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Welding Robot and Remote Handling System for the Yucca Mountain Waste Package Closure System

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ABSTRACT

In preparation for the license application and construction of a repository for housing the nation's spent nuclear fuel and high-level waste in Yucca Mountain, the Idaho National Laboratory (INL) has been charged with preparing a mock-up of a full-scale prototype system for sealing the waste packages (WP). Three critical pieces of the closure room include two PaR Systems TR4350 Telerobotic Manipulators and a PaR Systems XR100 Remote Handling System (RHS). The TR4350 Manipulators are 6-axis programmable robots that will be used to weld the WP lids and purge port cap as well as conduct nondestructive examinations. The XR100 Remote Handling System is a 4-axis programmable robot that will be used to transport the WP lids and process tools to the WP for operations and remove equipment for maintenance. The welding and RHS robots will be controlled using separate PaR 5/21 CIMROC Controllers capable of complex motion control tasks. A teleoperated PaR 4350 Manipulator will also be provided with the XR100 Remote Handling System. It will be used for maintenance and associated activities within the closure room.

INTRODUCTION

The U.S. Department of Energy (DOE) is responsible for accepting and disposing spent nuclear fuel and high-level waste in a geological repository. To meet this responsibility, these materials will be sealed inside waste packages (WP) and disposed of at the DOE-owned Yucca Mountain site in Nevada. In preparation for the license application and construction of the repository, the Idaho National Laboratory has been charged with preparing and demonstrating a full-scale working prototype system for sealing the waste packages. The Waste Package Closure System (WPCS) will be located within Yucca Mountain facilities and will encompass all operations required to seal a WP. Once a WP is sealed and has passed inspections, the WP will be moved into the repository for final storage.

The WP consists of a 316 stainless steel inner vessel and an outer Alloy 22 shell with two closure lids; one lid for the inner vessel and one lid for the outer shell. WP closure operations will include closure of the waste-filled WP by (a) welding and nondestructive examination of the two lids and of one stainless steel purge port cap, (b) purging and filling the inner vessel with an inert gas, and (c) stress mitigation on the final welds. All processes will be performed remotely due to the radiation fields associated with the waste.

Three critical pieces in the closure room include two PaR Systems TR4350 Telerobotic Manipulators and a PaR Systems XR100 Remote Handling System. The TR4350 Manipulators are 6-axis programmable robots that will be used to weld the WP lids and purge port cap as well as conduct nondestructive examination of the welds. The two weld robots (TR4350 manipulators) are mounted on a large, circular precision bearing positioned 180° from each other on the bearing. Each weld robot will be responsible for welding one side of the WP lid. The XR100 Remote Handling System (RHS) is a 4-axis programmable robot that will be used to transport the WP lids and process tools to the WP for operations as well as remove equipment for maintenance.

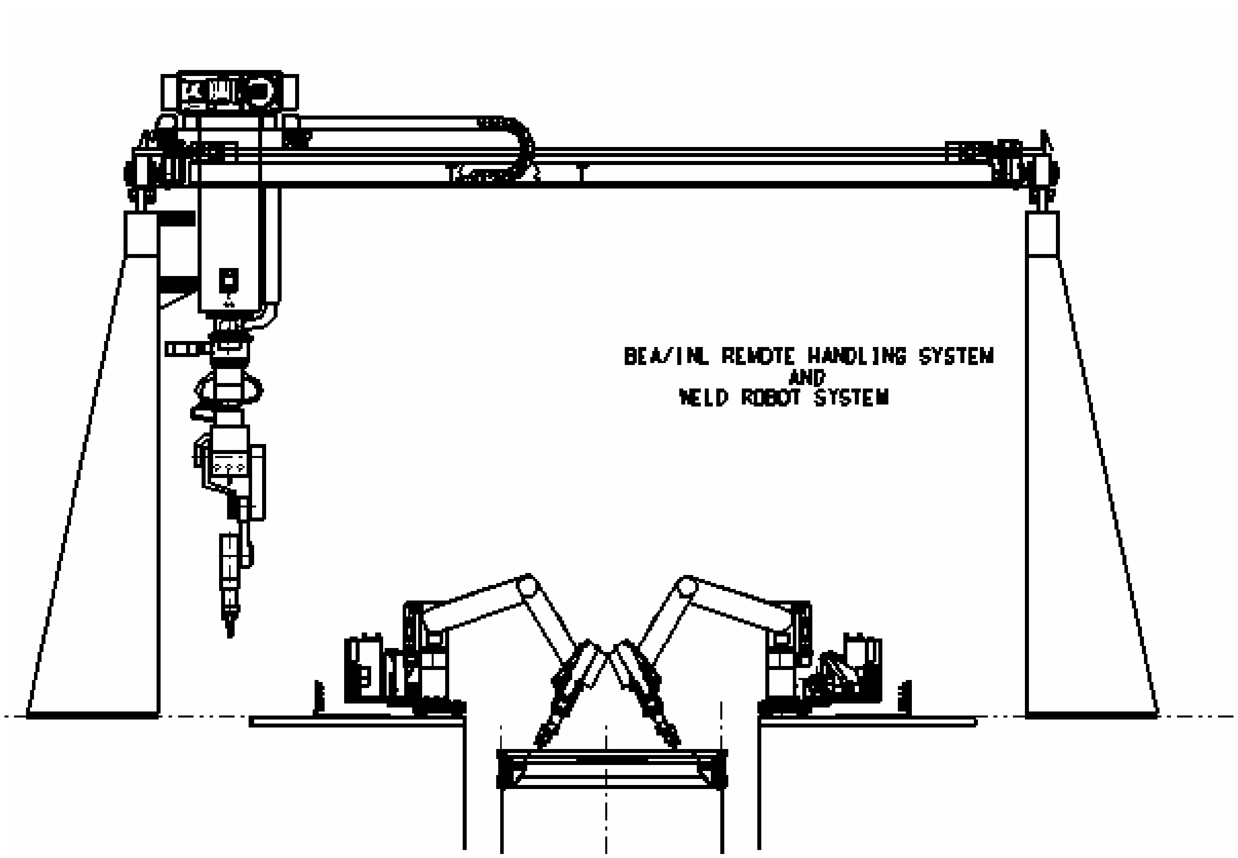


Figure 1. Remote Handling and Weld Robot Systems with WP (Initial Concept)

OVERVIEW OF THE WASTE PACKAGE CLOSURE PROCESS

1. The waste package (WP) moves into place below a large opening in the floor inside the closure room. Using an overhead camera system, the position of the WP is determined.
2. Using the RHS, the WP lid is moved from the lid staging location to the WP through the floor opening and placed on the WP.
3. A laser scanner on the welding end effector scans the lid position within the WP to determine the weld path.

4. The welding and inspection system controller calculates the data defining the desired motion path. This data file defining the desired weld location is sent to the controller for the primary weld robot (master).
5. The controller for the primary weld robot (master) calculates the robot orientation for both robots and sends the controller for the secondary weld robot (slave) its orientation information.
6. Both weld robots move their tools to respective positions, typically 180 degrees across the WP apart from each other.
7. The welding cycle begins with both robots actively welding each respective side of the WP as they rotate on the bearing ring.
8. Between each weld pass, each robot reaches behind the robot to the tool tray and changes end effectors as needed to perform non-destructive examination, brushing of the weld surface, or weld repair. Several weld passes will be required to complete a WP.
9. Within the WP closure process, the RHS will maneuver the leak detection, evacuation/backfill, and stress mitigation equipment.

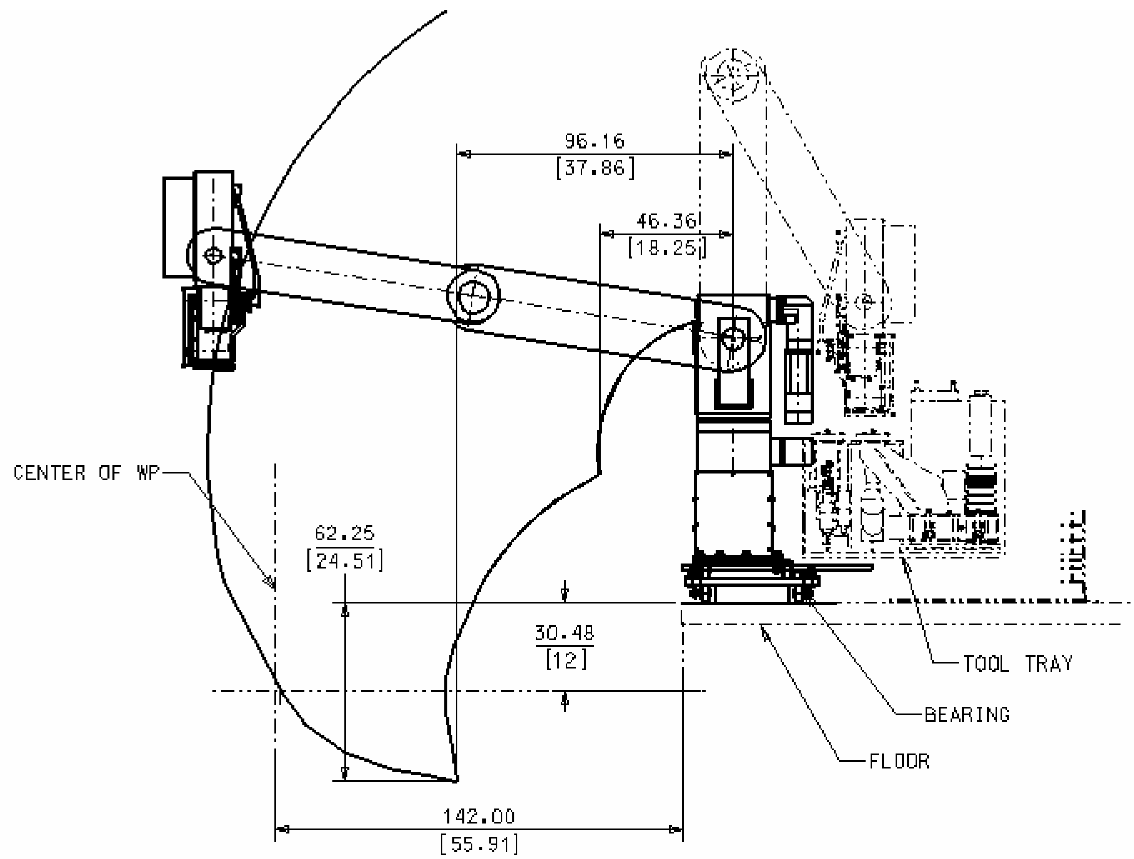
WELD ROBOT DETAILS AND CAPABILITIES

The weld robot design is based on the standard power manipulators that PaR has provided to the nuclear industry for 46 years. These manipulators utilize the robust features of precision industrial robots, yet incorporate features necessary for hazardous environment operation. The TR4350 weld robot is sealed, uses corrosion resistant materials and finishes, has a minimal number of cavities and has internal wiring for minimizing contamination traps and for easy wash down and decontamination. The electromechanical drive system of the weld robot utilizes torque sharing between the shoulder, elbow and wrist pivots and thereby reduces the robot deadweight by locating all the pivot drive components in the shoulder housing. Positioning of the weld robot is precise and repetitive. Compact box construction gives maximum rigidity and external smoothness while allowing operation in restricted places. All axes are protected using slip clutches which also allows for recovery of the manipulator in the event of a power outage or stall. A quick change tool plate is mounted on the wrist of the manipulator allowing for ease of switching end effectors for the WPCS operations. In the event of a power outage, the motors on the weld robot are fail safe and will not drop the load. The TR4350 manipulator differentiates itself from the other manipulators in the industry in that it was designed for operation in a radiation environment and is resistant to a total integrated exposure of 10^8 rad equivalent dose of gamma radiation.

The kinematics of the weld robot allow for positioning the shoulder and elbow pivot motions without changing the wrist orientation. The singularity (position of infinite mathematical solutions) for the weld robot was shifted from the typical vertical orientation to a horizontal orientation so the weld robot can weld absolutely vertical if required. The weld robot kinematics also tie the six axes of the weld robot to the bearing position (7^{th} axis) as well as tying the two weld robot locations to each other. Each axis of the weld robot is complete with dual, absolute load-side resolvers which, in combination with the axis servomotors, define a complete position feedback loop. This gives the primary (master) and secondary (slave) controllers knowledge of exactly where the robots are in the weld cycle thus allowing the primary (master) controller to make adjustments as necessary. The two robots were designed to work in tandem and are configured such that one robot is the primary (master) robot and the other robot is the secondary (slave) robot. The robots are identical and therefore can be configured to either mode. This is likewise the case for the controllers; a primary (master) and secondary (slave) controller must also be identified prior to commencing work. To maintain control of the position of both welding robots within the WPCS, the secondary (slave) robot gets its positional information directly from the primary (master) controller.

Table I shows the range of motion capabilities of the weld robot with respect to the WP and the tool tray.

Table I. Weld Robot Travel Limits Summary



AXIS	EQUATION	NEGATIVE LIMIT	POSITIVE LIMIT	TRAVEL RANGE
SHOULDER ROTATE	THETA_SR	-175	175	350
SHOULDER PIVOT	THETA_SP	-105	105	210
ELBOW PIVOT (REL TO GRND)	THETA_EP	-175	90	265
WRIST PIVOT (REL TO GRND)	THETA_WP	-260	90	350
WRIST CROSS-PIVOT	THETA_WCP	-89	74	180
WRIST ROTATE	THETA_WR	-175	175	350
ELBOW PIVOT (REL TO SHLDR)	THETA_EP - THETA_SP	-150	150	300
WRIST PIVOT (REL TO ELBOW P)	THETA_WP - THETA_EP	-150	150	300

CIMROC 5/21 CONTROLLER

The weld robots and RHS each have a CIMROC controller. The CIMROC controller allows complex computer numerical control (CNC) tasks to be performed including a complete range of motion control, straight-line tool tip motion, time optimized interpolation and circular interpolation in absolute, relative and transformed frames. Because the weld robots and RHS are programmable, multiple diameters of WPs or additional closure operations can be accommodated.

REMOTE HANDLING SYSTEM DETAILS AND CAPABILITIES

The RHS is an electro-mechanical friction driven top-running gantry built to CMAA-70 [1] standards. The RHS is comprised of a bridge-trolley-telescoping vertical mast system running on a precision runway mounted on a set of 8 columns in the demonstration facility. Attached to the end of the vertical telescoping mast is a manipulator arm capable of gripping and maneuvering light equipment. Figure 2 graphically details the components of the RHS.

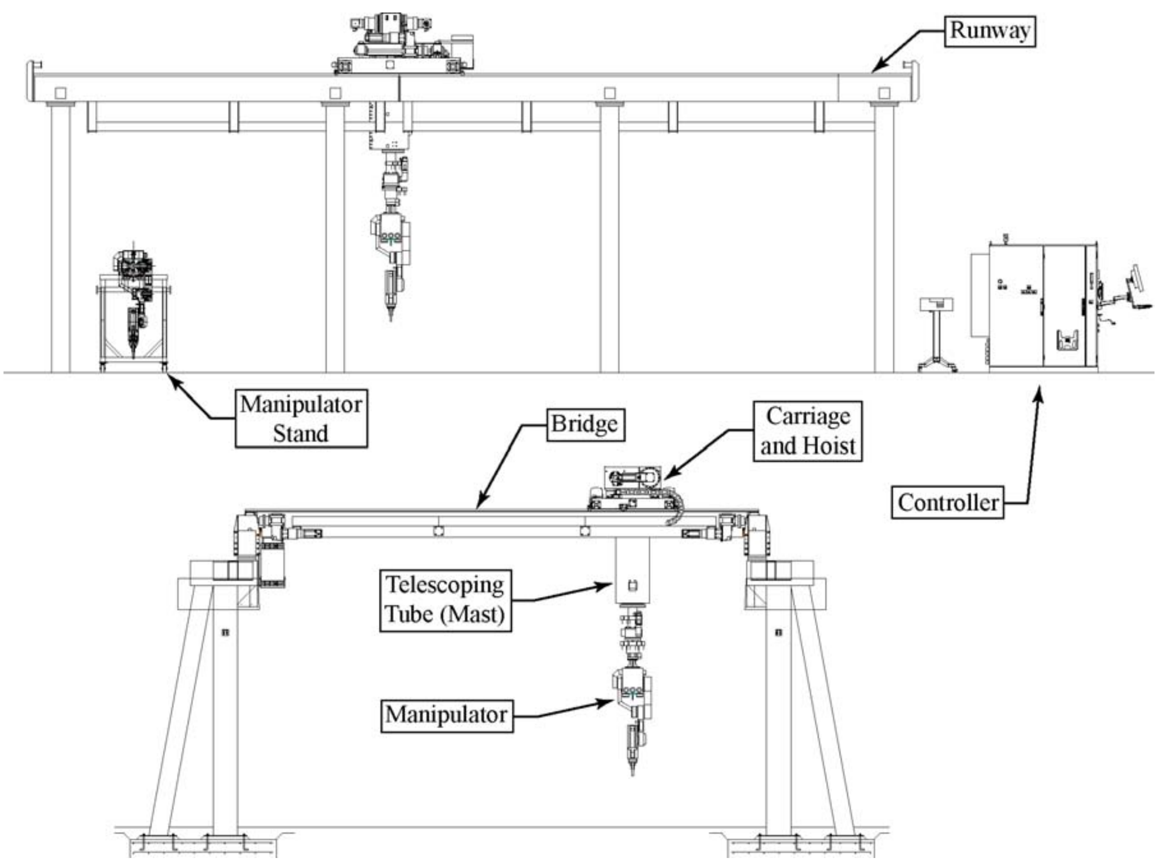


Figure 2. Remote Handling System Side View of the Installation at the INL Demonstration Facility

Once the concept has been proven, the design will be implemented in production at the Yucca Mountain facility. The RHS rails may be wall mounted in its final location in Yucca Mountain.

The teleoperated manipulator can be removed from the RHS using quick change tool plates which allow for heavier tools and modules to be attached and maneuvered. With the manipulator removed, the RHS can robotically pick up and operate the necessary equipment needed for the various supporting closure operations of the WP. The closure equipment will be staged in tool storage racks in defined locations around the outer perimeter of the closure room and deployment of the closure equipment will be programmed for remote retrieval and replacement operations. The closure support equipment includes, but is not restricted to, welding tool trays, evacuation/backfill equipment, leak detection modules, weld stress mitigation, and WP cleanup equipment. When not fulfilling WP closure operations, the RHS may be used for required maintenance needs such as remote cleanup activities or repairs inside the closure room. The RHS can reach nearly all areas of the WPCS closure room as shown in Figure 3.

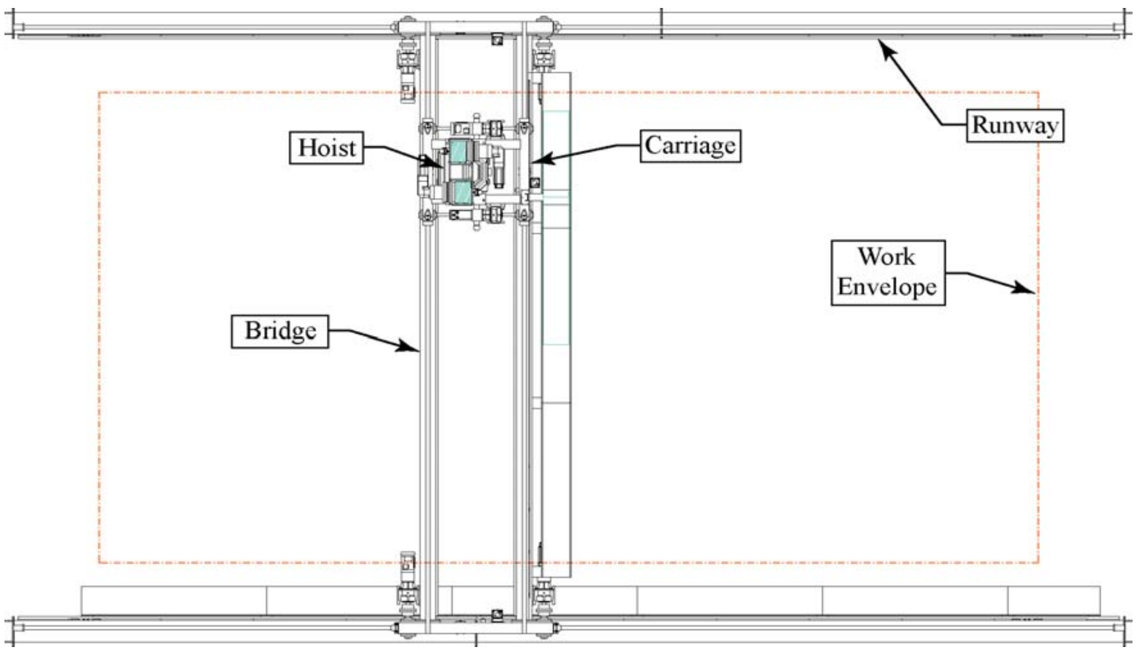


Figure 3. Remote Handling System Top View of the Installation at the INL Demonstration Facility

The RHS has several unique attributes designed to meet the requirements of the Yucca Mountain WPCS. The RHS is a 4-axis servo system (X, Y, Z, and R) with load-side encoders. Since the bridge and trolley utilize friction driven wheels, the load-side encoders provide absolute positional feedback and help detect any motion problems. The bridge drive wheels are independently driven and the load-side encoders in combination with the control software also ensure the bridge does not skew or become misaligned during operation.

The bridge, trolley and hoist of the RHS each have recovery capability. AC motors are tied into the unguided side of the bridge and trolley assemblies. Upon loss of servo control, the AC motors can be activated and the RHS moved to a recovery area in the closure room. The hoist consists of two drums and two wire ropes independently attached to an equalizer assembly which is then ultimately attached to the quick change tool plate. The two hoists are configured as primary (master) and secondary (slave) with the secondary hoist's position dependant on the primary hoist's positional control loop data. In the event of a wire rope failure, the RHS hoist was designed such that the complete loading of the RHS system can be supported by one wire rope. Slip clutches on the rotate assembly and the RHS 4350 manual manipulator allow for further recovery capability.

There are three means for running or controlling the RHS. First, the RHS can be controlled from the control console on the CIMROC controller. This control will also be extended to an operations control room, via Ethernet. Second, using the teach pendant and the third method for operating the RHS is using joystick controls. Each control method can be toggled between the servo-controlled components of the RHS (bridge, trolley, hoist and rotate components) and the RHS 4350 manual manipulator.

During a seismic event, the RHS will not drop or release its load. While not considered important to safety, the RHS will not collapse during a seismic event either. The RHS was analyzed and designed to prevent its failure under the Design Basis Ground Motion (DBGM) using an equivalent static approach in accordance with ASCE Standard 4-98, Section 3.2.5. This equivalent approach required that a factor of 1.5 be applied to the peak spectral accelerations to account for multi-mode responses. With Peak Spectra Acceleration of 3.0g vertically and 4.0 horizontally, this meant the equipment had to be designed to withstand a maximum of 6G of acceleration. A three-dimensional computer model was generated and analyzed using GT-STRUDL using a finite element method (FEM) stiffness analysis.

The bridge span for the RHS is 840.1 cm (330.75 in), the longest PaR XR100 bridge span to date. To handle the seismic demands on this bridge, the runway rails were designed using 1045 low carbon steel instead of the typical A36 low carbon steel rails and the bridge was manufactured using 40.6cm x 20.3cm x 1.3cm (16in x 8in x 0.5in) thick low carbon steel tube.

The last unique attribute of the RHS is the cable management design. The compact end effector was designed to fit into a 50.8 cm x 50.8 cm (20in x 20in) window representing the ability to reach within the umbilicals associated with the tool trays. Typically PaR routes all cables internal to the equipment, but the large volume of INL and robot cables required to support the tool interfaces precluded this and all cables had to be routed externally on the equipment. A nested cabling configuration mounted along the mast allowed for the collapsing Z-mast tubeset to operate freely. The cables were then divided into 3 bundles and routed externally down to the quick change tool plate. Enough service loop was included to allow for +/- 185° of rotation.

All axes of the RHS have over travel protection with four levels of redundancy: soft limits in both the software and servo drives, mechanical limit switches and, finally, hard stops mounted on the equipment. The rotate assembly utilizes a sliding switch and stop to accommodate the additional 5° of travel beyond the normal half rotation required.

Table II details the performance capability of the RHS and the weld robots.

Table II. Performance Specifications

AXIS	TRAVEL	MAX SPEED	CAPACITY
X-Bridge	1208 cm (475.63”)	9 m/min (30 ft/min)	
Y-Trolley	657.2 cm (258.75”)	9 m/min (30 ft/min)	
Z-Mast	426.7 cm (168”)	4.5 m/min(15 ft/min)	
Theta 1 (Rotate)	+/-185°	2 rpm	2177 kg (4800 lb) Change Plate 2721.5 kg (6000 lb) Dead Lift
RHS 4350 Manipulator (DC)	158.75 cm (62.5”) overall reach	2 rpm (pivots)	102 kg (225 lb) Hand 453.6 kg (1000 lb) Shoulder Hook
Weld Robot 4350 Manipulator (Servo)	226 cm (89”) overall reach	2.17 rpm (pivots)	30 kg (66 lb) Hand

CONCLUSION

While designing the RHS and weld robot equipment had its challenges as described above, the equipment was successfully built, powered up, and tested. With recovery and several layers of redundancy designed into the system, the WPCS weld robots and RHS are expected to safely and solidly contribute to our country’s need to safely store spent nuclear fuel and high-level waste. The welding robots and RHS were installed in the demonstration facility at INL in fall 2007.

REFERENCES

1. CMAA Specification #70, Rev. 2004 “Specification for Top Running Bridge & Gantry Type Multiple Girder Electrical Overhead Traveling Cranes”