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BWRVIP BWR Vessel & Internals Project 2000-099

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Attention: C. E. Carpenter

Subject: Project 704 - Transmittal of "BWR Vessel and Internals Project, Underwater Weld Repair of Nickel Alloy Reactor Vessel Internals (BWRVIP-44)," EPRI Report TR-108708NP, March 2000.

Reference: Letter from C. Terry to C. E. Carpenter, October 27, 1997: Transmittal of "BWR Vessel and Internals Project, Underwater Weld Repair of Nickel Alloy Reactor Vessel Internals (BWRVIP-44)," EPRI Report TR-108708, September 1997.

Enclosed are two (2) copies of the subject report. This is the non-proprietary version of the document submitted to the NRC by the letter referenced above.

If you have any questions on this subject please call Steve Lewis of Entergy, BWRVIP Assessment Committee Chairman, at (601) 368-5444.

Sincerely,

Carl Terry
Niagara Mohawk Power Company
Chairman, BWR Vessel and Internals Project

Enclosure

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BWR Vessel and Internals Project Underwater Weld Repair of Nickel Alloy Reactor Vessel Internals (BWRVIP-44NP)

REPORT SUMMARY

The Boiling Water Reactor Vessel and Internals Project (BWRVIP), formed in June 1994, is an association of utilities focused exclusively on BWR vessel and internals issues. This report describes worked performed to qualify a flux-core welding process for use in repairing reactor internals at a water depth of up to 50 feet.

BACKGROUND
A number of BWRs have experienced cracking in various internal components due to intergranular stress corrosion cracking. Where required, repairs have been made by use of mechanical clamps or, in certain cases, by welding. The use of welding is restricted, however, to relatively shallow water depths or to applications which permit creating an isolated environment in which the welding can be performed. It is anticipated that, at some future date, a utility may be required to repair a cracked inconel component where welding is the only feasible approach but at depths beyond current capabilities.

OBJECTIVES
To develop and qualify a flux-core welding process which can be used on inconel at depths up to 50 feet without an environmental chamber.

APPROACH
The project team first evaluated prior work done by EPRI to determine what enhancements to that work were required to meet the current project objectives. Scoping tests showed that improvements were needed in the welding power supplies used and that a gas shielding technique would be needed to achieve acceptable results at the maximum depth. Once these improvements had been made, a qualification program was conducted to establish that the welds met the requirements of ASME Code Case N-516. Finally, a demonstration program was conducted to confirm that the technique could be used for repair in a variety of typical configurations.

RESULTS
The qualification program was successfully conducted with the modified power supply and the new gas cup. Welds in all positions were found to be acceptable. In addition, the demonstration tests showed that successful welds can be performed for fillet, overlay and V-groove configurations. The necessity for use of a gas cup to shield the weld at depth represents a complication for certain configurations.

EPRI PERSPECTIVE
Results of the qualification and demonstration tests indicate that the flux-core process is a viable technique for weld repair of stainless steel and inconel components at depths up to 50 feet. Improvements in the gas cup design to facilitate application to all welding positions would be useful.

TR-108708NP

Key words
Boiling Water Reactor
Stress corrosion Cracking
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BWR Vessel and Internals Project

Underwater Weld Repair of Nickel Alloy Reactor Vessel Internals (BWRVIP-44NP)

TR-108708NP
Research Project 501

Final Report, March 2000

Prepared by
EPRI Repair and Replacement Applications Center

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ORDERING INFORMATION

Requests for copies of this report should be directed to the BWRVIP Program Manager, 3412 Ave., Palo Alto, Ca. 94304, (650) 855-2340.

ACKNOWLEDGMENTS

The following people were the principal investigators for this report.

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EXECUTIVE SUMMARY

The Boiling Water Reactor (BWR) Vessel and Internals Project (VIP) Repair Committee requested that the EPRI Repair and Replacement Applications Center develop a welding process for addressing the underwater repair of non-irradiated reactor pressure vessel (RPV) internal components at depths up to 50 feet. This type of repair was intended to address intergranular stress corrosion cracking (IGSCC) concerns. A welded repair offers a permanent corrosion-resistant repair with crevice-free conditions. A welded repair option may be necessary for some components and configurations that are not suited to a mechanical repair or where replacement requires structural welding. Location and accessibility in the lower two-thirds of the reactor limits the use of diver-assisted welding processes and has generated the need for an automated underwater welding process. Based on earlier EPRI studies, underwater flux-cored arc welding was selected for development of welding procedures to provide high-quality welds for repair of Alloy 600 and Type 304 stainless steel in limited access locations.

This report provides the technical basis for utilizing the underwater wet flux-cored arc welding process at depths of up to 50 feet. Code acceptance criteria established in Code Case N-516 and ASME Section IX were utilized in performing mechanical test requirements. The report includes background information, equipment evaluation, welding parameter development, and mockup feasibility test results that can be utilized as a guideline for developing procedures for the repair of specific components.

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BACKGROUND

1.1 Introduction

During the past several years, domestic boiling water reactors (BWR) facilities have discovered cracking in a variety of RPV internal components. As additional components are inspected, using increasingly sensitive inspection equipment, additional cracking may be identified. Repair technology must continue to be developed to provide a repair option for potential cracking locations.

The two approaches to repairs are mechanical repairs and welded repair techniques. Mechanical repairs have been a cost-effective solution for the repair of cases where orientation and accessibility are favorable. Welded repairs have also been utilized in areas accessible to divers on components with low fluence levels. There is a need for welding repair technology to address components that are not accessible to divers and may not be suitable for mechanical repairs. The benefit of underwater wet welding is that a permanent corrosion-resistant repair with crevice-free conditions can be obtained in a timely manner using automated equipment. Welding of highly irradiated components is not addressed in this document.

1.2 BWRVIP Needs

The inaccessibility and shutdown dose rates for components in the lower two-thirds of a reactor pressure vessel have generated the need for an automated underwater wet welding process to address repair applications. The EPRI Repair and Replacement Applications Center (RRAC), at the request of the BWR Vessel and Internals Project (BWRVIP), developed a program using automatic wet flux-cored arc welding (FCAW) to address the repair of non-irradiated RPV internal components at depths of up to 50 feet.

This program is intended to address repairs to RPV internals located above the core top guide (Zone 1) and below the lower core support plate (Zone 3). Water depth for these repairs has been limited to 50 feet, which may require partial reduction of the water level in the vessel for welding of below core structures. Zone 2 (irradiated core region) repairs were not addressed in this development but may be determined to be weldable based on a plant- and component-specific analysis to determine the helium content of the irradiated material. (BWRVIP work on the weldability of highly irrradiated components is addressed in a separate report.)

Materials evaluated included Type 304 stainless steel and Inconel 600 for the target components, using Inconel filler metals 625, 52, or 152 for repair activities. As an alternative repair approach, manual welding with shielded metal arc welding (SMAW) was also targeted for Zone 1 repair activities.

1.3 Prior Technology Developed by EPRI

EPRI initiated an underwater wet welding program at the EPRI Repair and Replacement Applications Center (RRAC) in 1989 aimed specifically at the development of mechanized underwater flux-cored arc welding (FCAW) methods for the repair of reactor pressure vessel internals. This program was successful in that halogen-free FCAW consumables were developed and underwater weld repairs were simulated to a depth of 50 feet for stainless steel applications and to a depth of 20 feet for Inconel 625, with limited joint configurations. The importance of the halogen-free filler materials is that they minimize the potential for stress corrosion cracking (SCC) due to halogen contamination of the reactor water chemistry. Weldment test results included acceptable mechanical (bend, tensile) properties, along with good microstructural properties.

1.4 BWRVIP Project Objectives

To develop and qualify an underwater welding process that can be used to effectively repair stainless steel and nickel-based reactor components at depths up to 50 feet.

The project objectives primarily address the underwater weld repair of nickel-based (Inconel) BWR reactor vessel internal components at depths up to 50 feet. The project was divided into three separate phases: Phase 1, Welding Process/Parameter Development, addressed welding of Alloy 600 and Type 304 stainless steel at a depth of 50 feet to meet ASME Section XI, Code Case N-516. Welding equipment, consumables, and techniques were established to ensure that the next phases could be fully accomplished. Phase 2, Weldment Fabrication and Testing, utilized technology developed in Phase 1 to test as-welded properties of typical weld configurations to meet Code Case N-516. Welds were qualified in all positions with Alloy 625 filler material. Phase 3, Demonstration of Underwater Weld Repairs, included underwater mockup welding to establish feasibility for typical joint configurations including:

- Weld buildup for overlays
- Fillet weld for repair of bracket/attachments

- Groove welds for repair of excavated cracks

A summary of the three project phases is presented below.

Phase I: Welding Process/Parameter Development. Studies were conducted to: 1) select welding process parameters, filler materials, and power supplies for welding on Inconel and stainless steel materials at depths up to 50 feet; and 2) establish material properties that will meet the requirements established by ASME Code Case N-516 and Section IX. Weld development was performed on Alloy 600 and Type 304L base materials. Originally, Alloy 52 or 152 filler materials were to be used with the flux-cored arc welding process for the repair of Alloy 600 components. However, due to weldability concerns, Alloy 625 filler metal was substituted for all test welds.

Welding evaluations consisted primarily of bead-on-plate applications with single and multi-layer weld configurations. FCAW process development to address welding at greater depths included selection of welding power supplies, adjustment/refinement of the flux formulations and fill ratios of the welding consumables, and welding parameter selection. Parameter selection was evaluated for out-of-position welding applications including vertical, horizontal, overhead, and flat positions. All underwater welding was performed in the hyperbaric chamber at RRAC, which accurately simulates depth via applied pressure. Completed weldments were evaluated metallographically and mechanically to determine the suitability of the welding process.

Phase II: Weldment Fabrication and Testing. This phase was dependent on the results of the first task and included additional welding samples developed for mechanical/metallurgical property data, produced with base materials including 1/2-inch thick Alloy 600 to Type 304 stainless steel joint configurations. These combinations address a majority of the in-vessel repairs and provide confidence that both stainless steel and Inconel base materials can be effectively welded. Filler materials included Alloy 625 and Type 308L flux-cored welding wires. Samples underwent a series of mechanical tests, including bend tests and tensile tests, in addition to detailed metallographic evaluation to document microstructure, weld penetration, and dilution.

The weldments consisted primarily of groove weld configurations to support ASME Section IX mechanical testing requirements and Code Case N-516 qualification requirements. Samples were welded in four positions to address all position welding qualifications as required by N-516. Radiography, ultrasonic testing, and visual inspections were also performed to evaluate the overall quality of typical repair weldments per ASME Section IX.

Phase III: Demonstration of Underwater Weld Repair Applications. Component-specific repair approaches were evaluated and demonstrated based on the successful completion of Phase II discussed above. This included the demonstration of techniques developed in the earlier tasks applied to mockups representing potential repair locations. Detailed metallographic testing plus NDE was also performed on these demonstration samples. The sample weldments included the following:

- 3/4-inch weld build-up for overlay
- 1/2-inch fillet weld for repair of brackets/attachments
- 1/2-inch groove weld for repair of excavated cracks

The emphasis of this task was to demonstrate that the underwater welding repair techniques are suitable for repair of nickel-alloy and stainless steel reactor materials with typical repair configurations at depths of up to 50 feet. Demonstration specimens consisted of 3/4-inch thick overlay weldment, 1/2-inch V-groove, and 1/2-inch fillet weld configurations. These configurations were welded on Inconel 600 and 304 SS base materials with Alloy 625 and Type 308L consumables.

A companion program was conducted in parallel with Phase III to evaluate the use of SMAW and FCAW for repair of core spray piping. The Core Spray Repair Program included SMAW and FCAW overlays on stainless steel pipe material using Type 308L, 309L, and Alloy 625 consumables. Overlay specimens were produced for the evaluation of ultrasonic inspection techniques, as well as shrinkage and distortion measurement. Complete results from this companion program are described in *Technical Basis for Part Circumference Weld Overlay Repair of Vessel Internal Core Spray Piping*, BWRVIP-34 [1]. The ultrasonic testing (UT) evaluations from that program are also discussed in Section 4 of this report since they are directly applicable to the Phase III results. These UT results will ultimately provide requirements on weld overlay surface conditions for UT inspections.

1.5 Summary Conclusions

This project has demonstrated that:

- High quality underwater welds, meeting all current ASME code requirements, can be produced.
- Quality underwater FCAW repairs meeting ASME code requirements can be made.
- Complex repair/weld configurations will likely require partial draindown (to reduce water depth) or establishment of a "damp" atmosphere to compensate for lack of gas shielding.
- Adequate inspections of underwater repair welds can be performed utilizing current equipment.

A detailed description of the results of Phases I, II, and III are presented in Sections 2, 3, and 4 of this report, respectively. Section 5 summarizes project results and presents conclusions.

2

WELDING PROCESS/EQUIPMENT DEVELOPMENT

2.1 Introduction and Scope

Initial underwater (UW) development work utilized conventional welding power supplies. Conventional power supplies were found to limit the working range for UW flux-cored arc welding (FCAW) applications due to their inherent arc characteristics and the underwater environment. To overcome this problem, sophisticated power supplies were investigated to accommodate arc phenomena occurring in the UW environment. Use of the advanced power supplies dramatically enhanced underwater welding performance. However, weld quality at 50 feet with the Ni-alloy materials was still not adequate to achieve Code quality results, which are similar to in-air welding.

At this point, both advanced power supplies and conventional systems were being operated in the short circuit mode in the underwater environment. To further enhance the UW welding process, it was thought that a weld mode other than short circuiting would be required (for example, globular or spray transfer). Two areas were considered for improvement: filler material enhancement and external shielding of the arc location using a gas nozzle.

Ultimately, with the advanced power supplies, improved filler materials, and gas nozzle development, a consistent arc characteristic was achieved with Ni-alloy material at a depth of 50 feet. In this phase of the project, UW FCAW development was structured around the following three areas:

- Welding power supplies
- Gas nozzle development
- Manufacturing of UW flux-cored welding wires

After these three areas were addressed and Code quality welds were achieved at a depth of 50 feet, welding parameter selection for each welding position was established to support qualification of weld specimens as described in Section 3 of this report.

2.2 Conventional Power Supplies

Conventional power supplies such as motor generators, transformer rectifiers, and inverters are commonly used in the industry for repair applications. Constant voltage (CV) machines are typically utilized with gas metal arc welding (GMAW) and flux-cored arc welding (FCAW) processes. The constant current (CC) machines are typically used with shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) processes, although CC power supplies have been utilized with remote GMAW and FCAW processes that maintain a constant stickout length (contact tip to workpiece distance).

The CV power supplies limit the arc length and voltage while allowing variations in the current. A significant factor in the conventional power supply performance is the inductance (inherent or designed) into the power supply. Variation in inductance determines the lapse in time between arc length (voltage) and current. The greater the inductance, the more sluggish the response time. With inverter-type power supplies, the inductance is typically very low due to the size of transformer, allowing for nearly instantaneous changes in current. For UW welding, rapid changes in the current level produce unstable arc characteristics and decrease the ability to manipulate the electrode. Inverters can be modified to accommodate UW welding by providing additional electronic inductance.

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In this report, wet self-shielded welding refers to welding underwater with no attempt to displace the water around the arc, using only the flux from the filler wire to protect the weld pool. Utilization of a gas nozzle to protect the weld pool, in conjunction with the conventional power supplies, did not significantly improve the process. Wet gas-shielded welding refers to wet welding conditions where the water is removed in an area immediately surrounding the arc. Wet gas-shielded welding described later in this report is not the same as dry hyperbaric chamber welding.

Conventional power supplies incur the similar limitations in both the wet gas-shielded and wet self-shielded conditions due to inherent power supply characteristics (for example, amp-volt curves, voltage pick-up, and so on). Power supplies have changed to improve arc characteristics that enhance arc stability and anti-spatter control, as well as waveform control.

Many standard conventional power supplies were tested for UW FCAW. All the machines produced various qualities of welds when utilized in an underwater environment. Only a few welding machines were able to deposit weld metal with an acceptable bead appearance, spatter level, and uniform weld quality (arc stability).

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2.2.1 Results Using Conventional Power Supplies

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2.3 Advanced Welding Power Supplies

Advanced systems including ac-GMAW, dip transfer power supplies, and "current waveform control" welding systems offer an improved arc characteristic for UW FCAW applications. These systems offer spatter control by maintaining and controlling current at arc initiation and as short circuiting initiates (see Figure 2-1). The constant arc characteristic maintains a stable molten puddle, reducing spatter generation and arc starting problems and improving penetration control.

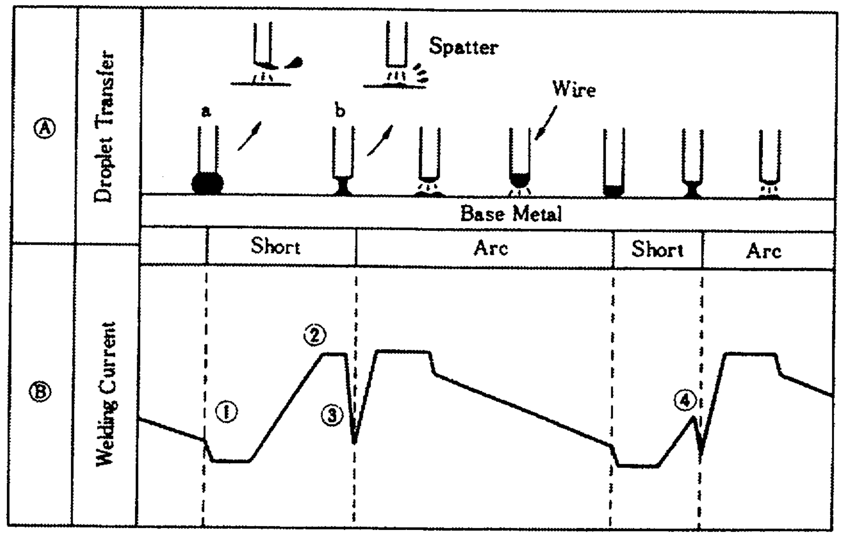

Figure 2-1
Droplet Transfer and Welding Current Waveform [2]

The new generation of waveform controlled GMAW/FCAW machines have had a tremendous impact on both underwater and "in-air" welding quality. These machines have brought a new level of arc control and symmetry in the energy levels delivered to the base material and also to the welding wire being consumed. The new generation equipment is designed to achieve optimum waveform characteristics for specific welding applications.

Benefits of advanced systems have primarily been seen in robotic arc welding applications, where a constant arc length can be maintained via the current control system. These systems have been used in improving bead appearance and arc characteristics in both wet self-shielded welding and the newly developed wet gas-shielded process. Typical benefits of the advanced power supplies include:

- Anti-spatter control
- Mode selection for wire diameter (solid wire and flux core)
- Response to changes in the arc length (wire stickout)
- Reduction in operator skill level
- Reduction in size and weight of equipment

- Real-time response to changes in the actual welding environment

New generation power supplies adjust in real time for changes in the arc pool and joint geometry. These changes occur as a result of heat buildup in the weld pool and the constant changes in the weld puddle and work environment (such as steam, resistivity, and oxides). Previous technology could not control the rate of increase in the current level and arc length when the welding process was in progress.

The real-time response provided by the advanced power supplies is the reason for the dramatic decrease in spatter and fume generation, which is of major importance to underwater welding, as well as in-air welding. The reduction of spatter buildup inside the gas diffuser reduces cleanup for the next weld beads and provides a better appearance in the overall weldment. The reduction in fume generation results in a lower degree of turbulence both in the weld pool and within the gas diffuser. High vapor pressure elements in the weld wire also benefit from the stable environment and are more likely to transfer across the arc into the molten weld puddle.

The new generation power supplies have allowed (for the first time) out-of-position wet welding. This includes the vertical down position at a depth of 50 feet. Weld deposition rate is enhanced, allowing a convex bead profile to be obtained in the vertical position. Conventional power supplies typically produced a concave bead appearance with low deposition rate.

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Figure 2-2
Lincoln STT Power Supply

The current is controlled by sensing changes in the arc voltage and lowering the set background current level as the arc is shorted across the workplate. The current is then ramped up to assist the transfer of the weld droplet to the weld puddle. The instant before the droplet transfer is complete, the current is again reduced. When the detachment is complete, the current is increased to promote electrode melting, and then reduced back to the set background current.

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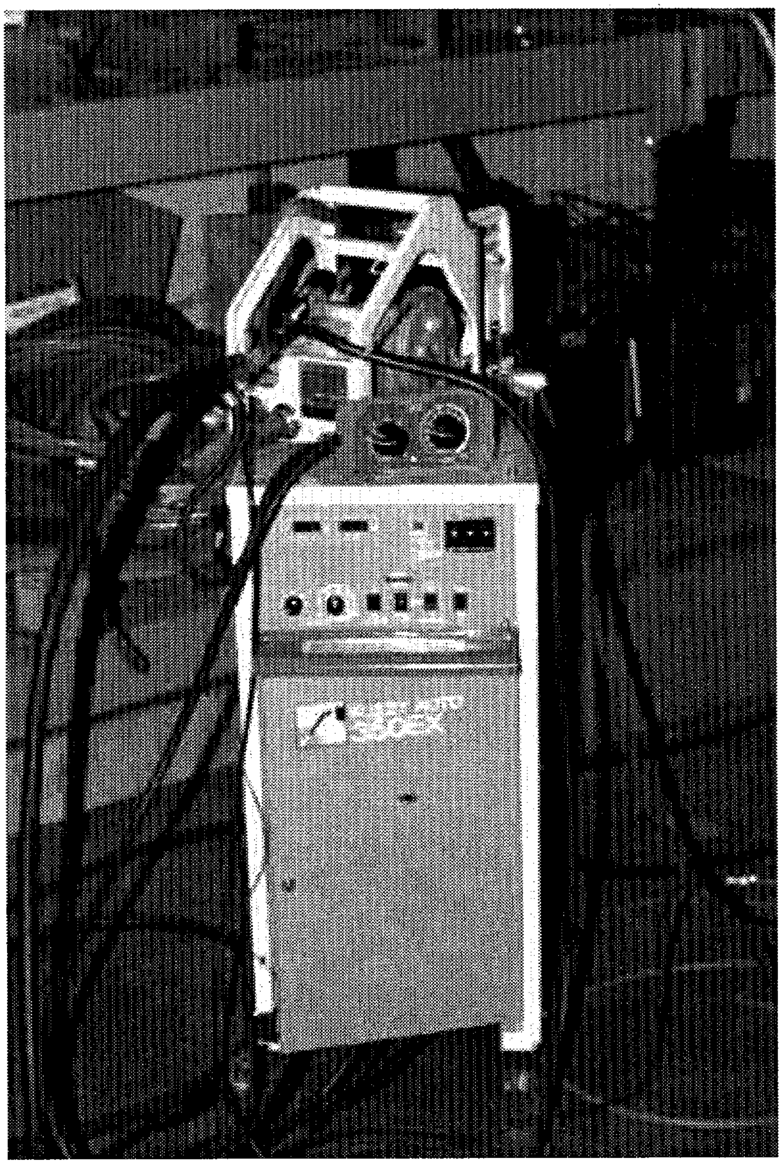

Figure 2-3
OTC/Daihen Fuzzy Auto 350EX Power Supply

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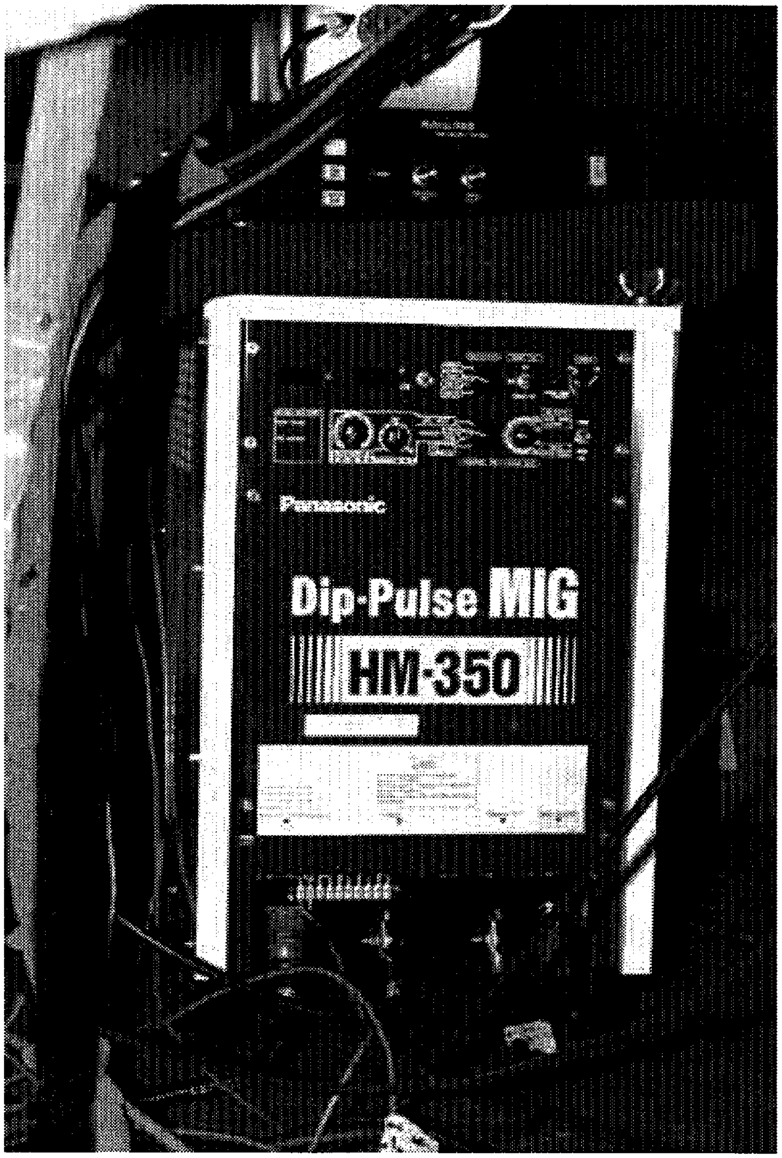

Figure 2-4
Panasonic HM-350 Power Supply

2.3.1 Results Using Advanced Power Supplies

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2.4 Evaluation of Supplemental Gas Shielding

Supplemental gas shielding was introduced to improve bead quality and heat input characteristics for multi-pass welds with the advanced power supplies at depths over 30 feet.

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2.4.1 Gas Nozzle Cup Design

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Figure 2-5
Cross-Section of Supplemental Gas Shielding/Evacuation Cup for UW Welding

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2.4.2 Limitations Of Cup Design

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2.4.3 Gas Evaluation with Gas Nozzle

In the development of the gas nozzle design, various gases and flow rates were evaluated to ensure that the weld zone was evacuated and that the inner chamber provided adequate shielding for the molten weld material. A set of operating parameters was established for welding Alloy 625 and Type 308L at a depth of 50 feet with the present gas nozzle configuration. These parameters are listed in Table 2-1.

Table 2-1
Welding Parameters for Alloy 625 with Advanced Power Supplies

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2.5 Flux-Cored Filler Material Development

EPRI RRAC has developed and evaluated halogen-free flux formulations (EPRI Patent #5,236,517) to specifically address underwater wet self-shielded flux-cored arc welding of stainless steel and Ni-based alloys. The FCAW process utilizes a continuously fed, consumable welding wire that consists of a metal sheath containing flux and alloying elements. The flux formulation in a self-shielded flux-cored wire is used to stabilize the welding arc, form a slag, and produce shielding gas to protect the molten metal transfer and weld puddle, similar to the SMAW process.

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Typical Ni-based filler metal compositions are referenced in Table 2-2.

Table 2-2
Filler Metal Comparison Chart

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2.5.1 Fill Ratio, Sheath Materials, and Manufacturers

Flux-cored wires with sheath materials consisting of 80 Ni/20 Cr, Alloy 625, Ni-200 have been evaluated for Alloy 625 chemistries.

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Manufacturing techniques have contributed to variations in UW weld quality and bead appearance. Proprietary manufacturing techniques including sheath material, thickness and width of sheath material, fill ratios, drawing techniques, and annealing need to be controlled precisely.

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Manufacturing techniques have played a vital role in consistency and reproducibility of weld quality. To improve the consistency of welding with the flux-cored wires, a standard manufacturing practice was established.

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2.6 Weld Parameter Development

2.6.1 Power Supply Parameter Development

Underwater welding parameters were initially established with conventional power supplies for Ni-based materials as documented in Table 2-3. Limitations of typical power supplies made it necessary to evaluate more sophisticated welding power supplies. The advanced welding power supplies with real-time adaptation to the arc condition improved welding capabilities at depth as required for the qualification tests. Typical parameters developed with three advanced power supplies at a depth of 50 feet are listed in Table 2-1.

Table 2-3
Conventional Power Supplies and Welding Parameters

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All parameter development and weld qualification at the 50-foot level was completed with the advanced power supplies and with the assistance of the gas nozzle. The optimum parameters were based primarily on bead appearance, spatter level, and heat input.

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2.6.2 Gas Diffuser Set-Up

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2.6.3 Vertical Position

Earlier development work in wet self-shielded welding indicated that vertical down welding with a lead angle of 15 ° produced acceptable weld quality. The early development work was limited to stringer beads, due to limitations in the manipulation equipment.

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Table 2-4
Vertical Position Welding Specifications

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2.6.4 Flat Position

The OTC/Daihen Fuzzy Auto 350EX was used for welding in the flat position for qualification welds and parameter development. The flat position allows for a higher wire feed rate and amperage to be utilized, compared to horizontal and overhead welds, since bead placement is not as critical.

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Table 2-5
Flat Position Welding Specifications

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2.6.5 Horizontal Position

The OTC/Daihen Fuzzy Auto 350EX was used for all parameter development and qualification welding in the horizontal position.

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Table 2-6
Horizontal Position Welding Specifications

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2.6.6 Overhead Position

The OTC/Daihen Fuzzy Auto 350EX was used for all parameter development and qualification welding in the overhead position.

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Table 2-7
Overhead Position Welding Specifications

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2.6.7 Specifications for Weld Head and Controls

Table 2-8 outlines the preliminary recommendations for the weld head and controls for welding at a depth of 50 feet. The specifications in Table 2-8 are based on utilizing the OTC/Daihen with the gas nozzle and must be modified per specific repair application. These specifications encompass the range of parameters used in qualification tests for all positions.

Table 2-8
Specifications for Weld Head and Controls

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3

QUALIFICATION OF WELDMENTS AND TESTING WELDING AT 50 FEET

UW FCAW test plates typically undergo a series of mechanical tests including bend tests and tensile tests established by ASME Code Case N-516 and Section IX. Utilizing welding parameters and techniques developed in Section 2, Alloy 625 was tested on Alloy 600 and Type 304 stainless steel. In prior tests, not reported here, Alloy 625 and 308L have been evaluated on 304 stainless steel, Alloy 600, and Alloy 690 base materials, as well as Alloy 82 cladding material, at depths of 3, 20, and 50 feet. The underwater welding development has resulted in Code quality mechanical properties in most welding conditions and materials at depths up to 50 feet. This section provides the results of tests conducted with Alloy 625 on Type 304 SS and Alloy 600 base material with a standard V-groove configuration. Side bends and tensile tests were conducted for each weld position (vertical, horizontal, flat, and overhead) and results are recorded in Tables 3-1 through 3-4.

3.1 Technique

Welding techniques and parameters were developed in Section 2 for all welding positions and materials. The qualification welds required precise bead positioning, work angle, and stickout lengths to accommodate actual welding conditions per qualification weld. All welding was completed with stringer beads with the exception of vertical welding.

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3.2 Joint Geometry

The weld specimens for the qualification welds consisted of V-groove configurations to support ASME Section IX mechanical testing requirements and Code Case N-516 qualification requirements. All test plates were fabricated from 1/2-in. thick Type 304

SS and Alloy 600 base material. The plates were machined to accommodate a 70° included angle with a root opening approximately 1/8 in. wide. A seal weld was placed in the root with GTAW for all weld specimens to prevent gas pockets, which typically introduce porosity into the weld metal, from forming between the backing bar and the test plates. Typical in situ repairs address crack excavation and repair or fillet-type weld geometry where a backing bar is not utilized. These test configurations are similar to actual geometries that can be encountered when performing in situ repairs on reactor internal components.

3.3 Positions

Manipulation equipment was positioned inside the hyperbaric chamber to accommodate welding positions. The qualification specimens were welded in four positions: horizontal, vertical, overhead, and flat.

3.4 Qualification Test Results

Tensile and side bend test results for the flat position are listed in Table 3-1. Flat position weld bend specimens and tensile specimens are illustrated in Figures 3-1 and 3-2. Tensile and side bend test results for the horizontal position are listed in Table 3-2. Horizontal weld bend specimens and tensile specimens are illustrated in Figures 3-3 and 3-4. Test results for the overhead position are listed in Table 3-3. Overhead weld bend specimens and tensile specimens are illustrated in Figures 3-5 and 3-6. Test results for the vertical position are listed in Table 3-4. Vertical weld bend specimens and tensile specimens are illustrated in Figures 3-7 and 3-8. All results were considered acceptable per ASME IX UTS requirements for in-air weld qualifications. Photos of the welds for each position are shown in Figures 3-9 to 3-13.

Table 3-1
Flat Position Type 304 SS to Alloy 600

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Table 3-2
Horizontal Position Type 304 SS to Alloy 600

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Table 3-3
Overhead Position Type 304 SS to Alloy 600

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Table 3-4
Vertical Position Type 304 SS to Alloy 600

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Figure 3-1
Bend Samples from Flat Position 1G Test Plate

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Figure 3-2
Tensile Samples from Flat Position 1G Test Plate

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Figure 3-3
Bend Samples from Horizontal Position 2G Test Plate

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Figure 3-4
Tensile Samples from Horizontal Position 2G Test Plate

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Figure 3-5
Bend Samples from Overhead Position 4G Test Plate

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Figure 3-6
Tensile Samples from Overhead Position 4G Test Plate

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Figure 3-7
Bend Samples from Vertical Position 3G Test Plate

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Figure 3-8
Tensile Samples from Vertical Position 3G Test Plate

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Figure 3-9
1G Weld Plate 304 SS to Alloy 600 (Cover Passes)

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Figure 3-10
2G Weld Plate 304 SS to Alloy 600 (Root Pass Only)

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Figure 3-11
4G Weld Plate: 304 SS to Alloy 600 (Root Pass Only)

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Figure 3-12
3G Weld Plate 304 SS to Alloy 600

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Figure 3-13
Cross-Section of Overhead Groove Weld, Alloy 625

4

DEMONSTRATION OF UNDERWATER WELD REPAIR APPLICATION

4.1 Demonstration Welds Test Matrix

A matrix of weld configurations was developed to demonstrate the capabilities and limitations of the UW FCAW process with the newly developed gas nozzle. The following configurations and parameter variations were tested:

- Fillet weld configuration
- Overlay configuration
- V-groove configuration
- Effects of travel speed
- Effects of water depth
- Effects of welding over a crack
- Effects of interpass cleaning
- Effects of gas nozzle orientation

The results of these tests are presented in Sections 4.2 through 4.9 below.

With the exception of the tests conducted to assess the effects of water depth, all welds were conducted at a simulated depth of 50 feet.

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4.2 Fillet Weld Configuration

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Two lap joint configurations in the horizontal position were utilized to establish limitations. The first was a 3/8-in. to 3/8-in. lap joint with Type 308L filler material on Type 304 SS. Detailed parameters are shown in Table 4-1.

Table 4-1
Demonstration Weld: 3/8-In. Fillet Weld

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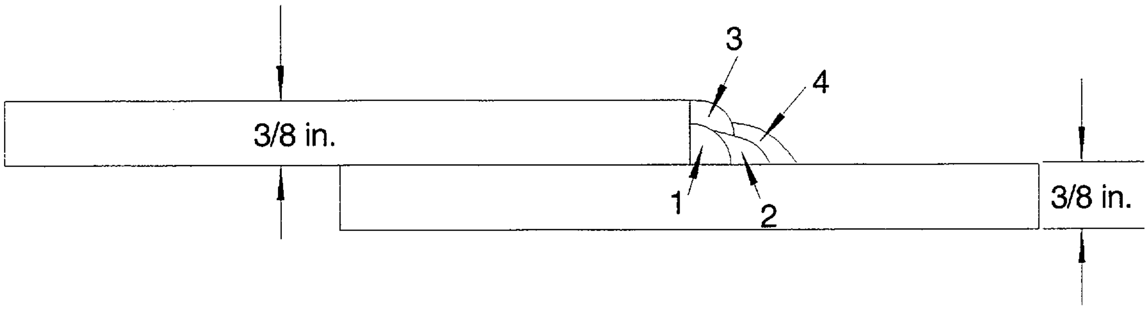

Figure 4-1
3/8-In. to 3/8-In. Type 304 SS Lap Joint Bead Sequence

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Figure 4-2
3/8-In. to 3/8-In. Type 304 SS Lap Joint

Table 4-2
Bead Sequence and Welding Parameters for 3/8-In. to 3/8-In. SS Lap Joint

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The second lap joint configuration was completed on 1/2-in. to 3/4-in. Type 304 SS base material with Type 308L filler material (see Table 4-3).

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Table 4-3
Demonstration Weld: 1/2-In. Fillet Weld

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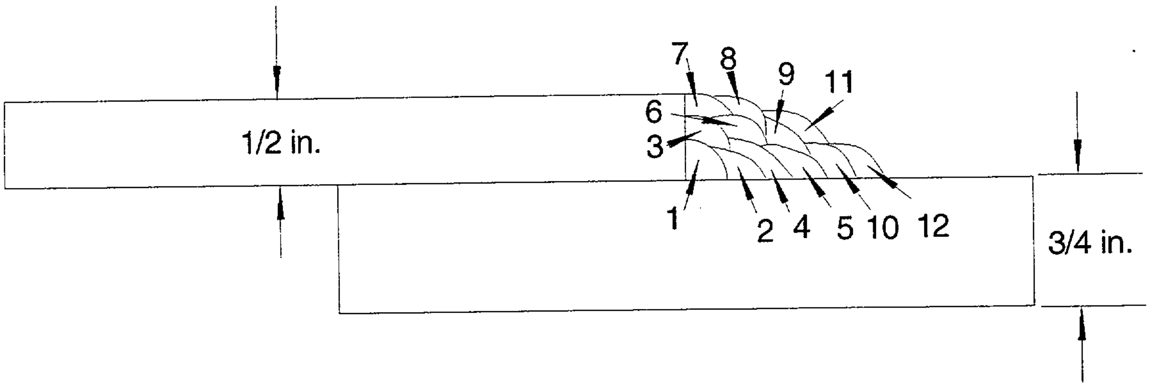

Figure 4-3
1/2-In. to 3/4-In. Type 304 SS Lap Joint Bead Sequence

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Figure 4-4
1/2-In. to 3/4-In. Type 304 SS Lap Joint

Table 4-4
Bead Sequence and Welding Parameters for 1/2-in. to 3/4-in. SS Lap Joint

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4.2.1 Results

The lap joint configuration welds were inspected with radiography to verify weld quality. The weldments were inclusion- and porosity-free as seen in Figures 4-5 and 4-6.

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Figure 4-5
Cross-Section of 3/8-In. to 3/8-In. Type 304 SS Lap Joint

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Figure 4-6
Cross-Section of 1/2-In. to 3/4-In. Type 304 SS Lap Joint

4.3 Overlay Configuration

The second demonstration weldment was a 3/4-in. overlay in the flat position on Type 304 SS with Type 308L filler material (see Table 4-5). The first layer consisted of eight passes with each pass placed adjacent to the previous pass (typical overlay bead sequence). Layers 2 and 3 consisted of six and five passes, respectively. The width of layers 1, 2, and 3 was increased to support additional layers as needed. The bead sequence is documented in Table 4-6 and Figure 4-7. A total of nine layers was applied for a total of 84 passes to achieve a 3/4-in. overall buildup, as shown in Figure 4-8.

Table 4-5
Demonstration Weld: 3/4-In. Overlay Weld

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Table 4-6
Bead Sequence and Welding Parameters for Overlay Demonstration Weld

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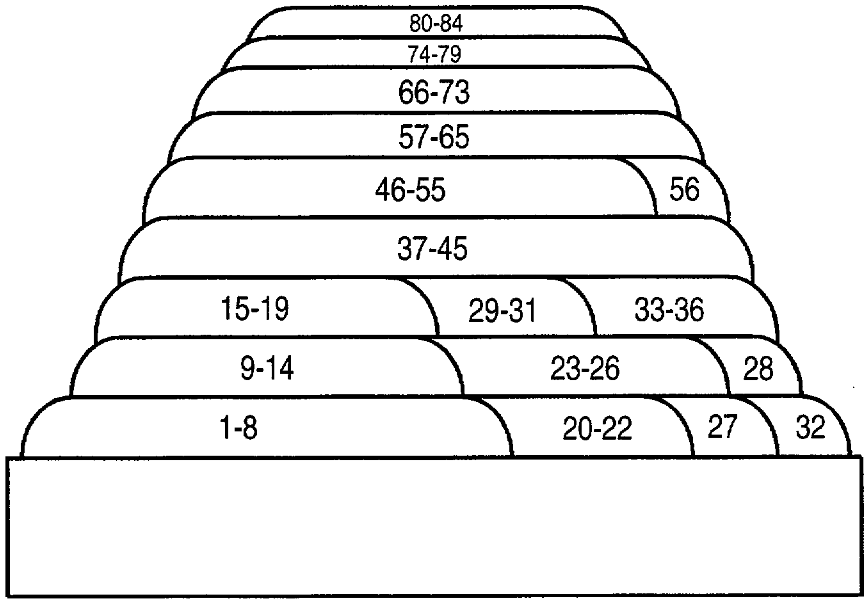

Figure 4-7
3/4-In. Overlay Bead Sequence

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Figure 4-8
3/4-In. Overlay Demonstration Weld

4.3.1 Results

The overlay demonstration weldment was tested with radiography to verify weld quality. The entire specimen was free of porosity and inclusions as seen in Figure 4-9.

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Figure 4-9
Cross-Section of 3/4-In. Overlay

Table 4-7
Measurement of Buildup Height per Layer

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4.4 V-Groove Configuration

The third demonstration weld was a 3/4-in. V-groove configuration on Alloy 600 base material with Alloy 625 filler material. Initial attempts to weld a 3/4-in. V-groove with a 70° groove angle were successful on the root passes and intermediate welds.

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Table 4-8
Demonstration Weld: 1/2-In. V-groove with Overlay

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Table 4-9
Bead Sequence and Welding Parameters for V-Groove Demonstration Weld

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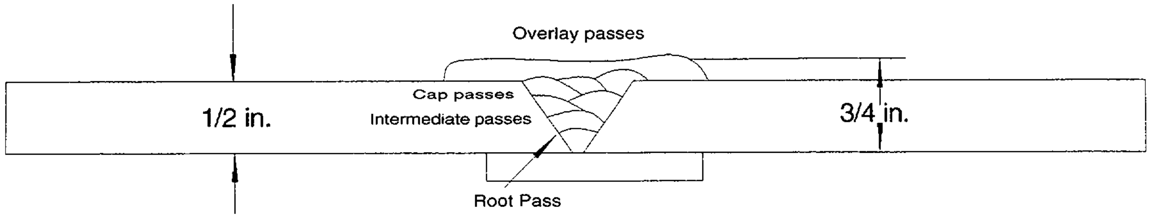

Figure 4-10
Bead Sequence of V-Groove Demonstration Weld

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Figure 4-11
V-Groove Demonstration Weld

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Figure 4-12
Cross-Section of V-Groove Configuration

4.4.1 Results

The V-groove demonstration weldment was tested with radiography to verify weld quality. The entire specimen showed micro-porosity scattered through the weld but was free of any large inclusions as seen in Figure 4-12. Weld quality was considered acceptable as a result of the qualification described in Section 3.

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4.5 Effects of Travel Speed

The effects of travel speed on the degree of penetration were evaluated by increasing the travel speed incrementally through an acceptable range. All weld tests were conducted in the flat position with bead-on-plate (BOP) welds at a depth of 50 feet (see Table 4-10). The travel speed was evaluated through a range (16–20 ipm) without altering welding parameters or shielding gas flow rates. All welds were considered acceptable through the range of travel speeds tested (see Table 4-11). The test plate is illustrated in Figure 4-13.

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Table 4-10
Travel Speed Demonstration Welds

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Table 4-11
Welding Parameters for Travel Speed Tests

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Figure 4-13
Travel Speed Test Plate

Table 4-12
Test Results for Travel Speed vs. Bead Profile

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4.6 Effects of Water Depth

The effects of water depth on the degree of penetration were evaluated in BOP tests by increasing the depth in the hyperbaric chamber incrementally (see Table 4-13). The depth was increased from 20 ft. to 90 ft. maximum. All welds were completed without altering welding parameters or shielding gas flow rates and pressures. The line pressure for the shielding and evacuation gas was set at and maintained at values appropriate for welding at 50 feet.

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Table 4-13
Travel Speed Demonstration Welds

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Table 4-14
Welding Parameters

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Figure 4-14
Water Depth Test Plate

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Figure 4-15
Water Depth Test Plate (Close-Up)

Table 4-15
Test Results

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4.7 Effects of Welding over a Crack

Tests were conducted with cracks oriented both in the direction of travel and transverse to the direction of weld travel.

4.7.1 Crack in the Direction of Weld Progression

A single bead seal weld was attempted on an increasing gap width to determine the maximum crack width that could feasibly be seal welded. The mockup was fabricated by butting two plates together at one end and allowing a gap of approximately 0.153 in. at the opposite end (see Figure 4-16). The plates were tacked to a strongback prior to welding. Test parameters are shown in Table 4-16.

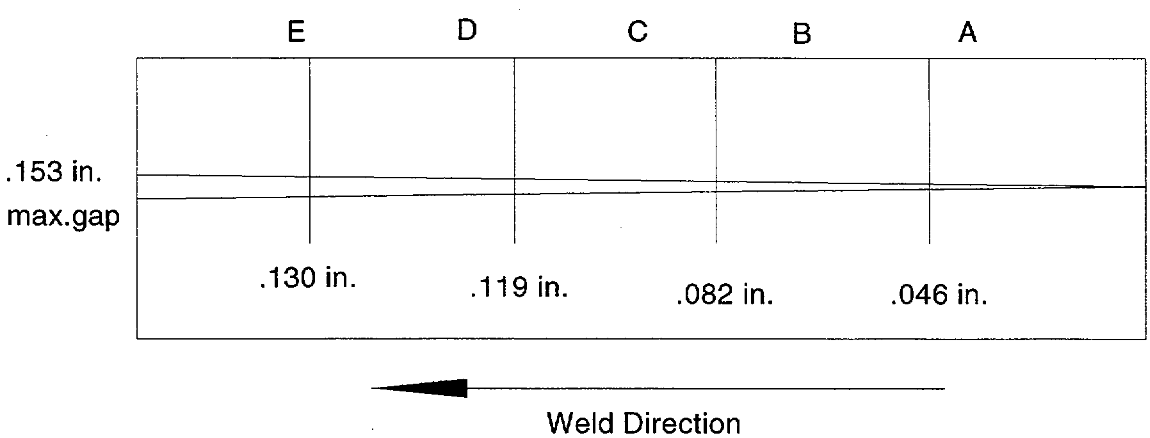

Figure 4-16
Crack Joint Configuration

Table 4-16
Demonstration Test Parameters

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4.7.2 Results

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Table 4-17
Weld Quality at Set Gap Width

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Figure 4-17
Seal Weld on Wedge Plate Mockup (Weld Direction from Right to Left)

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Figure 4-18
Seal Weld on Wedge Plate Mockup, Beginning of Weld

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Figure 4-19
Seal Weld on Wedge Plate Mockup, End of Weld

4.7.3 Welding Transverse to the Crack Direction

Five welds were placed across a crack or gap produced by butting two sections of plate together as seen in Figure 4-20. The mockup had no gap at one end and a maximum gap of approximately 1/4 in. at the opposite end. The plates were tacked to a strongback prior to welding. Test parameters are shown in Table 4-18.

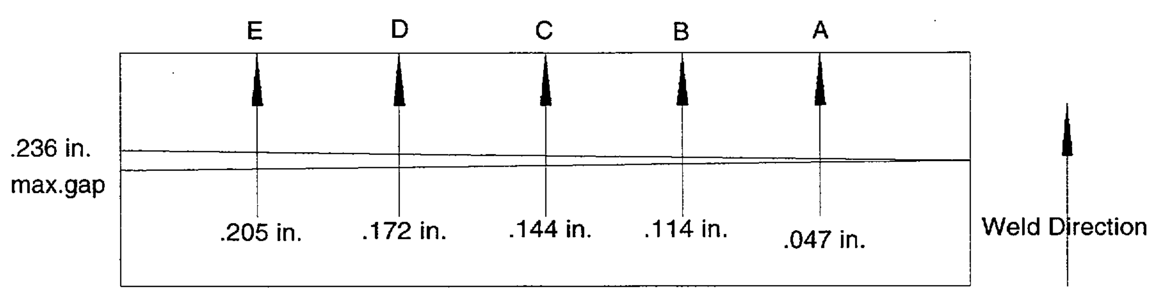

Figure 4-20
Crack Joint Configuration

Table 4-18
Demonstration Test Parameters

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4.7.4 Results

Welds were made across a gap at increasing gap widths until welding became unstable.

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Figure 4-21
Wedge Plate with Transverse Welds

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Figure 4-22
Transverse Weld Plate at 0.047-In. Gap (Location A)

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Figure 4-23
Transverse Weld Plate at 0.114-In. Gap (Location B)

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Figure 4-24
Transverse Weld Plate at 0.144- and 0.172-In. Gap (Locations C and D)

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Figure 4-25
Transverse Weld Plate at 0.205-In. Gap (Location E)

Table 4-19
Transverse Wedge Plate Weld Results

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4.8 Effects of Interpass Cleaning

Tests were conducted to determine the need for interpass cleaning on stainless steel and Ni-based materials in both the flat and horizontal positions.

4.8.1 Flat Position Evaluation, Stainless Steel Materials

Stainless steel welds were evaluated to determine the need for interpass cleaning. Cleaning is typically accomplished by manual wire brushing or pneumatic wire brushing. Welds with and without cleaning were evaluated. Welding without cleaning was evaluated with multi-pass welds with no attempt to remove spatter or slag coverage (as-welded condition). Test conditions are shown in Table 4-20.

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Table 4-20
Demonstration Test Parameters

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Figure 4-26
Cleaning Demonstration Weld on Stainless Steel, Flat Position

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Figure 4-27
Bead-on-Plate Passes with Interpass Cleaning (Location 1)

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Figure 4-28
V-Groove Weld without Interpass Cleaning, Flat Position (Location 3)

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Figure 4-29
Bead-on-Plate Passes without Interpass Cleaning, Flat Position (Location 2)

4.8.2 Horizontal Position Evaluation, Stainless Steel Materials

Stainless steel welds made in the horizontal position were also evaluated to determine the need for interpass cleaning. Welding without cleaning was evaluated with multi-pass welds with no attempt to remove spatter or slag coverage (as-welded condition). Cleaning was accomplished by wire brushing between passes.

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Table 4-21
Weld Parameters, Horizontal Position, SS, No Cleaning

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Table 4-22
Weld Parameters - Horizontal Position, SS, with Cleaning

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Figure 4-30
Cleaning Demonstration Welds on Stainless Steel, Horizontal Position

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Figure 4-31
Horizontal Position Evaluation, Weld Location 5 (with Cleaning) and 3 (without Cleaning)

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Figure 4-32
Horizontal Position Evaluation with Cleaning, Weld Locations 2, 1, and 4

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Figure 4-33
Demonstration Welds on Stainless Steel, Horizontal Position

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Figure 4-34
Horizontal Position, Five Individual BOP Welds (Cleaning), Weld Location 1

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Figure 4-35
Horizontal Position, V-Groove, and BOP Welds (Cleaning), Weld Locations 2 and 3

4.8.3 Flat and Horizontal Position, Ni-Based Materials

Ni-based welds were also evaluated to determine the need for interpass cleaning. Cleaning was typically done by manual wire brushing or pneumatic wire brushing. Welding without cleaning was evaluated with multi-pass welds with no attempt to remove spatter or slag coverage (as-welded condition).

Welding parameters for the tests are shown in Table 4-23. Test results are shown in Figures 4-36 and 4-37.

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Table 4-23
Weld Parameters, Horizontal Position, SS, with Cleaning

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Figure 4-36
Flat and Horizontal Position, V-Groove and BOP Welds (Cleaning)

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Figure 4-37
Horizontal Position, V-Groove and BOP Welds (Cleaning), Weld Locations 1, 2, and 3 (Close-Up)

4.9 Effects of Gas Nozzle Orientation, Horizontal Position

Stainless steel welds were evaluated in the horizontal position to determine the effects of inherent high-/low-pressure zones of the gas cup. The orientation is described by indicating the number of low-pressure zones or legs that are aligned toward the top of the weld. The pressure zones are a result of alignment of the inlet ports as discussed in Section 2. The first weld was also completed with the wire and cup submerged underwater for over one hour prior to welding. Welding parameters are listed in Table 4-24.

The following welds were applied to the test plate (see Figure 4-38):

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Close-up pictures of the welds are shown in Figure 4-39 and 4-40.

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Table 4-24
Weld Parameters, Horizontal Position, SS, with Cleaning

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Figure 4-38
Evaluation of Cup Orientation (BOP), Welds 1 through 6

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Figure 4-39
Evaluation of Cup Orientation, Welds 2, 3, and 4

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Figure 4-40
Evaluation of Cup Orientation, Welds 1, 5, and 6

4.10 NDE Results for Demonstration Welds

The inspectability of the FCAW repairs was evaluated by examination of a number of overlay welds. Ultrasonic examinations were performed on five overlay samples, some containing controlled, artificial defects. Detailed reporting of the measurements will appear in BWRVIP-03, Reactor Pressure Vessel and Internals Examination Guidelines , Revision 1 [3]. The results with respect to surface examination demonstrate that:

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5 CONCLUSIONS

The project objectives were to develop underwater weld repair capabilities for nickel-based (Inconel) BWR reactor vessel internal components at depths of up to 50 feet in "non -irradiated" locations. The project entailed three phases including :

- Welding process development
- Qualification of weldments
- Demonstration of underwater weld repairs

Phase one provided UW welding capabilities through the development and testing of welding equipment, gas nozzles, and filler materials. Alloy 625 filler material was substituted in this phase for Alloy 52 due to its inherent welding characteristics at 50 feet. Phase two utilized the development work in phase one to qualify welding of Alloy 600 to Type 304 SS test plates with Alloy 625 filler at 50 feet per ASME Section IX. Phase three demonstrated the welding process in typical joint configurations and environmental conditions to show limitations and capabilities of the welding process.

The results of the project have clearly demonstrated that high-quality welds can be produced, meeting all current ASME Code requirements:

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REFERENCES

1. Technical Basis for Part Circumference Weld Overlay Repair of Vessel Internal Core Spray Piping, BWRVIP-34. Electric Power Research Institute, Palo Alto CA: May 1997. Report TR-108198.

2. Elliot K. Stava. "The Surface-Tension-Transfer Power Source: A New, Low-Spatter Arc Welding Machine," AWS Welding Journal. Vol. 72, No. 1, pp. 25–29 (1993).

3. Examination of Weld-Overlaid Pipe Joints. Electric Power Research Institute, Palo Alto CA: October, 1986. Report EPRI NP-4720-LD.

6.1 Bibliography

"Development in Intelligent Control of Arc Welding Power Supplied," Welding & Metal Fabrication. pp. 37-39, July 1994.

Findlan, S. and G. Frederick. Underwater Wet Flux-Cored Arc Welding Development of Stainless Steel and Nickel-based Materials. Interim Report, Electric Power Research Institute, Palo Alto CA: February 10, 1994.

Frederick, G., S. Findlan, and W. Newell. Underwater Welding and Cutting Guidelines. Electric Power Research Institute, Palo Alto CA: April 1994.

Ogasawara, T. et al., "A Power Source for Gas Shielding Arc Welding with New Current Waveforms," Welding Journal. March 1987.

Ushio, M., H. Yamamoto, Y. Nishida, and T. Mita. "Recent Advances in Welding Power Systems for Automated Welding," Elsevier Science.LTD 0043-2288/94, pp. 185-190 (1994).

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Nuclear Power

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