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Yucca Mountain Waste Package Closure System

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Abstract – *The current disposal path for high-level waste is to place the material into secure waste packages that are inserted into a repository. The Idaho National Laboratory has been tasked with the development, design, and demonstration of the waste package closure system for the repository project. The closure system design includes welding three lids and a purge port cap, four methods of nondestructive examination, and evacuation and backfill of the waste package, all performed in a remote environment. A demonstration of the closure system will be performed with a full-scale waste package.*

I. INTRODUCTION

A large percentage of our nation's spent nuclear fuel (SNF) and high-level waste (HLW) generated since we engaged in nuclear research and energy production over 50 years ago is sitting in temporary storage throughout the country. The Nuclear Waste Policy Act in 1982 mandated that the U.S. Department of Energy (DOE) find a suitable location, build, and operate a geological repository for disposal of this waste. In July of 2002, approval was given to begin preparing a license application for the Nuclear Regulatory Commission to operate a repository at Yucca Mountain, Nevada. Facilities and process equipment are currently being designed as part of the license application and for subsequent construction. SNF and HLW will be received at the repository, loaded into waste packages (WPs), sealed, and placed into the mountain drifts.

Idaho National Laboratory has been tasked with the development, design, and demonstration of a full scale prototype system for sealing the WPs. This article describes that system called the Waste Package Closure System (WPCS). Closure operations include welding the lids in place, evacuating and backfilling the WP with an inert gas, nondestructive examination of welds, stress mitigation, material handling, maintenance, and automated control. Figure 1 illustrates the system in action, welding a lid in place.

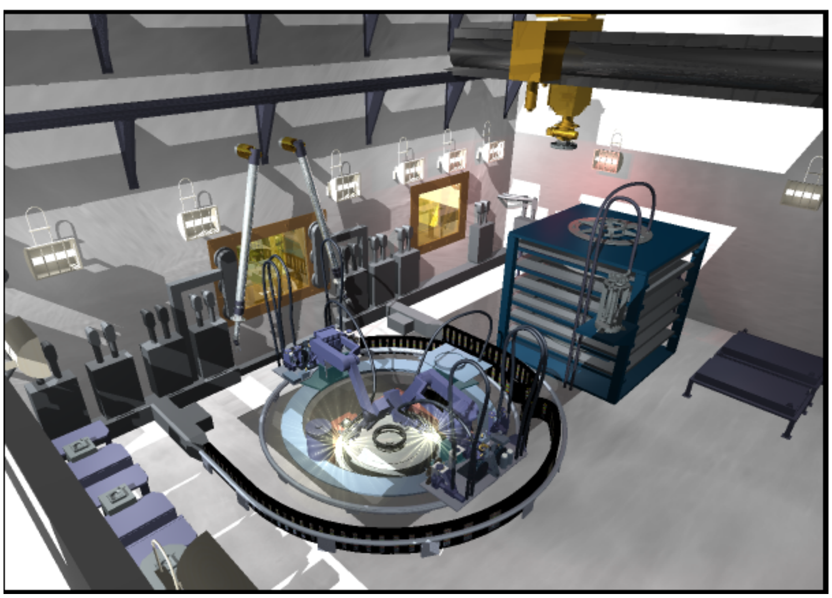

Fig. 1. An illustration of the Yucca Mountain Waste Package Closure System welding a waste package lid in place.

II. WASTE PACKAGE

Describing the closure system begins with a description of the WP, which consists of two cylindrical containers, one nested inside the other. The inner container, known as the inner vessel, provides the primary structural integrity for containing the waste and is designed to the *ASME Boiler and Pressure Vessel Code*, Section III, Division 1 (Section III, Division 3, which provides requirements for SNF storage systems, did not exist during initial WP design. The Nuclear Regulatory Commission accepts the use of Division 1 for SNF storage It has a 50.8-mm (2.0-in.)-thick wall of 316 stainless steel. This inner vessel resides within a secondary container that provides substantial corrosion resistance and, therefore, is called the outer corrosion barrier. It has a 20.3-mm (0.80-in.)-thick wall of alloy C-22.

Each package has three lids as seen in the broke out cross section in Figure 2. The inner lid, common to the inner vessel, is mechanically captured in place by a unique one-piece spread ring that is seal-welded in place with two fillets. Unlike more traditional multi-piece spread rings, the one-piece ring simplifies the installation and has only one end splice weld. The middle and outer lids are both welded to the outer corrosion barrier. The middle lid joint is a fillet weld, and the outer lid joint is a full-thickness narrow-groove weld.

The closure system must accommodate nine different sizes of WPs. However, the wall thicknesses and the dimensional geometry of the closure joints as shown in Figure 2 remain the same for all WPs. The WP diameters range from about 1.2 to 2.1 m (4 to 7 ft), and the heights range from about 3.4 to 5.8 m (11 to 19 ft). In the center of the inner lid is a purge port for evacuating and backfilling the WP with helium. The purge port is sealed with both a threaded plug and a cap that is welded in place over the top of the plug.

III. WASTE PACKAGE CLOSURE SYSTEM

Weld closure of the WP, as shown in Figure 1, is performed remotely by robotic arms inside a shielded closure cell. Radiation levels at the top of the WP preclude any personnel access during operations. Therefore, the closure operations are performed fully remotely. In addition, the operations are largely automated to meet the required cycle time of completely closing a WP in 44 hours or less. This aggressive cycle time is driven by the current backlog of SNF and HLW, which will require closure of approximately 12,000 WPs.

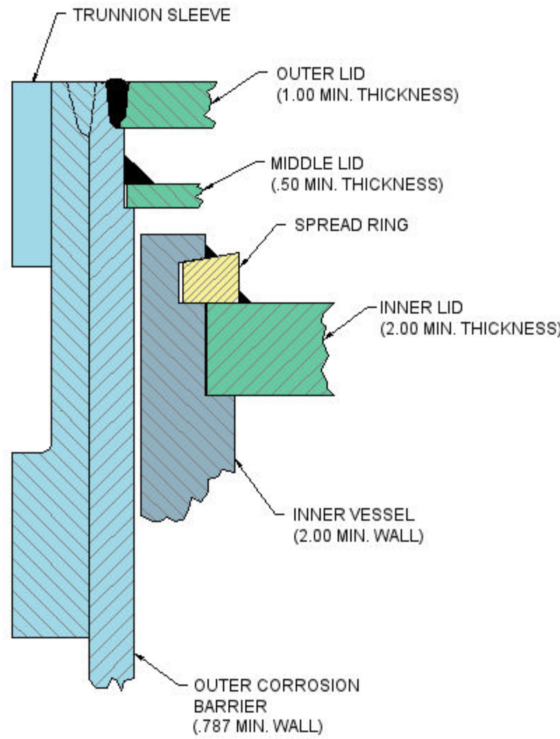

Fig. 2. A broke out cross section of a waste package showing the lid weld joints.

Recently, DOE has proposed to have the utilities canisterize their SNF prior to delivery to Yucca Mountain, which will eliminate the contamination associated with loading bare fuel into the WPs. Also, the canisters may incorporate shield plugs to reduce the radiation. Because the plans for canisterizing SNF have only recently been proposed, the closure system described here is the baseline system for the worst case conditions. Possible modifications to the baseline system to capitalize on reductions in radiation and contamination are discussed briefly in the section titled Improvements.

The description of the WPCS is organized topically according to the primary and support operations listed below.

Primary Operations:

- Welding the lids to the WP
- Evacuating and backfilling the WP with helium
- Inspecting the integrity of the welds
- Repairing any weld defects
- Mitigating the residual stresses in the surface of the outer lid weld.

Support Operations:

- Material handling
- Maintenance
- Control and data management.

III.A. Welding

Notice in Figure 1 the WPs do not actually enter the closure cell for welding. Instead, they are transferred beneath the floor and aligned below a 9-foot-diameter hole in the floor referred to as the process opening. Although there are different WP heights, they are always staged approximately 10 inches below the floor.

Concentric with the process opening is a circular bearing that rotates two robotic arms around the head of the WP. With changeable end effectors, these robotic arms perform the welding, the weld inspection, and the weld repair. With two arms working simultaneously the welding and inspection time is cut in half, a major boost in process cycle time for two time-intensive operations. Other cycle time benefits of the system are (a) the arms conveniently fold back out of the way providing access to place subsequent lids without lifting or moving the system and (b) the single system will weld all WP diameters.

The arms are fixed on the bearing 180 degrees apart. Welding 180 degrees apart helps minimize weld distortion. The bearing makes only half a revolution to complete a single circumferential weld. The cable management around the perimeter of the bearing does allow for 200 degrees of rotation to provide some overlap at the ends of the rotational stroke.

At the base of each weld robot is a weld tray carrying the different end effectors for welding, inspection, and repair (see Figure 3). Each end effector has its own independent umbilical cable. They are independent rather than shared to avoid a large number of switches that would compromise both function and signal reliability. The umbilicals are external versus internal to the robots. This avoids custom-wired robots and makes both the robot and the umbilicals easier to replace.

Figure 4 shows a photograph of the welding end effector. Cold wire gas tungsten arc welding was dictated as the process to be use based on its reliability. Each weld tray has a single welding end effector that can remotely load the correct filler wire for the 316 stainless steel or Alloy 22 welds.

Rather than manipulating the mass of the robot to control the end effector's radial position, oscillation, and arc gap, these fine movements are incorporated into the end effector, which has less mass, making it easier to move and control. The robotic arm is used primarily to orient the axis of the end effector at the nominal radius. A laser seam tracker on board the end effector controls the fine radial position and makes adjustments using the oscillation axis. Automatic voltage control on board the end effector provides fine control of the arc gap.

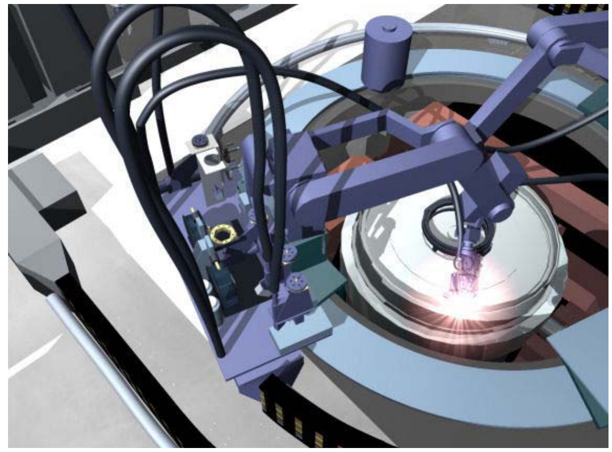

Fig. 3. An illustration showing the robot welding and the detachable weld tray located behind it with end effectors and umbilicals.

Fig. 4. Photograph of the welding end effector showing the welding torch, wire feeder, fore and aft arc viewing cameras, and seam tracker.

The laser seam tracker projects a laser stripe on the lid weld area and based on the reflection of the stripe generates a cross-sectional view of the surface. This cross-sectional view is how the system identifies and tracks the weld groove. Knowledge of the groove geometry allows evaluation of joint fit up prior to welding and during welding, and allows an adaptive fill routine to be employed that varies the weld deposition rate so the groove is filled evenly. The seam tracker maps the welds with sufficient resolution, allowing it to serve also as the visual inspection system.

The weld torch is custom designed to provide unique features beneficial to this application. The torch is rated for 300 amps at 100% duty cycle and is air cooled. Typically, air-cooled machine torches have a maximum rating of approximately 150 amps at 60% duty cycle. An air-cooled torch is required to eliminate the possibility of torch cooling water accidentally being released into the WP, which could cause a criticality concern.

Another unique feature of the torch is the tungsten stick-out, which is adjusted by moving the gas cup versus the electrode. The fore and aft weld cameras are aligned to view the weld at the tip of the electrode. If the electrode were moved, the cameras would have to be mechanized to move with it. The design avoids this complexity by keeping the electrode and cameras stationary and remotely raising or lowering the gas cup to adjust the electrode stick-out. The welding end effector has proven to work well on nearly 2500 feet of test welding to date.

III.B. Inerting

After the inner lid has been seal welded in place, the inner vessel is evacuated and backfilled with helium. The addition of an inert gas inhibits internal corrosion, improves heat transfer between the contents and the WP, and provides a medium for leak testing the inner vessel closure welds. At the center of the inner lid is the port for inerting the WP with a preinstalled threaded plug as seen in Figure 5. When the plug is partially backed out as shown, it exposes side holes in the plug that allows evacuation and backfilling of the WP.

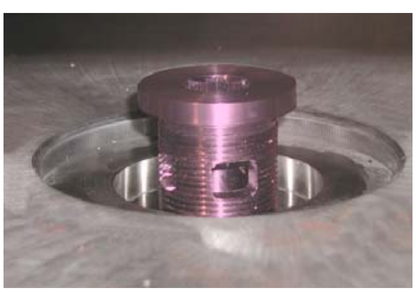

Fig. 5. A purge port plug is shown partially backed out of a lid to expose the side holes that allow inerting of the waste package. (Lavender color is for clarity.)

Inerting is done with a purge port tool that connects to a handling ring on the lid with a bayonet interface and seals to the lid with an inflatable seal. It has a motor-driven spindle that unthreads the purge plug to expose the side holes for inerting and then torques the plug after backfilling. Two remote valves regulate the evacuation and backfill functions. The WP is sealed with one atmosphere of helium pressure above ambient conditions.

After the plug is seated in the lid, it is leak tested by the purge port tool. Seals on the purge port tool isolate the region above the plug. This region is evacuated and monitored by a mass spectrometer for helium leaking past the plug. The mass spectrometer is located outside the closure cell in the operating gallery. Once the plug proves to be leak tight, a cap is welded over the plug as a secondary seal.

III.C. Inspecting Weld Integrity

The WPCS uses four different nondestructive techniques for inspecting the integrity of the closure welds; leak detection, visual, eddy current (ET), and ultrasonic (UT) inspections. Each closure weld is inspected using at least two of these methods, with the exception of the purge port cap. The inner lid welds are inspected visually prior to the leak test, and the middle lid is inspected first visually and then by eddy current. The outer lid is inspected by three methods; visual, eddy current, and ultrasonic. All three outer lid inspections are performed before and after the completed weld undergoes stress mitigation, which is discussed in a subsequent section. The purge port cap weld receives only a visual inspection, but the plug beneath it is leak tested as discussed in the previous section. Between each weld pass of the outer lid, the weld is inspected ultrasonically to detect any defects as early as possible and thereby reduce the time spent removing material for repair.

Leak testing of the inner lid spread ring weld is performed after a successful visual inspection, but before the purge port is sealed to allow for repeat leak testing if a weld repair is needed. The process for leak testing the inner lid spread ring welds is essentially the same as that described in the previous section for leak testing the purge plug. The leak test tool (shown in Figure 6) is a ring with a cupped cross section that seals along the edges to isolate the region above the welds. This region is evacuated and monitored by a mass spectrometer for helium leaking through the welds. Multiple leak test rings are required to fit the different WP diameters.

As mentioned in the welding section, the high resolution of the laser seam tracker on board the welding end effector makes it effective for performing the visual inspections. Profiles of surface cross sections generated by the seam tracker are used to evaluate geometric criteria like reinforcement height and effective throat size, and defects like underfill, undercut, and cracks.

Eddy current is effective for inspecting surface and near surface defects. An excited coil is used to inductively couple with the electrically conductive material being examined. Cracks, porosity, and inclusions are detected and sized by monitoring changes in the coil impedance. The WPCS eddy current probes use an array of multiple, independent, closely packed, small coils to increase the spatial coverage while scanning, which reduces scan time and probe wear. The face of the probes must be configured to closely conform to the profiles of the surfaces they are used to inspect so that the coils are kept close to the surface for effective coupling. The surface profiles of the three applications of eddy current in the WPCS lead to three probes; one for the middle lid weld, one for the outer lid weld, and one for repair groove cavities (discussed in the weld repair section). The middle lid and repair groove probes are collocated on a single end effector, and the outer lid eddy current probe is collocated with the outer lid ultrasonic probe on another end effector.

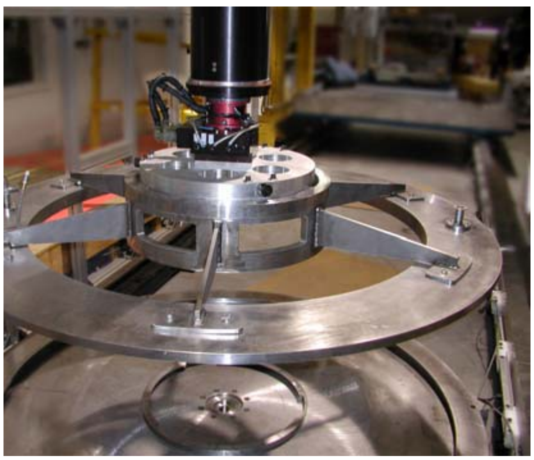

Fig. 6. A leak test ring being lowered by a z-mast on to a mockup of the inner lid.

The ultrasonic process uses sound waves to inspect for subsurface defects in the full volume of the weld. The closure system uses phased array ultrasonic probes to minimize the number of probes and the scan time. A phased array probe has many individually controlled, closely packed transducer elements. By controlling the firing patterns of the multiple transducer elements, the phased array technology offers the flexibility of linear scanning, beam steering, and variable depth of focus to achieve a thorough volumetric examination. One phased array probe can examine the weld from multiple angles during a single scan.

The ultrasonic probes incorporate a special membrane having sound transmittal characteristics similar to water for coupling the sound waves between the probe and the WP. The special membrane does still require a thin film of water between it and the WP, but the amount of water required is significantly reduced and thereby minimizes any criticality concern.

Inspection data are evaluated against project specified acceptance criteria based on the ASME Boiler and Pressure Vessel Code that meets the robustness and longevity requirements of the WP. Commercial software is used for the visualization of the large amounts of data collected during inspection, which simplifies interpretation and evaluation of the data.

III.D. Brushing and Repairing Welds

Wire brushing to clean the surface of welds or grinding out weld defects is performed by a separate end effector located on the tool tray. Depending upon the job to be performed, the robotic arm manipulates the end effector to grasp the appropriate wire or grinding wheel. A vacuum system is integrated into the end effector to capture removed material.

When grinding out a defect, the geometry of the repair groove will be closely controlled so only a single eddy current probe with a matching profile is required for examining the repair groove surface. An iterative grind and examination approach will be used to verify complete removal of the defect before welding.

III.E. Stress Mitigation

After the outer lid groove weld is completed and has passed initial visual, eddy current, and ultrasonic inspections, the weld under goes a stress mitigation process to remove residual tensile stresses in the surface of the weld. Residual tensile stresses that set up in the weld as the molten material cools and shrinks have the potential to initiate cracks that could propagate with corrosion. Compressing the surface of the weld and adjacent margins replaces any tensile stresses with compressive stresses that resist crack initiation. One of two processes, laser peening or burnishing, will be selected for inducing the compressive stresses.

III.F. Material Handling

The placement of lids, the maneuvering of tools, and the handling of materials inside the closure cell is predominantly performed by a programmable, bridge-mounted telescoping z-mast, known as the remote handling system (RHS). A quick change tool interface plate located at the end of the mast is used for remotely coupling with the different tools inside the closure cell.

Additional handling capability is provided by a 5-ton bridge crane, a teleoperated manipulator arm for the RHS, and a pair of masterslave manipulators with telescoping reach. These handling options have limited roles during normal operations, but are available to assist if needed. They are particularly important in dealing with off normal events.

Materials are usually transferred into the cell using a rail mounted transfer cart. The transfer cart is driven by a linear synchronous motor that provides an advantage in a contaminated environment. The field windings of the commercial motor are located in a trough beneath the floor, totally isolated from the cell environment. They are easily extracted from outside the cell if a repair is required. On the underside of the cart inside the cell is a large magnet that interacts with the field windings to move the cart.

III.G. Maintenance

Maintenance of tools and refurbishment of weld trays is performed outside the closure cell in a glovebox. The transfer cart shuttles tools and materials between the glovebox and the closure cell through a shielded tunnel. The tunnel serves as a position for radiological surveying and decontaminating equipment being transferred to the glovebox.

Under normal circumstances only an annual entry will be made into the cell to perform general maintenance; intermediate maintenance and repair of movable equipment will be performed in the glovebox. The WPCS has a duplicate set of weld trays allowing one set to undergo refurbishment in the glovebox while the other set is in use. The glovebox is equipped to check out the operations of the weld tray end effectors and the functions of all other tools prior to releasing them into the closure cell.

III.H. Control and Data Management

Control of the WPCS is managed at six workstations in the operating gallery as seen in Figure 7. All six workstations are essentially identical both physically and in terms of software. One is for supervisory control, two for welding operations, two for weld inspection operations, and one for controlling material handling operations.

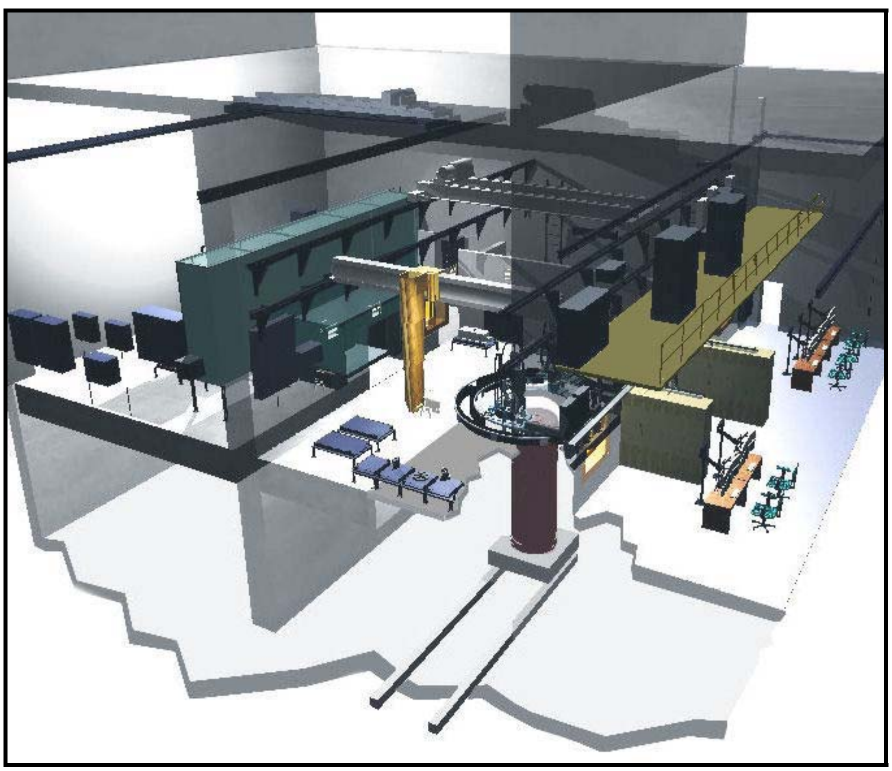

Fig. 7. An overview of the WPCS; at the center is the closure cell, to the right is the operating gallery with the control work stations, to the left is the support room with the maintenance glovebox, and below is a waste package in position for closure.

The WPCS will be controlled on three levels of hierarchy. The highest supervisory level oversees all closure operations and interfaces with other operations in the facility. A process control level, which includes the workstations, allows operators to interface in real time with the components at the third level. An Ethernet network joins all three levels together. The individual hardware and software components are modular to allow addition or subtraction of units as necessary. Process data will be collected from the components, temporarily stored at the process level, and either transferred to the facility database as a permanent quality record via the supervisory level or discarded. Off-the-shelf software will be used for control and modified where necessary to meet the specific task.

The workstations may have four to six monitors on which the operator can choose to display camera images, data, or documents of choice. There are multiple fixed position cameras inside the closure cell, the glovebox, and the support room that have pan, tilt, and zoom capabilities, which operators can select and control for their particular operations. Task-specific cameras are provided on board the welding end effector, the general purpose cleanup tool, and the RHS. Up to four video streams can be recorded simultaneously for documenting operations.

The camera on the RHS is integrated with special commercial software making it a machine vision system capable of robot guidance. It has the ability to make precise measurements and recognize specific patterns. This capability is used to identify the location and orientation of the WP in the process opening, which is essential information needed by the welding robots and the RHS. The system is also used to identify the orientation of tools, allowing the RHS to couple precisely with them without requiring special fixturing of the tools. An example of this benefit is seen with the transfer cart. No fixturing is required on the cart to accurately position all the different items it transports, nor does the cart position have to be precisely controlled.

An independent safety system constantly monitors the closure system interlock and emergency circuits. It uses state-of-the-art redundant voting techniques and self diagnostics to ensure high reliability.

IV. IMPROVEMENTS

There are currently four improvements being considered that would simplify closure operations. First are modifications to the lid joint designs to provide additional clearance for installing lids and yet simplify welding by minimizing gap widths that must be bridged by the welds. The proposed joint modifications would give all three lids a 1/4-inch diametric clearance for installation, and limits weld gaps to 1/16-inch or less.

The second proposed improvement is a new design for the inner lid that would eliminate the spread ring and simplify welding of the inner lid. The concept uses bayonet lugs to mechanically retain the lid similar to the lid of a household pressure cooker. When the lid is installed, the lugs on the lid and vessel vertically slide past one another and then rotation secures the lid lugs beneath the vessel lugs. A lip on the top surface of the lid extends over the lug pockets in the side wall of the vessel. The lid is sealed by a single fillet weld between the lip on the lid and the side wall of the vessel. Besides eliminating the spread ring, the concept reduces the circumferential fillet welds from two to one and eliminates the weld required to seal the spread ring ends.

A new design for the purge plug has been introduced that combines the purge port cap and plug into a single piece. Benefits are it eliminates a separate part that must be placed, and the cap is self restrained so it does not have to be held down to keep it from lifting when tack welded.

A concept introduced and under consideration by the DOE is to have the SNF prepackaged in sealed containers before it is loaded into a WP. The sealed containers, known as transportable, ageable, and disposable canisters may also incorporate shielding to decrease radiation. This concept reduces the baseline environment to one of low radiation and low contamination and offers several design and operational simplifications. Nonradiation-hardened equipment could now be used. Periodic human access may be possible for hands-on assistance. Also, without contamination, the glovebox would not be required and maintenance would be simplified. The existing baseline design of the WPCS is easily tailored to the new environment. The automation would be retained for meeting the demands of high throughput, high reliability, and high quality.

V. SUMMARY OF UNIQUE FEATURES

In designing the Yucca Mountain WPCS, many new and unique features were introduced that may be directly applicable, or the seeds for new ideas in other nuclear closure operations. Table 1 is an abbreviated summary of unique features of the WPCS discussed in this paper. Feel free to contact any of the authors for additional information.

TABLE 1. WPCS Unique Capabilities

Carousel Welding System	High closure throughput is achieved by mounting two robotic arms on a carousel with changeable end effectors to perform the welding, weld inspection, and weld repair. All three operations are performed by a single system, and the system never needs to be relocated to make room for installing the lids as would be required by the more traditional center pivot type of system.
Radiation-hardened Arc Viewing Cameras	Radiation-hardened cameras and arc viewing cameras have existed, but the two features will now be available in a single commercial camera as a result of the WPCS development.
Movable Gas Cup to Adjust Tungsten Stick-out	When using arc viewing cameras, adjusting the stick-out by moving the tungsten will require the same adjustment of the camera to preserve the alignment of the cameras with the weld pool. Moving the gas cup to adjust the stick-out allows the tungsten and camera relationship to remain fixed.
Ultrasonic (UT) Water Membrane	A unique membrane that transmits UT sound waves similar to water significantly reduced the amount of water needed as a couplant for UT inspections.
300-Amp Air-Cooled Torch	A 300-amp, 100% duty cycle, air-cooled torch was developed for the WPCS to reduce the presence of water in the closure cell; commercial air-cooled machine torches are typically limited to 150 amps at 60% duty cycle.
Weld Joint Geometry	Weld joint geometry was introduced that meets the competing demands of clearance for assembly, but minimizes gaps for weldability.
No Spread Ring to Retain Inner Lid	Rather than use a spread ring to retain the inner lid, recessed lugs on the underside of the lid do the job and simplify the weld.
Combined Purge Port Plug and Cap	Combining the cap with the purge port plug simplifies the placement and welding of the cap.
Linear Synchronous Motor for Transfer Cart	Using a linear synchronous motor to drive the transfer cart allows it to be isolated from the contaminated environment where the cart operates.

ACKNOWLEDGMENTS

The WPCS system is being designed by the Idaho National Laboratory (INL), under the direction of Bechtel SAIC Company, LLC, the Department of Energy's prime contractor for the Yucca Mountain project. (INL is performing the work under DOE contract number DE-AC07-05ID14517). Credit for the WPCS rests not with the authors, but a team of experts in remote nuclear operations, welding, and control systems.