Method for Repair of Steam Generator and Heat Exchanger Tubing by Partial Replacement

TR-111355

Final Report
December 1998

Prepared for
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This report describes research sponsored by EPRI. The report is a corporate document that should be cited in the literature in the following manner:

Method for Repair of Steam Generator and Heat Exchanger Tubing by Partial Replacement, EPRI, Palo Alto, CA: 1998. Report Number TR-111355.

REPORT SUMMARY

This report details the development of a laser weld repair methodology used for steam generator tube failures at the tube-to-tubesheet region. It includes the development of an internal laser welding system, welding parameter evaluation, and the design of the weld metal insert rings, which attach the replacement section of the tube to the existing tube with the resulting structural integrity exceeding that of the original tube.

Background

Steam generator tubes in pressurized water reactor (PWR) power plants are susceptible to several types of corrosion mechanisms that can ultimately lead to leakage or significant wall thinning. These include primary water stress corrosion cracking (PWSCC), secondary side intergranular attack (IGA), secondary intergranular stress corrosion cracking (IGSCC), and secondary side wastage. Current mitigation techniques for these corrosion-induced problems include plugging degraded tubes, sleeving degraded tubes, and steam generator replacement. Each of these repair methods exhibit economic and technical drawbacks including removing the tube from service, limitation of future repairs, and high cost.

Objectives

- To provide a means of repairing the most common steam generator tube failures, located at the tube-to-tubesheet region
- To use existing repair equipment and capabilities available from service contractors and original equipment manufacturers (OEMs)

Approach

A repair methodology was developed to provide a permanent repair for tubing that is affected by stress corrosion cracking or other damage at the tube-to-tubesheet region. This included:

- Removing the affected portion of the tube and replacing it with a corrosion-resistant Alloy 690 tube

- Attaching the new section of tube by laser welding a weld metal insert ring designed specifically to assist in aligning and connecting the new section of tubing
- Designing a weld metal insert that provides sufficient filler metal to obtain a permanent, leak-tight connection with the resulting structural integrity exceeding that of the original tube

Results

A laser repair methodology was developed to address heat exchanger tubes with defects located at the tube-to-tubesheet region. The principal applications of this repair method include repair of steam generator tubing that has significant degradation from stress corrosion cracking or other corrosion damage. The repair methodology has been demonstrated on basic tube-to-tube insert connections with both ID and OD laser end effectors. An effective means of applying a weld metal insert ring was established, which significantly reduced the required internal laser welding cycle.

EPRI Perspective

Additional research needs to be performed upon successful completion of this feasibility study to include corrosion studies and evaluation of structural properties. Weld metal insert rings will ultimately be designed to accommodate the results of these tests. In situ field application of this technology will require the development of a delivery system to apply and position the laser end effector at the weld metal insert connection.

TR-111355

Interest Categories

Applied science & technology
Steam generators
Piping, reactor vessel & internals

Keywords

Laser welding and joining
Steam generators
Heat exchangers
Partial tube replacement

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INTRODUCTION

Steam generator (SG) tubes in pressurized water reactor (PWR) power plants are susceptible to several types of corrosion mechanisms that can ultimately lead to leakage or significant wall thinning. These include primary water stress corrosion cracking (PWSCC), secondary side intergranular attack (IGA), secondary intergranular stress corrosion cracking (IGSCC), and secondary side wastage. Primary side degradation typically occurs at locations of high tensile residual stress such as expansion transition areas, inner row U-bends, and dented tube support locations. Secondary side degradation occurs at locations where impurities can concentrate, thus providing corrosion sites such as tube-to-tubesheet crevices, tube support plate-to-tube interfaces, anti-vibration bars, and sludge pile regions (located at the tubesheet).

Current mitigation techniques for these corrosion-induced problems include plugging degraded tubes, sleeving degraded tubes, and steam generator replacement. Each of these repair methods exhibit economic and technical drawbacks, including removing the tube from service, limitation of future repairs, and high cost.

The Nd:YAG laser welding process for partial tube replacement, which was developed by EPRI Repair & Replacement Applications Center, offers a cost-effective means of permanently repairing the most common location of failures in steam generator tubes.

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PROJECT PURPOSE AND SCOPE

Due to corrosion and residual stresses, a majority of the steam generator tube cracks occur at the tubesheet region, at the lowest region of the steam generator tube bundle. This is typically the first location at which cracking is observed for steam generator tubes. The objective of this program was to provide a means of repairing the most common steam generator tube failures, located at the tube-to-tubesheet region. A secondary objective was to use existing repair equipment and capabilities available from service contractors and original equipment manufacturers (OEMs).

Most of the removal and replacement of the degraded tube section was accomplished with available tooling that is currently used for removal of tube sections for evaluation purposes (Figure 2-1). The tooling first severs the tubing at a selected location below the first support plate. The tube is then removed from the tube sheet by relaxing the expansion fit of the tube. This is typically accomplished by a gas-tungsten arc torch used to heat the tube within the tubesheet region. The tube section is then simply withdrawn through the tubesheet. The tube section is replaced with a new section of Alloy 690 tube and a compatible weld metal insert ring (Alloy 52 or Alloy 72, both highly corrosion-resistant materials).

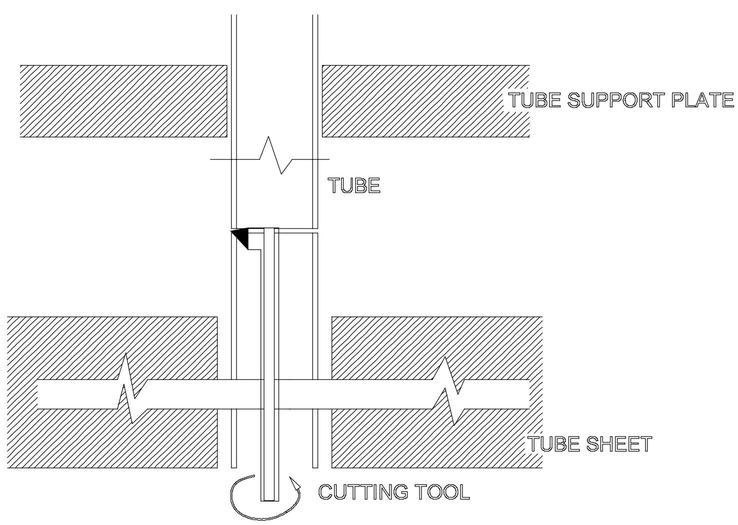


Figure 2-1
Common Tube Removal Process

The new section of tube is attached by laser welding a weld filler metal insert ring, designed specifically to assist in aligning and connecting the existing tube and the new section of tubing (Figure 2-2). Once the insert ring and new section of tubing are laser welded in place, a post-weld heat treatment (PWHT) is performed on the weldment to relieve residual stresses and to restore the weld HAZ to a metallurgical state that is resistant to stress corrosion cracking. The heat treatment can be performed using conventional electric resistance heating techniques, or with LASER heating methods. In either method, the tube-to-tube weld region is heated to temperatures of 1300-1600° F for up to five minutes.

To prevent corrosion products from forming between the newly installed tube and tubesheet, the tube is expanded within the tubesheet. Expansion can be performed with a number of techniques that are commonly in use by the original fabricators.

As a final step, the lower end of the tube is welded to the tubesheet cladding. By sequencing the replacement procedure in this manner, residual stresses along the tube and at the weld location are minimized. Because the lower tube-to-tubesheet weld and expansion are not performed until after the tube-to-tube weld and heat treatment are completed, the tube is not restrained in a fixed position and is free to move. This permits the tube to expand and contract freely during welding and heat treatment (Figure 2-2). Thus, no undesirable stresses are created during the application of these processes.

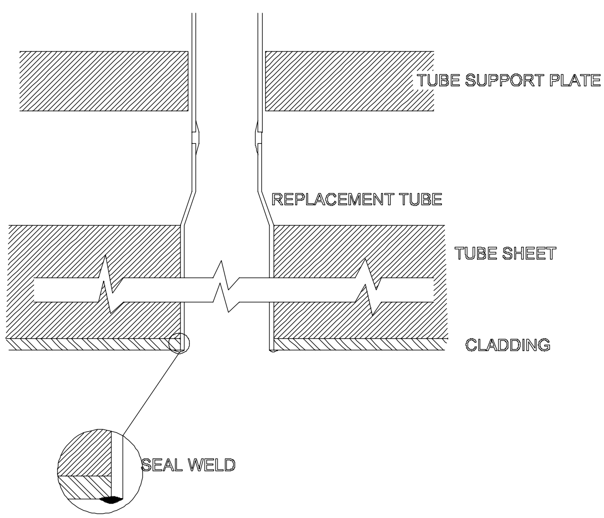


Figure 2-2
Tube Replacement Process

The intention of this program was to develop a process to weld the metal insert connection between the replacement tube and the original tube material with a resulting structural integrity that exceeds that of the original tube. This will include laser process development (that is, weld end effector) and designing and testing weld metal inserts that provide sufficient filler metal to obtain a permanent leak-tight connection.

3

LASER PROCESS DEVELOPMENT

The laser welded repair approach includes the development of a laser weld head or end effector, welding parameter evaluation, and the design of the weld metal insert rings that attach the new replacement section of corrosion resistant tube to the existing steam generator tube. Two welding methods, as outlined in Section 3.1 *Laser Welding Evaluation—Externally Delivered* and Section 3.2 *Laser Welding Evaluation—Internally Delivered,* were used for evaluating the laser welding process.

Basic insert designs were used to connect Alloy 600 steam generator tube mockup assemblies (tube-to-tube connection). The final design of the weld metal insert ring should be established to meet installation requirements combined with corrosion and mechanical testing that is not in the scope of this program. Insert ring design criteria was established during the welding process development and was modified throughout the welding trials. Section 3.3 *Weld Metal Insert Development* discusses general design criteria for the weld metal inserts.

The shape of the weld metal insert is such that it is self-aligning with respect to the original tube. The insert might be formed in a T-ring fashion, which assists with alignment and provides adequate filler metal for reinforcement of the weld region. A tapered edge incorporated into the insert ring could also assist in alignment when the new section of tube is inserted into the tubesheet and aligned with the original tube. A mandrel can be used to perform rough alignment where the original tube was shifted in relation to the tubesheet. Once the replacement and insert are in place the laser weld head or "end effector" is inserted into the tube and positioned at the insert location. The laser beam fuses the weld metal insert and a portion of each tube section, permanently joining the two sections of tubing. The laser welding process might be performed with similar laser welding systems used for laser sleeving or cladding repair methods. The insert can be fully or partially welded to the replacement tube prior to installation.

The replacement tube section is fabricated from a section of Alloy 690 steam generator tube, typically used in replacement steam generators. Alloy 690 tube material is considered to be resistant to PWSCC under normal operating conditions. An alloy 690 compatible filler material such as Alloy 52 or 72 is used to machine the metal insert rings.

3.1 Laser Welding Evaluation—Externally Delivered

The initial laser welding evaluation used a standard Nd:YAG laser system with fiber optic delivery and a standard F2 (2-in. focal length) laser end effector (Figure 3-1) to establish welding parameters (that is, laser power requirements, travel speeds, and beam delivery characteristics). Acceptance criteria for the welding parameters was based on the weld penetration through the weld metal insert and the original tube material. The test specimens consisted of a simple weld metal insert that joined two sections of Alloy 600 tube together. The tube material was typical 7/8-in. Alloy 600 steam generator tubing with a .049-in. wall. The weld metal inserts consisted of Alloy 600, Alloy 625, and Type 303 S.S. materials of various configurations.

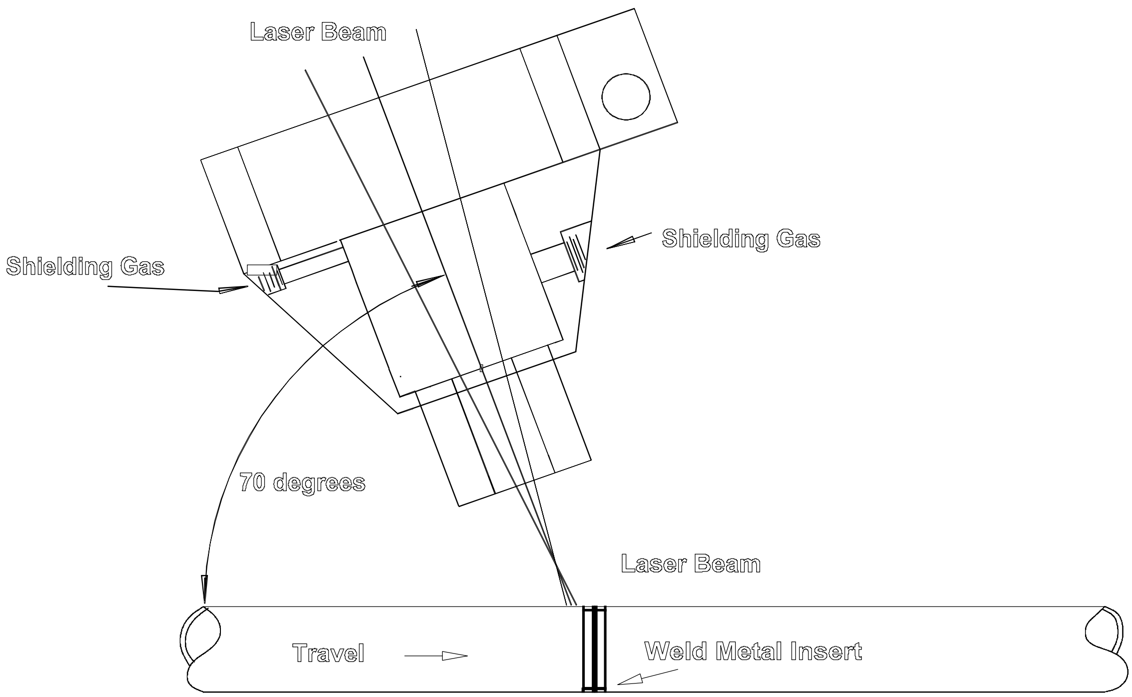


Figure 3-1
External Weld Trials with Weld Metal Inserts

Two distinct weld metal insert designs were fabricated (Figure 3-2). The OD and ID-type insert consisted of a cylindrical connection that allowed the two sections of tube to be coupled together. Both insert types had a wall thickness of 0.030-in. with a center thickness matching the overall wall thickness (.049-in.). Initial weld trials were conducted on Type 303 S.S. insert rings for ease of machining, although this material is not considered an acceptable replacement material. The externally delivered laser beam was focused directly on the OD surface of the tube in the ID insert configuration and directly on the insert material in the OD insert configuration.

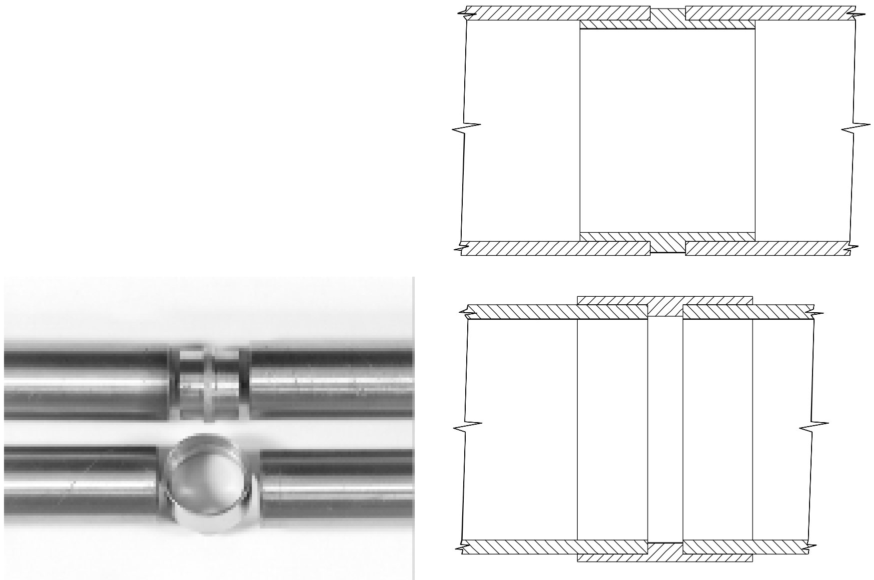


Figure 3-2
ID (Top) and OD (Bottom) Weld Metal Inserts

A matrix of welding parameters was evaluated to acquire a range of penetration through the insert into the tube material. This was accomplished by axially manipulating the laser welding end effector across the stationary tube-to-tube connection to apply a linear weld across the insert. A total of eight weld beads were applied to the OD insert as seen in Figures 3-3 and 3-4. All welds were performed at a constant +16-mm focal length, at a 70° incident angle, simulating the spot size of a typical ID weld end effector. The welds were metallographically evaluated to determine the weld penetration and bead width (Table 3-1).

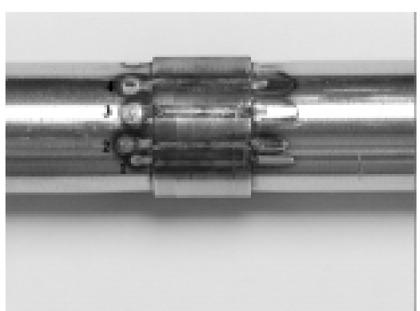


Figure 3-3
Welds 1-4 on OD Insert to Establish Penetration Depth

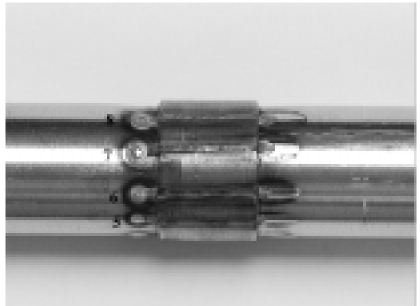


Figure 3-4
Welds 5-8 on OD Insert to Establish Penetration Depth

An additional weld was performed at the same welding parameters as weld #8 (Figure 3-5) to simulate a continuous weld application. The weld beads were overlapped approximately 50% by indexing the stationary tube clockwise under the weld end effector. All weld beads penetrated through the weld metal inserts into the steam generator material as seen in Table 3-1. The penetration depth was measured between .035-in. and .065-in. depending on laser power and travel speeds utilized. The variation in bead width was of less importance, although it followed the same trends as the penetration.

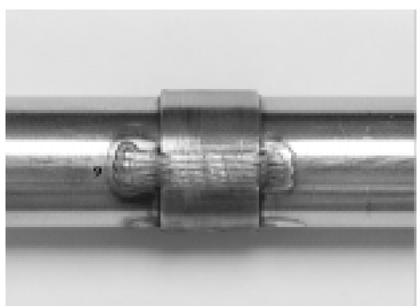
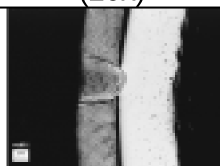
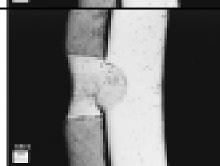
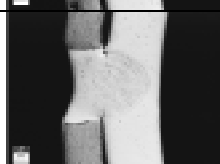
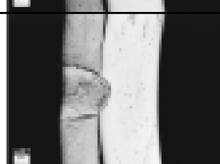
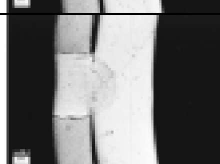
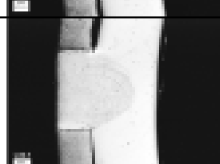
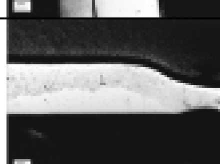


Figure 3-5
Overlapping Weld Sequence (Weld #9) on OD Insert for Parameter Development

Table 3-1
Results for Initial Laser Welding Trials on OD Insert

Weld #	Cross-section	Travel Speed	Laser Power	Focal Length	Bead Width	Penetration
	(20x)	(ipm)	(Watts)	(mm)	(in.)	(in.)
#1 Fig. 3-3		14	650	+16	.043	.035
#2 Fig. 3-3		14	950	+16	.050	.046
#3 Fig. 3-3		14	1150	+16	.051	.055
#4 Fig. 3-3		14	1230	+16	.056	.065
#5 Fig. 3-4		10	650	+16	.043	.038
#6 Fig. 3-4		10	950	+16	.048	.048
#7 Fig. 3-4		10	1150	+16	.057	.054
#8 Fig. 3-4		10	1230	+16	.059	.061
#9 Fig. 3-5		10	1230	+16	n/a	.042

OD Inserts - Type 303 S.S.

The laser welding parameters utilized for the penetration tests were used to apply a continuous circumferential weld to join the two sections of tubes with an OD weld metal insert. The laser welding end effector was manipulated axially across the tube-to-tube connection while the tube assembly was rotated at a constant speed, resulting in a continuous overlapping weld. Parameters were evaluated by applying two distinct welds on each OD insert. Each weld was initiated in the tube section and progressed toward the center of the weld metal insert (Figure 3-1). The welds typically overlapped in the center of the insert.

A matrix of welding parameters, including rotational rate (rpm) and laser power, was established to acquire a range of penetration through the insert into the tube material. All welds were performed at a positive 16 mm focal length, simulating the spot size of a typical ID weld end effector. A total of seven weld beads were applied to the OD inserts as seen in Figures 3-6 and 3-9. The welds were metallographically evaluated to determine the weld penetration and bead width as seen in Table 3-2. The weld penetration was significantly reduced with the circumferential welding process. Penetration ranged between .015-in. and .019-in. The penetration was affected by the rotational rate required to maintain an acceptable overlap or weld pitch at the minimum linear travel rate (0.5-in / min.) set by the equipment. Only a small increase in the penetration was observed with an increase in the laser power level (weld #7).

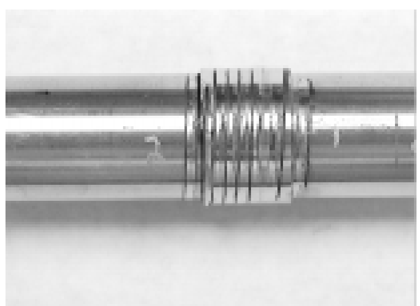


Figure 3-6
Externally Delivered Beam Weld Tests—Weld #1 (right) and #2 (left)

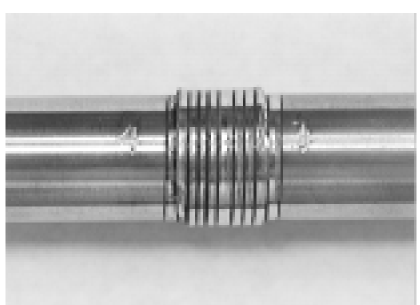


Figure 3-7
Externally Delivered Beam Weld Tests—Weld #3 (right) and #4 (left)

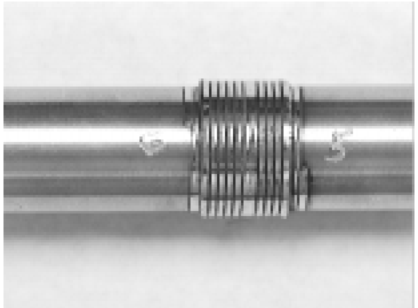


Figure 3-8
Externally Delivered Beam Weld Tests—Weld #5 (right) and #6 (left)

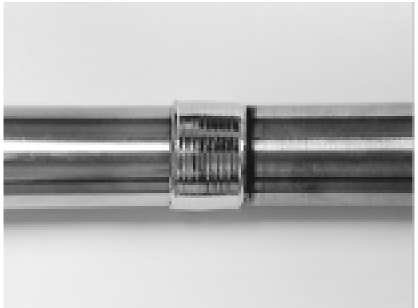


Figure 3-9
Externally Delivered Beam Weld Tests—Weld #7

Table 3-2
OD Weld Metal Inserts Welding Evaluation

Weld #	Rotation	Linear Travel	Laser Power	Bead Width	Penetration	Picture
	(rpm)	(ipm)	(Watts)	(in.)	(in.)	
1	20	1.0	950	.078	.017	Figure 3-6
2	20	0.5	650	.062	.016	Figure 3-6
3	22	0.5	800	.073	.016	Figure 3-7
4	25	0.5	950	.085	.018	Figure 3-7
5	30	0.5	950	.062	.015	Figure 3-8
6	30	0.5	800	.062	.015	Figure 3-8
7	30	0.5	1150	.073	.019	Figure 3-9

Met. Lab #01772, OD Insert - Alloy 600

Similar welding parameters used with the OD inserts were applied to ID weld metal insert configurations (Figure 3-2). Welding parameters were evaluated on four tube-to-tube connections as seen in Figures 3-10 through 3-13. The laser welding end effector was manipulated axially across the tube-to-tube connection while the tube was rotated at a constant speed to apply a continuous overlapping weld.

A matrix of welding parameters was established to acquire a range of penetration through the tube material and insert. A total of four weld beads were applied to the ID inserts as seen in Figures 3-10 and 3-13. All welds were performed at a constant positive 16 mm focal length, simulating the spot size of a typical ID weld end effector. Weld numbers 8 and 9 were welded with the laser beam focused on the top center of the tube (typical) and welds 10 and 11 focused the beam on the side, approximately 30° from the top. The welds were metallographically evaluated to determine the weld penetration and bead width as seen in Table 3-3. Penetration was similar to the OD weld metal inserts, ranging from 0.016-in. to 0.019-in. No improvements in the penetration were observed as a result of altering the location in which the laser beam was focused.

Figure 3-10
Externally Delivered Beam Weld Tests—Weld #8

Figure 3-11
Externally Delivered Beam Weld Tests—Weld #9

Figure 3-12
Externally Delivered Beam Weld Tests—Weld #10

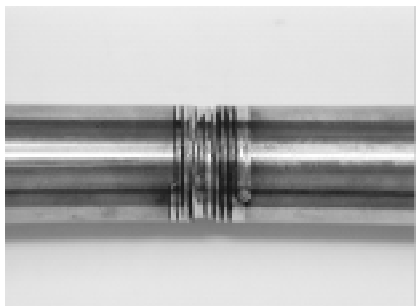


Figure 3-13
Externally Delivered Beam Weld Tests—Weld #11

Table 3-3
ID Weld Metal Insert Evaluation

Weld #	Rotation	Linear Travel	Laser Power	Bead Width	Penetration	Picture
	(rpm)	(ipm)	(watts)	(in.)	(in.)	
8	30	0.5	1150	.086	.019	Figure 3-10
9	30	0.5	1150	.079	.016	Figure 3-11
10	30	0.5	1150	.093	.018	Figure 3-12
11	30	0.5	1150	.092	.017	Figure 3-13

Met. Lab #01773, ID Insert Alloy 600

3.2 Laser Welding Evaluation—Internally Delivered

A laser welding end effector and optical assembly was developed to access the ID of the SG tubes and the weld metal inserts (Figure 3-14). The new laser welding system uses a previously developed weld end effector modified to accommodate welding the tube-to-tube configurations (Figure 3-15). Modifications to the system allowed the beam delivery to be altered from the standard 27° incident angle to a 45° incident angle. Weld trials were conducted with the ID accessible end effector to establish weld quality similar to the external delivery system. Alterations to the weld metal insert design and shielding gases were also made to improve the welding capabilities of the internally delivered welding system.

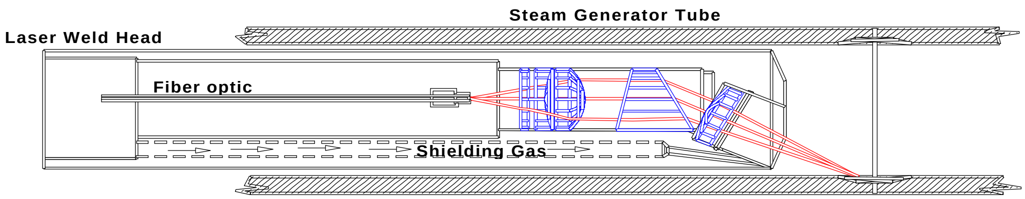


Figure 3-14
Schematic of ID Weld End Effector

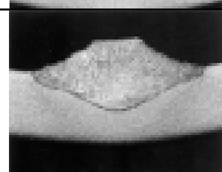
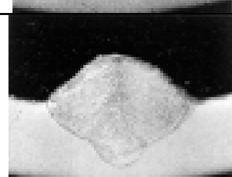
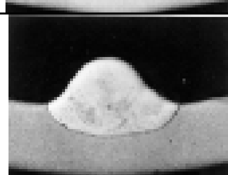
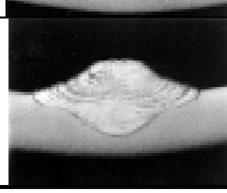
Figure 3-15
ID Laser Welding Apparatus

The weld metal insert ring and original tube material require a shielding gas to prevent oxidation during the welding process and to achieve acceptable weld quality. The shielding gas is primarily introduced co-axially through the welding end effector, which uses the gas flow to both protect the launch optic, remove the plasma formation, and to shield the molten weld metal. Gas properties (that is, thermal conductivity, atomic weight, etc.) affect the weld bead shape, penetration and appearance, which affects the design of the weld metal insert. As a means of controlling penetration and minimizing the wall thickness of the insert ring, various gas mixtures and pure gases were evaluated for laser welding inside the Alloy 600 SG tubes. Pure Argon and Helium were used for all of the external laser welding trials.

Shielding gases were compared by applying a continuous linear weld with a wire feed laser welding system, on the ID surface of a 7/8-in. SG tube. The ID weld trials evaluated pure inert gases, mixtures of inert gases, and active gas mixtures containing CO_2 and hydrogen (Table 3-4). The weld beads were applied axially on the ID surface of the tubes with Alloy 72 filler material at identical laser power levels (1150 watts) to determine the variations in the penetration and bead profile (that is, bead width, bead height). Travel speed (37.5 ipm), wire feed speed (100 ipm), and gas flow rates were also held constant during the gas evaluation.

Each weld specimen was metallographically evaluated to observe the effects of shielding gas (Table 3-4). The addition of CO_2 (25CO_2 /75Ar) drastically increased the penetration (0.96-mm), yet reduced surface quality . This limited the ability of the weld metal to wet out, resulting in a narrow weld bead with a heavy build up. Smaller additions of CO_2 (2.5CO_2 /7.5 Ar/90He) significantly reduced the penetration and bead width, while maintaining an acceptable surface appearance. Mixtures of Argon and Helium all produced acceptable bead appearance and, in some cases, a small increase in penetration (that is, 75 Ar /25 He and 25Ar/75 He). All pure gases achieved basically the same penetration (.070 - .072-in.), although they showed a trend of increasing bead width with Helium, Argon, and Nitrogen, respectively. Nitrogen allowed more heat to be transferred in the base metal, followed by Argon, then Helium.

Table 3-4
Results of Shielding Gas Evaluations

Shielding Gas	Cross-section	Bead Width	Penetration	Build up
		(mm)	(mm)	(mm)
Argon		2.9	.72	.58
75% Argon 25% Helium		2.9	.80	.58
50% Argon 50% Helium		2.94	.72	.56
25% Argon 75% He		2.9	.82	.56
98% Argon 2% Hydrogen		2.9	.72	.54
75% Argon 25% CO_2		2.48	.96	.82
90% Helium 7.5% Argon 2.5% CO_2		2.19	.64	.70
Nitrogen		3.06	.70	.56
Helium		2.76	.70	.56

Three weld specimens were completed to further evaluate the effect of Argon, Helium and Nitrogen on controlling penetration. A standard 27° weld end effector was used to apply a continuous circumferential weld overlay with Alloy 72 filler material, on the ID of a 7/8-in. Alloy 600 SG tube. Each shielding gas was evaluated under identical welding parameters including gas flow rates, laser power, and travel speed. The welds were metallographically evaluated to determine the penetration and build up (Table 3-5). Nitrogen was found to significantly increase the penetration into the SG tube (Figure 3-16) under these conditions. The weld with nitrogen penetrated throughwall with significant burn-through on the OD surface. The weld with Argon (Figure 3-17) produced 3/4 wall penetration and the Helium (Figure 3-18) produced approximately 1/3 wall penetration.

Table 3-5
Shielding Gas Evaluation

Shielding Gas	Linear	Rotation	Laser Power	Penetration	Buildup (in.)
	(ipm)	(rpm)	(watts)	(mm)	(mm)
Helium	.7	12	1150	.46	.75
Argon	.7	12	1150	.79	.73
Nitrogen	.7	12	1150	1.2	.83

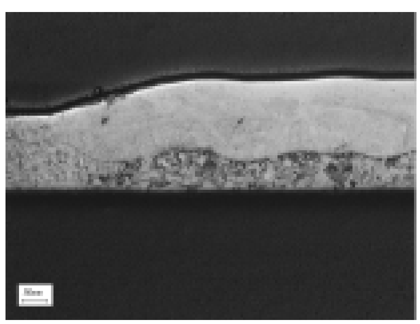


Figure 3-16
Argon Shielding Gas Evaluation (Met. Lab #1672)

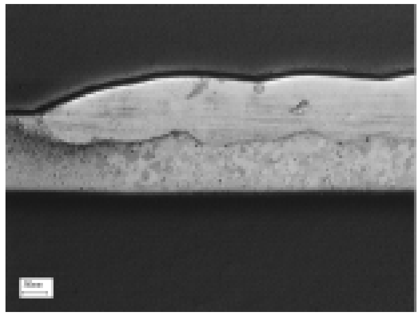


Figure 3-17
Helium Shielding Gas Evaluation (Met. Lab #1673)

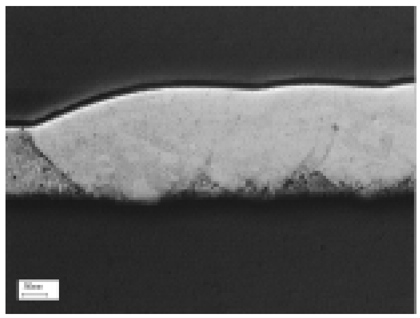


Figure 3-18
Nitrogen Shielding Gas Evaluation (Met. Lab #1674)

Welding trials were continued utilizing the standard 27° weld end effector and the modified 45° weld end effector shown in Figure 3-15. Autogenous welds were completed to establish the appropriate welding pitch (rotations per inch) for the continuous circumferential welding procedures necessary for welding inserts.

Tables 3-6 and 3-7 compare the penetration produced with the 27° and the 45° weld end effectors at various power levels. A standard welding pitch of 15 rotations per inch was maintained for the initial welding trials. The pitch was maintained at three distinct linear travel speeds and at the corresponding rotational rate. The laser power was incrementally increased from approximately 950 watts to 1250 watts with the 27° end effector, and from 650 to 950 watts with the 45° end effector. Additional welds (3) were conducted with the 45° weld end effector at a higher pitch (40 rotations per inch) and lower laser power level (Figure 3-19).

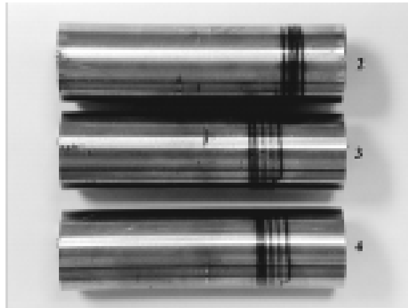


Figure 3-19
ID Weld Trials (Table 3-8)

The weld specimens were metallographically evaluated to determine the trends in penetration. An increase in penetration occurred at all laser power levels as the rotational rate decreased. This was true for both the 27° and the 45° weld end effectors. The penetration also increased with increased laser power for each rotational setting with the exception of 1250 watts at 1 ipm and 15 rpm (Table 3-6). The specimens welded at a higher pitch produced penetration between .012-.013-inches, which is significantly higher than expected for this rotational rate (Table 3-8).

Table 3-6
Penetration Evaluation With 27 Degree Weldhead (15 Pitch)

Depth of Penetration (μin.)							
Welding pitch (15)		**Laser power (Watts)**					
Linear speed	Rotation	950	1050	1150	1200	1230	1250
1 ipm	15 rpm	n/a	10.6	11.6	14.6	16	13.5
.7 ipm	10.5 rpm	11.6	13.8	17.0	18.6	20.4	n/a
.5 ipm	7.5 rpm	14.3	18.1	22.2	n/a	n/a	n/a

Table 3-7
Penetration Evaluation With 45 Degree Weldhead (15 Pitch)

Depth of Penetration (μin.)							
Welding pitch		**Laser power (W)**					
Linear speed	Rotation	650	800	950	1050	1150	1200
1 ipm	15 rpm	2.6	8.5	19.6	n/a	n/a	n/a
.7 ipm	10.5 rpm	6.6	15.7	21.9	n/a	n/a	n/a
.5 ipm	7.5 rpm	10.4	19.0	27	n/a	n/a	n/a

Table 3-8
Penetration Evaluation With 45 Degree Weldhead (40 Pitch)

Weld	Linear Speed	Rotation	Laser Power	Bead Width	Penetration
	(ipm)	(rpm)	(watts)	(in.)	(in.)
#2	.5	20	500	.067	.013
#3	.5	20	500	.063	.012
#4	.5	20	500	.060	.013

Met. Lab. #01779

The weld metal inserts were modified to allow the internal weld head to be fully inserted through the tube-to-tube connection and to be pulled through the coupling during the welding process. The modified insert design maintained the tube wall thickness through the entire length of the tube-to-tube connection. This was accomplished by machining the OD of both tube sections to approximately 50% of the wall thickness and machining the insert to match the tube, as seen in Figure 3-20. Three tubes of this design were fabricated and tack-welded together prior to laser welding. The laser end effector was inserted past the insert and a continuous weld was applied from the original tube through the first intersection of the insert and tube.

Five tube-to-tube connections were welded, as seen in Figures 3-21 through 3-24. Welds #5 and #6 (Figure 3-21) were welded with an earlier OD insert design and a modified OD insert. Welds #7, #8, and #9 (Figure 3-22 through 3-24) were welded with modified inserts seen in Figure 3-20. The length of the welds on the modified OD inserts were limited due to the distortion caused by the tack welds prior to laser welding and the overall length of the tube-to-tube connection. The weld specimens were metallographically evaluated to determine the trends in penetration (Table 3-9). The penetration of welds #8 and #9 was approximately 0.025-inches, which matches the thickness of the insert thickness. The results indicate that the insert length and thickness need to be modified to consistently achieve penetration through the insert material into the tube material.

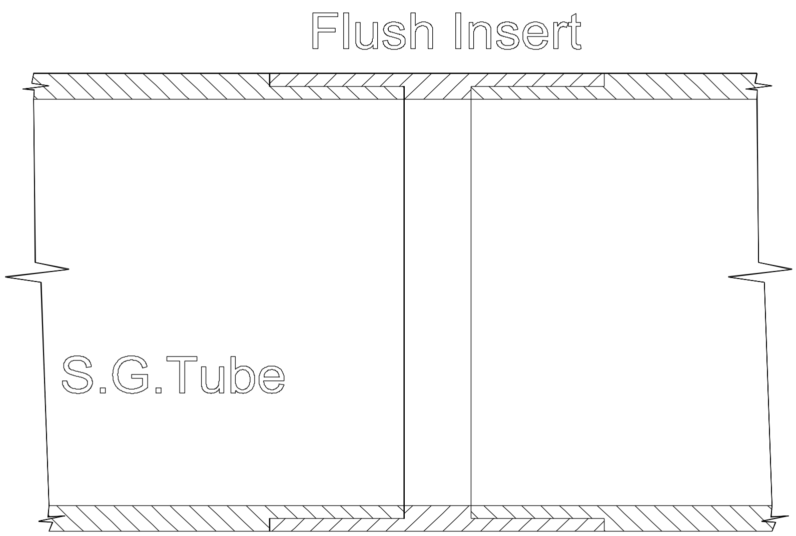


Figure 3-20
Modified Weld Metal Insert

Figure 3-21
Internal Weld Trials On Tube #5 (Top) And #6 (Bottom)

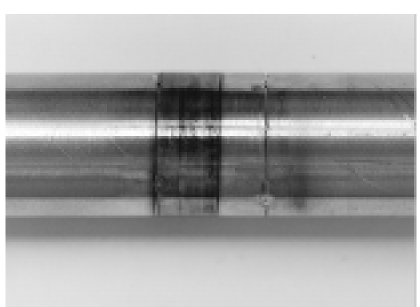


Figure 3-22
Internal Weld Trials with Modified Insert - Tube #7

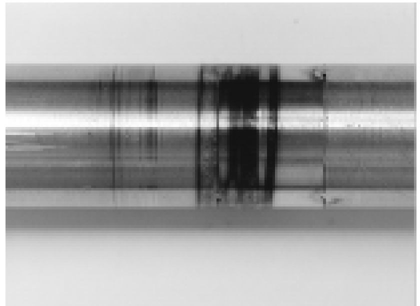


Figure 3-23
Internal Weld Trials with Modified Insert - Tube #8

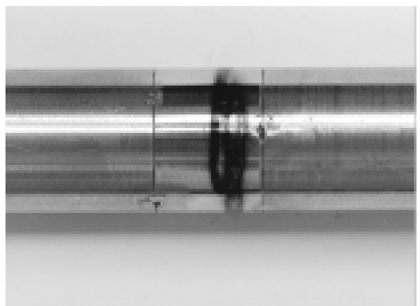


Figure 3-24
Internal Weld Trials with Modified Insert - Tube #9

Table 3-9
ID Welding of Weld Metal Inserts

Weld #	Linear	Rotational	Laser Power	Penetration	Pictures
	(ipm)	(rpm)	(watts)	(in.)	(Figures)
5	.5	20	950	.020	3-21
6	.5	20	800	.020	3-21
7	.5	20	1150	.017	3-22
8	.4	20	1150	.025	3-23
9	.4	20	1150	.025	3-29

Met. Lab #01790 ID weld metal insert material: Alloy 625 insert - Tube #6, #7, #8, and #9 and Type 303 S.S. - Tube #5.

3.3 Weld Metal Insert Development

The initial weld tests (Section 3.1 and 3.2) indicated that additional insert ring design development might be worthwhile to enhance alignment for field installation and to improve weldability. The downfalls of the initial designs were the overall length and thickness, which required long weld times and higher laser power. The higher heat input resulted in distortion of the tube-to-tube connection during the welding, which interrupted or produced inconsistent manipulation of the weld head during the welding process. To address these concerns, two adjustments were considered: 1) a shorter overall length of the insert, 2) pre-welding the insert onto the replacement tube.

The shorter insert would reduce the contact surface area between the existing SG tube and the replacement tube, and would considerably reduce the welding time and travel distance. The shorter insert would still allow the existing tube to seat inside the replacement tube for adequate positioning (Figure 3-25). This design would also eliminate the need to machine the existing tube inside the SG, although it would not allow the present weld head to pass completely through the weld area. The present design of the weld head would allow the laser beam to be delivered to both sides of the weld area as long as the overall length of the insert did not exceed 0.300-in. This would allow the insert to be completely welded from the accessible side of the replacement tube. To ensure the insert remained in place and was seated firmly to the replacement section of the Alloy 690 tube, the insert could be tacked in place by conventional Gas Tungsten Arc Welding (GTAW) process or laser welded prior to insertion into the SG.

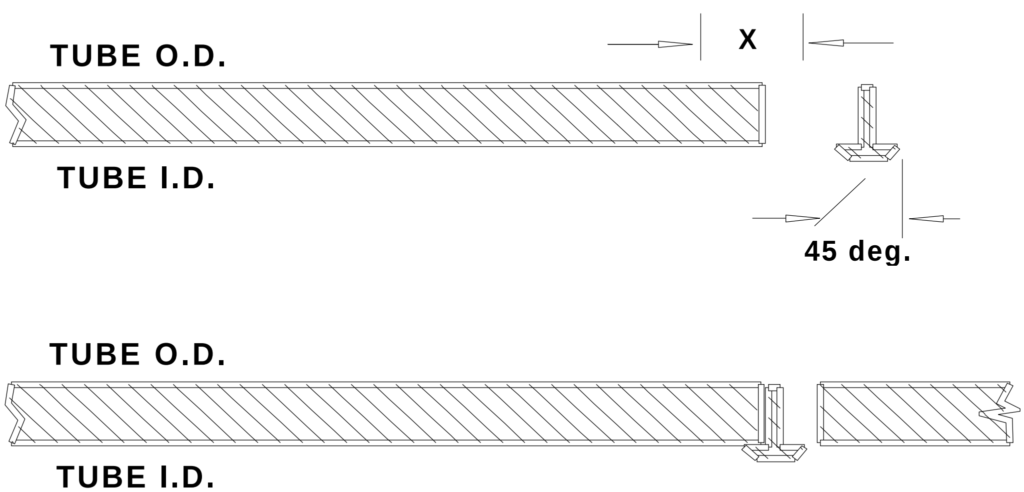


Figure 3-25
Shortened Insert Ring Set-Up Procedure

To further improve on the design of the shortened insert ring, a method of directly applying the weld filler material on the edge of the replacement tube was considered. This process was accomplished by applying a continuous layer of weld metal on the edge of the tube, using a laser powder welding technique. The laser powder build up was accomplished by rotating the tube beneath a focused laser beam while continuously feeding powder (Figure 3-26). The tube was manipulated to assure weld metal was applied to the ID and OD surface as well as to the leading edge of the tube. The next step was to machine the OD surface flush and face off the leading edge. The build up was allowed to remain on the ID surface (dimension h in Figure 3-27). The build up on the face of the tube and on the ID was then machined to match the existing tube.

The final step was to taper the build up to assist in seating the existing tube onto the replacement tube and to improve the ability of the laser to consume the weld metal as seen in Figures 3-28 and 3-29. The powder build up process reduced the amount of welding time and translation distance required per welding sequence. The deposited chemistry can also be readily altered to achieve desired corrosion and strength properties. Figures 3-30 and 3-32 show the basic set-up of the tube-to-tube connection, laser weld head insertion, and the actual welding process.

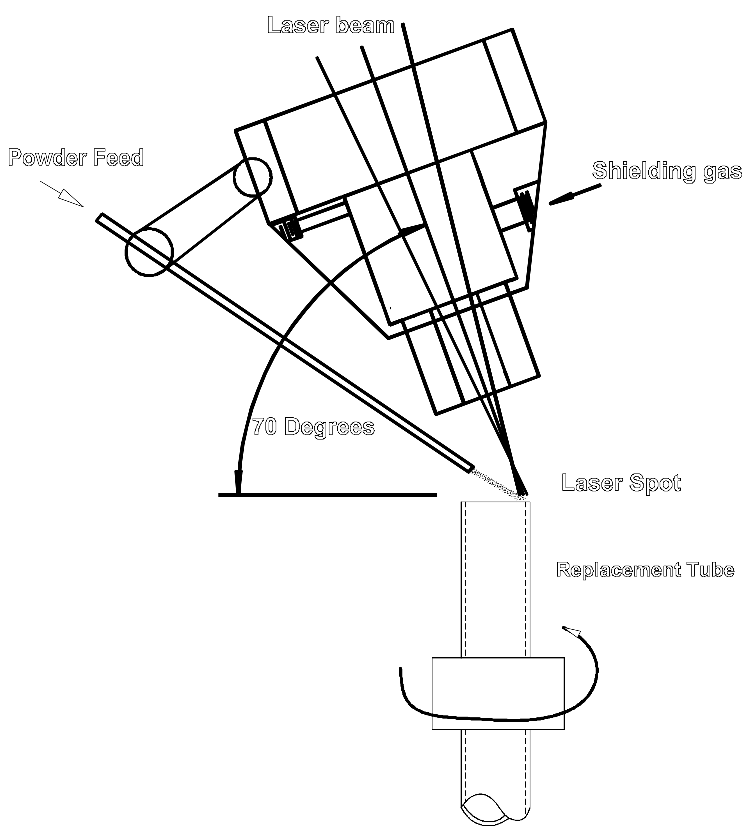


Figure 3-26
Powder/Laser Weld Insert Build Up Process

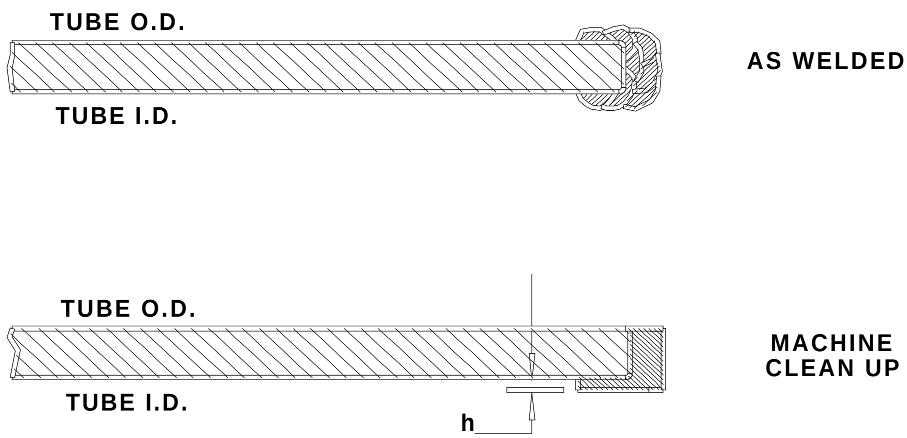


Figure 3-27
Initial Step in Laser Powder Insert Build Up

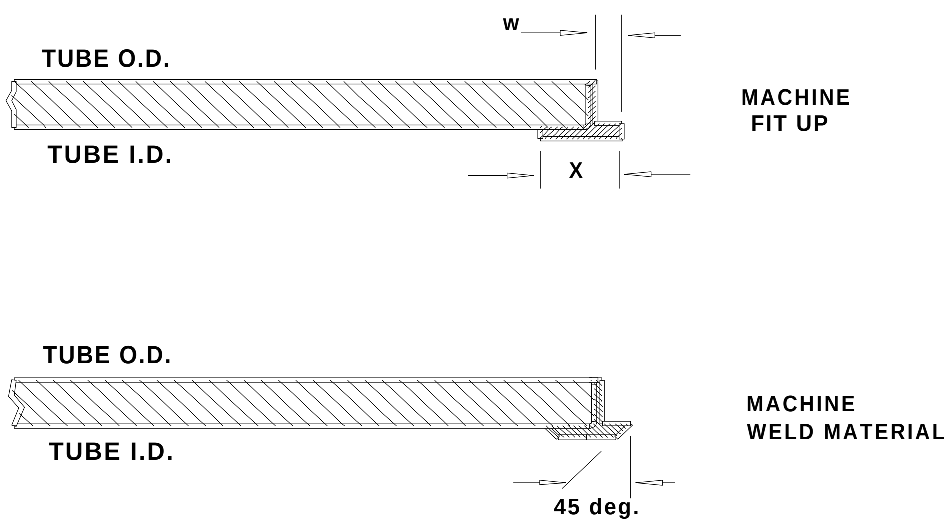


Figure 3-28
Final Step in Laser Powder Insert Build Up

Figure 3-29
Powder Welded Insert

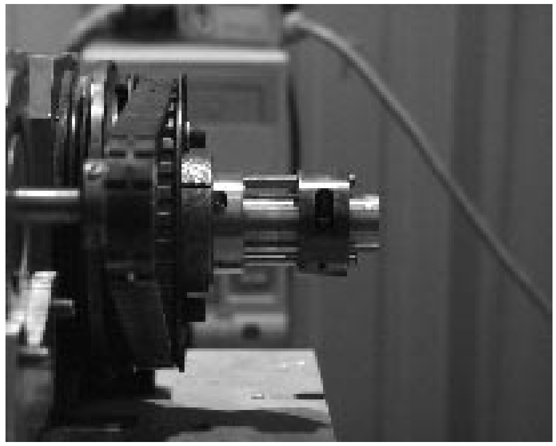


Figure 3-30
Welding Set-Up for Powder Welded Insert Configurations

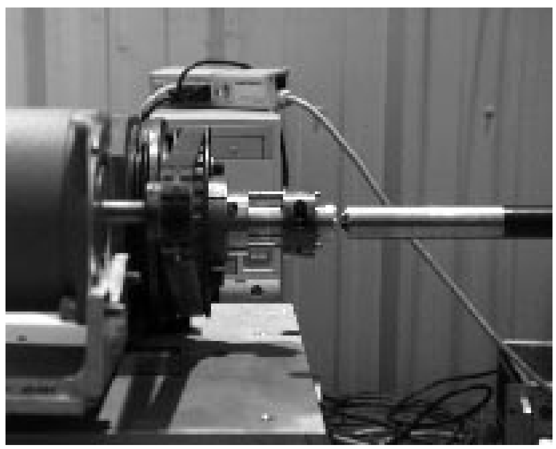


Figure 3-31
Inserting the Weld Head into the Tube-to-Tube Connection

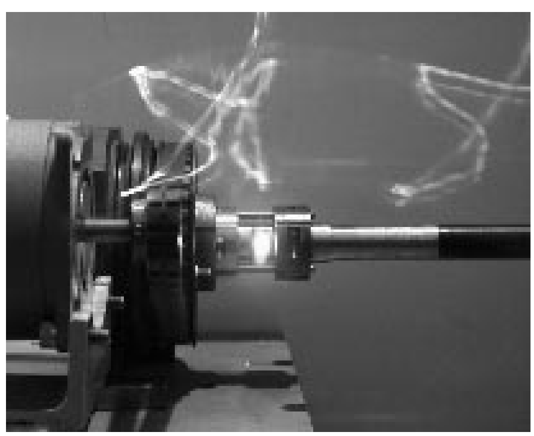


Figure 3-32
Laser Welding Process

4

CONCLUSION AND RECOMMENDATIONS

A laser repair methodology has been developed to address heat exchanger tubes with defects located at the tube-to-tubesheet region. Principal applications of this repair method include repair of steam generator tubing that has significant degradation from stress corrosion cracking or other corrosion damage in the tube-to-tubesheet region. The repair approach consisted of removing the affected portion of the tube and replacing the section of tube with a corrosion-resistant Alloy 690 tube. The new section of tube was attached by laser welding a weld filler metal insert ring designed specifically to assist in aligning and connecting the existing tube to the new section of tubing. The weld metal insert ring consisted of an Alloy 690-compatible material such as Alloy 52 or 72, which has a material chemistry highly resistant to stress corrosion cracking (SCC).

The advantages of the system include the following:

- Restoration of near full-flow performance of the repaired tube
- Installations using a variety of welding or heat treatment probes, allowing for the use of commercially available equipment
- Installation times comparable to those of re-sleeving techniques
- Replacement of existing materials with a corrosion-resistant tube section, which permanently repairs the degraded tube

The repair methodology has been demonstrated on basic tube-to-tube insert connections with both laser end effectors.

To address field installation, future work will need to include additional structural analysis and finalization of the insert ring design. It is anticipated that one of the primary concerns will be the ability of a partially replaced tube to withstand operating pressures. Destructive testing will include burst testing and corrosion testing.

The successful completion of this feasibility analysis has yielded positive feedback from the industry. The RRAC expects to have a full program initiated in the near future to expand on the work done to date.