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RESEARCH AND DEVELOPMENT PROGRAM

TASK X

ROLLING AND WELDING TYPE 430M TUBES TO STAINLESS STEEL OVERLAID CARBON STEEL TUBESHEETS

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SUMMARY

In the fabrication of the steam generator on APPR-1A it was considered necessary to roll the Type 430M tubes into carbon steel tubesheets to ASTM Specification A350-Grade LF-1, modified with 1.66% nickel; and weld the tube ends to the stainless steel overlay previously applied to the tubesheet. The rolled joint was a necessary precaution to prevent secondary water, that might contain chlorides, from contacting the stainless steel weld joining the tubes to the tubesheets. The welded joint provided the mechanical strength for attaching the tubes to the tubesheets. This laboratory program was conducted, therefore, to develop practicable procedures for welding the Type 430M tubes to the stainless steel overlay; as well as to assure that the tubes could satisfactorily be rolled to the tubesheets.

Automatic and manual tungsten-arc welding procedures were developed that were capable of consistently providing an austenitic weld having a strength exceeding that of the heat affected zone or the unaffected tube itself.

Type 430M tubes in the "as-received" and softened conditions were rolled into prototype test units under various conditions of rolling. It was concluded that the Type 430M tubes in the "as-received" condition could be satisfactorily rolled into the A350-Grade LF-1 tubesheet and be tight to a pressurized helium leak test.

To translate the laboratory procedures into fabrication practice for the steam generator consisting of the same materials, detailed welding and rolling procedures were outlined and transmitted to the fabricator, as well as included in this report.

INTRODUCTION

Engineering specifications for the steam generator on APPR-1A initially specified a Type 430M weld metal overlay on the tube side of the carbon steel tubesheet. Type 430M tubes were to be welded to this tubesheet overlay in order to provide a full strength leakproof seal between the tube side and shell side media. The basic purpose of utilizing these Type 430M materials, containing 16% chromium, 1% nickel and less than .03% carbon, was to provide optimum resistance to chloride stress corrosion that could occur in the crevice on the shell side of the tubesheet from the secondary water.

The application of a Type 430M weld metal overlay on carbon steel was considered conducive to metallurgical problems resulting from the dilution of the applied weld metal with the tubesheet base material. Essentially, the pick up of carbon from the tubesheet and its combination with the chromium from the overlay metal would be conducive to the formation of hard brittle structures in the weld and fusion zone. This could result in cracking that may not be detected by normal nondestructive testing. The welding of

Type 430M tubes to such an overlay to provide a ferritic weld nugget having optimum resistance to chloride stress corrosion, could also present a difficult metallurgical problem from a welding, as well as thermal treatment, standpoint.

Although other organizations have conducted research on the overlay and tube joint welding problems involving the Type 430M materials, it was the general consensus of representatives of the Army Engineering Research and Development Laboratory, the Navy Department-Bureau of Ships, and ALCO PRODUCTS, INCORPORATED, that the limited information available, the difficulty in procuring materials of suitable composition for qualifying procedures and production purposes, and the time factor required to meet production schedules required that a potentially more foolproof procedure should be developed and a change made in the engineering specifications.

Under AEC Contract No. AT(30-3)-326, Paragraph C, Section 1 of Article II, Task X, ALCO was authorized to conduct a development program that would result in suitable fabrication procedures and would assure satisfactory fabrication of the APPR-1A steam generator as well as meet all the applicable codes of the APPR-1A construction contract, DA95-507-ENG-1116.

The specific objectives and scope of the work to be performed under this contract were:

1. Perform necessary development work on rolling Type 430M tubes into carbon steel tubesheet material.

2. Perform necessary development work on welding Type 430M tubes to an austenitic overlay on a carbon steel tubesheet.

This report describes the results of the laboratory program that resulted in the successful development of procedures for rolling the Type 430M tubes into the carbon steel tubesheet that would be tight to a helium leak detector test.

Practicable and metallurgically suitable manual and automatic welding procedures were developed for successfully welding Type 430M tubes to a stainless steel overlay and having a weld composition essentially the same as the overlay on the tubesheet.

Mechanical tests on the welded tube-to-tubesheet joints and thermal cycling tests were conducted to establish the strength, quality and integrity of the welded joints.

Shop fabrication procedures have been written and transmitted to the fabricator of the APPR-1A steam generator to avoid any delay in the fabrication schedule. These procedures are also included in this report.

MATERIALS

TUBING

The tubing used for the welding and rolling tests was obtained from two of the three lots of tubing to be used in the construction of the steam generator on APPR-1A. The tubing, identified by the proprietary name of Croloy 16-1, was obtained from the Babcock and Wilcox Company, Tubing Division.

This material, which is basically an AISI 430 steel, was developed by the Babcock & Wilcox research laboratory under Bureau of Ships Contracts NObs 67018 and NObs 72167. An adjustment in the chemical composition, consisting of adding 1% nickel and reducing the carbon content below .03%, provided improved resistance to chloride stress corrosion in aqueous environments.

The tubing, having a nominal size of 7/8" o.d. X 15 BWG, was purchased to ASME Specification SA-268-55, Type 430, modified with nickel and reduced carbon as described above, and having a maximum hardness of 90 Rockwell B. All tubes were ultrasonically tested and had a specified surface finish of 125 rms, or better.

TABLE A

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF TYPE 430 M TUBING

	B&W Heat 23380		B&W Heat 13876		
	Mill Report	ALCO Check	Mill Report	ALCO Check	SA-268-430M* Croloy 16-1
Carbon%	.022, .020	.023	.026	.030	.030 max.
Manganese %	.51, .57	.46	.67	.57	.75 max.
Sulfur%	.021, .020	.015	.016	.019	.030 max.
Phosphorus%	.020, .016	.027	.010	.026	.030 max.
Silicon %	.25, .20	.22	.41	.37	.50 max.
Chromium %	16.50, 16.64	16.21	15.37	15.25	14.0-16.0
Nickel %	1.02, .85	.88	1.09	1.04	1.0-1.5
Molybdenum %	-	.05	.09	.15	-
Copper %	-	-	.10	.09	-
Ultimate Tensile Strength, psi	85,200	75,230	87,600	-	60,000 min.
Yield Point, psi	74,700	64,010	71,400	-	35,000 min.
Elongation in 2", %	31	31.0	24	-	20.0 min
Rockwell B	78-80	90.5	82-88	89	90 max.

*The chemical composition limits recommended by B&W in "Investigation of Fabrication Procedures of Ferritic Stainless Steels, NObs 67018, Index No. N.S.-200-027, Fourteenth Progress Report, January 18, 1957".

TUBESHEET MATERIAL

The material used for rolling tests was forged steel from the same heat and having the same heat treatment as that used on the APPR-1A steam generator. The material was purchased to ASTM Specification A350-57T, Grade LF-1, modified with 1.66% nickel. Forging size was 12" X 17" X 5" thick.

TABLE B

CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF TUBESHEET

	Forging - ALCO Ht. #76840		Required Spec.
	Mill Report	ALCO check	A350-LF-1 mod.*
Carbon %	.13	.14	.30 max.
Manganese %	.78	.73	1.06
Phosphorus %	.025	.026	.04 max.
Sulfur %	.030	.030	.05 max.
Silicon %	.27	.21	-
Nickel %	1.65	1.66	1.5-2.0*
Ultimate Tensile Strength, psi	70,000	73,000	60,000 min.
Yield Point, psi	53,250	50,000	30,000 min.
Elongation 2", %	31.5	32.5	25
Reduction in Area,%	57.4	61.0	38
Rockwell "B"			
Surface	82	83	-
Cross section	-	86	-

*Nickel addition required to meet low temperature impact properties for materials having a thickness in excess of 5 inches. This modification was approved by the ASME Boiler Code, under Case Ruling 1255.

WELD OVERLAY ON CARBON STEEL

The steam generator for APPR-1A required welding of Type 430M tubes to a stainless steel overlaid carbon steel tubesheet. The tube-to-tube-sheet welding tests were conducted on carbon steel plate to ASTM Specification A212, Grade B, two inches thick; and the forged tubesheet material to Specification A350-Grade LF-1, modified as described above.

The stainless steel weld metal overlay was deposited using the same welding conditions, and the same heat and size of welding wire, used for overlaying the tubesheet for the steam generator.

The stainless steel overlay, which must meet the minimum alloy requirements for a Type 304 analysis, had the following nominal composition:

C.	Mn	Si	Cr	Ni
.07%	1.35%	.87%	22.5%	12.5%

WELDING WIRE

The welding wires for manual metallic-arc welding of the tubes-to-tubesheet were both to commercial specification as follows:

BARE WIRE

ASTM A371-53T	ER 310	1/16" diameter
ASTM A371-53T	ER 308L	1/16" diameter
ASTM A371-53T	ER 309	1/16" diameter

COATED ELECTRODES

ASTM A298-55T	E 309-15	3/32" diameter
ASTM A298-55T	E 308 ELC-15	3/32" diameter

WELDING TYPE 430M TUBES TO STAINLESS STEEL OVERLAID CARBON STEEL TUBESHEETS

THEORETICAL APPROACH

In welding dissimilar metals, the resulting chemical composition and metallurgical structure of the weld nugget can vary over a wide range, depending upon the relative amount of each of the base metals (and supplementary filler metals) melted during welding. Where the ratio of chromium-alloy tubes to the amount of stainless steel overlaid weld metal is high, a coarse grained ferritic weld would be predominant. Conversely, where this ratio was low, a completely austenitic weld would result. For this particular application, it was considered desirable for the weld nugget to be austenitic to avoid the low notch toughness that characterizes a high chromium ferritic structure. Furthermore, since the tubes were to be rolled into the tubesheet, the austenitic weld structure would not be subjected to the influence of chloride impurities in the shell side water that could cause deterioration by stress corrosion.

For predicting the relationship between the degree of dilution of the tube and tubesheet overlay materials while welding and the microstructure of the resulting as-deposited weld metal, the Schaeffler Constitution (1) (2)

NOTE:

Numbers indicating foot notes refer to Bibliography reference contained in the back of this report.

Diagram was used as shown in Figure 1. Assuming that a weld consisted of fusing equal parts of tube and stainless steel overlay, its resulting composition would theoretically be about 19.5% chromium, 6.5% nickel and .05% carbon. Reference to the Schaeffler Constitution Diagram (Figure 1) indicates that such a dilution and resulting composition should produce a metallurgical structure consisting of austenite, ferrite and martensite. This would be considered undesirable for this application. One of the austenite formers, such as the nickel content of the weld metal, must thus be increased sufficiently high to produce a predominantly fully austenitic weld. To assure a crack-free weld, it has been found desirable to retain about 5% delta ferrite in the austenitic weld matrix.[(1) (2)] A modification in weld metal composition may be achieved by either the addition of a supplementary filler metal, or by controlling the dilution by means of developing an applicable joint design and companion welding procedure.

The laboratory program for establishing a suitable procedure for welding Type 430M tubes to the stainless steel weld metal overlay to be used in fabricating the steam generator for APPR-1A was based on the foregoing theoretical approach. Because of the urgency for such a procedure, it was considered necessary to explore concurrently the automatic and manual inert gas shielded tungsten arc welding processes (hereafter referred to as tungsten-arc welding), as well as manual metallic-arc welding with coated electrodes (hereafter referred to as manual metallic-arc welding).

WELDING PROCESSES AND JOINT DETAILS

All tube-to-tubesheet weld tests were made on simulated tubesheets of A212, Grade B carbon steel two inches thick overlaid with stainless steel weld metal having a uniform nominal composition of: 22.5% chromium, 12.5% nickel, and .07% carbon. The overlay was machined to provide a thickness of 1/4 inch. The holes in the tubesheet were drilled to a 7/8 inch nominal diameter on a 1-1/8 inch triangular pitch layout, thus providing a 1/4 inch ligament. These conditions were exactly the same as those specified for the APPR-1A steam generator. Since it is feasible to position the steam generator during fabrication, all test welds were made with the tubesheet horizontal and the tubes vertical. Such positioning is conducive to more uniform welding, because of better control of the weld puddle and the degree of penetration.

Test welds were made by the automatic and manual tungsten-arc welding processes and the manual metallic-arc process. For each test, a sufficient number of welds were made to assure reproducibility of the conditions being tested. The welded joints were inspected visually for contour, uniformity and surface quality. The welds were then cross sectioned by cutting through the center of the tube-to-tubesheet joint. Sectioned joints were polished and examined macroscopically to evaluate the side and general soundness of the weld nuggets. Representative samples were prepared and subjected to microscopic examination to appraise the metallurgical structure of the weld, as well as the heat affected zone of the stainless steel overlay and Type 430M tubes.

AUTOMATIC TUNGSTEN ARC PROCESS- Automatic tungsten-arc welding was performed with a Revere, Model B, tube welding gun. This is a commercially available welding apparatus that consists essentially of a pilot that is inserted into the tube and a tungsten arc, shielded by a suitable inert gas, that circumscribes a circle around the periphery of the tube joint. The path of the arc can be concentrated at the proper location to provide the desired amount of melting of the tube and tubesheet materials by a radial adjustment.

A mixture of 75% argon and 25% helium was used as the shielding gas throughout this investigation. Such a mixture (established by past experience in welding similar materials) was conducive to obtaining the desired penetration with accompanying suitable arc stability.

Since the automatic tungsten-arc process does not readily permit the addition of supplementary filler metal, it was necessary to obtain the desired austenitic weld metal composition by a trial and error evaluation of various joint designs and variations in welding conditions, such as amperage, voltage, travel speed and point of arc concentration with respect to the tube joint. Schematic details of five of the basic joint designs used for these tests are illustrated in Figure 2. Welding conditions were varied for each joint until the most favorable dilution ratio and best resulting microstructure were obtained. The final welding conditions for each joint are also given in Figure 2.

Photomicrographs of the weld metal structures resulting from fusing the various ratios of overlay and tube material are shown in Figures 3, 4, 5, 6 and 7. It is apparent that by changing from joint styles 1 through 5 (Figure 2) there is an accompanying decrease in the ferritic and martensitic phases, and a progressive transition toward a predominantly austenitic weld structure containing the desired delta ferrite, as shown in Figure 7. The foregoing photomicrographs show the fusion line and heat affected zone at the stainless steel overlay to be uniform and essentially the same regardless of the joint design and the resulting weld composition.

The heat affected zone of the Type 430M tubes, however, shows grain growth immediately adjacent to the fusion line. Such grain growth is characteristic of a ferritic chromium stainless steel. The depth of this heat affected zone for automatic tungsten arc welds averaged about .030". This heat affected zone is considered to be the weak link in the tube-to-tubesheet joints and will be discussed later in this report.

The uniform weld nugget size and smooth surface with a contour blending into the inner tube wall made by the automatic tungsten-arc process are illustrated in Figures 8 and 9. From consistency studies, it was determined that a minimum weld size of 1-1/4T could be guaranteed and the overall average weld size would be 1-1/2T. See Figure 16.

MANUAL TUNGSTEN-ARC PROCESS - In welding the steam generator for APPR-1A, it is necessary to use manual welding methods in areas that are inaccessible to automatic welding equipment. It was, therefore, necessary to determine a weld joint design and welding procedure suitable for providing the necessary weld metal composition for joining the Type 430M tubes

tubes to the stainless steel overlaid tubesheet. Details of the joint styles investigated and the final welding procedure for producing satisfactory manual tungsten-arc welds are shown in Figure 10.

Various combinations of filler metal additions were used in order to assure that the weld metal joining the tube-to-tubesheet overlay was austenitic. In manual tungsten-arc welding, the human element is a basic factor whose limitations must be recognized. Since it is impossible to nondestructively evaluate the internal quality of a tube-to-tubesheet weld, it is often considered desirable for critical applications, such as for nuclear equipment, to deposit a second pass on all manual tube-to-tubesheet weld joints. This provides an interrupted leak path, as well as an added precaution against localized deficiencies. Since the stainless steel overlay on the tubesheet is required to meet the minimum chemical composition of Type 308 stainless steel, a Type 308L filler wire was used for all second pass welds to assure a uniform and compatible analysis of the metal on the face of the tubesheet.

Figure 11 is a photomicrograph of manual tungsten-arc weld using Type 309 filler metal for the first pass. The weld deposit is a complex structure, consisting of austenite, martensite and ferrite.

Figure 12 is a photomicrograph of a weld using Type 310 filler metal for the first pass. It may be seen that the weld metal is essentially fully austenitic as a result of the increased nickel content imparted to it from the filler wire. It can also be observed in both Figures 11 and 13 that the grain size in the heat affected zone of the Type 430M tubes is greater than that resulting from welds made by automatic tungsten-arc process, shown in Figure 7. (The reason for the dark etching of the heat affected zone for the Type 430M tubes in Figures 11 and 12 was not investigated. It is believed, however, to be a result of heating while depositing the second weld pass.)

This increased grain growth is attributed to the tube material being subjected to elevated temperatures for a sufficiently long period of time to make such a change occur. This is a direct result of higher energy input during welding. Figure 12 also shows the location at which fracture occurred in tube pull out tests to evaluate the strength of tube-to-tubesheet weld joints. This aspect will be discussed in a later portion of this report.

Typical weld cross sections and the surface appearance of the manually deposited tungsten-arc welds are shown in Figure 8, 9 and 17. These welds, as their automatic tungsten-arc counterpart, are considered to be sufficiently smooth with a contour blending into the inside tube wall without resorting to any surface conditioning. By using joint style 8 and the welding conditions specified (Figures 10 and 17), a weld size having a 1-1/4T minimum and an average weld size of 1-1/2T or larger can be assured.

MANUAL METALLIC-ARC WELDING - Often times manual metallic-arc welding with coated electrodes becomes the preferred method for making tube-to-tubesheet joints of dissimilar metals. Proper choice of electrodes and electrode coating, along with careful joint design are required to assure a weld of consistent and suitable quality.

The manual metallic-arc process generally has less heat input per inch of weld than the manual tungsten-arc process, because of its faster rate of arc progression. The lower heat input is desirable to inhibit grain growth in the heat affected zone of the Type 430M tubes, as well as keep the degree of base material dilution to a minimum. The manual metallic-arc process, however, has the definite disadvantage of less precise operator control that may result in nondetectable slag inclusions, minute porosity, incomplete fusion, and uncontrolled roll over. For this reason, a two pass weld is generally specified for tube joints welded by this process.

Because of the limited time to develop a suitable tube-to-tubesheet welding procedure to meet the production schedule for the steam generator, the manual metallic-arc welding investigation was conducted concurrently with the tungsten-arc investigations. The manual metallic-arc phase of the program was discontinued, however, when it became apparent that the tungsten-arc welding processes would be practicable and the welds metallurgically satisfactory.

The work conducted, however, resulted in a procedure that could be used, if necessary, but had several characteristic drawbacks. The joint design used was the same as that for manual tungsten-arc welding, shown in Figure 10, Style 8. The first weld pass joining the Type 430M tubes to the stainless steel overlay was deposited with 3/32" diameter, Type 309 (25% chromium-12% nickel) electrodes.

From Figure 13, it can be observed that this weld metal contained sufficient nickel to produce a sound austenitic weld. The second pass of weld metal was deposited using Type 308L electrodes to produce a chemical composition essentially as required for the overlay.

From Figure 13, it can also be observed that the grain growth in the heat affected zone of the Type 430M tube was essentially the same as for automatically deposited tungsten-arc welds. (Figure 7), and was smaller than the grain size for manual tungsten-arc welds (Figure 12).

Figures 8 and 9 illustrate the cross sectional and surface appearance respectively of tube-to-tubesheet welds made by the manual metallic-arc process. It will be observed that the welds are rougher in surface appearance, as well as indicate more roll over on the inner surface of the tube, than those welded by the tungsten-arc processes. To meet the requirements for surface smoothness, it would be necessary to perform considerable grinding on the welds. This grinding could result in nondetectable damage caused by undercutting the weld or the tube.

COMBINATION AUTOMATIC-MANUAL TUNGSTEN-ARC WELDING - During production fabrication, there is always the possibility that repairs may be required because of failure of the mechanical aspects of equipment or the human element controlling the welding. Repair procedures were investigated, therefore, for both manual and automatic tungsten-arc welding.

Figure 14 illustrates a weld made by the automatic tungsten-arc process that failed to fuse the full tube wall thickness. Such a condition may be caused by slight eccentricities of the arc path, with respect to the tube joint, or because of tolerances within the tube itself and its relationship to the diameter of the pilot on the welding equipment. Visual inspection can easily detect this weld deficiency. It can be adequately repaired by refusing the entire circumference of the weld by the automatic tungsten-arc process. There is slight increase in grain size and heat affected zone depth in the Type 430M tube, as compared with the single pass automatic weld shown in Figure 7. This grain size and depth, however, is significantly less than obtained by a two pass manual tungsten-arc weld shown in Figure 12. This repair procedure for production welding is included in the fabricating welding procedure given in Figure 16.

For repairing gross porosity, or other major defects in the weld, it is generally necessary to carefully remove the defect with a milling or grinding tool. The repair can then be made by the manual tungsten-arc process by fusing a Type 310 filler metal into the repair area to assure a suitable austenitic weld where the tube fuses to the tubesheet. Applying a second manually deposited weld pass with a Type 308L filler metal provided a suitably repaired joint. Examination of the metallurgical structure and heat affected zone of such a repaired joint indicated that it was essentially the same as for a manually deposited tungsten-arc weld or an automatic tungsten-arc weld repair, as described above. Such a repair procedure for production fabrication is given in Figure 16.

WELD JOINT PROPERTIES

WELD SIZE - The APPR-1A specifications require the tube-to-tubesheet weld to have a minimum leak path of 1-1/4T, where T represents the tube wall thickness. The leak path is defined as the weld size measured from the fusion zone to the outside of the weld along the vertical interface of the tube and tubesheet. The average leak path obtained with the automatic tungsten-arc welds was 1.6T, while the manual two pass tungsten-arc weld had an average leak path of 1.5T. Figure 8 illustrates typical weld sizes that were consistently obtained by these procedures.

CHEMICAL COMPOSITION - Light surface cuts were carefully machined from a number of manual and automatic tungsten-arc welds for chemical analyses. The composition of the weld metals is given in Table C.

TABLE C

CHEMICAL COMPOSITION OF WELDS

Tungsten Arc Process	Sample	Composition Percent		
		Chromium	Nickel	Carbon
Manual	1	19.50	10.50	.056
Automatic	2	20.98	10.97	[illegible]
	3	21.16	11.07	.070
	4	20.90	11.17	.072
	5	21.20	11.07	.064
Overlay Composition	-	21.99	13.01	.077

From these analyses, it can be seen that the weld composition is essentially the same as that of the stainless steel weld overlay and is well above the minimum chemical composition for a Type 304 analyses required by the APPR-1A specifications.

The chromium and nickel equivalents of the basic alloying elements of the weld on the Schaeffler Constitution Diagram are located as shown in Figure 1. It will be observed that a proper dilution ratio of the stainless steel overlay to that of the Type 430M tube (and with Type 310 filler wire for manual tungsten-arc welds) was developed to produce an austenitic weld having essentially the desired 5% delta ferrite considered necessary to prevent cracking. The microstructure of the automatic tungsten-arc welds shown in Figure 7, and that of the manual tungsten-arc welds shown in Figure 12, are consistent with the results of the final weld composition plotted on Figure 1.

JOINT STRENGTH - For evaluating the strength of the welded tube-to-tubesheet joint (without rolling), tensile tests were made of joints welded by both the automatic and manual tungsten-arc processes. The strength of the joints and the fracture locations are given in Table D.

TABLE D

PULL OUT STRENGTH OF TUBE JOINTS

Tungsten Arc Procedure	Weld Joint(1) Style	No. Passes	Filler Metal	Tensile Strength Pounds	Tensile Strength PSI	Fracture Location
Automatic	4	1	None	13,500	74,200	Tube H.Z.
				14,350	78,900	Tube
Automatic	5(2)	1	None	14,050	77,200	Tube H.Z.
				14,200	78,000	Tube
Automatic	5(3)	1	None	14,050	77,200	Tube
				13,950	76,700	Tube
Manual	8	2	(310)	13,200	72,500	Tube H.Z.
			(308L)	13,000	71,400	Tube H.Z.
Automatic-Manual	5(3)	2	(None)	13,500	74,200	Tube H.Z.
			(308L)	13,850	76,100	Tube H.Z.
Min. Requirements for Type 430M Tube					60,000	

NOTES: (1) Refer to Figures 2 and 10 for joint style details.
(2) Tube inserted .090 inch.
(3) Tube inserted .110 inch

From these data, it is evident that the tensile strength of the joint was considerably above the minimum strength requirement for Type 430M tubing. It is further significant that failure occurred in the heat affected zone or in the tube outside of the heat affected zone, as shown in Figures 12 and 15. None of the tests indicated, as well as other tests, failed in the weld itself.

These tests further indicated that the coarse-grain heat-affected zone of the Type 430M tubes may have a slightly lower strength than that of the unaffected tube. This condition is a little more pronounced for the wider and coarser heat-affected zone adjacent to welds made by the manual tungsten-arc processes, or by the combination automatic-manual tungsten-arc process where two weld passes were deposited.

THERMAL CYCLING TESTS

Since the tube-to-tubesheet joints consist of dissimilar metals, there was expressed concern over the influence that thermal cycling might have on the joints. A simulated tubesheet of 2 inch thick A212-Grade B steel was overlaid with stainless steel weld metal and Type 430M tubes were welded to it by the automatic tungsten-arc, and manual tungsten arc and manual metallic-arc processes, as shown inFigure 9. The test sample was inserted into a furnace having a temperature of 500°F. After holding at temperature for one hour, the sample was removed from the furnace and placed on a refractory brick so that fan circulated air was applied directly to the weld face and through the tubes. After cooling to 100°F or lower, the test unit was again placed back into the furnace. The cycle was repeated twenty times. Dye penetrant inspection was performed on the welds after every four cycles. Upon completion of the twenty-cycle test, several welds deposited by each of the three processes were sectioned and examined microscopically. There was no evidence of cracking observed upon dye penetrant inspection or metallographic examination.

RECOMMENDED FABRICATION PROCEDURES

To finalize on the automatic and manual tungsten-arc welding procedures, qualification test plates, consisting of two-inch thick A212, Grade B steel having a stainless steel overlay, were welded in accordance with the qualification procedure set forth in the APPR-1A specifications. This qualification consisted of "minimum of four tube-to-tubesheet joints, using the exact conditions set forth in the welding procedure specifications submitted. The four joint clusters are to be surrounded by one circle of welds on the layout design and pitch that will be used on the production unit. The four inner tube joint clusters shall be welded after the outer circle of tube joint welds has been completed. The four inner joints shall be sectioned, as well as two joints in the outer circle and prepared for a microscopic examination".

The qualification welds made by both the manual and automatic tungsten-arc processes exceeded the minimum weld size of 1-1/4 times the tube wall thickness, and were completely sound and free of any detrimental deficiencies.

Based on the results of this investigation, and the qualification samples, the shop fabrication procedures were finalized, as shown in Figures 16 and 17.

ROLLING TYPE 430M TUBES TO CARBON STEEL TUBESHEETS

In considering the materials to be used for the steam generator construction on APPR-1A, serious consideration had to be given to the possibility of chloride stress corrosion under the conditions imposed during service. The use of ferritic materials appeared to be an immediate solution to the problem, as the austenitic chromium-nickel grades of stainless steel have shown an undesirable tendency toward stress corrosion cracking in aqueous environments containing the chloride ion. Since ferritic materials were specified on the original steam generator engineering drawings, it was not considered necessary for the tubes to be rolled into the tubesheet, as the full strength of the tubes-to-tubesheet joints would be developed by welding.

With the decision to change the overlay on the surface of the tubesheet from a Type 430M chromium ferritic alloy to an austenitic stainless steel, it became necessary to roll the tubes to the tubesheet. This operation being necessary to seal off the shell side water, which may contain chlorides, from reaching the austenitic tube-to-tubesheet weld joint. Although proper rolling of the tube-to-tubesheet should provide adequate holding strength, the welded joint was still considered the basic strength mechanism for securing the tube to the tubesheet.

The carbon steel tubesheet material to ASME Specification SA-350, Grade LF-1, was modified in accordance with Case Ruling 1255, which included the addition of about 1.6% nickel to improve its low temperature properties. The Case Ruling also permitted accelerated cooling from the normalizing temperature, in order to develop the metallurgical structures and strength properties required by the specification which normally obtain in smaller section sizes by cooling in still air. Accordingly, it would be impossible to significantly increase the hardness properties of the tubesheet. Since at the time of this investigation the Type 430M tubes had not left the tube manufacturer's mill, there remained the possibility that hardness modifications could be made, if there was an undesirable hardness relationship between the tube and tubesheet materials for proper rolling.

This phase of the laboratory program was directed toward evaluating the ability and limitations for Type 430M tubes to be rolled into the carbon steel tubesheet materials of the same composition and heat treatment as the materials to be used in construction of the APPR-1A steam generator.

ROLLING AND TESTING PROCEDURE

The success of a rolled joint is dependent upon the following basic conditions: The relative hardness of the tube to that of the tubesheet, cold working properties of the tube, the dimensional tolerances between tube and tube hole, and the manner in which the rolling is performed. In order to evaluate these factors, two prototype test units were made using two of the three heats of Type 430M tubes, and the same tubesheet material that will be used on the steam generator. (Refer to page 4, Materials.)

At the outset of this phase of the investigation, there were two basic avenues of approach that were considered. First, in a tube-to-tubesheet assembly involving both rolling and welding, it is necessary to roll the tubes first, when it is mandatory to test for 100% leak tightness of the rolled joints. Second, for best welding conditions, it is desirable to weld the tube joint prior to rolling, as adverse gas pressures can develop between the tube and tubesheet from the welding heat that may result in porosity at the closing point of the weld. Since the former course was essential for protection against possible chloride stress corrosion, this procedure was followed for the laboratory investigative program.

To simulate the conditions that could be experienced in the fabrication of the steam generator, two test units were made, as shown in Figures 18, 19 and 20. These units were essentially small pressure vessels, consisting of a tubesheet having a pressure shell welded to it. The tubes were joined to the tubesheet by rolling. The ends of the tube within the pressure shell were sealed, so that the tube-to-tubesheet joints could be tested by inserting pressurized helium gas through a coupling in the shell.

The Number One test unit had the tubesheet face overlaid with stainless steel weld metal that was finished to provide a 1/4 inch thick overlay for welding the tubes to it.

The tubesheet on the Number Two test unit was not overlaid, as tube welding was not included in that test.

The tubesheets were drilled and reamed to three different dimensions to provide variation in tube-to-tubesheet clearances, as shown in Figures 18 and 19. Several holes on the Number Two test unit were drilled with the automatic Lahr equipment using the actual drills made for drilling the tubesheet of the steam generator. It will be noted that the location of the tube-hole grooving was closer to the surface for the Number Two unit than for the Number One unit. Stress conditions that might possibly develop from the rolled and welded tubes require the grooving to be as close to the face of the tubesheet as possible. The location of the top groove, one half inch from the face of the tubesheet as used on test unit Number Two, avoided the point of overlapping of the adjacent roll passes that occurred on the Number Two unit that had the grooves cut one inch from the tubesheet face. The one half inch dimension was also far enough away from the point of welding so that it would not be affected by the welding heat.

The tubes were rolled into the tubesheet with an air operated manual-type tube rolling machine, using tapered rollers to provide a parallel rolling pattern. The effective rolling length of the rollers was 1-1/4 inches. The Number One test unit was rolled in two passes, whereas the Number Two unit was rolled to within 1/8 inch of the full tubesheet thickness.

From a welding standpoint, it is desirable to avoid the use of a rolling lubricant because of the possible contamination of the tube and tubesheet joint which could be conducive to defective welds. For some tubes, however, it is impossible to roll them properly without the use of a lubricant. Consequently, the influence of: (1) no lubricants, (2) a minute amount of distilled water, and (3) a water soluble compound having the trade name "KS-Lube-a-Tube", was applied to the rollers to study their influence on the effectiveness of rolling.

After completing the rolling, the shell side of the units were pressurized with helium gas. A helium leak detector was used to probe the face of the tubesheet to determine effectiveness of rolling and the tightness of the joints when rolled under the various conditions given in Figures 18 and 19.

After testing the rolled joints on test unit Number One, the tube joints were welded using the manual tungsten-arc procedure given in Figure 17. This unit was welded to determine whether the stresses that might develop during welding would disrupt the seal of the tube-to-tubesheets obtained from rolling.

The Number One welded unit was again pressurized with helium and tested. One half of the tube weld joints were then removed by machining across the face of the tubesheet, and resubjecting these tubes to the helium leak test, as shown in Figure 21.

Both test units were sectioned, as indicated in Figures 18 and 19, for further evaluation of the tube-to-tubesheet materials and the influence that rolling had upon them.

TUBE AND TUBE HOLE TOLERANCES

The tolerances between the tube and tube hole for commercial applications may range from .004 to .014 inch, because of permissible variations of the tube dimensions and the necessary machining tolerances for the finished hole. When the tolerances between the tube and tube hole is too small, difficulty may be encountered in inserting the tube into the tubesheet. On the other hand, where the tolerance is excessively high, tubes may not roll properly because of detrimental cold working properties. To determine the optimum tolerance for rolling Type 430M tubes to the carbon steel tubesheet, the tube holes in the two test units were drilled and reamed to produce nominal tube hole tolerances of .006, .009 and .012 inch for tubes having a measured diameter averaging .878 inch. The actual measurements of the tubes before and after rolling into tubesheet holes and calculations to show the amount of expansion after metal-to-metal contact, as well as total expansion of the tube, are given in Tables 1 and 2 (at the end of this report) and summarized in Table E on the next page

The Number One test unit was completely tight after rolling to a depth of 2-5/16 inches with two overlapping roll passes. Two different heats of tubing in the "as-received" condition were rolled into the A350-LF-1, modified, carbon steel tubesheet. The percentage total expansion average ranged from 3.00% for the .006 inch nominal clearance to 3.80% for the greater tube-to-tube hole clearance of nominal .012 inch. From these data, it appeared reasonable and practicable to set a specific limit of 3.75% total expansion, based on the following formula:

$$\% \text{ Total Expansion} = \frac{\text{Final Tube I.D.} - \text{Initial Tube I.D.}}{\text{Initial Tube I.D.}} \times 100$$

TABLE E

SUMMARY OF TUBE ROLLING EXPANSION DATA

Nominal Tube-to-Tubesheet Clearance, Inch	Percent Expansion					
	No. 1 Unit		No. 2 Unit			
	Drilled & Reamed		Drilled & Reamed		Lahr Drilled	
	Range	Average	Range	Average	Range	Average
% TOTAL EXPANSION						
.006	2.46-3.94	3.00	2.46-2.73	2.64	2.45-3.58	3.15
.009	3.00-3.68	3.31	2.87-3.72	3.16		
.012	3.42-4.23	3.80	2.72-3.00	2.79		
% EXPANSION AFTER METAL-TO-METAL CONTACT						
.006	1.49-3.10	2.21	1.75-2.17	1.98	1.21-2.73	2.18
.009	1.62-2.43	2.09	1.48-2.73	2.04		
.012	1.74-2.29	1.99	.90-1.62	1.23		

It is of interest to note that, while the percentage in total expansion increased with an increase in tube-to-tube clearances, percentage expansion after metal-to-metal contact has an inverse relationship, ranging from 2.21% to 1.99%. However, the fact that the tubes rolled satisfactorily and were leak tight to a helium test indicated that it was practicable to use a percentage total expansion figure of .375% maximum as a production control criterion.

The Number Two test unit was made to check the results of the Number One test unit. Upon sectioning the Number One test unit, it was found that the drilling and reaming operation had produced a phonographic finish, rather than a smooth tube hole that would be representative of the steam generator. The number two test unit, in addition to having drilled and reamed holes, had five holes that were made with the Lahr drill and the drilling tool made for drilling the production steam generator tubesheet.

Although all the tubes in the Number Two unit were from one heat, five of the tubes in this unit were of the "as-received" hardness (Rockwell B-90), whereas the remainder had been heat treated to the softest level possible (Rockwell B-78) for this material. The tube holes on this unit were smooth, and the tubes were rolled to within 1/8 inch of the full thickness of the tubesheet. The expansion data, however, were not as well defined as for the Number One unit. It is significant, however, that both the softened, as well as the harder tubes, were helium leak tight regardless of the expansion limits and the manner of drilling the tube hole.

The expansion after metal-to-metal contact was in the magnitude of 2 percent (with the exception of the data shown on the Number Two unit having a nominal .012 inch clearance). This means that the amount of working to complete the rolling was essentially the same regardless of the indicated tube hardness or the amount of initial expansion to obtain metal-to-metal contact.

EVALUATION OF ROLLING LUBRICANT

When tubes are required to be rolled to the tubesheet prior to welding, every precaution must be taken to assure optimum cleanliness of the contacting tube and tube hole surfaces. Contamination resulting from the use of an excessive amount of lubricant for the tube rollers could be conducive to welding difficulties and poor weld quality. On the other hand, extensive past experience has shown that when tubes are rolled dry, deterioration of the inner tube surface, as well as excessive roller breakage, both of which could affect the uniformity of the tube expanding process may occur. Three different conditions of rolling were included in the rolling tests investigated -- dry rolling, distilled water and a water soluble compound obtained under the trade name of "KS-Lube-a-Tube".

The Number One test unit was rolled with the foregoing lubricants for tubes of different tube-to-tubesheet clearances, as well as tube materials from two different heats, as detailed in Table 1. The Number Two unit, having both soft and hard tubes from one heat, was rolled using a minute amount of "KS-Lube-a-Tube" only. Refer to Table 2.

With the limited number of tubes rolled using the three different procedures, it was virtually impossible to obtain a true quantitative evaluation of the relative merits of the three procedures. By careful application of a very limited amount of the paste-like "Lube-a-Tube" compound directly to the rollers, followed by careful removal of the substance with a solvent after rolling, satisfactory rolling could be consistently obtained without any apparent detrimental contamination on the subsequent welding.

TUBESHEET HOLE FINISH

Fabrication of tubular heat transfer equipment generally specifies a drilled and reamed hole with a smooth surface. Such a hole finish is usually obtained by drilling and reaming, or by precision drilling on equipment such as a Lahr automatic horizontal drill.

It was considered desirable on this investigation for the test unit to have holes of the same smoothness that would be expected on the production steam generator.

The tubesheet on the Number One test unit was drilled and reamed to provide the desired tube-to-tube hole clearances. It was later found, however, that the reaming operation had produced a phonographic finish in the magnitude of about 225 rms. Since the tubes were indicated to be harder than the tubesheet material and other variables were involved (Refer to Table 1), the exact influence of this phonographic finish on the helium leak tightness of the Number One test unit was of definite concern. It was observed that the phonographic finish had made well defined impressions on the tube surface where they had been rolled into the tubesheet. Since this condition would be virtually impossible to reproduce on the production unit, a second unit was made with tube holes drilled and reamed to a very smooth finish. Part of the holes were also drilled on the Lahr machine using the same drill that would be used on the production unit. These tube holes had a smooth finish comparable to that of the drilled and reamed holes.

The Number Two test unit contained both soft and hard tubes. The tubes were rolled to within 1/8 inch of the full tubesheet depth and using the "KS-Lube-a-Tube" compound. This unit was also tight to a helium leak test. Complete data are given in Table 2.

Since both test units, having different tube hole serrations and rolled under a wide variety of conditions, were tight to a helium leak test, it was concluded that the surface finish of the materials involved was not of primary significance and that the surface finish of the holes on the production steam generator should be a smooth hole in accordance with past practice.

INFLUENCE OF HARDNESS

In rolling tubes to tubesheets on commercial heat transfer equipment, it is generally considered good practice to have the tubes softer than the tubesheet. The Babcock & Wilcox engineering reports on the Croloy 16-1 (Type 430M) tubing indicated that the hardness of such tubes may range from 64-94 Rockwell B. The tube manufacturer advised that the tubing for the steam generator would be on the high side of the range, and up to the maximum of the purchase specification limit of 90 Rockwell B. The surface hardness of the tubesheet material was Rockwell B-82, while cross section hardness measurements average Rockwell B 86.

The objective of this phase of the investigation was to determine if the tubes could be softened to improve their rolling properties and to evaluate the true tube and tubesheet hardness that would be expected on the production steam generator.

HEAT TREATING TESTS - Type 430M tubes, taken from two of the three lots of material to be used on the APPR-1A steam generator, were stress relieved at different temperature levels ranging from 1100°F to 1450°F. After holding at temperature for one hour, the tubes were removed from the furnace and air cooled. Hardness readings were made on the outside surface of the tubing using the Rockwell B and the Rockwell superficial hardness 30T indenters. The latter readings were converted to Rockwell B. The results of these tests, shown in Table F, indicate that maximum tube softness could be obtained at the 1300°F to 1400°F temperature levels. These values were significantly below the hardness of about Rockwell B-90 for "as-received" tubes.

TABLE F

INFLUENCE OF STRESS RELIEVING HEAT TREATMENT ON THE HARDNESS OF TYPE 430M TUBES

Heat and Sample No.	(1) Heat Treatment	Superficial Hardness Direct 30T	Superficial Hardness Converted Rkw B	Direct Rkw B
13876-1	1450°F	77-77.5	91-92	91-92
2	1400°F	73	84	81-82
3	1300°F	72.5	83	80-81
4	1200°F	72-73	83-84	81-82
5	1100°F	72-73	83-84	81-82
6	As-Rec.	74-76	87-89	87-90
23380-1	1450°F	68-69	77-78	75-76
2	1400°F	69-70	78-80	75-76
3	1300°F	69-71	78-81	75-76
4	1200°F	72-74	83-86	81-84
5	1100°F	73-74	84-86	84-85
6	As-Rec.	75-77	88-91	90-92

(1) Tubes inserted into warm furnace, brought to indicated temperature, held 1 hour and air cooled.

Additional tests were conducted at the 1300°F and 1400°F levels with holding times at temperature being one and two hours respectively. The results of these tests, given in Table G on the next page, indicate that maximum tube softness for B&W Heat 23380 was obtained at 1400°F and that the holding time was not significant. The data were also consistent with the results given in Table F. The tests conducted at 1300°F however, had the same hardness regardless of the holding time, but were higher than indicated for the tests recorded in Table F. The hardness level, however, was still essentially about ten points Rockwell B lower than the "as-received" tube hardness.

Tensile tests were conducted to make certain that the strength of the tubes was not below the 60,000 psi minimum set by the specification. Table G shows that this minimum limit was generally exceeded by a magnitude of over 5,000 psi.

TABLE G

MECHANICAL PROPERTIES OF TYPE 430M TUBES GIVEN DIFFERENT STRESS RELIEVING HEAT TREATMENTS (B&W Heat 23380)

Tube No.	Heat Treatment	Hold. Time(1) Hrs.	Yield Point psi	Tensile Strength psi	Elong. in 2" %	Superficial Hardness Direct 30T	Superficial Hardness Converted Rkw B	Superficial Hardness Direct Rkw B
1	1300°F	1	48,970	65,380	(2)	71-72	81-83	81-81
2	1400°F	1	40,480	64,830	40.5	70-72	80-83	74-76
3	1300°F	2	44,860	66,740	24.5	71-73	81-84	80-81
4	1300°F	2	42,950	65,100	33.5	70-73	80-84	74-76
5	As-rec.	-	64,010	75,230	31.0	75-77	88-91	91-91
Specified Minimum			--	60,000	20.0	-	-	90 max.

(1) All specimens air cooled.
(2) Failed near grips

From these tests it was concluded that by accurately controlled heat treatment, it would be possible to reduce the tube hardness to the same hardness level (or below) as the tubesheet (Rockwell B-82). It was also evident that different heats of the Type 430M materials may react differently and may require different temperature levels to achieve maximum softness.

For production tubing, it was considered possible that the tube ends may be softened without exposing the entire tube to heat treatment and the subsequent straightening operation that could again impart the undesired hardness to them.

WORK HARDENING CHARACTERISTICS - In rolling tubes to tubesheets, the tube upon expanding may show cold working tendencies that are reflected by increased hardness of the material. To evaluate the influence of cold working on the hardness of Type 430M tubing, hardness tests were conducted on longitudinal sections of the "as-received", and stress relieved tensile-tested tubes. (Figure 22). The results of hardness measurements taken at 1/4 inch increments from the point of fracture and correlated with reduction in tube wall thickness are shown in Table H.

TABLE H

INFLUENCE OF COLD WORKING ON THE (1)
HARDNESS OF TYPE 430M TUBES STRESSED TO FAILURE
(B&W Heat 23380)

Inches From Fract.	Wall Thickness AS Rec'd.	Wall Thickness S.R. 1400°F	Red. in Tube Wall Thickness % (2) As Rec'd.	Red. in Tube Wall Thickness % (2) S.R. 1400°F	Vickers (4) DPH-5gm As Rec'd.	Vickers (4) DPH-5gm S.R. 1400°F	Converted Rkw B As Rec'd.	Converted Rkw B S.R. 1400°F
0	.051	—	27.1	-	241	—	98	—
.25	.057	.053	18.6	24.20	246	234	99	98
.50	.063	.057	10.0	18.60	225	225	97	96
.75	.064	.058	8.6	17.20	229	187 (3)	97	89 (3)
1.00	.064	.058	8.6	17.20	229	208	97	93
1.25	.064	.062	8.6	10.40	226	219	96	96
1.50	.065	.063	7.2	10.00	225	221	96	96
1.75	.066	.063	5.7	10.00	225	178 (3)	96	87(3)
2.00	.068	.063	2.9	10.00	225	223	96	96
2.25	.068	.064	2.9	8.60	221	216	95	95
2.50	.068	.064	2.9	8.60	210	216	94	95
2.75	-	.065	-	7.20	-	214	-	95
3.00	-	.065	-	7.20	-	208	-	93
Control Hardness Data from Table A							90-92	75-76

NOTES:

(1) Refer to Figure 22. Tube No. 5 for "as-received" sample and Tube 2 for heat treated sample.
(2) Calculations based on tube wall thickness of .070 inch.
(3) Values appear to be erratic.
(4) Hardness

From these data, it can be observed that some increase in hardness from cold working occurred as a direct function of the reduction in tube wall thickness. The tube, stress relieved at 1400°F, showed a considerably greater amount of reduction in tube wall thickness over a greater depth of the tubing than the "as-received" tube. This is consistent with the data given in Table B showing an elongation of 40.5% for the stress relieved tube compared with 31% for the "as-received" tube. The control hardness data of the tubes prior to tensile testing indicate that the stress relieved, as well as the "as-received" tube, show a significant hardness increase as the result of the work hardening during tensile testing.

To correlate the foregoing data with the cold working that obtains during rolling of Type 430M tubes into tubesheets, Knoop microhardness traverses were made across the wall of tubing having measured total expansions of 3.28% and 3.70% respectively. The hardness results taken at several different rolling locations are summarized in Table I.

TABLE I

INFLUENCE OF COLD WORKING DURING ROLLING TYPE 430M TUBES INTO TUBESHEETS (B&W Heat 13876)

Location of Cross Section Hardness Traverse	Knoop Hardness Converted to Rkw. B — 3.28% Total Expansion O.D.	C.	I.D.	3.70% Total Expan. O.D.	C.	I.D.
Center first roll area	93.5	95.0	94.5	92.0	93.0	92.5
At serrations	91.5	95.5	93.5	93.0	93.0	93.0
Center second roll area	91.0	93.0	94.0	93.5	93.0	90.5
Unrolled tube	92.0	93.0	90.5	90.0	90.0	91.0

It is concluded from the tests indicated in the foregoing Table H and I, that the amount of cold working during rolling the "as-received" Type 430M tubes into the tubesheets is not significantly great to cause a detrimental increase in hardness.

TESTING FACTORS- During the course of this investigation, there appeared to be a wide variation in the true difference in hardness between the Type 430M tubes and the A350-Grade LF-1 modified material used for the tubesheet. This phase of the investigation was directed toward determining if these discrepancies occurred in the method of making hardness measurements or from an inconsistency in the materials themselves.

Tubes from two lots of material to be used on the production steam generator were subjected to hardness tests using Rockwell 30T, Vickers and Knoop indenters, whose values were then converted into Rockwell B values. Direct Rockwell B readings were also made. Standard test blocks having an accuracy of ± 1 Rockwell B number were used for control purposes. The hardness data are shown below in Table J.

TABLE J

INFLUENCE OF TESTING PROCEDURE ON HARDNESS READING RESULTS

		Heat 13876				Heat 23380		
		30T	Vickers	Knoop		30T	Vickers	Knoop
Test Location	Direct Rkw B	Conv. to Rkw B	Conv. to Rkw B	Conv. to Rkw B	Direct Rkw B	Conv. to Rkw B	Conv. to Rkw B	Conv. to Rkw B
Unpol. I.D.	87	89	-	-	88	93	-	-
Pol. I.D.	87	87	-	-	89	92	-	-
Long. Sect.	-	-	87	86	-	-	91	91
Unpol. O.D.	86	87	-	-	88	88	-	-
Pol. O.D.	86	87	-	-	87	88	-	-
Other Reference Data								
Unpol. O.D.	87-90	-	-	87-90	90-92	-	-	87-93
Cross Sect.	-	-	-	-	-	88-93	-	-

From the foregoing hardness evaluations for the various methods of testing, it did not appear feasible to develop correction factors for the different hardness testing methods. Probably more significant than testing factors are the normal hardness variations that appear between different heats of tubing, as well as tests made on different tube samples from the same heat.

Since the tubesheet for the production steam generator was in the process of fabrication, core samples were taken from the center and from the outer tube circle of the tubesheet. Rockwell superficial 30T hardness tests were made on the polished core sections. The hardness of the center core ranged from 85-92 Rockwell B, with an overall average of 88 Rockwell B. The hardness of the core from the outer tube circle ranged from 82-90 with an average of 87.6 Rockwell B.

These average Rockwell B hardnesses of the core samples correspond with the average Rockwell B hardness of 86 measured on the cross sectional face of the test plate that was representative of the material used for the production steam generator. It was apparent that the hardness of the internal portion of the tubesheet is about three to five points Rockwell B harder than the surface measurements reported by the mill and subsequently checked during this investigation.

RECOMMENDED ROLLING PROCEDURE

From the foregoing investigation covering the influence of rolling procedure, tube-to-tube hole clearances, tube hole finish and relative hardness of the tube-to-tubesheet, it was concluded that it was feasible to roll the Type 430M tubes in the "as-received" condition into the A350, Grade LF-1 modified tubesheet to provide a helium leak tight joint. A recommended rolling procedure for fabrication of the steam generator is given in Figure 23.

The true hardness measurements of the tube and tubesheet materials to be used on the steam generator were found to be within about the same hardness range. Since the rolling tests were satisfactory, regardless of the relative hardness variations for these specific materials, it was not considered desirable to take the risks involved to further reduce the hardness level of the tube ends by furnace stress relieving.

CONCLUSIONS

1. Type 430M tubes can be welded to an austenitic stainless steel overlay on carbon steel tubesheets by the automatic and manual tungsten-arc processes to produce austenitic welds of consistently adequate size (1.5T average) and quality to develop a joint strength exceeding that of the tube or its heat-affected zone.

2. The weld metal composition and microstructure can be accurately controlled by the joint design and welding procedure (which may or may not include the addition of filler wire) to produce an austenitic weld of essentially the same composition as the tubesheet overlay and containing about 5% delta ferrite.

3. A definite grain growth occurs in the heat affected zone of the tube immediately adjacent to the fusion line of the tube-to-tubesheet weld joint. This enlarged grain zone varies directly with the amount of heat input during welding. The strength of this heat zone is of about the same magnitude as the base tube and considerably higher (about 25% for the heat of tubing used for these tests) than the 60,000 psi minimum strength level specified for the Type 430M tubing.

4. Welded tube-to-tubesheet joints, subjected to thermal cycling tests imposing a more severe stress on the weld than that expected to be encountered by the APPR-1A steam generator in service, were found to be sound and free of any evidence of failure upon dye-penetrant inspection and microscopic evaluation.

5. Type 430M tubes in the "as-received" condition having an average hardness of Rockwell B-90, or in the softened condition (Rockwell B-80), can be satisfactorily rolled into A350-LF-1 modified tubesheet material having an average hardness of Rockwell B-82 to provide a joint that is leak tight to pressurized helium.

6. A total expansion limit of 3.75% was found to be a practicable production control criterion for rolling Type 430M tubes into the A350-LF-1 modified tubesheet. Nominal tube-to-tube hole clearances of up to .008 inch were considered optimum, although a maximum clearance of .013 inch can be permitted.

7. Type 430M tubes having an average "as-received" hardness of 90 Rockwell B could be softened 10 Rockwell B numbers (or more) by stress releiving heat treatment. Different heats of tubing appear to react differently and require different temperature levels to achieve maximum softness.

8. Type 430M material hardens from cold working. The amount of cold working during rolling Type 430M tubes into tubesheets is not significantly great to cause a detrimental increase in hardness.

9. Rolling and welding procedures considered suitable for joining Type 430M tubes to the stainless steel overlaid A350-LF-1 modified tubesheet on the APPR-1A steam generator are included in this report. All requirements set forth in the APPR-1A steam generator specifications were attained.

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FIGURES

Figures (cont.)

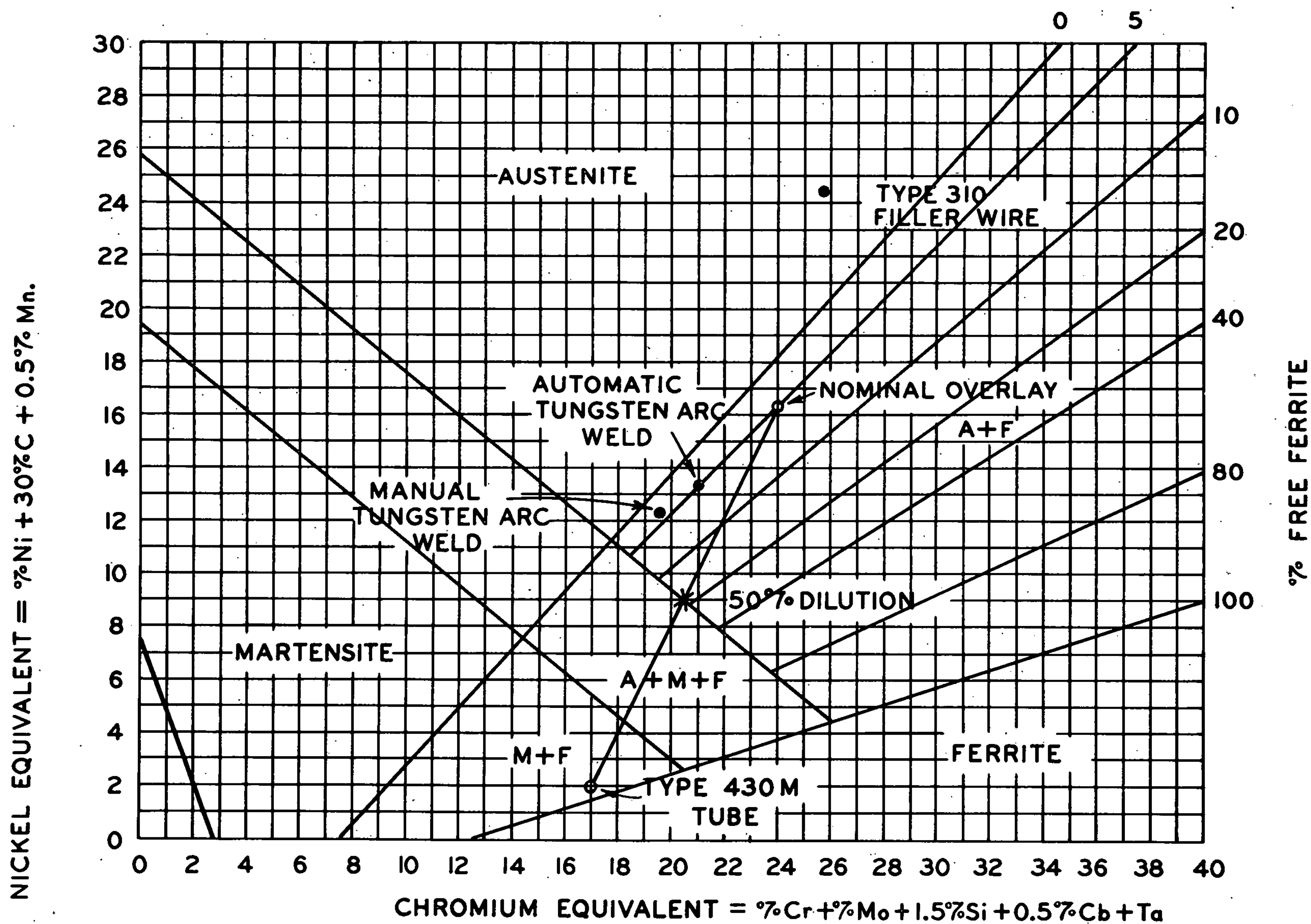


FIG. I CONSTITUTION DIAGRAM FOR AUSTENITIC WELD METAL SHOWING INFLUENCE OF DILUTION BY WELDING TYPE 430M TUBES TO STAINLESS OVERLAYS.

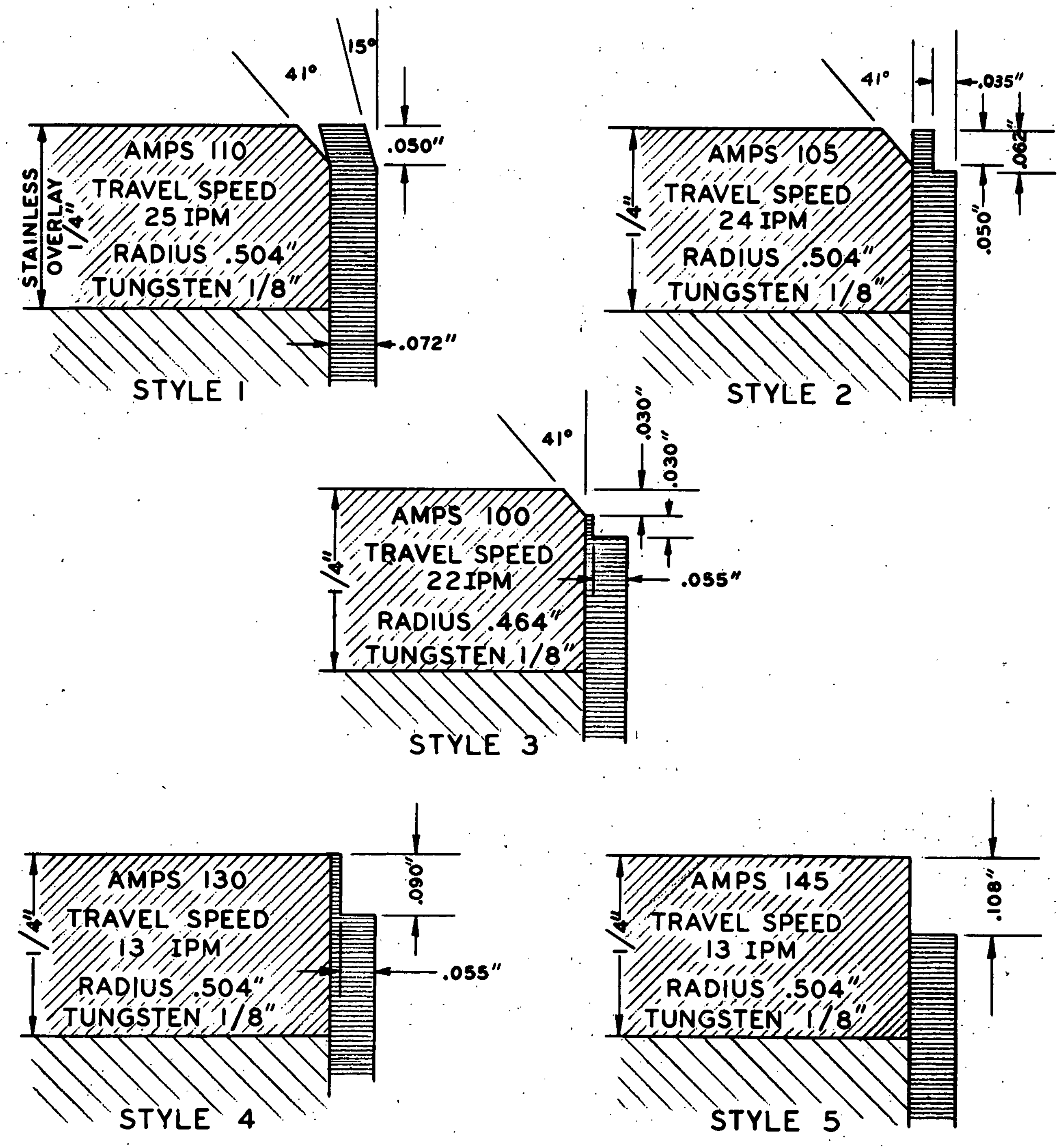
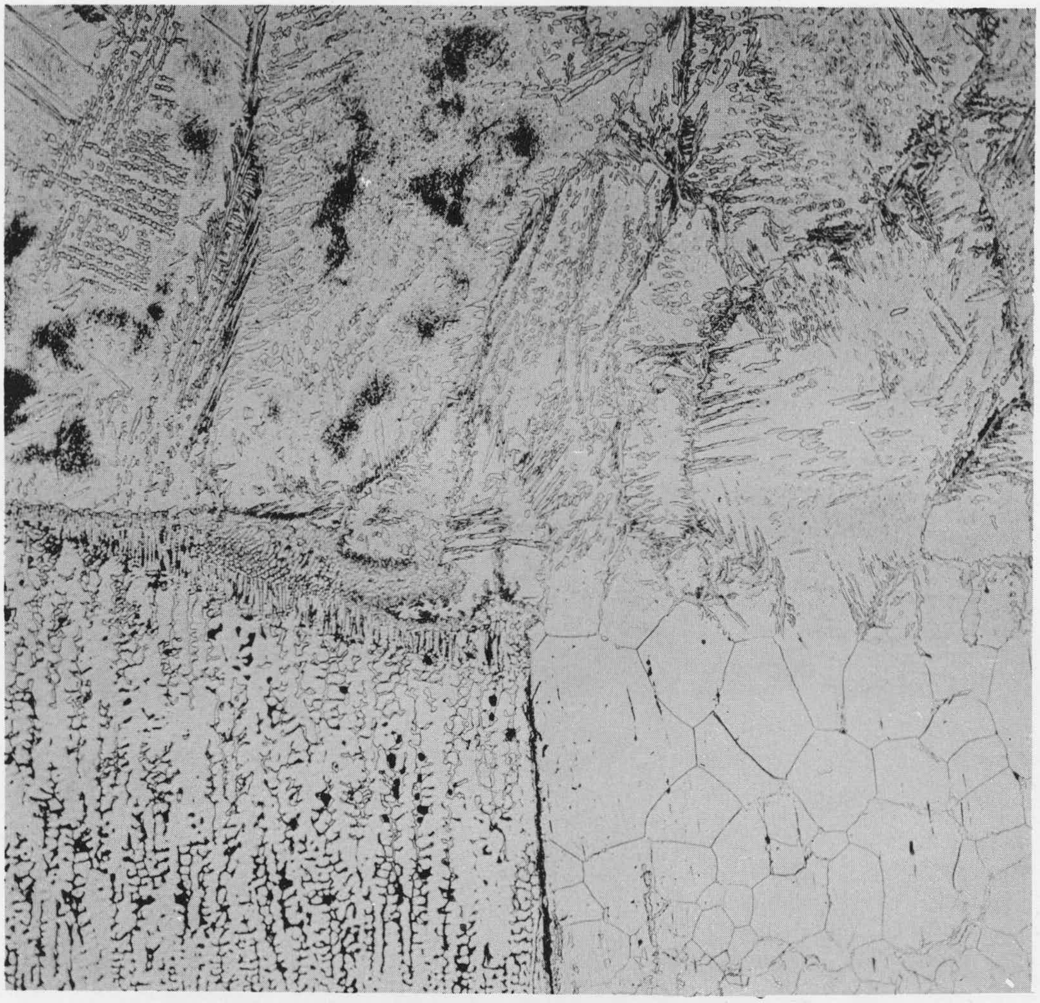


FIG. 2 DETAILS OF JOINT DESIGNS USED FOR AUTOMATIC TUNGSTEN – ARC WELDING TYPE 430 M TUBES TO STAINLESS STEEL OVERLAY.

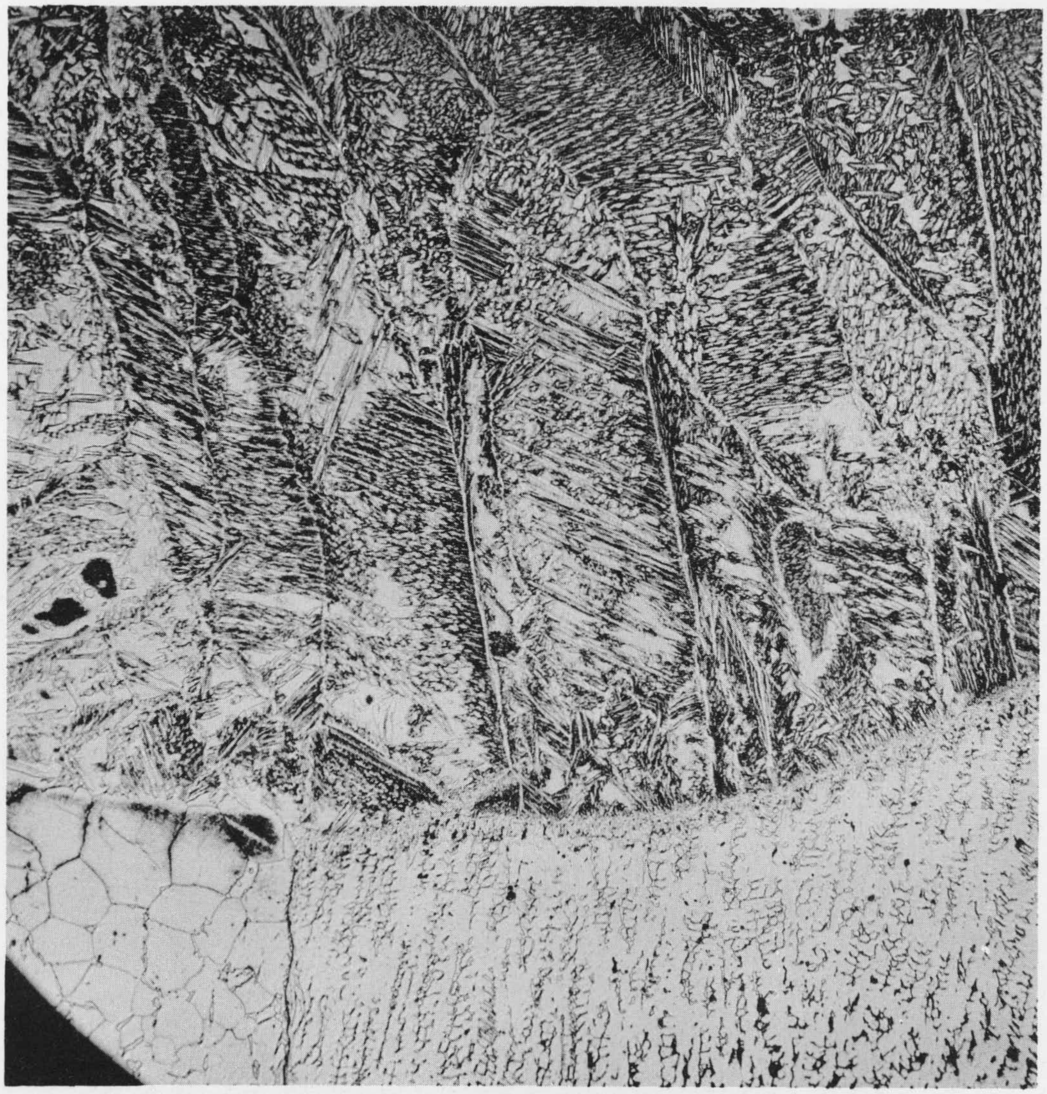
Weld Metal



2901 A 100X | Stainless Overlay | Tube | Etch 5% Chromic

Figure 3. Microstructure of Automatic Tungsten-Arc Weld Joining Type 430M Tubes to Stainless Overlay Using Joint Style 1 (Fig. 2). Complex Structure Predominately of Ferrite and Martensite.

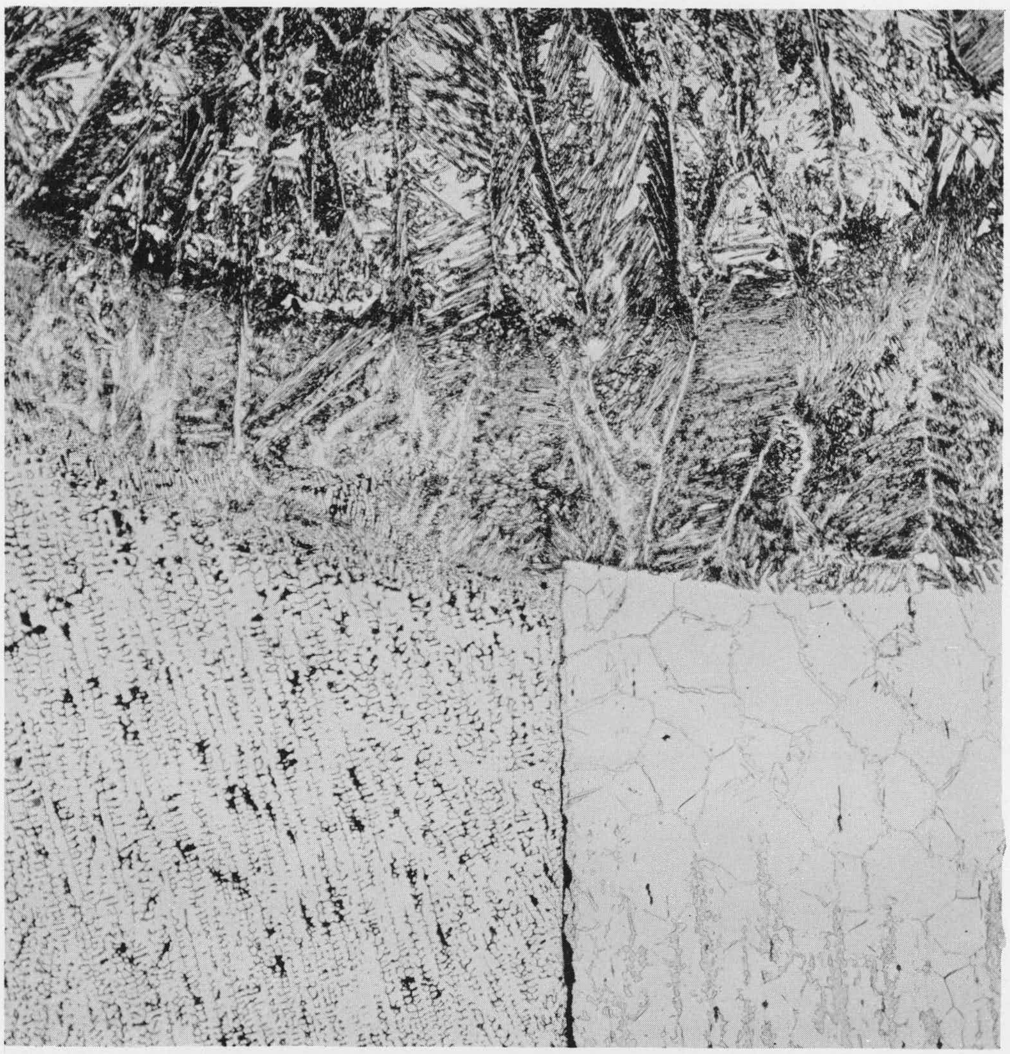
Weld Metal ↓



2901 B 100 X	↑ Tube	Stainless Overlay ↑	Etch 5% Chromic

Figure 4. Microstructure of Automatic Tungsten-Arc Weld Joining Type 430M Tubes to Stainless Overlay Using Joint Style 2 (Fig. 2). Complex Structure Predominately of Austenite, Martensite and Ferrite.

Weld Metal

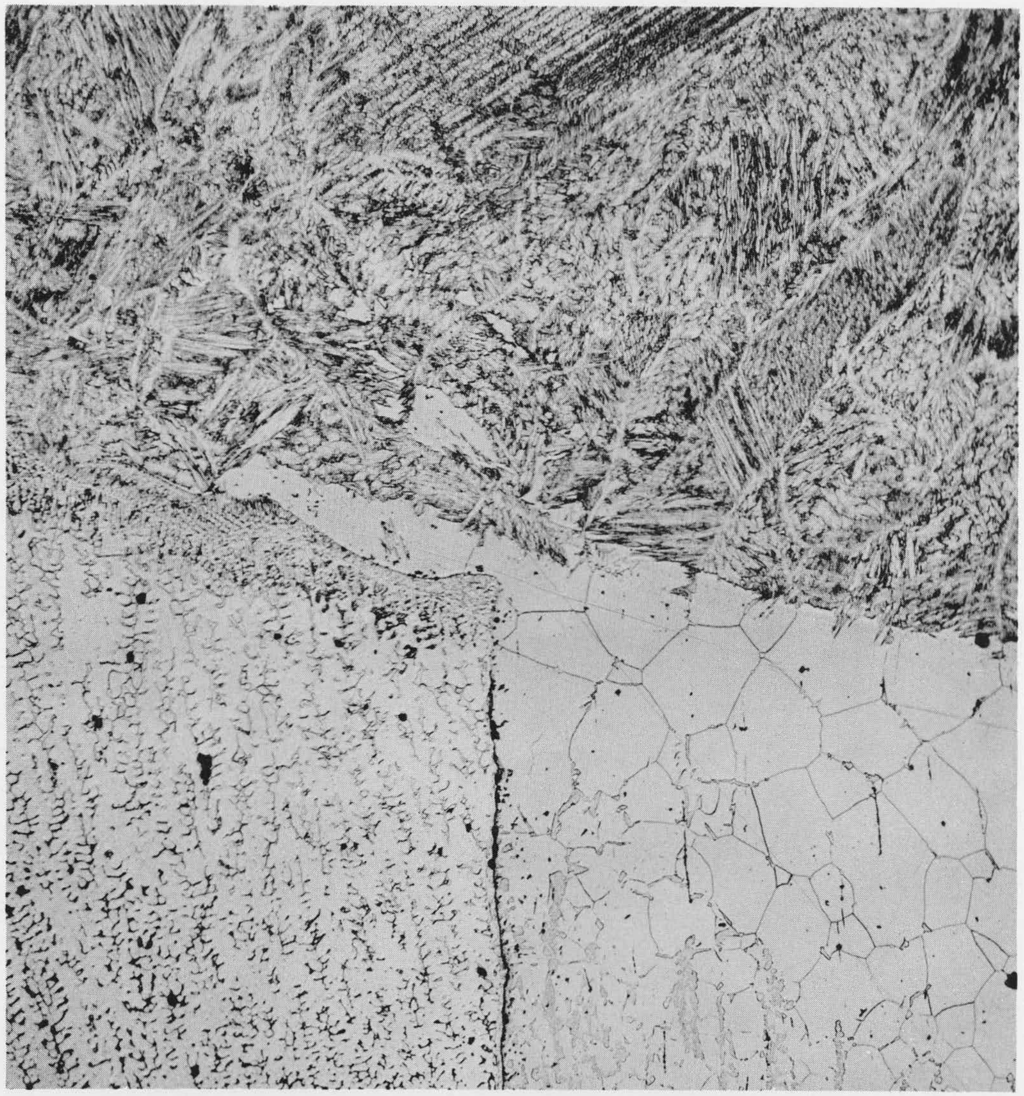


2901 C — Stainless Overlay — Tube — Etch

100 X — Overlay — 5% Chromic

Figure 5. Microstructure of Automatic Tungsten-Arc Weld Joining Type 430M Tubes to Stainless Overlay Using Joint Style 3 (Fig. 2). Complex Structure of Austenite, Martensite and Ferrite.

Weld Metal



2901 D
100 X

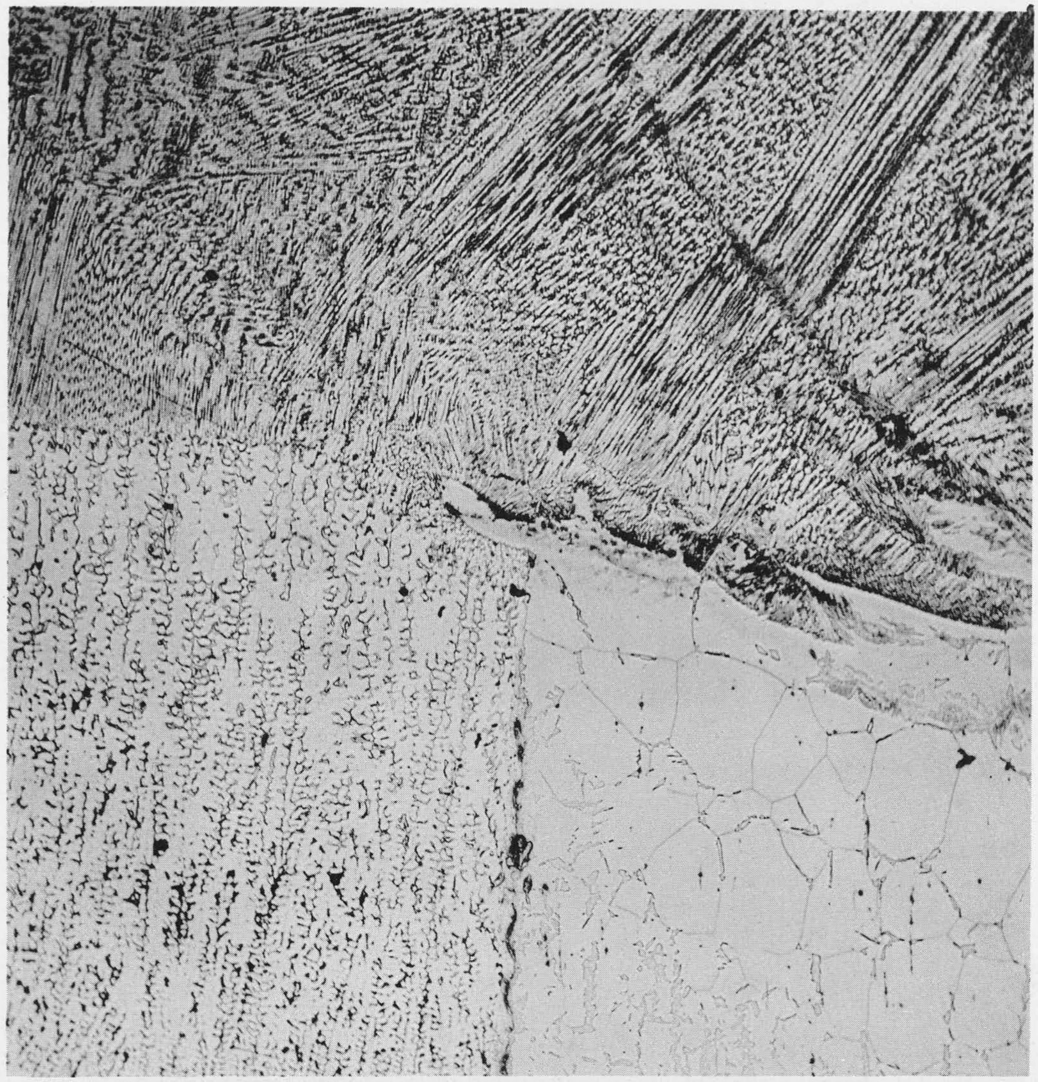
Stainless Overlay

Tube

Etch
5% Chromic

Figure 6. Microstructure of Automatic Tungsten-Arc Weld Joining Type 430M Tubes to Stainless Overlay Using Joint Style 4 (Fig. 2). Complex Structure of Austenite, Martensite and Ferrite.

Weld Metal



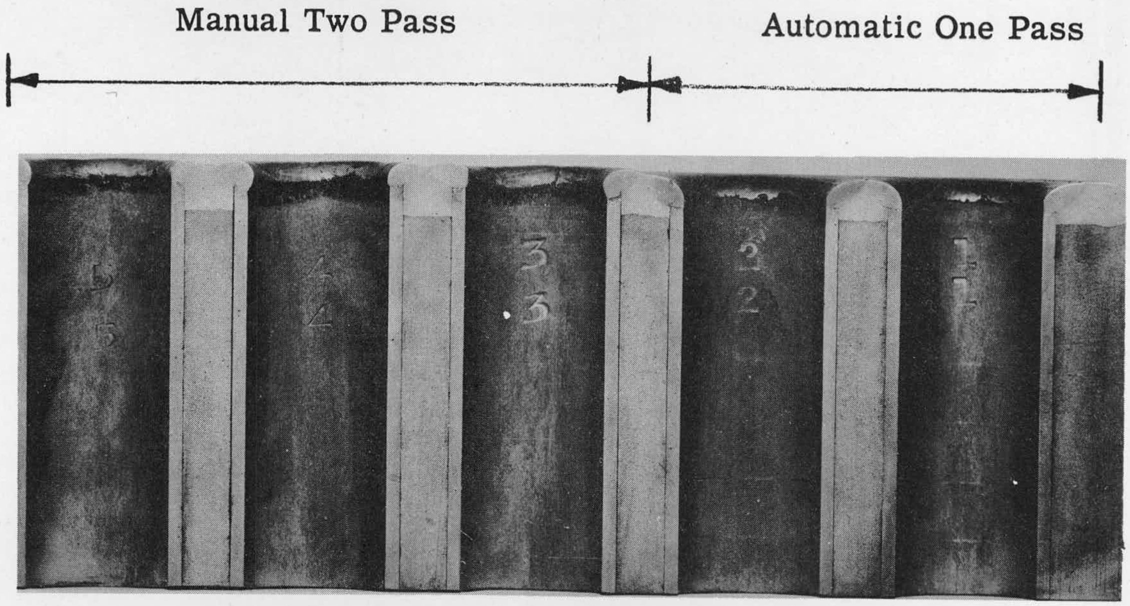
2901 E
100 X

Stainless Overlay

Tube

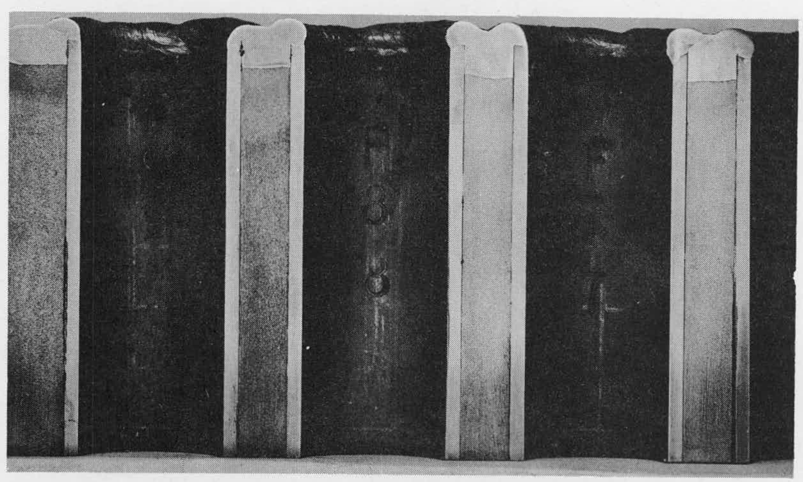
Etch
5% Chromic

Figure 7. Microstructure of Automatic Tungsten-Arc Weld Joining Type 430M Tubes to Stainless Overlay Using Joint Style 5 (Fig. 2). Structure Austenite With Some Delta Ferrite.



2901 F 1 X

A. Tungsten Arc Welds



2901 G 1 X

B. Manual Metal Arc Welds

Figure 8. Macrosection of Welds Made by Joining Type 430M Tubes to Stainless Steel Overlay

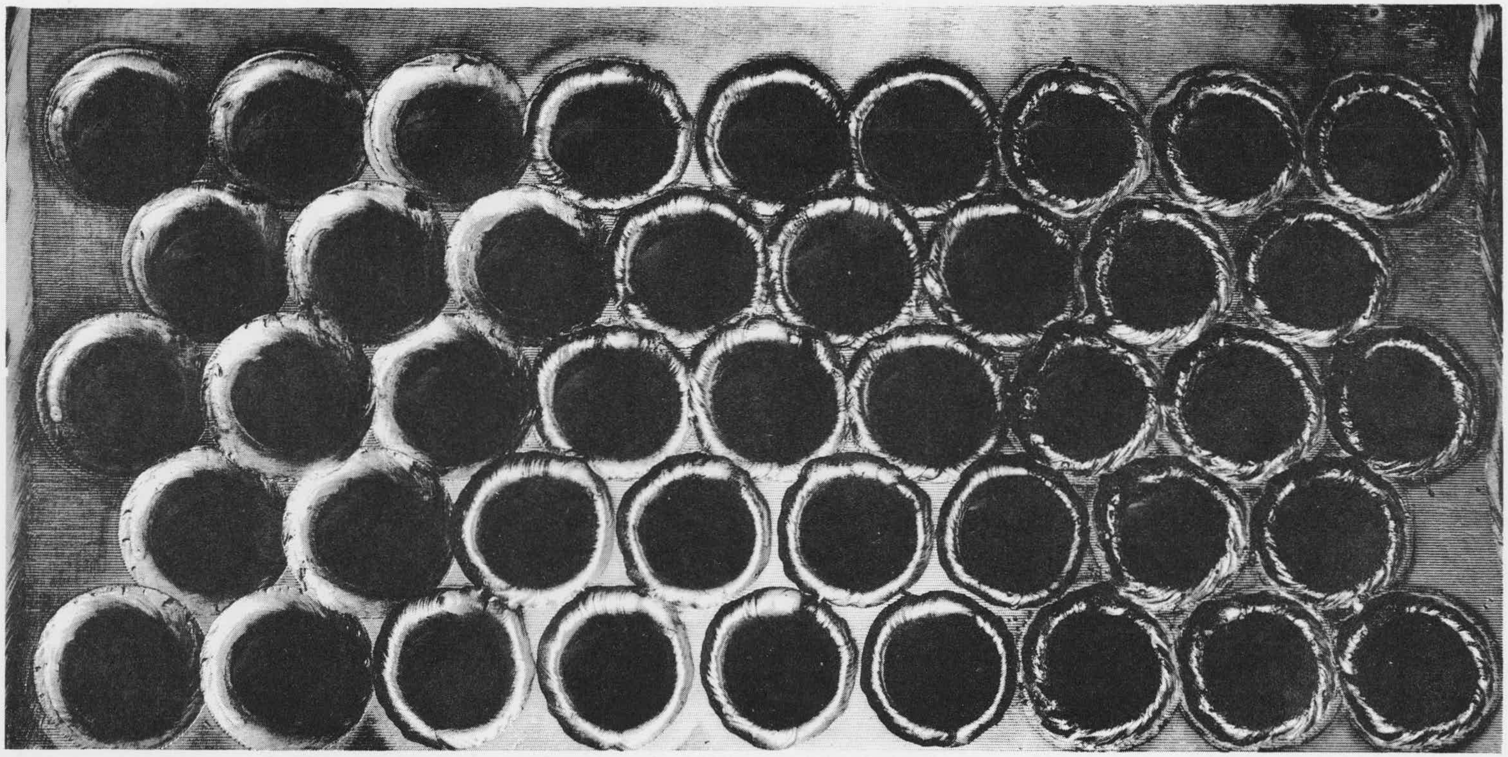


Figure 9. Surface Appearance of Welded Tube Joints Made Using the Tungsten-Arc and Metal-Arc Processes. This Sample Was Used for Thermal Cycling Tests.

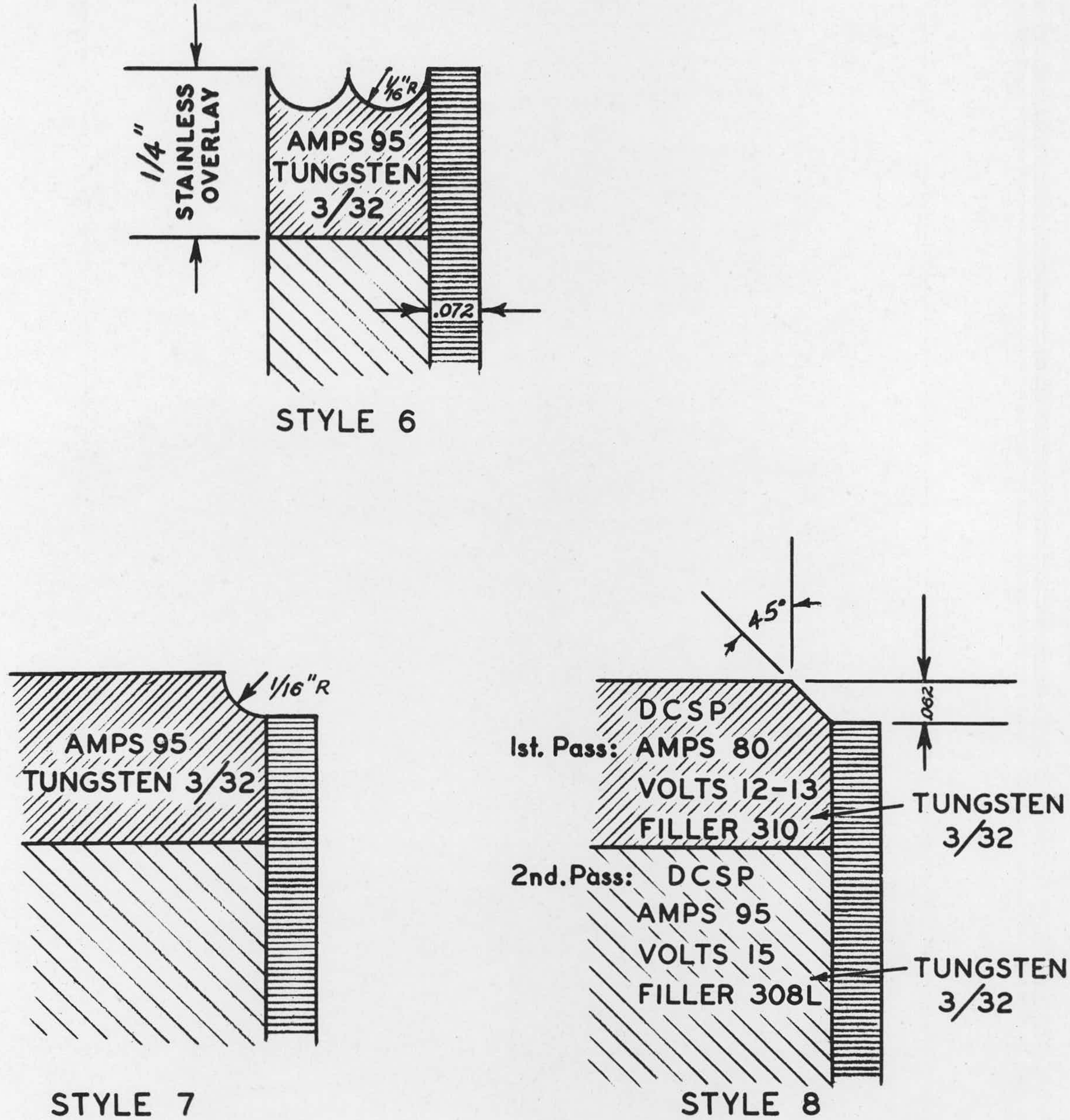
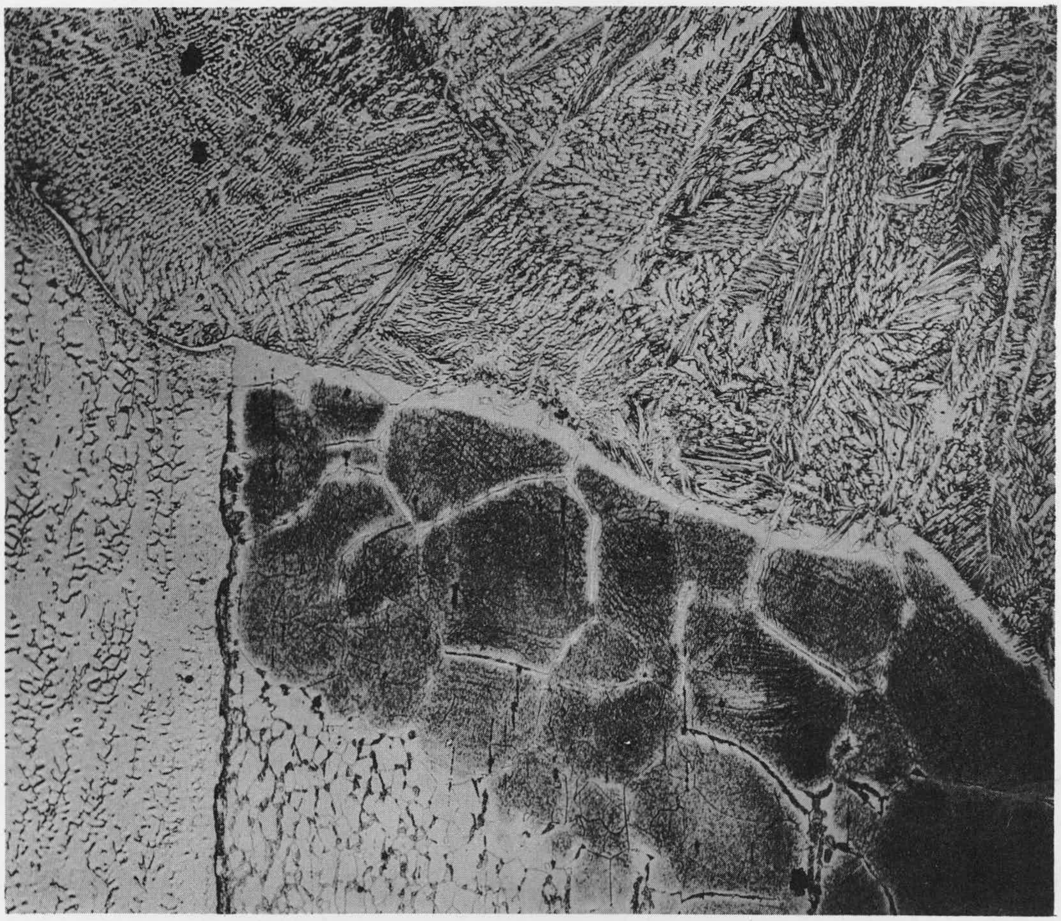


FIG. 10 DETAILS OF JOINT DESIGNS USED FOR MANUAL TUNGSTEN-ARC WELDING TYPE 430 M TUBES TO STAINLESS STEEL OVERLAY.

Weld Metal



2901 I
100 X

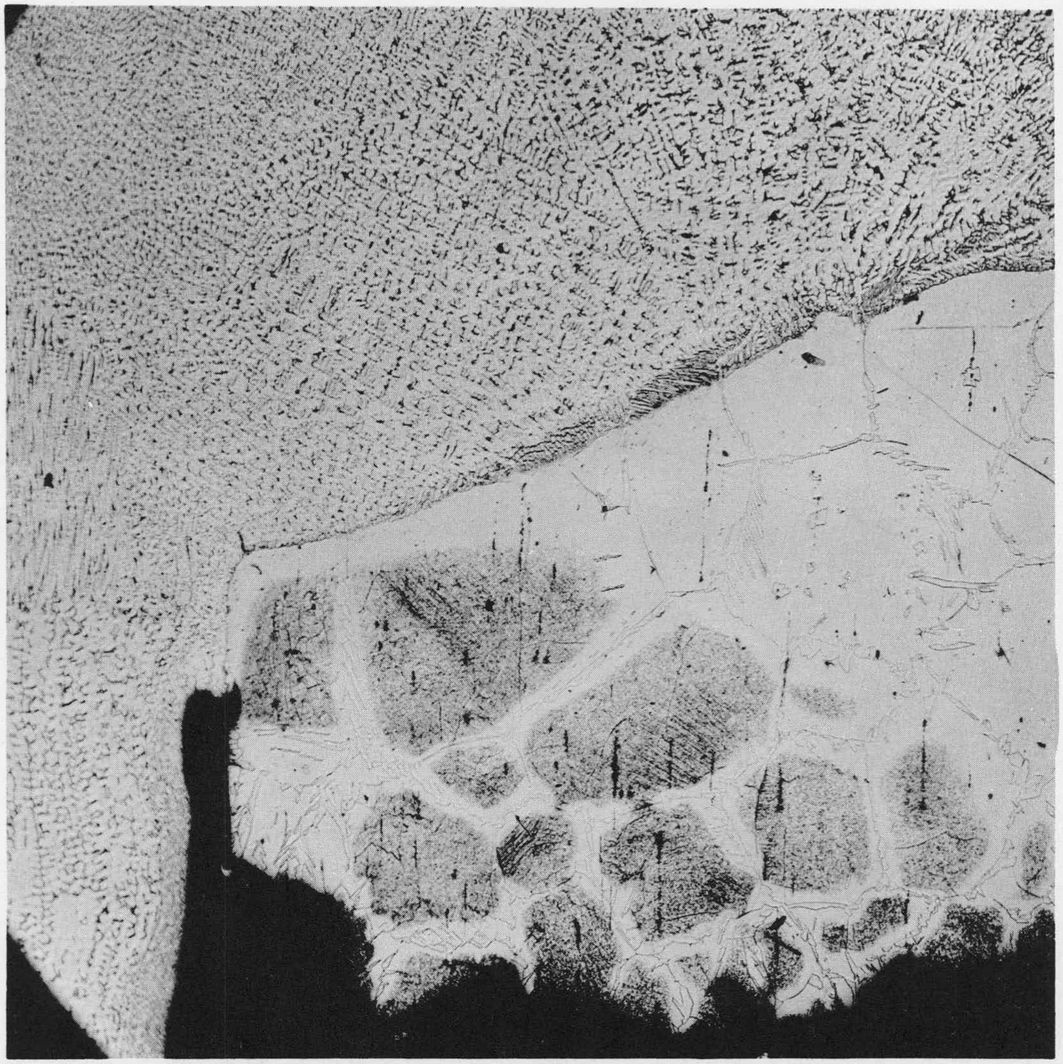
Stainless
Overlay

Type 430M
Tube

Etch:
5% Chromic

Figure 11. Microstructure of Two-Pass Manual Tungsten-Arc Weld Joint Type 430M Tubes to Stainless Overlay. Type 309 Filler Wire and Joint Style 8 (Fig. 10) Were Used. Weld Structure Consists of Austenite, Martensite and Ferrite.

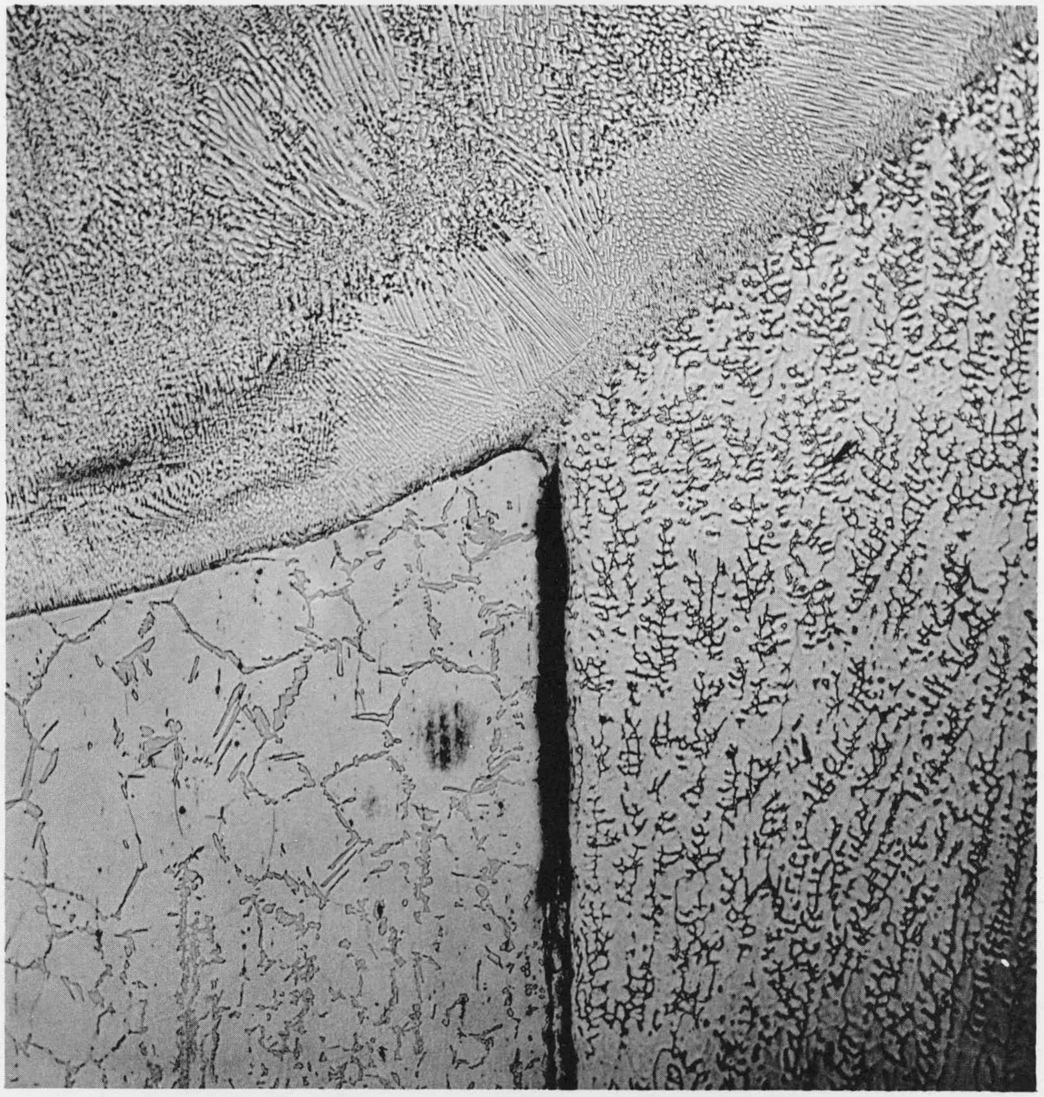
Weld Metal ↓



2901 J ↑ Stainless Tube ↑ Etch:
100 X Overlay 5% Chromic

Figure 12 Microstructure of Two-Pass Manual Tungsten Arc Weld Joining Type 430M Tubes to Stainless Overlay. Type 310 Filler Wire and Joint Style 8 (Fig. 10) Were Used. Weld Structure is Predominately Austenite. Fracture From Pull-Out Test Shown.

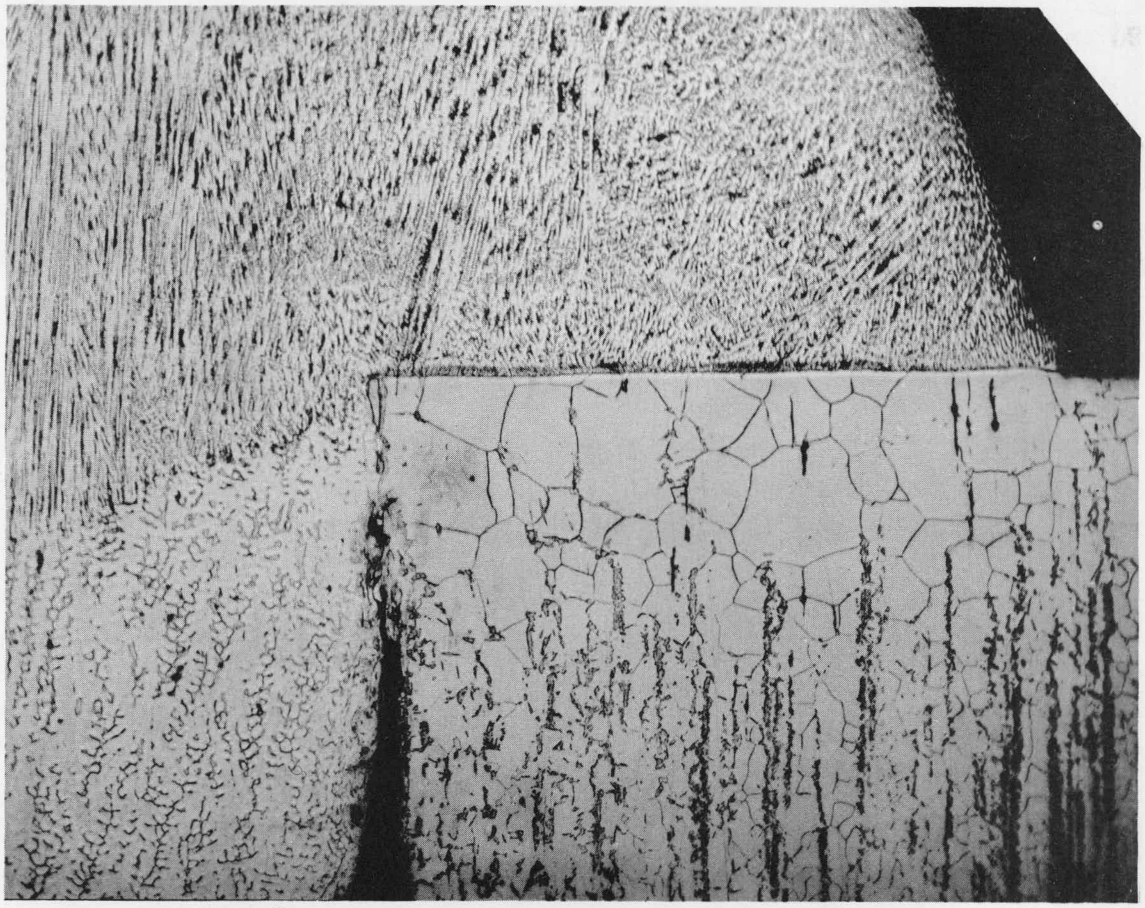
Weld Metal



2901 K 100 X — Tube — Stainless Overlay — Etch: 5% Chromic

Figure 13. Microstructure of Manual Metal-Arc Weld Joining Type 430M Tubes to Stainless Overlay. Type 309 Coates Electrodes and Joint Style 8 (Figure 10) were Used. Weld Structure is Predominately Austenite.

Weld Metal



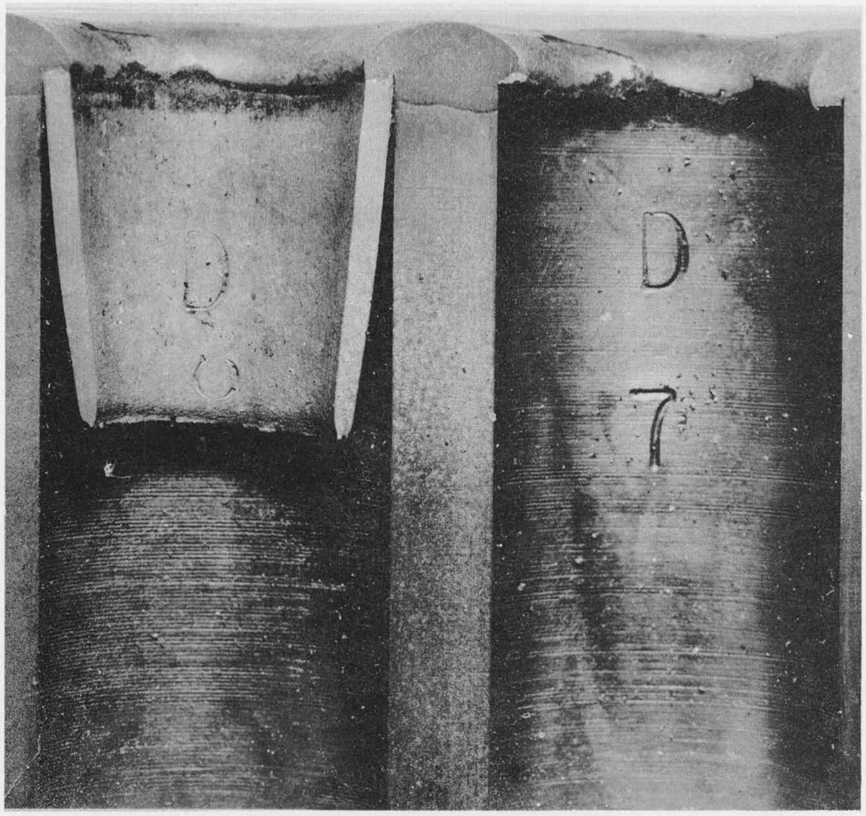
2901 L
100 X

Stainless Overlay

Tube

Etch:
5% Chromic

Figure 14. Single Pass Automatic Tungsten-Arc Weld Showing Incomplete Fusion of the Full Thickness of the Type 430M Tube.



2901 M

2 X

Figure 15. Macrosection of Automatic Tungsten-Arc Welded Tube Joints After Tensile Testing. Failure Occurred in Unaffected Tube (Left) or Tube Heat Zone (Right).

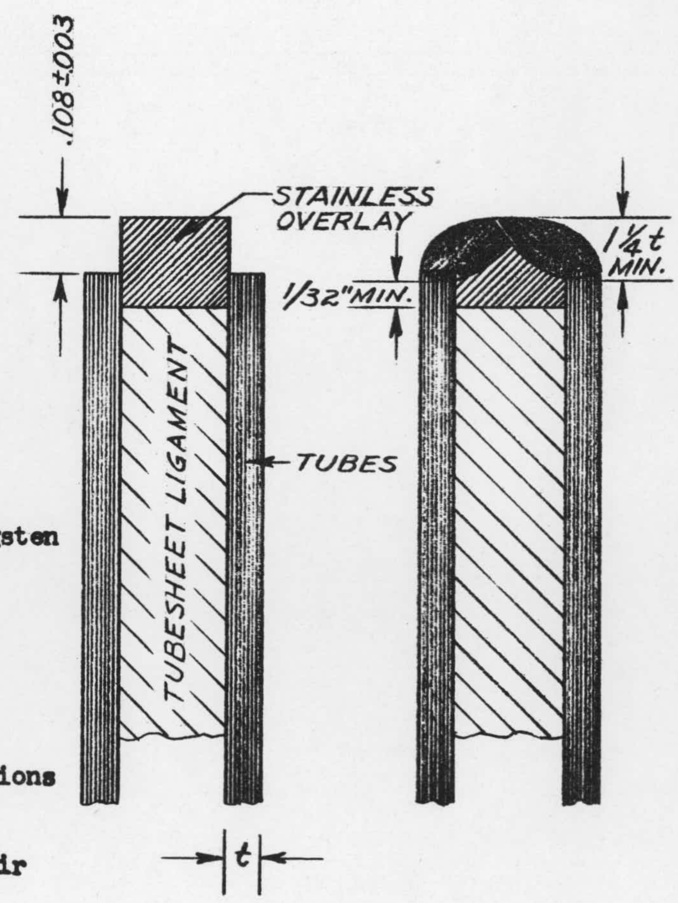
MATERIALS

1. Tubesheet: A350-LF-1 (Mod. with up to 2% Ni)
2. Tubes: Type 430M, 7/8" o.d. X 15 BWG
3. Overlay: Stainless steel:
   C-.08% max., Cr-18% min., Ni-8% min.
   (Cr & Ni content to be adjusted to provide a tube-to-tubesheet weld structure of austenite containing at least 5% delta ferrite and no martensite.)
4. Tube Weld Filler Metal: None

PROCEDURE

1. The thoroughly cleaned tubes shall be rolled into the thoroughly cleaned tubesheet prior to welding.
2. A preheat of 100°F min. shall be applied prior to welding.
3. Welding shall be performed by the automatic, tungsten-arc welding process without the addition of filler metal.
4. Welding shall be done in one pass using essentially the following conditions:

Current:	DCSP	Electrode:	1/8" dia., 2% Thoriated tungsten
Amperage:	140-150	Arc Gap:	.020" nominal
Voltage:	11-13	Radius of Arc Travel:	0.505"
Travel Speed:	13 ipm 15 sec/rev	Shielding Gas:	75% argon-25% helium
		Gas Flow:	15 CFH



INSPECTION

1. Appearance: The weld surface shall be left "as welded", except where repairs are required, or where dye-penetrant inspection shows indications of a deficiency in weld quality.
2. Dye Penetrant: All completed welds shall be dye-penetrant inspected. Any cracks, blow holes, crevices, or other deficiencies that may impair the service function or weld quality shall be removed.

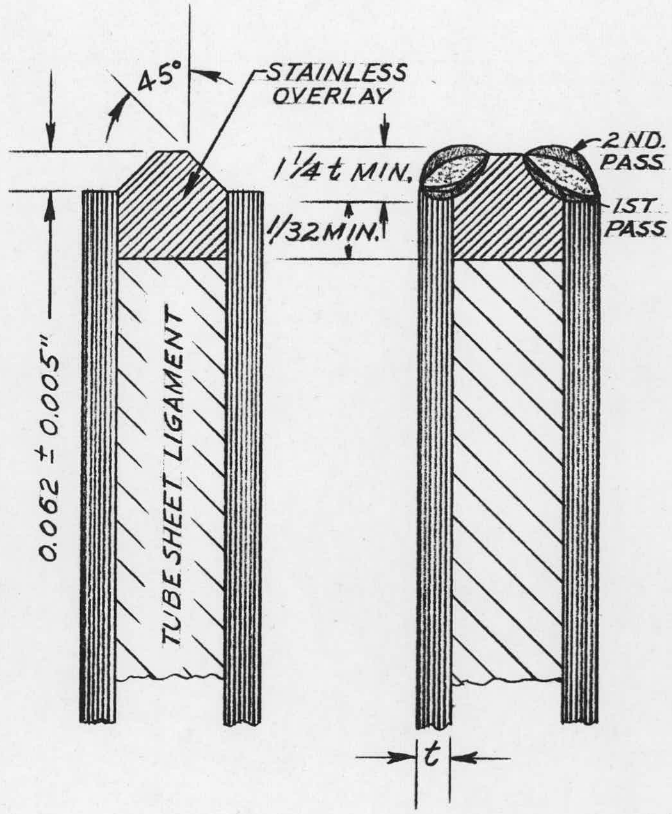
REPAIRS

When required, repairs shall be made by refusing the weld using the above procedure. Where defective weld metal is removed by grinding or counter boring, the two pass manual procedure, including dye-penetrant inspection given in Figure 17 shall be followed.

FIGURE 16. PROCEDURE FOR AUTOMATIC TUNGSTEN-ARC WELDING OF TYPE 430M TUBES TO A350-LF1(MOD.) TUBESHEETS

MATERIALS

1. Tubesheet: A350-LF1 (Mod. with up to 2% Ni)
2. Tubes: Type 430M 7/8" o.d. X 15 BWG
3. Overlay: Stainless Steel:
   C-.08% max., Cr-18% min., Ni-8% min.
4. Tube Weld Filler Metal: 1st Pass - AISI Type 310 - 1/16" dia.
   2nd Pass - AISI Type 308L-1/16" dia.
   (Tube-to-tubesheet weld structure to be austenite with at least 5% delta ferrite and no martensite.)



PROCEDURE

1. Thoroughly cleaned tubes shall be rolled into the thoroughly cleaned tubesheet prior to welding.
2. A preheat of 70°F min. shall be applied prior to welding.
3. Welding shall be performed in two passes by the manual inert gas shielded tungsten-arc process with filler metal addition.
4. Welding conditions shall be essentially as follows:

	1st Pass	2nd Pass
Current:	DC SP	DC SP
Amperage:	78-83	95-100
Voltage:	12-13	14-15
Filler Metal:	Type 310	Type 308L
Electrode:	3/32" dia. 2% thor. tungsten	
Shielding gas:	Welding grade argon	
Gas Flow:	12 CFH	

INSPECTION

1. Appearance: The weld surfaces shall be left "as welded", except where repairs are required or where dye-penetrant inspection shows indications of a deficiency in weld quality.
2. Dye Penetrant: All completed welds shall be dye-penetrant inspected. Any cracks, blow holes, crevices, or other deficiencies that may impair the service function or weld quality shall be removed.

REPAIRS

Defective weld metal shall be removed by grinding or counter boring. Repair welds shall be made by the procedure outlined above.

FIGURE 17. PROCEDURE FOR MANUAL TUNGSTEN-ARC WELDING OF TYPE 430M TUBES TO A350-LF1 (MOD.) TUBESHEETS

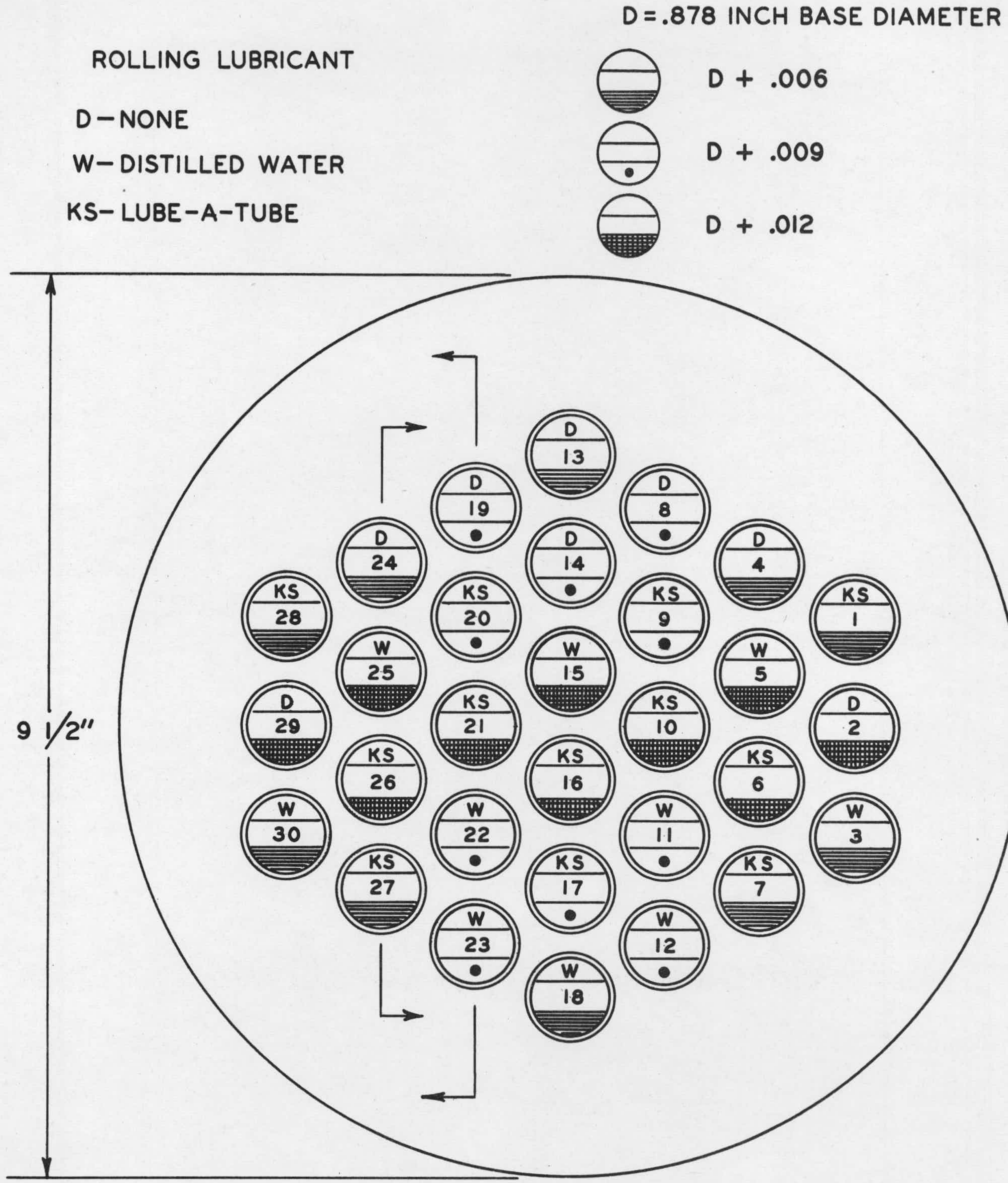


FIGURE 18. SCHEMATIC LAYOUT FOR TUBE ROLLING TEST UNIT NUMBER 1 (REFER TO TABLE 1 FOR DETAILS.)

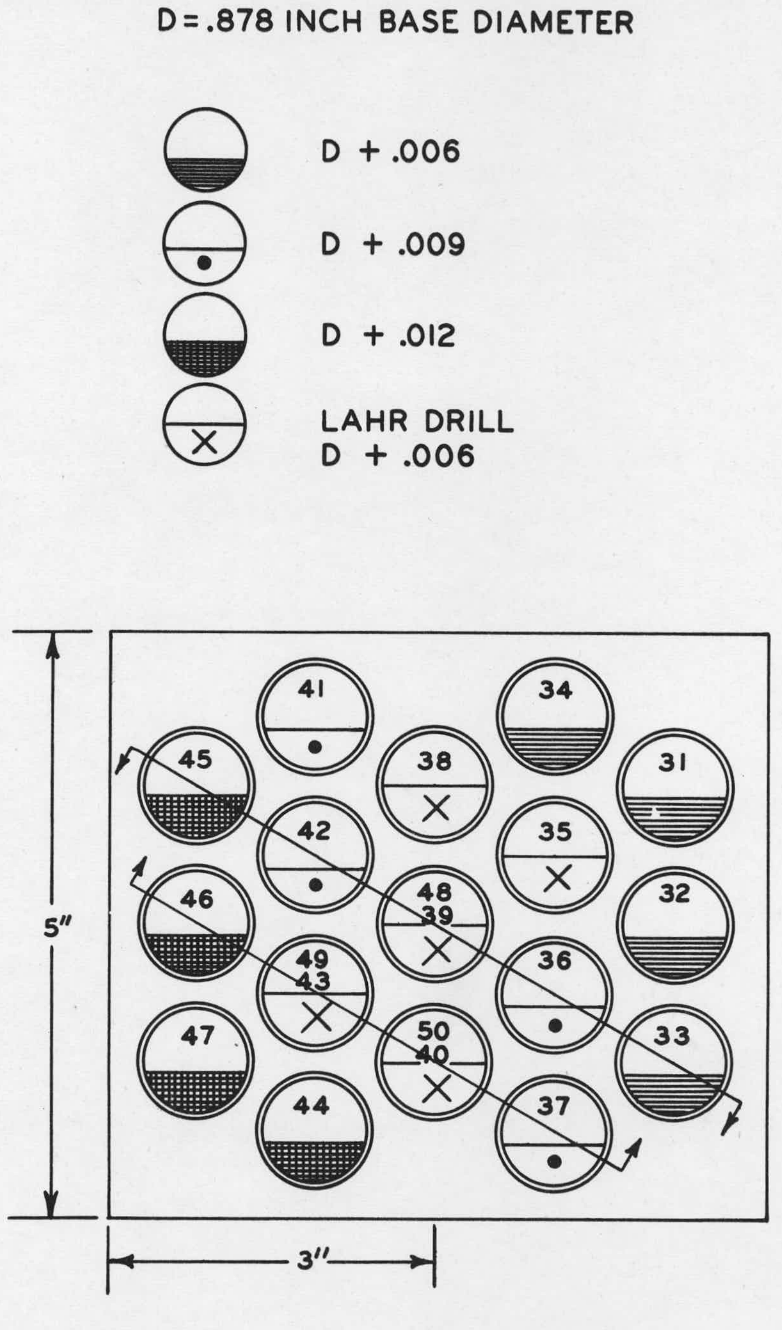
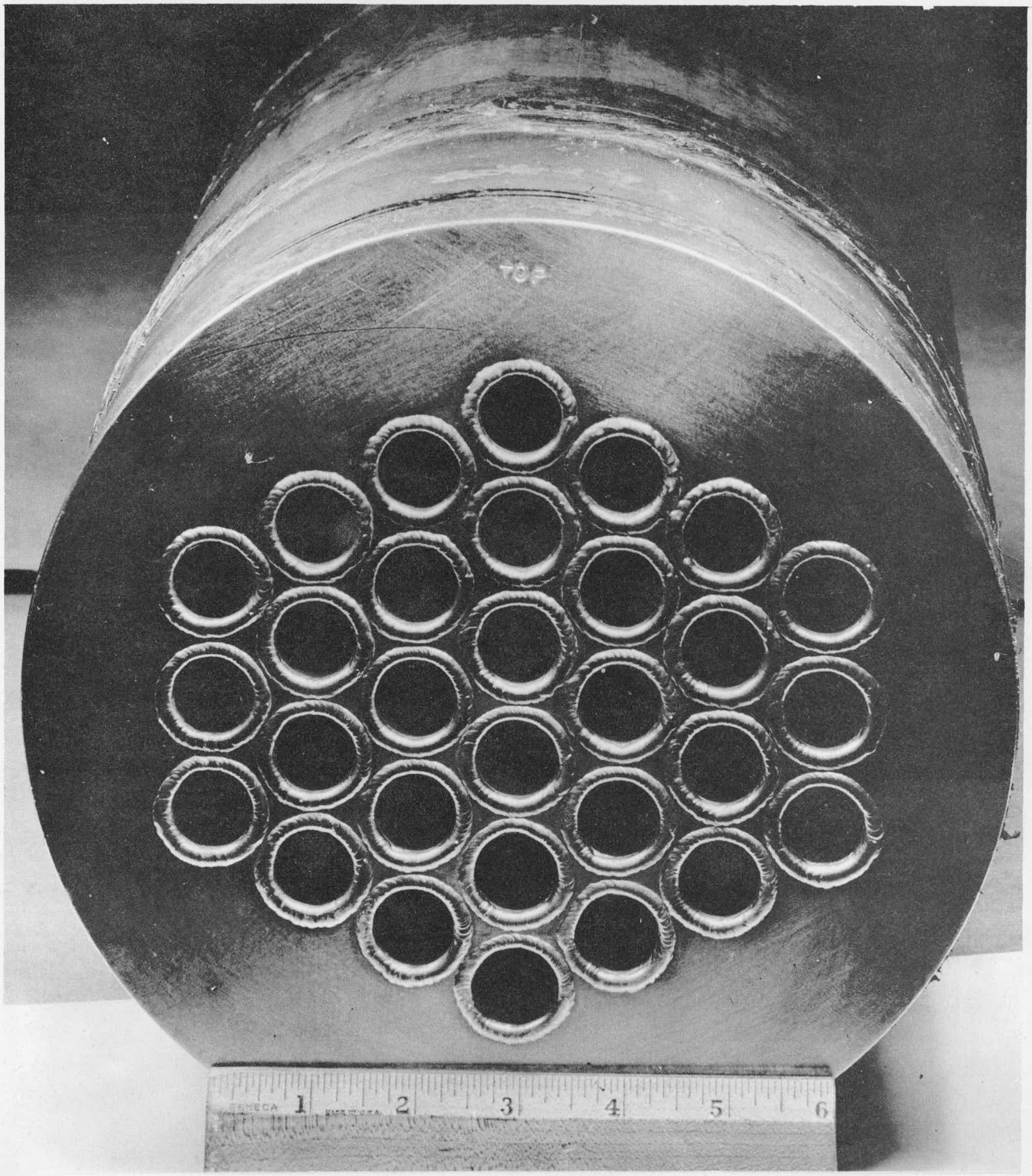
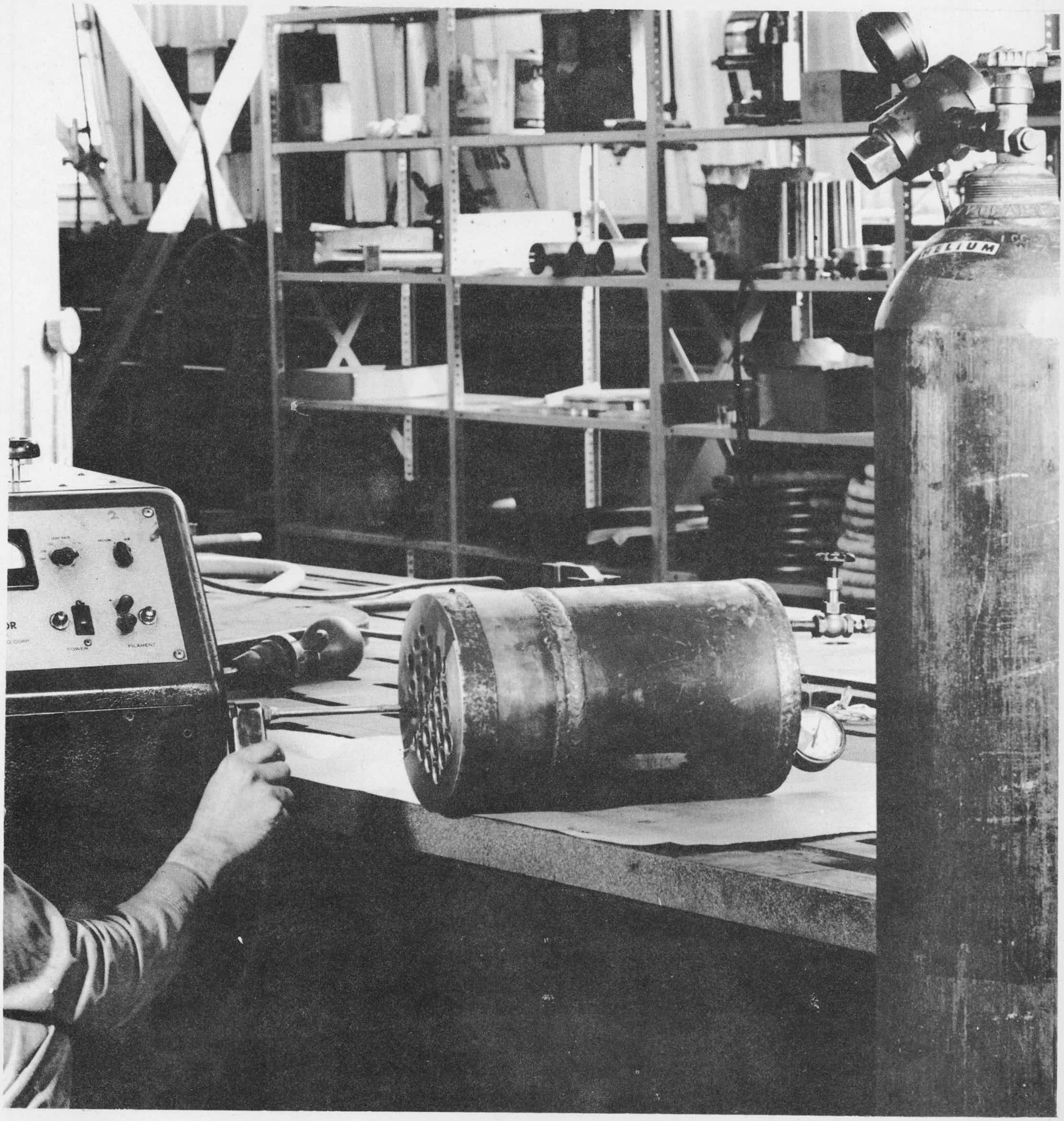


FIGURE 19. SCHEMATIC LAYOUT FOR TUBE ROLLING TEST UNIT NUMBER 2 (REFER TO TABLE 2 FOR DETAILS.)



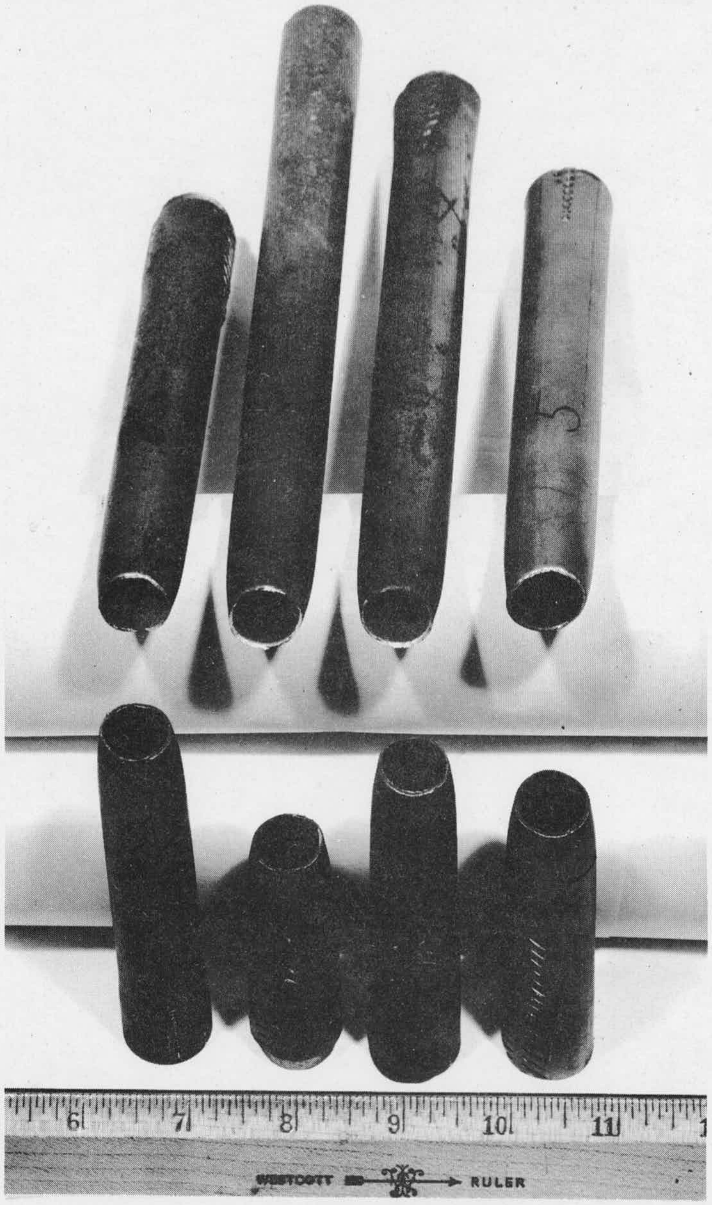
2901 N 2/3 X

Figure 20. Test Unit Number One Having Type 430M Tubes Rolled and Welded to an A350-LF1 (Mod.) Tubesheet.



2901 P

Figure 21. Test Unit Number One Being Helium Leak Tested at 120 psi After Removing the Weld From Half of the Joints.



2901 O 1/2 X

Figure 22. Fractured Tensile Test Specimens of Type 430M Tubing Heated to Different Temperature Levels. Refer to Table B. (Left to Right, Tube Nos. 2, 3, 4, 5).

ROLLING PROCEDURE

1. The tubes and tube holes shall be thoroughly cleaned prior to assembly.

2. The tube hole diameter shall not exceed the nominal tube diameter by more than .008 inch. Under no circumstances shall the tube-to-tube hole clearance exceed .013 inch.

3. A minute amount of rolling lubricant, such as distilled water, "KS Lube -A-Tube", or other equivalent water soluble compound may be used for tube rolling.

4. The tubes shall be rolled into the tubesheet (design as shown) to a minimum depth of 2-1/2 times the tube diameter. For full depth rolling the tube shall not be expanded more than 1/8 inch from the backside face of the tubesheet.

5. The true average hardness of tubes shall not exceed the internal true tubesheet hardness by more than 5 Rockwell B hardness numbers. Actual surface measurements of tubes and tubesheets shall not exceed a maximum of 10 Rockwell B hardness numbers.

6. The percent total expansion should not exceed 3.75%.

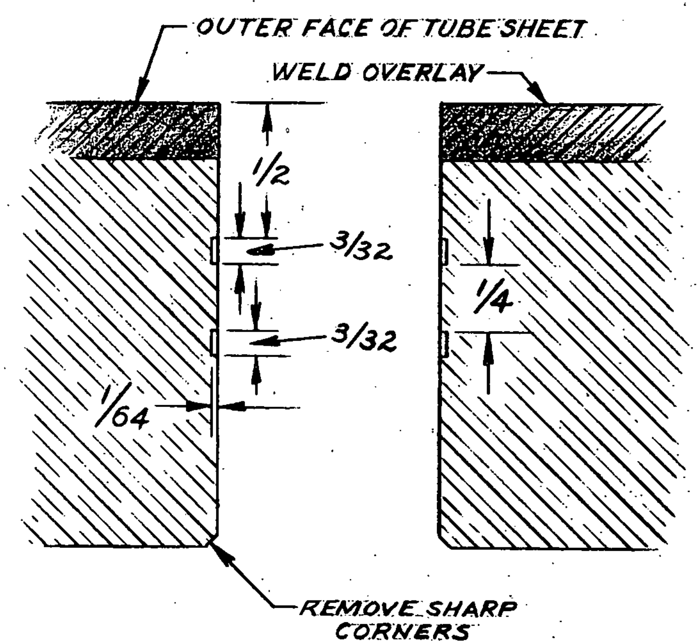


FIGURE 23. RECOMMENDED PROCEDURE FOR ROLLING TYPE 43UM TUBES TO A350-LF1 (MOD) TUBESHEETS

TABLES

TABLE 1

TUBE ROLLING DATA FOR NUMBER ONE TEST UNIT

Tube Ident. No.	Hole Dia. Inch	Tube O.D. Inch	Actual Clear. Inch	Tube I.D. Inch Before Rolling	Tube I.D. Inch After Rolling	Total Exp. Inch	Exp. (3) M-M Cont.	%(2) Total Exp.	% Exp. (3) M-M Cont.	Rolling (4) Lubricant
	Nominal Tube-to-Tube Hole Clearance .006 Inch									
1	.884	.878	.006	.732	.754	.022	.016	3.00	2.17	KS
3	.884	.879	.005	.734	.756	.022	.017	3.00	2.30	W
4	.884	.879	.005	.732	.752	.020	.015	2.73	2.04	D
7	.884	.879	.005	.735	.759	.024	.019	3.26	2.57	KS
13	.884	.878	.006	.734	.751	.017	.011	2.32	1.49	D
18	.885	.878	.006	.736	.765	.029	.023	3.94	3.10	W
24	.884	.878	.006	.731	.755	.024	.018	3.28	2.44	D
27	.884	.878	.006	.732	.752	.020	.014	2.73	1.90	KS
28	.884	.878	.006	.731	.749	.018	.012	2.46	1.63	KS
30	.884	.878	.006	.730	.754	.024	.018	3.29	2.45	W
	Nominal Tube-to-Tube Hole Clearance .009 Inch									
8	.887	.879	.008	.731	.753	.022	.014	3.01	1.89	D
9	.887	.879	.008	.733	.759	.026	.018	3.55	2.43	KS
11	.887	.879	.008	.732	.754	.022	.014	3.00	1.89	W
12	.887	.879	.008	.734	.760	.026	.018	3.54	2.43	W
14	.887	.875-.878	.009	.734	.757	.023	.014	3.13	1.88	D
17	.888	.873-.878	.010	.735	.762	.027	.017	3.67	2.28	KS
19	.888	.878	.010	.731	.755	.024	.014	3.28	1.89	D
20	.888	.878	.010	.730	.757	.027	.017	3.25	2.30	KS
22	.888	.878	.010	.732	.754	.022	.012	3.00	1.62	W
23	.888	.878	.010	.734	.761	.027	.017	3.68	2.28	W
	Nominal Tube-to-Tube Hole Clearance .012 Inch									
2	.890	.879	.011	.731	.756	.025	.014	3.42	1.89	D
5	.891	.879	.012	.732	.759	.027	.015	3.69	2.02	W
6	.890	.879	.011	.732	.760	.028	.017	3.82	2.29	KS
10	.895	.879	.016	.733	.762	.029	.013	3.96	1.74	KS
15	.892	.878	.014	.733	.764	.031	.017	4.23	2.28	W
16	.890	.878	.012	.731	.758	.027	.015	3.69	2.02	KS
21	.890	.878	.012	.731	.760	.029	.017	3.97	2.29	KS
25	.892	.878	.014	.732	.759	.027	.013	3.69	1.74	W
26	.892	.878	.014	.730	.757	.027	.013	3.70	1.75	KS
29	.892	.878	.014	.730	.758	.028	.014	3.83	1.88	D

NOTES TO TABLE 1

(1) Circled numbers indicate tubes from B&W Heat 23380. All other tubes from B&W Heat 13876.

(2) $$\% \text{ TOTAL EXPANSION} = \frac{\text{Final Tube I.D.} - \text{Initial Tube I.D.}}{\text{Initial Tube I.D.}} \times 100$$

(3) Exp. M-M Contact - Means expansion after metal-to-metal contact.

$$\% \text{ EXPANSION M-M Contact} = \frac{\text{Exp. After M-M Contact}}{\text{Initial Tube I.D.} + \text{Actual Clearance}} \times 100$$

(4) Rolling Lubricants:
- KS = KS Lube-a-Tube compound.
- W = Distilled water.
- D = No lubricant - dry rolling.

(5) Rolling Procedure (Refer to Figure 18).

(6) Material Hardness

(a)

Type 430M Tubes	Direct Rkw B	Knoop	Knoop Converted to Rkw B
B&W Heat 23380	90-92	190-219	87-93
B&W Heat 13876	87-90	189-202	87-90
		190-196	87-89

(b) A350-LF-1 (Mod.) Tubesheet
- Surface - Rkw B 83 average.
- Cross Sectional Face - Rkw B 86 average

TABLE 2

TUBE ROLLING DATA FOR NUMBER TWO TEST UNIT

(1) Tube Ident. No.	Hole Dia. Inch	Tube O.D. Inch	Actual Clear. Inch	Tube I.D. Inch Before Rolling	Tube I.D. Inch After Rolling	Total Exp. Inch	(3) Exp. M-M Cont.	(2) % Total Exp.	%(3) Exp. M-M Cont.	Avg. RkwB Tube Surf.	Cross Section Tube Hardness Rkw 30T	Cross Section Tube Hardness Conv. Rkw B
Nominal Tube-to-Tube Hole Clearance .006 Inch												
31	.886	.875	.011*	.730	.748	.018	.007	2.46	0.90	76	67-70	75-80
32	.881	.876	.005	.732	.752	.020	.015	2.73	2.03	79	69-70	78-80
33	.879	.875	.004	.732	.752	.020	.016	2.73	2.17	78	68-69	77-78
34	.883	.878	.005	.730	.748	.018	.013	2.46	1.75	76	67-68	75-77
Nominal Tube-to-Tube Hole Clearance .009 Inch												
36	.883	.879	.004*	.733	.751	.018	.014	2.45	1.90	-	70-70	80-80
37	.888	.878	.010	.731	.752	.021	.011	2.87	1.48	77	65-67	72-75
41	.886	.879	.007	.727	.748	.021	.014	2.88	1.91	82	72-73	83-84
42	.886	.879	.007	.725	.752	.027	.020	3.72	2.73	77	66-68	74-77
Nominal Tube-to-Tube Hole Clearance .012 Inch												
44	.891	.879	.012	.734	.754	.020	.008	2.72	1.07	78	68-69	77-78
45	.890	.880	.010	.735	.755	.020	.010	2.72	1.34	77	70-70	80-80
46	.890	.880	.010	.732	.754	.022	.012	3.00	1.62	90	75-76	88-90
47	.890	.877	.013	.732	.752	.020	.007	2.73	0.90	88	76-76	90-90
Lahr Drilled Nominal Tube-to-Tube Hole Clearance .006 Inch												
35	.881	.879	.002*	.732	.752	.020	.018	2.73	2.45	80	71-72	81-83
38	.886	.877	.009	.735	.753	.018	.009	2.45	1.21	75	65-66	72-74
39	.881	.879	.002	.731	.752	.021	.019	2.87	2.59	75	67-68	75-77
40	.886	.880	.006	.726	.752	.026	.020	3.58	2.73	77	68-70	77-80
43	.885	.879	.006	.727	.752	.025	.019	3.43	2.59	78	66-67	74-75
Tube Numbers 39, 40 and 43 Removed and Replaced by the Following												
48	.886	.876	.006**	.735	.753	.018	.012	2.45	1.62	90	76-77	90-91
49	.888	.876	.006**	.730	.749	.019	.013	2.60	1.77	89	76-76	90-90
50	.888	.876	.006**	.734	.752	.018	.012	2.46	1.62	90	78-78	93-93

NOTES TO TABLE 2

(1) All tubes from B&W Heat 23380.
Circled numbers indicate tubes in the "as-received" condition.
All other tubes softened by stress relieving at 1350°F. for one hour followed by air cooling.

(2) $$\% \text{ TOTAL EXPANSION} = \frac{\text{Final Tube I.D.} - \text{Initial Tube I.D.}}{\text{Initial Tube I.D.}} \times 100$$

(3) Exp. M-M Contact - Means expansion after metal-to-metal contact.

$$\% \text{ Exp. M-M Contact} = \frac{\text{Exp. After M-M Contact}}{\text{Initial Tube I.D.} + \text{Actual Clearance}} \times 100$$

(4) Hardness of A350-LF-1 (Mod.) Tubesheet
Surface Rkw B 83 average
Cross Sectional face Rkw B 86 average

*Data appear to be erratic.

**Nominal dimension-not measured.