WASTE PACKAGE FABRICATION AND CLOSURE-WELD DEVELOPMENT FOR THE YUCCA MOUNTAIN PROJECT – GFY 2000

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ABSTRACT

Framatome ANP, formerly Framatome Technologies Group (FTG), as part of the Civilian Radioactive Waste Management System Management & Operating Contractor (CRWMS M&O) for the Department of Energy’s (DOE’s) proposed repository at Yucca Mountain, is developing and demonstrating fabrication and remote welding techniques for waste packages. These waste packages will be used for long-term storage of spent nuclear fuel from commercial nuclear power plants, and high-level waste and spent fuel from the U.S. defense-programs complex. The waste packages will be designed to contain bare spent nuclear fuel assemblies, canistered fuel, and other high-level waste, including solidified material from waste processing and immobilized plutonium. The fuel and canistered waste will be sealed within robust waste packages that are designed to isolate these radioactive materials from the environment for thousands of years.

The development program conducted during Government Fiscal Year (GFY) 2000 was used to verify the ability to fabricate the newly-configured waste package closure. The closure region was redesigned to minimize residual weld stresses and facilitate post-weld induction annealing. The region includes a reinforced circumferential area to accommodate trunnion rings for lifting. The waste package is designed as a cylinder-within-cylinder containment system. The previously constructed mockups of the waste package used an interference-fit between the inner barrier’s outer surface and the outer barrier’s inner surface to enhance the thermal conductivity of the package. This year’s mockup was fabricated with a 0- to 4-mm (0.00- to 0.158-in.) radial gap between the inner cylinder and outer barrier. This gap will still allow heat transfer across the interface, as verified by computer models and analyses.

The waste package mockup comprises an outer cylinder; a corrosion barrier (Material Type: ASME SB-575, Alloy 22), 25 mm (1.00 in.) thick by 1,575 mm (62.00 in.) outside diameter and 1,320 mm (52.00 in.) long; and an inner cylinder (Material Type: ASME SA-240, Type 316 NG Stainless Steel), 51 mm (2.00 in.) thick by approximately 927 mm (36.50 in.) long.

The development program had three objectives: fabricate a full-diameter, partial-length mockup of the waste package; demonstrate that remote, automatic (machine) gas-tungsten-arc welding (GTAW) of the Alloy 22 and 316 NG stainless steel lids limits the residual weld stresses resulting from the closure weld; and complete the non-destructive examination (NDE) investigation to identify the minimum detectable defect. The development program is being performed under the FTG Safety-Related Quality Assurance Program (QAP) in accordance with the requirements of American Society of Mechanical Engineers (ASME) NQA-1, 10 CFR 50, Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants.”
INTRODUCTION

The waste package closure-weld program is a part of the nation’s effort to find a safe means of disposal for more than 70,000 metric tons of heavy metals, consisting of commercial and DOE spent nuclear fuel, and other highly-radioactive materials and wastes. The program is designed to develop fabrication processes, closure methods, and NDE techniques to ensure container integrity.

The waste package development program for GFY 2000 concentrated on successfully developing an outer barrier weld joint to the reconfigured outer lid. The outer lid joint was redesigned to reduce high residual weld stresses that could provide a mechanism for waste package breaches resulting from stress corrosion cracking, or SCC. While last year’s program demonstrated that remote NDE of the closure welds are achievable, alternative remote surface examination techniques were explored this year for applicability to the program, and for assurance of defect-free welds in the closures. This year’s waste package mockup will be used to verify computer analyses of the induction-annealing process being developed. This annealing process will be used to further relieve weld stresses and induce compressive stresses in the outer fibers of the outer closure joint to mitigate, or preclude, initiation of SCC.

WORK DESCRIPTION

All the work by Framatome ANP and its suppliers on this closure-weld development program was performed according to the FTG Safety-Related QAP. The QAP meets all the requirements of ASME NQA-1, Appendix B, and is approved by the U.S. Nuclear Regulatory Commission.

Cylinder Construction

A mockup comprising two concentric cylinders was constructed. The outer cylinder construction is of nickel-based ASME SB-575, Alloy 22, approximately 25 mm (1.00 in.) thick by 1,320 mm (52.00 in.) long with an outside diameter of approximately 1,575 mm (62.00 in.). The inner cylinder construction is of stainless steel, ASME SA-240, Type 316 NG, approximately 51 mm (2.00 in.) thick by 927 mm (36.50 in.) long – see Figure 1. Four datum lines (A, B, C, and D) were scribed on the outer surface of each cylinder, longitudinally from top to bottom, and at 90° circumferential intervals. Datum A is centered on the longitudinal weld. Datums B, C, and D are located at 90° circumferential intervals from Datum A, and in a clockwise direction when viewed from the top. Both cylinders have permanent identification indicating top and bottom. The outer cylinder was fabricated with a machined ring to support the inner cylinder during the assembly of the inner and outer cylinders. The bottom end lids on each of the cylinders were welded in place before the inner cylinder was placed within the outer cylinder. Installation of the inner cylinder within the outer cylinder resulted in a final inner-outer cylinder interface tolerance of 0 to 4 mm (0.00 to 0.158 in.), except in the region of the welds of the inner cylinder closure lid.
The inner cylinder was then fully inserted into (inside of) the outer cylinder to the point of contact with the support ring. Outer cylinder heating was not required. Nooter Fabricators, Inc., St. Louis, Missouri, fabricated the mockup with the exception of performing the inner and outer, upper closure lid welds and NDE.

**Closure Welding**

The bottom lids were welded onto each of the cylinders during fabrication, and the upper lid on the inner cylinder was welded before the two cylinders were assembled. The welding of the top end outer closure was performed after cylinder assembly. Figure 2 shows the configuration of the weld joints for the inner closure. The weld joint configurations for the outer closure welds are depicted in Figure 3.

The weld joint configurations were designed to minimize weld volume, thereby minimizing distortion and deposition time, while providing sufficient assurance of a defect-free weld. However, during welding of the stainless steel bottom lid to the inner cylinder, the weld prep geometry was not optimized to allow for one-bead-per-layer welding as desired. It was acknowledged at the outset of the project that, due to the unique first-of-a-kind geometry of the lid-to-cylinder weld, adjustments to the final top lid would be necessary. These adjustments would be made after the weld process was developed and refined, based on experience gained during welding of the bottom lid. The weld-joint opening experienced shrinkage during welding to the extent that insufficient access was available for proper fusion of the prep to the sidewalls.
Ultrasonic testing (UT) defects were detected at numerous circumferential locations, generally at an approximate depth of 51 to 63.5 mm (2.00 to 2.50 in.). The bevel (angle) on the lid side was increased from 3 degrees to 7 degrees for the top-lid to inner-cylinder weld. No reportable UT defects were found on the top-lid weld.
The automatic GTAW process was primarily used for these welds; however, manual techniques were used for tack welding. GTAW is an inherently clean welding process when proper weld prep design and cleaning are done, and optimum welding parameters are used. Even though other welding processes may have higher deposition rates, when considering weld-defect repairs etc., automatic GTAW is the process of choice.

Welding procedure specifications and performance qualifications for all welds were in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Subsection NB, 1995 Edition, 1996 Addenda. The closure-weld welding process specifications, associated procedure qualification records, and applicable weld control records (WCRs) are contained in the referenced Waste Package FY-00 QA Development Program Results Package (CRWMS M&O 2000a).

The longitudinal weld for the outer cylinder was examined by radiographic testing, UT, and liquid-penetrant testing (PT). UT and PT were used to examine the bottom end weld for both cylinders. The top end of the outer cylinder was welded after cylinder assembly, whereas the top end of the inner cylinder was welded before inner-to-outer cylinder fitup. Both UT and PT were used to examine all closure welds. NDE of these welds was in accordance with ASME Boiler and Pressure Vessel Code, Section III, Subsection NB, 1995 Edition, 1996 Addenda.

Residual Stress Measurements

Residual strain measurements were taken after the bottom outer lid was welded to the bottom of the outer cylinder. All of the measurements were taken using the ring-core method, employing equipment calibrated in accordance with the FTG QAP. Measurements were also taken on the longitudinal weld near each end and in the center of the length of the outer cylinder weld. Each of the measurements was taken before, and after, annealing the outer cylinder. At each axial location, measurements were taken at the weld centerline, the fusion line, 5.1 mm (0.2 in.) into the heat-affected zone (HAZ), and 7.6 mm (0.3 in.) into the HAZ.

Before the heat treatment, the data showed a maximum principal-residual-stress variation, at all locations measured, of +48.26 MPa (+7 ksi) to +579.16 MPa (+84 ksi), where positive (+) is tensile stress and negative (−) is compressive stress. The minimum principal-residual-stress variation was −393.0 MPa (−57 ksi) to +124.11 MPa (+18 ksi). After heat treatment the data showed a maximum principal-residual-stress variation, at all locations measured, of −193.05 MPa (−28 ksi) to −496.42 MPa (−72 ksi), and a minimum principal-residual-stress variation of −268.90 MPa (−39 ksi) to −592.95 MPa (−86 ksi). It is notable that all measured residual stresses at all locations, in all directions, were compressive after heat treatment.

Outer Cylinder Anneal

The outer cylinder was annealed after the bottom lid had been welded and inspected and stress measurements had been taken. The outer cylinder was furnace-heated and held at a soak temperature of 1121°C ±28°C (2050°F ±50°F) for at least 20 minutes. Cooling was performed by immersion in water. The cooling rate for the entire cylinder was greater than 55.6°C (100°F) per minute from the soak temperature to below 37°C (70°F). The furnace and quench charts can be found in Waste Package FY-00 QA Development Program Results Package (CRWMS M&O 2000a).
Inner Lid Fit and Weld – Top End

Prior to inner-outer cylinder assembly, the inner top lid was welded to the inner barrier using the automatic GTAW process. Weld parameters, including the filler material heat/lot number, type, and size used, are recorded on the applicable WCR and included in the QA data package (CRWMS M&O 2000a). The calculated arc time was 46 hours. Measurements of shrinkage and distortion were also recorded and are provided in Waste Package FY-00 QA Development Program Results Package (CRWMS M&O 2000a). After the lid was welded, the applicable NDE was performed in accordance with Waste Package Operations FY-00 Closure Weld Technical Guidelines Document (CRWMS M&O 2000b), Sections 3.7 and 3.8. No recordable indications were found.

Outer Lid Fit and Weld – Top End

After fitting the inner cylinder into the outer cylinder, the outer top lid was welded to the outer barrier using the automatic GTAW process. Weld parameters, including the filler material heat/lot number, type, and size used, are recorded on the applicable WCR and included in the QA data package (CRWMS M&O 2000a). The theoretical arc time was 12.13 hours. Measurements of shrinkage and distortion were also recorded and are provided in Waste Package FY-00 QA Development Program Results Package (CRWMS M&O 2000a). After the lid was welded, the applicable NDE was performed in accordance with Waste Package Operations FY-00 Closure Weld Technical Guidelines Document (CRWMS M&O 2000b), Sections 3.7 and 3.8. No recordable indications were found.

Ultrasonic and Liquid-Penetrant Examinations – Top Lid

Both UT and PT examinations were performed after each of the top lids was welded. The examinations were performed in accordance with ASME Boiler and Pressure Vessel Code, Section III, Subsection NB, 1995 Edition, 1996 Addenda. No recordable indications were found by either technique.

GFY 1999 Deferred Work

There were two unfinished tasks from the GFY 1999 development program. The two tasks denoted below were completed as part of the GFY 2000 development program:

- Development of the plasma-arc welding process as part of the weld process strain study that also included cold-wire gas-tungsten-arc welding (CW GTAW) and hot-wire gas-tungsten-arc welding (HW GTAW) for comparison of residual strains
- Evaluation of UT as an alternate surface examination technique.

Residual Stress Specimens

Three 254-mm- (10.00-in.-) diameter Schedule 80 SA-312 TP 316 stainless steel pipe sections were welded for evaluating residual stress. Cylindrical coupons were used rather than plate coupons because cylindrical coupons provide a more consistent and controllable distortion response. Stainless steel was used because it has a high coefficient of thermal expansion and
provides larger material deformation due to high stresses imposed by the welding process. This allows the strain differences to be more easily monitored.

One girth seam was welded using automatic CW GTAW; two girth seams were welded using automatic HW GTAW; and four girth seams were welded using the automatic plasma-arc welding (PAW) process. The weld prep configurations were based on the GFY 1998 mockup weld prep configuration to the extent practical. PAW parameters were established, and a weld procedure qualification was performed under the FTG Safety-Related QAP and the requirements of ASME Boiler and Pressure Vessel Code, Section IX.

As expected, the PAW process, using the keyhole method in the thick root area, resulted in the least axial and circumferential shrinkage. The HW GTAW coupons had the greatest axial and circumferential shrinkage, and the CW GTAW process provided results between those for PAW and HW GTAW. Table I provides a tabulation of the recorded data. The primary reasons for these expected results are weld volume and heat input. The PAW process, because of the distinct advantage offered by the keyhole root welding technique, provides the least total weld volume and least total heat input to the component.

<table>
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<th>Process</th>
<th>Measurement Locations (deg.)</th>
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<th>Diametrical Shrinkage Inside Diameter (in.)</th>
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<td>0.065</td>
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**ALTERNATIVE SURFACE EXAMINATION TECHNIQUES**

The objective of this task was to evaluate alternative surface examination techniques for detecting surface-connected flaws. PT examination techniques are typically used for surface examination of austenitic materials. However, PT techniques are difficult to apply remotely and generate hazardous waste due to the chemicals involved in the process. If a suitable alternative surface examination technique could be applied, the negative aspects of using PT could be avoided.

Two techniques were evaluated: Magneto-Optic Imaging (MOI) and Alternating Current Field Measurement (ACFM). MOI is an eddy-current technique that is capable of providing a real-time image of the electromagnetic field as the probe is passed across the surface of the part. ACFM is a technique that induces a uniform magnetic field and measures the resultant magnetic field
strength above the part. Each of these techniques is best described by literature available from the manufacturer. This report focuses on the results obtained using these technologies when intentionally-flawed mockups were used. Test results obtained from each of the techniques on flawed samples are included in following sections of this report.

Two plates were used to directly compare the technologies: Alloy 600 material, identified as Plate FT-01-01 and Plate FT-01-02. Each plate contained three thermal-fatigue cracks. Plate FT-01-01 flaws were in the HAZ adjacent to the root, while Plate FT-01-02 flaws started at the fusion line and extended into the weld. An additional plate of Alloy 22 was also investigated with the MOI and ACFM techniques. This plate, identified as 9C-016, contains a lack-of-fusion flaw that is surface-connected. PT was not used on this plate, though due to the nature of the flaw, PT would have easily detected it.

PT easily detected all of the flaws. Flaws with significant bleed-out of the dye provided an indication as to the depth of the flaw. Each of the flaws was examined with the MOI and ACFM techniques for comparison.

**Magneto-Optic Imaging Technique**

The equipment used for the MOI technique was the Model 308/7 instrument manufactured by PRI Research & Development Corporation, 25500 Hawthorne Blvd. #2300, Torrance, California 90505. The instrument has adjustable frequency settings to optimize sensitivity to the flaws being investigated. It also has fixed- and rotating-field generating capability to accommodate different flaw orientations relative to the probe direction. The inspection is accomplished by manually traversing the probe over the area of interest while viewing the scanned image on a monitor. For purposes of this comparison the probe was positioned over each flaw and the image was captured. When detectable, the images are annotated to show the flaw location. In some cases when flaws are imaged, the end points of the flaws can be detected, but not the center of the flaw. This is due to the increased field strength at the flaw ends, and it is not always apparent that a linear flaw is being imaged. Because of this phenomenon, end points could easily be mistaken for two separate, smaller indications. Thus, the frequency selector was varied to provide the best possible image of the flaw.

In general, the Model 308/7 instrument performed well on flat plates, but when lift-off resulted due to the height of the weld on plates FT-01-01 and FT-01-02, its sensitivity was severely degraded, making flaw detection difficult. The literature suggests that increasing the magnetizing coil sizes can reduce the effect of lift-off. The flat plates mentioned above included some thin titanium plates that were sent with the instrument for evaluation. The plates contained drilled holes with small EDM notches extending radially from the holes. These plates represent rivet holes in aircraft structures where this equipment is routinely used for NDE.

**Alternating Current Field Measurement Technique**

The ACFM technique was investigated using the AMIGO Crack Microgauge manufactured by TSC Inspection Systems, 6 Mill Square, Featherstone Road, Wolverton Mill Lilton Keynes, MK12 5RB, United Kingdom. The instrument is connected to a personal computer for display and recording of data as the probe scans the surface to be examined. The primary display format for this instrument is a chart recorder and a butterfly plot. The chart recorder display contains two horizontal lines that measure the field strength parallel to the crack (Bx) and perpendicular to the
surface (Bz) as the probe travels along the weld. The butterfly plot merely plots Bx vs. Bz, which results in the characteristic butterfly shape when the probe is passed across a flaw. The magnitude of the Bz trace indicates relative flaw depth and correlates well with the actual size of the flaw scanned. The deflection from the flat trace on the Bx line represents the flaw length. During investigation of the ACFM technique data points collected correlated well with the actual end points of the flaws.

All of the flaws were easily detectable. In addition to the two Alloy 600 plates and the Alloy 22 plate, a carbon steel plate provided with the AMIGO Crack Microgauge was also scanned. The carbon steel plate contained an as-welded plate with two narrow EDM notches adjacent to the toe of the weld. Even though the materials of the plates were different, all scans were done with the probe and equipment settings recommended by the manufacturer. The versatility of the equipment was well demonstrated by performing tests on a variety of specimens. All of these scans were done with a single-element probe. However, the manufacturer also makes an array probe that incorporates several elements to enhance the area scanned. Among software features included with the array probe is a C-scan-type plot function, which shows the orientation of detected flaws by length and depth, relative to the area scanned. Unfortunately, the array probe was not available for evaluation at the time of this investigation.

The lift-off effect was also investigated with the AMIGO Crack Microgauge because one of its stated advantages is relative insensitivity to lift-off. The investigation included placing a mouse pad over the weld and performing a scan. The flaws were still detectable.

**INDUCTION HEATING TEST MOCKUP**

Three mockups were fabricated to support the induction-heating study. Two were flat plate mockups and configured to be similar to the cross section of the top end of the waste package mockup. These mockups were made from Alloy 22 that was “left over” from the waste package mockup. An additional mockup was re-configured into a ring using material from the GFY 1998 waste package mockup. These mockups will be used to establish coil configurations for the induction-heating study and to prove feasibility of induction heating. The testing to be performed on these mockups is beyond the scope of this report.

**CONCLUSIONS**

The development program has demonstrated that Alloy 22/stainless steel full-cylinder mockup top lids for inner and outer cylinders can be welded using the automatic GTAW process while limiting the residual stress resulting from the closure weld. The inner and outer top lid welds were deposited and were PT- and UT-clear with no in-process weld repairs required.

Furthermore, residual stress magnitudes were measured on the outer cylinder before annealing with residual stress magnitudes being tensile at all locations. After heat treatment the outer shell residual stresses were compressive at all locations measured.

Both the MOI and ACFM techniques appear to be suitable alternatives to PT examination. The most significant advantage of the ACFM technique is its ability to handle lift-off effects with negligible loss of sensitivity. Further studies are recommended for the ACFM to evaluate the effectiveness of the array probe for rapid weld examination, for accessing the minimum detectable flaw size, and for flaw-sizing capability in the material type selected for the final canister design.
This can be accomplished by building mockups containing representative flaws and performing tests to optimize the equipment settings and evaluate effectiveness. ACFM results seem easier to interpret than the MOI results, and AFCM is also capable of providing length and depth sizing for detected flaws. Based on results obtained during this investigation, and as evident in the results presented in this report, ACFM is the recommended technology to pursue as a replacement for PT examination.

REFERENCES

5. FTG Quality Assurance Program, Safety-Related, Doc. Id. No. 56-1201212-04

CODES, STANDARDS, REGULATIONS, AND PROCEDURES