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Remote Welding, NDE and Repair of DOE Standardized Canisters

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ABSTRACT

The U.S. Department of Energy (DOE) created the National Spent Nuclear Fuel Program (NSNFP) to manage DOE's spent nuclear fuel (SNF). One of the NSNFP's tasks is to prepare spent nuclear fuel for storage, transportation, and disposal at the national repository. As part of this effort, the NSNFP developed a standardized canister for interim storage and transportation of SNF. These canisters will be built and sealed to American Society of Mechanical Engineers (ASME) Section III, Division 3 requirements.

Packaging SNF usually is a three-step process: canister loading, closure welding, and closure weld verification. After loading SNF into the canisters, the canisters must be seal welded and the welds verified using a combination of visual, surface eddy current, and ultrasonic inspection or examination techniques. If unacceptable defects in the weld are detected, the defective sections of weld must be removed, re-welded, and re-inspected.

Due to the high contamination and/or radiation fields involved with this process, all of these functions must be performed remotely in a hot cell. The prototype apparatus to perform these functions is a floor-mounted carousel that encircles the loaded canister; three stations perform the functions of welding, inspecting, and repairing the seal welds. A welding operator monitors and controls these functions remotely via a workstation located outside the hot cell.

The discussion describes the hardware and software that have been developed and the results of testing that has been done to date.

INTRODUCTION

The U.S. Department of Energy (DOE) must manage the disposal of its spent nuclear fuel (SNF). The National Spent Nuclear Fuel Program (NSNFP) coordinates and integrates the actions of DOE sites for disposal of their spent nuclear fuel. As part of this effort, the NSNFP developed standardized DOE-SNF canisters (Fig. 1.) for handling and interim storage of SNF at various DOE sites, as well as transport, handling, and disposal at a permanent repository.

The NSNFP management approach is to package all fuel in DOE's standardized canisters. These 316L stainless steel (UNS 31603)[1] canisters will have an internal structural array of a neutron absorbing material to separate the SNF and prevent inadvertent nuclear criticality. The irradiated SNF will be loaded into canisters remotely, in a hot cell, and the top head will be welded to the canister body. Because the canisters are part of an interim storage, transport, and final disposal system, they are designed and built to American Society of Mechanical Engineers (ASME) Section III, Division 3 Code[2] requirements. Thus, full volumetric inspection of the final closure welds is required. As well as meeting ASME requirements, the final closure welds must have

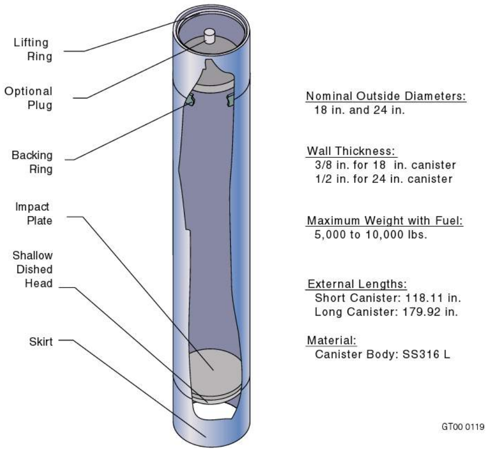

Figure 1. DOE standardized canister.

corrosion integrity to provide a design life of up to 100 years. The canister, the final closure weld, and the nondestructive evaluation (NDE) of the canister must comply with the repository Quality Assurance Program (DOE/RW/0333P).[3]

Due to the high radiation fields, closure welding and inspection must be performed within a hot cell environment. Specialized equipment and processes have been designed to seal the canisters with minimal heat input and metallurgical structure interruption to maximize their design life for dry storage and facilitate safe transport and handling. The standard canister is considered a critical item for the repository and will have specific performance requirements allocated to it to mitigate design basis accidents in the surface facility.

Development of the welding, inspection, and repair hardware began at Idaho National Laboratory in 2001 and will continue until the end of 2007. The welding and repair hardware is currently undergoing testing and continued development. The NDE hardware is currently undergoing development in the laboratory and is scheduled to be complete at the end of year 2007. After all the components are completed, they will be integrated and deployed as a complete system in 2008.

HARDWARE OVERVIEW

The canister closure system is composed of three subsystems: the welding subsystem, the inspection subsystem, and the repair subsystem. All three subsystem tooling posts are mounted on top of a carousel that rotates the entire system around the canister (Fig. 2). The carousel is a hollow equipment rack mounted to a large circular bearing; it is driven via a ring gear. During operation, the canister is raised or lowered into position then secured while the carousel rotates. Thus, the canister does not need to be moved or rotated during closure operations.

Carousel

The carousel will house the support equipment required for the three subsystems. Power is supplied to the carousel through a slip ring arrangement underneath the carousel, allowing for continuous rotation. This configuration greatly simplifies cable management. The cables between the support equipment and the tool posts are all fixed within the carousel, without any relative rotation.

A shielding tube, mounted on the hot cell floor, protrudes above the carousel. This tube shields the equipment from the high radiation within the canister and eliminates the need for shield plugs within the canister. Because the shield tube is fixed to the floor, this large mass does not have to rotate with the carousel. The equipment on the tooling posts is only raised above the top of the shield tube when needed. This method minimizes the equipment's exposure to high radiation levels, prolonging its service life.

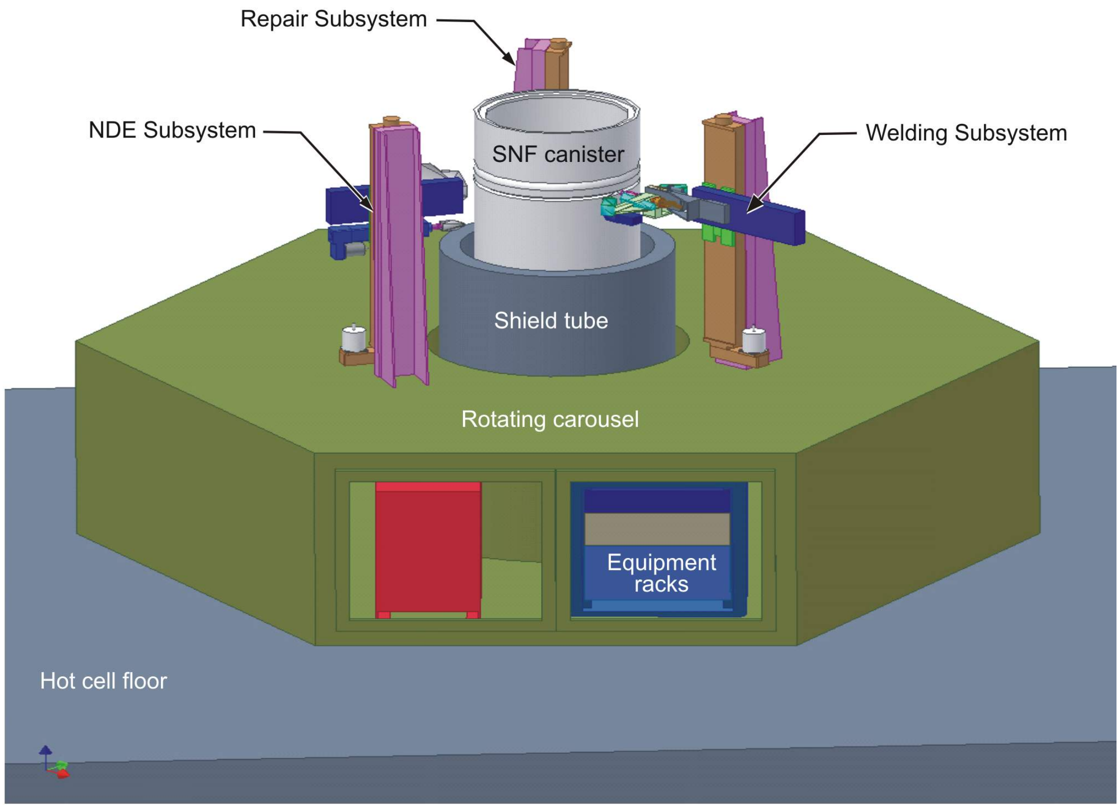

Figure 2. Artists concept of rotating carousel layout.

Each of the three subsystems, welding, inspection, and repair, is mounted on a separate tower. Each tower has a vertical positioning axis to locate the tooling over the center of the weld, and a horizontal axis to position the tooling radially in and out (Fig. 3). This arrangement allows canisters of different heights and diameters to be welded and inspected. This design has the added benefit of accommodating slightly out of round canisters, or canisters that may not be positioned exactly on the vertical centerline of the carousel's rotation.

Welding subsystem

The weld head is mounted at the end of the radial positioning axis (Figs. 4, 5). The system is designed to use cold-wire tungsten inert gas (TIG) welding at up to 300 amps. The torch operates using touch starting instead of high frequency arc starting to eliminate the potential for stray high-frequency voltages that could damage sensitive computer hardware. The head consists of an air-cooled gas tungsten arc welding torch, a wire-feed positioner, dual arc viewing cameras, and a seam tracking/visual inspection sensor. The entire weld head can be oscillated vertically across the weld joint when weaving is required. The radial positioning axis is controlled automatically during welding to provide a constant arc voltage. This arc voltage control cancels any variations caused by uneven fill from the previous weld passes.

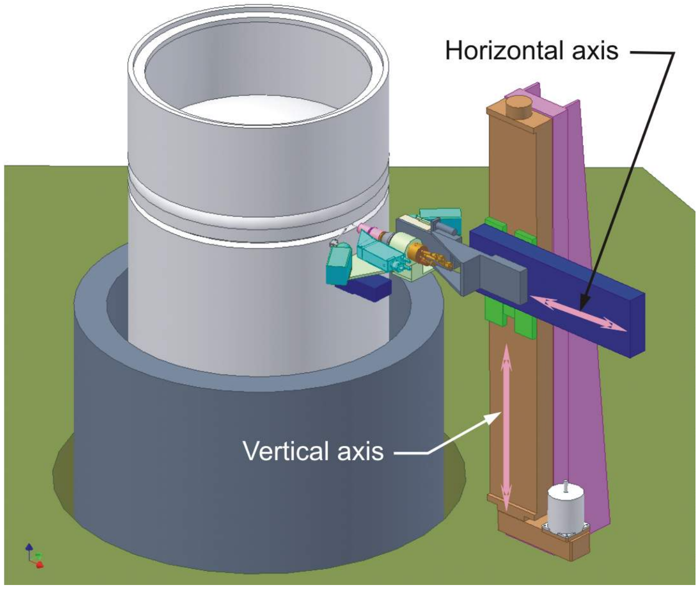

Figure 3. Welding subsystem showing vertical and horizontal motion axes.

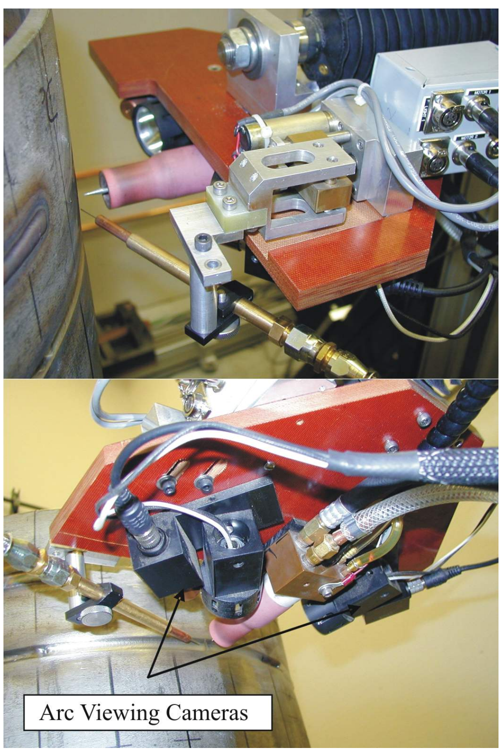

Figure 4. Top view (top) and underside view (bottom) of the welding end effector positioned over a typical SNF canister weld joint.

Figure 5. Welding subsystem shown welding on a mock-up SNF canister.

Arc viewing cameras

The weld head is equipped with two “lipstick” CCD cameras, one mounted forward of the weld torch and one mounted aft of the weld torch, as well as lights for viewing in low light environments. The cameras operate in two modes. In “arc off” mode, they function as regular CCD video cameras, allowing the weld system operator to position the welding equipment during manual operations.

During welding, these cameras automatically switch into “arc on” mode, which suppresses the arc light enough to allow the operator to watch the weld in real-time (Fig. 6). This allows the operator to make fine adjustments to welding parameters if needed. INL is currently producing radiation-hardened versions of these cameras to be used around high radiation fields.

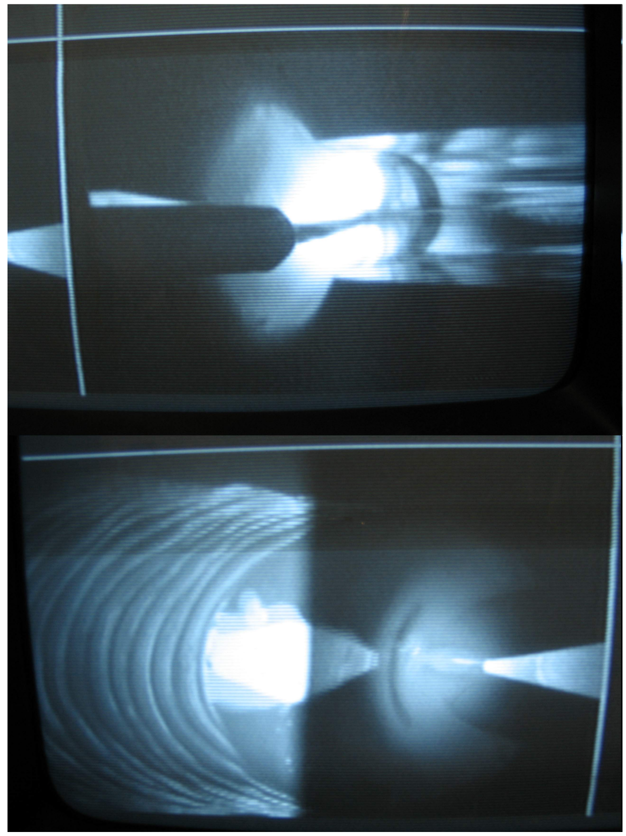

Figure 6. Leading edge (top) and trailing edge (bottom) arc viewing cameras during narrow groove TIG welding.

Air cooled torch

Conventional welding torches typically do not have the features necessary for remote welding. Therefore, the INL teamed with CK Worldwide Inc. to develop a torch that meets the needs of this application. This torch allows remote tungsten electrode change out and remote adjustment of tungsten stickout. The stickout is adjusted by moving the gas cup rather than moving the tungsten. Since the arc viewing cameras are focused on the end of the tungsten, if the tungsten were moved, as in a traditional torch, the cameras would have to be repositioned every time the stickout was adjusted. With the new design, the varying stickout lengths required as the deep weld joint is filled can be obtained without repositioning the cameras.

Design requirements also limit the amount of liquids in the hot cell where this welding system will operate. But welding torches rated for the currents necessary to weld stainless steel are typically water cooled. Therefore, this torch incorporates air cooling using compressed air that eliminated the need for water cooling. The torch provides up to 300 amps continuous duty capacity.

Wire positioner

The weld head incorporates a wire positioner that can move the wire relative to the tungsten both across the weld and into and out of the weld. This allows the operator to precisely control where the wire enters the pool to produce a high quality weld.

Laser profile sensor

The weld head will be fitted with a Servo Robot Mini I/60 laser-tracking sensor. The sensor consists of a laser diode and a CCD video imager. The sensor emits a laser stripe across the weld joint that is detected by the video imager. The video information is fed into the sensor's computer, which fits the detected laser image to a catalog of known weld joints. From that information, the sensor is able to determine the shape of the weld joint and its location relative to the weld head (Fig. 7).

This joint information is used for two purposes. First, the information can be fed into the motion control hardware for seam tracking. Second, the information can be used for post-weld quantitative visual inspection as described later.

Repair subsystem

In addition to welding and inspecting the canisters, the system must be able to make repairs in case defects are created during welding. Several options for this process were considered, including machining, arc gouging, and grinding. However, the requirements of hot-cell operation limit the types of processes that can be used. Cutting fluid is not allowed, which eliminates most machining processes. In addition, because of the requirement for automated, remote welding, any repair groove must follow the original contours of the weld groove as closely as possible; this eliminates arc gouging. Therefore, grinding with a conventional grinding disk was the most acceptable process available (Figs. 8, 9).

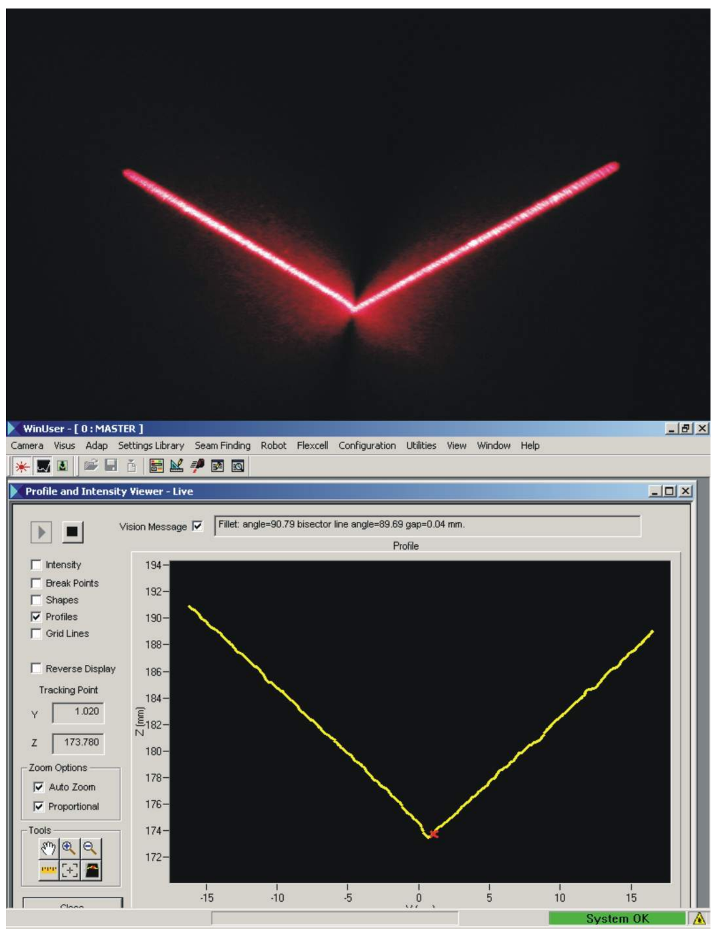

Figure 7. Laser profile sensor fitting the laser strip to a weld joint.

Figure 8. Repair subsystem grinding apparatus.

Figure 9. Close up of grinding wheel over simulated defects on canister mock-up.

The repair subsystem performs dual roles. After a welding pass, it first wire brushes the weld joint to remove the oxides formed during welding. Then the weld is inspected and, if defects are found, the repair subsystem grinds out the defect and creates a repair cavity with a controlled, consistent geometry for rewelding[4].

The head has remotely changeable tooling to allow different grinding and brushing wheels to be used (Fig. 10). The tower design includes a tool caddy for storing wire brushes and grinding wheels. The head has a compliance joint that allows the wire brush or grinding head to float over uneven weld surfaces without creating excessive tool loads that might damage the wheels. The head has a contact sensor to provide feedback to the control system when the wheel first comes into contact with the canister. This provides a zeroing feature to the coordinate system and accommodates unknown weld fill and canister location.

The grinding operation is completely computer controlled. The grinding control system gets information from the inspection system on defect location, depth, and size (Fig 11). From this information, the grinding control system develops a grinding profile that removes the minimum material necessary to completely eliminate the defect, while maintaining the original joint geometry as closely as possible (Fig. 12). This simplifies the process of inspecting and rewelding the repair cavity.

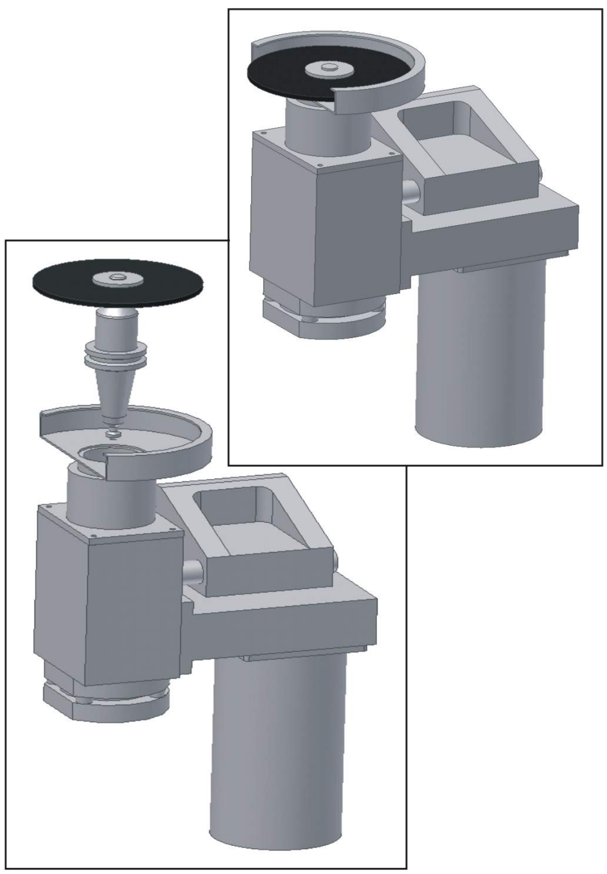

Figure 10. Grinding wheel is released from collet with compressed air.

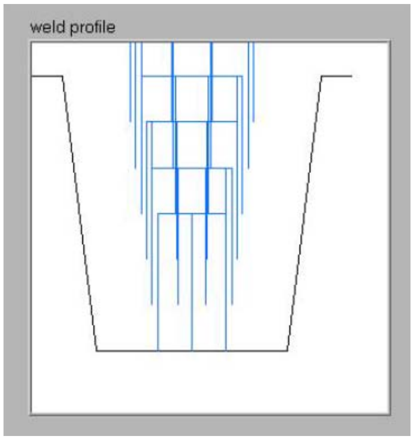

Figure 11. Grinding profile calculated by the control computer based on defect size. Each vertical blue line represents one grinding pass.

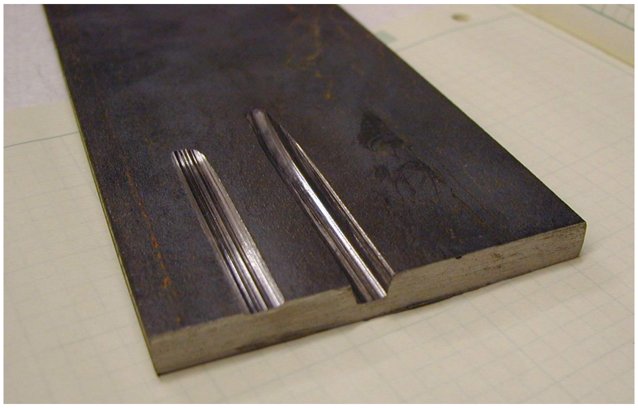

Figure 12. Side view of grinding profiles for shallow (left) and deep (right) defect repair cavities.

NONDESTRUCTIVE EVALUATION

The welds will undergo surface and volumetric inspection in accordance with ASME Boiler and Pressure Vessel Code, Section III, Division 3, Subsection WB. In addition, a surface inspection of repair grooves will verify that the flaw has been removed. The tower contains probes to perform surface inspection with eddy current examination and volumetric inspection with ultrasonic examination (Figs. 13, 14). The welding subsystem contains the laser-based sensor that will be used for visual surface inspection.

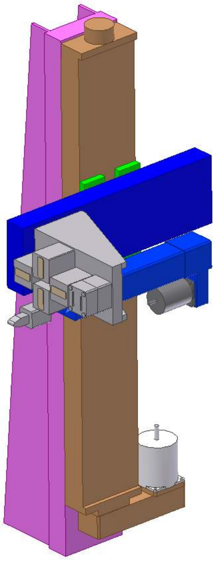

Figure 13. Nondestructive evaluation subsystem concept.

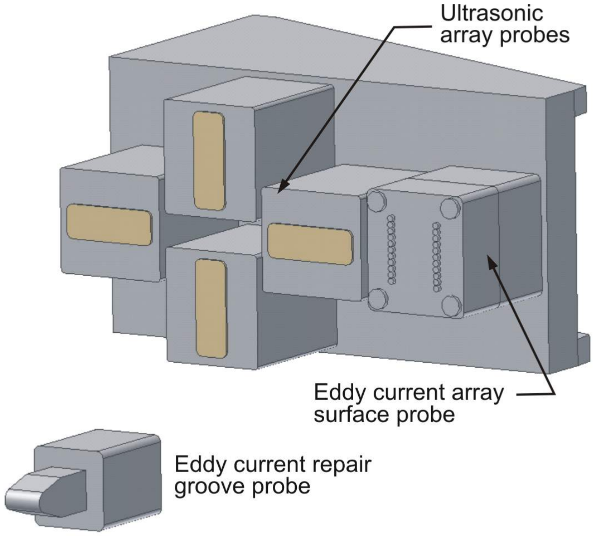

Figure 14. Nondestructive evaluation head concept detail.

Eddy current inspection

To eliminate waste streams and minimize human exposure to the radiation environment, eddy current techniques were selected for surface inspection. However, the Code requires surface inspection by magnetic particle or liquid penetrant examination; therefore, a Code Case has been presented to ASME to allow eddy current testing (ET) for surface examination. Work has been completed to demonstrate ET's suitability for detecting flaws required by the Code's acceptance criteria.

To simplify mechanical design, an eddy current array will be used rather than mechanically scanning with a single probe. The probe will be designed to conform to the surface of the weld (Fig. 15). A repair groove probe will be designed to fit the consistent shape of the repair groove design to allow a single probe to examine any depth of repair necessary (Fig 16).[5]

Ultrasonic inspection

The design of the ultrasonic examination system uses phased array ultrasonic technology to simplify the mechanical design and provide greater flexibility in the NDE process. Phased array transducers consist of many small elements that are energized separately, allowing the timing sequence to control the direction and focal depth of the sound. A linear phased array transducer can electronically perform the raster scan necessary to examine the entire volume of the weld, thus avoiding the complicated mechanical design necessary to perform two-dimensional scanning.

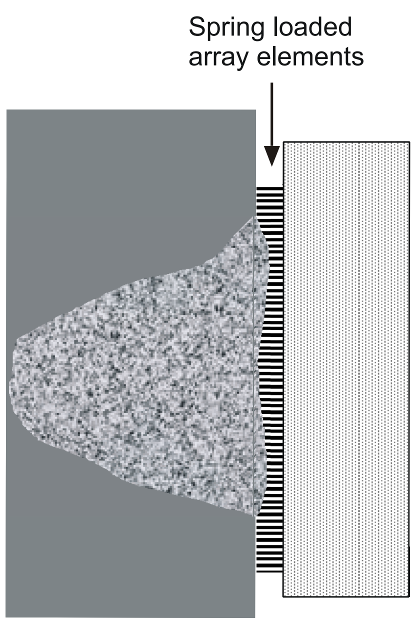

Figure 15. Concept of eddy current inspection array. Each eddy current probe in the array is pressed against the weld surface to maintain consistent contact.

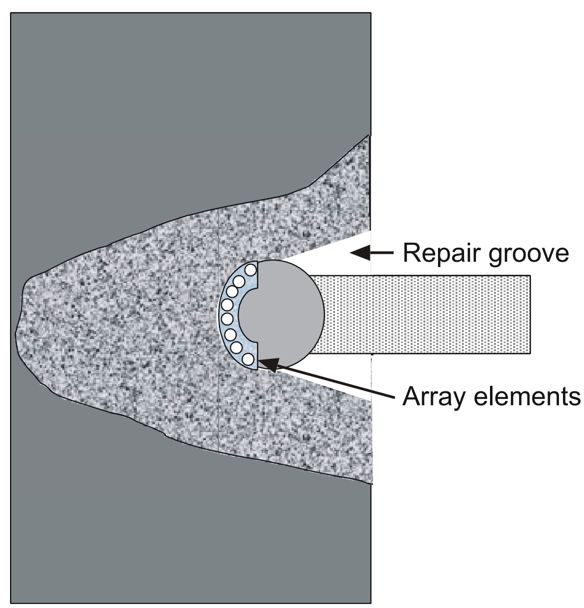

Figure 16. Eddy current probe for inspection of repair grooves.

Furthermore, a single phased array probe can produce ultrasonic beam paths at the multiple angles required by the ASME Code. Other sophisticated techniques, such as a tandem pitch/catch sound path, can be implemented using the phased array to analyze vertical planar defects. This is an effective means of complying with Code requirements to evaluate defect indications to determine if they are serious crack or lack of fusion flaws.

Phased array ultrasonic probes have the flexibility to implement complex sound paths (Fig. 17). Phased array software presents the acquired data as an image to assist in consistent post-acquisition analysis as outlined in ASME Section V, Article 4, Nonmandatory Appendix E, "Computerized Imaging Techniques." Multiple probes will be included in the inspection equipment to efficiently cover the weld from the required directions of examination (i.e., angle beam transverse to the weld from both sides, angle beam parallel to the weld, and straight beam).

Techniques are being developed to account for the difficulty of using ultrasonics in austenitic material.[6] A transducer frequency of 2.25 MHz has been found to reduce the noise in the signal due to material grains in shear wave angle beam inspections. Additionally, longitudinal wave mode will be available through beam steering with the same transducer. Signal processing methods (e.g. matched filters and wavelet decomposition) have also been applied to signals to assist in increasing the signal-to-noise ratio.[7]

Visual inspection

The laser profile sensor mounted on the welding subsystem head will be used for visual inspection of the weld. This inspection is performed for two reasons. The first is to quickly detect and repair any visible surface defects. The second is to measure the weld profile to ensure it meets the workmanship requirement and is suitable for the ultrasonic and eddy current probes.

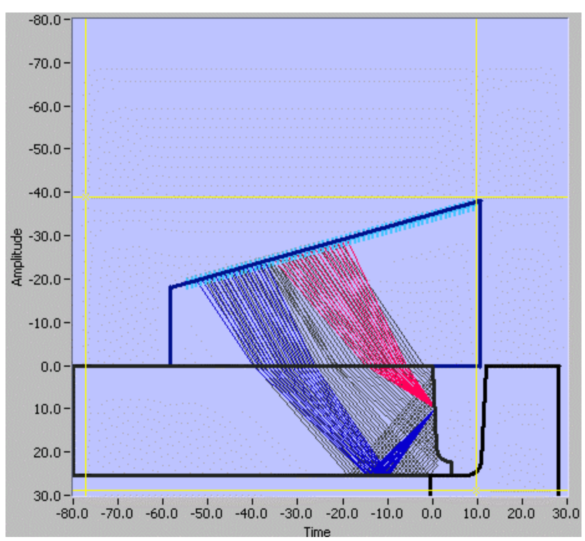

Figure 17. Computer-generated sound paths for ultrasonic phased array probe.

The visual inspection sensor obtains three-dimensional measurements of the weld profile by illuminating the surface of the weld with a plane of laser light and photographing the area of the weld with a camera. Using the location of the laser stripe on the camera's imaging array, the profile can be determined. The associated software can be programmed to automatically identify when the weld surface does not meet workmanship criteria or when visible defects are present (Fig. 18).

CONTROL SYSTEM

Hardware

The control for the canister closure system is separated into two systems: the operator workstation and the control hardware. The operator workstation is located in the control room and serves as the interface between the operator and the hardware. The control hardware, located in the hot cell on the rotating carousel, controls the actual functions of the welding, repair, and inspection hardware.

Operator workstation

The operator workstation is the primary control interface for the human operator of the canister closure system. The workstation consists of a standard Windows PC with four monitors that allow the user to observe the closure process (Fig. 19). Data being collected from the closure process and the live video feeds from the arc viewing cameras are displayed to the operator in real time. The operator has real-time control over the welding process and can adjust the welding and inspection parameters as necessary.

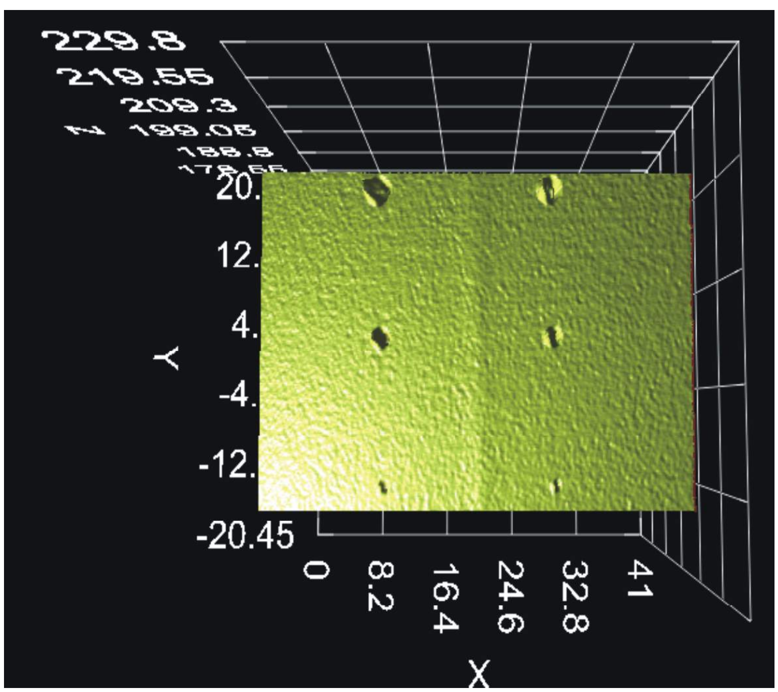

Figure 18. Contour map generated by laser profiling sensor over sample weld with artificial surface defects.

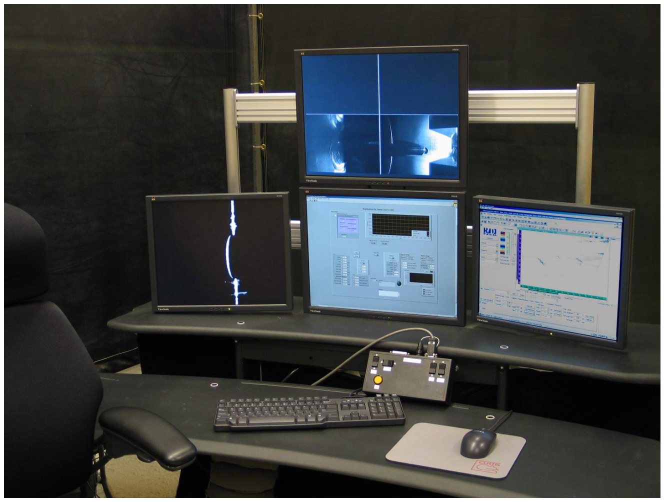

Figure 19. Operator workstation.

Control hardware

The control hardware for the canister closure system is located in the hot cell on the rotating carousel. The carousel has instrument racks under its top deck to house the control hardware. These racks are sealed against airborne contamination and provide radiation shielding for the delicate electronic instruments. A computer running a real-time operating system from National Instruments controls all of the functions of motion, welding, repair, and inspection that are required for successful closure of the canister. The computer also provides the interface to the operator workstation over a wireless Ethernet link, eliminating the need for any cabling between the control hardware and the operator workstation.

The design concept for the canister closure system is that all of the hardware required for welding, inspection, and repair should be on the carousel. The only cables that need to be run to the carousel are for 480 3-phase power, which is carried into the carousel by a series of slip rings. (The power cables are fixed and do not rotate with the carousel.) This allows the carousel to rotate more than 360 degrees in any direction.

Software

The software, like the hardware, is separated into two systems: the operator interface software and the hardware control software. The operator interface software provides the user interface to the human operator (Fig. 20). This interface allows the user to control all of the necessary functions for welding, repair, and inspection. In the current version of the user interface software, the operator has complete control over all of the functions during weld and inspection setup and in real time during the closure operations. This is necessary during system development and weld parameter development.

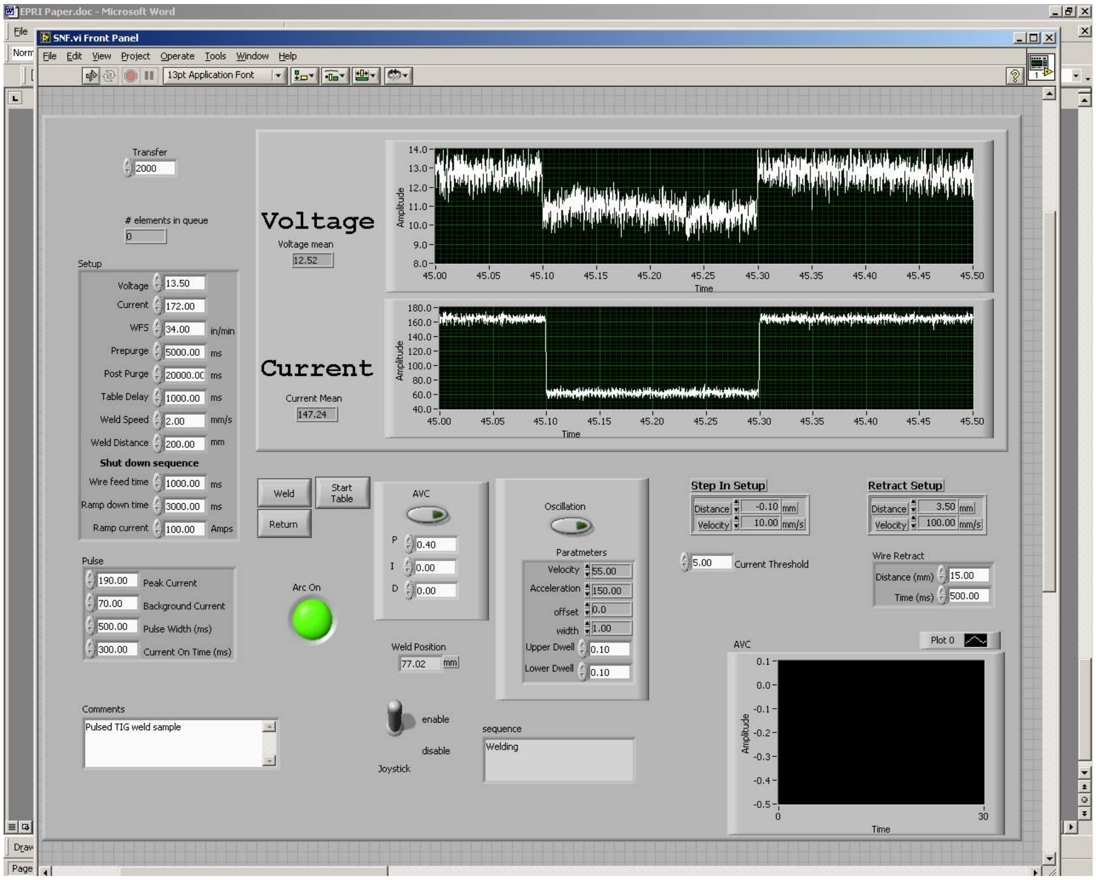

Figure 20. Operator workstation graphical user interface screen.

During actual production, however, the operator will have limited access to the weld and inspection parameters. The operator will have access to parameters such as wire entry position and torch position; only engineers qualified to the applicable ASME Codes will be able to change the majority of welding and inspection parameters. This security arrangement will prevent unauthorized changes to the welding parameters.

The hardware control software resides on the control computer located within the rotating carousel. This software runs on a robust, real-time operating system platform that provides reliable, deterministic control of the low-level hardware functions. These functions include motion control, weld parameter feedback control, inspection hardware control, and feed-back control of the repair hardware. This software is designed to operate in cooperation with the operator interface software to allow the operator to monitor and control the hardware in real time. In addition to real-time monitoring of the weld and inspection process, the operator workstation computer records and archives the data taken during closure operations (Fig. 21). This allows a qualified engineer to review the data at a later time to analyze the process and correct parameters or troubleshoot the system should problems arise during production operations.

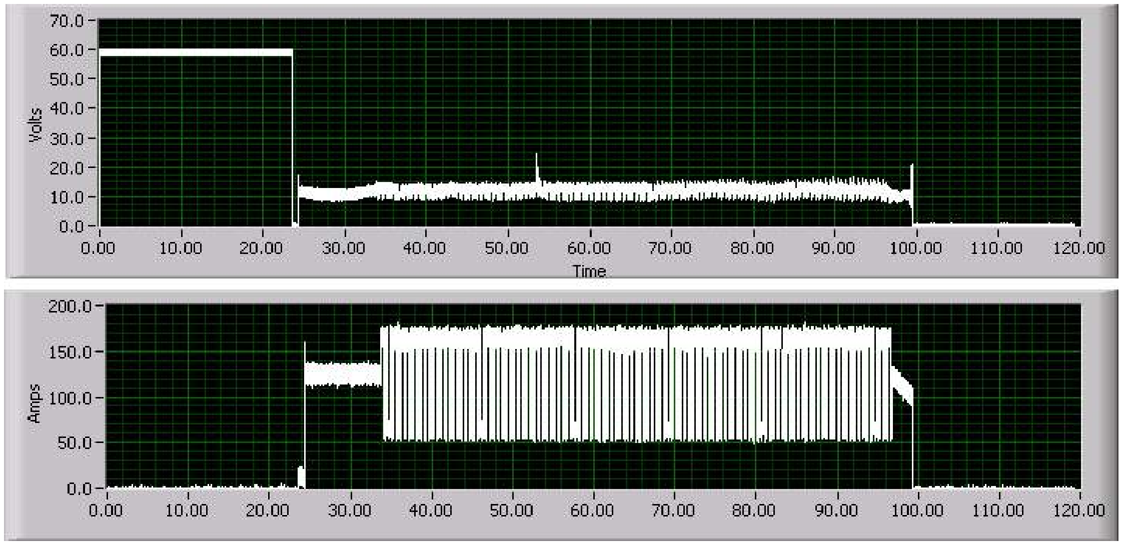

Figure 21. Arc voltage (top) and current data (bottom) taken during pulsed current TIG welding.

CONCLUSIONS

This paper describes a system for sealing DOE spent nuclear fuel in standardized canisters. This remote, semi-automated welding, inspection, and repair system allows a trained operator to seal canisters to ASME Section III, Division 3 Code requirements. The system is designed to run within a hot cell to limit personnel exposure to radiation. It provides methods of protecting sensitive hardware from harmful effects of radiation to increase the useful life of the hardware. The system provides real-time video and data feed back to the operator, as well as full archiving of welding and inspection data for post-weld analysis.

ACKNOWLEDGEMENTS

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