Versatile Remediation Module Final Operational Testing Results

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Integrated Waste Management System
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February 28, 2020
M3SF-20OR020408014
ORNL/SPR-2020/1434

ACKNOWLEDGMENTS

This report was prepared with significant contributions and reviews from Bruce Bevard at Oak Ridge National Laboratory and Josh Jarrell, Colleen Shelton-Davis, Denis Clark, Eric Larsen, and Michael Clark at Idaho National Laboratory.

The authors would also like to thank Steve Reeves, John Kessler, Brian Gutherman, and Adam Levin for their expert input and guidance during the initial concept development; Paris Cornwell for his technical assistance in the neutron diffraction experiments; Craig Mauer and Christopher Crawford for their technical support in the design; and Doug Kyle for performing the repair welding.

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SUMMARY

This report documents the work performed under the Spent Fuel and Waste Disposition Program for the US Department of Energy Office of Nuclear Energy. This work was performed to fulfill the Level 3 milestone M3SF-20OR020408014, "Versatile Remediation Module Final Operational Testing Results," within work package SF-20OR02040801.

Oak Ridge National Laboratory (ORNL) successfully demonstrated the Versatile Remediation Module (VRM), a prototype module designed and built by ORNL for performing the on-site remote repair of welded stainless-steel storage containers for spent nuclear fuel and high-level radioactive waste. This report describes the VRM prototype and its design features, components, qualification tests, operational procedures, and demonstration results to support continued long-term storage or off-site transportation of spent nuclear fuel and high-level radioactive waste currently stored in storage containers. A remote (i.e., 100 ft away from the simulated radiative environment) demonstration of the VRM was successfully performed on a full-scale mock-up welded stainless-steel canister. The VRM is designed with features to accommodate remediation techniques beyond those currently selected and described in this report. Therefore, many of the VRM's features could benefit other remote nuclear or nonnuclear applications. The VRM is envisioned to serve as a development center to facilitate and enhance the further development of new remediation technologies.

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ACRONYMS

AC	Alternating Current
ASME	American Society of Mechanical Engineers
AVC	arc voltage control
BPVC	ASME Boiler and Pressure Vessel Code
CW	cold wire
DOE	US Department of Energy
DPC	dual-purpose canister
DSS	dry storage system
e-stop	emergency stop
GTAW	gas tungsten arc welding
GUI	graphical user interface
MERF	Mobile Examination and Remediation Fixture
NDE	nondestructive examination
ORNL	Oak Ridge National Laboratory
VRM	Versatile Remediation Module

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SPENT FUEL AND WASTE DISPOSITION PROGRAM

VERSATILE REMEDIATION MODULE FINAL OPERATIONAL TESTING RESULTS

1. INTRODUCTION

Since 2019, efforts have been underway to develop capabilities for remote remediation of a dry storage canister, if needed. To support this effort, Oak Ridge National Laboratory (ORNL) is developing a Mobile Examination and Remediation Fixture (MERF) with functions and capabilities for the onsite remediation of nonconforming canisters and casks [1]. Once developed, the MERF (illustrated in Figure 1) would be intended to perform necessary processes to ascertain the condition of dry storage canisters and perform repairs when necessary. Specifically, the MERF would be functionally designed to inspect a canister using various nondestructive examination (NDE) methods, excavate material surrounding identified flaws, and perform repair welds on the affected area of the canister. To achieve a complete remediation, the MERF is anticipated to have at least three modules: the weld repair module, the NDE module, and the surface preparation module. The MERF would comprise tool modules to allow remote remediation operations (e.g., inspecting, welding, grinding) to be performed on the canister’s surface. The canister would be placed on a rotary table for coarse positioning to allow the canister to rotate in clockwise and counterclockwise directions. The modules would be placed on a lifting platform and positioned in front of the remediation area. The modules and the canister would be surrounded by shielding to protect operating personnel from radiation exposure, and the MERF would accommodate canisters with nominal diameters ranging from 1,701.8 to 1,917.7 mm (67 to 75.5 in.). ORNL successfully built and demonstrated the first module, hereafter referred to as the *Versatile Remediation Module (VRM)*.

Radiation levels at the surface of storage containers preclude any personnel access during remediation operations. Therefore, remediation operations must be performed remotely. Additionally, operations should be largely automated to meet quality and time requirements. This report describes the design, features, components, and operational tests of the VRM that enable the remote and automated delivery of remediation tools to any point on a dry storage canister’s cylindrical wall. This report also presents procedure qualification results, operational sequence, and the results of a remote (i.e., 30 m from the simulated radiative environment) demonstration of the VRM on a full-scale mock-up welded stainless-steel canister.

1.1 Background

The continued storage and off-site transportation of spent nuclear fuel currently stored in dry storage systems (DSSs) could be affected by the aging of the confinement boundary and by the impact of aging on system performance (Figure 1) [2–8]. Hence, remediation capabilities must be developed that could be used at multiple storage installations. These capabilities would permit repairs to existing DSSs for continued storage or off-site transportation, if necessary. Previous work [9–13] identified and evaluated mitigation and remediation methods and techniques for welded stainless-steel canisters and their components as part of the confinement boundary. Chatzidakis et al. concluded that five options are available: (1) use as is, (2) overpack, (3) repair, (4) rework, and (5) replace (i.e., repackage).

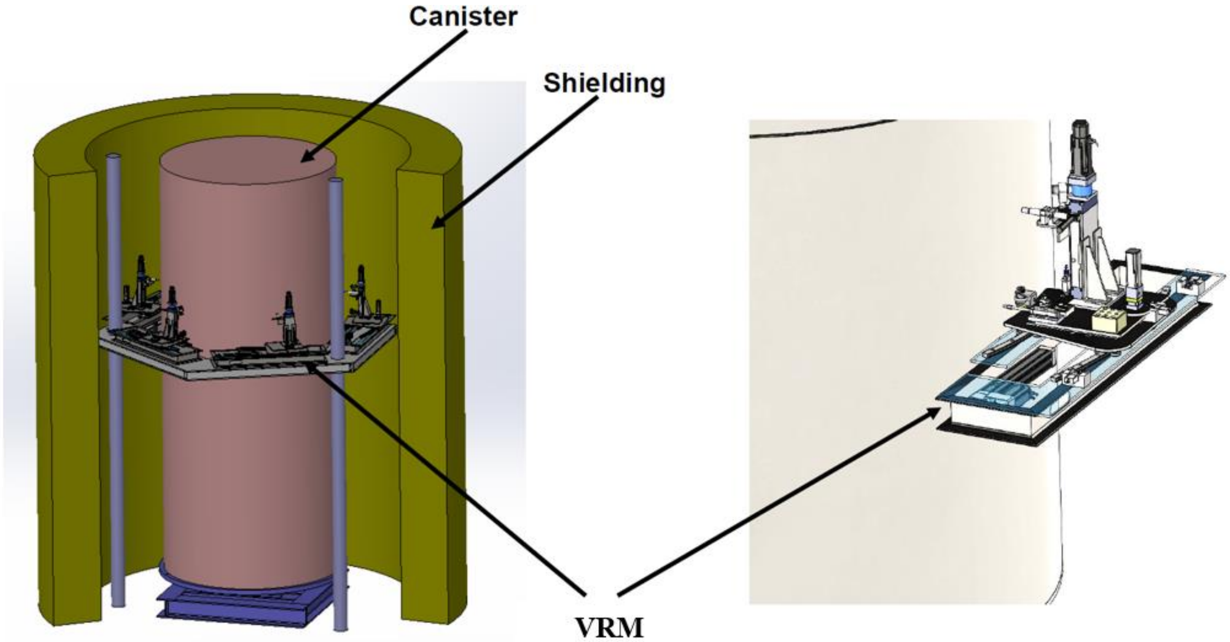

Figure 1. MERF concept. *Note: This is an early concept for illustration purposes and is subject to change.*

1.2 Purpose

This report describes a prototypic fixture that includes a remediation module capable of accurately delivering remediation tools to any point on the canister cylindrical wall. Once developed, this module will be used to promote the development and demonstration of commercial remediation tools using American Society of Mechanical Engineers (ASME)-qualified procedures to the extent practical [14]. Before being used to possibly remediate a dual-purpose canister (DPC), all equipment must undergo rigorous testing in an environment that is as realistic as possible.

This report summarizes the main results from the VRM development and demonstration task that was part of the MERF project. Details on VRM functions and requirements, equipment specifications, design features, and qualification procedures can be found in the following milestone reports.

- DOE 2019a. *Versatile Remediation Module Design and Specifications*. Prepared for DOE, Integrated Waste Management Program, D. Giuliano, J. Slade, and S. Chatzidakis (ORNL). Report no. M5SF-19OR020408012, Revision 0, 2019.
- DOE 2019b. *Versatile Remediation Module and Mock-up Canister Design and Specifications*. Prepared for DOE, Integrated Waste Management Program, D. Giuliano, J. Slade, and S. Chatzidakis (ORNL). Report no. M4SF-19OR020408017, Revision 0, 2019.
- DOE 2019c. *Initial Fabrication of Versatile Remediation Module and Supporting Components*. Prepared for DOE, Integrated Waste Management Program, S. Chatzidakis (ORNL). Report no. M4SF-19OR020408018, Revision 0, 2019.
- DOE 2018a. *Weld Repair Qualification and Demonstration*. Prepared for DOE, Integrated Waste Management Program, S. Chatzidakis, R. Miller, W. Tang, J. Chen, and J. Scaglione (ORNL). Report no. M4SF-18OR020408016, Revision 0, 2018.

- DOE 2018b. *Past Experience in Repairing Dry Storage Systems*. Prepared for DOE, Integrated Waste Management Program, S. Chatzidakis, and J. Scaglione (ORNL). Report no. M4SF-18OR02040801, Revision 0, 2018.

Storage container remediation is an active development area, and advanced remediation technologies might become available soon. Therefore, the VRM was designed with features to accommodate remediation techniques beyond those currently selected and described in this report. The VRM could serve as a development center to facilitate and enhance further development of new remediation technologies. Furthermore, many VRM features could benefit other remote nuclear or nonnuclear applications.

1.3 Scope

This report forms part of the technical basis needed to support MERF design studies, safety assessment studies, performance demonstrations, and potential performance specifications. It includes: (1) VRM and supporting equipment design details, (2) equipment layout, and (3) qualification tests, operational procedures, and demonstration results.

The VRM only applies to components that are part of the confinement boundary and that no longer conform to the regulatory requirements for continued storage or transportation off-site. The scope of this report does not include nonconformances related to other DSS components that do not represent the confinement boundary and that are more easily remediated or replaced, such as vertical concrete overpacks, vertical metal overpacks, and horizontal concrete storage modules for canisters. The scope also does not include DSSs before entering service (i.e., preservice).

This document may be updated as appropriate to incorporate specific changes in technical scope or performance requirements that could have significant program implications. Such updates may include changes to the program mission, operational capabilities, and potential stakeholder requests.

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2. DESIGN DESCRIPTION

This section summarizes the main VRM design features and focuses on the main VRM components (i.e., vertical, angular, and radial actuation). The design does not include any shielding or support structures, which will be determined later in the design process following a structural and shielding analysis.

2.1 Versatile Remediation Module

The VRM's main configuration and components are illustrated in Figures 2–9. The VRM consists of a gas tungsten arc welding (GTAW) weld torch for performing the required repair welds. During repair welding operations, the welding module applies parallel linear weld beads in a singular direction spaced apart by half the diameter of the weld bead; the filler rod must lead the welding arc. During welding operations, the amount of standoff will be dynamically controlled by the arc produced. This is accomplished through arc voltage control (AVC) software.

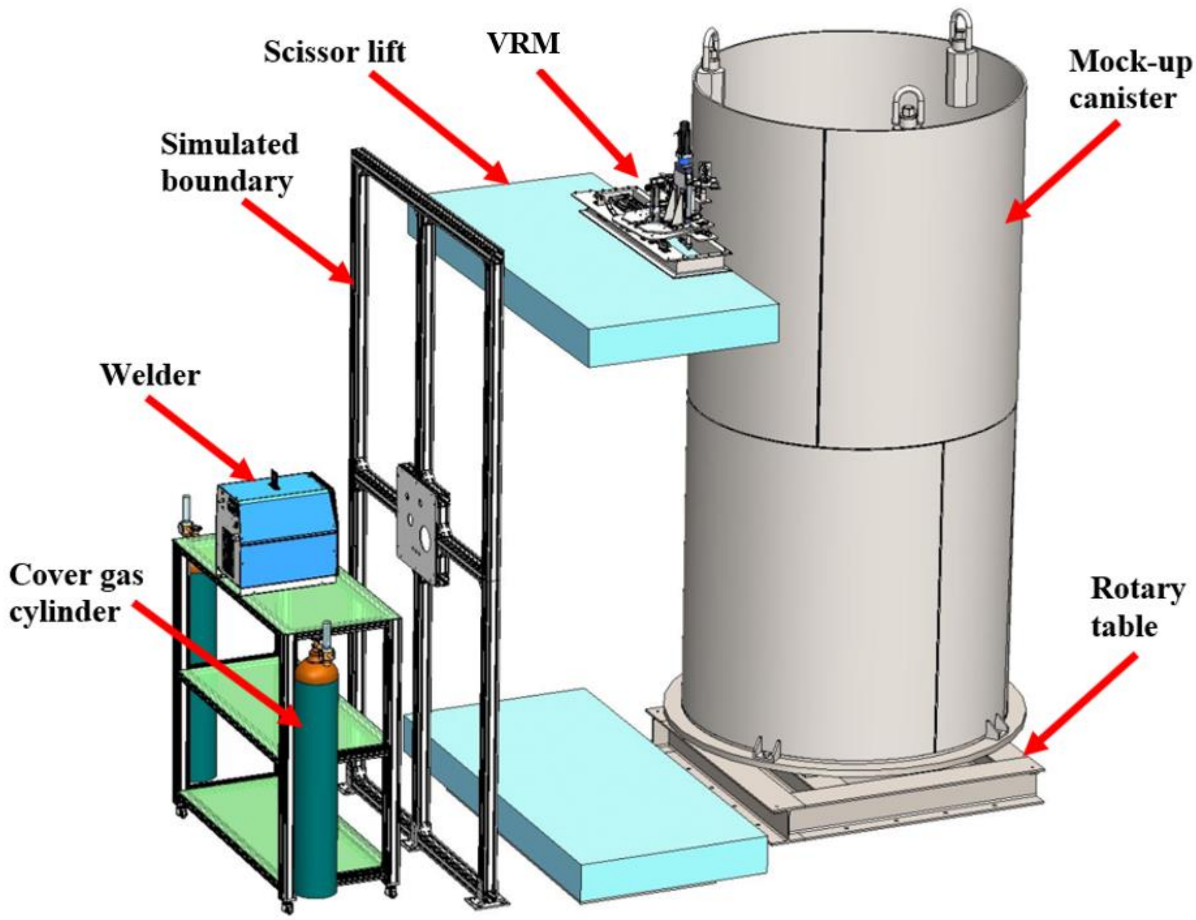

Figure 2. Equipment configuration during the development and demonstration phase.

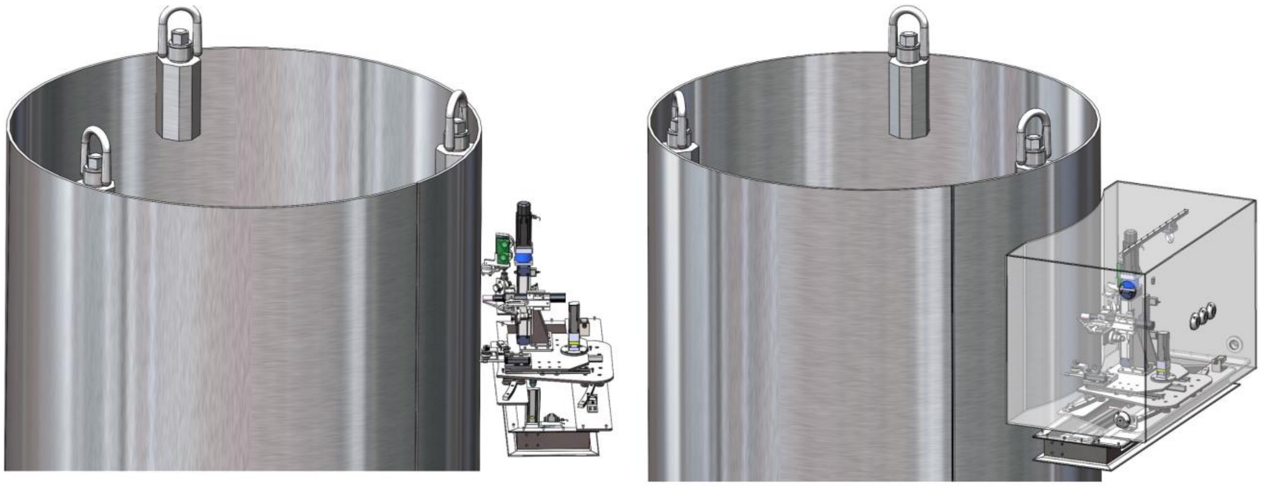

Figure 3. VRM concept without (left) and with (right) fume exhaust box.

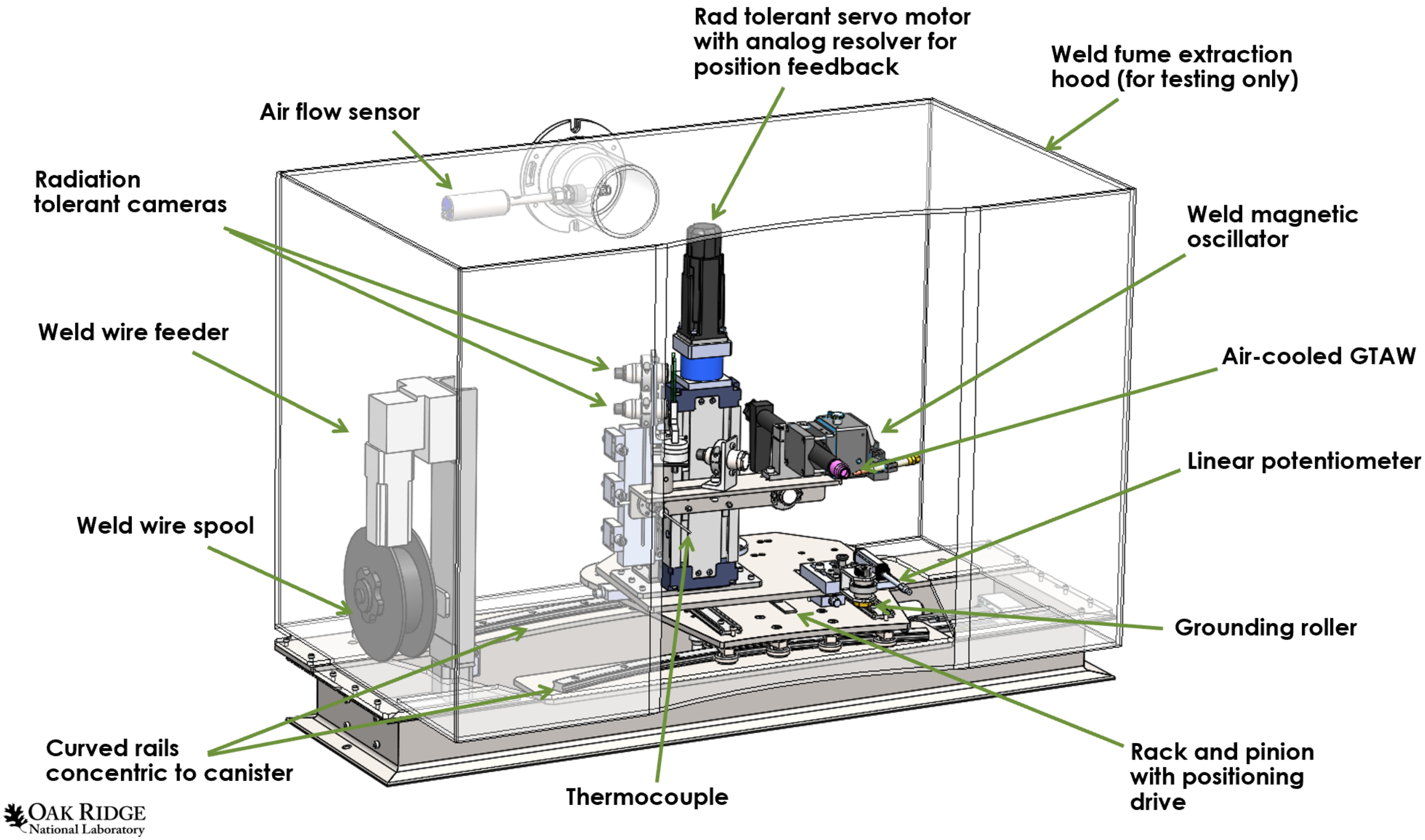

Figure 4. VRM main features and components.

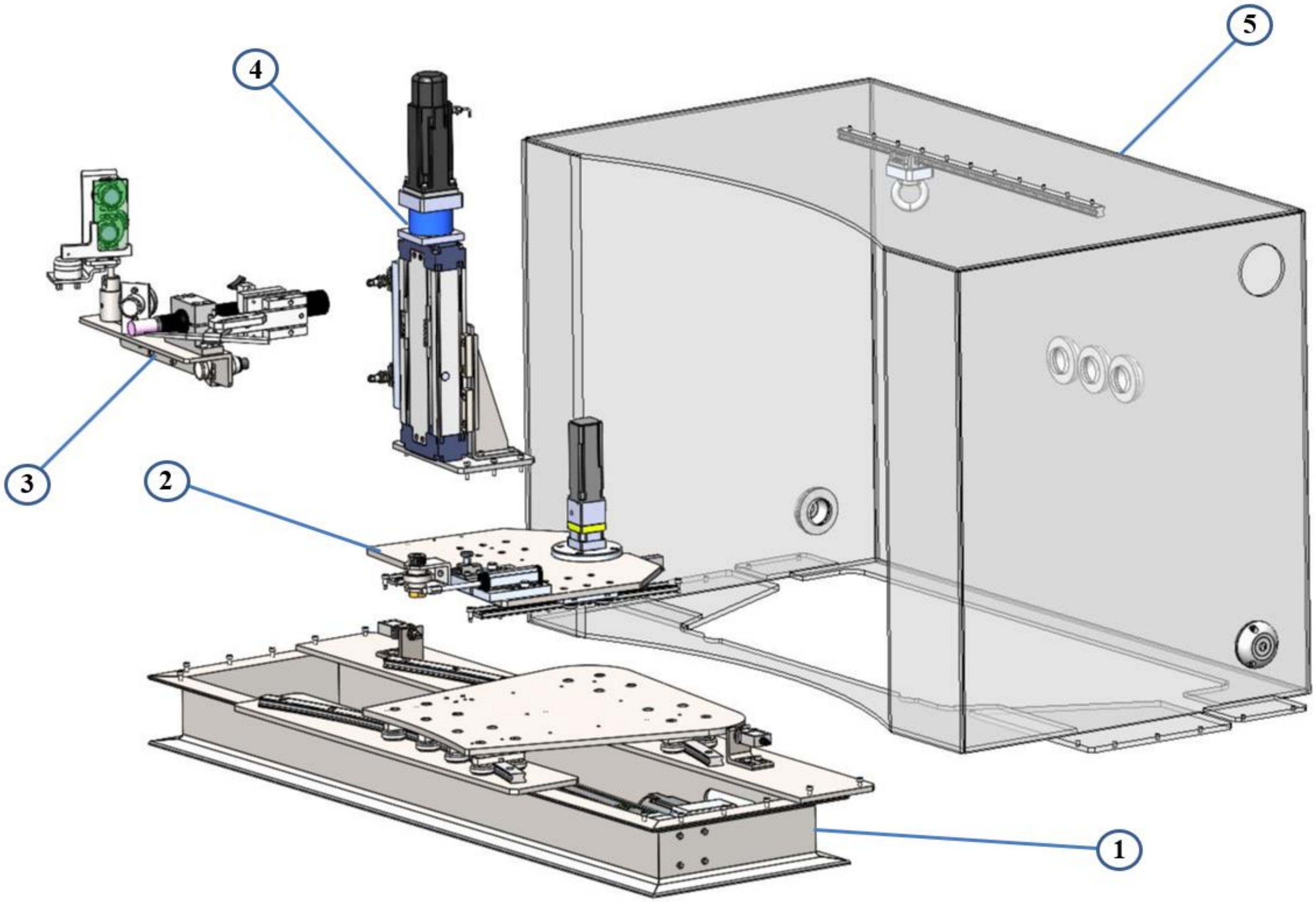

Figure 5. VRM exploded view: (1) support base, (2) radial carriage and actuator, (3) welding head, (4) welding head base and axial actuator, and (5) fume extraction box.

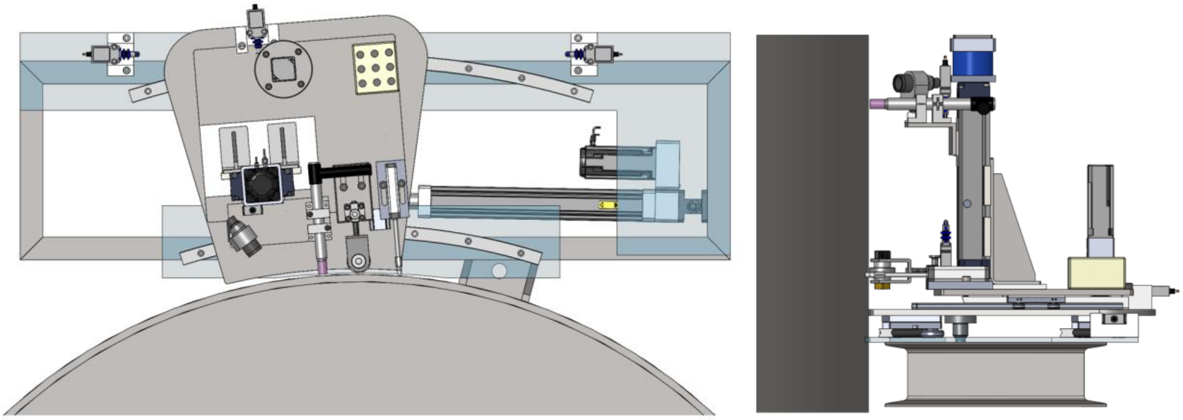

Figure 6. VRM top view (left) and side view (right).

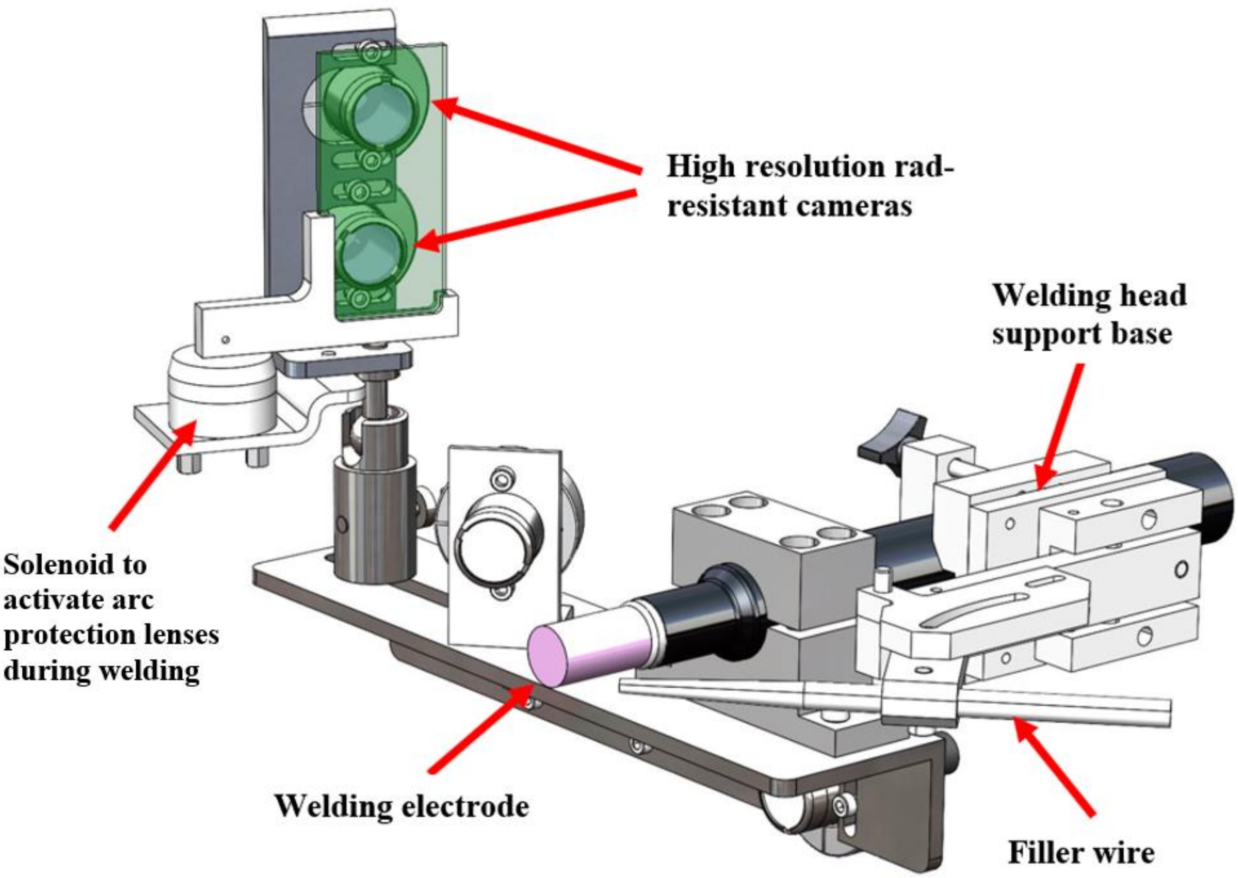

Figure 7. Welding head details.

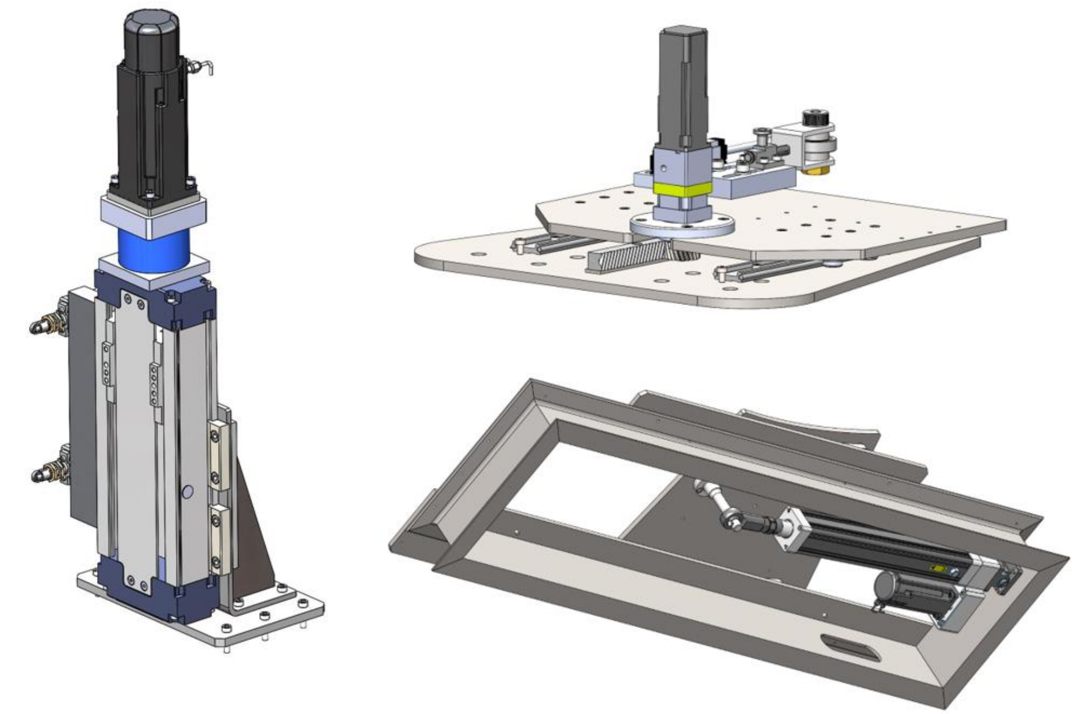

Figure 8. Vertical actuator (left), radial actuator (top right), and angular actuator (bottom right).

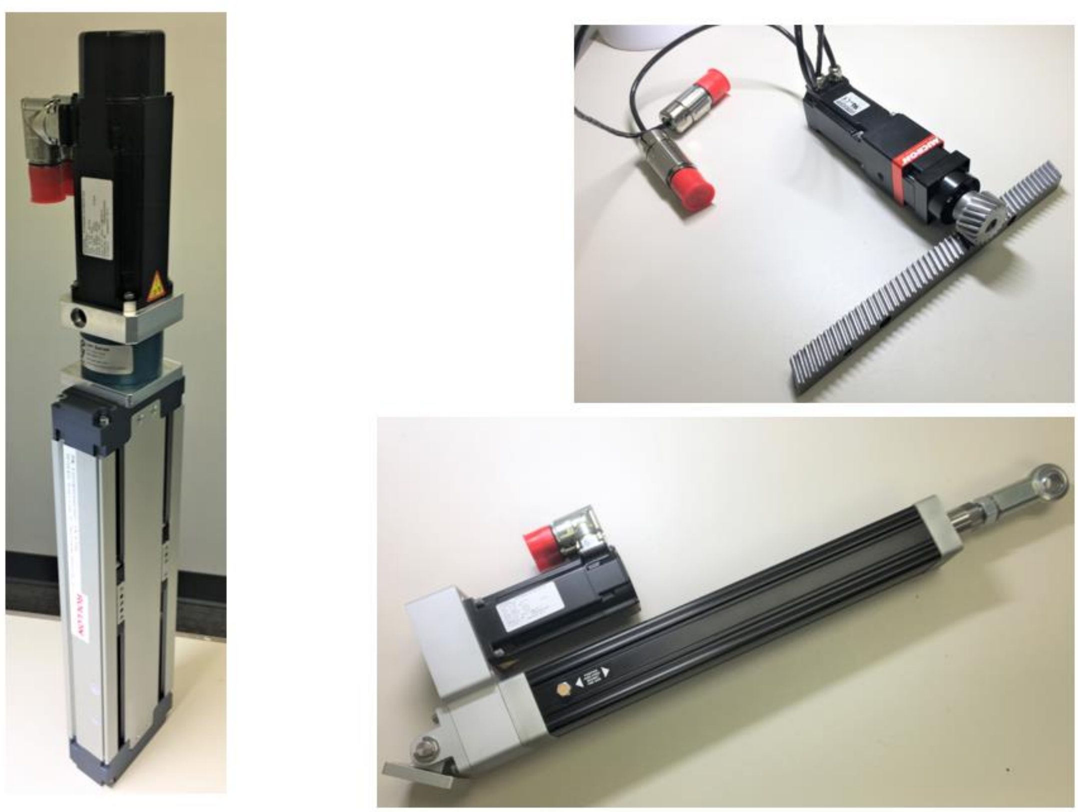

Figure 9. Photos of equipment. Vertical actuator (left), radial actuator (top right), and angular actuator (bottom right).

2.1.1 Equipment Summary

The main equipment comprising the VRM are summarized below.

- **Welding module:** Allows the GTAW welding torch to be operated. Allows movement in three directions and includes motors, limit switches, cameras, rails, carriages, junction boxes, and welding torch.
- **Scissor lift:** Supports and positions the welding module at the height of the area in which the repair will occur.

  Note: the scissor lift is a temporary piece of equipment. It will be replaced by a lifting platform to allow elevation of all the remediation modules. The scissor lift will not be part of the final MERF.
- **Fume exhaust system:** Removes fumes generated during the repair process.

  Note: this system is deployed on the mock-up platform to protect personnel working on VRM development. This system will not be part of the final MERF.
- **Wire feeder assembly:** Provides and guides the weld filler wire to the torch.
- **Welder:** Provides power to the welding torch.
- **Instrumentation and control:** Comprise the sensors, motor drives, and controllers needed to control the VRM.

The supporting equipment necessary for testing and demonstration are summarized below.

- **Mock-up canister:** A full-scale mock-up canister that uses the same materials and fabrication methods as a real canister with embedded flaws to evaluate and demonstrate the VRM.
- **Rotating table:** Positions the canister to present the flaw or defect area in front of the welding module. Allows the canister to rotate in clockwise and counterclockwise directions.
- **Operating workstation:** An operator workstation with a graphical user interface (GUI) displayed on a monitor and controlled by a combination of a joystick, keyboard, and a mouse. The layout of the GUI is similar to that of commercially available products so that there is a minimal operator learning curve.

2.1.2 Design Features

The VRM achieves coordinated motion through three modes of actuation: radial, vertical, and angular. All modes of actuation are protected by mechanical stops and limit switches. In the radial actuation, a linear proximeter is used to determine the initial standoff from the canister. Two onboard rad tolerant cameras are mounted to allow a direct view of the front and back of the weld. To allow active weld viewing, a solenoid actuated shutter is used to move weld glass in front of the camera lenses when the arc is struck. The welding operation is performed by the onboard automation weld torch with a weld wire feeder. The welding machine used is a programable GTAW welder with computer control input capabilities.

The VRM can perform a repair weld to the surface of a dry storage canister after it is prepared by the grinding module. It adds sufficient weld filler material to cover the entire area affected by the stress corrosion cracking or any other detected defect. Additional design features are as follows:

- **Cover gas:** Ultrahigh-purity argon gas used as a cover gas.
  Basis: Argon gas provides an inert atmosphere in which the weld can occur. The ultrahigh purity reduces unwanted reactions and contaminants in the weld.
- **Wire feeder:** An additional weld wire feeder is required to sit beside the module to provide the weld wire for the operation. Future efforts will attempt to incorporate the weld wire feeder into the module.
  Basis: A small, compact weld wire feeder will be required to be mounted next to the welding module. The weld wire feeder will feed the weld wire to the welding location.

- **Viewing:** Two onboard radiation-tolerant cameras with solenoid-actuated shutters are required for positioning and weld viewing.
  Basis: Two cameras are required to view the front and back of the welding operation. To view the active welding operation, weld glass shutters are actuated via a solenoid over the camera lenses.
- **Operating space:** The repair space in which the welder will perform the repair weld will be 6 × 6 in.
  Basis: Given the space restrictions, the largest acceptable area that can be worked on is 6 × 6 in.
- **Radial actuation:** The welding module allows for a radial actuation of at least 8 in. to accommodate DPCs of smaller diameters.
  Basis: Given the space restrictions, the welding module can extend to reach at least 8 in. toward the center of the canister.
- **Actuation motors:** Motors used for the module are AC servo motors with drivers capable of moving the respective parts of the module up to 0.5 in./sec.
  Basis: Motors are required for radial actuation and vertical actuation. AC synchronous servo motors with onboard resolvers and AC drivers are the most advantageous for this application since they do not require additional sensors to provide positioning information to the control system.
- **Standoff sensors:** A radiation-tolerant linear proximeter is used to determine standoff.
  Basis: The linear proximeter is used for gross positioning. Once the weld torch is within an inch of the canister, the torch will provide the standoff information
- **Protection:** Limit switches are required for each end of the three axes of travel.
  Basis: To ensure that the linear transfer carriages do not travel past the limits of their respective rails, limit switches and mechanical stops are included for each of the three axes of travel.

The general arrangement drawing of the VRM is shown in Figure 10.

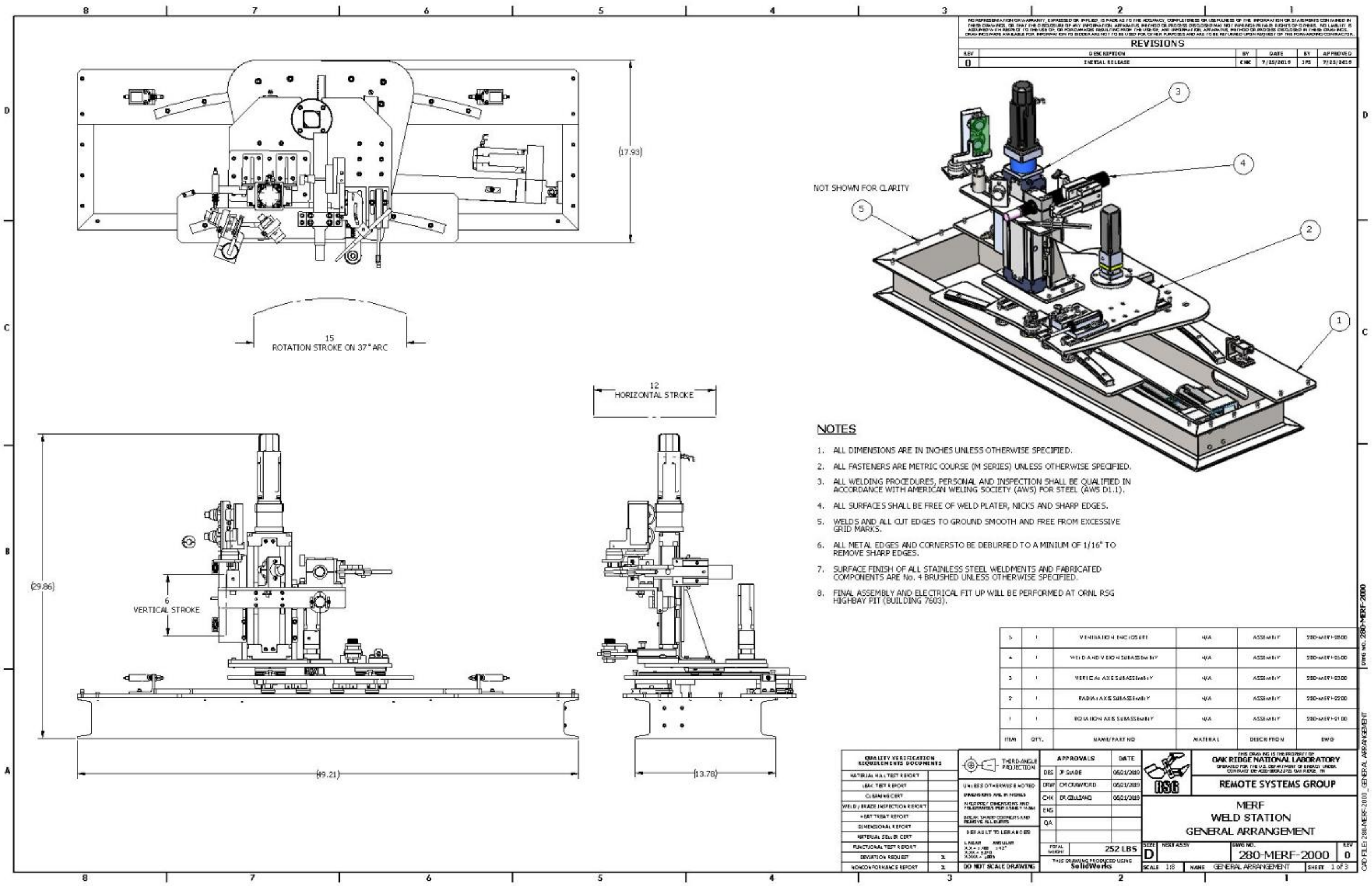

Figure 10. Sample engineering drawing showing key VRM details (dimensions in inches).

2.2 Control System

The VRM remote control system has two levels. The first level comprises software modules that allow the operator to remotely supervise, manage, and control the VRM from a workstation (e.g., positioning equipment, initiating weld-related operations). The second level comprises hardware modules, which include motor controllers, position controllers, automated welding controllers, switches, and more. The VRM control system takes positioning information from the three motor resolvers on the module and ultrasound proximeter to provide the system with the weld torch's position information. Using the position information, the control system initiates a preprogrammed welding sequence at the proper time to provide enough gas purge time, strike an arc, and initiate the weld wire feed roller to start the weld bead at the proper location. The control system is divided into individual components with a central controller coordinating the devices and the remote operators. Figure 11 provides an example architecture of the control system.

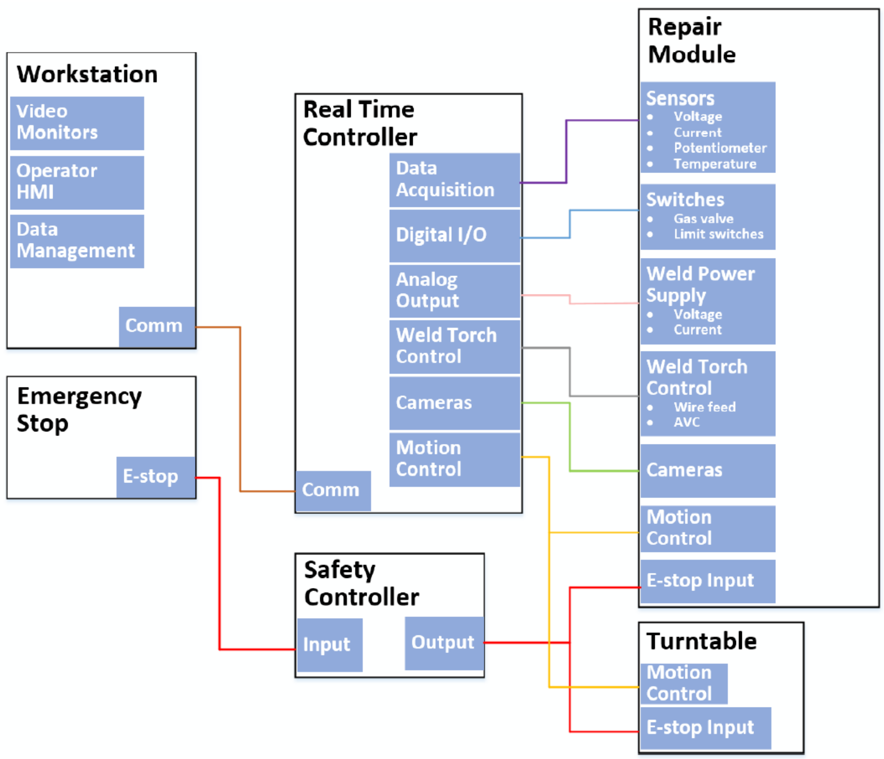

Figure 11. Control system architecture. The top-level components for the purpose of control are the real time controller, operating workstation, repair module, turntable, safety controller, and hardware e-stop.

A real-time controller is used to integrate all the process controls into a cohesive architecture, switch on/off, and provide data acquisition from sensors, weld power supply control, weld torch control (via AVC), video input from cameras, and motion control of all motors. The real-time controller interfaces directly with the operator workstation to display data and control information to operators by using standard ethernet communication, which allows the operator workstation computer to be remotely located. This interface is an ideal architecture for operating equipment in a hazardous environment since the real-time controller can be located near the VRM, minimizing the cable lengths needed to control the hardware, whereas the operation workstation can be in a safe area to minimize hazards to the operator.

The operator workstation has a GUI displayed on a monitor and is controlled with a combination of a joystick, keyboard, and mouse. This workstation provides the operator with a level of familiarity with the computer system that reduces training needs. The operator video monitors the interface with the cameras. The operator workstation includes video and data recording capabilities for the recording and playback of operations in the event of off-normal conditions that need further analysis, as well as for a permanent record of the processes performed. Finally, an "operator manual override" capability was designed into the system and joysticks for the manual control of all motors.

The safety controller is the primary safety control that prevents and inhibits operations that could significantly affect safety. The safety controller is independent of the real-time controller and operator workstation and operates on independent inputs and outputs, preventing any interference between the controls systems. The emergency stop (e-stop) system is integrated with the safety controller and provides inputs that the operator can use to shut down the system in the event of off-normal conditions that could have safety implications. This e-stop system consists of mushroom-type e-stop switches located at the operator workstation. Importantly, motion cannot automatically be reinitiated upon clearing the e-stop switches. Motion can only be reinitiated upon command by the operator after the e-stop condition is cleared.

The control system architecture is shown in Figures 11 and 12.

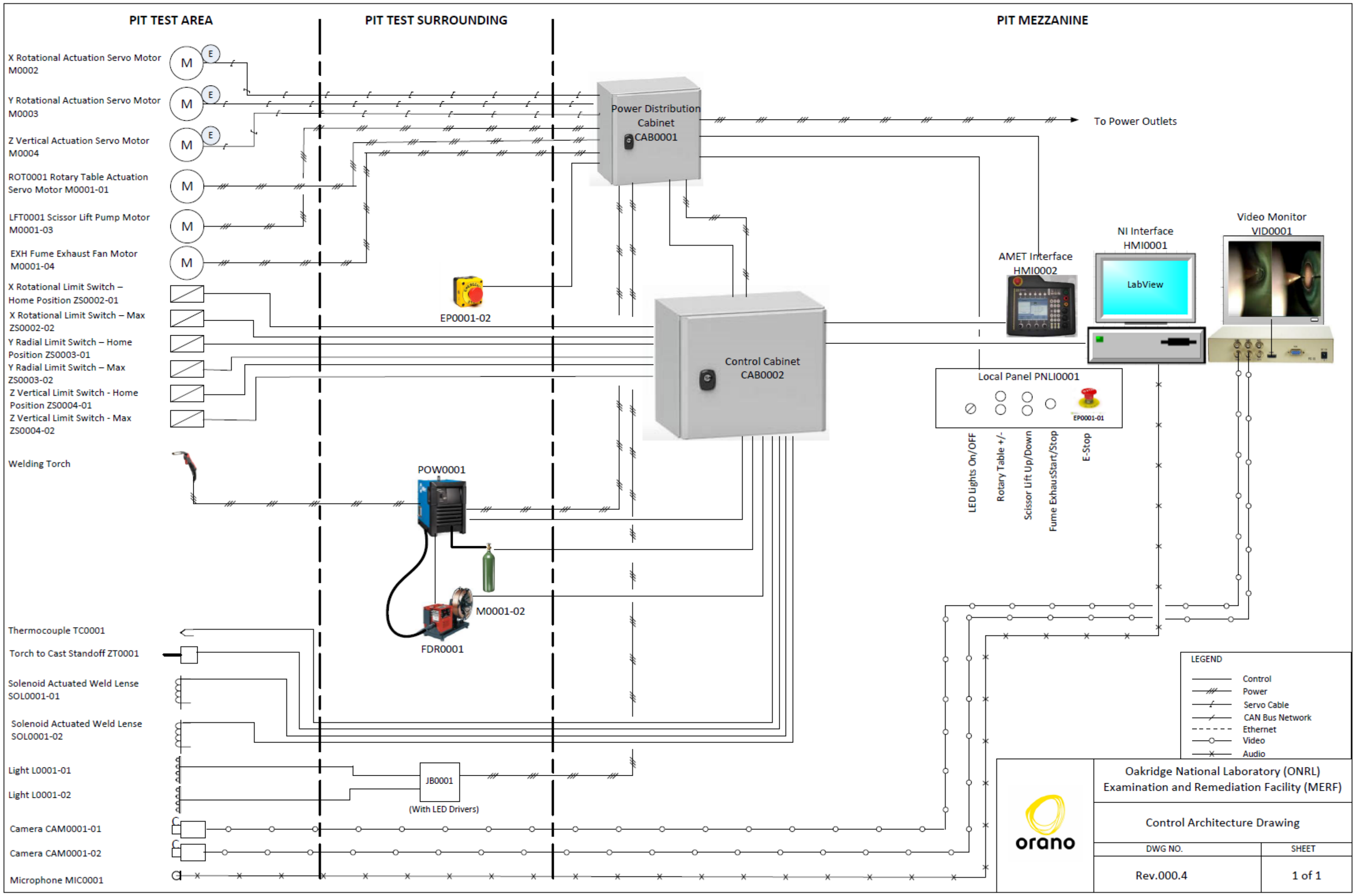

Figure 12. Control architecture.

2.3 Mock-Up Canister

A full-scale welded 304/304L stainless-steel mock-up canister using the same materials and fabrication as a real canister was manufactured to test and demonstrate the VRM. Currently, nearly all storage canister designs use 304 or 304/304L stainless steel and are constructed predominantly using multi-pass arc welding with a double-V edge preparation. The mock-up canister comprises two cylindrical shells, each 1,819.2 mm (71.625 in.) long and 1,828.8 mm (72 in.) in diameter. After adding the 19.05 mm (0.75 in.) thick bottom plate, the mock-up canister is 3,657.6 mm (144 in.) high, 1,828.8 mm (72 in.) in diameter, and 12.7 mm (0.5 in.) thick. The canister has two longitudinal welds and one circumferential weld to join the two cylindrical shells. Another circumferential weld joins the canister shell with the bottom plate. Each shell was formed by cold forming a plate into a cylinder, then making a single longitudinal weld to form the cylinder. Each weld was subjected to visual and dye penetrant inspections. Mock-up canister details are shown in Figure 13.

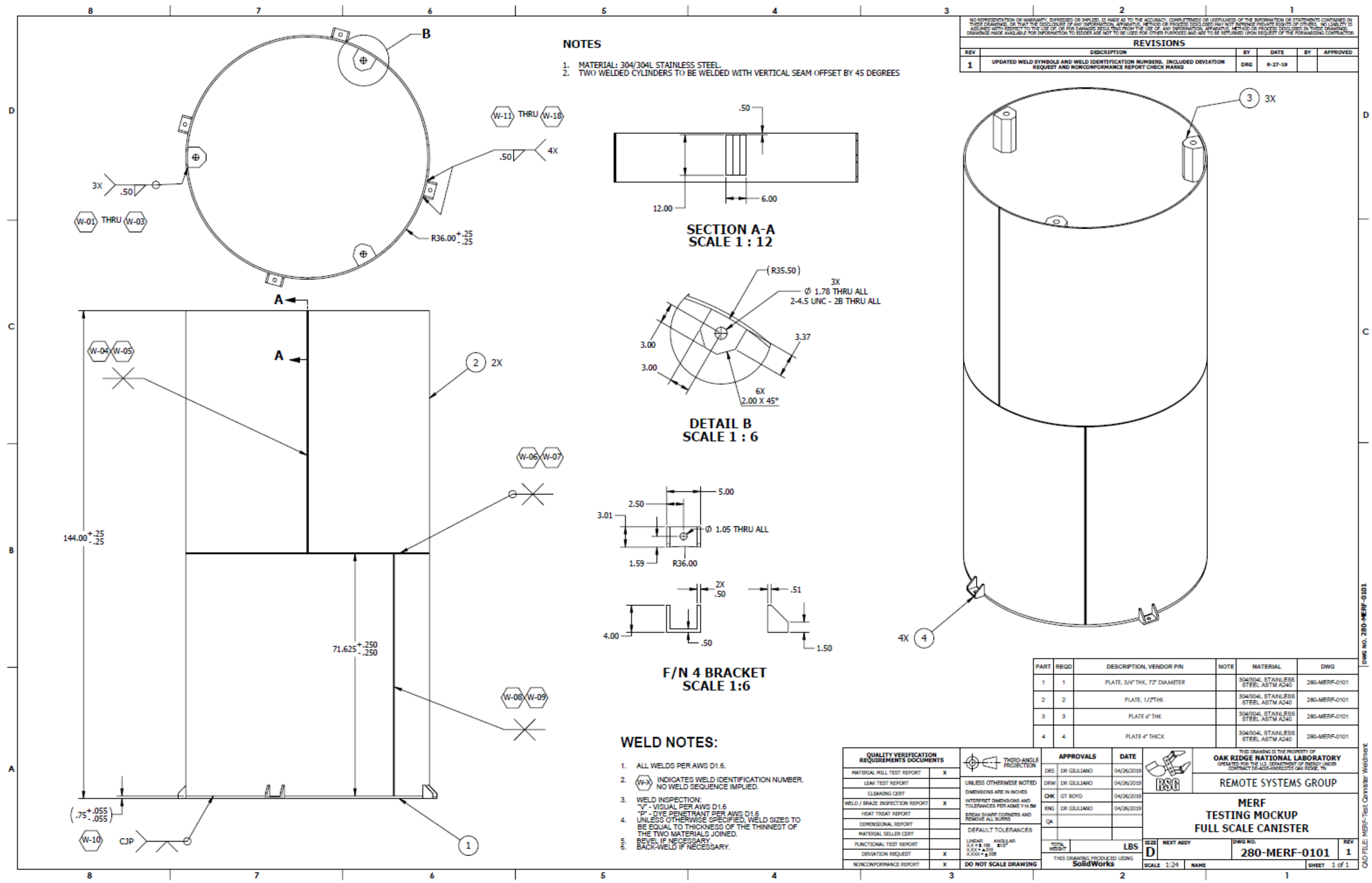

Figure 13. Mock-up canister details (dimensions in inches).

2.4 Mock-Up Rotating Table

A rotating table is a necessary component of the MERF. The rotating table and a vertical actuation platform are needed for gross positioning to place the flaw in front of the various modules for examination and repair. The rotating platform is required to support the weight of the fully loaded DPC while rotating it to the desired location. To test the VRM capabilities, a stand-alone rotating table was designed for VRM testing at ORNL.

The rotating table allows the canister to rotate in clockwise and counterclockwise directions and is needed to position the canister to present the flaw/defect area in front of the VRM. The rotating table consists of three main components: a table, a bearing/drive, and a support structure. The table is constructed of powder-coated 3.81 cm (1.5 in.) thick A36 carbon steel with a hole in the center. The table is designed for rigidity as opposed to strength and can support the canister without any sizable deflection. The slewing ring bearing is rated for 136,000 kg (300,000 lb) under static loading conditions and 36,287 kg (80,000 lb) in dynamic loading conditions. The support structure is constructed of steel structural beams, and its main purpose is to distribute the load from the rotating table over a larger area. Using the support structure, the rotating table is floor-limited at 8,164 kg (18,000 lb). For seismic considerations, 42 cm (16¾ in.) bolts are used to mount the rotating table to the floor. Rotating table details are shown in Figure 14.

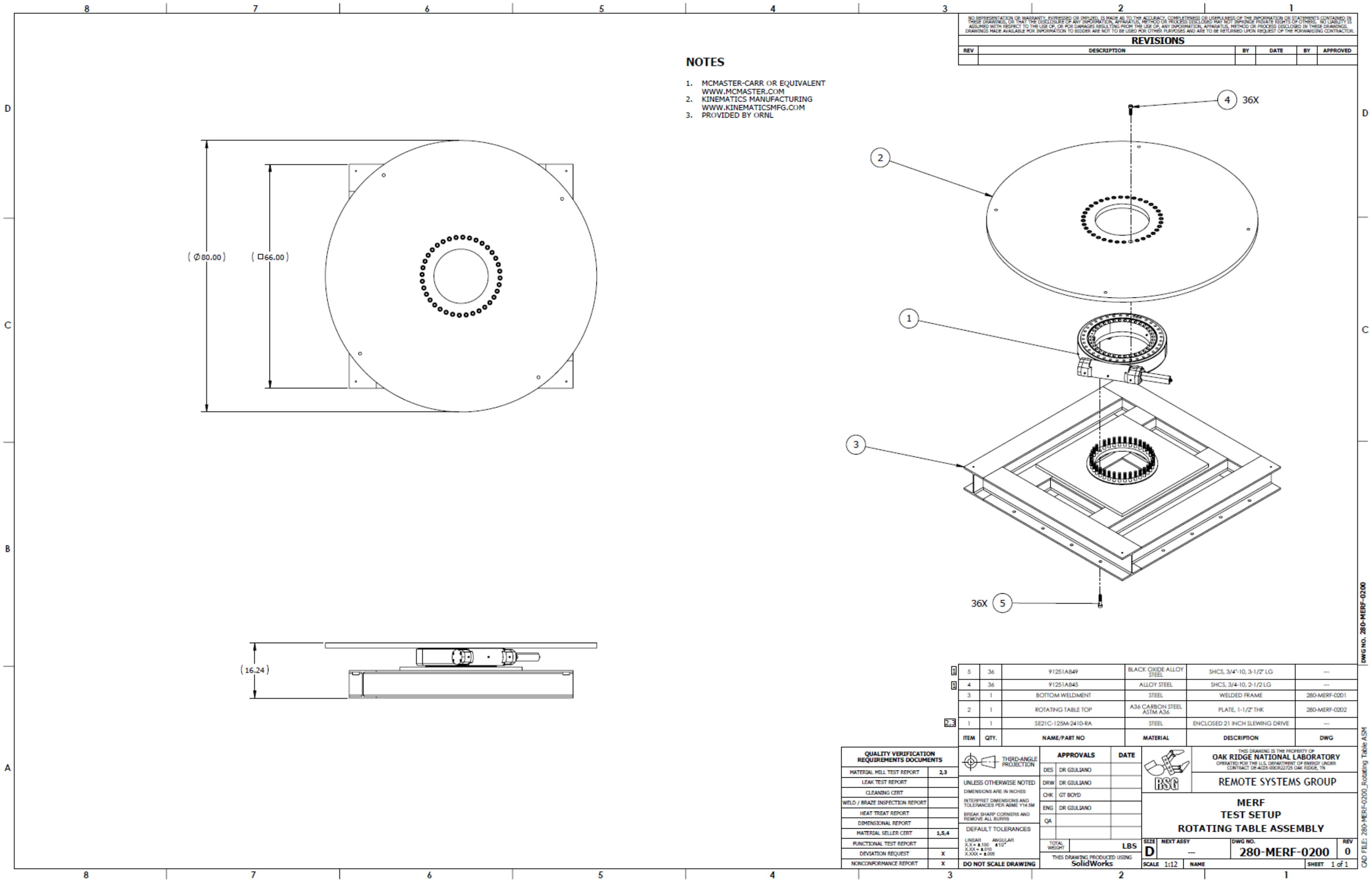

Figure 14. Rotating table assembly details (dimensions in inches).

2.5 Equipment Layout

The prototype is assembled in the “pit” of Building 7603 and is operated remotely from the adjacent mezzanine with no direct line of sight to the pit (Figure 15). The motion and weld controls equipment are housed in a control panel/cabinet that is adjacent to a seated operator workstation. This layout simulates the remote location of the electronics from the field radiative environment. All development tasks occur in this non-radiation environment in the test area.

The cable length between the VRM and operator workstation is approximately 40 m (120 ft). This layout simulates the remote location of the electronics from the field radiative environment. Additional equipment installed in the pit area includes a welding machine, cover gas cylinders, a rotating table (i.e., turntable), a full-scale mock-up canister, a fume exhaust system for removing fumes generated during the repair process, and a scissor lift that supports and positions the VRM at the height of the area in which the repair will occur.

Figures 15–17 show the equipment layout details. The as-built equipment configuration during the development and demonstration phase is shown in Figure 18.

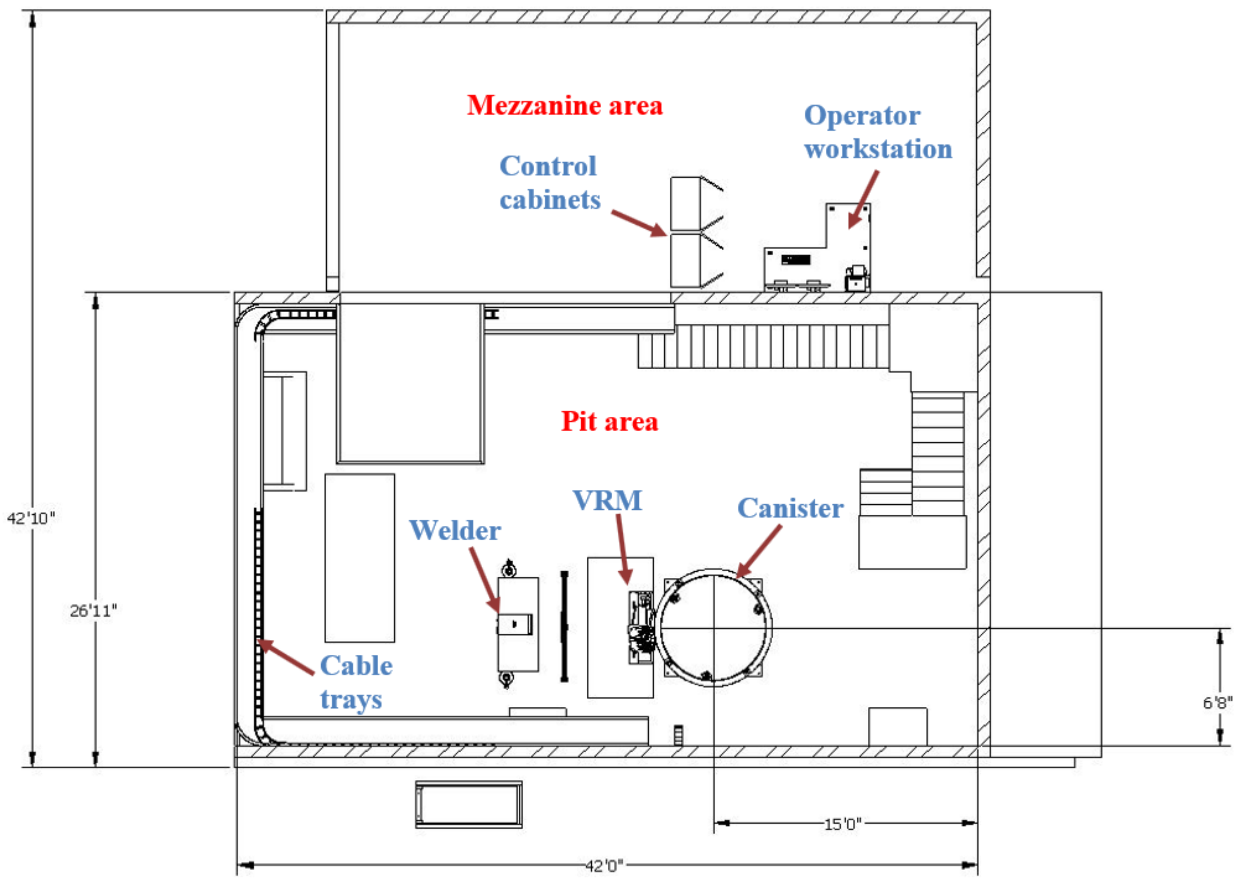

Figure 15. Equipment layout (dimensions in feet and inches).

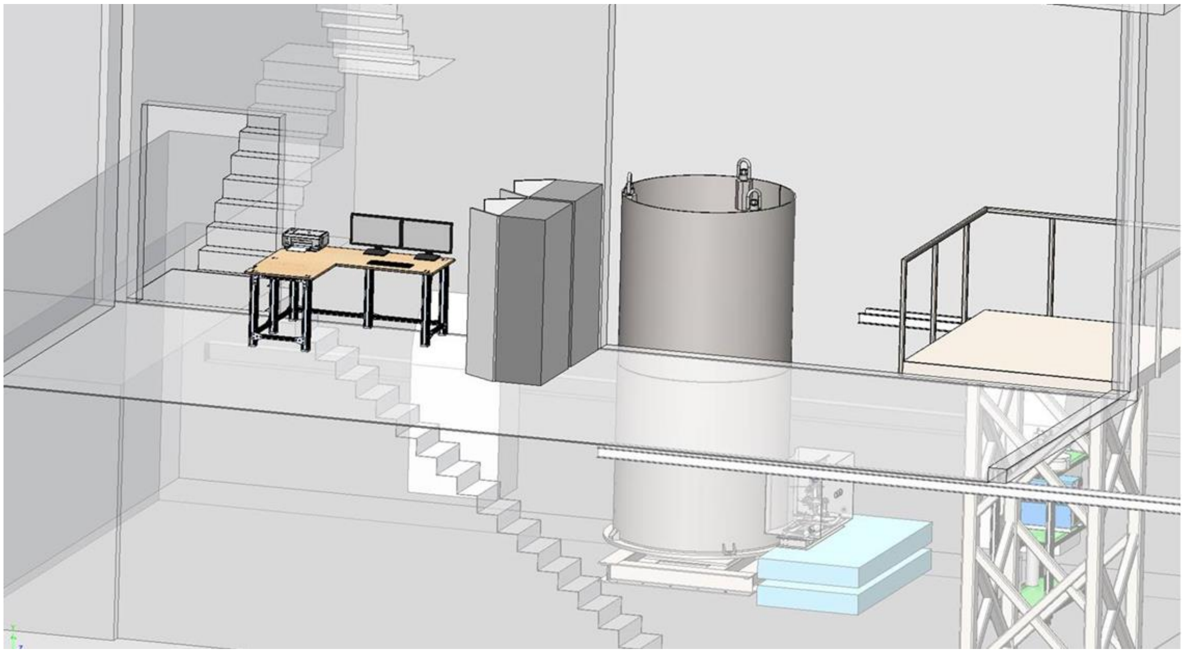

Figure 16. Equipment layout.

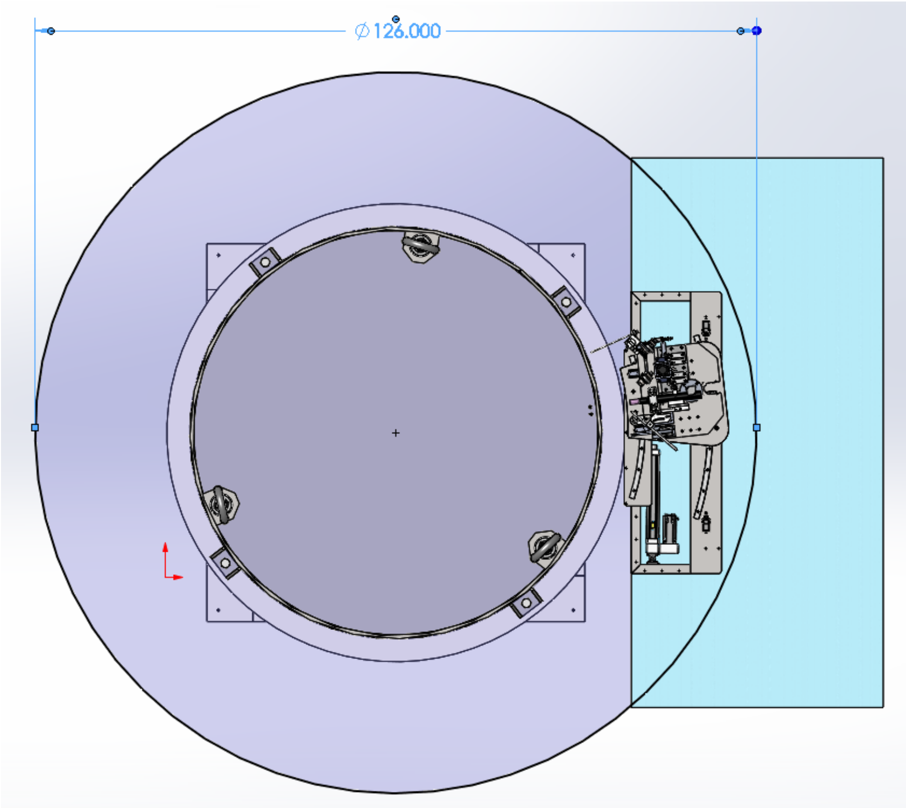

Figure 17. Top view of the canister and VRM layout. The large circle indicates a simulated boundary (dimensions in inches).

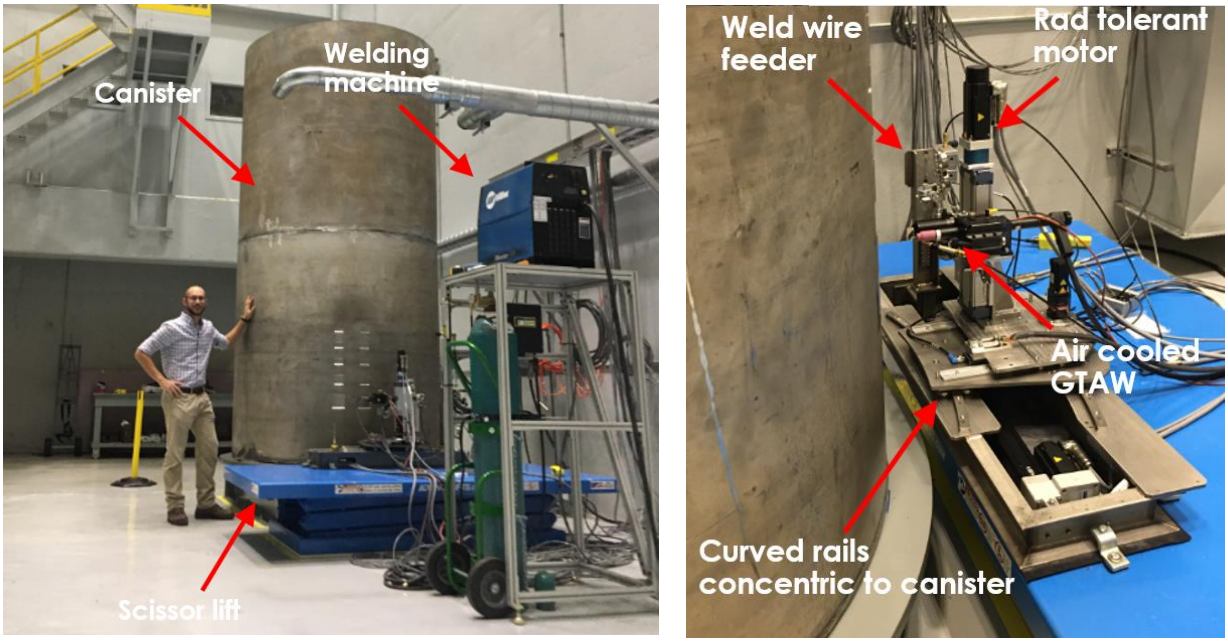

Figure 18. "As-built" equipment configuration during the development and demonstration phase. (Left) As-built equipment configuration during development and demonstration phase. (Right) A full-scale welded 304/304L stainless-steel mock-up canister using the same materials and fabrication methods as a real canister with embedded flaws to evaluate and demonstrate the VRM.

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3. DEMONSTRATION AND RESULTS

This section summarizes the qualification tests, operational procedures, and demonstration results.

3.1 Weld Trials for Parameter Selection

Cold-wire (CW)-GTAW trials were performed on 304/304L stainless-steel plates with simulated shallow and deep or through-thickness cracks to select proper welding parameters, including welding current, voltage (arc gap), wire feed speed, and welding travel speed. To simulate shallow cracks, eight artificial cracks with 3.175 mm (⅛ in.) depths were produced by a milling machine on two pieces of 12.7 mm (0.5 in.) thick 304L stainless-steel plate. To simulate deep or through-thickness defects, waterjet cutting was used to create three 38.1 mm (1.5 in.) long through-thickness artificial cracks on a 12.7 mm (0.5 in.) thick 304L stainless-steel plate. A hand grinder was used to produce simulated crack excavations. Shallow cracks were excavated by the hand grinder. For deep cracks, two kinds of excavations were performed: one 3 mm (~⅛ in.) deep and the other 9.5 mm (~⅜ in.) deep. Shallow (3 mm) grooves were made to simulate partial penetration repair welding, and deep (9.5 mm) grooves were made to simulate full penetration repair welding. Then, 100% Ar cover gas was used for shallow crack repair welding, and 75% He + 25% Ar cover gas was used for deep crack repair welding. Two CW-GTAW welding passes were applied on the shallow excavations, and six were applied on the deep excavations. All the weld trials passed the visual and liquid penetrant evaluations. Welding parameters that resulted in adequate penetration without observable defects were selected for qualification and demonstration. The selected welding parameters are shown in Table 1.

Table 1. CW-GTAW parameters selected for qualification [15].

Welding process	Current (A)	Travel speed (cm/min)	Wire feed speed (cm/min)
CW-GTAW	135	10	50.8

3.2 Weld Procedure Qualification

The weld repair procedure qualification was performed with 9.52 mm (⅜ in.) certified 304/304L stainless-steel plates. Two welds were produced for procedure qualifications: one with 100% Ar cover gas and another with 75% He + 25% Ar cover gas to improve the welding penetration. The visual inspection of the welds on 9.52 mm (⅜ in.) test plates was acceptable. Face and root weld transverse side-bend tests were performed on GTAW welds and were acceptable to the requirements of the ASME Boiler and Pressure Vessel Code (BPVC) [14]. Transverse tensile tests were also performed and met the requirements of ASME BPVC, the results of which are shown on the right side of Figure 19. Yield strength was 294 MPa. Ultimate tensile strength was 627 MPa, which is higher than the 482 MPa strength required by ASME BPVC [14].

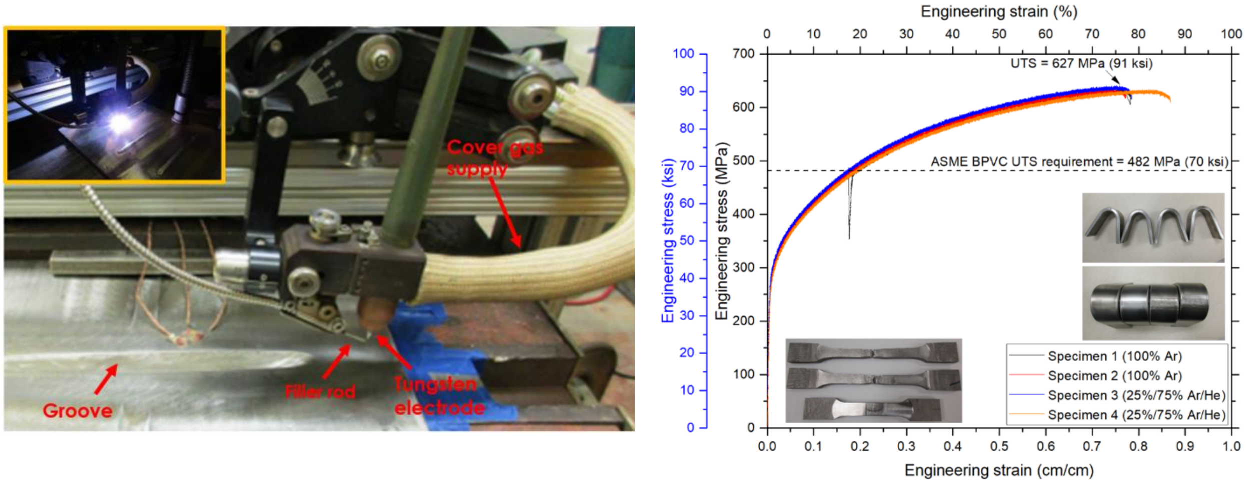

Figure 19. Welding configuration and qualification tensile and bend test results. (Left) The welding configuration. A CW-GTAW torch used for performing weld repairs. The electrode was tungsten, the filler rod was 308L stainless steel, and the cover gas was a mixture of 75% He + 25% Ar. (Right) CW-GTAW joint transverse tensile curves and bend tests for different cover gases.

3.3 Operational Sequence

A typical operational procedure consists of the following steps. First, the operator uses the motion control system to position the welding torch over the area that will be welded first. The operator visually verifies the torch location using the welding cameras. After using a touch-retract torch movement to position the torch at a proper standoff location, the operator tuns on the shield cover gas and runs it for a specific period of time (typically 5–10 sec) to purge the air in the vicinity of the weld. Then, weld power supply is enabled, and an open circuit voltage is measured to verify that the power supply is operating properly. After verifying that the power supply is enabled, the welding arc is initiated via touch start (in this case, the torch is moved until light contact is made with the base material and then is lifted to initiate the arc) or high-frequency start. The operator must ensure that the tungsten torch is not pushed too hard into the material to prevent tungsten breakage or tungsten contamination of the base metal. After the arc start, the torch is moved via the preprogrammed path while maintaining the proper voltage via the AVC. As the welding progresses, the operator observes the process in the arc viewing cameras and adjusts the welding process, as needed. Typically, these adjustments include laterally positioning the torch to ensure that the groove sidewalls are sufficiently wetted and positioning the weld wire in the weld pool to ensure sufficient wire melting. GTAW welding speeds are typically 5–15 cm (2–6 in.) per minute, which is relatively slow. These slow speeds give the operator time to make adjustments without having an overwhelming workload. Experience shows that adjustments are typically necessary only while welding approximately the first inch of the material.

3.4 Neutron Diffraction Residual Stress Measurements before and after Repair

Neutron diffraction was performed at the Neutron Residual Stress Mapping Facility (NRSF2) of the High Flux Isotope Reactor at ORNL to assess the residual stress profiles before and after a weld repair. The NRSF2 exploits the large penetration depth of neutrons to measure residual stresses deep within a material by detecting the change in the diffraction pattern of an incident neutron beam. Neutron diffraction is the only nondestructive method that can provide a through-thickness mapping of residual stress in steel. Residual strains in *x* (longitudinal/axial—welding direction), *y* (transverse/hoop), and *z* (normal/radial) directions along the five contours were measured. The measured strains in the radial direction were near zero. Thus, the plane strain condition was justified to calculate the weldment strain and stress accordingly in the hoop and axial directions. The details of the test results for the hoop (circumferential), radial, and axial (longitudinal) residual stresses profiles for as-welded and repaired specimens are shown in Figure 20. The maximum tensile residual stress for the as-welded specimen was 340 MPa. The maximum residual stress was in the fusion zone and oriented in the axial direction. The residual axial tensile stress also indicates that tensile stresses exist throughout the thickness of the weldment in the fusion zone. The maximum axial tensile residual stress of the repaired specimen increased by ~65 MPa to 406 MPa (from 340 MPa on the as-welded specimen), and there was a shift in position. However, the full profile was not tensile through-thickness, and compressive stresses were introduced in some regions. Similarly, for the repaired hoop, residual stresses were reduced significantly compared with the as-welded residual stresses. This reduction indicates that the repair could redistribute the stresses in a beneficial way. The specimen was constrained during the repair to simulate a representative field repair, but the specimen had to be released during neutron diffraction measurements. As a result, there might have been some additional stress relaxation when the constraint was released that were not accounted for during the neutron diffraction measurements.

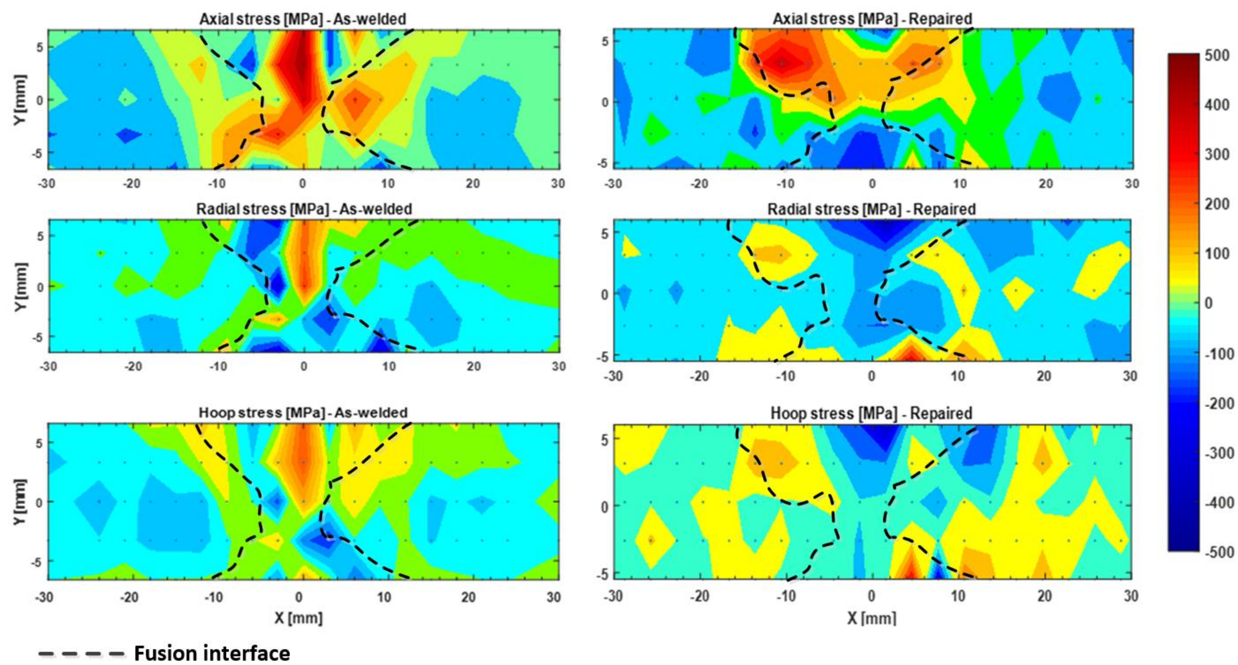

Figure 20. Through-thickness residual stress contour mapping for as-welded and repaired specimen. Axial, radial, and hoop residual stress through-thickness mapping for an as-welded (left column) and repaired (right column) specimen. The dotted line represents the fusion zone interface. High tensile residual stresses were observed throughout the thickness of the as-welded specimen in the fusion zone and heat-affected zone. A redistribution in residual stresses is observed in the repaired specimen.

3.5 Procedure Demonstration

A complete remote repair weld was demonstrated on a “pocket” excavated on the canister surface. The pocket was completely filled with welding material using the VRM that was fully automated to perform the operation. The pocket was filled with five weld passes in ~10 min. Similar welding parameters used during the repair welding procedure qualification were also used for the repair welding demonstration. The completed repair weld is shown in Figure 21.

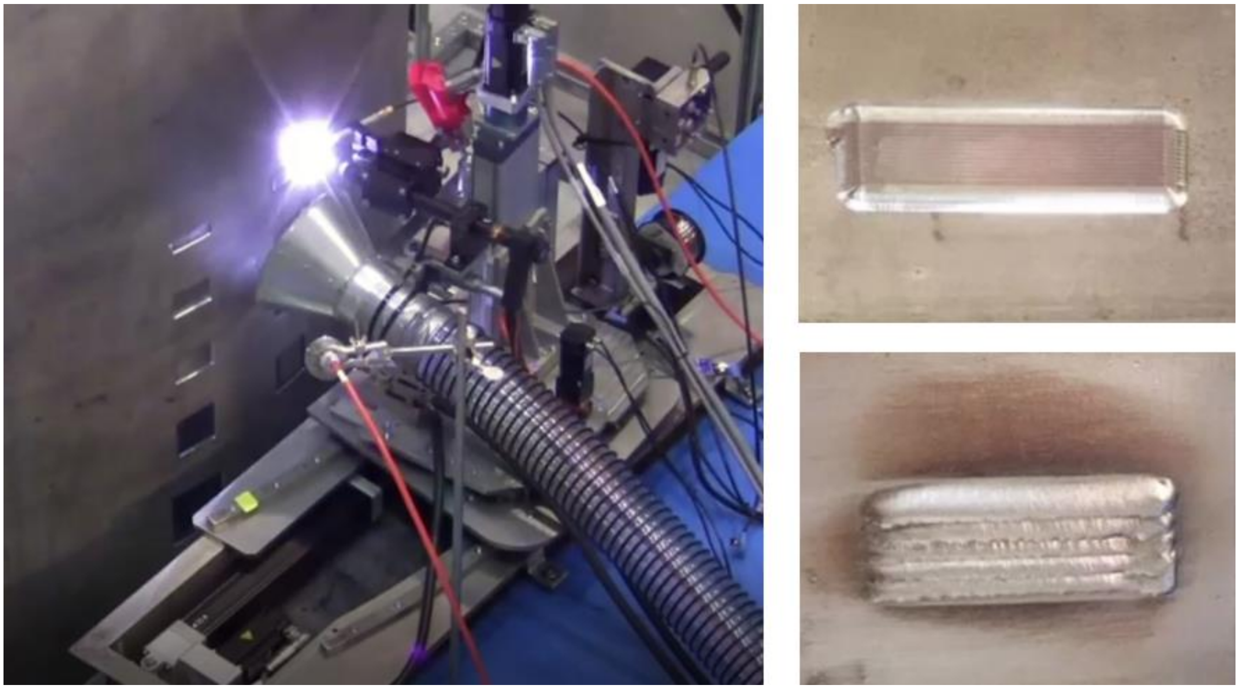

Figure 21. VRM in operation and a completed repair weld. (Left) Photo of VRM in operation. (Top right) As-excavated pocket on canister surface. (Bottom right) Pocket filled with five passes of overlay weld material.

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4. SUMMARY

Oak Ridge National Laboratory (ORNL) successfully demonstrated the Versatile Remediation Module (VRM), a prototype module designed and built by ORNL for performing the on-site remote repair of welded stainless-steel storage containers for spent nuclear fuel and high-level radioactive waste. This report described the VRM prototype and its design features, components, qualification tests, operational procedures, and demonstration results to support continued long-term storage or off-site transportation of spent nuclear fuel and high-level radioactive waste currently stored in storage containers. A remote (i.e., 100 ft away from the simulated radiative environment) demonstration of the VRM was successfully performed on a full-scale mock-up welded stainless-steel canister. The VRM is designed with features to accommodate remediation techniques beyond those currently selected and described in this report. Therefore, many of the VRM's features could benefit other remote nuclear or nonnuclear applications. The VRM is envisioned to serve as a development center to facilitate and enhance the further development of new remediation technologies.

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