

Eddy Current Examination of Spent Nuclear Fuel Canister Closure Welds

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Abstract

The National Spent Nuclear Fuel Program (NSNFP) has developed standardized DOE SNF canisters for handling and interim storage of SNF at various DOE sites as well as SNF transport to and SNF handling and disposal at the repository. The final closure weld of the canister will be produced remotely in a hot cell after loading and must meet American Society of Mechanical Engineers (ASME) Section III, Division 3 code requirements thereby requiring volumetric and surface nondestructive evaluation to verify integrity. This paper discusses the use of eddy current testing (ET) to perform surface examination of the completed welds and repair cavities. Descriptions of integrated remote welding/inspection system and how the equipment is intended function will also be discussed.

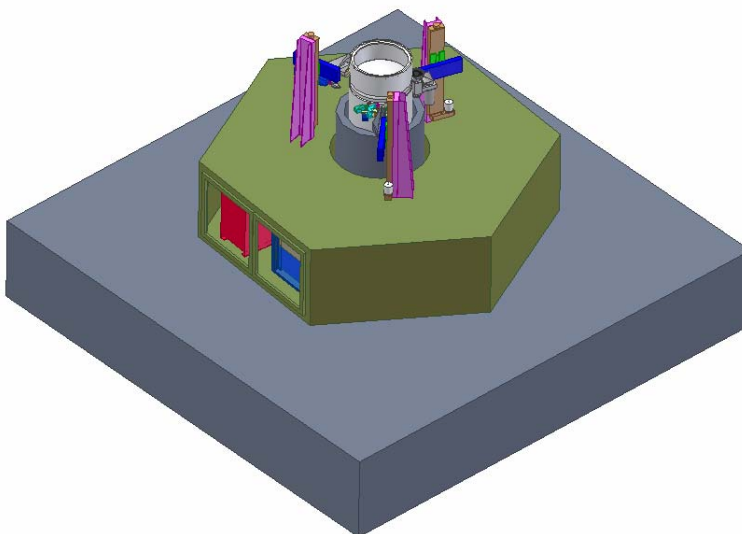
Introduction

The National Spent Nuclear Fuel Program (NSNFP) provides direct support to the Department of Energy (DOE) to coordinate and integrate the actions of DOE sites for disposal of their spent nuclear fuel (SNF). As part of this effort, the NSNFP developed standardized DOE SNF canisters for handling and interim storage of SNF at various DOE sites as well as SNF transport to and SNF handling and disposal at the repository. Final closure welding of the standardized canister must be performed remotely in a hot cell after loading of the SNF into canisters. Because the container will be part of an interim storage, transport, and final disposal system during their useful lifetime, the containments are designed and built to American Society of Mechanical Engineers (ASME) Section III, Division 3 requirements. Furthermore, final closure welds must not only meet these requirements but must also have corrosion integrity to meet a design life of up to 100 years. The specifics of a standardized canister is provided in Figure 1.

This paper describes efforts to develop remote welding and nondestructive examination equipment that insures the closure welds on DOE standardized canisters meet ASME Code. Descriptions of remote welding equipment and how the equipment was developed and tested will be discussed. In particular, initial development of eddy current techniques for final weld and repair cavity surface examinations will be discussed in detail.

Background

A system is being designed to complete the process of closing the standardized spent nuclear fuel canisters. The system design includes the components necessary to weld, inspect, and repair weld defects in a manner that will be efficient and compliant with “As Low As Reasonably Achievable (ALARA)” goals for minimizing personnel exposure to radiation. The base of the system is a rotating carousel that transports the welding, inspection, and grinding components around a stationary canister. Each of the three major system components is deployed on stands (“towers”) that have



actuators to position the devices in the appropriate proximity to the canister. The welding tower positions the welding torch in the groove of the weld. Cameras are positioned around the torch to provide visual feedback to the weld. The welder can then control the mostly automated process for a remote workstation. The inspection tower contains the devices for performing non-destructive examination (NDE) of the weld as required by the governing fabrication code. The tower includes probes to perform volumetric inspection with ultrasonic examination, visual inspection using a laser based surface profiling sensor, and surface inspection via eddy current examination. This paper focuses on the eddy current examination and the process of obtaining acceptance of eddy current in lieu of liquid penetrant or magnetic particle. A brief introduction to the other aspects of the system is given in this section.

The welding process is completed to ASME Section III, Division 3. The welding hardware includes a welding power supply, torch, wirefeeder as needed to complete cold wire gas metal arc welding... (Leave this for Art)

The requirements for ultrasonic volumetric inspection of the weld are given in ASME Boiler and Pressure Vessel Code Section III, Division 3, Subsection WB in WB-5000. Section V, Article 4 covers the details of the ultrasonic examination. The ultrasonic system design implements the examination with phased array ultrasonics technology to simplify the mechanical design and provide greater flexibility to the NDE process. Phased array transducers are constructed as 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 perform the raster scan, necessary to exam the entire volume of the weld, electronically and avoid a complicated design to perform raster scans. Furthermore, a single phased array probe can produce ultrasonic beam paths at multiple angles required by the code. Other sophisticated techniques such as a tandem pitch catch sound path for most affectively analyzing vertical planer defects can implemented using phased array, assisting with compliance with code requirements that defect indications be evaluated as to whether they are serious crack or lack of fusion flaws. Figure xx illustrates the flexibility of phased array to implement a complex sound path. 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 on Computerized Imaging Techniques. Multiple probes will be included in the inspection equipment to most efficiently cover the weld from the required directions of examination (angle beam transverse to the weld from both sides, angle beam parallel to the weld, and straight beam examination).

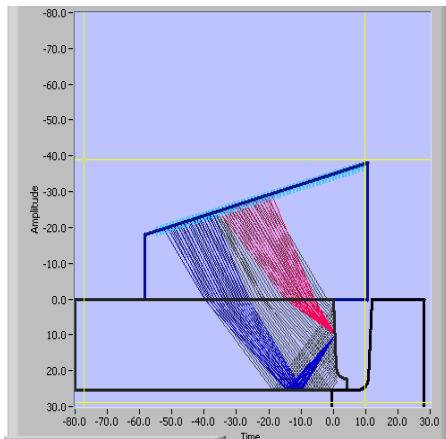


Figure xx. Illustration of a phased array ultrasonic probe implementing a tandem inspection of a weld side-wall for lack of fusion defects.

Visual inspection with the laser profiling sensor is completed for a dual purpose. The first is that any visible surface defects will be detected and repaired quickly. Secondly, the profile of the weld can be measured to ensure it meets the workmanship requirement that the weld be suitable for the ultrasonic and eddy current probes. The visual inspection sensor provides three dimensional measurements of the weld profile by illuminating the surface of the weld with a plane of light and photographing the area of the weld with a camera. Depending on the location of the laser stripe on the camera's imaging array the profile can

be measured. Figure XX. Shows the operation of the device. The associated software can be programmed to automatically identify when weld is out of specification or visible defects are present.

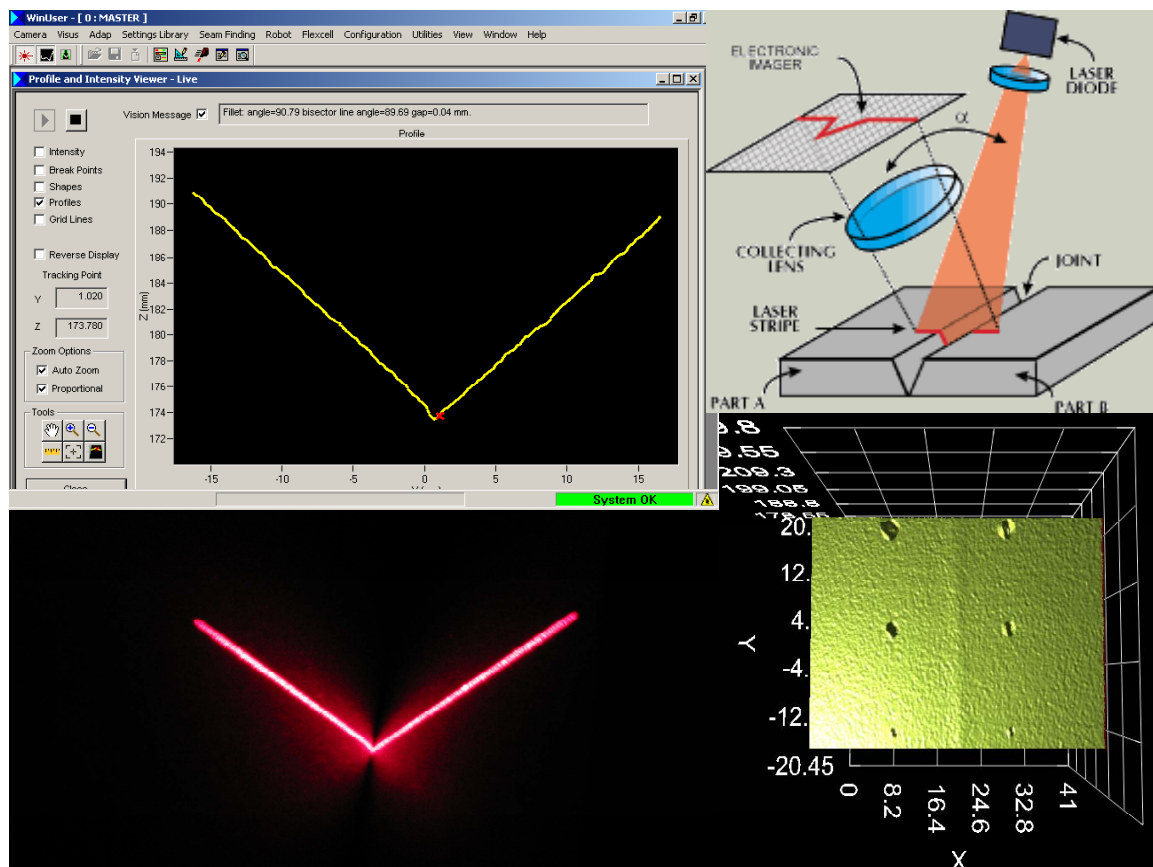


Figure illustrating the operation of the laser profiling sensor. Upper right shows how the profile is measured. Upper left shows the software display of the profile versus the actual image in the lower left of the laser stripe in a fillet weld groove. The lower right shows a software display of a scan over artificial defects on a plate.

If defects are identified, a third tower consisting of a computer controlled grinder is used. The grinder is specially designed to removed weld material to produce a regular shaped repair groove. A consistent repair groove allows of a simple eddy current probe to inspect the surface of the weld groove and provides an adequate joint for depositing weld material to complete the repair. The repair tower consists of actuator to position the grinder and a vacuum system to collect removed weld material.

To integrate the actuators and sensor acquisition, a control system will be implemented in software. The control system will position the appropriate component to the weld, initiate welding or inspection, and to perform coordinate tracking between the equipment on the various towers. Tracking of the coordinates and providing transformations to ensure different components act on the correct portion of the weld is a necessary requirement (e.g. the grinder needs to be accurately position to the location where NDE detected a flaw). The system will be implemented on a real-time computer system.

Eddy Current Examination Details.

Eddy current testing (ET) is an established technology used to characterize and/or inspect metallic components in a variety of applications where component failure present safety or economic issues. Although heavily used to inspect tubular and flat components as well as components with geometric symmetry, ET has not been widely applied to weld inspection.¹⁻³ This can be attributed to its inability to perform volumetric inspection of welds in ferromagnetic materials or heavy section welds of nonferrous materials and the difficulties associated with weld crown geometries. High magnetic permeability severely

limits eddy current penetration and the rough surface geometry introduced by weld crown structure will generate unwanted signal responses that can mask defect responses. Penetration into thick section welds is also limited in nonferrous materials but not to the extent of ferromagnetic materials. However, ET is well suited for surface/near surface inspection and in many cases has been used to detect surface breaking defects or characterize weld uniformity in thin sections.⁴⁻¹¹ The problem of weld crown geometry has also been addressed through the use of signal processing techniques or by the development of specialized eddy current probes designed to mitigate irregular surface geometries.¹²⁻¹⁸

In this application, ET will be used to perform a surface inspection of canister closure welds to detect and characterize surface breaking defects of 1/16 in. (1.6 mm.) and larger. Test conditions to be encountered include as-welded surface geometries, elevated surface temperatures as high as 2008F, and radiation fields on the order of ????. To mitigate the effects of radiation and elevated temperatures, an eddy current array approach will be implemented. The array approach groups multiple eddy current generation/sensing elements into a single linear probe that provides increase coverage when scanned over a region of interest. With the appropriate electronics, each of the test coils/array elements can be individually controlled or combined to work as differential or transmit-receive pairs. When compared to raster scanning of a single element probe, arrays provide increased spatial coverage while maintaining resolution nearly equivalent to the individual elements/coils, increased inspection rates, simplified scanning mechanisms, and reduced probe wear.

Of specific interest for weld inspection is a probe design that utilizes orthogonal wound coils operated in a differential mode. This design, see Figure 1, provides significant advantages for inspecting welds without the need for more complex signal processing approaches. The two test coils are wound perpendicular to each other and set with their axes parallel to the test piece. As configured, the test coils interrogate and compare approximately the same physical location but with perpendicular eddy current paths. In differential mode, slowly varying material properties or physical structures that are common to both coils are subtracted thereby providing no or very little response. Examples of this are symmetric changes in electrical conductivity or magnetic permeability due to gradual microstructural or temperature variations. Lift-off responses are suppressed in the similar fashion since both coils see the same amount of decoupling. Any significant material condition that is not common to both coils will yield a differential response that is measurable. Maximum probe response is seen when an electrical conductivity/material discontinuity such as a crack is 90° to either coil and at a minimum at a 45° angle. Scanning will be performed with the axes of the orthogonal coils aligned parallel and transverse to the axis of the weld. The reduced response for linear defects oriented at 45° is not considered a significant weakness for this weld application since minimal driving forces will exist to produce such defects. This type of coil arrangement can also be run in a driver-pickup mode that in some circumstances improves the lift-off response, but it does result in preferential detection of linear defects in one orientation and is susceptible to temperature variations. However, with any probe, lift-off needs to be controlled to maintain sensitivity. The primary approach to mitigate this problem will be the use of a surface-riding probe designed to minimize lift-off variations.

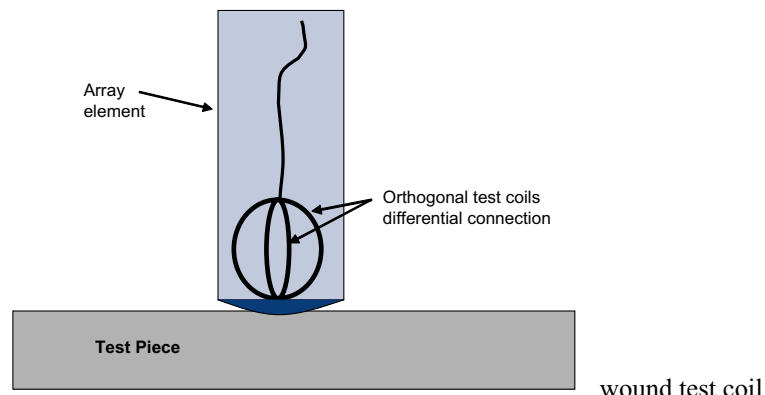


Figure 1. Orthogonal arrangement

Defect Detection

A suitable array probe with surface riding orthogonal wound elements is presently not available but is being developed in collaboration with eddy current array system vendors. However, raster scanning with a single element probe can be used to illustrate the utility of this approach. Figure 2 is a raster scan of a test weld in SS316L material containing a series of EDM notches used to simulate linear defects. The notches are 0.020 in. (0.51 mm) deep by 0.010 in. (0.25 mm) wide with lengths that range from 0.0313 in. (0.80 mm) to 0.188 in. (4.78 mm). Notches were orient longitudinal and transverse to the weld. A ZETEC 3477-1-A plus point probe containing PP11A coils combined with a ZETEC MIZ 22 instrument was used to collect the data. A 240 kHz Test frequency was utilized and data acquisition/scanning was controlled via Utex WinSpect® software. Probe scan rate was 5 deg/sec (0.81 in./sec or 20.6 mm/sec) on the simulated canister welds and data was collected every 0.1 deg. with raster steps of 0.02 in. (0.5 mm).

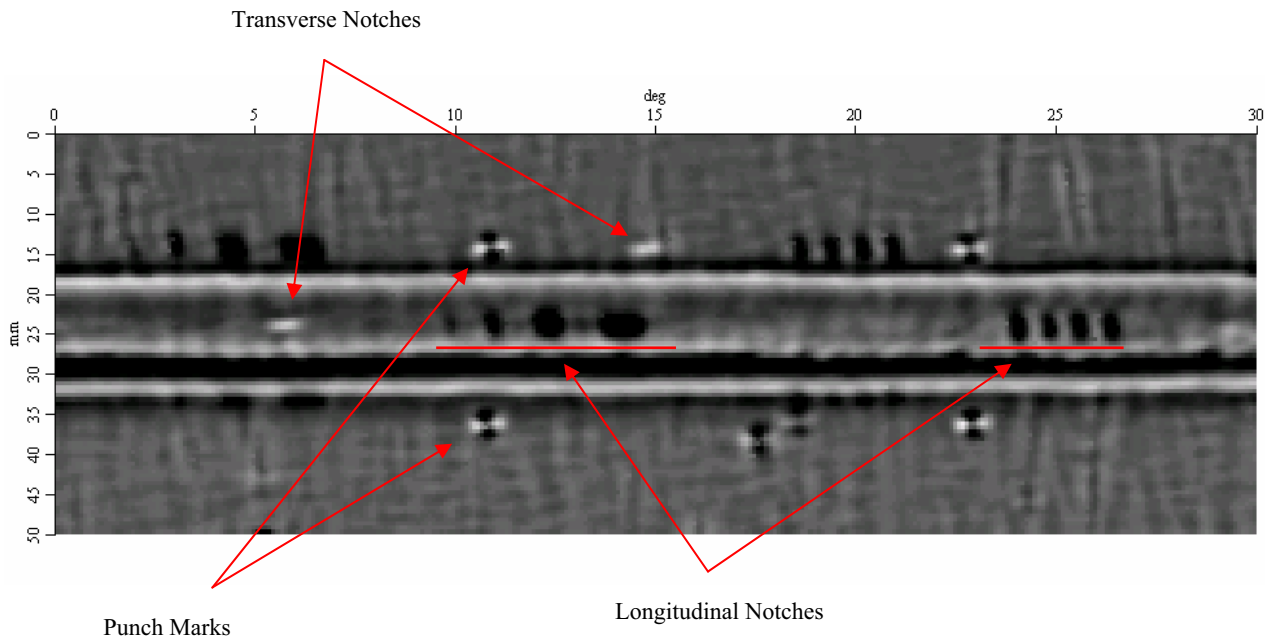


Figure 2. Presented is the 08 component of the eddy current response collected during a raster scan of a simulated canister weld containing EDM notches.

Note that the linear indications in Figure 2 yield characteristic responses that are indicative of orientation and are distinguishable from a rounded indication produced by the punch marks. This results from the orthogonal arrangement of the test coil pair that produce preferential detection of defects based on orientation and different signal polarities due to the differential mode of operation. Rounded indications, such as the punch marks, will produce symmetric bipolar responses generated by the combined responses from both test coils. Also note that the high weld toe entrance angle on the lower half of the weld held the eddy current probe off the test material thereby resulting in a loss of sensitivity. Weld parameters will need to be tailored to minimize this problem to allow instability.

Defect Sizing

The information available for defect sizing is amplitude, phase, and the scan image. Selective use of this information along with calibration reference standards allows calibration curves to be developed for sizing. Knowledge of the probe configuration/response will also contribute to defect type identification and sizing. Note that calibration curves are developed after the system has been setup and adjusted using a predefined test procedure that specifies system configuration and sensitivity. For example, scanning over a set of

notches, see Figure 3, provides an image and signal amplitudes characteristic of linear defects having different lengths. A simple plot of signal length versus known notch length yields one type of calibration curve from which defect size can be estimated for other imperfections having similar characteristics. The red symbols (Δ) in the plot are measurements made from other known defects indicating the relative size of measurement error that is seen with the test equipment and parameters used and this simple approach to sizing. Further refinement of the scanning parameters and sizing techniques may improve measurement scatter.

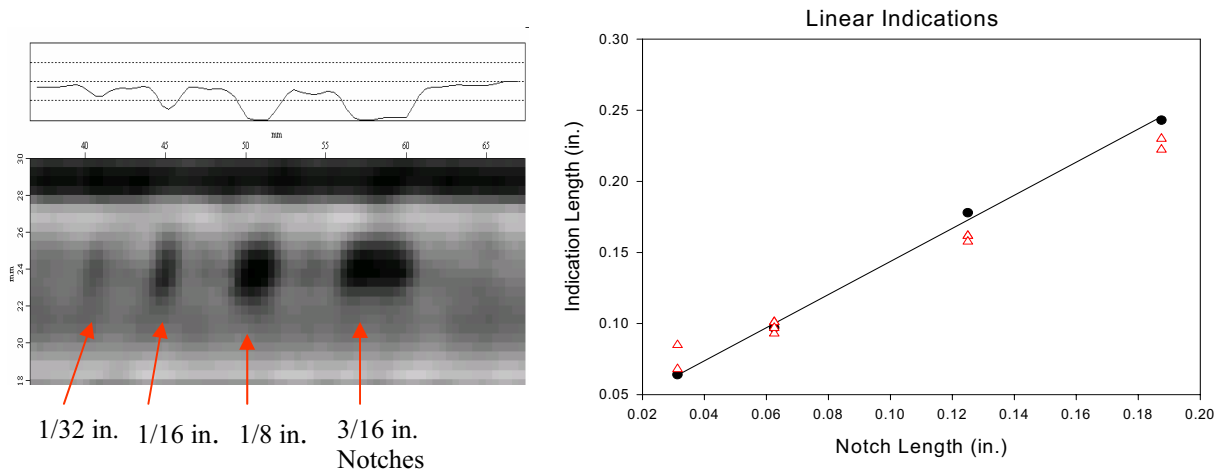


Figure 3. The ET responses to known defects can be used to generate a calibration curve for sizing of similar defects. The red symbols (Δ) in the plot are measurements made from scans of other known defects indicating the relative size of the measurement error for this approach.

Inspection of Repair Cavities

All rejectable weld defects will be eliminated via an automated repair process in which the defect is removed by grinding and the repair cavity filled with weld material. Included in this process is the use of an ET surface examine to verify that the defect has been fully removed. To accomplish this, the cross sectional geometry of the repair cavity will be held constant allowing a shaped ET probe to iteratively scan the cavity surface as it is being ground into the defect area. Either a single element probe or an array eddy current probe can be designed and built to accommodate the specified cavity geometry. However the single element probe has the limitation of not being able to provide transverse location of any remaining defect structure.

Conclusions

Nondestructive evaluation of canister closure welds is required to meet ASME Section III, Division 3 code requirements as a means to assure the integrity of the completed canister. The different evaluation techniques discussed here work in concert to provide information relevant to volumetric and surface irregularities as well as obtain dimensional data specific to weld workmanship requirements and overall inspectability. It has been demonstrated that ET can be used to perform the surface inspections required by ASME code with the advantages of being adaptable for remote operation in a hot cell and unlike the penetrant testing it replaces, provides a minimal waste stream.

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