APAE NO. 123

MASTER

TUBE - TO - TUBESHEET WELDING DEVELOPMENT PROGRAMS FOR 30 MEGAWATT PROTOTYPE SODIUM INTERMEDIATE HEAT EXCHANGER AND STEAM GENERATOR

ALCO

ALCO PRODUCTS, INC.

RESEARCH AND DEVELOPMENT DEPARTMENT

SCHENECTADY, N. Y.

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TUBE-TO-TUBESHEET WELDING DEVELOPMENT PROGRAMS FOR 30 MEGAWATT PROTOTYPE SODIUM INTERMEDIATE HEAT EXCHANGER AND STEAM GENERATOR

Submitted to

UNITED STATES ATOMIC ENERGY COMMISSION
CHICAGO OPERATIONS OFFICE
9800 SOUTH CASS AVE.
ARGONNE, ILLINOIS

Contract No. AT(11-1)-666

ALCO PRODUCTS, INC.
Research and Development
Schenectady, New York

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INTRODUCTION

INTRODUCTION

During 1959, the United States Atomic Energy Commission initiated a program to design and construct an integrated nuclear power facility in which sodium would be utilized as the prime heat transfer fluid. ALCO Products' participation in this sodium components project involved the design and fabrication of an intermediate heat exchanger and steam generator. In order to eliminate the radiation hazard in the steam generator, the intermediate heat exchanger will be employed to transfer heat from radioactive to non-radioactive sodium.

Reliable performance and trouble-free service must be insured for the long time operation of these components. Type 316 stainless steel was, therefore, selected for fabrication of the units, because of its superior high temperature strength properties and excellent resistance to mass transfer by sodium. Since the stainless steel in the steam generator will be subjected to intermittent wetting and drying by steam and water, problems arising from stress corrosion cracking may also result. It is, therefore, essential that all surfaces of the steam generator be protected from intimate contact with the steam phase. This will be accomplished by using Inconel weld overlays on the stainless steel tubesheets and channels, and also by using special Inconel-stainless steel composite tubes.

Since the proposed heat exchanger and steam generator design represents a departure from the conventional, it was necessary to develop special welding procedures prior to releasing the design for fabrication. The program for the development of the required welding procedures was divided into three specific programs: Overlaying Inconel Filler Metal 82 on Type 316 Stainless Steel, Welding Type 316 Stainless Steel Tubes to a Type 316 Stainless Steel Tubesheet and Welding Inconel-Type 316 Stainless Steel Composite Tubes to Inconel Weld Overlaid Type 316 Tubesheets.

In order to produce tube-to-tubesheet welded joints of highest possible integrity, it was considered desirable to utilize a fully automatic welding system previously developed by Alco Products, Inc. The initial procedure for the intermediate heat exchanger was designed to employ a first pass without filler metal addition, followed by the inclusion of a preplaced filler metal ring for the second pass. However, with the later development of a cold wire feed system, it became evident that the latter approach was preferable to the use of a ring as the filler metal. Although a satisfactory procedure was developed using the filler ring for the intermediate heat exchanger weld joint design, the final procedures developed for both the intermediate heat exchanger and the steam generator will employ the cold wire feed system. The welding procedure using the filler ring, however, is included as a part of this report.

Under normal operating conditions, service temperatures and pressures will impose complex stress patterns on the component parts of the heat exchanger and steam generator. In addition, casualty conditions that must be anticipated, such as reactor scrams, emergency shutdowns, pump failures, etc. may result in drastic thermal transients. The most severe thermal transient specified for design purposes in both units will result in a drop in sodium temperature from 1175°F to 650°F in 14 to 16 seconds. Although this condition may never occur in service, it was stipulated for stress calculations and engineering consideration. In actual operation of these units, this condition will be considerably less drastic. Each unit was designed to withstand a maximum of 25 of these transient cycles. Metal temperature will lag the drop in sodium temperature during the transient, but stresses nevertheless will build up in the metal due to the transient. These stresses are of particular importance at the tube-to-tubesheet welds.

The shock test described in Section 4 of this report was devised to attempt to assimulate the most drastic thermal transient that could occur in both units and to evaluate the effect of the resulting stresses on the Inconel overlay and the tube-to-tubesheet welds.

This is the final report on this contract and is broken down into the four sections for reporting simplicity.

Section 1	Introduction
Section 2	Inconel Weld Overlay on Type 316 Stainless Steel
Section 3	Welding Tube-to-Tubesheet joints for the Intermediate Heat Exchanger and the Steam Generator
Section 4	Thermal Shock Tests

SECTION 2

INCONEL WELD OVERLAY ON TYPE 316 STAINLESS STEEL

INCONEL WELD OVERLAY ON TYPE 316 STAINLESS STEEL

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SECTION 2
INCONEL WELD OVERLAY ON TYPE 316 STAINLESS STEEL

OBJECTIVE

The objective of this phase of the development program was to provide a procedure for automatically depositing an Inconel weld overlay on Type 316 stainless steel. Overlays are required to exhibit satisfactory mechanical and metallurgical properties in the "as-welded" condition and meet chemistry requirements of a nominal Inconel composition specified by Sodium Components Material Specification Na-666-30MW-17.

CONCLUSIONS

1. Type 316 stainless steel overlaid to a thickness of 1/4 inch with two layers of Inconel Filler Metal 82 using the developed inert gas shielded metal-arc process, exhibited acceptable mechanical properties as measured by transverse side and longitudinal face bend tests.

2. Metallographic examination and hardness surveys of Type 316 stainless steel overlaid with Inconel Filler Metal 82 showed normal metallurgical structures with uniform hardness and no cracking indications.

3. The chemical composition of the Inconel 82 overlay on the Type 316 stainless steel exceeded the 65 per cent minimum nickel requirement, and was below the 10 per cent maximum iron content specified per Na-666-30MW-17.

MATERIALS

Inconel overlays were deposited on 2-1/2 inch thick Type 316 stainless steel plate meeting ASTM Specification A240-58T, Type 316.

The chemical composition and ASTM Specification chemical requirements of the base material are listed in Table 2-1.

The welding wire used in this investigation was 1/16 inch diameter Inconel Filler Metal 82, conforming to Na-666-30MW-17 and Specification MIL-E-21562, Type EN87.

The chemical composition of the Inconel Filler Metal 82 wire used in the investigation and the MIL-E-21562 specification requirements are presented in Table 2-1.

Welding grade argon was employed as the shielding gas.

EQUIPMENT

All welding was conducted using a Linde automatic inert gas shielded metal arc welding unit. The welding head, mounted on an OM-48 side beam carriage, was provided with a pendulum type (end-dwell) oscillating attachment.

Power was supplied by a Westinghouse Constant Potential DC Rectifier Model RCP (500-650 amps capacity) and dynamic reactor. Welding current and voltages were automatically recorded on Esterline-Angus strip chart recorders. The welding equipment is shown in Figure 2-1.

DEVELOPMENT PROCEDURE

WELDING

Several 2-1/2 inch thick Type 316 stainless steel plates were surface machined and thoroughly cleaned with acetone to remove oil, dirt and other contaminators. Prior to welding, test plates were fully restrained by tack welding to plates of equal thickness.

Preliminary test plates were preheated to 300°F to provide control of bead width. The interpass temperature was held below 400°F. Interbead spacing was accomplished using a manual feedscrew arrangement. Each bead was cleaned with a stainless steel brush prior to depositing the adjacent bead to assure sound fusion at bead overlay areas. Welding conditions are given in Table 2-2A.

Test overlays were also deposited on Type 316 stainless steel plate which had the preheat reduced to 70°F prior to welding. Furthermore, the maximum interpass temperature was not allowed to rise above 350°F. These modifications were evaluated to provide conditions more suitable to production application. The final overlay test plate was made under these conditions of preheat and using the welding schedule shown in Table 2-2B and as detailed in Appendix 2-A.

TESTING PROCEDURE

The mechanical properties of the Inconel Filler Metal 82 overlay on Type 316 stainless steel test plates were evaluated by guided bend tests; the specimen size and manner of testing being in accordance with Section IX of the ASME Boiler and Pressure Vessel Code (1959). Three side bend tests were used for evaluating each of the preliminary test plates. On the final test plate representing the developed procedure, four side bend tests were made.

Chemical analyses were made to evaluate the amount of base metal dilution in the first, as well as successive passes, to be certain that the composition was adequate to meet corrosion resistance requirements. The samples were analyzed for iron, chromium and nickel contents.

On the preliminary test plates, the basic effort was directed toward obtaining minimum base metal dilution consistent with sound fusion of the overlay to the base material, thus chemical analyses were made on the first pass only. On the final weld overlays, samples were taken at 1/16 inch increments from the finished surface to a depth which would be 1/8 inch above the reference surface of the Type 316 stainless steel.

Metallographic examinations were made of representative overlaid test plate sections to evaluate metallurgical structure, soundness and to assure that there were no detrimental conditions present.

Hardness traverses were made across the Inconel Filler Metal 82 overlay and the Type 316 stainless steel base material. A Vickers hardness tester having a five kilogram load was used. Indentations were made at 1/32 inch increments and diamond pyramid hardness numbers obtained were converted to Rockwell A readings using nickel and nickel alloy conversion charts, ASTM E-140-58, Table IV.

RESULTS OF PRELIMINARY OVERLAY TESTS

The ALCO Welding Laboratory had previously developed procedures for automatically depositing Inconel weld metal on carbon steel and Type 304 stainless steel. The preliminary weld overlay tests were therefore conducted using these previously developed procedures as a starting point. Preliminary welding tests conducted are recorded in Table 2-2A.

The preliminary tests were specifically directed toward developing the proper combination of amperage, travel speed, degree of oscillation, and interbead spacing required to produce a suitable overlay. As shown in Table 2-2A, it was found that if the heat input was too low, lack of fusion would occur at the areas where the adjacent beads overlapped. On the other hand, if the heat input was too high, excessive base metal dilution would occur, or that an excessively high iron pick-up would result, as indicated in test 565-3, where the iron content was 16.30 per cent. Regardless of this high iron content, the transverse side bend tests were satisfactory, indicating that this iron content was not detrimental to overlay ductility. However, such high dilution would necessitate the deposition of additional weld metal layers to provide sufficient thickness to meet the chemistry requirements.

The best combination of welding conditions to obtain good fusion with the base metal with a minimum amount of dilution was obtained by using the conditions shown in test 565-5, Table 2-2A. This intermediate current range resulted in the first pass having an iron content of 10.96 per cent. The application of succeeding weld passes reduced the iron content to the required level.

Since dilution was not a problem on succeeding overlay passes, the welding conditions were modified to obtain the highest possible deposition rate in order to provide the best manufacturing economy. However, when higher amperage was applied (with the other conditions remaining the same) an irregular overlay surface developed. This irregularity was reduced by modifying the interbead spacing, as shown in tests 565-5, 565-6, and 565-7, Table 2-2A.

At this stage of the investigation, it was considered that preheat may not be essential and in fact may have been the cause for the random defects noted in side bend tests (see Table 2-2A), since Inconel has exhibited some susceptibility to hot tearing. A test overlay (565-8) was deposited with the test plate preheat level reduced to 70°F and restricting the maximum interpass temperature to 350°F. No observable defects were noted in three transverse side bend test samples.

The final test overlay (565-9), using Inconel Filler Metal 82 deposited on 2-1/2 inch thick Type 316 stainless steel plate, was made using the conditions given in Table 2-2B and as detailed in Appendix 2-A. Two weld passes were required to provide sufficient overlay thickness to assure satisfactory chemistry at the machined overlay surface. Testing of the final overlay is detailed in the following section.

EVALUATION OF THE FINAL OVERLAID TEST PLATE

METALLOGRAPHIC EXAMINATION

The typical surface appearance of an Inconel Filler Metal 82 overlay on Type 316 stainless steel is shown in Figure 2-2. It will be noted that the bead edge is straight and uniform and makes a low angle of incidence with the plate surface, thus assuring sound fusion of adjacent beads to the previously deposited weld metal.

Five full cross-sections of the final overlay on Type 316 stainless steel were cut from different parts of the test plate for macro inspection. A typical macro-section is illustrated in Figure 2-3. The papillary indications at the bead edges are characteristic of overlays automatically deposited by the inert gas shielded metal-arc process using a pendulum type oscillator. There were no deficiency indications observed at 15X magnification in any of the specimens.

Microscopic examination of representative samples of the overlay on Type 316 stainless steel was conducted at magnifications up to 250X. In no instance were any areas of segregation, micro-fissuring, or other deficiencies observed.

Figure 2-4A shows the Inconel 82-Type 316 stainless steel interface in the as-welded condition. The interface is sound and no undesirable microstructures are apparent in either the overlay or heat affected zone.

Figure 2-4B shows the second pass - first pass interface area. The dendritic grain boundary pattern is less evident in the first pass due to the homogenization effect of the heat due to depositing the second pass of the overlay.

A summary of the hardness survey across an as-welded two pass Inconel Filler Metal 82 overlay and into the base metal is presented below. No localized hardened areas were noted.

HARDNESS SURVEY ACROSS TWO PASS INCONEL FILLER METAL 82 OVERLAY ON TYPE 316 STAINLESS STEEL BASE METAL

Location	DIAMOND PYRAMID NUMBER Variation	DIAMOND PYRAMID NUMBER Average	ROCKWELL "A"* Variation	ROCKWELL "A"* Average
Base Metal	197-203	200	56.5-57.0	56.8
First Pass	204-208	206	57.0-57.5	57.3
Second Pass	197-204	199	56.5-57.0	56.7

* Readings were taken at 1/32 inch intervals with the Vickers Hardness Tester using a 5 kilogram load and 2/3 inch objective. Diamond Pyramid Numbers (DPN) obtained were converted to Rockwell "A" readings using nickel alloy conversion charts (ASTM-E140-58).

GUIDED BEND TESTS

Two longitudinal face bends and four transverse side bends (Test No.565-9) were sectioned from the final as-welded two pass Inconel 82 overlay on Type 316 stainless steel. Before and after bending, all specimens were macroscopically examined at 20X magnification and dye penetrant inspected with a Group I dye as set forth in MIL-I-25135C (ASG) (October 21,1959).

No defects were observed in the six samples indicating satisfactory overlay ductility and weld metal soundness. The bend test specimens are shown in Figure 2-5.

CHEMICAL ANALYSIS

Two successive 1/16 inch deep cuts were made from the final two passes in order to ascertain the chemical composition of the deposited overlay. Both cuts consisted of second pass weld metal and were made to a depth 1/8 inch above the original base metal line. The results of these analyses are presented below.

CHEMICAL ANALYSIS OF FINAL TWO PASS INCONEL FILLER METAL 82 OVERLAY ON TYPE 316 STAINLESS STEEL

	Iron	Chromium	Nickel
Top 1/16 inch	3.00%	20.17%	71.45%
Second 1/16 inch	2.97%	20.00%	71.20%
Na-666-30MW-17	10.0 Max.	Not Specified	65.0 Min.

The chemical composition is well within the requirements per Na-666-30MW-17.

It may be concluded that the welding procedure used to prepare the final evaluation overlaid test plate is completely adaquate for meeting all requirements of Na-666-30MW-17.

TABLE 2-1
CHEMICAL ANALYSIS OF MATERIALS

	WELDING WIRE Inconel Filler Metal 82		BASE PLATE Type 316 Stainless		
	MIL-E-21562 Type EN87	ALCO CHECK	ASTM A240-61T	MILL ANALYSIS	ALCO CHECK
Nickel	67.0 min.	72.58	10/14	13.23	12.92
Iron	3.0*	1.68	Bal.	Bal.	Bal.
Chromium	18/22	19.95	16/18	17.05	17.12
Manganese	2.5/3.5	2.76	2.0*	1.64	1.60
Silicon	0.50*	0.45	1.0*	0.54	0.69
Carbon	0.08*	0.036	0.08*	0.056	0.062/0.068
Sulphur	0.015*	-	0.030*	0.010	-
Phosphorous	-	-	0.045*	0.023	-
Titanium	0.75*	0.38	-	-	-
Columbium & Tantalum	2/3	2.18	-	-	-
Molybdenum	-	-	2/3	2.50	2.47

* Maximum percentages.

TABLE 2-2A

WELDING CONDITIONS AND RESULTS OF PRELIMINARY OVERLAY TESTS OF AUTOMATICALLY DEPOSITED INCONEL 82 WELD METAL ON TYPE 316 STAINLESS STEEL

								Chemistry (%)			Side Bend Results[2] Location of Indications					
Test No.[1]	Pass No.	Amperage	Voltage	Travel Speed	Interbead Spacing (1/32 Inch)	Preheat (°F)	Interpass Temp. (°F Max.)	Fe	Cr	Ni	WM-BM[3]	Inter-pass	Pores	Total	Overlay Thickness (Inch)	Remarks
565-1A	1	240	32	7	21	175	250	7.56	19.04	66.65	3	0	0	3	5/32	Overlay deposited using previously developed Inconel overlay conditions. All defects less than 1/32 inch; appear to be lack of fusion.
565-1B	1	240	32	7	21	175	250	7.56	19.04	66.65						
	2	270	36	8½	30	175	250	3.92	19.40	70.71	2	0	1	3	1/4	
565-3	1	280	35	8	21-27	300	400	16.30	19.35	58.93						Current increased on first pass to eliminate lack of fusion areas. Excessive dilution. 27/32 inch interbead spacing area sound. Interpass defects at overlap. Travel speed too fast.
	2	280	35	8	21-27	300	400	6.88	19.60	68.19	0	2	1	3	9/32	
565-4	1	230	31	7	21	300	400	-	-	-						Lower current and travel speed to minimize dilution, interpass defects.
	2	280	35	7	30	300	400	-	-	-	2	0	0	2	1/4	
565-5	1	255	32	7	27	300	400	10.96	-	63.76						Slight increase in buildup with successive beads due to high current and close interbead spacing on second pass.
	2	295	35	7	30	300	400	8.01	-	66.69	0	0	1	1	7/32	
565-6	1	255	32	7	27	300	400	-	-	-						Excessive interbead spacing on second pass caused occasional "missing" at overlap. Bend tests from sound overlay area.
	2	295	35	7	33	300	400	-	-	-	0	2	0	2	7/32	
565-7	1	255	32	7	27	300	400	-	-	-						Final overlay Procedure - 2 longitudinal face bends free of observable defects. Side bend defects less than 1/16 inch. Chemistry acceptable.
	2	285	34	7	30	300	400	8.42	16.69	67.83	0	3	0	3	11/32	
	3	285	34	7	30	300	400	5.42	18.85	70.71						
565-8	1	255	31	7	27	70	350	-	-	-	0	0	0	0	1/4	No defects observable in three (3) transverse side bends.
	2	280	34	7	30	70	350	-	-	-						

TABLE 2-2B

FINAL OVERLAY TEST FOR PROCEDURE QUALIFICATION

Test No.	Pass No.	Amperage	Voltage	Travel Speed	Interbead Spacing (1/32 Inch)	Preheat (°F)	Interpass Temp. (°F Max.)	Fe	Cr	Ni	WM-BM	Inter-pass	Pores	Total	Overlay Thickness (Inch)	Remarks
565-9	1	255	31	7	27	70	350	3.0	20.17	71.45	0	0	0	0	1/4	No defects in four transverse side bends and two longitudinal face bends. Chemistry acceptable.
	2	285	34	7	30	70	350	2.97	20.00	71.20						

(1) All overlays were 2-pass except 565-1A which was a single pass overlay, and 565-7 which was a three pass overlay.
(2) Three guided side bend tests were made from each overlaid plate.
(3) Weld Metal - Base Metal Interface.

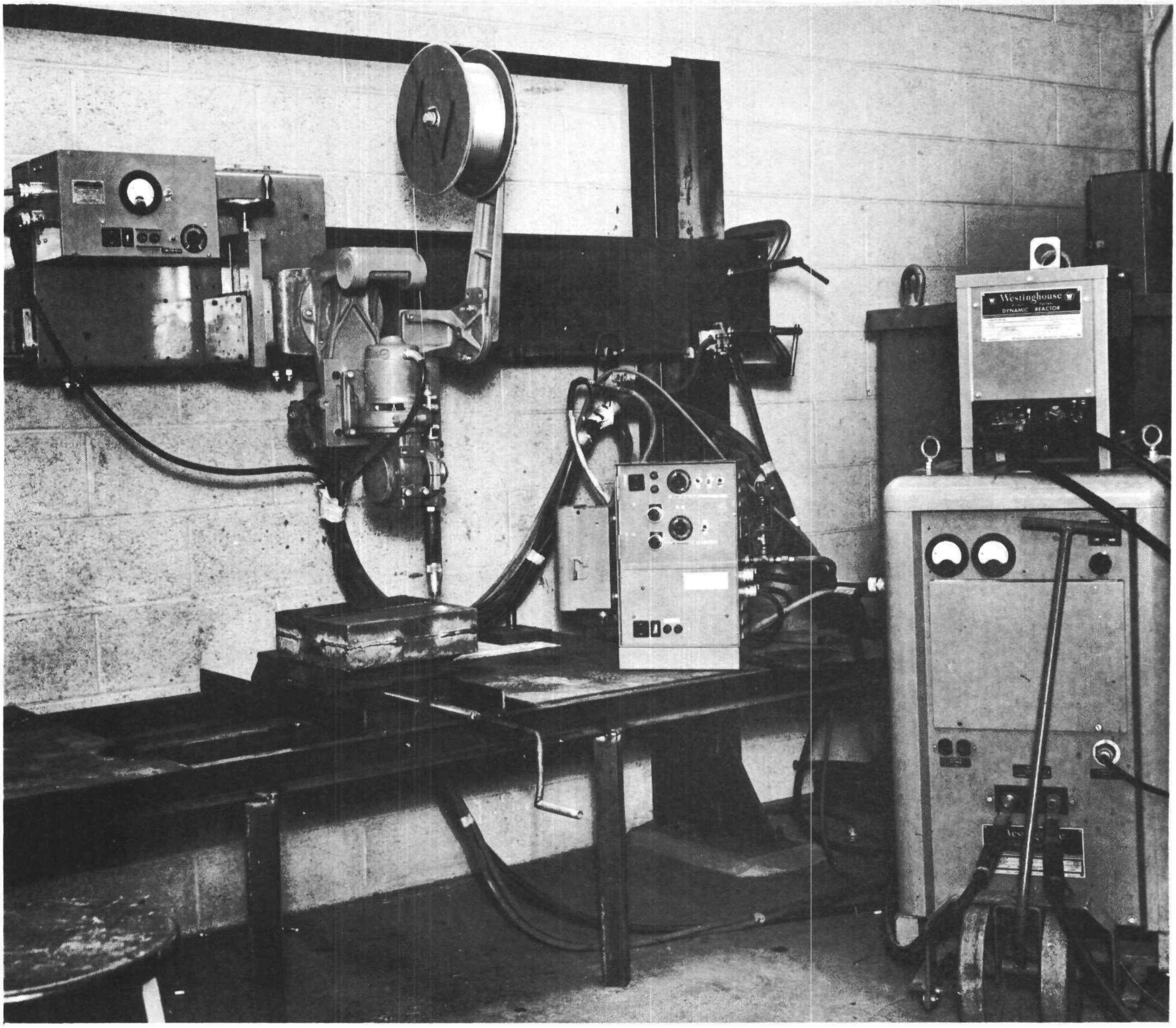
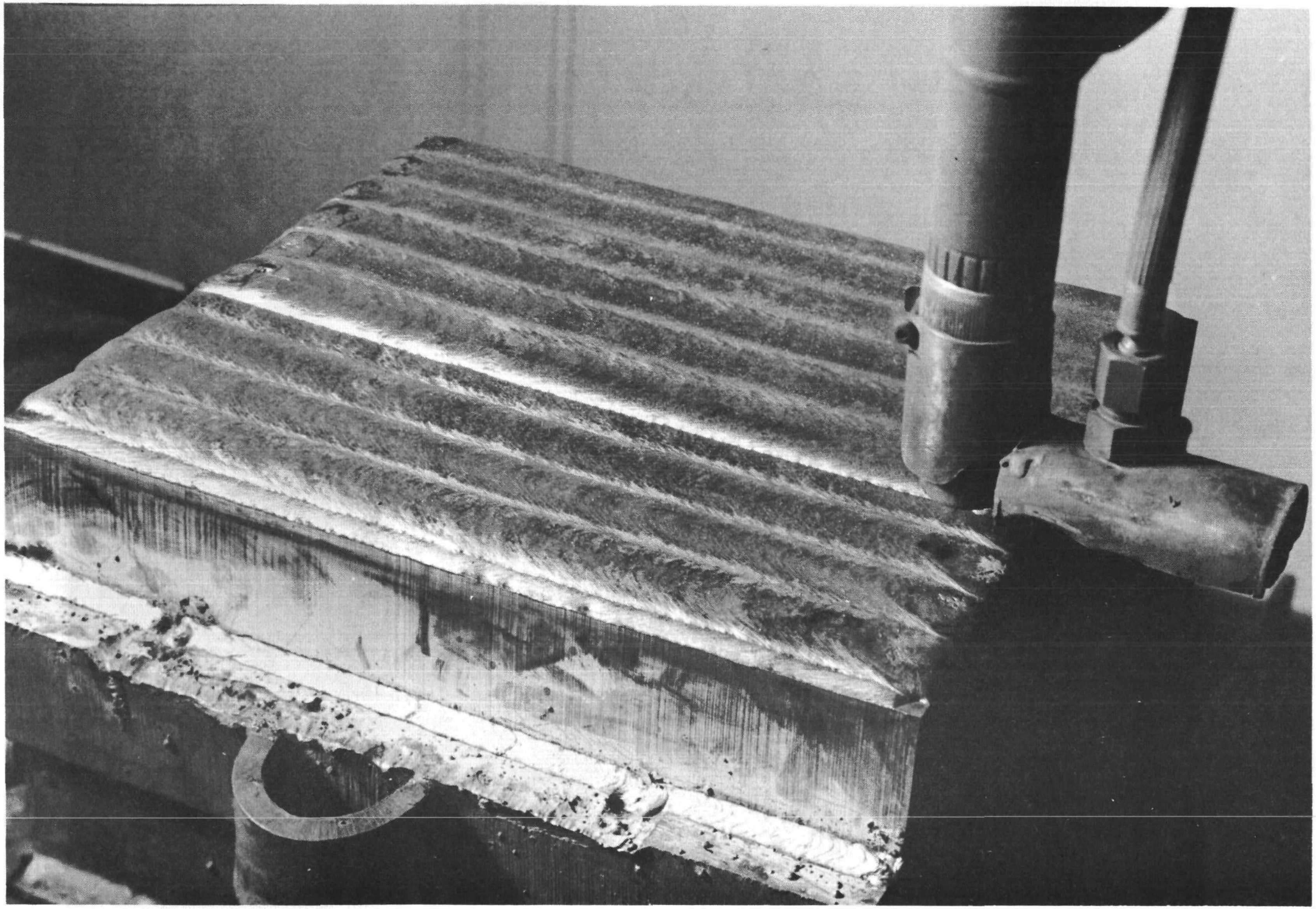


Figure 2-1

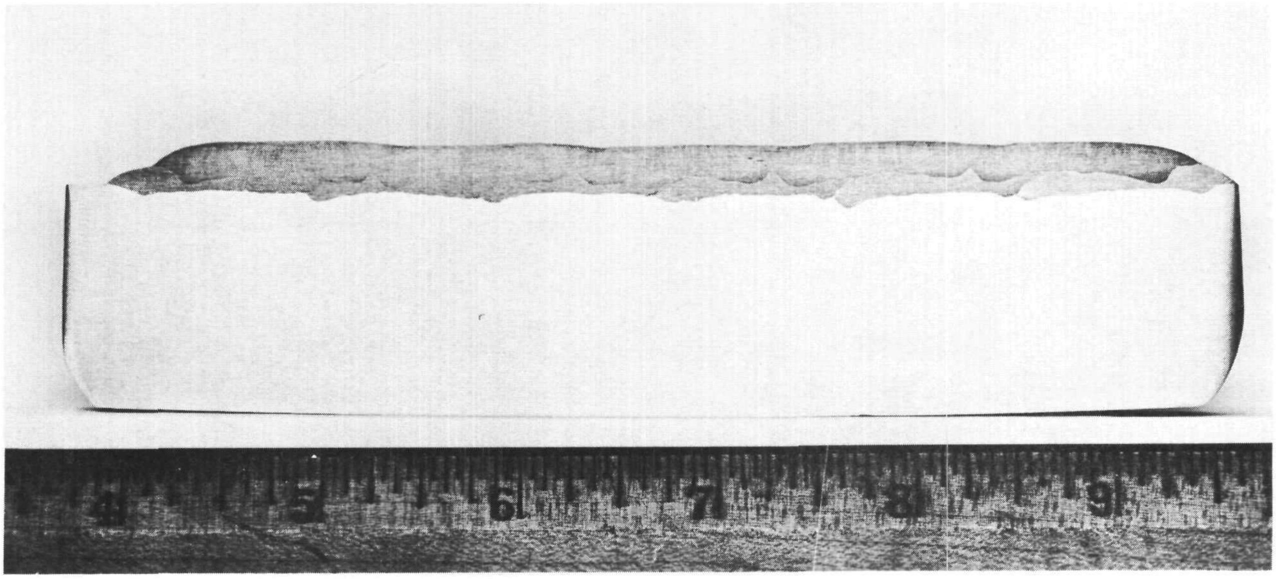
Linde automatic Sigma welding head and controls with Westinghouse Rectifier and Dynamic Reactor power supply used for depositing Inconel Filler Metal 82 overlays on Type 316 stainless steel plate.



1059 1/2X

Figure 2-2

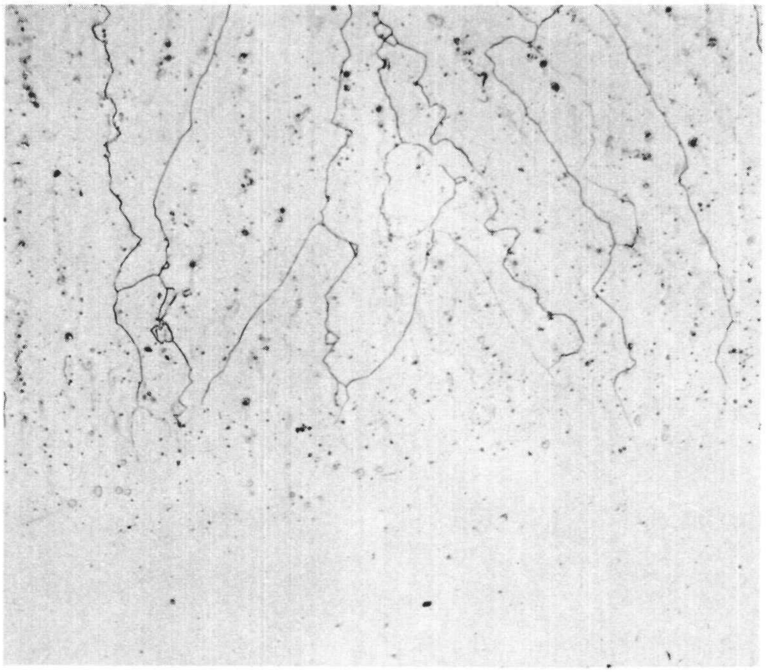
Typical surface appearance of a Type 316 stainless steel plate automatically overlaid with three passes of Inconel Filler Metal 82.



1179-B 1X

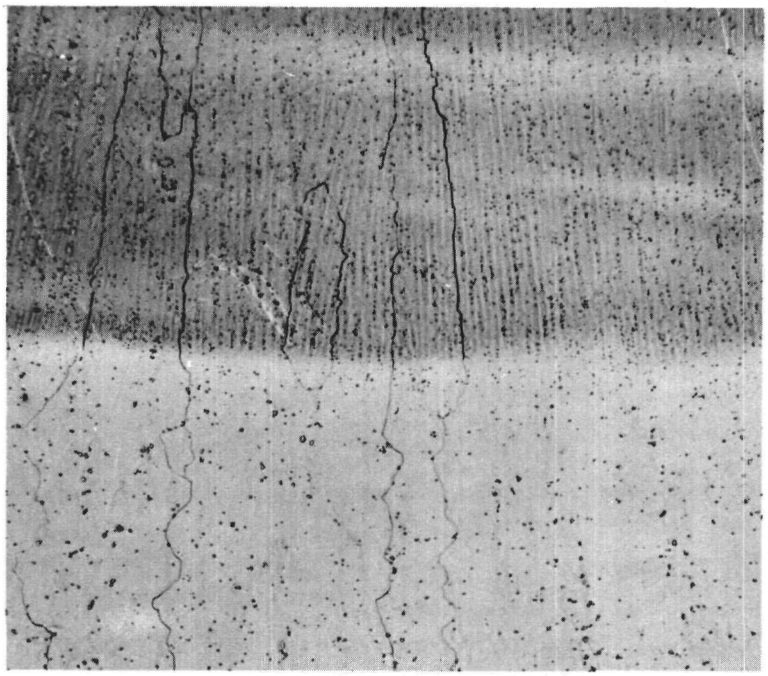
Figure 2-3

Cross section of the test plate of Type 316 stainless steel overlaid with two passes of Inconel Filler Metal 82. Etchant-chromic acid, electrolytic.



13270-A 250X

A) Inconel 82 - Type 316 stainless interface



13270-B1 250X

B) Second pass (Top) - First pass interface

Figure 2-4

Photomicrographs showing the as-welded structure of Type 316 stainless steel automatically overlaid with Inconel Filler Metal 82. Etchant - Chromic acid, electrolytic.

1178-B 7/8X

Figure 2-5

Two longitudinal face bends (Left) and four transverse side bend specimens (Center and Right) of a two pass Inconel 82 overlay on Type 316 stainless steel. No indications are evident.

APPENDIX 2-A

PROCEDURE FOR AUTOMATIC INERT GAS SHIELDED METAL ARC WELDING OF AN INCONEL 82 OVERLAY ON FORGED TYPE 316 STAINLESS STEEL TUBESHEET

MATERIALS:

1. Forging: Na-666-30MW-3 (ASTM A182-59T, F-316 Stainless Steel)

2. Filler Wire: Inconel Filler Metal 82, 1/16" diameter to Na-666-30MW-17 (MIL-E-21562, Type EN87)

PROCEDURE:

1. The base plate shall be machined prior to overlaying to provide a smooth surface and remove all scale. The machined surface shall be thoroughly cleaned of all grease, oil or other contaminators.

2. Prior to welding, the tubesheet shall be preheated to 70^{O} minimum. The maximum interpass temperature shall be 350^{O}F.

3. The overlay shall consist of a minimum of two passes using the automatic inert gas shielded metal arc process (Linde's SIGMA, or equivalent).

4. Each bead shall be power wire brushed to remove any oxide film and/or vaporized metal deposit prior to the deposition of an adjacent bead.

WELDING CONDITIONS:

	First Pass	Second Pass
Current:	DCRP	DCRP
Amperage:	250-260	280-290
Voltage:	32	34
Travel Speed; ipm:	7	7
Shielding Gas:	Welding grade argon	Welding grade Argon
Gas Flow; cfh:	Torch - 50	Torch - 50
	Trailing Shield - 20	Trailing Shield - 20
Contact Tip to Work Distance, inch:	1-11/32	1-11/32
Nozzle to Work Distance; inch:	1/2	1/2
Approximate Arc Length; inch:	3/16 to 1/4	3/16 to 1/4
Oscillation Rate/min:	70	70
Oscillation Width; inch:	7/8	7/8
Interbead Spacing; inch:	27/32	15/16
Bead Width; inch:	1-1/8	1-3/8
Work Position:	Flat	Flat
Torch Position:	Vertical	Vertical
Thickness of Overlay:	-	1/4 inch minimum
Power Supply:	Constant potential rectifier, similar to the Westinghouse, Type RCP.	

INSPECTION:

The overlay should have a shiny, uniform flat surface. Bead edges should be straight with approximately a 30° shoulder with the base plate. Other requirements of Na-666-30MW-17 shall also be met.

REPAIR:

Defective overlay areas shall be removed by milling or grinding. When permissible, repairs shall be made using the same procedure; otherwise, a similar manual inert gas shielded metal arc procedure shall be used.

STRESS RELIEF:

None required.

SECTION 3

WELDING TUBE-TO-TUBESHEET JOINTS FOR THE INTERMEDIATE HEAT EXCHANGER AND STEAM GENERATOR

WELDING TUBE-TO-TUBE SHEET JOINTS FOR THE INTERMEDIATE HEAT EXCHANGER AND STEAM GENERATOR

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SECTION 3
WELDING TUBE-TO-TUBESHEET JOINTS FOR THE INTERMEDIATE HEAT EXCHANGER AND STEAM GENERATOR

This section of the report contains a discussion of the programs and the results obtained from the development of automatic procedures for welding tubes to tubesheet joints for both the intermediate heat exchanger and the steam generator. In pursuing these programs, there was certain equipment and procedures that were common to both. Thus to minimize repetition, this information is presented here for this section of the report.

EQUIPMENT

The equipment used for the development of procedures for attaching tubes to tubesheets for both the intermediate heat exchanger and the steam generator was basically the same.

Tube rolling was accomplished with standard "Airetool" rolling equipment using hardened parallel-type rollers. Tapered rollers were also used to flare the ends of the bimetallic composite tubes for the steam generator joints.

Tube welding was done automatically with an Alco designed and built precision tube welding gun. This equipment incorporates the inert gas shielded tungsten arc welding process. Welding may be accomplished by fusing the component materials directly or by the supplementary addition of a filler material having suitable chemistry and of the proper diameter. A photograph of the Alco welding gun with the cold wire attachment used during this program for welding assimilated tube joints for the intermediate heat exchanger is shown in Figure 3-1. (The specimen shown in the photograph was subsequently welded and used for thermal shock testing reported in Section 4.) The power source and sequence controls for operation of the Alco tube welding gun are shown in Figure 3-2.

For welding the sodium component steam generator, the welding gun required extension of the lower gun barrel and cold wire feed tube to permit accessibility to the tube sheet on the outer tube rows. Accessibility at this location is somewhat restricted by the skirt projection on the periphery of the tubesheet.

ALIGNMENT OF WELDING GUN AND TUBESHEET

For successfully welding tube joints to high quality standards, it is mandatory that a precise and constant arc length be maintained during the welding traverse. This precision becomes more critical as the tube wall thickness decreases. To assure this precision, it is essential that the central axis of the tube gun be accurately aligned with the center of the tube and perpendicular to the tube sheet. The laboratory welding gun is mounted on a pantograph, whereas for production welding, the gun is mounted on a precision slide-bar fixture to achieve this precise alignment. A complete step-by-step procedure for aligning the welding gun with respect to the tubesheet is contained in Appendix 3-A.

PART A
INTERMEDIATE HEAT EXCHANGER

OBJECTIVE

The objective of this portion of the program was to develop a fully automatic welding procedure for producing welded joints of a high integrity between 1/2 inch OD x 0.035 inch, Type 316 welded stainless steel tubing and Type 316 stainless steel forged tubesheets that would meet all provisions of Specification Na-666-30 MW-15, included in Alco Report APAE 112, Volume III, dated June 29, 1962.

CONCLUSIONS

1. A fully automatic procedure has been developed for making two pass fillet welds to join Type 316 welded stainless steel tubes to Type 316 forged stainless steel tubesheets on the intermediate heat exchanger. This procedure is contained in Appendix 3-A of this report.

2. The welds produced, consistently meet the size, quality, leak path and other requirements stipulated in Specification Na-666-30MW-15.

3. Tensile pull-out tests of rolled joints having a root pass weld, as well as full-size two-pass weld joints, showed the joint efficiency to be 100% under both conditions.

4. The importance of cleanliness of the tubes and tubesheets during the assembly, fabrication and inspection sequence and precise alignment of the tube welding gun with the tube joint cannot be overemphasized.

MATERIALS

COMPONENT BASE MATERIALS

Simulated tubesheets were machined from 1-1/8 inch thick hot rolled and annealed stainless steel plates purchased to ASTM Specification A240-61T-TP316, and from 1-1/2 to 3 inch thick Type 316 stainless steel forgings conforming to Specification Na-666-30MW-3. The forgings were from the same heat of material used in production of the intermediate heat exchanger.

The tube material used for conducting welding and qualification tests consisted of tubing 1/2 inch OD x 20 BWG (0.035 inch wall thickness) conforming to Specification Na-666-30MW-2 for Type 316 austenitic welded steel tubing. Tube material was also from the same heat of material used in the intermediate heat exchanger.

Mechanical properties of these base materials are listed in Table 3-1 and their chemical composition are listed in Table 3-2.

WELDING WIRE

Filler metal for the second pass weld was Type 316 Modified (16% Cr - 8% Ni - 2% Mo) 0.020 inch diameter bare wire. No filler metal was used for the first weld pass. The chemical analysis of the wire is shown in Table 3-2.

SHIELDING GAS

Welding grade argon.

DYE PENETRANT

Liquid dye-penetrant inspection of welds was conducted using non-water-washable dye-penetrant of MIL-I-25135C, Group I Specification and in accordance with Specification Na-666-30MW-9.

PREPARATION OF TEST JOINTS

The assimilated tube sheets of Type 316 stainless steel plate were drilled to a diameter nominally 0.012 inch larger than the smallest tube diameter available for these tests. This diameter was used as it represents the nominal tube-to-tube sheet joint tolerance specified for the upper tube sheet on the heat exchanger and is more severe from a rolling and welding procedure standpoint than the 0.008 inch nominal diameter required for the lower tube sheet. The various joint designs used during this development program, shown in Figure 3-3, were machined with tools of the proper geometry subsequent to drilling the tube sheet hole.

Both tubes and tubesheet materials were thoroughly cleaned with acetone prior to assembly to remove oil and other contaminators. Experience has dictated that cleanliness of the tube joint is a fundamental factor contributing to the success of a sound weld.

The test materials were assembled by inserting the tube to project 1/4 inch above the extreme face of the machined projection on the tube sheet surface. The tubes were held in place for rolling by tack welding them to the underside of the tube sheet. This operation is not performed in the fabrication of the exchanger.

Tubes were rolled until firm contact was established with the tube sheet. No lubricant was used during rolling as a precaution against contaminating the joints for welding. The tube rolling operation is another significant factor contributing to successful automatic welding as well as the quality of the weld at the tube joint. A tight joint at the point of welding the tube to the tube sheet minimizes the propensity for cracking in the root pass weld. Subsequent flaring of the tube projection to a 6 degree included angle provides a precision fit at a common center for the tube gun locator and the tube. A concentric traverse of the welding arc and the tube joint interface is then measured to assure it is within the acceptable tolerance limit set at 0.005 inch on the radius.

The tube joints are now ready for welding.

DEVELOPMENT OF WELD JOINT DESIGN

One of the initial steps taken to develop a procedure for automatic fillet welding tubes-to-tube sheets was to establish a suitable joint geometry to accommodate the melting and solidification cycle created by the welding arc to fuse the tube to the tube sheet. For the Type 316 tube and tube sheet materials used in the intermediate heat exchanger, an early basic procedure decision was made to first explore welding the root pass of the tube weld without the addition of supplementary filler metal.

Since the tube wall thickness was 20 gauge (0.035 inch), it was apparent that a small machined projection of the tube sheet surface was necessary to control weld penetration and prevent burning through the tube wall. In addition to absorbing the direct intensity of the welding arc, the projection also provided a source of metal to affect a weld of suitable cross section and contour upon melting and resolidification. The four basic tube joint preparations evaluated by preliminary weld tests are shown in Figure 3-3, along with a statement of the results obtained.

FINALIZING THE ROOT PASS WELDING PROCEDURE

Concurrently with establishing the design of the tube joint, variations were made in the welding conditions to melt and fuse the tube sheet projection with the outer tube surface to obtain a sound fillet weld without burn through of the tube wall.

For these tests, both tube and tubesheet materials were from the same heats to be used in the construction of the heat exchanger. This practice was mandatory to assure that upon melting, mixing and solidification of the component materials, a metallurgically and physically sound root pass fillet weld could be consistently made without external filler metal addition.

The joint design for the final development and consistency tests, as well as that specified for fabrication of the tube-to-tubesheet joints on the intermediate heat exchanger, is given in Appendix 3-A, Figure A, which is essentially the same as given in Figure 3-3.

The adequacy of the root pass fillet welds was evaluated by liquid dye penetrant inspection as well as high magnification of the weld surfaces. All welds were cross sectioned and examined macroscopically to assure there were no cracks, cold shuts, lack of fusion or other deleterious conditions. The size and contour of the root pass was also sufficient to accommodate the subsequent second pass to provide a weld to meet the specified dimensions as well as have a distinct interrupted leak path through the final weld.

The final welding procedure and conditions for making consistently satisfactory root pass fillet welds, as illustrated in Figures 3-4 and 3-5, are given in Table 3-3.

DEPOSITION OF THE SECOND WELD PASS

The established root pass procedure was used to prepare a number of tube-to-tubesheet joints for continuing the program to develop a procedure for automatically applying the second weld pass. This approach also provided the opportunity to further evaluate the consistency of the root pass welds. The weld surfaces were therefore inspected visually to evaluate surface contour, size and general appearance. Liquid dye penetrant inspection was also performed as a further quality measure. No relevant indications or deficiences were observed from these inspections. The tube sheets were then thoroughly cleaned to prevent contaminating the subsequently deposited welds.

Specification Na-666-30MW-15 requires that, "The average leak path through weld metal from the unfused root of all welds be at least 1-1/2 times the minimum tube wall thickness, T, with no weld having a leak path less than 1-1/4 T. The length of the leg of the weld disposed along the tube as measured from the unfused root of all welds shall be an average of 2 T with no leg length less than 1-1/2 T." Other quality conditions stated in the specification must also be met by the two pass fillet welds.

In order to provide a weld of the size required to meet Specification Na-666-30MW-15 as well as provide a distinct interrupted leak path from the point of fusion of the tube and tubesheet components, it was necessary to apply supplementary filler metal. This filler metal, in spooled wire form 0.020 inch diameter, was conveyed to the weld by an automatic feeder incorporated with the Alco automatic tube welding gun shown in Figure 3-1. The filler wire was Type 316 modified with the composition given in Table 3-2.

Numerous second pass welds were made using a variety of welding conditions. In addition to visual and liquid dye penetrant inspections of the weld surfaces, extensive macroscopic and microscopic examinations were made of the completed welds. It is only by destructive examination that the weld size and leak path measurements can be determined and the weld soundness, microstructure and overall quality evaluated. From these tests, the second weld pass conditions given in Table 3-3 were established.

CONSISTENCY TEST EVALUATION

A fifty tube consistency test was made to confirm the adequacy of the entire procedure and equipment for consistently making fillet-welded tube-to-tube sheet joints of a size and quality set forth by Specification Na-666-30MW-15 as being necessary for the intermediate heat exchanger to meet its design and service functions. This test incorporated the final tube joint design, cleaning and rolling procedures, welding procedures, inspections and metallographic examinations to evaluate the weld size and quality, and tensile pullout tests to determine weld joint efficiency.

A photograph of a portion of the fifty tube joint consistency test having a two pass automatically deposited fillet weld is shown in Figure 3-6.

LIQUID DYE PENETRANT TESTS

Dye penetrant inspection of all the first and second pass welds did not show any indications. The inside surface of each tube at the weld location was also subjected to dye penetrant inspection. Although two of the tube walls showed areas of being fused through by the first pass welds, there was no relevant indications present. The quality of the welds, based on this inspection process, were considered entirely satisfactory.

MACROSCOPIC EXAMINATION

All of the fifty tube welds from the consistency test specimen were cut so that one side of the sectioned welded joint would be a half circle section to produce a true weld cross section (two joint faces) for examination. All sections were observed under a stereoscopic microscope to magnifications up to 45X. There were no defects of any nature observed in these welds.

The leak path from the point of fusion of the joint components was measured with a calibrated filar eye piece on the steroscopic microscope for the fifty tube joints (100 sectioned faces). The results of these measurements are given in Table 3-4. The overall average leak path through the weld throat was 1.58T which slightly exceeded the 1.5T average and the 1.25T minimum required by Specification Na-666-30MW-15. The average leak path along vertical leg of the fillet weld, however, was 1.86T which was below the 2T average required by the specification.

Inasmuch as all the other requirements and quality aspects of the consistency test welds met the specification requirements, it was decided that a repeat test in the Alco laboratory was unnecessary and that the procedure and operator qualification tests made at the Alco Dunkirk plant should proceed.

A fifty tube qualification test plate was made at Dunkirk using tubing, tube sheet material, and filler wire from the same heats of material allocated for use in the fabrication of the intermediate heat exchanger. Fabrication of the qualification test plate was performed in accordance with the procedure requirements and conditions set forth in Appendix 3-A, incorporating the details developed during this program. A slight modification was made in the location and rate of introducing the filler metal for the second pass weld to raise the height of the weld on the tube and slightly increase the size.

From the Dunkirk qualification test plate, twenty-nine (29) joints were cross sectioned to provide fifty eight (58) weld joints for macroexamination and leak path measurement. These measurements, given in Table 3-5, show an average weld throat leak path of 1.95T. The vertical weld leak path averaged 3.15T. These measurements substantially exceeded the specification requirements for weld size and interrupted leak path.

Typical cross section of the two pass fillet welded joints are shown in Figures 3-7 and 3-8. Figure 3-8B clearly illustrates a distinct interrupted two pass leak path from the point of fusion of the component tube and tubesheet. The freedom from undercut at both weld toes should also be noted.

METALLOGRAPHIC EXAMINATION

Welded tube joint sections were taken at random from the laboratory consistency test specimen and the Dunkirk procedure and welder qualification test plate. Examinations were made at magnifications up to 500X. There was no evidence of any gross cracking or microcracking in the weld metal or fusion zones. Structure appearance was the typical austenitic dendritic structure shown in Figure 3-8B. It was concluded from these examinations that the weld metal in the root pass, resulting from melting the tube and tubesheet components, would be conducive to crack free welds on the intermediate heat exchanger. The second weld pass resulting from a partial fusion of the root pass weld, base metal components, and controlled composition filler wire was also metallurgically sound.

The complete absence of porosity from all welds examined was also noteworthy.

TENSILE PULL-OUT TESTS

Tensile pull-out tests were made of two (2) tube-to-tubesheet joints having a single root pass fillet weld and two (2) joints of full size having a two pass fillet weld. In addition to contact rolling the tube to the tube sheet prior to welding, the joints were also rolled after welding. The test results are recorded in Table 3-6. All specimens, upon testing, failed in the heat affected zone of the tube or the unaffected tube per se, thus indication a 100% joint efficiency.

RECOMMENDED WELDING PROCEDURE

From the results of this development program, the detailed procedure contained in Appendix 3-A was recommended and used for automatically fillet welding the Type 316 stainless tubes to the Type 316 forged stainless steel tube sheet on the intermediate heat exchanger.

ALTERNATE WELDING PROCEDURE

At the outset of this development program, there appeared to be an abnormally close schedule for developing the fillet welding procedure in order to prevent delay in the fabrication of the intermediate heat exchanger. The cold wire feed attachment for introducing supplementary filler metal to the weld for the second weld pass was still under development on another program and was not considered ready for the program reported herein.

For fillet welding tube-to-tube sheet joints on other nuclear heat exchangers of different materials, Alco had developed an automatic procedure involving the use of a preformed ring placed over the tube. These rings were then melted to provide the desired weld size. This procedure given in Appendix 3-B, although capable of producing welds of satisfactory size and quality, had certain inherent economic and production drawbacks which would inhibit its use unless absolutely necessary.

As a result of a change in the production schedule and earlier availability of the cold wire feed attachment for the Alco gun, it was possible to develop and use the procedure in Appendix 3-A for welding the intermediate heat exchanger rather than the alternate procedure involving the preplaced rings given in Appendix 3-B.

PART B
STEAM GENERATOR

OBJECTIVE

The objective of this portion of the program was to develop a fully automatic welding procedure for producing joints of high integrity between composite Inconel - Type 316 stainless steel tubes 1/2 inch OD x 0.105 inch and Inconel overlaid Type 316 stainless steel forged tube sheets that would meet all the provisions of Specification Na-666-30MW-16, included in Alco Report APAE 112, Volume III, dated June 29, 1962.

CONCLUSIONS

1. A fully automatic welding procedure has been developed for making fifteen pass fillet welds to join Inconel - Type 316 stainless steel bimetallic tubes to an Inconel weld overlayed Type 316 stainless steel tubesheet on the steam generator. This procedure is contained in Appendix 3-C of this report.

2. The welds produced, consistently met or exceeded the size, quality, leak path and other requirements stipulated in Specification Na-666-30MW-16.

3. Cleanliness of the component tubes and tubesheets during the assembly, fabrication and inspection sequence is mandatory. Precise alignment of the tube welding gun and adherence to the welding procedure sequence is essential to provide a fillet weld of proper size and having a smooth transition into the tubesheet in order to minimize localized stress concentration.

MATERIALS

COMPONENT BASE MATERIALS

The tubes used for conducting welding and qualification tests consisted of bimetallic tubing 1/2 inch OD x 0.105 inch total wall thickness. Type 316 stainless steel comprised the outer surface while Inconel 0.030 inch thick was metallurgically bonded to the inside of the stainless steel. The bimetallic composite tubes were procured to Specification Na-666-30MW-1. Tube materials used for this program were obtained from several different preliminary preproduction lots. The chemical composition of the lot of tubing used for the final consistency test evaluation is given in Table 3-7.

On the steam generator, the tube sheet will be forged Type 316 stainless steel overlayed with a minimum of 1/4 inch Inconel 82 weld metal. The objective of this phase of the development program is to develop an automatic procedure for welding bimetallic composite tubes to the Inconel weld overlay. Thus the basic materials to which the Inconel 82 overlay was applied was of secondary importance as long as the overlay was of a composition and quality representative of production conditions. The basic materials overlayed for these tests were Type 316 stainless steel plate 1-1/8 inch thick and carbon steel plate 1-1/2 inch thick meeting ASTM Specification A285-57T Grade C.

WELDING WIRE

The welding wire for making tubesheet overlays was 1/16 inch diameter Inconel Filler Metal 82. The chemical analysis of the wire used for this program is shown in Table 3-8.

The welding wire for making fillet welded tube-to-tube sheet joints was 0.030 inch diameter Inconel Filler Metal 82. Table 3-8 shows the chemical analysis of this wire.

SHIELDING GAS

Welding grade argon.

DYE PENETRANT

Liquid dye-penetrant inspection of welds was conducted using non-water-washable dye penetrant of MIL-I-25135 Group I Specification and in accordance with Specification Na-666-30MW-9.

PREPARATION OF TEST JOINTS

The assimilated tube sheets of both Type 316 stainless steel and medium carbon steel used for this program were overlayed with Inconel Filler Metal 82 to provide a finish thickness of 1/4 inch minimum. The overlay was deposited using the procedure discussed in Section 2 of this report and outlined in Appendix 2-A of Section 2. This procedure provided an overlay having a uniform composition independent of the composition of the underlying base material. Thus for expediency, overlayed carbon steel base material was used for the major portion of this phase of the program.

After measuring the diameter of the composite tubes, the tube holes in the assimilated tube sheet were drilled 0.012 inch larger which, in this case, the tube holes were 0.530 inch diameter. This tolerance is representative of that used for the upper tubesheet and is more severe than the 0.008 inch tolerance for the lower tubesheet. The various joint designs used were machined on the overlayed facing after drilling by using machine tools having a properly ground contour. The basic joint designs investigated are shown in Figure 3-9.

After thoroughly cleaning the components with acetone to remove all contaminators, the tubes were fit into the tubesheet holes to provide a projection of 0.410 $\pm$ 0.005 inch above the tubesheet surface. This amount of projection was required to produce a fillet welded tube joint of the size specified in Na-666-30MW-16. The relatively short lengths of tubing were held in place by tack-welding them to the underside of the tubesheet. (This operation would not be done during fabrication of the steam generator). The tubes were rolled snug to the tubesheet hole with the Airetool rolling equipment using hardened parallel rollers. The projected tube ends were further rolled using hardened tapered rollers to provide a six (6) degree included angle flare that extended from the end of the tube to about 1/16 inch below the tubesheet surface. This flaring was necessary to provide intimate contact of the tube to the tubesheet at the point where the fusion or root pass fillet weld is applied to the joint. It also provides a means of accurately accommodating the tapered locator (five degree included angle) of the tube welding gun into the tube to establish precise alignment and positioning of the welding gun with respect to the tube joint. For successful fillet welding tubes-to-tube sheets, it is mandatory that the concentricity of the tube outside diameter and the traverse of the tungsten electrode be held within 0.005 inch.

To facilitate rolling of the relatively heavy-wall bimetallic tubes and minimize galling on the inner Inconel tube surface, a water soluble lubricant was carefully and sparingly applied to the expanding rollers. Upon completion of rolling, the inner tube surface was carefully cleaned with an acetone-damp swab to prevent any contamination upon subsequent welding of the joint.

DEVELOPMENT OF WELD JOINT DESIGN AND ROOT PASS PROCEDURES

The two basic tube joint designs evaluated during this phase of the program for welding bimetallic composite Inconel-Type 316 stainless steel tubing to the Inconel overlayed assimilated tube sheet are shown in Figure 3-9. Since the tube wall was relatively heavy, the problem of burn-through was minimized. The weld size of a 1-1/2 T average (0.146 inch - minimum design value) and a 3T projected length (0.291 inch) required the supplementary addition of filler metal to provide the necessary weld size.

The tube joint design is most important to the initial weld pass for fusing the tube to the tubesheet. For these particular fillet welded joints, metallurgical and stress conditions exist that must be fully evaluated. The metallurgical condition stems from the fact that if an excessive (maximum limit undetermined) amount of the Type 316 stainless steel tube is mixed with the Inconel weld overlay of the tubesheet, a positive cracking tendency exists. Thus minimum penetration of the tube wall and further addition of Inconel Filler Metal 82 to the molten weld puddle, by means of the cold wire feeder on the tube welding gun, keeps the influence of the stainless steel constituents to a minimum. The stress condition is a function of the rigidness of the joint components so that the full stress developed during and after solidification of the weld must be completely withstood by the relatively small weld cross section.

The square type tube joint without any special preparation, as shown in Figure 3-9A, was evaluated first because of its simplicity and economic benefit. Root pass welds, with various amounts of Inconel Filler Metal 82 added, generally, showed cracking especially at the root of the joint interface. It was concluded from these exploratory tests that excessive stress in the small weld during solidification was the predominant factor causing the cracking. Furthermore, the arc action, the addition of filler metal into the square corner and wetting of the tube wall was erratic which contributed to inconsistent weld quality.

To relieve the stress on the root pass weld, the tubesheet surface was machined to provide a small projection with a generous radius as shown in Figure 3-9B. A satisfactory procedure then evolved for making sound, crack-free root pass welds. This procedure is detailed in Appendix 3-C to this Section of the report.

The adequacy of the procedure for consistently making high quality root pass fillet welds was evaluated by a series of welds that were sectioned and examined both macroscopically and microscopically. Fusion between the joint components was satisfactory and the weld metal was sound and free of cracks and other deleterious conditions.

COMPLETION OF THE TUBE JOINT WELDING PROCEDURE

After establishing a satisfactory root pass welding procedure, effort was then directed toward developing the welding conditions and a deposition sequence to most economically and effectively complete the fillet weld. Each weld pass was thoroughly cleaned of surface oxides with a stainless steel wire brush and liquid dye penetrant inspected. No cracking was observed throughout this phase of the program. Some surface defects did occur, however, which were predominantly a result of the arc fouling from the cold wire feed or from a surface irregularity. When such deficiencies occur, regardless of their origin, they must be carefully removed and tapered into the adjacent weld metal before proceeding. Although all welding conditions and mechanical adjustments on the tube welding gun can be defined in terms of numbers and settings, the introduction of the cold wire to the weld puddle cannot be accurately defined but must be located from experience gained by the operator.

In order to provide all surfaces on the tube side of the steam generator with complete coverage of Inconel, the tube joints must be capped with Inconel weld metal to cover the end exposure of the stainless steel portion of the composite tube. Application of the capping pass completed the fillet welding procedure.

To meet the fillet weld size requirement of 1-1/2T (0.146 inch based on the minimum tube wall design thickness of 0.097 inch), it was necessary to relocate the tungsten electrode in the welding gun collet as the traverse required for deposition of the outermost pass was beyond the limits of the cam adjustment. The importance of proper deposition of this outer most pass (toe of the weld) to provide a reasonably smooth transition of the fillet weld into the tube sheet is indicated in Section 4 of this report relating to shock tests of assimilated tube sheets with fillet welded tube joints.

The complete welding procedure required fifteen (15) passes to make fillet welds that would consistently have an average weld size of 1-1/2T (0.146 inch) with the length of the weld along the tube from the point of fusion being at least 3T (0.291 inch) as required by Specification Na-666-30MW-16. The complete procedure details of the welding and other settings and conditions that were finalized for making consistently satisfactory fillet welds is given in Appendix 3-C to this Section.

CONSISTENCY TEST EVALUATION

During the development of the procedure, about one hundred and sixty (160) welded tube joints were sectioned and examined macroscopically and metallographically for soundness, general quality, contour and size. The procedure was then further evaluated by making a fifty (50) tube consistency test evaluation. Although the welds made on this test were of satisfactory quality, the size of the welds was marginal and the tie-in of the weld toe into the tubesheet was too abrupt, thus creating localized stress concentrations. To compensate for this condition, the tungsten electrode was relocated in the welding gun collect to extend its traverse. The initial finalized procedure was slightly modified to apply the additional weld metal required at the toe of the weld.

A final weld consistency check was then made using the procedure given in Appendix 3-C of this section. All weld joints for both the initial fifty (50) tube consistency test and the final sixteen (16) tube consistency check were fully evaluated as subsequently discussed.

LIQUID DYE PENETRANT TESTS

Liquid dye penetrant inspection was applied to all root pass welds and the completed weld joint. The inside of all tubes was visually inspected for burn-through. Since no burn-through occurred, dye penetrant inspection was not applied to the inner tube surfaces at the weld joint location.

The quality of the welds, based on this inspection process, were considered completely satisfactory.

MACROSCOPIC EXAMINATION

The fifty tube welds from the initial consistency test and the sixteen tube welds from the final consistency check were sectioned to provide two true cross-sections for each joint. All sections were examined under a stereoscopic microscope to magnifications up to 45X. With the exception of several welds showing small voids, all welds were sound and free of deleterious defects. The voids observed were within the limits set by Specification Na-666-30MW-16 and were not considered detrimental to the quality of the welded joint nor an indication of a deficient welding procedure. A photomacrograph of representative weld cross-sections is shown in Figure 4-10.

The weld size was determined by measuring the minimum leak path through the weld from the point of fusion of the joint components with a calibrated filar eye piece on the stereoscopic microscope. It has already been mentioned that the average weld size for the initial fifty tube consistency was marginal or slightly undersize. On the sixteen-tube final consistency check, the overall average of the thirty two (32) weld sections measured averaged 1.51T with the minimum size measured being 1.29T. The average leak path along the vertical leg of the fillet weld was 3.19T with a minimum value of 3.00T. The fillet welding procedure was thus considered suitable for producing welds of a size to meet or exceed the requirements of Specification Na-666-30MW-16. Leak path measurements to evaluate weld size are given in Table 3-9.

Prior to fabrication of the steam generator, the welding procedure adequacy and resulting weld joint consistency will again be evaluated from a fifty (50) procedure qualification test made by the fabricator.

METALLOGRAPHIC EXAMINATION

Welded joint sections, taken from the initial fifty-tube consistency and the sixteen-tube consistency check test, were prepared for metallographic examination at magnifications up to 500X. The welds and adjacent fusion zone and heat affected zones of the joint components were sound and free of any deleterious conditions. The capping pass provided adequate overlay of the exposed end of the stainless steel portion of the composite tube, thus assuring full Inconel coverage of the tube sheet portion of the steam generator.

A photomicrograph, showing the weld metal structure at the toe of the fillet weld where it fuses to the Inconel overlay on the tubesheet, is shown in Section 4, Figure 4-10.

RECOMMENDED WELDING PROCEDURE

From the results of this development program, the detailed procedure contained in Appendix 3-C to this Section is recommended for automatically fillet welding the Inconel-Type 316 stainless steel composite tube to an Inconel weld overlayed tube sheet on the steam generator.

TABLE 3-1
MECHANICAL PROPERTIES OF MATERIALS*

Material	Yield Strength psi	Tensile Strength psi	Elongation in 2" Per Cent	Reduction of Area Per Cent	Brinell Hardness
Type 316 - Stainless Plate					
Allegheny Ludlum Steel Corp. Heat #26730-18 1-1/8" Thick	40800	79700	65	70	143
ASTM A240-61T - Type 316 Min. Requirements	30000	75000	40	--	217 max.
Type 316 - Stainless Forging**					
Alco Products, Inc. Heat #701407 2" & 3" Thick	30000	75250	64.5	75.9	--
Na-666-30MW-3 (ASTM A182-61T-F316) Min. Requirements	30000	75000	45	50	--
Type 316 - Stainless Tubing**					
Union Steel Corp. Heat #301252 1/2" OD x 20 BWG	43200 44800	88200 90500	47 49	--	80-82 Rkw. B
Na-666-30MW-2 (ASTM A249-61T - TP 316) Min. Requirements	30000	75000	35	--	90 Rkw. B max.

* Mill test report data.
** Same heat of material to be used for fabrication of the intermediate heat exchanger.

TABLE 3-2
CHEMICAL COMPOSITION OF MATERIALS*

Material	Elements Per Cent							
	C	Mn	P	S	Si	Ni	Cr	Mo
Type 316 Stainless Plate								
Allegheny Ludlum Steel Corp. Heat #26730-18 1-1/8" Thick	0.053	1.60	0.018	0.013	0.43	13.47	17.70	2.33
ASTM A240-61T - Type 316 Requirements**	0.08	2.00	0.045	0.030	1.00	10.-14.0	16-18.0	2-3.0
Type 316 Stainless Forging								
Alco Products, Inc. Heat #701407 2" & 3" Thick	0.058	1.69	0.020	0.015	0.14	12.01	17.90	2.46
NA-666-MW-3 (ASTM A182-61T - F316) Requirements**	0.08	2.00	0.040	0.030	1.00	10-14.0	16-18.0	2-3.0
Type 316 Stainless Tubing								
Union Steel Corp. Heat #301252 1/2" OD x 20 BWG	0.052	1.50	0.023	0.017	0.38	12.42	17.09	2.49
Na-666-30MW-2 (ASTM A249-61T - TP 316) Requirements**	0.08	2.00	0.040	0.030	0.75	11-14.0	16-18.0	2-3.0
Type 316 Modified Wire (16 Cr-8 Ni-2 Mo)								
Champion Rivet Co.* 0.020" dia. bare wire Heat No. 659	0.071	1.57	0.022	0.012	0.19	8.08	15.42	1.62

* Mill test report data.

** Single values shown are maximum percentages.

TABLE 3-3
WELDING CONDITIONS
FUSION ROOT PASS AND COLD WIRE FEED SECOND PASS

WELDING MACHINE CONTROL PANEL

Main Rheostat	-	Maximum
Remote Output Control	-	Remote Position
Soft Start	-	Inoperative
Process	-	Inert-gas Arc-welding
High Frequency	-	Automatic
HF Control	-	Phase Shift 1/4 Intensity 3/4
Range Switch	-	Medium Range
Selector Switch	-	DC Straight Polarity

SEQUENCE TIMER CONTROL PANEL

	Fusion First Pass		Cold-Wire Feed Second Pass	
	Panel	Meter	Panel	Meter
Rheostat "A" Starting Current	6.0	82 amps	6.2	85 amps
Rheostat "B" Welding Current	5.4	75 amps	6.2	85 amps
Rheostat "C" Finishing Current	4.0	30 amps	4.0	30 amps
Timer "A" Seconds	5.3	-	0.5	-
Timer "B" Seconds	5.2	-	5.2	-
Timer "C" Seconds	2.0	-	2.0	-
Speed (5.1 sec./rev.)	Low 54		Low 54	

ALCO TUBE WELDING GUN

	Fusion First Pass	Cold-Wire Feed Second Pass
Electrode Diameter*	0.125"	0.125"
Electrode Collet Angle	5°	5°
Electrode Travel Radius	0.297"	0.312"
Travel Radius Gun Setting	5	10
Tube Hole Radius	0.259"	0.259"
Electrode Projection	0.250"	0.250"
Arc Gap	0.035"	0.045"
Shielding Gas	Welding grade argon	
Shielding Gas Flow Rate	18 cfh	18 cfh
Water Pressure	50 psig	50 psig
Filler Metal	Trepan	16-8-2 wire
Filler Wire Diameter	-	0.020"
Wire Feed Setting	-	6
Rate of Filler Wire Feed	-	36 ipm

* 2% thoriated tungsten electrode with the tip ground to a point on an angle of 45 degrees, and with a 0.030 inch flat along its side opposite the tip.

TABLE 3-4
LEAK PATH MEASUREMENTS OF TWO PASS FILLET WELDS
OBTAINED FROM THE LABORATORY CONSISTENCY TEST*

Tube Number	Parallel With Tube Wall	At Throat	Tube Number	Parallel With Tube Wall	At Throat
55	2.2T	1.5T	80	1.8T	1.6T
	1.9	1.6		2.4	1.9
56	1.6	1.2	81	1.9	1.6
	1.8	1.6		2.0	1.8
57	1.7	1.4	82	2.0	1.7
	2.2	1.5		1.6	1.4
58	2.5	2.0	83	1.9	1.7
	2.6	2.0		1.8	1.5
59	2.2	1.7	84	1.6	1.5
	1.8	1.5		2.0	1.6
60	1.8	1.5	85	1.4	1.4
	1.9	1.6		1.5	1.4
61	1.8	1.6	86	1.6	1.5
	2.0	1.8		2.2	1.7
62	1.7	1.6	87	1.8	1.6
	1.5	1.2		1.9	1.5
63	1.6	1.5	88	1.6	1.5
	1.2	0.8**		2.0	1.7
64	1.7	1.5	89	2.0	1.7
	1.5	1.2		1.9	1.7
65	2.0	1.8	90	3.0	1.8
	0.8	0.7**		2.3	1.8
66	1.8	1.6	91	2.2	1.8
	1.6	1.4		1.7	1.5
67	1.9	1.7	92	1.8	1.6
	1.6	1.4		1.6	1.5
68	2.0	1.7	93	1.6	1.6
	2.2	1.9		2.3	1.9
69	1.9	1.6	94	1.9	1.5
	1.6	1.4		2.4	1.5
70	1.9	1.8	95	1.7	1.5
	2.2	1.7		2.6	1.9
71	1.8	1.7	96	1.2	1.2
	2.0	1.5		2.4	1.8
72	2.3	1.9	97	1.4	1.2
	1.7	1.5		1.6	1.4
73	1.6	1.4	98	1.9	1.7
	2.3	1.7		1.9	1.5
74	1.5	1.2	99	2.0	1.7
	1.8	1.5		1.9	1.6
75	2.0	1.8	100	1.7	1.7
	2.0	1.7		1.9	1.6
76	1.8	1.6	101	1.6	1.5
	2.0	1.9		2.0	1.6
77	1.5	1.2	102	1.7	1.5
	2.2	1.9		1.8	1.7
78	1.6	1.3	103	1.7	1.6
	2.3	1.9		1.7	1.6
79	1.8	1.5	104	1.6	1.5
	2.0	1.5		1.8	1.7

* Leakpaths were measured at two (2) locations per tube, 180 degrees apart. Values are expressed in terms of the actual tube wall thickness (T).

** Unsatisfactory cold wire feed on second pass. On production weld, third pass would be required.

TABLE 3-5
LEAK PATH MEASUREMENTS OF TWO PASS FILLET WELDS OBTAINED FROM DUNKIRK QUALIFICATION TESTS*

Tube Number	Parallel With Tube Wall	At Throat	Tube Number	Parallel With Tube Wall	At Throat
1	3.31T	2.34T	16	3.32T	1.90T
	3.71T	1.85T		2.26T	1.79T
2	2.72T	1.85T	17	2.71T	1.73T
	3.51T	1.90T		2.26T	1.83T
3	2.83T	1.90T	18	3.03T	1.90T
	3.59T	2.05T		1.87T	1.55T
4	2.62T	2.12T	19	2.64T	1.78T
	3.87T	2.06T		2.28T	1.90T
5	2.82T	2.46T	20	2.09T	1.76T
	3.54T	2.68T		2.98T	2.03T
6	4.06T	2.60T	21	3.03T	1.59T
	4.28T	2.18T		2.16T	1.95T
7	3.66T	2.13T	22	3.06T	1.95T
	4.32T	1.99T		2.75T	1.78T
8	4.34T	1.81T	23	1.84T	1.44T
	3.58T	2.16T		3.04T	1.95T
9	3.87T	1.89T	24	2.37T	1.79T
	3.52T	2.04T		2.38T	1.72T
10	3.71T	1.69T	25	2.72T	2.00T
	4.02T	2.12T		2.92T	1.90T
11	3.22T	2.04T	26	2.48T	1.69T
	3.44T	2.46T		2.98T	1.83T
12	3.99T	1.82T	27	2.54T	1.95T
	3.92T	2.21T		3.42T	2.03T
13	4.18T	1.71T	28	1.81T	1.40T
	3.71T	1.99T		3.76T	1.83T
14	3.97T	2.14T	29	2.41T	1.59T
	3.49T	2.25T		2.59T	1.79T
15	4.52T	2.05T			
	3.92T	2.18T			

* Leakpaths were measured at two (2) locations per tube, 180 degrees apart. Values are expressed in terms of the actual tube wall thickness (T).

TABLE 3-6
TENSILE PULL OUT TESTS OF SINGLE AND TWO PASS FILLET WELDS
(TUBES ROLLED AFTER WELDING)

Tube No.	Type Weld	Load to Fracture (Lbs.)	Joint Efficiency*	Location of Fracture
177	Single Pass	4720	100%	HAZ** of Tube
178	Single Pass	4740	100%	Unaffected Tube
179	Two Pass	5000	100%	HAZ of Tube
180	Two Pass	4720	100%	Unaffected Tube

Load to fracture of base metal tubing = 4700#.

$$\text{* Joint Efficiency} = \frac{\text{Load to fracture of welded joint}}{\text{Load to fracture of base metal tubing}}$$

** HAZ = Heat-affected-zone.

TABLE 3-7
CHEMICAL COMPOSITION OF COMPOSITE TUBES
USED FOR FINAL ALCO CONSISTENCY TESTS

Elements	Inconel Ht. No. 85941	316 Stainless Steel Ht. No. 95489
Carbon	0.05%	0.05%
Manganese	0.29	1.66
Iron	7.49	Bal.
Sulphur	0.005	0.005
Phosphorus	0.008	0.020
Silicon	0.18	0.47
Copper	0.010	-
Nickel	76.17	13.34
Chromium	15.56	17.37
Molybdenum	-	2.41

TABLE 3-8

CHEMICAL COMPOSITION OF INCONEL FILLER METAL 82 USED FOR OVERLAYING ASSIMILATED TUBE SHEETS AND WELDING OF COMPOSITE TUBES TO OVERLAY

	Specification MIL-E-21562 Chemical Composition - %	0.030" Diameter Alloy Lot 6224-382	1/16" Diameter Alloy Lot A6270-382
Carbon	0.08 max.	0.01%	0.012%
Manganese	2.50/3.50	2.91	2.84
Iron	3.00 max.	2.07	1.86
Sulphur	0.015 max.	0.002	0.005
Silicon	0.50 max.	0.39	0.43
Copper	0.50 max.	0.01	0.06
Nickel	67.0 min.	71.72	72.82
Titanium	0.75 max.	0.32	0.39
Chromium	18.0/22.0	20.10	18.40
Cobalt	0.10 max.	0.005	0.005
Columbium plus Tantalum	2.00/3.00	2.56	2.64
Tantalum	0.30 max.	Not Reported	Not Reported

TABLE 3-9
LEAK PATH MEASUREMENTS OF FINAL LABORATORY WELD CONSISTENCY CHECK TESTS*

Tube Number	Parallel with Tube Wall	At Throat	Tube Number	Parallel with Tube Wall	At Throat
1	3.00T	1.37T	9	3.28T	1.71T
	3.19	1.62		3.40	1.54
2	3.18	1.51	10	3.01	1.67
	3.44	1.53		3.17	1.55
3	3.23	1.46	11	3.04	1.39
	3.33	1.52		3.08	1.46
4	3.22	1.55	12	3.15	1.45
	3.59	1.67		3.24	1.47
5	3.10	1.50	13	3.06	1.63
	3.33	1.78		3.11	1.29
6	3.15	1.61	14	3.40	1.63
	3.38	1.73		3.00	1.34
7	3.06	1.59	15	3.24	1.50
	3.24	1.57		3.00	1.44
8	3.21	1.67	16	3.07	1.34
	3.00	1.54		3.12	1.36

* Leakpaths were measured at two locations per tube, 180 degrees apart. Values are expressed in terms of the actual tube wall thickness (T) of 0.105 inch.

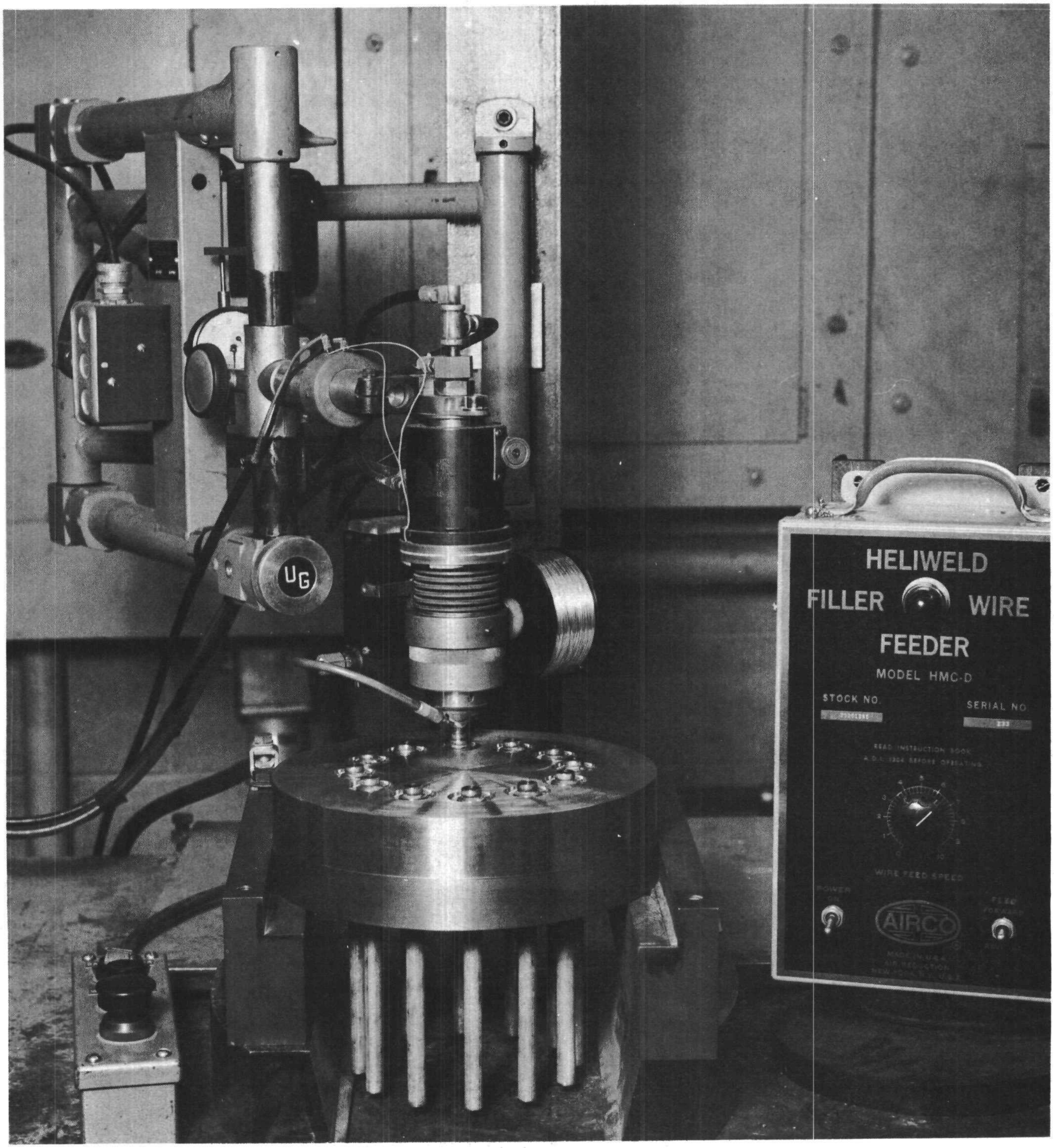


Figure 3-1 1259

Alco Precision Tube Welding Gun with Cold Wire Feed Attachment. (Note Shock Test Specimen)

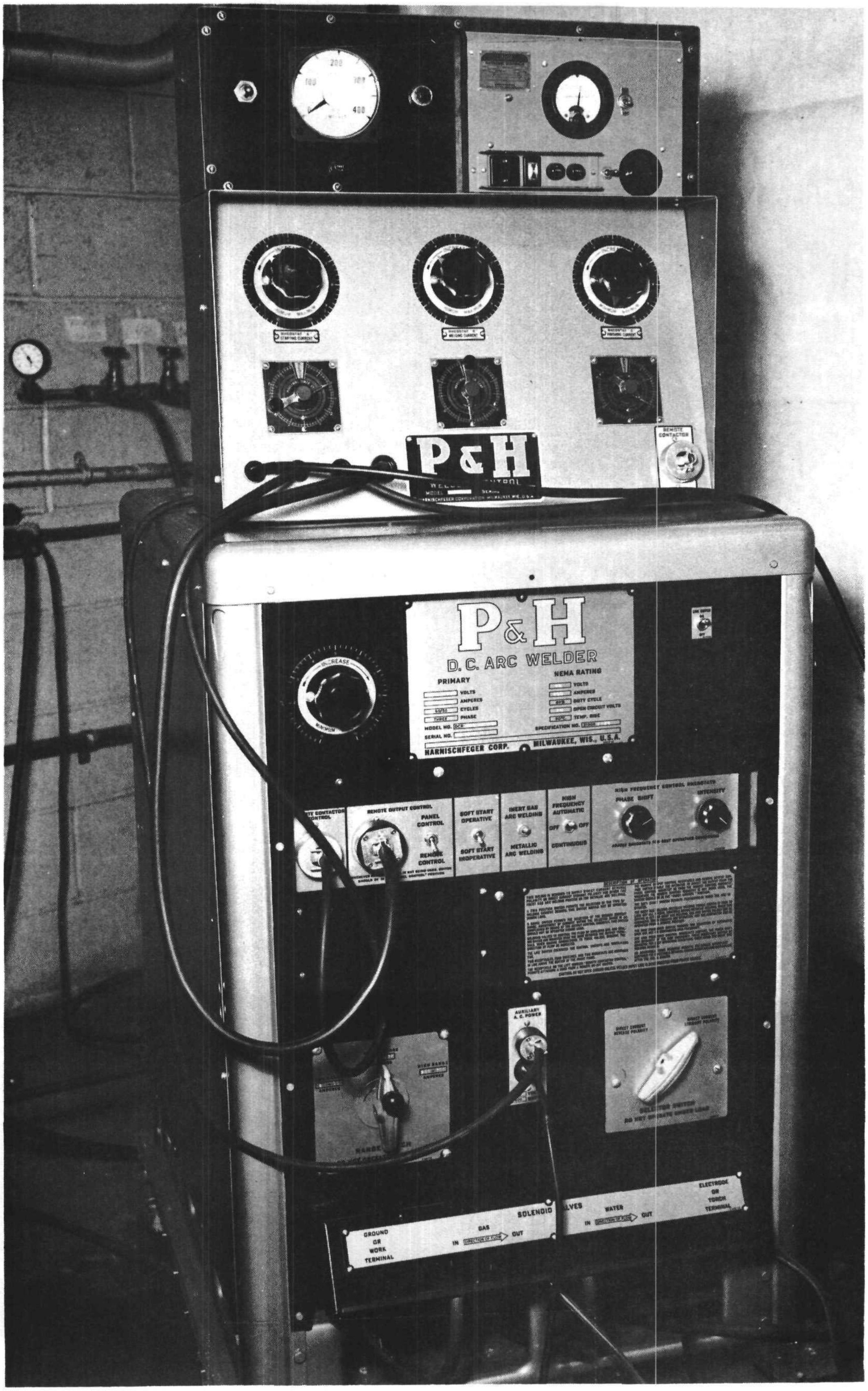
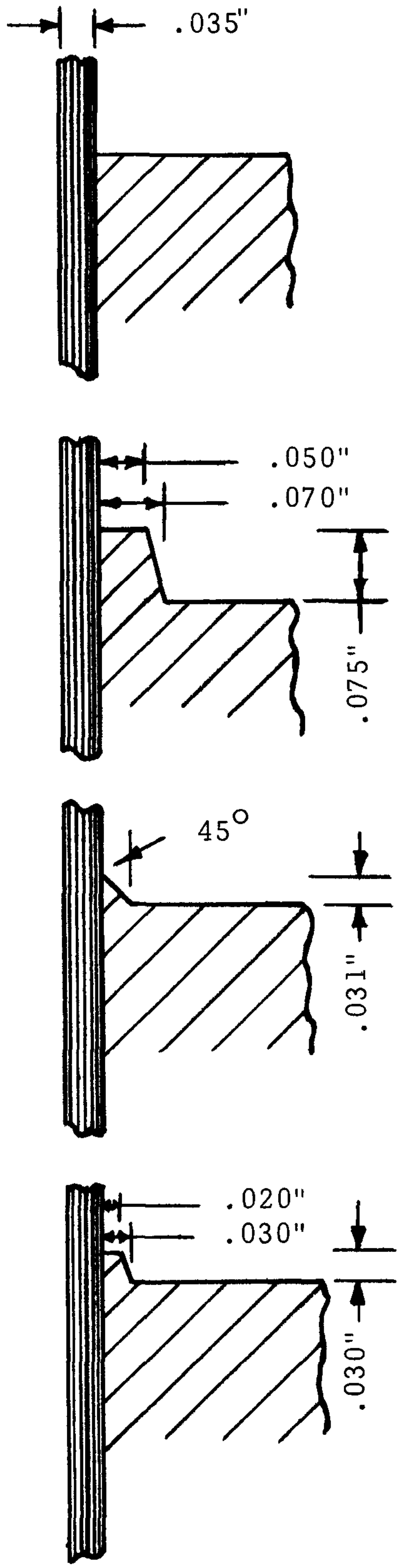


Figure 3-2 1260

Power Source and Sequence Controls for the Alco Tube Welding Gun.



A. Erratic Weld Quality, Poor Wetting Action, Tendency for Burn Through of Tube

B. Projection too Heavy, for Effective Melting and Fusion to Tube

C. Inadequate Projection, Tendency for Burn Through of Tube

D. Results Satisfactory Final Joint Design Used

Figure 3-3

Joint Designs Evaluated for Automatic Fillet Welding Type 316 Tubes to a Type 316 Tubesheet for the Intermediate Heat Exchanger.

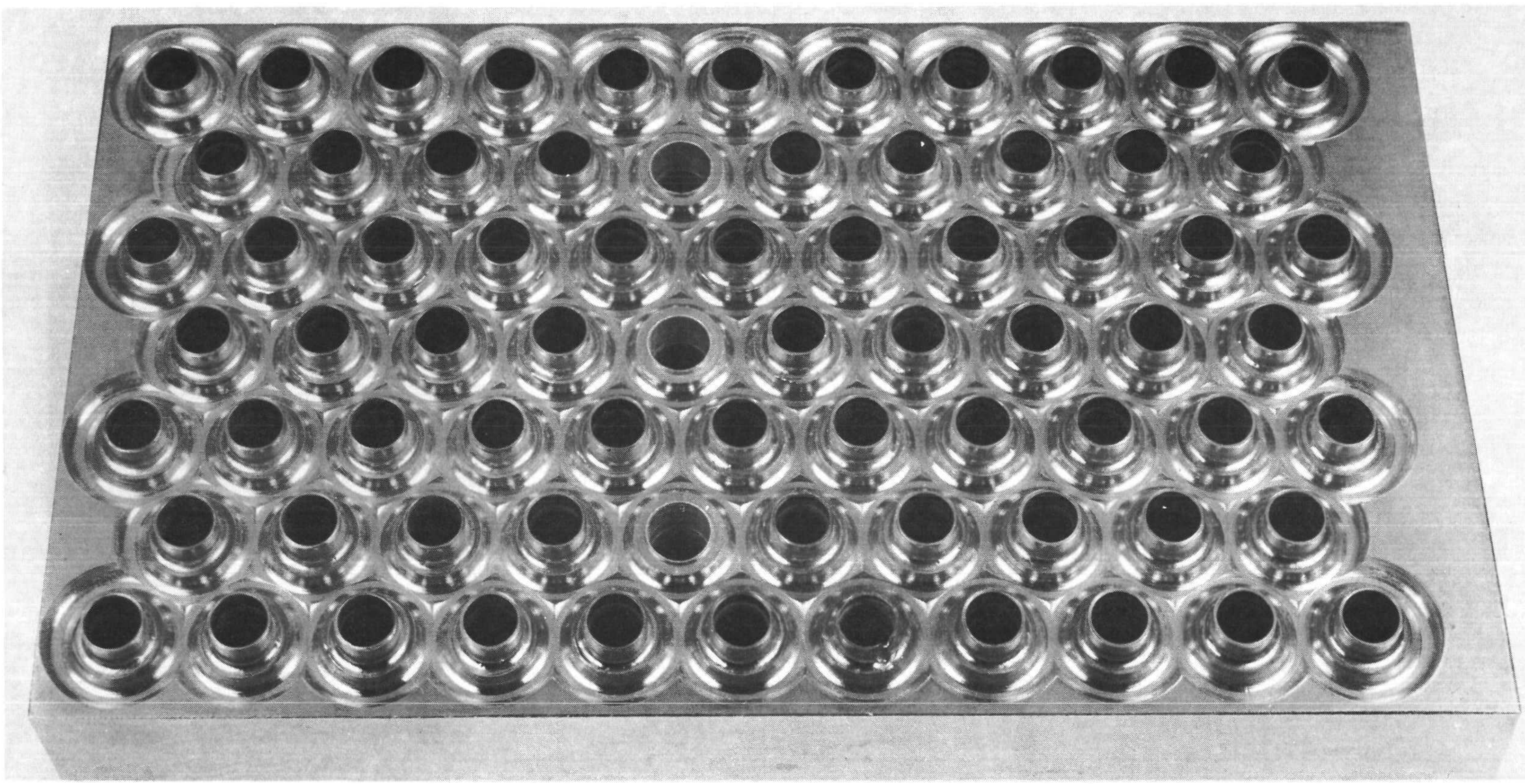


Figure 3-4 1261

Photograph of Assimilated Tubesheet for the Intermediate Heat Exchanger Showing Root Pass Fillet Welds (2/3X).

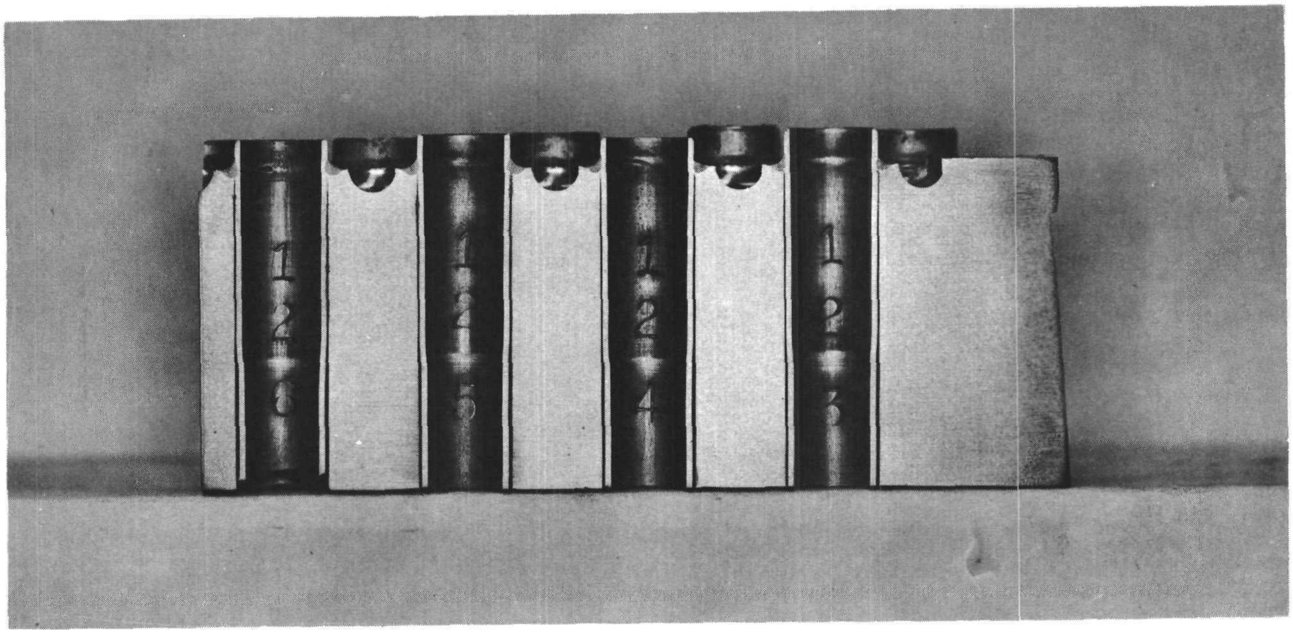
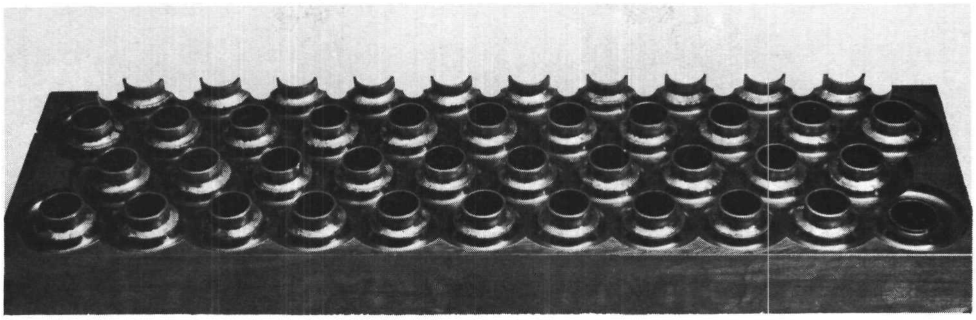


Figure 3-5 1111

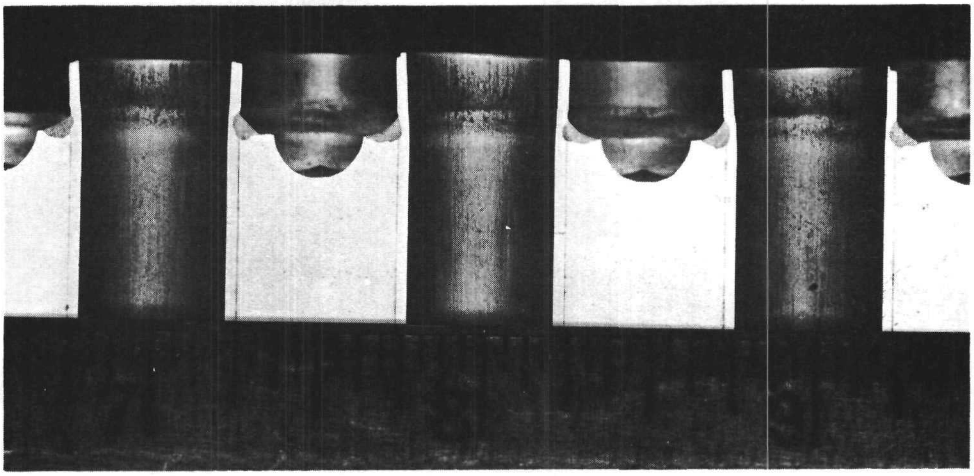
Cross Sections of Root Pass Fillet Welds Cut from the Test Specimen Shown in Figure 3-4 (1X).



1262 2/3X

Figure 3-6

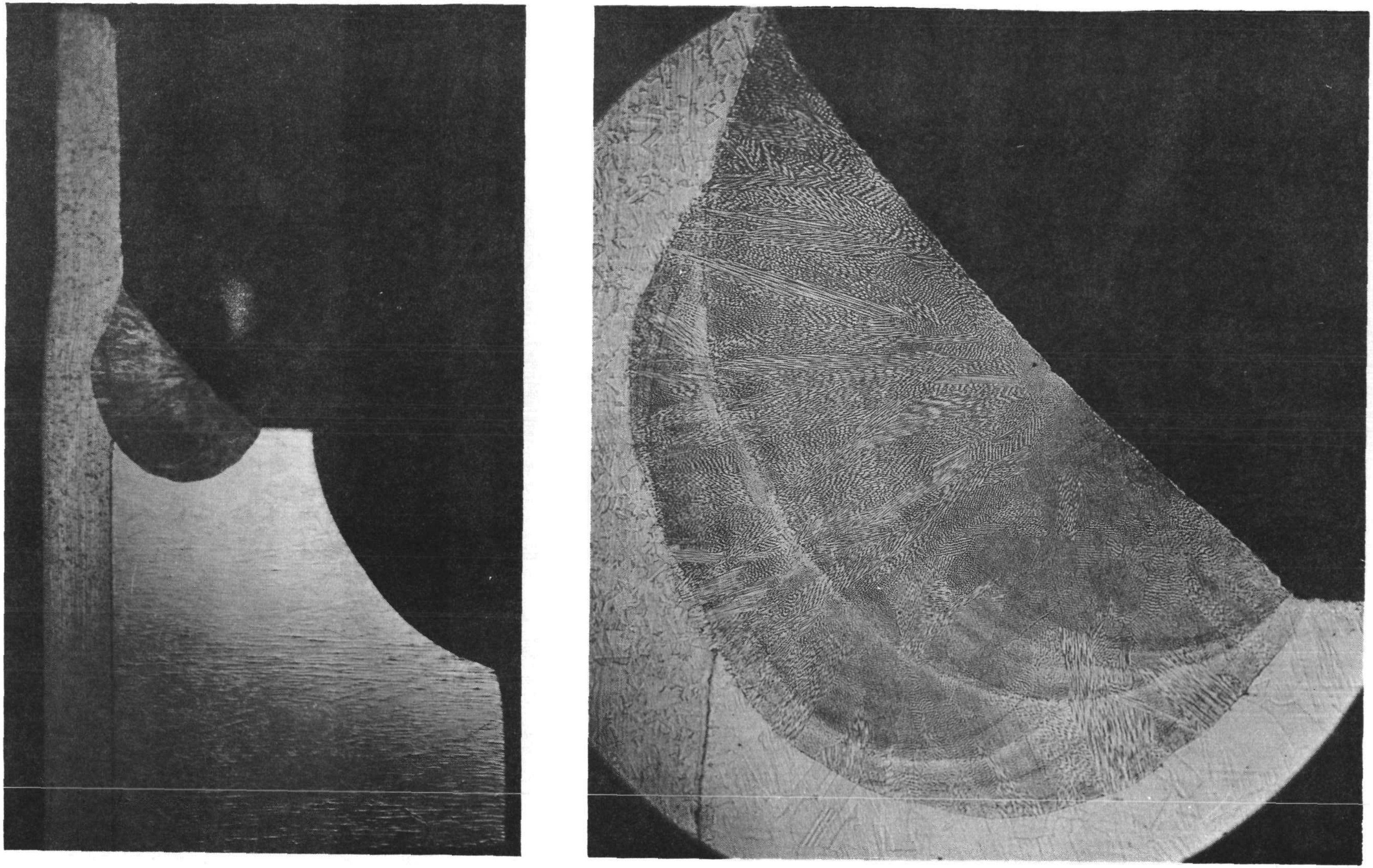
Photograph of a Portion of the Fifty Tube Consistency Test Having Two Pass Automatically Deposited Fillet Welds.



1251B 1-3/4X

Figure 3-7

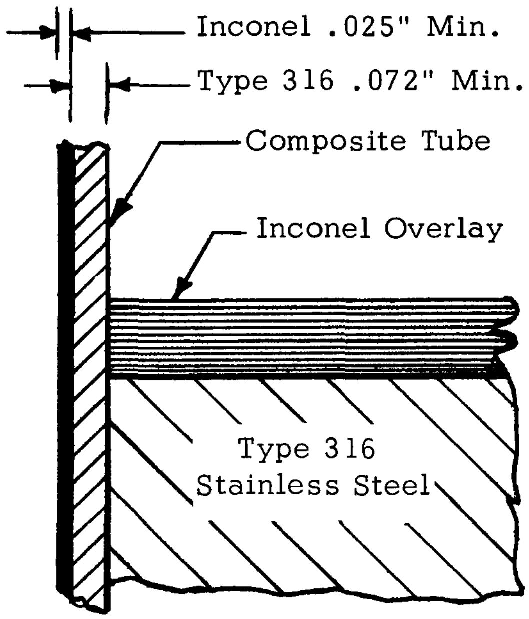
Typical Macrosection of Two Pass Fillet Weld Cut From the Dunkirk Procedure Qualification Test.



1247A A 12X 13355A B 50X

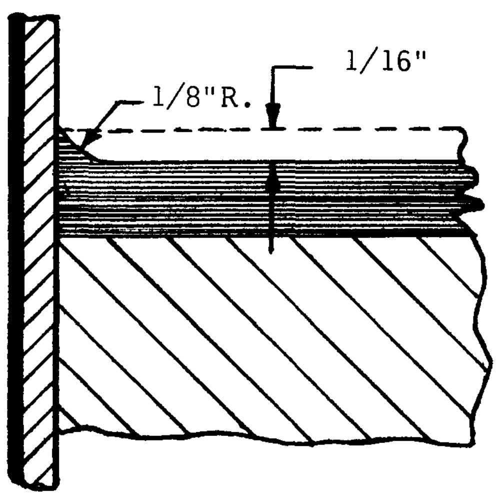
Figure 3-8

Photomacrogrphs of an Automatically Deposited Two Pass Fillet Weld.



Results Unsatisfactory.
Erratic Arc Action,
Poor Metal Flow and
Root Cracking.

A. Square Joint



Results Satisfactory.
Final Joint Design Used.

B. Machined Projection

Figure 3-9

Joint Designs Evaluated for Automatic Fillet Welding Composite Tubes to an Inconel Weld Overlay for the Steam Generator.

APPENDIX 3-A
RECOMMENDED PROCEDURE FOR AUTOMATIC INERT-GAS SHIELDED TUNGSTEN-ARC WELDING TYPE 316 STAINLESS STEEL TUBES TO TYPE 316 STAINLESS STEEL TUBESHEET WITH A COLD-WIRE FED SECOND PASS WELD

MATERIAL

1.	Tubesheet	Type 316 stainless steel forging to Specification Na-666-30MW-3 (ASTM Specification A182-61T-F316)
2.	Tubing	1/2 inch O.D. x 20 BWG Type 316 welded stainless steel to Specification Na-666-30MW-2 (ASTM Specification A249-61T-TP316)
3.	Bare Welding Wire	Type 316 stainless steel modified (16% Cr - 8% Ni - 2% Mo) 0.020 inch diameter wire to Specification Na-666-30MW-15

EQUIPMENT

1. ALCO Tube-welding equipment consisting of:

    a. Tube-welding gun with a tapered locator having a 5 degree included angle.

    b. P&H Model 400A DC rectifier with three stage sequence timer.

    c. Positioning equipment for the welding gun.

    d. "Linde" electronic governor.

2. "Airetool" tube-rolling tool.

3. Tube-flaring tool having an included angle of 6 degrees.

JOINT DESIGN

See Figure A, of this Appendix.

PROCEDURE

1. The tube sheet and the tube-ends in contact with the tube sheet shall be thoroughly cleaned with acetone or a similar solvent prior to welding. Cleanliness of materials shall be maintained to completion of all welding.

2. The tubes shall be inserted through the tube sheet to project 0.250 ± 0.005 inch beyond the extreme surface of the machined projection. Tubes shall then be snug rolled into the tube sheet for a depth of approximately 1-1/2 inches. Tubes shall be rolled dry. Do not use lubricant.

3. After tubes have been rolled into the tubesheet, the tube ends projecting above the face of the tube sheet shall be flared to a six (6) degree included angle to accommodate the locator which has a five (5) degree included angle. Tube ends shall be flared from the tip of the tube projections to the root of the weld joints (approximately 1/4 inch).

4. The tube-to-tube sheet joints shall be welded in the flat position, that is, with the face of the tube sheet lying in the horizontal plane.

5. The tube sheet and tube assembly shall be at ambient temperature for welding (70°F minimum).

6. Tube fillet welding shall be conducted in two interrupted passes by the inert-gas shielded tungsten-arc process using the machined projection for the first pass filler metal, and externally fed bare welding wire for the second pass. Tubes shall be welded in a random pattern to minimize heat buildup in the tube sheet.

7. Welding conditions and machine settings for each pass of the tube sheet welds are listed below. Since these conditions were established for welding on tubesheets having tube holes of 0.518 inch in diameter, proportional compensation will have to be made in the electrode travel radius setting for welding on tubesheets having tube holes of other diameters.

8. The tube welds shall be wire brushed manually with a clean stainless steel brush to remove surface oxides and condensed metal after each completed pass.

9. A precision set-up for mounting the tube-welding gun, and accurate alignment of the gun with the tube sheet during welding are essential and mandatory for successfully welding these tube-to-tubesheet joints. These procedures as outlined were developed using the ALCO Welding gun having an ultragraph positioning arm on a mounting post. Instructions for aligning the ALCO gun with a tubesheet assembly are included with this procedure. These instructions may, or may not, be applicable to production welding, depending upon the fixturing and positioning equipment used.

INSPECTION

1. The tube welds shall be examined visually after wire brushing each completed pass.

2. All welds and the tube inside surface opposite the weld shall be dye-penetrant inspected for evidence of cracks, porosity or other indications considered detrimental to the quality of the joint. Welds shall be examined in this manner after completion of each pass.

3. Other requirements set forth in Specification Na-666-30MW-15 shall be met.

REPAIRS

1. When necessary, defective weld areas shall be removed by machining or cutting with a high speed carbide deburring tool (chipping or mechanical gouging shall not be allowed).

2. Defects, such as incomplete fusion of weld metal with the tube wall, pinhole porosity, and cracks shall be repaired using the same welding procedure as detailed in this Appendix for the given pass. In this instance, the arc shall be established ahead of the defect. Random fuse-through areas on the tube inside diameter shall not be cause for rejection. Consistent fuse through, which is indicative of improper welding conditions is undesirable. Corrective action shall be in accordance with Specification Na-666-30MW-15.

3. Defective welds when impossible to repair with the established procedure shall be repaired by a welding procedure that shall be developed and qualified by the fabricator and approved by the contracting organization.

PROCEDURE FOR FILLET WELDING 1/2" O.D. X 20 BWG TYPE 316 STAINLESS STEEL TUBING TO TYPE 316 STAINLESS STEEL TUBESHEETS UTILIZING A FUSION ROOT PASS AND COLD-WIRE FED SECOND PASS

WELDING MACHINE CONTROL PANEL

Main Rheostat	-	Maximum
Remote Output Control	-	Remote Position
Soft Start	-	Inoperative
Process	-	Inert-gas Arc-welding
High Frequency	-	Automatic
HF Control	-	Phase Shift 1/4
		Intensity 3/4
Range Switch	-	Medium Range
Selector Switch	-	DC Straight Polarity

SEQUENCE TIMER CONTROL PANEL

	First Pass		Cold-Wire Feed Second Pass	
	Panel	Meter	Panel	Meter
Rheostat "A" Starting Current	6.0	82 amps	6.2	85 amps
Rheostat "B" Welding Current	5.4	75 amps	6.2	85 amps
Rheostat "C" Finishing Current	4.0	30 amps	4.0	30 amps
Timer "A" Seconds	5.3	-	0.5	-
Timer "B" Seconds	5.2	-	5.2	-
Timer "C" Seconds	2.0	-	2.0	-
Speed (5.1 sec./rev.)	Low 54		Low 54	

ALCO TUBE WELDING GUN

	First Pass	Cold-Wire Feed Second Pass
Electrode Diameter*	0.125"	0.125"
Electrode Collet Angle	5^{o}	5^{o}
Electrode Travel Radius	0.297"	0.312"
Travel Radius Gun Setting	5	10
Tube Hole Radius	0.259"	0.259"
Electrode Projection	0.250"	0.250"
Arc Gap	0.035"	0.045"
Shielding Gas	Welding grade argon	Welding grade argon
Shielding Gas Flow Rate	18 cfh	18 cfh
Water Pressure	50 psig	50 psig
Filler Metal	Trepan	16-8-2 wire
Filler Wire Diameter	-	0.020"
Wire Feed Setting	-	6
Rate of Filler Wire Feed	-	36 ipm

* 2% thoriated tungsten electrode with the tip ground to a point on an angle of 45 degrees, and with a 0.030 inch flat along its side opposite the tip. Point blunted to 1/64 inch flat.

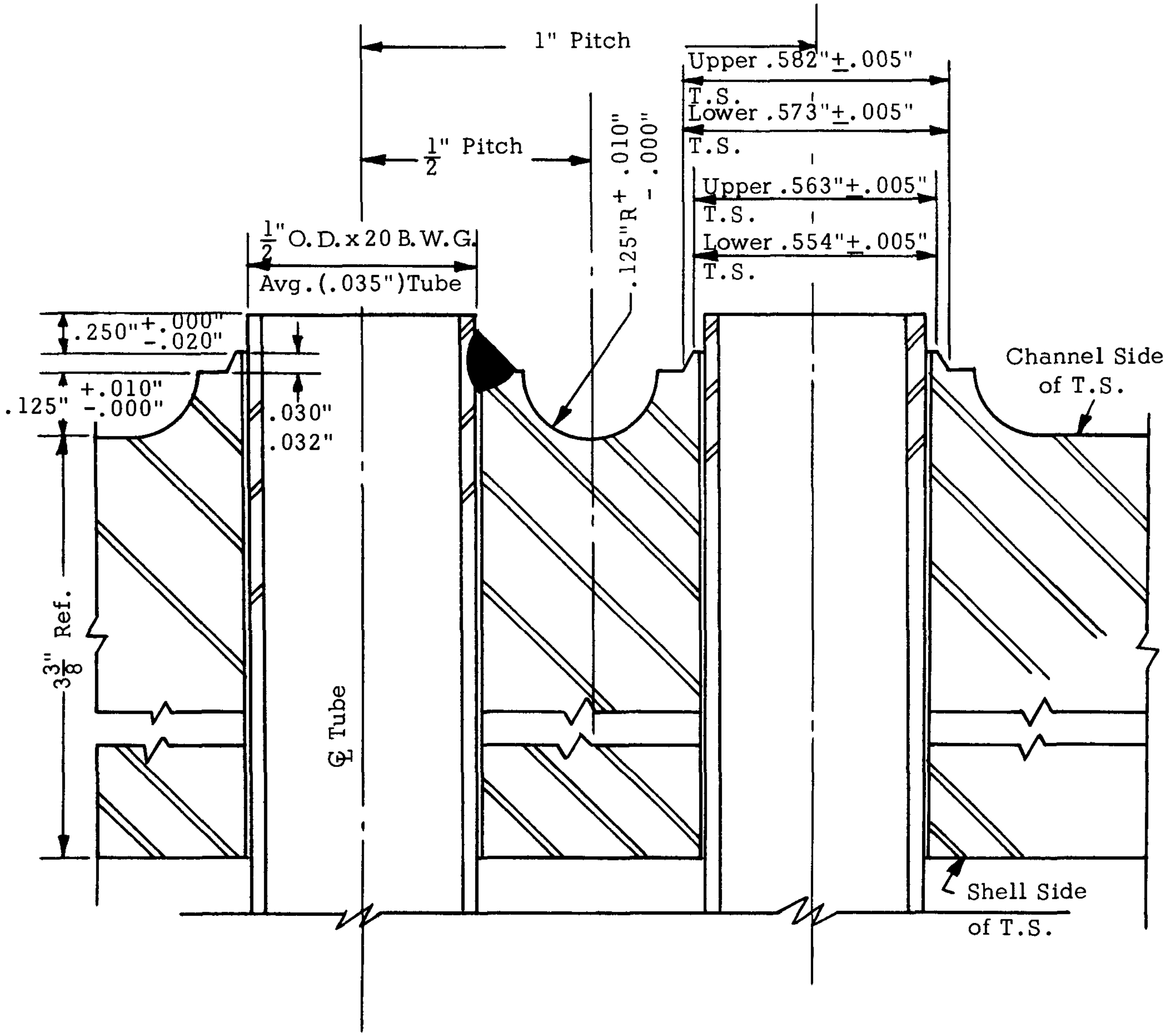


Figure A

Design Detail for Tube-to-Tubesheet Fillet Weld Joints for the 30 M.W. Intermediate Heat Exchanger (Not to Scale)

INSTRUCTIONS FOR ALIGNMENT AND SET-UP OF TUBE WELDING GUN PRIOR TO WELDING

1. Alignment of Tube Welding Gun with Mounting Post

The welding gun must be aligned parallel with the mounting post so that as the mounting post is adjusted perpendicular to the tube sheet to be welded, the welding gun will remain in a proper relative position. Parallelism of the welding gun and mounting post must be maintained during welding. Circular levels are attached to the welding gun and mounting post to obtain correct alignment.

a. Adjust the mounting post to a vertical position with the mounting screws on the base, using the circular level on the mounting post as a guide.

b. Adjust the welding gun to a vertical position with the four-way mounting bracket, using the circular level on the top of the gun as a guide.

2. Alignment of the Welding Gun with the Tube Sheet

Align the welding gun with the tube sheet to be welded by means of the adjusting screws on the base of the mounting post. Position the locator down until it bottoms against the stop and move the gun over the tube sheet surface to check alignment, using the tip of the locator as a guide. The welding gun should be aligned with the tube sheet to be welded within 0.005 inch.

3. Electrode Projection

Projection of the electrode from the shielding gas nozzle must be set at 0.220 inch with the gauge provided, prior to adjusting arc length. The electrode projection must be checked frequently and maintained at the proper length during the welding operation.

4. Arc Length Adjustment

a. Place the locator into a tube to be welded.

b. Move the gun down until the electrode touches the tube sheet.

c. Set the dial indicator to zero.

d. Move the gun up until the desired arc length is obtained.

e. Set the stop on the vertical travel.

NOTE: Extreme care should be exercised in performing step "b". If too much pressure is exerted as the electrode touches the tube sheet, the electrode can be moved within the collet or the positioning arm can be moved upward and an incorrect adjustment will be obtained. After setting the dial indicator to the zero position, repeat step "b" without observing the dial indicator while the adjustment is being made, until at least three consecutive adjustments produce the same results.

APPENDIX 3-B
ALTERNATE PROCEDURE FOR AUTOMATIC INERT GAS SHIELDED TUNGSTEN-ARC WELDING TYPE 316 STAINLESS STEEL TUBES TO TYPE 316 STAINLESS STEEL TUBESHEET USING FILLER-RING SECOND PASS

MATERIAL

1. Tubesheet — Type 316 stainless steel forging to Specification Na-666-30MW-3 (ASTM Specification A182-61T-F316)

2. Tubing — 1/2 inch O.D. x 20 BWG
Type 316 welded stainless steel to Specification Na-666-30MW-2 (ASTM Specification A249-58T)

3. Filler Rings — 5/8 inch O.D. x 18 BWG tubing or wire.
Type 316 welded stainless steel tubing to Specification Na-666-30MW-15. See Figure B, of this Appendix for dimensions.

WELDING EQUIPMENT

ALCO Products, Incorporated tube welding equipment, consisting of:

a. Tube welding gun, having a tapered locating mandrel with expandable sleeve.

b. P&H Model 400A, DC rectifier, with three stage sequence timer.

c. Positioning equipment for tube welding gun.

d. Linde electronic governor.

JOINT DESIGN

See Figure A, of Appendix 3-A.

PROCEDURE

1. The tube ends, filler rings and tube sheet shall be thoroughly cleaned with acetone, or similar solvent, prior to welding.

   Cleanliness shall be maintained until all welding operations are completed.

2. The tubes shall be inserted through the tube sheet to project 0.250 ± 0.005 inch beyond the tube sheet surface. The tubes shall then be rolled snug in the tube sheet to a depth of approximately 1-1/2 inch. Tubes shall be rolled dry. Do not use a lubricant.

3. The machined projection shall then be swaged so as to crimp the projection to the snugged tube to lock the tubes in position prior to welding.

4. After the tubes are securely locked in position, the unit shall be positioned with the tube sheet horizontal.

5. It is mandatory that a precision set-up be used to mount the ALCO gun and maintain accurate alignment of the gun with the tube sheet during welding. These welding procedures were developed using the ALCO welding gun that utilizes an ultragraph positioning arm, mounted post, etc. The instructions for the ALCO gun alignment are included in Appendix 3-A, which may, or may not, be applicable to production welding.

6. No preheat is required; the assembly and mandrel shall be at ambient temperature (70°F minimum).

7. Tube fillet welding shall be conducted in two interrupted passes by the automatic inert gas shielded tungsten-arc welding process using the machined projection for the first pass filler metal and a pre-placed filler ring for the second pass. Tubes shall be welded in a random pattern to minimize heat buildup.

8. Welding conditions and equipment settings for each pass of the tube sheet welds are outlined in this Appendix.

   NOTE: Since the tube hole size for each tube sheet is different, a compensation must be made in electrode radius setting. Welding conditions listed are for tube holes 0.512 inch in diameter.

9. The tube welds shall be wire brushed with a clean stainless steel brush to remove surface oxides and condensed metal after each completed pass.

INSPECTION

1. The tube welds shall be examined visually after wire brushing each completed pass.

2. All welds and the tube inside surface opposite the weld shall be dye-penetrant inspected for evidence of cracks, porosity or other indications considered detrimental to the quality of the joint. Welds shall be examined in this manner after the completion of each pass.

3. Any cracks, surface porosity, or any other visible defects shall be removed and/or repaired as per procedures outlined below. All repaired areas shall be reinspected as outlined above.

4. Other requirements set forth in Specification Na-666-30MW-15 shall be met.

REPAIRS

1. When necessary, defective weld areas shall be removed by machining or grinding with the high speed carbide deburring tool (chipping or mechanical gouging shall not be allowed).

2. Defects, such as incomplete fusion of the trepan or filler ring to the tube wall, pinhole porosity, and cracks shall be repaired using the same welding procedure as detailed in this Appendix for the given pass. In this instance, the arc shall be established ahead of the defect. Random fuse-through areas on the tube inside diameter shall not be cause for rejection. Consistent fuse through, which is indicative of improper welding conditions is undesirable. Corrective action shall be in accordance with Specification Na-666-30MW-15.

3. Defective welds when impossible to repair with the established procedure shall be repaired by a welding procedure that shall be developed and qualified by the fabricator and approved by the contracting organization.

PROCEDURE FOR FILLET WELDING 1/2" O.D. X 20 BWG TYPE 316 STAINLESS STEEL TUBING TO TYPE 316 STAINLESS STEEL TUBE SHEETS UTILIZING A FUSION ROOT PASS AND FILLER RING SECOND PASS

WELDING MACHINE CONTROL PANEL

Main Rheostat	-	Maximum
Remote Output Control	-	Remote Position
Soft Start	-	Inoperative
Process	-	Inert Gas Arc Welding
High Frequency	-	Automatic
High Frequency Control	-	Phase Shift - Maximum Intensity - 1/2
Range Switch	-	Medium Range
Selector Switch	-	Direct Current Straight Polarity

SEQUENCE TIMER CONTROL PANEL

	First Pass		Second Pass	
	Panel	Meter	Panel	Meter
Rheostat "A" Starting Current	5.8	80 amps	7.3	100 amps
Rheostat "B" Welding Current	5.4	75 amps	6.8	95 amps
Rheostat "C" Finishing Current	5.0	40 amps	4.0	35 amps
Timer "A"	5.2 sec.	--	4.1 sec	--
Timer "B"	5.1 sec.	--	1.2 sec.	--
Timer "C"	2.0 sec.	--	2.0 sec.	--
Speed (5.1 sec./rev.)	Low 54		Low 54	

ALCO TUBE WELDING GUN

	First Pass	Second Pass
Electrode Diameter*	3/32"	3/32"
Tungsten Electrode Angle	5^{o}	5^{o}
Electrode Radius Setting No.	5	9
Tube Hole Radius	0.256"	0.256"
Electrode Projection	0.250"	0.150"
Shielding Gas	Argon	Argon
Shielding Gas Flow Rate, cfh	20	20
Water Pressure, psig	50	50
Filler Metal	Trepan	Filler Ring

* 2% thoriated tungsten electrode with tip ground to a point on an angle of 15^{o}, and with a 0.030 inch flat along its side opposite tip. Point blunted to 1/64 inch flat.

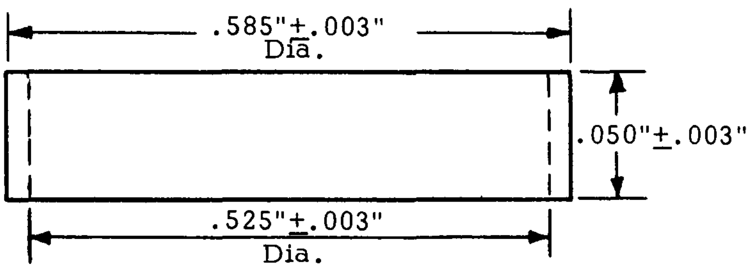


Figure B

Filler Ring Dimensions (Not to Scale)

APPENDIX 3-C
RECOMMENDED PROCEDURE FOR AUTOMATIC INERT-GAS SHIELDED TUNGSTEN-ARC WELDING COMPOSITE INCONEL - TYPE 316 STAINLESS STEEL TUBES TO INCONEL OVERLAID TUBESHEETS

MATERIAL

1.	Tubesheet	Type 316 stainless steel forging to Specification Na-666-30MW-3 (ASTM Specification A182-61T-F316) overlayed with an Inconel 82 deposit.
2.	Tubing	Composite tubing having Inconel on the inside and Type 316 on the outside in accordance Specification Na-666-30MW-1.
3.	Bare Welding Wire	Inconel Filler Metal 82, .030 inch dia., layer level wound on 2 lb. spool, annealed.

EQUIPMENT

1. ALCO tube-welding equipment consisting of:

   a. Tube-welding gun with a tapered locator having a 5 degree included angle.

   b. P & H Model 400 A DC rectifier with three stage sequence timer, Model H-780 Serial No. 1676.

   c. Positioning equipment for the welding gun.

   d. Linde Air Products Co. Electronic Governor, Type EG-104 Serial No. 1F1001.

2. "Airetool" tube-rolling equipment.

3. Tube-flaring tool having a flare of 6 degrees included angle.

JOINT DESIGN

See Figure A, to this Appendix.

PROCEDURE

1. Cleaning of the tubesheet and the tube-ends in contact with the tube-sheet shall be done with acetone or other suitable solvent prior to welding. Material cleanliness must be maintained throughout the welding phase.

2. The tubes when inserted through the tubesheet shall project a minimum of .410 ± .005 inch beyond the surface of the machined overlay. Tubes are to be rolled to a snug fit with the tubesheet for a depth of approximately 1-1/2 inches. A maximum upset of 0.003 inch on the diameter of the tube wall shall be allowed. The tubes shall be rolled without the use of any lubricants.

3. After rolling the tubes in the tubesheet, the tube ends projecting above the face of the tubesheet shall be flared to a six (6) degree included angle. This flare will then accommodate the locator which is tapered with a 5 degree included angle. The tube ends shall be flared from the tip of tube projection to a depth approximately 3/8 inch.

4. Welding of the tube-to-tubesheet joints shall be in the flat position, with the face of the tubesheet lying in the horizontal plane.

5. The entire tube-to-tubesheet unit shall be at ambient temperature (70°F minimum) for all welding sequences.

6. Machine settings and welding conditions for each weld pass of the tubesheet welding are included in this Appendix. Since the welding procedure was established using tubes of 0.511 and 0.524 inch in diameter, and tube holes of 0.529 inch diameter in the tubesheet, it may be necessary to make minor modifications to the tube gun settings during the final tube-to-tubesheet welding.

7. Fillet welding of the tube-to-tubesheet shall be performed in fifteen passes by the inert-gas shielded tungsten-arc process employing externally fed bare welding wire for all passes. The tubes shall be welded in a random pattern to minimize heat buildup in the tubesheet.

8. Manual brushing with a clean stainless steel brush shall be done on all tube welds to remove surface oxides and other contaminators after each weld pass.

9. Precision fixturing and mounting of the ALCO welding gun are mandatory for successfully welding of the tube-to-tubesheet joints. The procedures contained in this report were developed by employing the ALCO welding gun mounted on an ultragraph positioner attached to a vertical mounting post. Instructions for the proper alignment and positioning of the ALCO welding gun with the tubesheet are included in this Appendix 3-A.

Depending on the fixtures and related equipment used in production welding, these instructions may, or may not, be applicable.

INSPECTION

1. Upon completion of each weld pass, the tube joint shall be cleaned by wire brushing and examined visually.

2. Upon completion of the first weld pass and after the final weld passes have been made, the welds shall be dye-penetrant inspected for evidence of cracks, porosity or other indications considered detrimental to the qualityof the joint, in accordance with Specification Na-666-30MW-9 "Liquid Penetrant Inspection."

3. Other requirements of Specification Na-666-30MW-16.

REPAIRS

1. Where defective weld areas are encountered, the defect shall be removed, when necessary, by machining or cutting with a high speed carbide deburring tool (high speed tool steel deburring tools, chipping or other mechanical gouging shall not be permitted).

2. Types of defects, such as pin hole porosity, cracks and incomplete fusion of the weld metal with the tube wall, shall be repaired using the same welding procedure for the given pass as detailed in this Appendix. All necessary repairs shall be in accordance with Specification Na-666-30MW-16.

3. If it is necessary to repair a weld by another welding process or deviation from the established welding procedure, a welding procedure shall be developed and qualified by the fabricator and approved by the contracting organization.

PROCEDURE FOR FILLET WELDING 1/2" O.D. X 0.105" WALL INCONEL - TYPE 316 STAINLESS STEEL COMPOSITE TUBING TO INCONEL OVERLAID - TYPE 316 STAINLESS STEEL TUBESHEETS UTILIZING A COLD WIRE FEED

WELDING MACHINE CONTROL PANEL

Main Rheostat	-	Maximum
Remote Output Control	-	Remote Position
Soft Start	-	Inoperative
Process	-	Inert Gas Arc Welding
High Frequency	-	Automatic
High Frequncy Control	-	Phase Shift - Maximum Intensity - Maximum
Range Switch	-	Medium Range
Selector Switch	-	Direct Current Straight Polarity

ELECTRODE-FILLER WIRE-SHIELDING GAS

Tungsten Electrode	-	1/8" diameter, 2% thoriated tungsten with tip group to a point on an angle of 45 degrees, and with a 0.030" flat along its side opposite the tip. Point blunted to 1/64 inch flat.
Filler Wire	-	Inconel filler metal 82 or 82T, 0.030 inch diameter on 2 lb. spool, annealed.
Shielding Gas	-	Welding grade Argon, 40 cfh flow rate.

WELDING CONDITIONS

Pass No.	SEQUENCE TIMER CONTROL PANEL: Welding Current (± 5 Amps.)	SEQUENCE TIMER CONTROL PANEL: Rheostat Setting	SEQUENCE TIMER CONTROL PANEL: Weld Timers (Seconds)	ELECTRONIC GOVERNOR: Welding Speed LO	ELECTRONIC GOVERNOR: Welding Speed Sec/Rev	ALCO TUBE WELDING GUN: Electrode Angle (Degrees)	ALCO TUBE WELDING GUN: Arc Length (Inches)	ALCO TUBE WELDING GUN: Electrode Radius Setting	FILLER WIRE FEEDER: Vernier Setting	FILLER WIRE FEEDER: (In./Min.)
1	130-125-35	8.4-8.4-4.0	6.0-6.0-3.0	34.5	10	3	0.075	10	7-1/2	42
2	130-125-35	8.4-8.4-4.0	6.0-6.0-3.0	34.5	10	3	0.100	10	7-1/2	42
3	130-125-35	8.4-8.4-4.0	6.0-6.0-3.0	34.5	10	3	0.125	6	7-1/2	42
4	130-125-35	8.4-8.4-4.0	6.0-6.0-3.0	34.5	10	3	0.150	6	6-1/2	39
5	130-130-35	8.4-8.4-4.0	4.0-5.0-2.0	40	8	3	0.175	6	6	35
6	130-130-35	8.4-8.4-4.0	4.0-5.0-2.0	40	8	3	0.200	6	6	35
7	110-110-35	8.0-8.0-4.0	4.0-5.0-2.0	40	8	3	0.225	6	5	29
8	105-105-35	7.6-7.6-4.0	4.0-5.0-2.0	40	8	3	0.250	6	5	29
9	95-95-35	7.0-7.0-4.0	4.0-5.0-2.0	40	8	3	0.275	6	4	18
10	150-150-35	9.0-9.0-4.0	6.0-6.0-3.0	34.5	10	3 Mod.	0.100	10	7-1/2	42
11	150-150-35	9.0-9.0-4.0	6.0-6.0-3.0	34.5	10	3 Mod.	0.125	4	5	29
12	150-150-35	9.0-9.0-4.0	6.0-6.0-3.0	34.5	10	3	0.225	6	4	18
13	110-110-35	8.0-8.0-4.0	6.0-6.0-3.0	34.5	10	3	0.250	6	4	18
14	95-95-35	7.0-7.0-4.0	4.0-5.0-2.0	40	8	3	0.300	1	4	18
15	95-95-35	7.0-7.0-4.0	4.0-5.0-2.0	40	8	8-1/2	0.060*	8	3	15

* Arc length measured from top of tube.

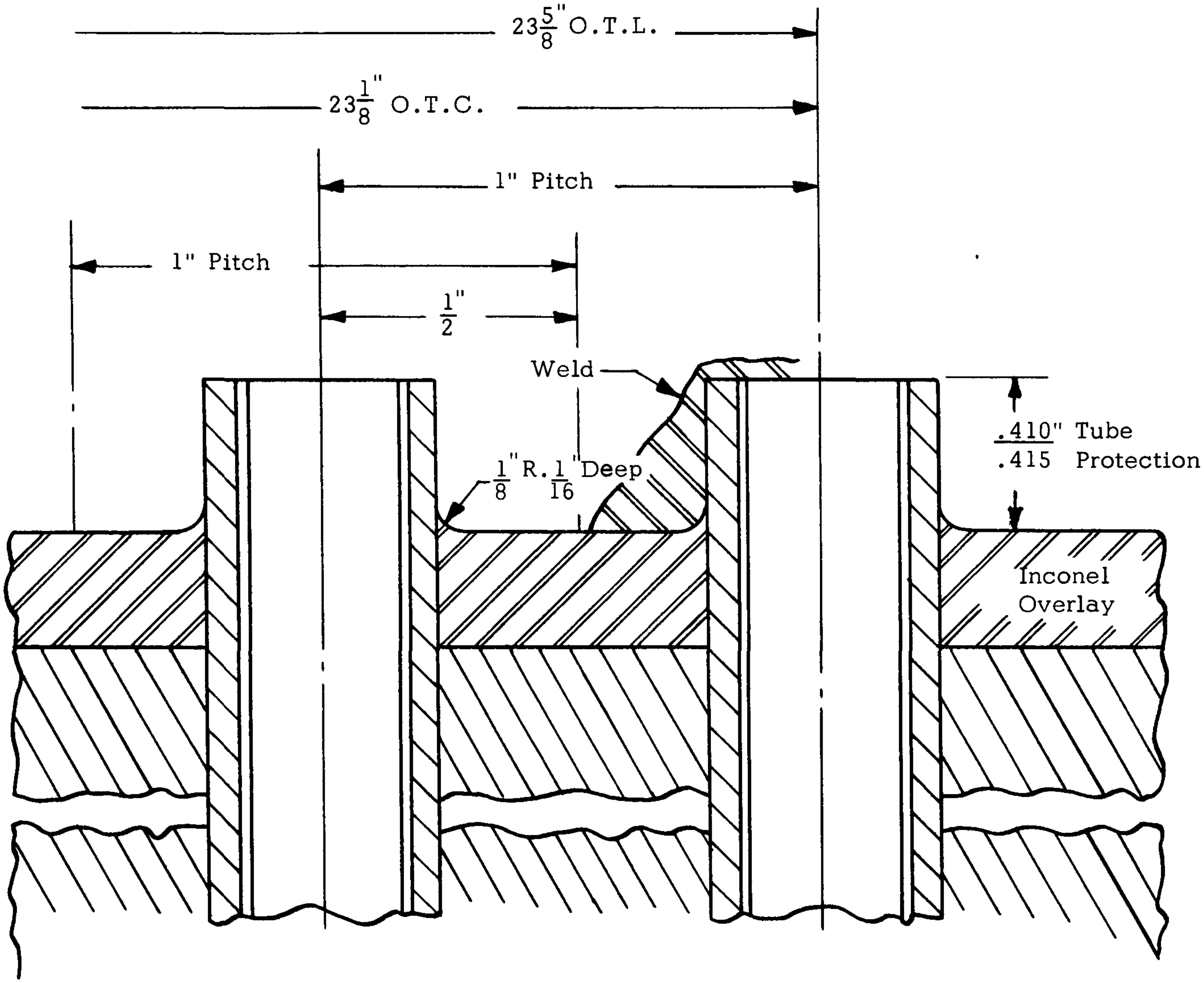


Figure C

Detail Tube-to-Tubesheet Welds for 30 M.W. Steam Generator
(Not to Scale)

SECTION 4
THERMAL SHOCK TESTS

THERMAL SHOCK TESTS

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SECTION 4
THERMAL SHOCK TESTS

This section of the report describes the thermal shock tests conducted to evaluate the effect that high, repetitive, thermal stresses would have on the tubesheet materials and tube joint designs for the intermediate heat exchanger and the steam generator.

OBJECTIVES

1. Intermediate Heat Exchanger.

To determine the effect of cyclical thermal stresses on assimilated tube-to-tubesheet weld joints of Type 316 stainless steel materials designed and fabricated in accordance with the qualified welding procedure for the intermediate heat exchanger.

2. Steam Generator.

(a) To determine the effect of cyclical thermal stresses on an assimilated Type 316 stainless steel tubesheet overlayed with Inconel weld metal.

(b) To determine the influence that cleaning solvents would have on stress-corrosion cracking in the crevice (interface) area of welded tube-to-tubesheet joints upon introducing thermal transients.

(c) To determine the effect of cyclical thermal stresses on an assimilated Type 316 stainless steel tubesheet overlayed with Inconel weld metal and having composite (Inconel - Type 316 stainless steel) tubes with joints designed and fabricated in accordance with the qualified welding procedure for the steam generator.

CONCLUSIONS

1. The test specimen assimilating the tube sheet of the intermediate heat exchanger was subjected to 506 thermal shocks. Examination indicated surface cracks at the bottom of the machined tube joint projection, completely away from the welded area. There was also random minor fissures found in the root crevices. In six welds small shallow cracks were observed. In view of the severity of the thermal transients introduced in the abnormally high number of thermal cycles applied beyond the design requirements, it was concluded that the tubesheet design and welding procedure was satisfactory to assure reliable performance of the exchanger in service within the scope of the design parameters.

2. The test specimen assimilating the Inconel weld overlaid Type 316 steam generator tubesheet with welded composite tubes was subjected to 474 thermal shocks. There was no apparent deterioration of the weld overlay per se nor of the fusing zone of the weld with the Type 316 base material. Although cracking was observed with both the flat and concentric-grooved joints, there was no evidence of stress corrosion cracking nor other deleterious effects in the tube joint or crevice resulting from the cleaning solvents.

3. The final test specimen assimilating the materials and design of the steam generator tubesheet was subjected to 50 thermal shocks which was 200% over the design requirements. There was no evicence of cracking resulting from these shocks. On the prior test specimen having undersize welds and a sharp notch at the toe of the weld where it meets the tubesheet surface, small cracks were observed at the notch after 75 thermal shocks. It has been concluded that the tube joint design and procedure for attaching the tubes-to-tubesheet are adequate for the steam generator to meet its service function and design requirements.

DESCRIPTION OF SHOCK TEST EQUIPMENT

The function of the shock test is to duplicate the maximum thermal stresses that may result from thermal transients introduced into the intermediate heat exchanger and steam generator during its service life. These assimilated thermal transients were introduced into the laboratory test specimens by heating the specimen mass to a uniform temperature, then directing a spray of hot steam condensate on the specimen face until the surface temperature reached a predetermined level. The tubesheet stresses develop from the temperature variation resulting from these thermal cycles.

The equipment used for performing the thermal shock tests is shown in Figure 4-1. A schematic diagram of the component details is given in Figure 4-2.

The heating and quenching unit consists of a refractory shell enclosing a cylindrical heating chamber 12 inches in diameter and 3 inches high. The lower portion of the chamber was formed of asbestos cement to provide a conical seat for the funnel returning the quenching water as well as locating the spray nozzle for conveying the quenching water to the specimen.

The test specimen was heated by a Nichrome resistance heating unit around the heating chamber. Temperature of the test specimen was controlled by three Chromel-Alumel thermocouples located at the midpoint of the specimen thickness 120 degrees apart around a three-inch circle at the center of the specimen. During operation of the test, the power to the heating element continues uninterrupted through both the heating and cooling phases of each cycle. The power is cut off only when the temperature of the specimen exceeds the maximum temperature of the cycle.

The test specimen is cooled by plant steam condensate sprayed on the tubesheet surface having the welded tube joints. The temperature of the test specimen was sensed for controlling the spray by three (3) Chromel-Alumel thermocouples located 120 degrees apart between the welded tube joints. The test specimens assimilating the intermediate heat exchanger tubesheet and for evaluating the overlay on the steam generator had the thermocouples buried to a depth of 3/16 inches beneath the tube joint surface. For more accurate temperature measurement while evaluating the influence of thermal transients on the two assimilated tubesheet tests for the steam generator, the thermocouples were located 1/8 and 1/16 inch beneath the test surface, respectively. These thermocouples were connected to a controller-recorder that indicated the cooling rate as well as initiated and terminated the spraying action. These thermocouples were completely independent from those controlling power input for heating.

SHOCK TEST OF ASSIMILATED TUBESHEET FOR THE INTERMEDIATE HEAT EXCHANGER

PREPARATION OF TEST SPECIMEN

The test specimen was prepared from a flat, circular, Type 316 stainless steel forging three (3) inches thick and ten-and-a-half (10-1/2) inches in diameter. Twelve (12) tubes of Type 316 welded stainless steel tubing .500 OD x .035 inch wall were welded into the tubesheet using the joint design and automatic welding procedure described in Section 3, Part A of this report. The materials, joint details and welding conditions were representative of the tube sheet assembly for the intermediate heat exchanger. A schematic diagram of the thermal shock specimen is shown in Figure 4-3. A typical shock test specimen is shown in Section 3, Figure 3-1.

After welding and prior to shock testing, the specimen was inspected visually and by liquid dye penetrant. No relevant indications were observed, Figure 4-4.

TESTING PROCEDURE

The test specimen was subjected to a total of 506 cycles during which the specimen temperature was raised to 1150°F and then cooled until the temperature measured 3/16 inch below the weld joint surface, reached 400°F. After

235 cycles, the test was interrupted to repair the control thermocouples and a leak between the test specimen and the drain funnel. A 10 micron filter was also installed in the steam condensate (cooling water) line to eliminate carry-over of iron oxide particles from the plant steam piping. Upon completion of the repairs and modifications, the test was continued for an additional 271 cycles.

Representative data for this series of shock tests are given in Table 4-1 and summarized below:

Material

Tubesheet: Type 316 stainless steel - 10-1/2" OD x 3" thick

Tubes: Type 316 stainless steel - .500" OD x .035" wall

Thermal Cycling Conditions

	Initial 235 Cycles	Final 271 Cycles
Top Temp. °F	1150	1150
Lower Temp. °F	400	400
Heating Time, Minutes	24-42	34-36
Cooling Time, Minutes	4.9-9.4	10-11.5
Condensate Temp. °F	150-180	150-180

For the first 235 cycles, the heating time shows a considerably greater range than for the final 271 cycles. This wide range was actually the result of a progressively longer heating cycle resulting from leakage through the drain funnel that gradually saturated the refractory. After the repair shutdown, the heating time was consistent within two minutes.

Upon completion of the 506 thermal shocks, the test specimen was again inspected visually and by liquid dye penetrant.

The test specimen was then cut through a plane one inch below the test surface having the welded tube joints. This section was subjected to x-ray evaluation.

Upon completion of non-destruction testing, a four (4) inch diameter hole at the center of the test plate was machined out to facilitate subsequent sectioning of the tube joints. It was observed that after removal of this center portion, the resulting hole was slightly eliptical which may be attributed to a redistribution or relief of stresses induced during the shock test. All twelve tubes were sectioned diametrically and polished for metallographic examination with, and without, an electrolytic chromic acid etch.

TEST RESULTS

Visual inspection and dye penetrant examination of the test specimen surface after shock testing did not reveal any indications of cracking. Radiographs, however, indicated the presence of cracks in the outer surface of tube joint projection numbers 7, 4 and 11. On joint projection 7, the crack was perpendicular to the plane of the tubesheet while on tubes 4 and 11 they were circumferential at the base of outer projection surface. No other deficiencies were apparent on non-destructive testing. It was observed, however, that the test sample was badly distorted and several of the tube joint projections were out-of-round as a result of the thermal stresses induced during shocking.

Metallographic examination of the twelve tube-joint cross sections revealed definite cracking around the outside base area of all the machined projections completely away from the weld as shown in Figure 4-5A. These cracks ranged from .050 to .070 inch deep. Other areas slightly above the root of the machined projection had random smaller cracks from .015 to .020 inch deep. Appraisal of the microstructure of the cracked projections revealed a cold worked structure extending to a depth of 1/8 inch from the bottom of the projection radius as shown in Figure 4-5B.

Microexamination of the fusion area between the tube and tubesheet also indicated cracks .005 to .015 inch long in all twelve tube joints (Figure 4-5A). Small shallow cracks (less than .002) were also observed in the weld of five joints.

While cracks did develop in the test specimen after 506 thermal transients, similar cracks in the production heat exchanger would not cause a leak between the coolant fluids. Since the cracks were produced by thermal transients more severe and twenty times the number required for design, it may be concluded that the proposed welding procedure and tube joint design will be entirely satisfactory for the tube-to-tubesheet joints of the production heat exchanger.

SHOCK TEST OF THE STEAM GENERATOR TUBESHEET WELD OVERLAY

The test described in the following section was a shock test conducted on an assimilated steam generator tubesheet. The primary objective was to evaluate the effect of rapid thermal transients on the Inconel weld overlay. It was also believed desirable, as a secondary objective, to determine if residue from cleaning solvents could promote stress corrosion cracking in the crevices between the tubes and tubesheet. In addition, a qualitative evaluation was also made of the merits of a flat versus a concentric groove and riser weld joint design. At the time this test was conducted, the final tube-to-tubesheet welding procedure for the steam generator had not been established and tubes were therefore welded by a manual procedure to facilitate preparation of the specimen. The purpose of the test was to investigate the conditions described above only and was not intended to evaluate the tube welds subjected to thermal stresses.

PREPARATION OF TEST SPECIMEN

The test specimen was prepared from a circular, flat, Type 316 stainless steel forging having a 12-inch diameter and a thickness of 2-13/16 inches. An Inconel weld overlay was applied to one face and machined to produce a finished thickness of approximately 3/16 inch. Twelve holes, 0.540 inch in diameter, equally spaced on a circle six inches in diameter were drilled completely through the overlayed tubesheet blank. Six grooves, having outside diameter of 1.260 inches, inside diameter of 0.760 inch, depths of 1/8 inch and 1/8 inch bottom radii were machined concentric to the holes and at alternate holes only (refer to Figures 4-3 and 4-6).

Metallurgically bonded composite tubing (0.522 inch OD x .072 minimum wall seamless cold drawn and annealed Type 316 stainless steel over .032 nominal wall seamless Inconel) was cut to twelve 9-inch lengths. Six tubes and tubesheet holes were cleaned with acetone, followed by distilled water rinse and then dried with a clean lint-free cloth. The remaining six tubes and tubesheet holes were cleaned with acetone only and dried with a clean cloth. The tubes were inserted in the holes in the tubesheet in such a manner as to provide 3/8 inch of tube projection beyond the overlayed face. Each tube was tack welded to the back side of the specimen to maintain the desired projection during tube welding. All tubes were expanded to a snug fit and welded into the tubesheet using a manual tungsten arc procedure and Inconel Filler Metal 82. The outside diameter of the tubesheet was machined to 10-1/2 inches to provide greater clearance with the heating element in the thermal shock unit.

Prior to testing, all tube-to-tubesheet welds and the Inconel overlay were inspected by the dye penetrant technique. This specimen is illustrated in Figure 4-6.

TESTING PROCEDURE

The test was conducted for a total of 474 cycles during which the specimen temperature ranged between 1150^{O}F and 400^{O}F as indicated by thermocouples embedded 3/16 inch below the specimen surface.

Representative data for this test are listed in Table 4-2 and summarized below.

Material

Tubesheet: Type 316 stainless steel, 10-1/2 inch OD x 2-13/16 inch thick.

Tubes: Composite tubes 0.522 inch OD x .072 inch min. Type 316 stainless steel metallurgically bonded to 0.032 inch Inconel.

Thermal Cycling Conditions

Number of shock cycles	474
Top Temp. °F	1150
Lower Temp. °F	400
Heating Time - Minutes	25.6 - 71.0
Cooling Time - Minutes	4.0 - 10.3
Condensate Temperature °F	120

After completion of the test, it was discovered that the inconsistency in heating and cooling times was a result of leakage of steam condensate through cracks in welds between the drain funnel and test specimen. This condition was improved on subsequent tests by welding the funnel to the specimen.

At the conclusion of the test after 474 thermal shock cycles, the specimen was removed from the test fixture and inspected visually and by dye penetrant.

The specimen was then cut through a plane one inch below the test surface and x-rayed. Upon completion of the above tests, the tubes were sectioned diametrically to include the welds, tube-tubesheet crevice and a portion of the Inconel overlay. All twelve sections were prepared for both macro and microexamination.

TEST RESULTS

Except for some minor indications, no gross defects or cracks were revealed in any areas on the test sample by either visual or dye penetrant inspection or radiography. Because of the possibility of entrapment of acid in the crevices between the tube holes and the tubes, the test sample could not be cleaned prior to the dye penetrant inspection. The thin oxide layer on the surface could have masked defects which were revealed by subsequent destructive tests.

Microexamination of the test samples revealed cracking in the crevice between the tube and tubesheet in all twelve specimens. The severity of the cracking could not be related to cleaning residue but appeared to be a result of thermal stresses rather than a stress corrosion mechanism.

All samples without the concentric grooves had cracks at the toe of the weld while the concentric grooves in the remaining samples contained cracks. The toe cracks ranged in length from 0.015 inch to 0.080 inch while the deepest cracks in the grooves were approximately 0.050 inch. The cracks at the toe of the weld were, in some cases, in the overlay and in the tube joint weld metal in others. In view of the fact that cracking occurred in both the flat and concentric type of weld joint, neither type offered any particular advantage over the other. The grooved design appeared to move the point of stress concentration away from the weld but the resultant cracks in both types of joints were equally undesirable. Since the concentric-groove joint design entailed more machining and heavier overlay thickness, it was subsequently eliminated as a requisite for the steam generator weld joint design.

Microscopic examination of all cracks emanating from the shocked surface indicated that they were produced by thermal shocking and not by a stress corrosion mechanism. The cracks were wide at the surface and gradually tapered to the end. Oxide was present in all defects. Surface oxide was thick and could have easily masked any defect during dye penetrant inspection.

As stated previously, the tube welds were prepared by a manual procedure and therefore this test was not intended to be an evaluation of the final weld design under specified thermal shock conditions.

Except for the cracking that has been described above, no defects were observed at the interface between the Type 316 stainless steel base metal and Inconel overlay or in any other areas.

On the basis of this evaluation, it can be concluded that there was no correlation between cleaning solutions or residue remaining in the crevice and crevice cracking and that the Inconel weld overlay per se could withstand severe thermal shock without any adverse effects.

SHOCK TESTS OF ASSIMILATED TUBESHEET FOR THE STEAM GENERATOR

In order to assure that the subject tubesheet could withstand the design thermal transients, an initial and repeat test were required. Upon completion of the first test, slight cracking was observed at the toe of the weld in several samples where the weld metal made a sharp angle with the overlay surface. The leak paths of these welds were also slightly less than that required by Specification Na-666-30MW-16. These conditions were corrected for the repeat test specimen, which met all requirements of the applicable welding specification.

PREPARATION OF TEST SPECIMEN, INITIAL TEST

The test specimen was prepared from a Type 316 stainless steel disc forging which was machined to a diameter of 10-1/2 inches and a thickness of 2-13/16 inches. A four-pass Inconel weld overlay, conforming to Na-666-30MW-17, was applied to one face and machined to produce a finished thickness of 1/4 inch. Twelve (12) .521 inch OD x .105 inch total wall Type 316 - Inconel composite tubes, produced in accordance with Na-666-30MW-1, were welded into the test tubesheet usingthe joint design and automatic welding procedure described in Section 3 Part B, of this report. The configuration of the test specimen with respect to location of the test welds, etc., was similar to the two tests previously described. This specimen, before testing, is illustrated in Figure 4-7.

After welding and prior to testing, the specimen was both visually and liquid penetrant inspected. No relevant indications were observed (Figure 4-7).

TESTING PROCEDURE, INITIAL TEST

This test was run for a total of 75 cycles, during which the surface temperature of the specimen ranged between 1150°F and 600°F. During the first cycle, surface temperature dropped to 300°F due to a defective valve. This test was interrupted after the 25th, 30th and 50th cycles for dye penetrant inspection. Heating and cooling times were as follows:

Cycles	Heating Time	Cooling Time
2 - 25	9 Min-2 Sec. to 10 Min-47 Sec.	35 Sec. to 45 Sec.
26 - 30	10 Min-38 Sec. to 15 Min-38 Sec.	63 Sec. to 69 Sec.
31 - 50	9 Min-40 Sec. to 11 Min-31 Sec.	59 Sec. to 80 Sec.
51 - 75	8 Min-54 Sec. to 11 Min-39 Sec.	71 Sec. to 2 Min-2 Sec.

Representative data for this test are presented in Table 4-3.

Adjustments in power input and steam condensate pressure account for the variations in heating and cooling times. Steam condensate temperatures range between 120° and 180°F during the course of the test.

The specimen was subjected to a liquid dye penetrant inspection after the 25th, 30th, 50th and 75th shock cycle.

An x-ray was taken of one-inch thick circumferential slice from the top face of the specimen after the final liquid penetrant inspection.

Upon completion of the above test, all twelve tubes were sectioned diametrically and prepared for metallographic examination. Contrary to the previous shock tests, the four-inch diameter hole was not drilled in this specimen in order to prevent the possibility of cracking that could result from the release of residual stresses.

TEST RESULTS, INITIAL TEST

Liquid dye penetrant, visual inspection and subsequent x-ray did not reveal any defects in the shock specimen.

Examination of macroetched cross-sections of the tube weld samples revealed fine cracks at the toe of the weld; i.e., at the juncture of the weld metal and overlay. Some cracks were observed in the weld metal and also in the overlay of fourteen of the twenty-four weld cross-sections examined. Ten sections did not show any cracks. The smallest crack was 0.002 inch deep and the longest 0.016 inch. The average depth was approximately 0.0075 inch. The 0.016 inch crack is illustrated in Figure 4-8.

After macro and microexamination of the test specimen, it was observed that the welds prepared for the shock sample did not meet specification requirements in regard to leak path. It was observed that cracks occurred only in the vertex of the sharp angle between the weld and the overlay. When this angle was less pronounced or a more generous fillet existed, cracks were very slight or non-existant. It was also found that cracking occurred in welds where the leak path through the throat was smallest. In welds where the throat leak path approached the 1-1/2 T specified, cracks were very slight or did not occur. Slight modifications of the automatic welding gun were required to increase the leak path through the throat of the weld beyond 1-1/2 T. However, in view of the fact that cracking did result from this shock test, it was necessary to repeat this test on a specimen in which all welds met the specified leak path requirements.

PREPARATION OF TEST SPECIMEN, FINAL TEST

As described under "Test Procedure" of the initial steam generator tube-to-tubesheet weld, the specimen was cut circumferentially one inch below the overlay surface to reduce material thickness for x-ray and to facilitate macro specimen preparation. In order to avoid unnecessary delays which could result from material procurement difficulties, the remaining section of initial test specimen was used as the base plate for this repeat test. The twelve tube holes were plugged with stainless steel bar stock and a four pass Inconel overlay was subsequently applied to one face. Twelve new holes, equally spaced on a circle 7-1/2 inches in diameter and displaced 15^{o} from the original holes, were drilled through the overlaid blank. The procedure for preparing the tube welds was identical to the method described in Section 3, Part B of this volume for "Tube-to-Tubesheet Welds for the Steam Generator." A photograph of this test specimen is presented in Figure 4-9.

TEST PROCEDURE, FINAL TEST

This test was conducted for a total of 50 thermal cycles, during which the surface temperature ranged between 1150° and 600°F. The thermocouples for indicating surface temperatures were moved to within 1/16 inch of the tubesheet surface so that the temperatures measured were closer to the actual surface temperature than in the previous test.

Representative data for this test is presented in Table 4-4 and are summarized below.

Material

Tubesheet:	Type 316 stainless steel - 10-1/2 OD x 2" thick.
Tubes:	Metallurgically bonded composite Inconel- Type 316 tube 0.521 inch OD x .305 ID.

Thermal Cycling Conditions

Number of Cycles	50
Top Temp. °F	1150
Lower Temp. °F	600
Heating Time, Minutes	8.7 - 15.4
Cooling Time, Minutes	1.1 to 2.3
Condensate Temperature, °F	173 to 205

A liquid dye penetrant inspection was performed on this specimen before testing and after 25th, 30th and 50th shock cycles. This specimen was not x-rayed.

After the 25th and 30th cycles, cross sections of tube No's 1 and 12 and 4 and 5, respectively, were examined at magnifications up to 45X.

Upon completion of the 50th cycle, the remaining eight tubes were sectioned diametrically and were prepared for metallographic examination.

TEST RESULTS, FINAL TEST

The liquid dye penetrant inspection performed after the 25th, 30th and 50th shock cycles did not reveal any defects in the test specimen.

Metallographic examination of the four tubes after the 25th and 30th cycles and the remaining eight tubes after completion of the test did not reveal any cracks in the toe of the weld, in the crevice or any other areas of the samples. All welds met the leak path requirements of Specification Na-666-30MW-I6. Photo macro and micrographs of a representative weld joint are illustrated in Figure 4-10. The fillet at the toe of the weld was considerably improved in comparison to the welds in the initial test.

After a thorough macro and microexamination of all tube-to-tubesheet welds and adjacent areas in the test specimens, it was concluded that 50 thermal shock cycles or 200% of the design requirement will not produce any deleterious effect on these welded joints. It is, however, of primary importance that all tube-to-tubesheet welds meet all the requirements of Na-666-30MW-16 and the welding procedure described in Section 3, Part B, of this report must be strictly followed.

TABLE 4-1
REPRESENTATIVE OPERATING DATA FOR THE INTERMEDIATE
HEAT EXCHANGER SHOCK TEST

Cycle Number	Power Input			Coolant Pressure	Cycle Time (Min.)			Spray Control Temp. (°F)		Heat Control Temp. (°F)	
	Amps	Volts	Kw	PSIG	Heat	Cool	Total	Start	Stop	Max.	Min.
1	97.8	46	4.5	30	14.7	4.9	151.9	1150	400	1150	700
2	97.8	46	4.5	30	41.5	4.9	46.9	1150	400	1190	700
3	114	53.5	6.1	30	28.9	5.7	34.6	1150	400	1190	700
4	112.8	52.8	6.0	30	27.4	6.3	33.7	1140	400	1185	680
5	114	53.5	6.1	30	30.0	6.9	36.9	1147	400	1100	635
8	114	53	6.0	20	27.8	9.4	37.2	1150	400	1095	605
9	114	53.5	6.1	20	28.3	9.0	37.3	1150	400	1100	600
10	114	53	6.0	20	27.5	8.3	35.8	1150	400	1090	610
11	114	53	6.0	20	26.5	7.5	34.0	1150	400	1095	600
30	112.2	54	6.1	20	24.3	6.3	30.6	1150	400	1100	665
31	112.2	53.8	6.0	20	24.9	6.2	31.1	1150	400	1080	665
201	105.0	55.0	5.8	20	-	5.9	-	1150	400	1100	670
202	109.8	56.5	6.2	20	42.2	6.0	48.2	1150	400	1100	670
227	108	57.0	6.2	20	41.9	6.0	47.9	1150	400	1110	667
320	94.8	42.2	4.0	20	34.0	10.0	44.0	1150	400	1092	520
419	93.0	42.0	3.9	20	36.0	11.5	47.5	1150	400	-	-

TABLE 4-2

REPRESENTATIVE OPERATING DATA FOR THE INCONEL OVERLAID SHOCK TEST

Cycle	Power Input			Coolant Pressure	Cycle Time (Min.)			Spray Control Temp. (°F)		Heat Control Temp. (°F)	
Number	Amps	Volts	Kw	PSIG	Heat	Cool	Total	Start	Stop	Max.	Min.
1	90	41	3.7	26	49	4	53	1150	400	1155	745
11	114	53	6.0	20	56.3	4.7	61	1150	400	1160	740
21	114	54	6.2	20	61.3	4.7	66	1150	400	1160	740
31	114	54	6.2	15	68.5	5.2	73.7	1150	400	1130	713
41	114	54	6.2	15	66.9	5.2	72.1	1150	400	1130	713
51	114	54	6.2	15	68.2	5.2	73.4	1150	400	1130	705
61	114	54	6.2	15	67.3	5.7	73.0	1150	400	1120	705
71	113	54	6.2	15	64.6	5.3	69.9	1150	400	1120	705
81	114	56	6.4	15	63.2	5.5	68.7	1150	400	1125	705
91	114	56	6.4	15	71.0	5.2	75.2	1150	400	1125	700
101	114	54	6.2	15	28.8	6.8	35.6	1150	400	1030	640
111	114	54	6.2	15	28.4	10.3	38.7	1150	400	-	-
121	105	49	5.1	28	25.6	7.4	33.0	1150	400	940	565
131	99	46	4.6	20	36.3	8.4	44.7	1150	400	-	-
141	99	46	4.6	20	34.3	7.0	41.3	1150	400	1030	605
151	108	51	5.5	20	31.8	6.7	38.5	1135	400	1005	610
161	111	52	5.8	20	31.9	7.0	38.9	1150	400	-	-
171	111	54	6.0	20	33.4	6.8	40.2	1150	400	-	-
181	111	54	6.0	20	33.6	6.8	40.4	1150	400	-	-
191	114	54.5	6.2	20	34.5	6.7	41.1	1150	400	1000	600
201	114	54.5	6.2	20	32.4	6.5	38.9	1150	400	-	-
211	114	55	6.3	20	33.1	6.9	40.0	1150	400	-	-
221	113	56	6.3	20	36.1	6.7	42.8	1150	400	1000	600
231	111	56	6.2	20	32.9	6.6	39.5	1150	400	-	-
243	111	56.3	6.2	20	36.8	7.3	44.1	1150	400	-	-
251	111	56	6.2	20	35.5	6.7	42.2	1150	400	-	-
268	108	56	6.0	20	36.3	6.8	43.1	1150	400	1010	605
278	111	55	6.1	20	38.4	6.6	45.0	1150	400	-	-
285	111	55	6.1	20	40.5	6.6	47.1	1150	400	-	-
300	111	55	6.1	20	39.3	6.6	45.9	1150	400	-	-
317	111	55	6.1	20	41.2	6.8	48.0	1150	400	980	580
340	111	58	6.4	20	36.4	7.0	43.4	1150	400	980	580
388	102	56	5.7	20	46.6	7.5	54.1	1150	400	-	-
416	102	56	5.7	20	47.4	7.0	54.4	1150	400	-	-
449	102	56	5.7	20	45.9	6.7	52.6	1150	400	1000	600

TABLE 4-3
REPRESENTATIVE OPERATING DATA FOR THE
STEAM GENERATOR TUBESHEET SHOCK TEST, INITIAL TEST

Cycle Number	Power Input Amps	Volts	Kw	Coolant Pressure PSIG	Cycle Time (Min.)(Sec.) Heat	Cool	Total	Spray Control Temp. (°F) Start	Stop	Heat Control Temp. (°F) Max.	Min.
5	Not Recorded		4.16	23	9'5"	40"	9'45"	1150	600	Not Recorded	
7	"	"	"	"	9'28"	43"	10'11"	"	"	"	"
9	"	"	"	"	9'17"	43"	10'00"	"	"	"	"
11	"	"	"	"	9'17"	38"	9'55"	"	"	"	"
13	"	"	"	"	9'11"	44"	9'55"	"	"	"	"
15	"	"	"	"	9'00"	45"	9'45"	"	"	"	"
17	"	"	"	"	8'50	45"	9'35"	"	"	"	"
19	"	"	"	"	9'12"	46"	9'58"	"	"	"	"
21	"	"	"	"	8'51"	40"	9'31"	"	"	"	"
25	"	"	"	"	9'20"	45"	9'20"	"	"	"	"
26	93.6	42.4	3.97	"	-	63"	-	"	"	"	"
28	"	"	"	"	12'6"	65"	13'11"	"	"	"	"
30	"	"	"	"	10'58"	69"	12'7"	"	"	"	"
32	96	44.0	4.22	17.5	11'31"	59"	12'30"	"	"	"	"
35	"	"	"	"	10'15"	1'11"	11'26"	"	"	"	"
40	"	"	"	"	9'45"	1'20"	11'5"	"	"	"	"
50	"	"	"	"	9'36"	1'16"	10'52"	"	"	"	"
60	96	44.0	4.22	17.0	9'3"	1'37"	10'40"	"	"	"	"
70	"	"	"		8'48"	1'30"	10'18"	"	"	"	"
75	"	"	"		8'29"	1'30"	9'59"	"	"	"	"

TABLE 4-4
REPRESENTATIVE OPERATING DATA FOR THE
STEAM GENERATOR TUBESHEET SHOCK TEST, FINAL TEST

Cycle Number	Power Input Amps	Volts	Kw	Coolant Pressure PSIG	Cycle Time (Min.) (Sec.) Heat	Cool	Total	Spray Control Temp. (°F) Start	Stop	Heat Control Temp. (°F) Start	Stop
1	Not Recorded		4.22	18	Start up	2'12"	-	1150	400	908	688
2	"	"	4.22	18	14'30"	2'30"	17'00"	"	"	890	660
3	"	"	4.58	18	14'06"	2'18"	16'24"	"	"	863	652
4	"	"	4.58	18	12'54"	2'00"	14'54"	"	"	835	643
5	"	"	4.32	18	13'30"	2'06"	15'36"	"	"	852	650
7	"	"	4.32	18	13'12"	2'06"	15'18"	"	"	832	640
9	"	"	4.32	18	12'18"	2'00"	14'18"	"	"	833	621
11	"	"	-	18	-	-	-	"	"	840	627
13	"	"	4.22	18	13'30"	2'18"	15'48"	"	"	837	639
26	"	"	4.37	18	Start up	2'00"	-	"	"	1050	819
27	"	"	4.41	18	14'18"	2'18"	16'36"	"	"	1050	772
28	"	"	4.77	18	15'24"	2'00"	17'24"	"	"	1040	768
30	"	"	-	18	-	1'36"	-	"	"	836	640
33	"	"	4.46	17	10'54"	-	-	"	"	941	761
36	"	"	4.46	18	8'54"	1'42"	10'46"	"	"	930	759
40	"	"	4.42	17	8'54"	2'18"	11'12"	"	"	922	742
45	"	"	4.44	17.5	9'18"	1'12"	10'30"	"	"	915	739
50	"	"	4.30	16	91'2"	1'6"	10'18"	"	"	925	750

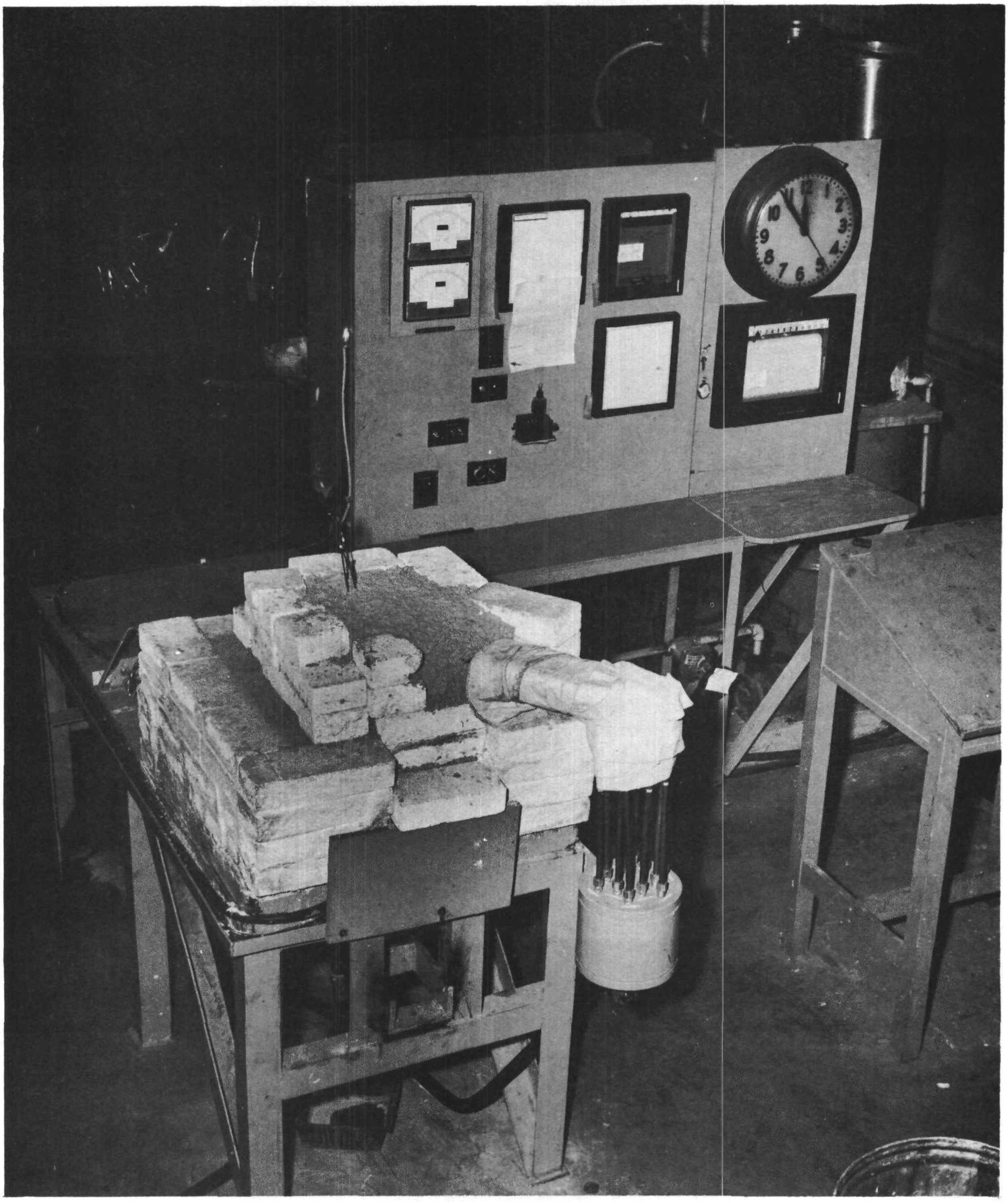
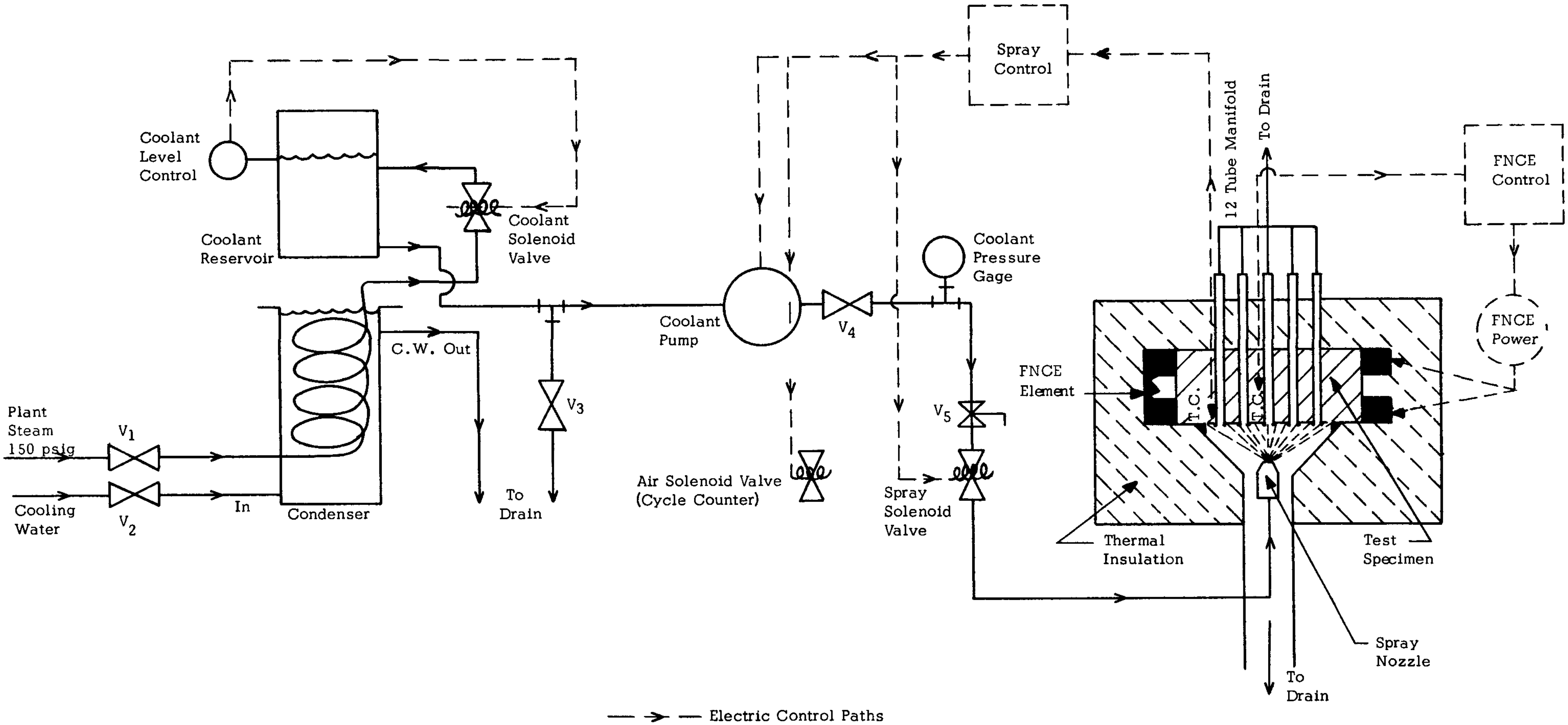


Figure 4-1 692565-11

Facilities for Conducting Thermal Shock Tests.



Indexed as M.E. Laboratory Sketch 132G

Figure 4-2 1326

Flow Diagram Thermal Shock Test of Tube-toTubesheet Welded Connections

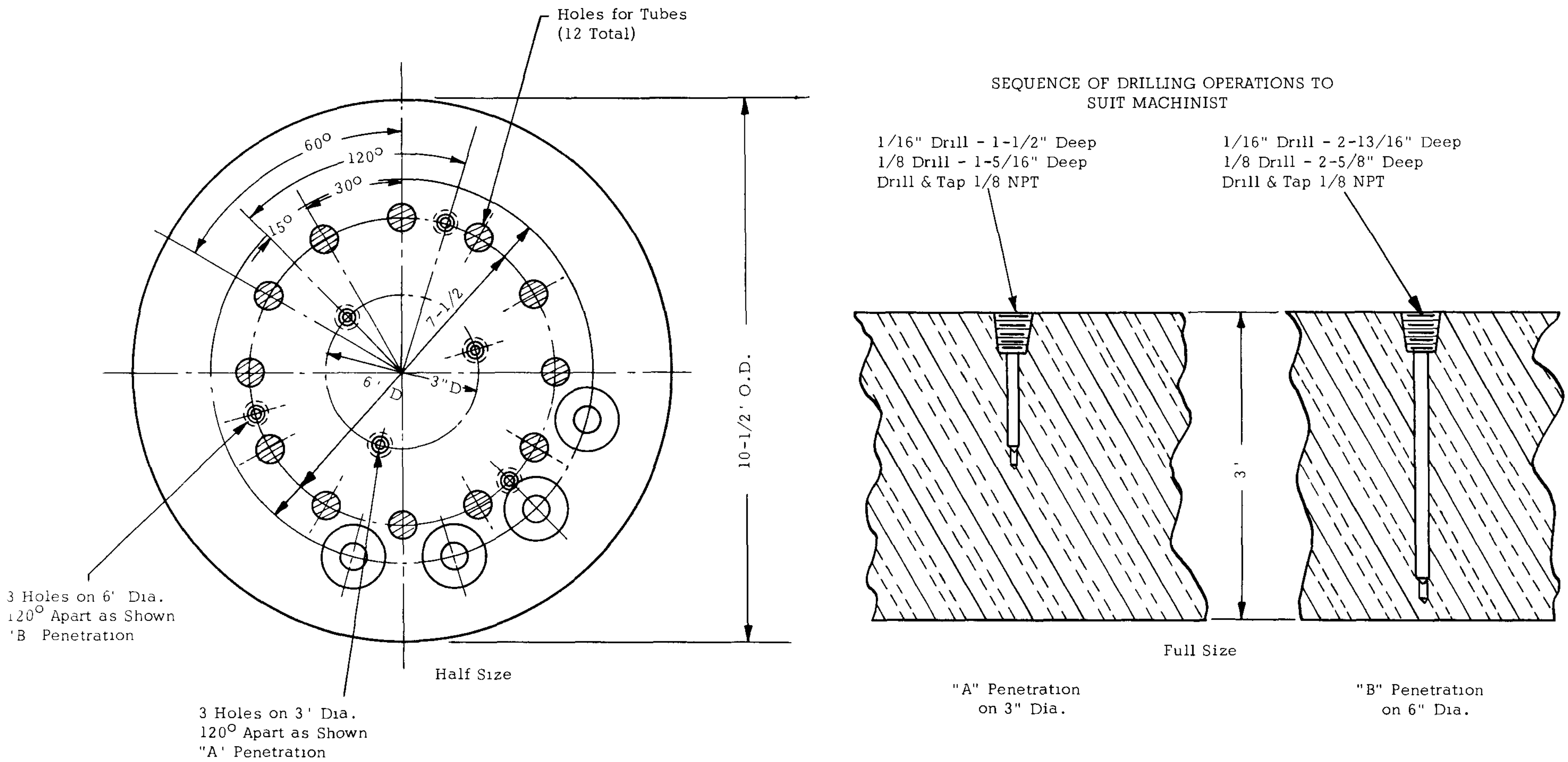


Figure 4-3 1319

Diagram of Thermal Shock Test Specimen

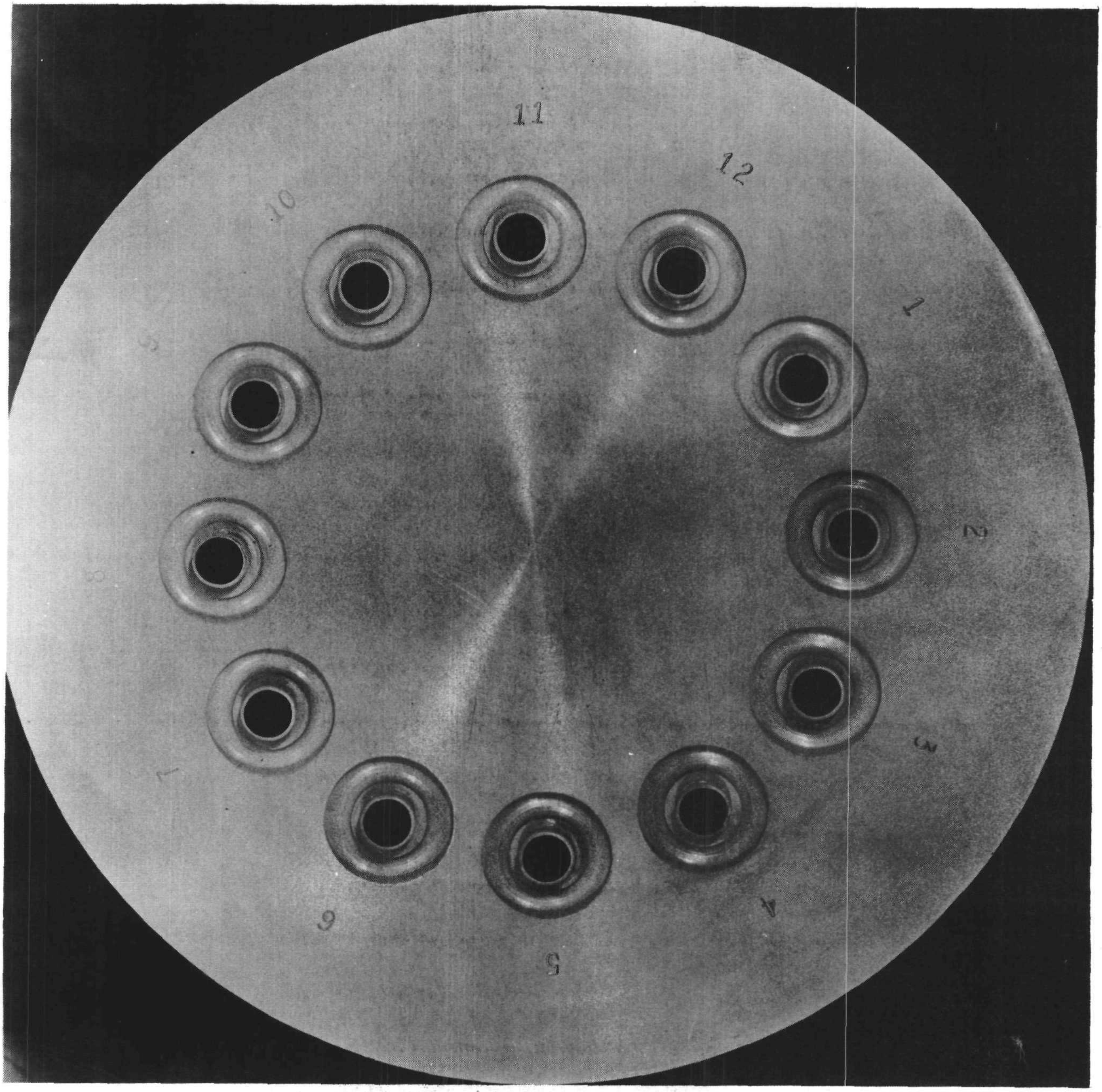
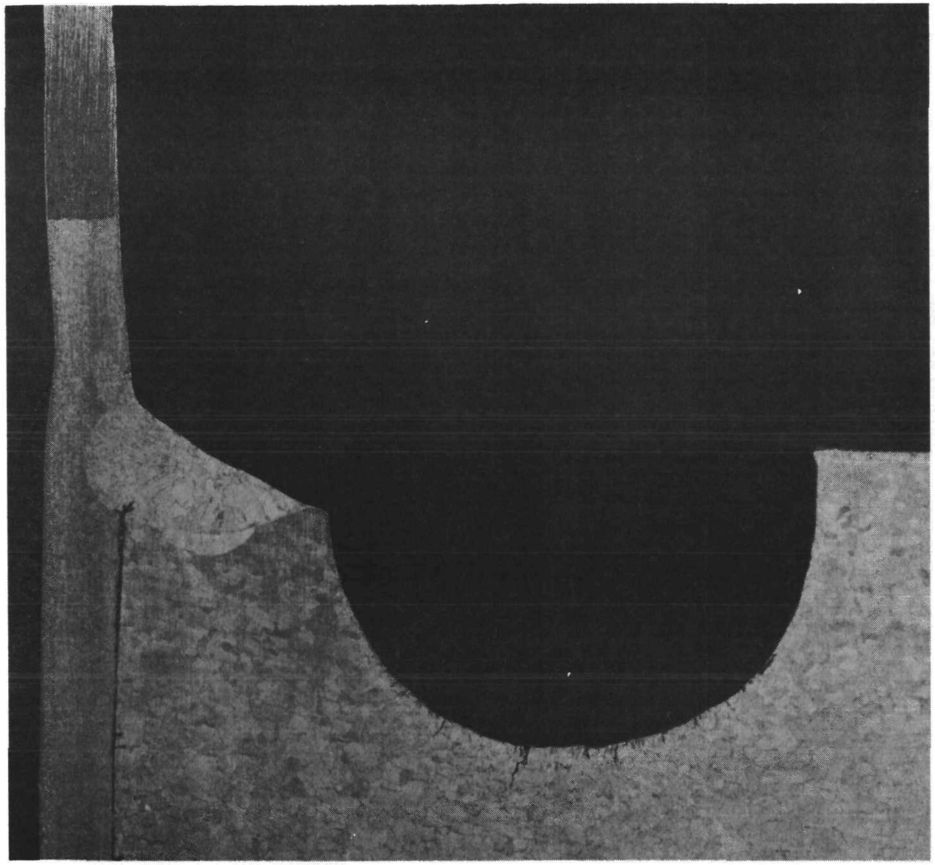


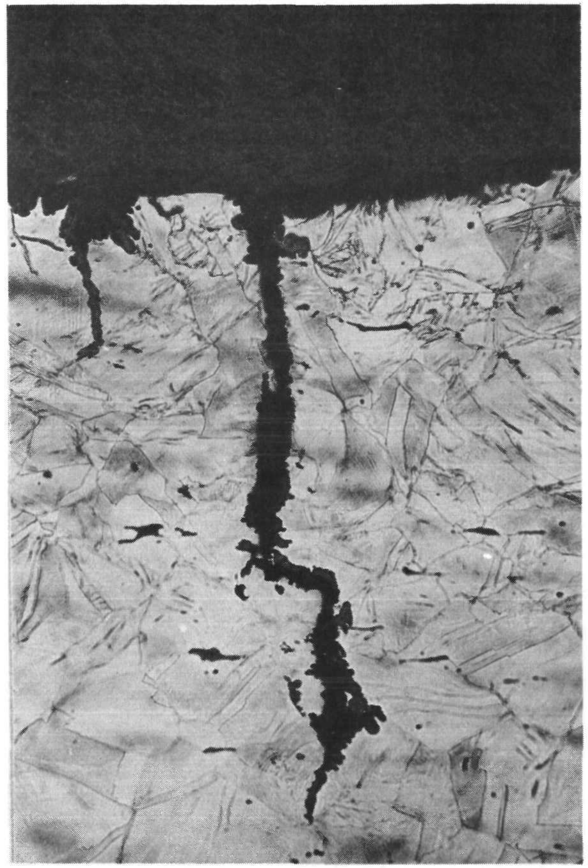
Figure 4-4 692565-5

Dye Penetrant Inspection of Shock Test Specimen Assimulating the Intermediate Heat Exchanger Prior to Shock Testing.



1321E 3X

A. Cracks in Radius of Machined Projection and Crevice



13363B 100X

B. Crack and Distorted Grain Structure

Figure 4-5

Typical Cracks Observed in the Shock Test Specimen Assimilating the Intermediate Heat Exchanger After 506 Thermal Cycles. (Electrolytic Chromic Acid Etch).

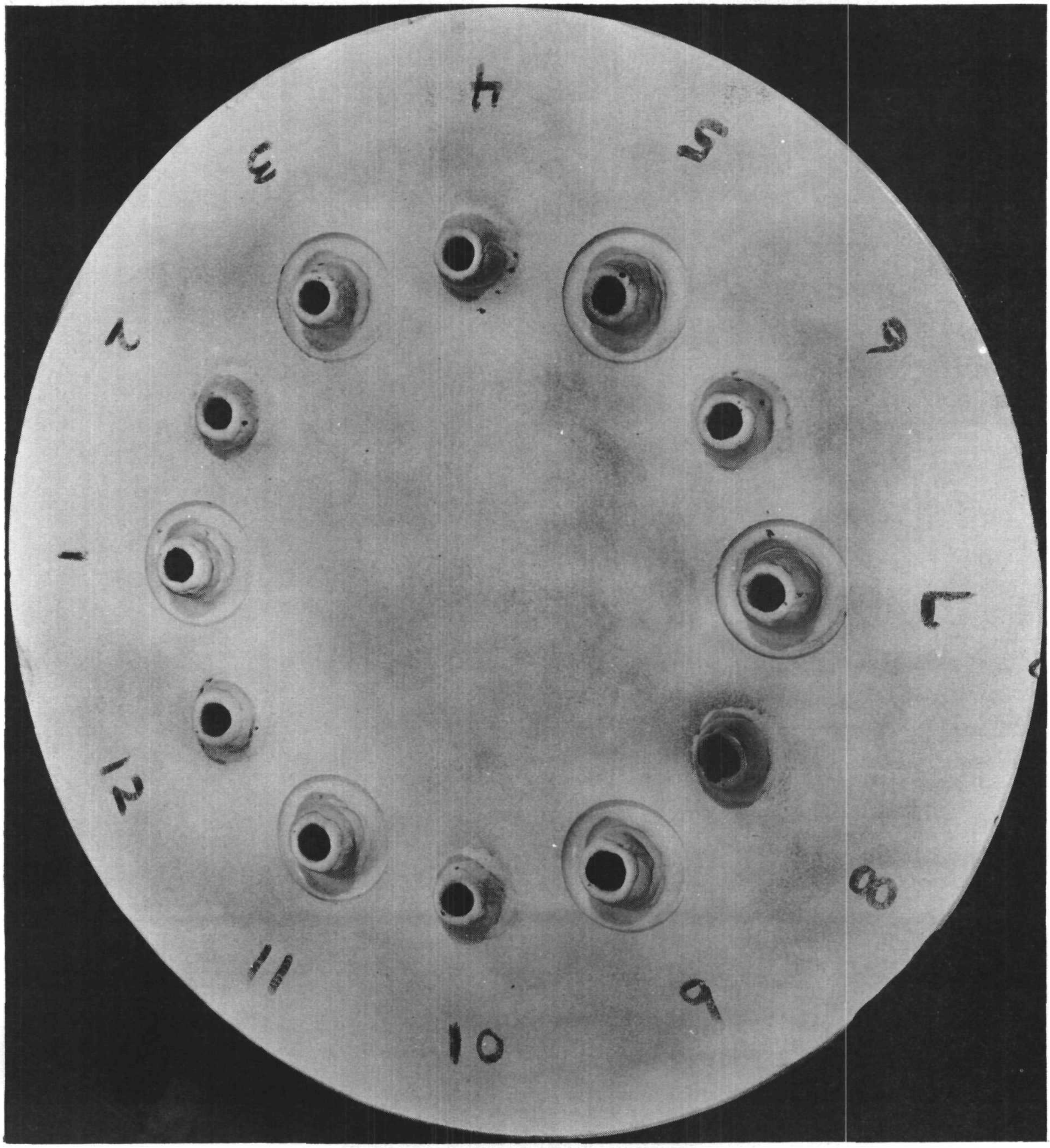


Figure 4-6 692565-2

Dye Penetrant Inspection of Welded Tube Joints and Inconel Overlay Prior to Thermal Shock Testing. Note the Concentric Groove on Alternate Tube Joints.

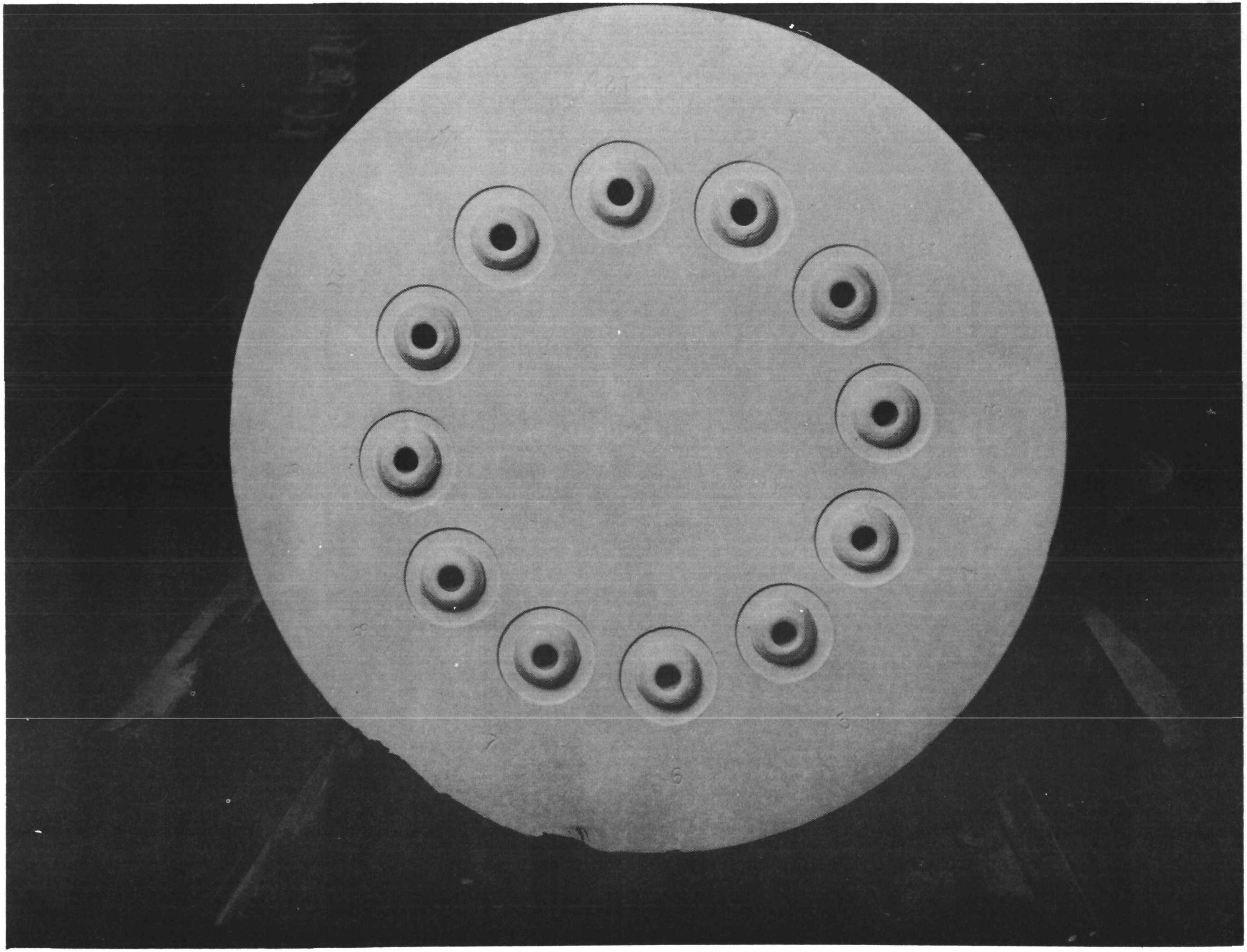
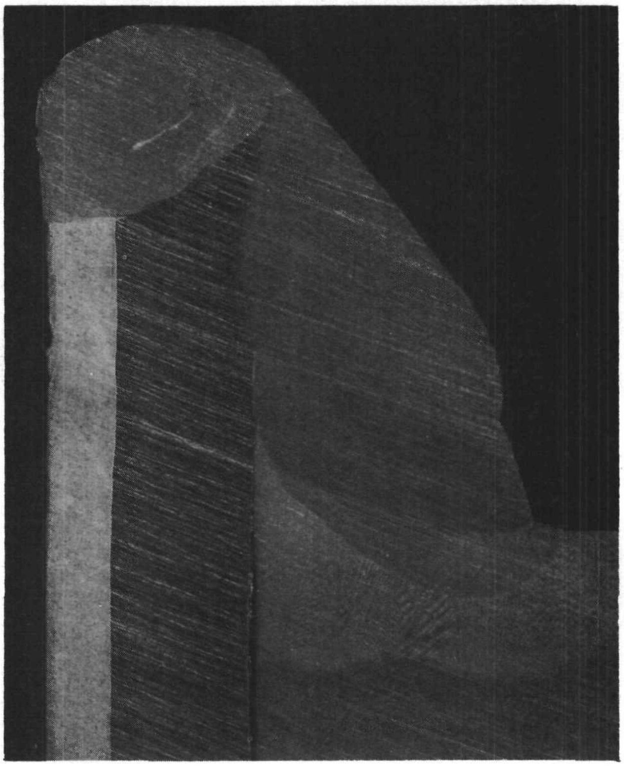


Figure 4-7

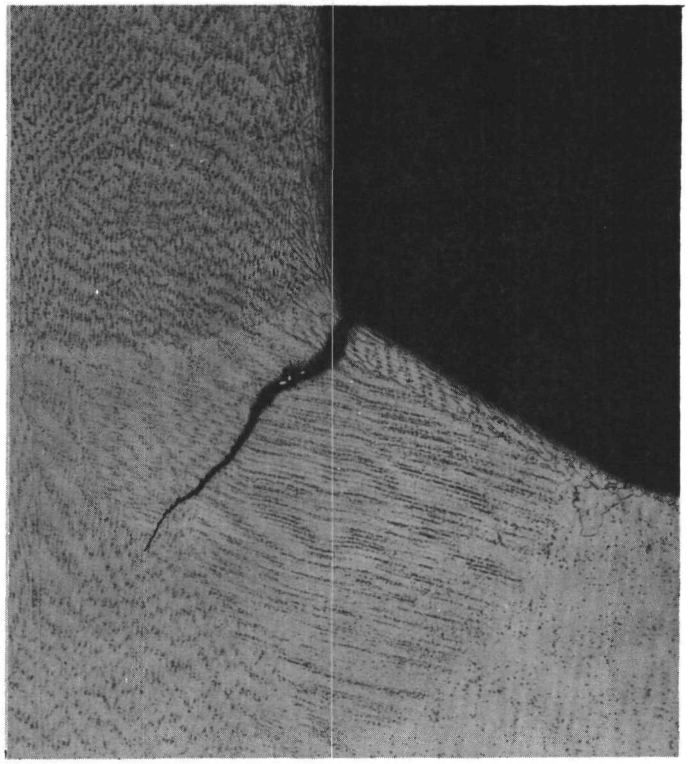
692565-6

Dye Penetrant Inspection of Initial Steam Generator Tube-to-Tubesheet Weld Shock Specimen Prior to Testing.



1324B 7X

A. Photomacrograph of Typical Composite Tube Joint Weld.



19B 100X

B. Microstructure and Crack at Toe of Weld and Overlay.

Figure 4-8

Cross Section of Composite Tube-to-Tubesheet Joint Obtained from the Initial Shock Test Specimen Assimilating the Steam Generator Tubesheet. The Crack shown was the Largest Observed (.016 Inch Deep).

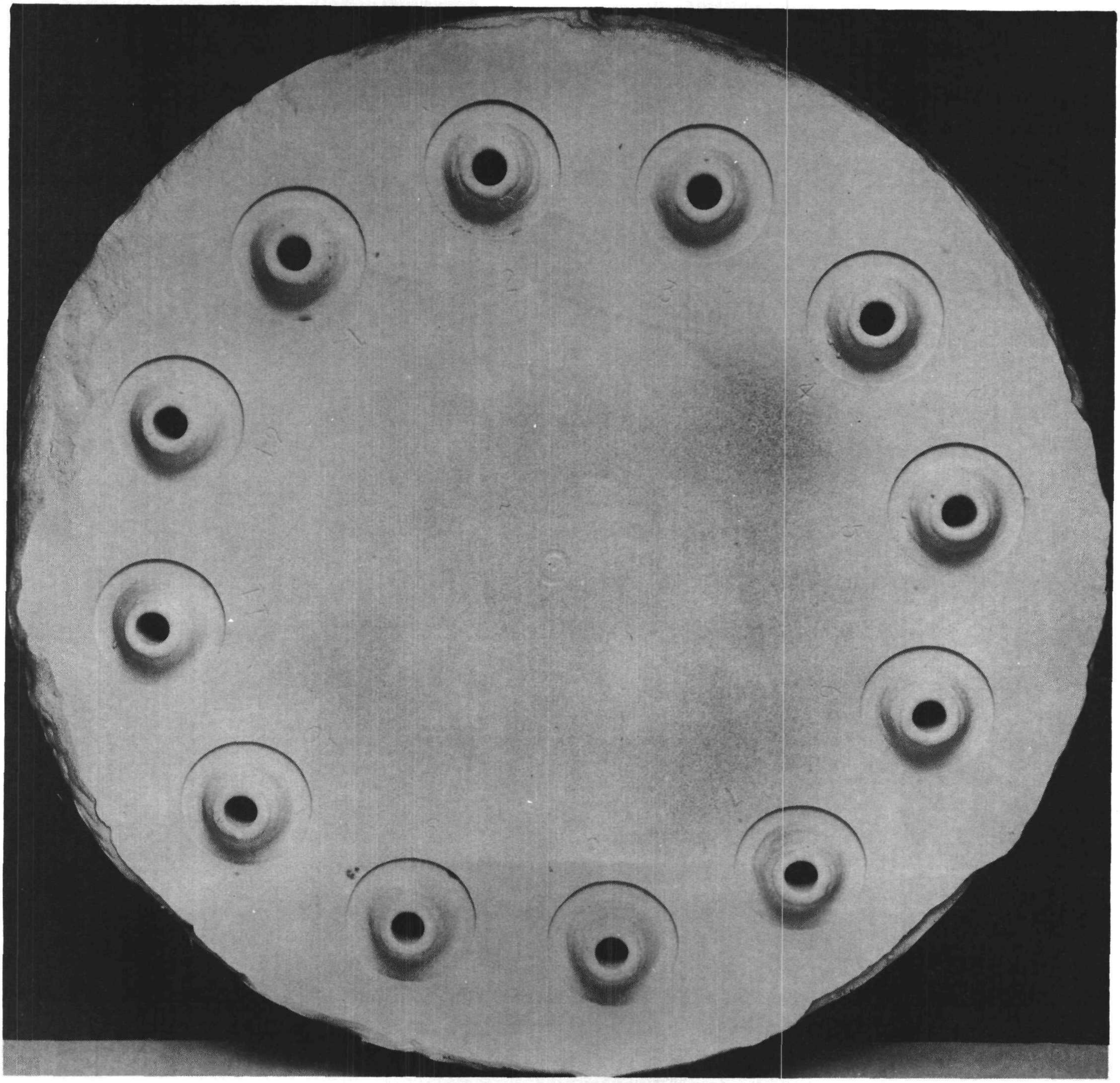
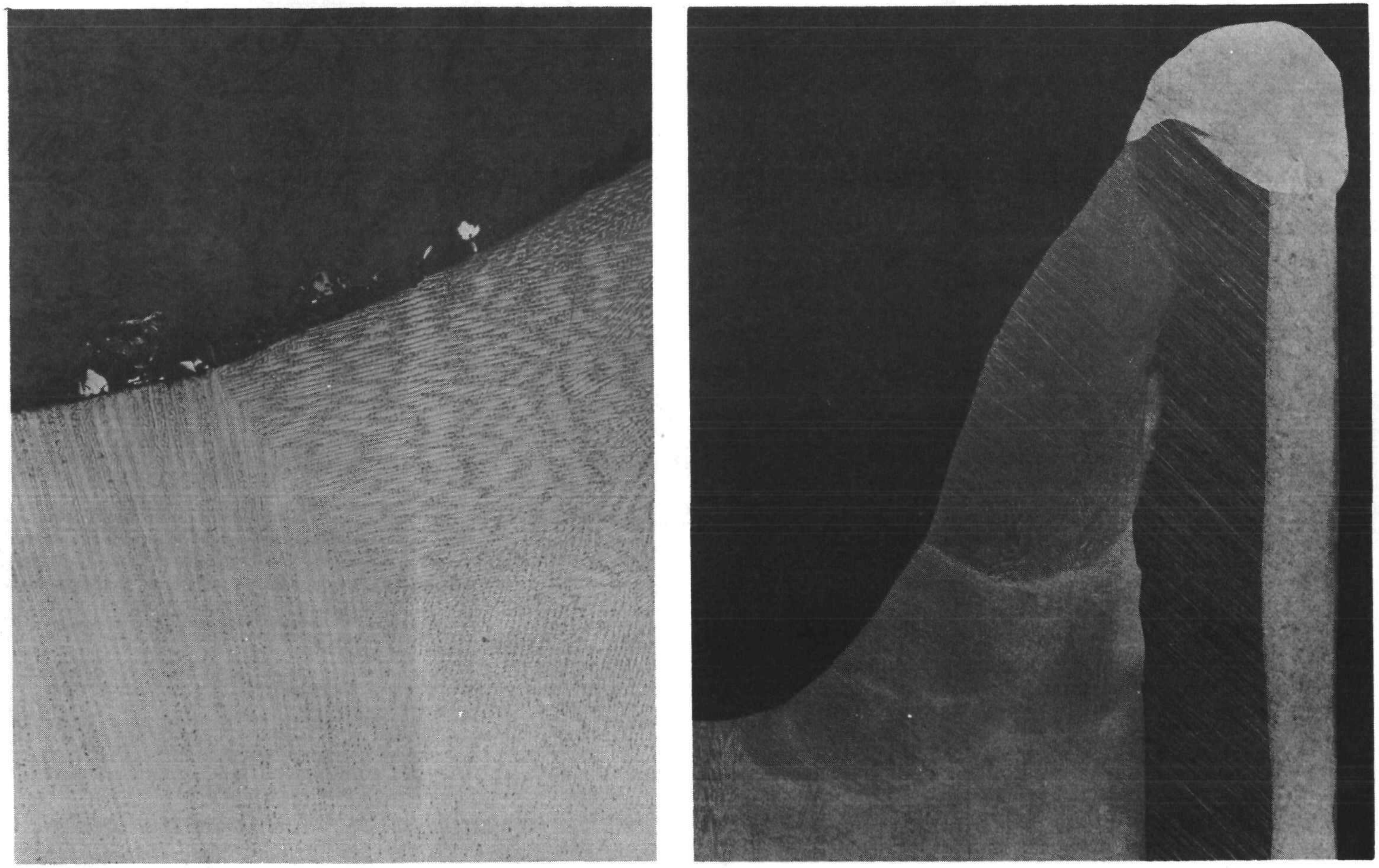


Figure 4-9 1329

Dye Penetrant Inspection of Final Steam Generator Tube-to-Tubesheet Weld Shock Specimen Prior to Testing.



20A 100X

A. Microstructure at Weld Toe.

1321C 10X

B. Photomacrograph of Typical Composite Tube Joint Weld.

Figure 4-10

Composite Inconel - Type 316 Tube to Inconel Overlaid Tubesheet Weld Joint Typical of those Sectioned from the Final Shock Test Specimen Assimilating the Steam Generator Tubesheet. Note Smooth Transition of Weld to Overlay.