a pneumatic system that locks all motions simultaneously.

III.D. Shield Windows

Through-the-wall manipulator operations require direct viewing of the task under way in order to maximize operator effectiveness. Shield viewing windows are used to achieve this direct in-cell viewing while still providing radiation shielding for personnel outside the cell. A “dry” viewing window is located at each remote maintenance workstation in the SNS target cell.

The radiation-shield window comprises three separate elements: the wall liner, the window housing including the glass, and the alpha shield. The wall liner is embedded in the concrete wall during construction and may be made from welded carbon steel or cast iron, but the exposed in-cell surfaces are stainless steel. The window housing is the steel structure that holds together the glass sections and is installed into the liner from the cold side of the cell. The liner and the housing have matching stepped shapes that prevent the streaming of radiation to the operator side of the window.

The window housing holds multiple glass slabs, each with varying densities. Figure 11 is a photo of a typical window housing. Dry shielding windows use nitrogen gas to fill the space between the glass slabs. This provides an advantage over oil-filled shielding windows, which can leak and require more frequent maintenance.

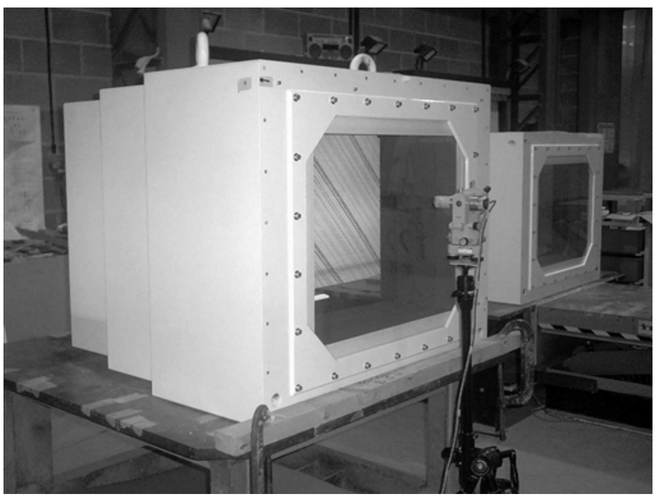

Fig. 11. Shield window housing with glass slabs.

The following requirements were addressed for specifying the SNS shield windows:

- Limit operator dose rate to 0.25 mrem/h on the cold side of the window.
- Use stabilized slabs of non-browning glass, of various densities, comparable to a 40-in. concrete shield wall with a density of 3.93 g/cc.
- The clear viewing area on the operator's side of the window is a minimum 48 in. wide by 36 in. high; viewing angles for the operator are 30° horizontal (right and left), 30° down, and 15° up.

III.E. Remote Viewing

The target cell cameras and lighting are designed for four different applications, based on their location: (1) facility wall-mounted cameras and lights, (2) bridge-mounted cameras and lights, (3) SM-mounted cameras and lights, and (4) MSM workstation cameras and lights. Monitors for the MSM cameras can be viewed at the shield window locations and supplement the limited viewing angles through windows.

The hot-cell cameras are radiation-resistant monochrome-type cameras. Hot cell camera assemblies include power remote pan/tilt, and power lens (zoom, focus, and iris). Depending on the particular location, the hot-cell cameras also include two lights and a microphone for sound. Cameras and lights are standardized as much as possible, depending on the particular application. System components, connectors, mounting design, etc, have a common design to minimize spare parts and simplify maintenance. Descriptions of the specific cameras for the four applications are discussed below. Twelve wall-mounted cameras are located in the hot-cell, as shown in Figure 12.

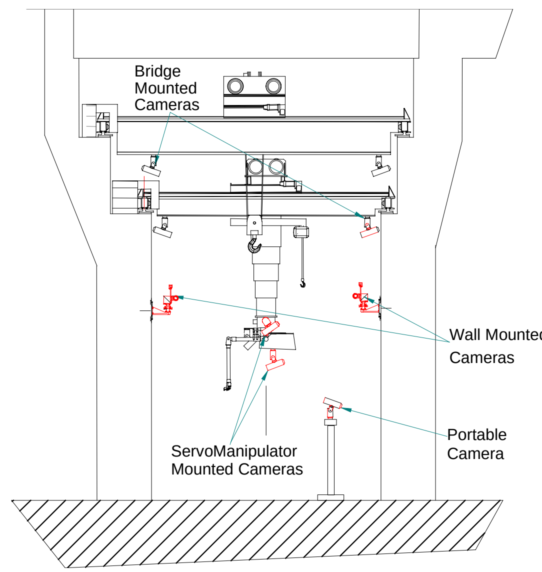

Fig. 12. Arrangement of hot cell cameras and lighting.

<u>Wall-Mounted Cameras and Lights</u>

The wall-mounted cameras provide overall views for positioning of the bridge cranes and SM transporter bridges. These cameras are mounted at a high location on the wall, but are accessible by the SMs for remote maintenance. Two of the cameras have microphones designed to monitor operational noise inside the hot cell. None of these are planned to have lights.

<u>Bridge-Mounted Cameras and Lights</u>

Four bridge-mounted cameras are located in the hot cell. One camera is mounted on each end-truck of the crane bridge and one camera is on each end-truck of the SM bridge, as shown in Figure 12. These four cameras provide overall views for positioning the crane hook and the SM transporter. The cameras also provide auxiliary views for the SM operators. One of the cameras has a microphone, but none of these will have lights.

Four 500-W halogen lamps are mounted on each of the bridges. The cabling for the lighting is included as part of the crane and SM cabling system. The lamps are hands-on replaceable. Lighting controls are integrated with the bridge control system, and they include variable-intensity-control features.

Servomanipulator-Mounted Cameras and Lights

Three cameras plus a connector for an inspection camera are located on the SM. They consist of two upper cameras on the positioning arms and one lower camera between the SM arms, as shown in Figure 12. The cameras provide the primary views for the SM operators. All three of the cameras have lights and one is equipped with a microphone. Each camera has two 75-W halogen lights. Cabling and connector are provided for a fourth camera that may be used as a manipulator-held inspection camera. The connector for this camera will be capable of remote connection and disconnection by the MSM arms. All of the camera-mounting pedestals will be equipped to accept cameras with or without microphones and lights.

Workstation Cameras and Lights

The four MSM workstations each include a circuit to add portable cameras that can be positioned in the cell as needed. The cameras are mounted on portable stands, one for each MSM workstation as shown in Figure 12. They provide auxiliary views for MSM operators during remote repair or inspection. The portable stand allows MSM operators to reposition a camera as needed for the remote repair task. The connector for this camera is capable of remote connection and disconnection by the MSM arms. Both of the cameras have microphones and lights. The portable stand is equipped to accept cameras with or without microphones and lights.

Camera Operations and Maintenance

The hot cell cameras and lighting are operated from the hot cell video control system. Video control stations are located in the remote maintenance control room and at portable video control consoles located at the MSM operators' gallery.

The wall-mounted cameras and connectors are designed to be remotely installed and removed with the in-cell dual-arm SM. The bridge-mounted and SM-mounted cameras will be hands-on maintained in the crane maintenance area. The MSM workstation cameras and connectors are designed to be remotely replaced with the MSMs or the SM.

General Hot Cell Lighting

General hot cell lighting is designed to provide adequate illumination for remote operations in the hot cell using remote video viewing and shielded viewing windows. Each light fixture is fabricated from stainless steel and radiation-resistant materials. SNS uses 400-W lights, sixteen in the main cell and four in the transfer cell. The light fixtures mount onto brackets that bolt into the hot cell wall. The ballasts are mounted on the outside of the cell wall near the electrical penetration.

The number and location of light fixtures is based on lighting requirements for the various viewing methods (remote CCTV cameras and shield windows) and on the resultant heat load in the hot cell. General hot cell lighting must provide an average of approximately 300 ft-c of illumination for the cells with CCTV viewing, and approximately 500 ft-c of illumination for shield window viewing.

The general hot cell lighting will be operated from the control room and from switches mounted on the exterior hot cell walls. The light fixtures will be hung on permanently installed wall brackets. The lights can be transported and maintained within the hot cell using the SM and MSMs once the power cable has been remotely removed from the fixture. Bulb replacement can be accomplished remotely at the MSM workstations.

IV. CONCLUSIONS

Development of remote handling equipment development for the SNS has been under way for the past three years at ORNL. The development and testing of remotely operated tools and modifications to commercially available equipment has been achieved using full-scale mock-ups and simulated operating conditions. These included special connectors, lift fixtures, hydraulic and pneumatic tools, lighting and viewing equipment, and various pieces of small hardware. In addition, specifications were developed to procure the major remote equipment from domestic and foreign sources. These included the through-the-wall manipulators, the shield windows, the bridge crane system, and the bridge-mounted SM system.

The majority of the tests that were planned have been completed with successful results, and modifications to tools and equipment have been incorporated into the actual hardware, or into the specifications for equipment that is in the final stage of fabrication.

ACKNOWLEDGMENT

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