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QA: N/A

JUN 18 2003

OVERNIGHT MAIL

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TRANSMITTAL OF KEY TECHNICAL ISSUE (KTI) AGREEMENT ITEM PRECLOSURE (PRE) 7.04

This letter provides the U.S. Department of Energy (DOE) response to the KTI Agreement Item PRE 7.04. This agreement is as follows:

> PRE 7.04: "Demonstrate that the non-destructive evaluation methods used to inspect the alloy 22 and 316 nuclear grade plate material and closure welds are sufficient and are capable of detecting all defects that may alter waste package mechanical properties.
> DOE will provide justification that the non-destructive evaluation methods used to inspect the alloy 22 and 316 nuclear grade plate material and welds are sufficient and are capable of detecting defects that may adversely affect waste package pre-closure structural performance. DOE agrees to provide the information in FY2003 and document the information in the Waste Package Operations Fabrication Process Report."

The response to KTI Agreement Item PRE 7.04 is provided in this letter and in the enclosed report. The report addresses nondestructive testing methods for the plate material and welds of the Alloy 22 component of the waste package. The response to KTI PRE 7.04 is provided in the enclosed report *Weld Flaw Evaluation and Nondestructive Examination Process Comparison Results for High-Level Radioactive Waste Package Manufacturing Program*, TDR-EBS-ND-000007, Revision 01. This report replaces the previously titled report *Waste Package Operations Fabrication Process Report*. The change to the report title was necessary to reflect work replanning.

During the past two years, the waste package closure design has evolved from a structurally welded inner cylinder of stainless steel 316 and a structurally welded outer cylinder of Alloy 22 to a spread ring closure for the stainless steel 316 cylinder and a structurally welded Alloy 22 cylinder. The stainless steel 316 cylinder provides the preclosure mechanical integrity for the waste package and the Alloy 22 cylinder functions primarily as the corrosion barrier for the waste package.

The study focused on the nondestructive examination of Alloy 22 base material and welded specimens. These specimens were joined using the Gas Tungsten Arc Welding method. The study confirmed that both ultrasonic testing (UT) and radiographic testing (RT) are capable of detecting volumetric flaws as small as one millimeter in size, with a strong correlation between the two methods. The nondestructive surface examination methods of eddy current and dye penetrant testing detected flaws with comparable results.

Metallographic evaluation of the welded area indicated several small gas-induced spherical pores less than one millimeter in size (most of which were significantly smaller). These pores were attributed to the use of reagent grade gas in the welding process. Gas-induced pores can be reduced or eliminated by specifying an appropriate welding gas composition. The UT method did not detect the gas-induced pores. This was because the pores were smaller than the detection limits for UT. These pores were also not observed on the RT film. These pores were essentially spherical and are significantly smaller than the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME B&PV Code, Section III, Division 1) acceptance criteria, which assures structural adequacy of the material.

The report does not address the nondestructive examination aspects of the stainless steel 316 cylinder plate and closure welds. As described earlier, the spread ring design has eliminated the need for full penetration welds for the stainless steel 316 material closure. The spread ring is held in place with a seal weld that also provides containment of one atmospheric pressure of helium within the stainless steel 316 cylinder. Visual inspection and a helium leak test are planned for these seal welds. The function of the seal weld in the stainless steel 316 material closure is limited to leak tightness until the Alloy 22 lids are welded in place. The Yucca Mountain Project uses a "no breach" criteria for the waste package during preclosure. This criterion is met by the overall design of the waste package including the Alloy 22 material. Also, it should be noted that stainless steel 316 plate and fabrication welds have been used in the nuclear industry for over 35 years. During this period, extensive applications of nondestructive examination methods have been conducted for nuclear piping and components. A substantial body of knowledge exists which shows that nondestructive inspections can reliably detect and size small flaws in stainless steel 316 material components. The same ASME B&PV Code nondestructive examination methods and flaw acceptance criteria used for years in the nuclear industry for the fabrication of stainless steel 316 components will be used for the fabrication and acceptance of the waste package inner cylinder. Therefore, additional studies on nondestructive testing for stainless steel 316 material are not warranted and were not performed.

KTI Agreement Item PRE 7.04 was also linked with GENERAL 1.01 Items 8, 21, and 64. The enclosed report addresses the aspect of these items linked to KTI Agreement Item Pre 7.04.

Based on the information presented in this letter and enclosed report, and pending U.S. Nuclear Regulatory Commission (NRC) review and approval, the DOE recommends that KTI Agreement Item PRE 7.04 be closed.

This letter contains no new regulatory commitments. Please direct any questions concerning this transmittal to Timothy C. Gunter at (702) 794-1343 or Kirk D. Lachman at (702) 794-5096.

Joseph D. Ziegler, Acting Director
Office of License Application and Strategy

OLA&S:TCG-0867

Enclosure:
Weld Flaw Evaluation and Nondestructive Examination Process Comparison Results for High-Level Radioactive Waste Package Manufacturing Program, TDR-EBS-ND-000007, Revision 01

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TDR-EBS-ND-000007 REV 01

May 2003

Weld Flaw Evaluation and Nondestructive Examination Process Comparison Results for High-Level Radioactive Waste Package Manufacturing Program

By
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Prepared for:
U.S. Department of Energy
Office of Civilian Radioactive Waste Management
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Under Contract Number
DE-AC28-01RW12101

ENCLOSURE

DISCLAIMER

Weld Flaw Evaluation and Nondestructive Examination Process Comparison Results for High-Level Radioactive Waste Package Manufacturing Program

Approvals:

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Mike Rice Senior Engineer Technical Checker	5/15/03 Date
Chris Johnson Senior Engineer Compliance Checker	5/15/03 Date
Daniel J. Tunney Quality Engineering Representative	5/15/2003 Date
Jerry A. Cogar Manager, Materials & Fabrication Technologies	5/15/03 Date

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CHANGE HISTORY

Revision Number	**Description of Change**
00	Initial issue.
01	Revised to incorporate DOE comments on Revision 00, to change disposal container to waste package, and to make editorial and clarification changes throughout. Change bars have been omitted because the changes are extensive.

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ACRONYMS AND DEFINITIONS

Acronyms

DOE	U.S. Department of Energy
DTN	data tracking number
ET	eddy current testing
GTAW	Gas Tungsten Arc Welding
KTI	Key Technical Issue
NDE	nondestructive examination
PT	liquid penetrant testing
PWR	pressurized water reactor
RT	radiographic examination
SFP	Senior Flexonics Pathway
UT	ultrasonic testing

Definitions

Specimen Ring	The welded assembly of an inner and outer coupon ring. Each specimen is a set of two (an inner and outer) rings welded together to simulate the final closure weld.
Flaw	An imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.
Machine Welding	Welding with equipment which performs the welding operation under the constant observation and control of a welding operator.

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1. INTRODUCTION

This engineering test program was conducted to provide technical information relative to the resolution of technical issues raised by the U.S. Nuclear Regulatory Commission Key Technical Issues (KTIs) related to the processes that will be used during fabrication, inspection, and final closure of the waste package. This specific KTI in this report is agreement item PRE 7.04, which states:

> Demonstrate that the non-destructive evaluation methods used to inspect the alloy 22 and 316 nuclear grade plate material and closure welds are sufficient and are capable of detecting all defects that may alter waste package mechanical properties. DOE will provide justification that the non-destructive evaluation methods used to inspect the alloy 22 and 316 nuclear grade plate material and welds are sufficient and are capable of detecting defects that may adversely affect waste package pre-closure structural performance. DOE agrees to provide the information in FY03 and document the information in the Waste Package Operations Fabrication Process Report. (Reamer 2001, Attachment 1, Topic 7).

1.1 PURPOSE AND SCOPE

This program was conducted to develop Alloy 22 welded joints for application for waste package closures, evaluate flaw information on weld, heat-affected zone, and base metal and assess nondestructive evaluation (NDE) methods to detect and determine flaw sizes in the final closure weld. It should be noted that all the Alloy 22 material in this study was procured as plate. The evaluation of 316 stainless steel is not addressed in this report.

1.2 QUALITY ASSURANCE

The waste packages are classified as Quality Level 1. For example, see the classification analysis for the uncanistered spent nuclear fuel waste package (CRWMS M&O 1999, p. 7). Therefore, *Quality Assurance Requirements and Description* (DOE 2003) applies to the development of this engineering report. The production of samples, their examination, and information generation was performed by a supplier that was surveyed, approved, and placed on the Management and Operating Contractor Qualified Suppliers List in accordance with the requirements of *Quality Assurance Requirements and Description* (see BSC 2002). This engineering report was prepared in accordance with AP-3.11Q, *Technical Reports*.

1.2.1 Subcontractor Quality

The subcontractor performing the test work was Senior Flexonics Pathway (SFP) located in New Braunfels, Texas. In addition to having been placed on the approved supplier list for the Office of Civilian Radioactive Waste Management work, this company possesses nuclear certificates for "N," "NPT," and "NS" awarded by the American Society of Mechanical Engineers. These certificates attest to the adequacy of SFP's quality assurance program verified for the scope of the activities described by the code symbol stamps. These certificates of authorization were valid during the period this work was performed (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 2.)

1.2.2 Subcontractor Procedures

SFP developed procedures specific to this effort for the work it performed. Additionally, it required that sub-tier suppliers also develop procedures that were submitted to SFP for review and approval. This approval included Bechtel SAIC Company, LLC, review and approval prior to start of work (Senior Flexonics Pathway 2002b, Paragraphs 5.1.1.2 b, 5.1.2.2 a, 5.2.2, 5.3.2, 5.4.2, 5.5.2, and 5.6.2).

The procedures used are as follows (Senior Flexonics Pathway 2002a, Appendix 10.17, Sections 5, 7, 9, 10, and 12):

1. SQP-501, Revision 9, Standard Quality Procedure for NDE Personnel Qualification and Addendum
2. AAI-WP-01, Revision 1, All American Inspection Written Practice
3. AAI/SFP NDE UT-03 SP, Revision 4, Ultrasonic Examinations
4. AAI/SFP NDT ET-01 SP, Revision 2, Eddy Current
5. AAI/SFP NDT PT-03, Revision 1, Liquid Penetrant Examination
6. AAI/SFP NDT RT-02, Revision 3, Radiographic Procedure
7. PCI Energy Services Project Instruction PI-41130-01, Revision B, Canister Orbital Welding System Operations Manual
8. Senior Flexonics Inc., Pathway Division, Welding Procedure 4408-6, Revision 1, Welding Procedure Specification for Nuclear Waste Package Set-up and Test Ring Longseams
9. Senior Flexonics Inc., Pathway Division, Procedure Qualification Record (PQR) 44-11
10. Senior Flexonics Inc., Pathway Division, Procedure Qualification Record (PQR) 44-12
11. Senior Flexonics Inc., Pathway Division, Welding Procedure 4409-6, Revision 1, Welding Specification for Nuclear Waste Package Closure Welds
12. Senior Flexonics Inc., Pathway Division, Welder Qualification Records (QW-484s)
13. Senior Flexonics Inc., Pathway Division, Procedure H87130-N390-FU, Revision 3, Specimen Circumferential Weld Fit-Up Procedure
14. Senior Flexonics Inc., Pathway Division, Procedure SMP-108, Revision 1, General Heat Treatment and Operations Procedure
15. Senior Flexonics Inc., Pathway Division, Procedure H87130-WFR-1, Revision 3, Procedure for Documenting the Location and Azimuth of Flaws

16. WH Laboratories CHEM 108, Revision D, Standard Method for Selecting, Preparing, and Evaluating Waste Package Weld Flaw Microstructure Specimens

17. Senior Flexonics Inc., Pathway Division, Procedure SQP 702, Revision 4, Standard Quality Procedure for Calibration of Dimensional Inspection Equipment

18. Senior Flexonics Inc., Pathway Division, Procedure SQP 704-H87130, Revision 1, Standard Quality Procedure for Calibration of Densitometers, Job #H87130

2. TEST SPECIMEN DEVELOPMENT

There were several individual companies providing materials and services for this effort. The following companies (Table 1) were subcontracted by SFP for support. SFP, as a qualified nuclear supplier, passed down all nuclear quality requirements to these sub-tier suppliers.

Table 1. List of Sub-tier Suppliers Used by Senior Flexonics

COMPANY	INVOLVEMENT
All American Inspections, Inc. (AAI) 119 West Rhapsody San Antonio, TX 78216	NDT Services to conduct UT, RT, PT, and ET and provide reports as required for baseline flaw data from inner and outer rings prior to welding and final flaw data from welded specimens.
Ionics, Incorporated 3039 Washington Pike Bridgeville, PA 15017	Machining of inner and outer specimen rings to sketches provided by SFP.
PCI Energy Services One Energy Drive Lake Bluff, IL 60044	Provide automated welding equipment and technicians to operate it for welding specimens.
WH Laboratories 8450 Rayson Road Houston, TX 15017	(1) Provide laboratory services for conducting product analysis and conducting all other testing required by the material specification for material used, including weld filler material. (2) Provide metallography services for sectioning welded specimen rings, mounting, polishing, and photomicrography of metallographic samples as directed by BSC.
Jet Machine Works 1107 Aldine Houston, TX 77039	Machining and assembly of fixture (except the fixture base, which was manufactured by SFP) to sketches provided by SFP.
Tex-Fab, Inc. 23138 US 290 Cypress, TX 77429	Roll SB-575 Inconel 622 into cylinders that will later be parted into inner and outer rings.

Table 1. List of Sub-tier Suppliers Used by Senior Flexonics (Continued)

COMPANY	INVOLVEMENT
Rothe Development Inc. Metrology Services Division 4614 Sinclair Road San Antonio, TX 78222-2099	Calibration of digital thermometer
Precision Calibration and Repair 3130 Farrell Road Houston, TX	Calibration of measuring and test equipment.
3D Welding 3016 Hwy 123 San Marcos, TX 78666	Argon and bulk tank used for this project.
National Institute of Standards and Technology (NIST) 100 Bureau Drive Stop 2322 Gaithersburg, MD 20899	Density strip for X-ray equipment
Laboratory Testing, Inc. 2331 Topaz Drive Hatfield, PA 19440	UT and ET Calibration blocks.
Special Metals Corporation 3200 Riverside Drive Huntington, WV 25705	SB-575 (Inconel 622) material for SU-2 (setup ring #2) and test rings K through Z
Corrosion Materials P.O. Box 62868 New Orleans, LA 70162	SB-575 (Inconel 622) for SU-2 (setup ring #1)
Special Metals Corporation 1401 Burris Road Newton, NC 28658	Weld filler material
Universal Steel 13123 W. Hardy Road Houston, TX 77060	SA-516 Grade 70 plate for fixture base.
TriVis, Inc. 2976 Pelham Parkway, Suite B2 Pelham, AL 35124	Project logistics co-ordination services

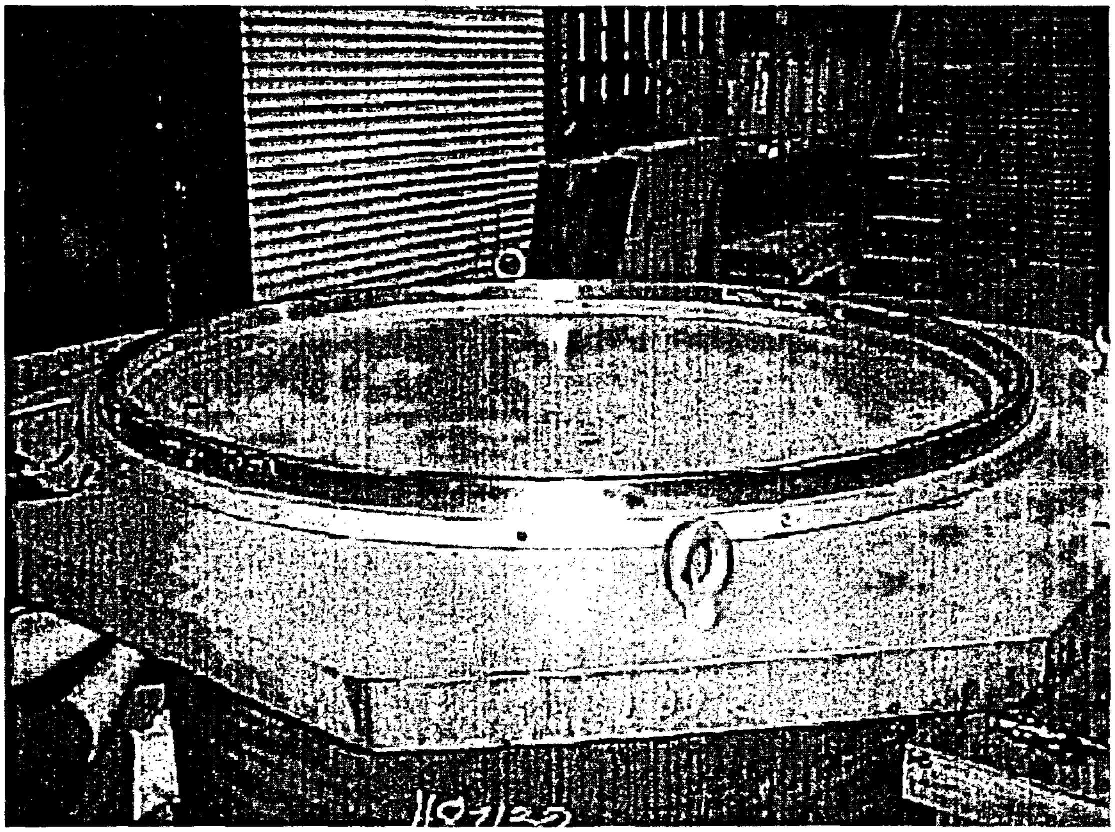
NOTE: BSC = Bechtel SAIC Company, LLC; NDT = nondestructive testing.

Source: Senior Flexonics Pathway 2002b, Paragraphs 9.1 and 9.2.

2.1 TEST FIXTURE MATERIALS

Figure 1 shows the test fixture. The fixture was fabricated from a 3-inch thick A-516, Grade 70 plate (ASTM A 516/A 516M-90 1991) and ground flat to ensure intimate contact with the surface of the test rings. The retainer rings that were designed to hold the test rings in place during welding were rolled and welded. The diameters were machined to assure that the rings, when welded, could be extracted from the test fixture. These rings were drilled and tapped in 16

places (every 22.5 degrees) and attached to the test plate with 1/2-inch bolts (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawings HB87130-2-2 and HB87130-2-3).



Source: Senior Flexonics Pathway 2002a, Waste Package Weld Flaw Analysis—Photographs in Final Report, TDR-EBS-ND-000007

Figure 1. Weld Test Fixture with Specimens

Test Fixture Functionality—The holes were drilled and tapped to accept a bolt that passed through the retainer rings every other 11.25 degrees. This allowed a bolt to be inserted to hold the test rings in place and to assure that the weld preparation gap was correct. There were 32 such bolts holding each test ring in place during welding (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawings HB87130-2-4 and HB87130-2-5).

2.2 TEST SPECIMENS

2.2.1 Test Specimen Material

The test rings were made of material that was purchased in accordance with the requirements of ASME 1998, Section II, Part B, with 1999 and 2000 Addendum, ASME SB-575, "Specification for Low-Carbon Nickel-Molybdenum-Chromium, Low-Carbon Nickel-Chromium-Molybdenum, Low-Carbon Nickel-Chromium-Molybdenum-Copper, Low-Carbon-Nickel-Chromium-Molybdenum-Tantalum, and Low-Carbon Nickel-Chromium-Molybdenum-Tungsten Alloy Plate, Sheet and Strip" (ASME 1998).

2.2.2 Filler Material

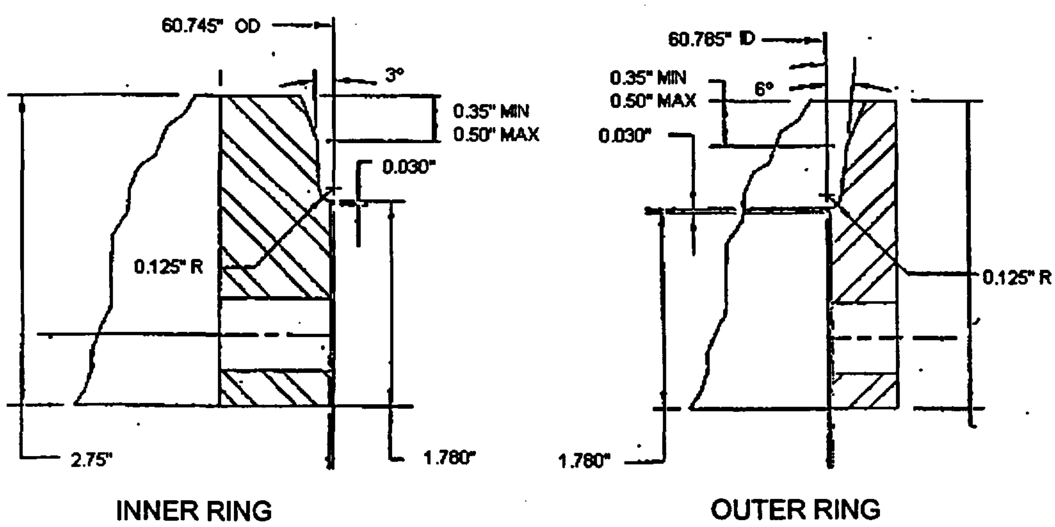
The weld filler material was purchased in accordance with the requirements of ASME Section II, Part C, SFA-5.14, 1998 edition, with 1999 and 2000 Addendum, "Specification for Nickel and Nickel-Alloy Bare Welding Electrodes and Rods," meeting the chemical requirements of ERNiCrMo-10 that matches the chemical requirements of the base material (ASME 1998).

2.2.3 Test Specimen Configuration

The test specimens fabricated for this test were made from Alloy 22 plate procured in accordance with nuclear quality assurance requirements (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 2). This base material was solution heat treated after the plate was welded and proper dimensions obtained (Senior Flexonics Pathway 2002a, Appendix 10.17, Sections 10 and 11). The intent was to duplicate planned processing of the waste package in that no heat treatment was performed after weld preparation machining. A total of 18 sets of rings were fabricated. Two of the sets were used to establish weld parameters for the Gas Tungsten Arc Welding (GTAW) process.

2.2.3.1 Test Specimen Geometry

A test specimen contained two rings that were designed to duplicate the configuration of the 21-pressurized water reactor (PWR) waste package. Figure 2 shows the configuration of the inside and outside test rings prior to assembly (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawings HB87130-3-2 and HB87130-3-3).

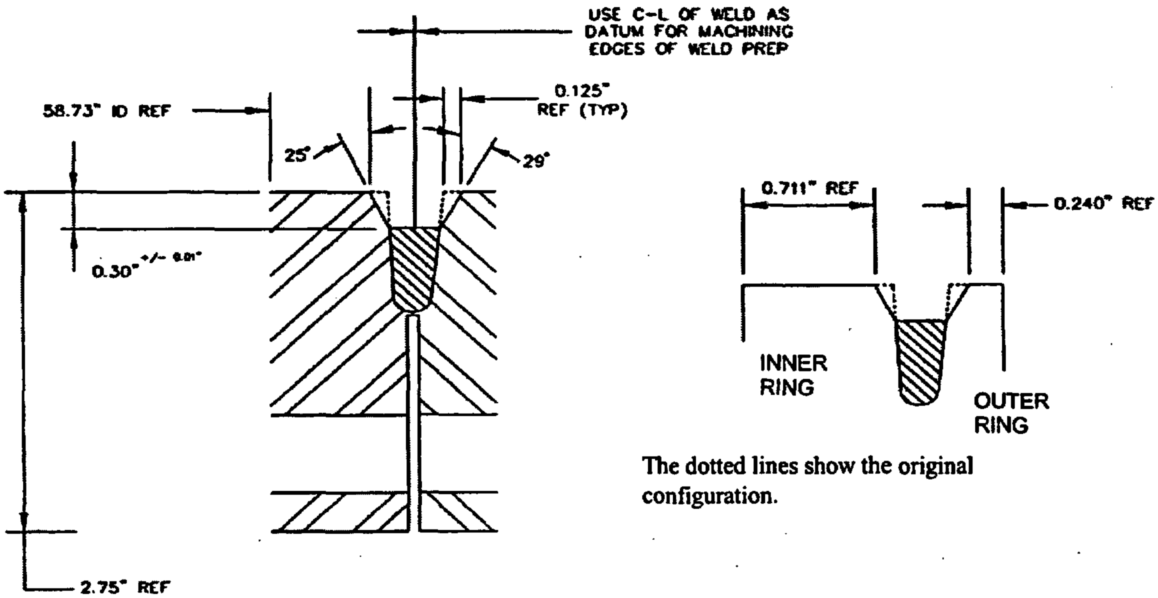


NOTE: OD = outside diameter; ID = inside diameter.
Source: Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawings HB87130-3-2 and HB87130-3-3.

Figure 2. Test Specimen Cross Section Showing Geometry

During welding, SFP could not successfully weld using the as-designed weld preparation. In order to ensure that the welding could be performed, the weld preparation was modified to allow

greater access. The weld preparation used is shown in Figure 3. This is the same configuration shown in Figure 2 but shown to indicate precisely what was used (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawing HB87130-3-4). The as-designed weld preparation was only used on ring K. The modified weld preparation was used on rings L through Z.



NOTE: C-L = centerline; ID = inside diameter.

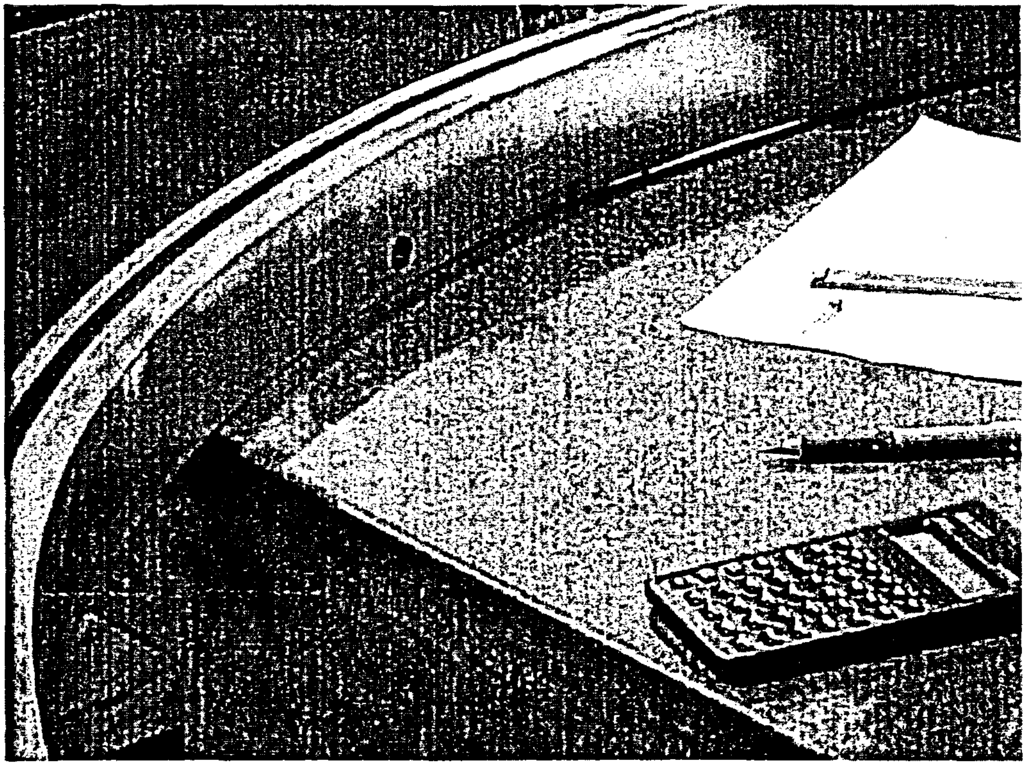
Source: Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawing HB87130-3-4.

Figure 3. Modified Weld Preparation

2.3 FABRICATION OF SPECIMENS

The specimens were fabricated from plate material by rolling the plate into a "mother" ring and then cutting the specimen rings from the rolled plate material (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawings HB87130-1-11 and HB87130-1-12). The rolled plate had been solution heat treated prior to cutting (Senior Flexonics Pathway 2002a, Appendix 10.17, Sections 7 and 10). After the rings were cut from the "mother" ring, they were machined to final dimensions including the weld preparation. The inside ring was 60.745 ± 0.01 inches outside diameter and 58.73 ± 0.01 inches inside diameter. The outside ring was 61.97 ± 0.03 inches outer diameter and 60.785 ± 0.01 inches inner diameter. Both specimens were 2.750 ± 0.005 inches high (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 9, Drawings HB87130-3-2 and HB87130-3-3).

A total of 18 sets of rings were fabricated; two of the sets were used to establish setup values of the essential variables during weld process development. Each specimen consisted of two rings: inner and outer rings that were of the same geometry and thicknesses as the 21-PWR canister. The two rings were set inside the test fixture retainer rings. Set screws in the fixture allowed the inner and outer rings to be adjusted in such a fashion to ensure that the weld gap was correct. Figure 4 shows a set of rings being checked for dimensions.

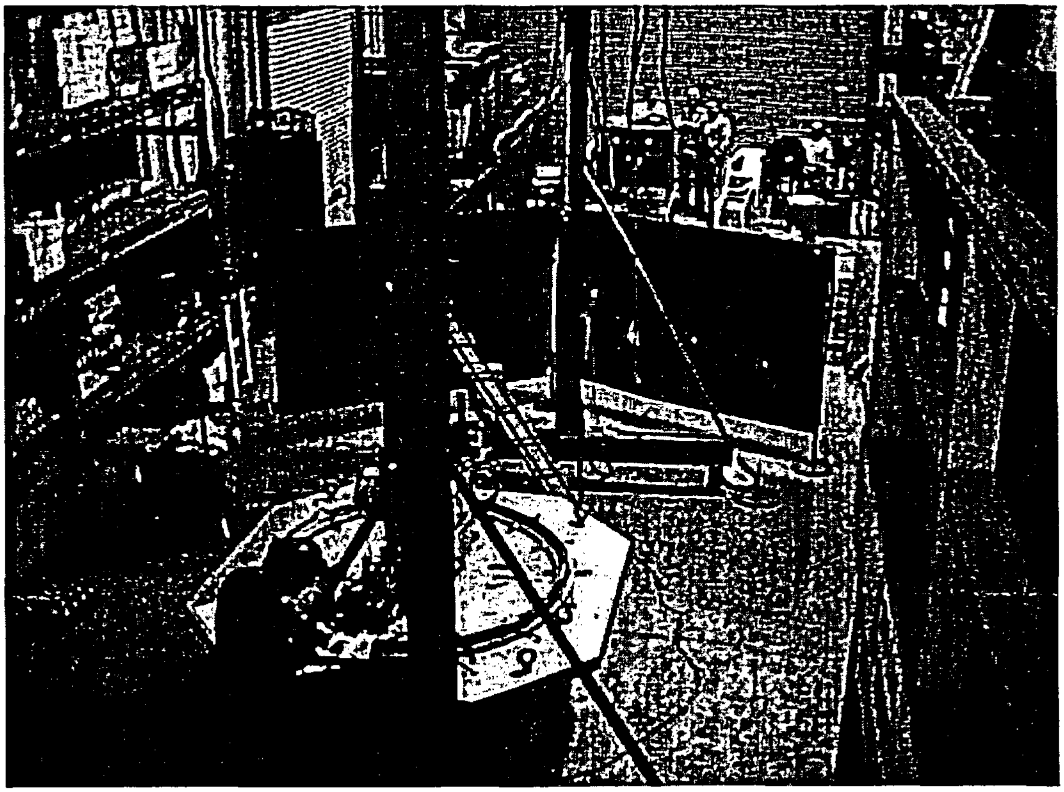


Source: Senior Flexonics Pathway 2002a, Waste Package Weld Flaw Analysis—Photographs in Final Report, TDR-EBS-ND-000007.

Figure 4. A Test Specimen Being Dimensionally Checked

2.3.1 Test Setup

A set of rings was assembled and placed into the test fixture, and appropriate weld preparation gaps were established. The welding equipment was then placed upon the weld fixture and bolted in place and dimensions were rechecked. Figure 5 shows the general arrangement of the weld setup. This particular photograph was taken during initial setup efforts to determine the best set of welding variables. After the physical space requirements had been established, the welding operator and the technician moved some distance from the actual welding location and performed the welding from that position. The welding process utilized an automated welding machine with the operator controlling some of the welding functions based on his observation of the arc, weld puddle, and his familiarity with the welding equipment.



Source: Senior Flexonics Pathway 2002a, Waste Package Weld Flaw Analysis—Photographs in Final Report, TDR-EBS-ND-000007

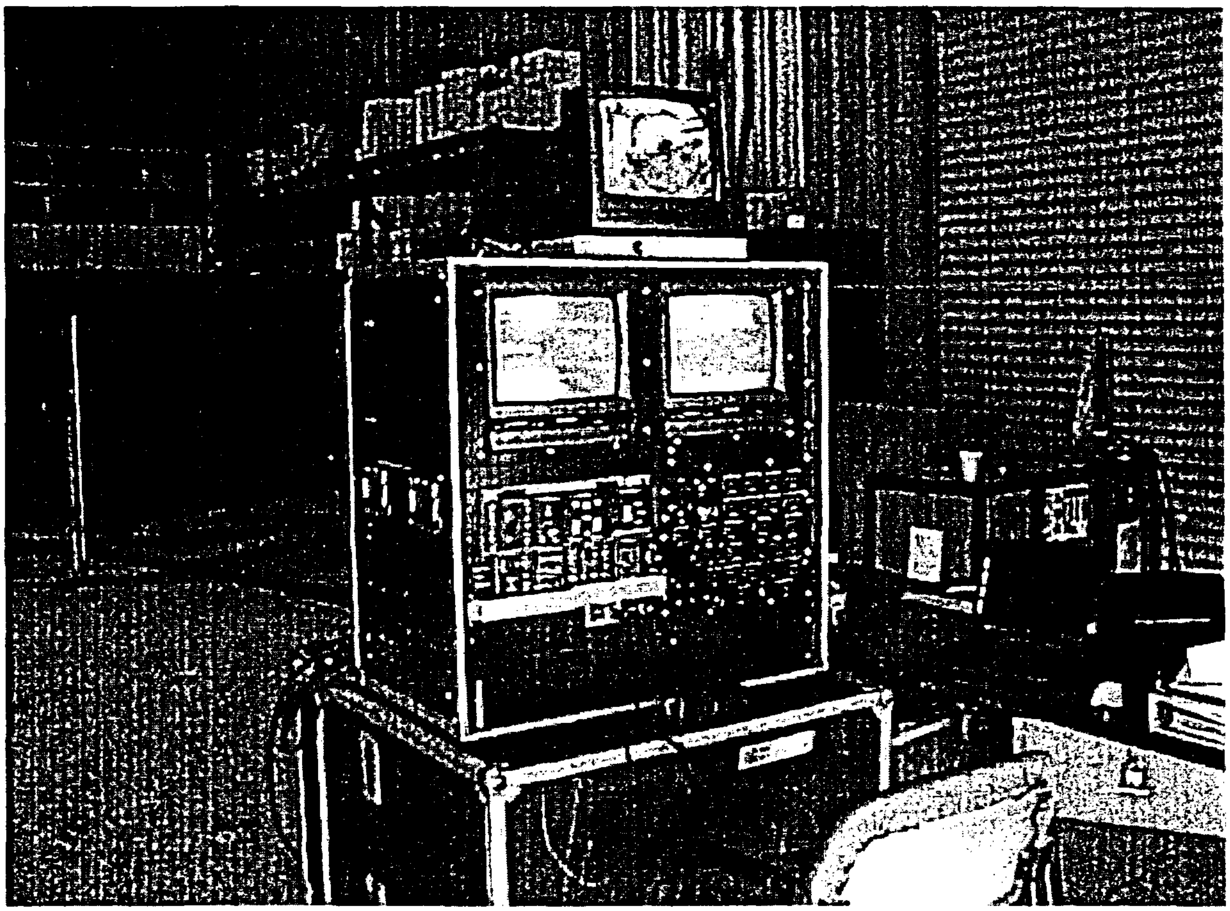
Figure 5. Welding Setup

2.3.2 Preparation to Weld

The welding process used was GTAW. This process was chosen primarily for its ability to provide high quality weld joints with optimum control of the welding variables. The process provides welds that can readily be inspected by automated and remote methods. Additionally, the election to use GTAW naturally limits and defines the nature (size and acuity) of the discontinuities that are induced during welding. The discontinuities generated by GTAW are well defined and include lack of penetration, lack of fusion, porosity, and microfissuring.

The welding equipment was subcontracted from PCI Energy Services, located in Lake Bluff, Illinois. This equipment was an older container orbital welding system that had been used in field welding operations to close nuclear storage containers at utility sites. Although functional, it did not possess the process controls being designed into the final closure welding system. Noteworthy in those controls missing was cross-seam tracking. Cross-seam tracking combined with dwell control is important in controlling lack of fusion-type flaws. The system used was capable of human-controlled operation from a remote location. In this operation, the operator was located some 30 feet from the actual welding (Senior Flexonics Pathway 2002b, Paragraphs 5.2.1 and 9.3; Senior Flexonics Pathway 2002a, Appendix 10.17, Section 7). This can be observed in Figure 5.

Figure 6 shows the control station for welding. The operator had multiple views of the weld process: (1) the top monitor shown in Figure 6 is a view from above the welding unit and shows the overall weld area and (2) the left and right monitors on the control console shows the left and right views of the weld puddle. Through his observation of the weld puddles, his skills in manipulating, and his knowledge of the process, the operator could make adjustments to the travel of the welding head between each side of the weld preparation (manual cross-seam tracking) (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 7).



Source: Senior Flexonics Pathway 2002a, Waste Package Weld Flaw Analysis—Photographs in Final Report, TDR-EBS-ND-000007.

Figure 6. Remote Welding Control Station

2.3.3 Welding Operations

A set of outer and inner rings was then chosen from the supply of inner and outer rings. This election was documented on the production traveler (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 3). The ring documentation was checked to assure that the baseline NDE had been performed. The filler material to be used on that set of rings was verified and documented on the traveler. The rings were cleaned with an approved cleaner and placed in the test fixture. The fit-up was verified and a fit-up inspection report completed (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 3). When all conditions preparatory to welding were verified,

the circumferential welds were completed. Welding operations were accomplished in accordance with SFP's nuclear shop traveler (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 3).

The selection of rings to be welded to form a specimen set is shown in Table 2.

Table 2. Selection of Rings to be Welded to Form a Specimen Set

Specimen Nomenclature	Inner Ring Identification	Outer Ring Identification
K	B-1	A-5
L	B-2	A-2
M	B-4	A-3
N	B-3	A-7
O	B-5	A-6
P	B-9	A-13
Q	B-6	A-8
R	B-14	A-12
S	B-15	A-15
T	B-11	A-11
U	B-8	A-14
V	B-10	A-16
W	B-16	A-9
X	B-12	A-10
Y	B-7	A-4
Z	B-13	A-1

Source: Senior Flexonics Pathway 2002b, Paragraph 7.3.

3. NONDESTRUCTIVE EXAMINATION OF SPECIMENS

3.1 METHODS USED

Four methods of NDE were used: ultrasonic testing (UT), radiographic examination (RT), eddy current testing (ET), and liquid penetrant testing (PT). RT and UT results were compared; ET and PT results were also compared. The details of those comparisons are shown in Section 3.7.1 (covers base material) and Section 6 (covers welds).

Calibration of NDE Equipment—Each method utilized appropriate calibration methods and standards. The calibration block used for UT was fabricated from the same material as the material being evaluated (Alloy 22) that was solution heat treated and contained a reference flaw of 1.0 mm. The distance amplitude curve was established in accordance to the procedure that had been reviewed and approved.

The RT also utilized a penetrameter appropriate to the material thickness being evaluated. The penetrameters used for this work were in accordance with ASME Section V, Article 22 (SE1025) (ASME 1998) and were used in accordance to the procedure that had been reviewed and approved.

The eddy current examination utilized a reference standard fabricated from Alloy 22 with a defect sized at 1.0 mm and in accordance to the procedure that had been reviewed and approved.

The PT method does not utilize a calibration standard; however, the equipment used during the penetrant inspection is calibrated on an annual basis. The PT performed on this test program adhered to the requirements of ASME Section V (ASME 1998) and was performed in accordance with the procedure that had been reviewed and approved.

3.2 RADIOGRAPHIC EXAMINATION

RT of metallic materials is a proven and accepted technology. RT introduces x-rays or gamma rays into a material being tested. The x-ray source is located on one side of the material and photographic film is placed on the other side of the material. The image generated by the energy source is generated onto photographic film which "displays" the contents of the material being tested. The image displayed on the film is then "read" by an interpreter to indicate what is a relevant indication and what is not. The density reveals any indications in the material. Light indications on the film are denser than the material being tested. Dark indications are less dense than the material being tested.

The work for this test was performed in accordance with a detailed, reviewed, and approved radiographic procedure (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5) specifically for nuclear work. The source for the gamma radiation was Iridium-192 and was placed in the center of the ring. The film and penetrameters were placed on the outside of the outer ring. Personnel performing the radiography were trained, qualified, and certified (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5) in accordance with ASME Section V (ASME 1998).

3.3 ULTRASONIC TESTING

UT is performed by introducing sound waves into the material being tested. To accomplish this a sound wave generator is connected to a transducer to which the sound waves are emitted. Couplant is applied to the material surface allowing the sound waves to travel from the transducer through the material and then back to the transducer. When the sound waves travel through the material and "hit" a discontinuity, the wave returns back to the transducer sooner than the waves that do not "hit" a discontinuity. All of the sound waves are collected and displayed on a screen, and a trained operator then interprets the signal generated. With this method a discontinuity can be sized and located within the material.

Personnel performing the UT were trained, qualified, and certified (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5) in accordance with ASME Section V (ASME 1998).

3.4 EDDY CURRENT TESTING

ET is an electromagnetic nondestructive testing method in which eddy current flow is induced in the test piece. Changes in the flow of the eddy currents caused by variations in the test piece of discontinuities in a weld are detected by a nearby coil or coils and measured by suitable instruments. The method can be used to detect certain discontinuities in welds; however, the results can be affected by variations in dimensions of the test piece or the testing arrangements.

In high-nickel alloys the method may be semi-volumetric in that a flaw very near to the surface can influence the coupling of the magnetic field thereby indicating a subsurface flaw.

As with the other methods used, personnel performing the ET were trained, qualified, and certified (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5) in accordance with ASME Section V (ASME 1998).

3.5 LIQUID PENETRANT TESTING

PT is a method that reveals open discontinuities (surface flaws) by bleedout of a liquid penetrant medium against a contrasting background developer. The technique is based on the ability of a penetrating liquid to set the surface opening of a discontinuity and to be drawn into it. If the discontinuity is significant, penetrant will be held in the cavity when the excess is removed from the surface. Upon application of a liquid-propelled or dry powder developer, blotter action draws the penetrant from the discontinuity to provide a contrasting indication on the surface. The basic steps involved in the application of a liquid penetrant test are relatively simple; however, inspectors performing the work must be appropriately trained and qualified. Personnel performing the PT were trained, qualified, and certified (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5) in accordance with ASME Section V (ASME 1998).

3.6 QUALIFICATION OF PROCEDURES AND STAFF

3.6.1 Procedures

Since the utility of NDE methods are dependent upon the skill of the operator as well as the physics of the method, the skills and procedures for the implementation of the NDE methods applied for this work were appropriately qualified. This included training, qualification, and certification in accordance with a number of requirements including:

ASME Section III, Division 1, "Rules for Construction of Nuclear Facility Components" (ASME 1998)

ASME Section V, "Nondestructive Examination" (ASME 1998).

3.6.2 Staff

Each technician and/or engineer engaging in NDE work was trained, their qualifications demonstrated through a formal written test and demonstration by an authority of the subcontractor, and their qualifications formally attested to in writing by their employer (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5).

3.7 BASELINE NONDESTRUCTIVE EXAMINATION

3.7.1 Ring Designators

As noted earlier, a test specimen consisted of two rings. The outer ring was assigned the nomenclature "A" and the inner ring "B." Table 3 provides the baseline NDE results. It should be noted that no radiography was performed on the flat plate since it was examined using

ultrasonics testing for acceptance. This decision was made in the interest of getting the material rolled into the ring configuration with the understanding that several radiographs would be made after the material had been rolled. It was more likely that flaws due to rolling would become evident after the material was formed into rings. When the welded rings (specimens) were received at the metallographic laboratory, each specimen had a unique identifier. Since alphabetical notations had been used for piece parts (A designation for inner rings; B for outer rings), the welded sets were named K through Z to avoid any identification problems. Since most specimen sets contained no flaws, it was established that six sets of metallographic samples would be randomly removed from specimen sets containing no flaws. Where flaws did exist, appropriate numbers of specimens were removed but always at least six. The naming convention used was, for example, K1, K2, K3, etc., wherein K was the ring name and 1, 2, 3, etc., was the metallographic specimen identification from that specimen set (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5).

The base material was purchased with ultrasonic testing as the basis of acceptance. The rings were tested again with UT after fabrication. There were no flaws identified.

Surface flaws identified with PT and ET were compared. It appears that ET identified more flaw indications than PT. This is because ET is a semi-volumetric examination method with nickel-based materials. PT is sensitive to cold shuts (traps penetrant) while ET is sensitive to cold shuts and subsurface disturbances wherein there may be no cold shut breaking the metal surface. Cold shuts are defects that can exist in a metal where two volumes of material have come together but failed to unite, fuse, or blend into a solid mass. The result can be a cracklike lap in the material that can hold penetrant and will show as a defect. Also imprint marks in the test specimen rings were caused by holding the rings with normal milling machine clamping forces without protective material between the chuck jaws and the Alloy 22 material. These imprint marks were generally identified with PT because the marks held penetrant; however, ET did not identify every imprint mark (Senior Flexonics Pathway 2002b, Paragraphs 7.2 and 7.3).

Table 3. Baseline Nondestructive Examination Results

Ring Set Designation	Inside/Outside Identification	PT Results	ET Results	UT Results
K	A-5	No flaws	No flaws	No flaws
	B-1	No flaws	No flaws	No flaws
L	A-2	No flaws	No flaws	No flaws
	B-2	No flaws	No flaws	No flaws
M	A-3	No flaws	No flaws	No flaws
	B-4	No flaws	No flaws	No flaws
N	A-7	No flaws	No flaws	No flaws
	B-3	No flaws	No flaws	No flaws
O	A-6	1 flaw: <10 mm rounded	6 flaws: one >10mm rounded, four 1–4 mm linear, one <1mm rounded	No flaws
	B-5	No flaws	No flaws	No flaws
P	A-17	No flaws	No flaws	No flaws
	B-9	1 flaw: <1 mm rounded	4 flaws: 1–4 mm linear	No flaws
Q	A-8	No flaws	No flaws	No flaws
	B-6	No flaws	No flaws	No flaws
R	A-12	No flaws	No flaws	No flaws
	B-14	No flaws	No flaws	No flaws
S	A-15	2 flaws: two <1 mm	No flaws	No flaws
	B-15	No flaws	No flaws	No flaws
T	A-11	1 flaw: 1–4 mm linear	1 flaw: 1–4 mm linear	No flaws
	B-11	1 flaw: 1–4 mm rounded	1 flaw: 1–4 mm linear	No flaws
U	A-14	No flaws	No flaws	No flaws
	B-8	No flaws	No flaws	No flaws
V	A-16	No flaws	No flaws	No flaws
	B-10	No flaws	No flaws	No flaws
W	A-9	No flaws	No flaws	No flaws
	B-16	No flaws	No flaws	No flaws
X	A-10	No flaws	No flaws	No flaws
	B-12	3 flaws: one 4–10 mm, one>10 mm, and one 1–4 mm	No flaws	No flaws
Y	A-4	No flaws	No flaws	No flaws
	B-7	No flaws	No flaws	No flaws
Z	A-1	No flaws	No flaws	No flaws
	B-13	1 flaw: 1–4 mm linear	No flaws	No flaws

NOTES: The measurements are given in mm since the calibration standard was in mm. A = outer ring; B = inner ring. RT was not performed on the flat plate base material.

Source: Senior Flexonics Pathway 2002a, Appendix 10.1 through 10.16, Metallography.

3.7.2 Evaluation of Surface Flaws

Each surface flaw was evaluated to characterize the flaw and determine, to the degree possible, what caused the indication. The conclusion was that the flaws were the result of either handling or material indentations when the material was placed into the lathe used to machine the weld preparations.

Surface flaws identified as caused by handling were generally very small; however, they were not evaluated using metallography because doing so would have destroyed the primary sample. Every surface flaw was visually examined to determine their severity and found to be minor (without characterization) based on experienced fabricator opinions. None of the surface flaws evaluated appeared to be capable of becoming more severe during service.

Surface flaws identified as machine tooling marks were preventable and should not have occurred. However, they were considered normal by the machining company and typically would have been ignored because they were fully expected. After the initial few had been identified, appropriate shims were used by the machinist, and no further surface flaws due to machine tools were observed. Avoidance of this type of preventable defect will be taken into account in future procurement statements of work.

The flaws identified on the outside surfaces of the specimen rings were not repaired since the existence of surface flaws had no bearing on weld flaw study. Surface defects within the area of the weld preparation were removed by buffing and then re-examined to ensure sound metal.

3.7.3 Volumetric Evaluation

The base materials were purchased with ultrasonic examination as the receipt inspection method. No volumetric flaws were found during receipt inspection (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 11) or subsequent baseline volumetric examinations (Senior Flexonics Pathway 2002a, Appendix 10.1 through 10.16, Baseline NDE). Figure 7 shows the baseline volumetric examination of the rolled test rings being performed prior to separation.

Source: Senior Flexonics Pathway 2002a, Waste Package Weld Flaw Analysis—Photographs in Final Report, TDR-EBS-ND-000007

Figure 7. Ultrasonic Examination of the Rolled Rings Prior to Cutting into Separate Rings

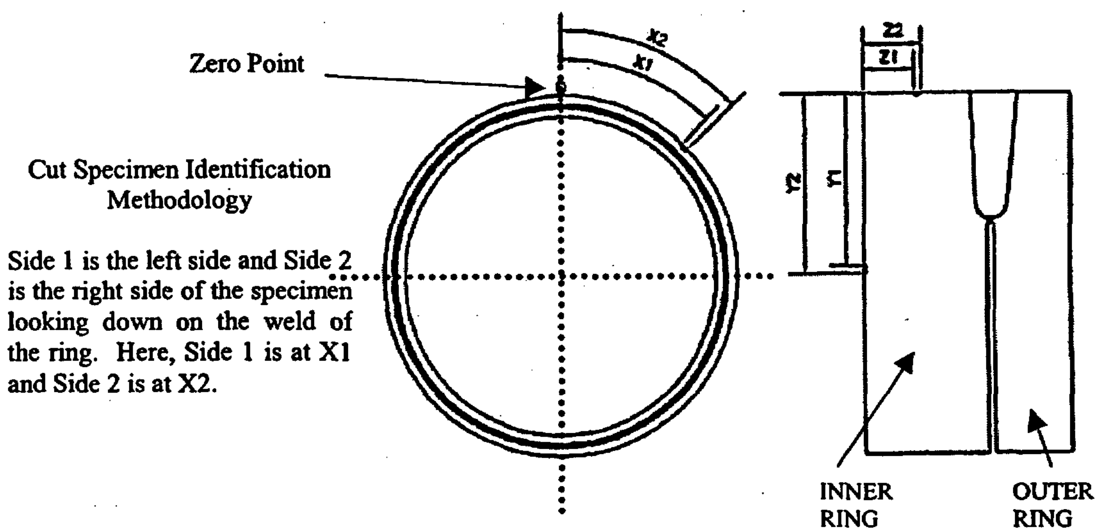
3.8 POST-WELD NONDESTRUCTIVE EXAMINATION

3.8.1 Performance of Nondestructive Examination

After welding was complete and the specimen allowed to cool to room temperature, the test rings were removed from the test fixture and prepared for NDE. The ring was then cleaned as necessary for UT and RT.

3.8.2 Documentation Method

A procedure describing the method used in mapping flaws was developed and followed (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5). The marking system used is shown in Figure 8.



Source: Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5.

Figure 8. Coordinate System Used to Locate Flaws

X is the distance along the circumference (outside diameter) (length).
Y is the distance from the top surface (thickness).
Z is the distance from the inside diameter of the ring (width).

The X2–X1 provided the length of the flaw as seen from that surface. The Y2–Y1 provided the thickness of the flaw as seen from that surface. The Z2–Z1 provided the width of the flaw as seen from that surface.

When the NDE was complete, the technician completed a "Location and Azimuth of Flaws Data Sheet" that captured all the information gathered. A blank, but abbreviated, duplication of that data sheet is shown in Table 4.

Table 4. Location and Azimuth of Flaws Data Sheet Example

Flaw Identification	NDE Method	X-1	X-2	Y-1	Y-2	Z-1	Z-2	CW or CCW
B-2-123°	PT-1	66 1/2	66 33/64					CW
Inspector __Name____		Level __I, II or III			Date: __(Date)____			

NOTES: Flaw Identification contains both the identification and location, e.g., B-2, 123° Clockwise from the "0" point.

NDE Method simply identifies the method and its identification.

X-1 and X-2 are location numbers, i.e., 66 1/2" would be 66 1/2 inches from the "0" point Clockwise.

Y-1 and Y-2 are the locations for Y locations.

Z-1 and Z-2 are the location for Z locations.

CW or CCW is the direction the location was measured from the "0" point (CW = clockwise; CCW = counterclockwise).

Inspector Name, Level (I, II, or III) and date the NDE was performed.

Source: Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5.

3.8.3 Flaw Evaluation Summary

The total number of flaws identified during this test is shown in Table 5. It should be noted that the precision of each set of numbers differs substantially. The start and stop values for the X directions are coarse compared to the Y and Z numbers. The X values are dependent upon the ability of the technician to mark the location of a transducer that varied in diameter from 1/2 inch to 1/4 inch. The values for Y and Z are very precise and are based on the calibrated filar gage in the metallograph capable of measuring down to the 1/10,000 of an inch or better.

Table 5. Flaw Lengths Verified by Metallography

Ring Set		X Direction (inches)			Y Direction (inches)		Z Direction (inches)	
		Flaw Start	Flaw End	Length	Flaw Start	Flaw End	Flaw Start	Flaw End
K3	Side 1	54 1/2			.280	.294	.958	.953
	Side 2		54 5/8	1/8	.244	.280	.941	.976
K4	Side 1	55 3/4			NOTE[a]			
	Side 2		56 3/8	5/8	.280	.317	.969	.990
R1F	Side 1	18 7/8			.858	.906	.920	1.020
	Side 2		19 7/8	1	.831	.846	.992	.976
R1FA	Side 1	18 1/8			.807	.862	1.047	.890
	Side 2		18 11/16	9/16	.803	.843	1.016	1.051
R3FA	Side 1	47 1/8			.850	.886	.953	.917
	Side 2		48	7/8	.803	.823	.906	.929
R3FB	Side 1	48 1/8			.886	.902	.969	.926
	Side 2		49 1/16	15/16	.874	.890	.921	.953
R5F	Side 1	162 1/2			.709	.728	.953	.929
	Side 2		163 1/4	3/4	.689	.709	.945	.988
W1F	Side 1	2 7/8			.717	.719	.872	.876
	Side 2		3 5/8	3/4	.657	.707	.907	1.026
X5F	Side 1	178 15/16			.500	.530	.896	.953
	Side 2		179 9/16	5/8	.484	.531	.898	.933
Total				6 1/4				

NOTE: [a]K4, Side 1 data is not noted on the Metallographic Examination Record Sheet.

Source: Senior Flexonics Pathway 2002a, Appendices 10.1, 10.8, 10.9, 10.13, and 10.14, Metallography.

4. METALLOGRAPHICAL ANALYSIS OF WELDED SECTIONS

4.1 APPROACH

The approach to perform the metallography was to ensure that the identification of each specimen was preserved and that the identification of each piece taken from the rings was preserved. Standard metallographic techniques were used so far as preparation, polishing, etching and photography. The purpose of the metallographic examination was to study the location and flaw characteristics as indicated by the nondestructive examination.

4.2 SPECIMEN MARKING AND IDENTIFICATION METHOD

When the welded rings (specimens) were received at the metallographic laboratory, each specimen had a unique identifier. Since alphabetical notations had been used for piece parts (A designation for outer rings; B for inner rings), the welded sets were named K through Z to avoid any identification problems. Since most specimen sets contained no flaws, it was established that six sets of metallographic samples would be randomly removed from specimen sets containing no flaws. Where flaws did exist, appropriate numbers of specimens were removed but always at least six. The naming convention used was, for example, K1, K2, K3, etc., wherein K was the ring name and 1, 2, 3, etc., was the metallographic specimen identification from that specimen set (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 5). The definition of the third character was not uniquely specified. The fourth character applies to specimens that were too long to mount in a metallographic mount were bisected and mounted as two different specimens. For example, R3F was in this category; the sample R3 was

bisected to form R3FA and R3FB. A minor amount of the flaw was lost due to cutting; however, bisecting the specimen was the only way to mount and evaluate the flaw.

4.3 SPECIMEN PREPARATION

4.3.1 Specimen Cutting

Each metallographic specimen was cut using a band saw blade purchased specifically for the materials since this alloy is one of the more difficult materials to machine. The cutting was performed while cutting oil was pumped on the cut surface to keep the temperature low. A special clamping device was used to ensure that every cut made was oriented through the geometric center of the ring set. This clamp was used for cuts of even smaller sections when cuts were necessary and every specimen was, however imperceptible, pie-shaped. This is important to understanding the mechanical interpretation later on because it must be understood that the Z dimensions were made relative to the center of the specimen rings, thus the measurement made from the inside diameter of the ring and sample are relative to the center of the circle and establishes the location of each flaw (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 12).

4.3.2 Specimen Cleaning

Each metallographic specimen was cleaned to remove all cutting oil and any debris and was uniquely identified. Great care was taken to ensure that each specimen set was kept together and the identification physically placed on the specimen prior to mounting. The specimen surface to be evaluated was placed in a mold, and a cold mounting epoxy was used to mount the specimen. The identity of every specimen can be observed within the epoxy mount. After the epoxy set, the specimen was taken to the preparation area for grinding, polishing, and etching (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 12).

4.3.3 Specimen Grinding

The grinding process involved a number of different grit papers beginning with 50 grit followed by 120, 240, 320, and 600 grit. Grinding was performed with water flow on the surface at all times (special care is required to keep the specimen surfaces flat). The surface was then visually examined to determine if (in the case of a known flaw's existence) the flaw could be observed. If a flaw was known to exist and was not observed, additional material was ground until the flaw could be seen in a microscope. If no flaw was known to exist, the specimen was taken to the polishing process (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 12).

4.3.4 Specimen Polishing

Polishing of specimens is as much an art as a science, and Alloy 22 is substantially more difficult to polish and etch than most. The polishing media used was diamond paste suspended in a soluble oil solution. The media size ranged progressively from 9μ, 3μ, 1μ diamond grits and then to 0.01μ aluminum oxide suspended in water (1μ = millionth of a meter or 0.001 millimeter). When the final polishing was completed, it was discovered through trial and error (and discussions with the material providers) that the polished surface would not etch if the surface was dried and exposed to air for a short time. The material passivates so quickly that the

surface would not etch; therefore, the surface of each specimen was kept under water (avoiding exposure to oxygen) until etching was performed (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 12).

4.3.5 Specimen Etching

The purpose of etching the surface of a metallography sample is to subject the surface of the material to preferential chemical or electrolytic attack in order to reveal metallurgical structure details. This is possible because the various constituents in multiple phases, or the section planes of differently oriented grains in a single-phase alloy, have inherently different rates of dissolution in the usual etching reagents. As a result of the etching process, the different surface planes revealed during etching each reflect light differently, thus one can observe the differences in appearance or microstructure. The observed microstructure can be interpreted by a metallurgist as indicating specific solidification structure that, in turn, provides information regarding the expected physical and corrosion performance of the specific material. In the case of weld specimens, defects (flaws) can be identified based on what is observed (the flaw morphology). For example, lack of fusion may be recognized based on the known pre-existing weld preparation geometry since lack of fusion generally has a similar geometry (Senior Flexonics Pathway 2002a, Appendix 10.17, Section 12).

4.4 MICROSCOPIC EXAMINATION METHOD

The microscopic method utilized in this engineering test can be called "standard" in that the essential parts of the metallograph consisted of (1) an illuminating source (light), (2) a condensing lens to collimate the light beam from the source, (3) a cooling cell to abstract heat from the illuminating beam before it enters the microscope proper, (4) an aperture diaphragm to control the amount of light entering the vertical illuminator and objective, (5) a field diaphragm to minimize internal glare within the microscope and to enhance contrast in the image, (6) a vertical illuminator to direct the incident light from the source through the objective and onto the surface of the specimen, (7) an inverted type of microscope, (8) a camera capable of photographing through the lens system, and (9) a complete set of objectives and eyepieces.

The test piece, having previously been through the steps outlined in Section 4.3, is placed upon the specimen holder, and the metallographer using his training and experience evaluates what is seen. It is possible to vary the magnification of the area viewed on the specimen based on the objectives (their magnification factor) to satisfy whatever magnification (within limits) the metallographer desires.

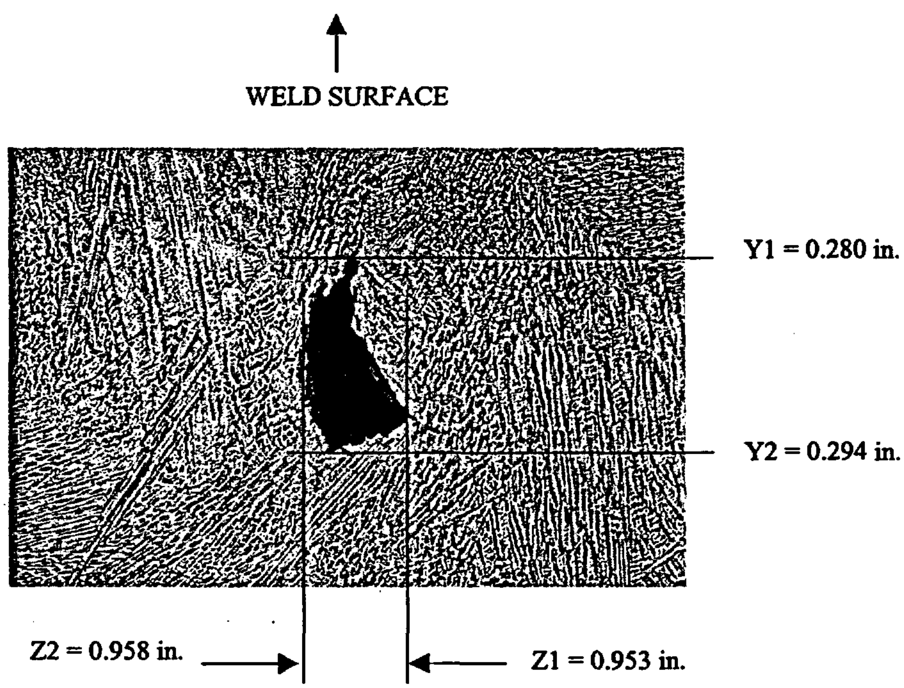
Having found the microstructure area of interest, the metallographer may take photographs of one or more area. This is the sequence of operations performed in this test program.

5. WELD, WELD ROOT AND BASE MATERIAL CHARACTERISTICS

5.1 WELD FLAWS

All flaws found in the test specimens were in the weld metal and root of the weld. The flaws were characterized as lack of fusion in each case. The following photomicrographs are typical of those observed. See Figure 8 for Side 1–Side 2 identification methodology.

Figure 9 is the weld flaw identified as K3. The view (side 1) is the left end of the flaw if one were looking down on the ring. Figure 10 is the right side of the same flaw.

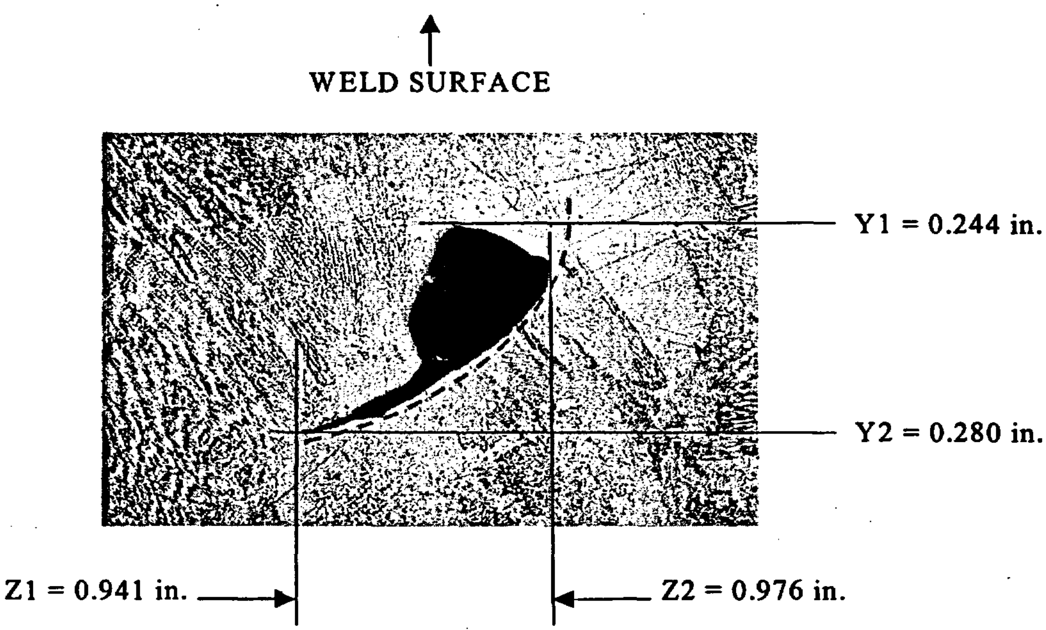


Source: Senior Flexonics Pathway 2002a, Appendix 10.1, Metallography.

Figure 9. Photomicrograph of Flaw in Specimen K3, Side 1 (95X)

The dotted lines in Figure 10 define the surface of the molten weld metal as it solidified. This is clearly lack of fusion owing to the microstructure and the fact that it is not continuous (structure does not indicate that the identical solidification structure exists at the top and bottom surfaces, but are weld metal solidification structure).

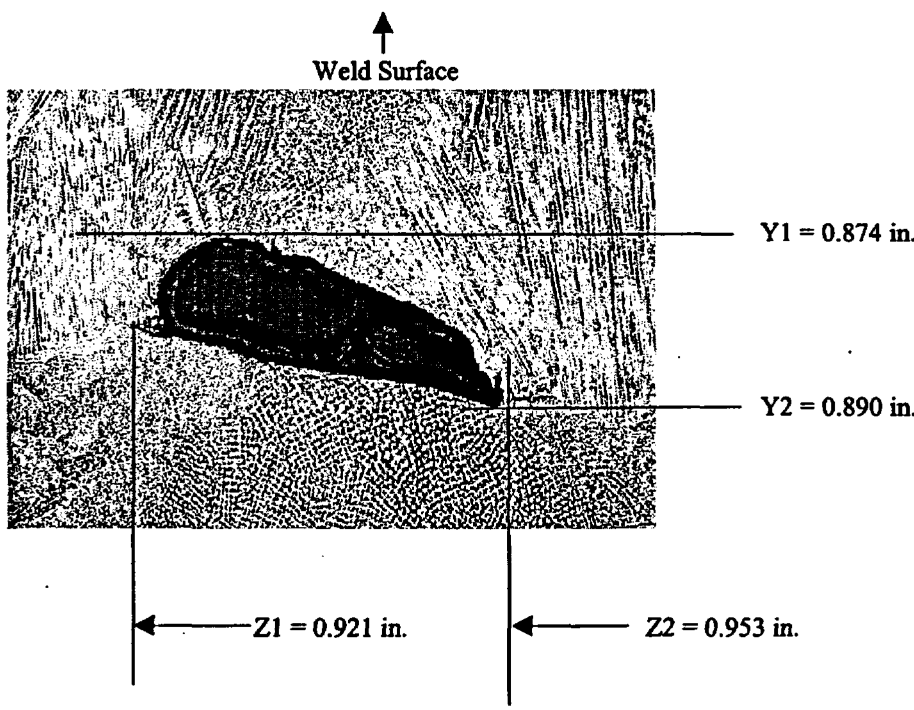
The micrograph in Figure 10 is the right side of the flaw. It was interpreted as lack of fusion by the NDE technician and the metallographer. The location relative to the inside surface of the test ring is 0.941 inches. Note that the Z1 and Z2 dimension are reversed since the view is of opposite ends. (A dotted line was placed on this photomicrograph to indicate the possible surface of the prior molten weld metal prior to solidification.) The microstructure in this view is also a typical weld metal structure and does not show identical microstructural flow on the upper surface of the flaw.



Source: Senior Flexonics Pathway 2002a, Appendix 10.1, Metallography.

Figure 10. Photomicrograph of Flaw in Specimen K3, Side 2 (95X)

Figure 11 is classic evidence of lack of fusion. The geometry of the top surface in this photomicrograph generally indicates the globular morphology of molten metal. The frozen weld metal structures of both surfaces have different orientations indicating the solidification mechanisms during weld metal freezing and that the two surfaces were never connected.

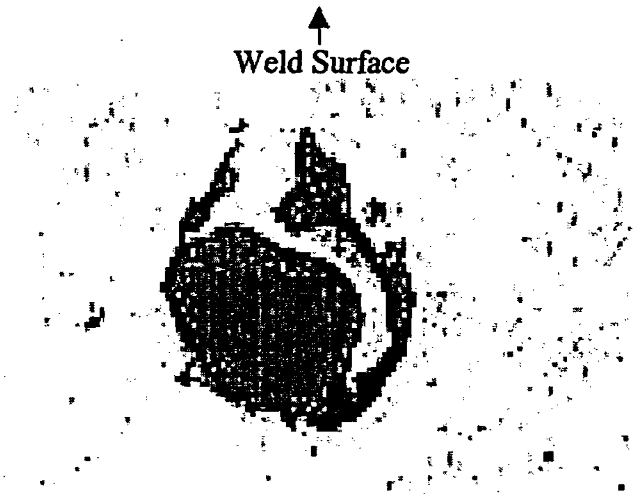


Source: Senior Flexonics Pathway 2002a, Appendix 10.8, Metallography.

Figure 11. Photomicrograph of Flaw R3FB, Side 1 (95X)

Figure 11 is the left end of the flaw and the probable continuation point of R3FA. As with the other flaws, the microstructure at the bottom and top of the flaw are not continuous; however, the structure is the same.

Metallographic evaluation of the welded area indicated several small gas pores less than 1 millimeter in size. Figure 12 shows a typical example of a gas pore. These gas pores were undetectable with UT due to being below the detection threshold of the process (Senior Flexonics Pathway 2002a, Appendix 10.8). Some contained remnants of the molten weld metal.

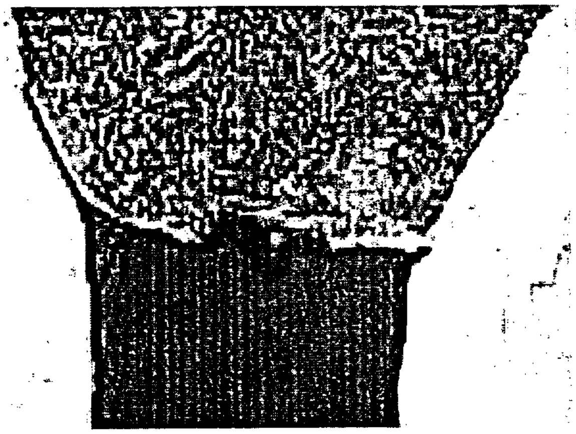


Source: Senior Flexonics Pathway 2002a, Appendix 10.9, Metallography.

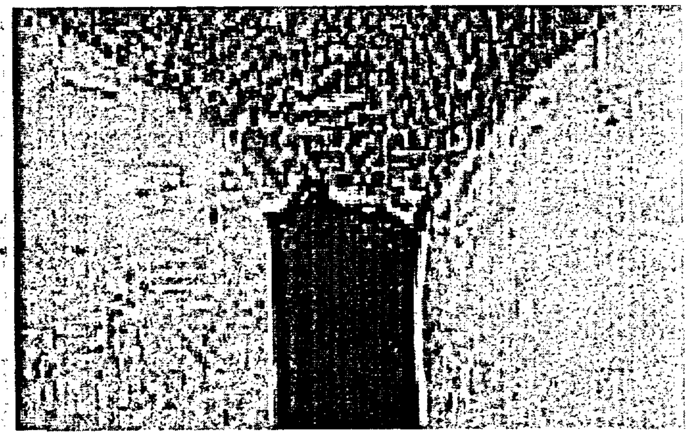
Figure 12. Example of Porosity (190X)

5.2 WELD ROOT FLAWS

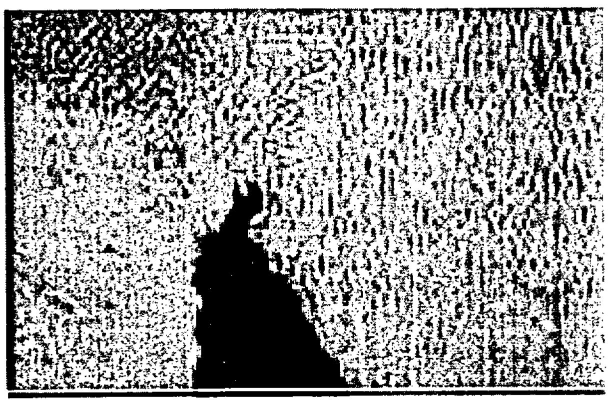
The examples in Figure 13 indicate the general condition of the root welds in this material during this test. The initial weld preparation gap design used by the contractor was too small (too tight) as described in Section 2.2.3.1. As a result, the walls of the nickel-based material "sucked back" during the early layers of the welding process. This prevented a quality weld from being produced. Subsequently, the weld preparation was modified to ensure that the weld could be successfully produced. This condition is not serious because welding with appropriate weld preparations is easily achieved. Current work will be evaluated to assure that proper root weld performance is achieved.



Root of Specimen K8 Magnification 95X



Root of Specimen K5 Magnification 95X



Root of Specimen L1 Magnification 95X

Root of Specimen M5 Magnification 95X

Root of Specimen M2 Magnification 95X

Root of Specimen N1 Magnification 95X

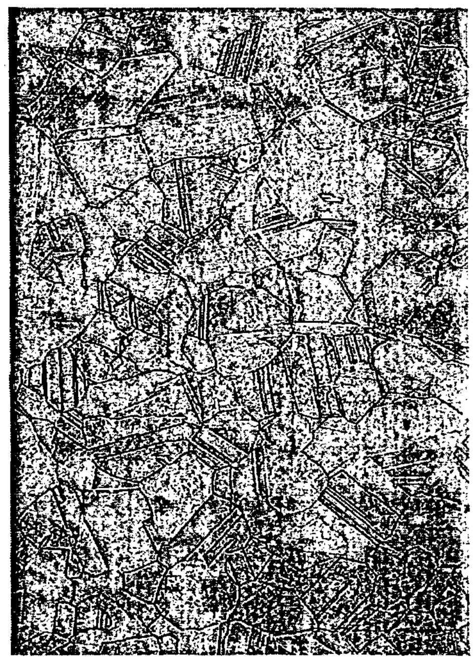
Source: Senior Flexonics Pathway 2002a, Appendices 10.1, 10.2, 10.3 and 10.4, Metallography.

Figure 13. Photomicrographs of Roots of the Welds

5.3 REPRESENTATIVE PHOTOMICROGRAPHS OF BASE MATERIAL

As discussed previously, there were no flaws identified with NDE in the base material before or after forming, heat treatment, or welding; however, it is considered prudent to provide representative photomicrographs. The following represent the general microstructures. The microstructure of the base metal was typical equiaxial structures. Normal twins were present and no precipitation of other phases was observed. The following micrographs in Figure 14 are typical. It should be noted that all specimens were etched as indicated previously in this document. It should be noted that all the rings were solution heat treated prior to machining. The four micrographs presented in Figure 14 are a random selection of base metal microstructures and are only a few of several hundred produced during this test (Senior Flexonics Pathway 2002a, Appendices 10.1 through 10.16).

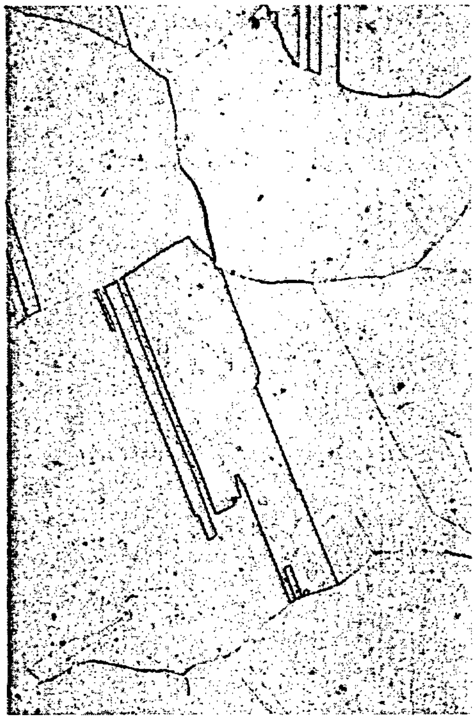
Specimen K7 Magnification 95X



Specimen O1 95X

Source: Senior Flexonics Pathway 2002a, Appendices 10.1, 10.3, 10.5 and 10.16, Metallography.

Figure 14. Base Metal Microstructures



Specimen Z1 380X

Specimen M4 380X

Source: Senior Flexonics Pathway 2002a, Appendices 10.1, 10.3, 10.5 and 10.16, Metallography.

Figure 14. Base Metal Microstructures (Continued)

5.4 RESULTS OF METALLOGRAPHIC STUDY

The results of the metallographic study confirmed most but not all of the volumetric flaws identified with NDE. The results are summarized as follows and in Table 6.

Specimen K—There were three flaws indicated by UT and RT in specimen K; however, K2 could not be verified with metallography. K3 and K4 flaws were confirmed with metallography.

Specimen R—Three locations were reported to have defects that were based on UT and RT testing: samples R1F, R3F, and R5F. Samples R1F and R3F were bisected. All three flaws were confirmed by metallography.

Specimen S—Two locations were reported to have defects; one based on both RT and UT and one based on RT only. These samples were designated S1F and S3F. Neither flaws were confirmed by metallography although the samples were ground and polished at approximately 0.010-inch increments arriving at a final sample thickness of about 0.05 inches.

Specimen W—One flaw was reported and identified as W1F. Although reported by UT and RT as an overlapping flaw, the flaw was confirmed with metallography to be a single flaw.

Specimen X—One flaw was identified as X5F. This flaw was confirmed with metallography.

6. COMPARISON OF WELD FLAW DATA FROM NONDESTRUCTIVE EXAMINATION AND METALLOGRAPHY

6.1 SURFACE FLAWS

Surface flaws identified with PT and ET were compared. ET identified more flaw indications than PT. This is because ET is a semi-volumetric examination method with nickel-based materials. PT is sensitive to cold shuts (traps penetrant) while ET is sensitive to cold shuts and shallow subsurface disturbances wherein there may be no flaw breaking the metal surface. Cold shuts are defects that can exist in a metal where two volumes of molten material have come together but failed to unite, fuse, or blend into a solid mass. The result can be a cracklike (lap) in the material that can hold penetrant and will show as a defect (Senior Flexonics Pathway 2002b, Paragraphs 7.2 and 7.3).

6.2 VOLUMETRIC FLAWS

The magnitude of the flaws identified with volumetric NDE methods is shown in Table 6. As can be seen in Table 6, there are very few flaws. The following presents the information developed in this study:

Flaw length in the X direction including all flaws found with UT is 4 15/16 inches.
Flaw length in the X direction including all flaws found with RT is 3 15/16 inches.

Whether UT or RT is more accurate or conservative depends on so many variables that it would be very difficult to make an informed decision. In this case the larger length of a flaw was identified utilizing UT.

UT has been used in industry for many years and is the basis for acceptance by most codes and standards. The dimensions of flaws obtained from UT are conservative when compared to metallography results.

In terms of flaw length, UT identified more flaws than RT. All of the flaws identified with volumetric methods were not confirmed with metallography. If the UT flaws that were not verified with metallography are removed, the total length of flaw is 4 1/8 inches.

Table 6. Volumetric Flaws Identified in the Test Program

RING	NDE TYPE	LOCATION (Clockwise)	LENGTH	THICKNESS	WIDTH	INDICATION TYPE
K2	UT	52 3/4" - 53 7/16"	11/16"	1/16"	1/8"	Linear
K2	RT	54 3/8" - 54 1/2"	1/8"	1/16"	-	Round
K3	UT	54 1/2" - 54 5/8"	1/8"	1/16"	1/16"	Round
K3	RT	56 1/8" - 56 1/4"	1/8"	1/16"	-	Round
K4	UT	55 3/4" - 56 3/8"	5/8"	1/16"	1/16"	Linear
K4	RT	57" - 57 1/4"	1/4"	1/16"	-	Linear
R1F	UT	19 1/8" - 19 7/8"	3/4"	1/8"	1/16"	Linear
R1F	RT	18 7/8" - 19 1/4"	3/8"	1/8"	-	Linear
R3F	UT	47 1/4" - 48 5/8"	1 3/8"	1/8"	1/16"	Linear
R3F	RT	47 1/2" - 49"	1 1/2"	1/8"	-	Linear
R5F	UT	173 7/16" - 173 13/16"	3/8"	1/8"	1/16"	Linear
R5F	RT	173 7/16" - 173 15/16"	1/2"	1/8"	-	Linear
S1F	UT	7 15/16" - 8 1/16"	1/8"	1/8"	0	Round
S1F	RT	7 5/8" - 7 15/16"	5/16"	3/16"	-	Round
S3F	RT	18 1/8" - 18 3/8"	1/4"	3/16"	-	Linear
W1F	UT	3 1/8" - 3 5/8"	1/2"	3/16"	1/8"	Linear
W1F	RT	3" - 3 1/4"	1/4"	1/8"	-	Linear
X1F	UT	190" - 190 3/8"	3/8"	9/16"	0	Linear
X1F	RT	189 7/8" - 190 1/8"	1/4"	1/8"	-	Linear

NOTE: The "-" in this table is for radiography where only two dimensions can be determined from a film.

Source: Senior Flexonics Pathway 2002a, Appendices 10.1 through 10.16, Metallography.

6.3 VOLUMETRIC FLAW AS A FUNCTION OF TOTAL WELD LENGTH

The total length of weld produced during this test is as follows:

Determine the circumference of the rings at the mid-point of the weld (D = diameter):

πD = Circumference of the ring
D = 60.765 inches
πD = 190.8987 inches
For all 16 rings 3,054.4 inches of weld was produced.

Using the UT data, the total flaw as a percentage of weld produced is 0.16% (3054.4 inches of weld containing 4.9375 inches of flaws). Using the UT flaw length data and removing the flaws not verified with metallography, the total flaw as a percentage of weld produced is 0.14% (3054.4 inches of weld containing 4.125 inches of flaws). Based on the author's experience, these percentages are far better than the normally claimed "less than one percent" claimed by metal fabricators. These percentages are considered conservative with regard to the sophistication of welding equipment currently being designed for the closure cell in the waste handling building. The planned welding process will be technically superior to the one used in this test program. The planned welding system will be a highly automated system with full process control and real time NDE not available in the equipment used in this test program (for

example, automated cross-seam tracking, automated pulse control, and programmable weld wire controls). The weld geometry in the test rings is similar to the current design planned for the waste package.

6.4 GAS PORES

Generally, one does not examine weld specimens for porosity of the sizes found during this test, but the laboratory was directed to evaluate each mounted specimen for flaws. A large number of very small pores ranging from 0.0005 inches to less than 0.003 inches were found in the weld metal. The gas pores are essentially spherical and have no notches to propagate cracks. These pores had no particular spatial relationships. They were well below the detection limits of UT and RT, and no clusters of pores were reported (see Table 7). The flaws detected are much smaller than the acceptance criteria of the ASME Code. Being able to detect and repair defects identified by UT methods to this criteria assures the structural adequacy of the material. These pores were attributed to the gas used. The gas supply for welding was welding grade, and the piping supply was a continuous tube so no aspiration was possible. Gas pores can be reduced or eliminated by specifying the purity of the gas supply (Senior Flexonics Pathway 2002a, Appendices 10.1 to 10.16, Metallography).

Table 7. Gas Porosity Distribution

Specimen	<1mm	≥1 mm - < 4mm	≥4mm - <10mm	>10mm
K	2	None	None	None
L	11	None	None	None
M	14	None	None	None
N	20	None	None	None
O	17	None	None	None
P	25	None	None	None
Q	32	None	None	None
R	133	None	None	None
S	34	None	None	None
T	42	None	None	None
U	47	None	None	None
V	40	None	None	None
W	27	None	None	None
X	35	None	None	None
Y	27	None	None	None
Z	24	None	None	None

Source: Senior Flexonics Pathway 2002a, Appendices 10.1 through 10.16, Metallography.

7. STUDY SUMMARY

This weld flaw evaluation and NDE study was conducted for the welding of Alloy 22 material. The study has shown that using a GTAW welding process, the flaw sizes produced are small (less than 1/16 inch through thickness dimension) and detectable by the NDE methods, UT and RT. PT and ET were used for surface defects, and RT and UT were used for volumetric examination. The processes for surface examination were compared, and the processes for

volumetric examination were compared. The intent was to show that each process duplicated the results. The study confirmed that both UT and RT are capable of detecting volumetric flaws as small as 1 millimeter in size with a strong correlation between the two methods. The nondestructive surface examination methods of ET and PT detected flaws as small as 1 millimeter with comparable results. PT and RT cannot be used in the high-level radioactive environment that will exist in the weld cells during closure; however, RT and PT are good comparative screens to validate UT and ET.

The need for a technically sound materials processing and inspection program is fundamental to the program's confidence in the ability of the high-level radioactive waste program to isolate nuclear waste from the environment. The selection of methods used to fabricate the materials into disposal waste packages is an important technical challenge.

Very few flaws were produced during this test. The percentage of flaws identified in 16 sets of weld rings was significantly less than one percent. Flaws identified and evaluated were all parallel to the hoop stress. The only unusual result in this test was the identification of many very small gas pores in the welds. Flaws of this geometry would not be detected using existing NDE methods unless large clusters of them exist. In this case they would be identified.

8. REFERENCES

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