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Fabrication of Stainless Steel Clad Tubing

by

C. W. Kovach

prepared for

National Aeronautics and Space Administration

April 7, 1978

Contract NAS 3-20098
Final Report

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
Materials Development Section
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16 Abstract

A program was carried out to evaluate the feasibility of producing stainless steel clad carbon steel tubing by a gas pressure bonding process. Such a tube product could provide substantial chromium savings over monolithic stainless tubing in the event of a serious chromium shortage. The process developed in this program consisted of the initial assembly of three component tubesets from conventionally produced tubing, the formation of a strong metallurgical bond between the three components by gas pressure bonding, and final conventional cold draw and anneal processing to final size. Tubes were successfully produced by this method demonstrating the feasibility of the process. The quality of the tubes was excellent from the standpoint of bond strength, mechanical and forming properties. The only significant quality problem encountered was carburization of the stainless clad by the carbon steel core. This problem can be overcome by further refinement through at least three different approaches. The estimated cost of clad tubing produced by this process is greater than that for monolithic stainless tubing, but not so high as to make the process impractical as a chromium conservation method.

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ABSTRACT

A program was carried out to evaluate the feasibility of producing stainless steel clad carbon steel tubing by a gas pressure bonding process. Such a tube product could provide substantial chromium savings over monolithic stainless tubing in the event of a serious chromium shortage. The process developed in this program consisted of the initial assembly of three component tubesets from conventionally produced tubing, the formation of a strong metallurgical bond between the three components by gas pressure bonding, and final conventional cold draw and anneal processing to final size. Tubes were successfully produced by this method demonstrating the feasibility of the process. The quality of the tubes was excellent from the standpoint of bond strength, mechanical and forming properties. The only significant quality problem encountered was carburization of the stainless clad by the carbon steel core. This problem can be overcome by further refinement through at least three different approaches. The estimated cost of clad tubing produced by this process is greater than that for monolithic stainless tubing, but not so high as to make the process impractical as a chromium conservation method.

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I. Introduction

The objective of the research described in this report was to develop the technology and demonstrate the feasibility of producing stainless steel clad-carbon steel core tubing by a gas pressure bonding process. This objective was established as part of a national goal to achieve less reliance on the overseas supply of critical raw materials. Stainless clad tubing, having the properties of monolithic tubing, would provide substantial savings in chromium which is in an unstable worldwide supply and currently not mined within the U.S.A. Tubing was selected for this program because substantial quantities of stainless steel tubing and pipe are used each year in many industrial processes serving such important requirements as food, chemical and energy production. Gas pressure bonding was selected as the cladding method after a review of various alternate processes because it appeared to offer the best opportunity for technical success and reasonable production cost.

A. Chromium Conservation

Stainless steels are important materials of construction for traditional food, chemical and energy production equipment. They will play an important future role in new processes that will help solve energy and pollution problems. These processes include flue gas scrubbing, coal gasification and liquification, advanced oil refinery equipment, and nuclear power. Stainless steels require a minimum of 12% and usually 18% by weight chromium to attain the corrosion resistance required for most applications. The consumption of stainless steel in the U.S.A. is about one million tons annually. Therefore, large quantities of chromium from a dependable source, or methods of chromium conservation, are necessary to assure the availability of these important steels.

The U.S.A. must import essentially 100% of its chromium requirements since no chromite ore is mined in the U.S.A. Known world chromite reserves are considered adequate to meet world demand through this century. Most of these reserves are located principally in the countries of South Africa, Rhodesia, and Russia. The continued availability of imports to the U.S.A. will depend on the political situation existing within these countries and our foreign policy. Thus, our supply of chromium could be seriously jeopardized by changing world conditions beyond control of the U.S.A.

Practicing various methods of chromium conservation will provide a means of minimizing our dependence on chromium imports. One method of chromium conservation is to develop and utilize materials that are clad with a thin layer of stainless steel on the outer surfaces. This has been practiced with plate, and to some extent sheet product, but not with stainless steel pipe and tubing. Since the production of stainless pipe and tubing exceeds 100,000 tons annually, the development and production of these products as stainless clad offers a substantial opportunity for chromium conservation.

B. Gas Pressure Bonding for Clad Tube Fabrication

The approach used in this program was to assemble three-component stainless-carbon steel-stainless tube packages of conventionally produced tubing and then metallurgical bond them into a composite tube hollow using a high temperature-pressure bonding process. These tube hollows were then processed to standard stainless tubing sizes by conventional processing procedures. This method was selected over the following alternate approaches: welding of clad strip into tubing, explosive cladding, alloy deposition, casting of a composite tube hollow, and simultaneous cold draw-bonding of tubing. The advantages and reasons for the selection of gas pressure bonding are discussed below.

The probability for technical success is high since no significant technological advances are required. The approach only combines several established technologies into a new concept for producing clad tubing. The gas pressure bonding approach has considerable product and process flexibility. It can be used for a virtually unlimited variety of tube diameters, wall thicknesses, and clad metal thicknesses and bonding can be performed as an early step, i.e., to produce a tube hollow, or close to final tube size, thus allowing optimization of the process for greatest cost effectiveness. Finally, and very importantly, the gas pressure bonding process that is developed for producing stainless-carbon steel-stainless in this program could be used with minor modifications to produce composite tubing from a variety of different alloy modifications. This feature means that the approach could be used to produce tubes having a unique combination of properties or be applied to other systems where material shortages might occur.

C. Technical Aspects of Gas Pressure Bonding

Gas pressure bonding at high temperature is a process that has recently been developed and is being utilized for the production of high integrity steel mill products and shaped components from metal powders. The process differs from conventional powder metal technology in that the required temperature and pressure for diffusion bonding is applied simultaneously in an autoclave. The major advantage of this process is that the combined high temperature-high pressure conditions existing during bonding cause the metals to deform and fill all pre-existing voids. A vacuum can also be utilized by encapsulating the components to be bonded in an evacuated can which effectively reduces surface oxidation.

Thus a product is produced that approaches 100 percent theoretical density and is relatively free of oxide contamination at interfaces. The properties of composites made by this process can then be expected to approach those made by the conventional cast-wrought production processes.

In the development of a process for clad tube fabrication by gas pressure bonding a number of technical considerations arise beyond those normally encountered with metal powder. These occur primarily because dissimilar metal, prefabricated tube components are being bonded and then processed to final size by cold drawing. These can be classified into three categories as discussed below.

1. The Bond Zone

The bond between clad components must have sufficient mechanical strength and ductility to withstand processing to final size and to sustain loadings that may be encountered in service. This requires that the selection of clad components and processing be designed to avoid the formation of embrittling phases at the interface. The selection of Type 304L and low carbon steel meet this requirement since no brittle intermetallic compounds form within this system. Furthermore, both alloys are austenitic and mutually soluble within the bonding temperature range. However, there is a possibility that low carbon martensite could form at some point across the interface.

Bond strength is also a function of the degree of initial surface cleanliness and topography. This program was based upon the utilization of initial tube components in a condition as close as practical to that normally supplied by tube producers. The surfaces of such tubing can, to various degrees, contain lubricants, scales and other contaminants. The surfaces also can have various degrees of roughness depending on the utilization of such finishing practices as pickling, cold drawing, etc. Also, although the fabrication method planned for this program included evacuating the tube assembly prior to bonding, the degree of evacuation and consequent residual gas could provide contamination and an affect on bond strength.

The experimental program was designed to include initial experiments aimed at developing data relative to the above considerations so that an optimum tube bonding process was utilized. These experiments included metallurgical evaluation of the bond interface and bond strength, the evaluation of initial surface condition and cleaning procedures, and a study of bonding time and temperature parameters.

2. The Stainless Surface

The stainless surface of a clad tube should have corrosion resistance and other characteristics similar to those of monolithic stainless in order for the clad tube to have utility as a replacement for monolithic stainless tubing. With one exception this should be possible because the fabrication procedures designed for processing the initial gas pressure bonded tube hollows to final size are the same as those employed for the manufacture of conventional tubing. The one exception relates to the possibility of significant carburization of the stainless clad layer from the low-carbon steel core. Carburization of Type 304 stainless can occur, either during gas pressure bonding or subsequent annealing, because the activity coefficient of carbon in low-carbon steel is much higher than it is in austenitic stainless steel. Consequently, the process must be designed to minimize this carburization as much as possible. Methods for doing this relate to the initial selection of clad and core components, and the minimization of time and temperature during bonding and annealing consistent with achieving the required bond strength final tube mechanical properties. The experimental program was also designed with initial experiments aimed at optimizing the process from the standpoint of this potential carburization problem.

3. Clad Tube Evaluation

An objective of this program was to produce a stainless clad tube that could replace monolithic stainless tubing in many existing applications, and to evaluate the economics of such a clad tube. To accomplish this objective it was necessary to fully evaluate the quality of properties of the clad tube. The properties evaluated as part of this program include size and size tolerance, the occurrence of surface and internal defects, corrosion resistance, and mechanical and forming properties. An economic analysis was also conducted using a hypothetical manufacturing process modeled after the fabrication procedures developed and found to be successful in the course of the project.

D. Clad Tube Scheduled for Fabrication

A description of the clad tubing scheduled for fabrication in this program is given in the following table.

Tube Size		Stainless Steel Clad	Thickness of Stainless Steel on OD and ID (mm)	Quantity 1.5 m (5 ft) min. Length
Diameter (mm)	Wall (mm)			
44.45 (1.75 in.)	1.651 (.065 in.)	20%	.165 (.0065 in.)	3
25.4 (1.00 in.)	2.413 (.095 in.)	20%	.241 (.0095 in.)	3
25.4 (1.00 in.)	2.413 (.095 in.)	10%	.114 (.0045 in.)	3
44.45 (1.75 in.)	3.404 (.134 in.)	20%	.342 (.0135 in.)	3

II. Development of Conditions and Materials for Gas Pressure Bonding

A. Carburization Experiments

Carbon diffusion studies were conducted using cold roll bonded coupons in efforts to provide guidance for material selection for the carbon steel core tubing. In these studies, samples of stainless Types 304 (0.066% C) and 304L (0.025% C) were cold roll bonded to three different carbon steels containing 0.011, 0.035 and 0.10% carbon. For these studies the stainless clad was 0.013 to 0.018 cm (0.005 to 0.007 in.) thick. Small samples of each of the six different bonded composites as well as Types 304 and 304L stainless were encapsulated in evacuated vycor bulbs to avoid oxidation attack and exposed for 3 hours at 954, 1066 and 1177°C (1750, 1950 and 2150°F) to simulate conditions that might be encountered in gas pressure bonding thermal treatments. After exposure, the samples were water quenched and the vycor capsules broken to allow rapid cooling. All samples were metallographically examined in the quenched condition to determine the extent of carbon enrichment. The results are summarized in Table II-1 in terms of the depth of carbon penetration into the thin stainless layer. With Type 304 clad, there was substantial carbon diffusion from all three carbon steels into the thin stainless layer. Carbon enrichment was evident in the form of randomly dispersed carbides extending from the carbon steel bond interface completely through the 0.015 cm (0.006 in.) Type 304 stainless layer. Figure II-1 illustrates the extent of carbon diffusion encountered with Type 304:0.10% C carbon steel bonds after 3 hours exposure at 954°C (1750°F). At higher exposure temperatures (e.g., 1066 and 1177°C), no evidence of carbide dispersions were observed due to increased carbon solubility of the Type 304 stainless at these higher temperatures.

Type 304L bonds also exhibited carbon enrichment from the three carbon steels tested. However, as shown in Table II-1, carbon diffusion in the Type 304L bonds was considerably less than that observed with Type 304 composites. Moreover, the diffusion of carbon into Type 304L from the 0.10% carbon steel was not substantially greater than that which occurred with a 0.035% carbon steel. The extent of carbon diffusion into Type 304L from the different carbon steels after 3 hours exposure at 954°C is shown in Figure II-2. As was the case with Type 304 composites, carbides were not observed in Type 304L bonds exposed at higher (1066 and 1177°C) temperatures (Figure II-3) due to the increased carbon solubility of Type 304L at these temperatures.

Carburization experiments were also conducted using elevated temperature compression testing equipment to more closely simulate the isostatic gas bonding process which begins with unbonded components. Several stainless/carbon steel coupons having a stainless steel coupon thickness of 0.050 cm (0.020 in.) were sealed in an evacuated nickel-base high temperature canister, heated to 954°C (1750°F) and held for 1 hour under an applied stress of 6.89 MPa (1000 psi). Heat-up time from ambient to test temperature was about 3 hours, similar to that encountered in gas pressure bonding. Initial tests were conducted in which the stainless coupons had a pickled finish. A 240 grit finish was applied to the bond surface of the carbon steels.

Under these uniaxial compression testing conditions, bonding was achieved between both Types 304 and 304L stainless and the 0.10% carbon steel. Metallographic examination of composites produced in this manner revealed that carburization in pack tests was similar to that encountered with roll bonded coupons. Samples of each composite coupon were annealed at 1010°C (1850°F) for 3 minutes and metallographically examined to determine the depth of carbon penetration from the bonded interface. The results of these studies given in Table II-2 show that carbon enrichment of Type 304 was evident to a maximum depth of about 0.018 cm (0.0071 in.) from the bond interface. Carbon diffusion was considerably less with Type 304L bonds in that carbide penetration was restricted to a maximum depth of about 0.014 cm (0.0057 in.) from the Type 304L bond interface. The extent of carbon enrichment in compression pack bonds is shown in Figure II-4.

B. Bond Strength Experiments to Optimize Surface Condition and Thermal Cycle

Experiments were conducted to establish the effects of bonding temperature and time and clad/core surface finish on bond strength and carbon diffusion under thermal conditions that might be encountered in gas pressure bonding. For these studies, strip samples were prepared with several different finishes (pickled, 240 grit, wire wheel and nickel plate*) for bonding trials in pack tests (conducted in a vacuum furnace) and in actual gas pressure bonding in a production autoclave.

For pack bonding studies, different surface finishes were applied to one surface of both Type 304L and AISI 1010 strip samples (25.4 mm wide by 76.2 mm long). Paired stainless/carbon steel couples representing all possible combinations of surface finishes were placed between stainless

* Nickel plating was applied only to the AISI 1010 carbon steel.

steel plates (50.8 mm by 50.8 mm), bolted together using a constant torque of 27.02 J (20 ft/lbs) and diffusion treated in a vacuum. In preparing these packs, the strip samples were intentionally made 25 mm longer than the pressure transmitting stainless plates to avoid bonding of one end of each composite strip. This was done to enable us to conduct a "peel test" to evaluate bond strength of each composite. Pack bonding tests were conducted at 954°C for 1, 3 and 7 hours and at 1066°C for 3 hours. All packs were slow cooled under a vacuum.

Peel tests were conducted by bending the unbonded ends of each composite component 90° to the length of the composite strip (180° to each other) and inserting the stainless component in one grip of a tensile machine and the carbon steel strip in the other. Once the composite strip was secured in position, the load on the bond interface was continuously increased until bond failure occurred. Peel tests were conducted on composite strips that had been pack bonded at 954°C for 3 and 7 hours and 1066°C for 3 hours. Samples that had been pack bonded at 954°C for 1 hour were not peel tested since bonds in these samples were very fragile and most failed during bending of the unbonded strip ends or during handling and aligning in the tensile machine.

Gas pressure bonding experiments were conducted to establish the effects of different stainless and carbon steel finishes on bond strength and carbon diffusion in actual gas pressure bonding processes using available cycles in a production autoclave. For these tests, several different finishes were applied to one surface of pre-oxidized Types 304 and 304L strips and one surface of each AISI 1010 (0.04 or 0.10% carbon) carbon steel strip. The pre-oxidized surfaces were used to allow for separation of individual components for peel testing. As in our pack bonding studies, paired stainless/carbon steel couples (25.4 mm wide by 25.4 cm long) containing all possible finish combinations were prepared. These were placed in a rectangular pressure transmitting container, the container was welded closed, evacuated by means of an evaucuation tube incorporated into the assembly and sealed. In this manner, as many as 15 or more different stainless:carbon steel composites could be gas pressure bonded in a single container. In this study the gas pressure bonding conditions were: 899°C (1650°F) for a total time at temperature of 2 hours and a bonding pressure of 103 MPa (15,000 psi).

The results of our pack peel tests are summarized in Table II-3 in terms of the load required to cause bond failure of 25.4 mm wide composite strips. The data for samples bonded at 954°C for 3 hours shows no significant differences in bond strength among samples prepared with different finishes. Tests conducted on samples that had been pack bonded for 7 hours at 954°C show that composites in which the stainless strips were prepared with wire wheel finishes generally displayed higher bond strengths than those in which the stainless strips had a pickled or 240 grit finish. Increasing the bonding temperature to 1066°C (3 hours) substantially improved bond strength. Among samples bonded at 1066°C, those stainless strips prepared with pickled or wire wheel finishes generally displayed highest bond strengths. Of all pack bonded specimens tested, the highest bond strength was displayed by the composite in which both the stainless and carbon steel components were prepared with a pickled finish and bonded at 1066°C.

In the gas pressure bonding experiments bonding was so strong that the 21 individual composite strips could not be separated from each other. Excellent bonding was obtained between composite couples having specially prepared surfaces as well as between adjacent carbon steel:oxidized T-304L stainless surfaces. Bonding between individual components was so strong that the gas pressure bonding treatment produced a solid composite section consisting of alternating layers of Type 304L stainless and carbon steels.

Metallographic examination of a section removed from the center portion of the composite revealed excellent bonding between all stainless and carbon steel prepared surfaces (Figure II-5a). Moreover, there was very good bonding between carbon steel samples and adjacent oxidized stainless strips (Figure II-5b).

Metallographic examinations showed that the extent of carbon enrichment of Type 304L from the 0.10% carbon steel in this gas pressure bonding treatment (899°C for about 2 hours) was not significantly different from that observed with cold roll bonded composites heated at 954°C (3 hours) and pack compression bonds made at 954°C for 1 hour. The extent of carbon enrichment of Type 304L from 0.04 and 0.10% carbon steels after gas pressure bonding at 899°C is shown in Figure II-6. Typically carbon enrichment of Type 304L was observed to a depth of about 0.089/0.102 mm in 0.04% carbon steel composites and about 0.102/0.127 mm in composites made with 0.10% carbon steel. Surface finish differences had no apparent effect on the extent of carbon diffusion from carbon steels into Type 304L stainless.

C. Selection of Conditions for Clad Tube Fabrication

1. Materials

At the inception of the program a survey was conducted to determine the commercial availability of candidate alloys in the required tube sizes. The survey showed that either Type 304 or Type 304L stainless would be available. However, the lowest carbon steel tube product that could be obtained in a reasonable time was AISI 1010 carbon steel. Lower carbon steels or titanium stabilized grades were not available as tube product.

The carburization data for the AISI 1010 carbon steel couples were then analyzed in relation to the anticipated thermal cycles and tube reductions required to produce the clad tubing. In the compression tests bonding was achieved with a 1 hour - 954°C (1750°F) cycle. For this cycle the depth of carburization in Type 304 coupled with AISI 1010 steel was 0.180 mm (.0079 in.) and was 0.144 mm (.00567 in.) in Type 304L stainless. The depth of penetration in Type 304 was nearly 2 times the intended final stainless wall thickness, 0.114 mm (.0045 in.), of the thinnest stainless wall tube scheduled to be made. It was concluded that this penetration could not be tolerated even though the tube processing plans called for a 50% cold drawing wall reduction following pressure bonding. Conversely, the maximum penetration of 0.144 mm (.00567 in.) in Type 304L indicated that Type 304L could be used without carbon penetration to the outside surface. It was also anticipated that the pressure bonding thermal cycle might be optimized to further minimize carbon penetration.

AISI 1010 carbon steel was therefore selected for the core material on the basis of it being the lowest carbon content material available. A lower carbon steel, or carbon stabilized steel, would be a preferred choice and presumably could be produced for a commercial clad tube production process. Type 304L stainless was selected for the clad component because the carburization experiments indicated compatability with an AISI 1010 carbon steel core.

2. Surface Condition

Bonding studies conducted to determine the effects of different surface finishes on bond strength and carbon diffusion yielded mixed results. Pack tests (at 954°C) showed that composites in which the stainless samples were prepared with wire wheel or pickled finishes generally displayed highest bond strengths. Strongest bonding was obtained when both stainless and carbon steel samples were prepared with pickled finishes and pack bonded at 1066°C. More importantly, in contrast to pack test results, outstanding bonding was obtained with all finish combinations during gas pressure bonding at 899°C. Although we were unable to measure the bond strength of the different gas pressure composites, metallographic examinations indicated intimate bonding for all finish combinations. Even more impressive is the fact that unbreakable bonds were established between carbon steel samples and intentionally oxidized stainless spacers intended as bonding inhibitors. Equally strong bonds were formed between pickled stainless samples and intentionally oxidized stainless spacers.

The good bond strengths obtained for most conditions of surface finish allow the selection of surface condition for tube fabrication to be made primarily on the basis of cost and efficiency of fabrication. The stainless condition selected was the annealed and pickled tube polished lightly with 360 grit abrasive followed by detergent cleaning and an alcohol wipe drying. This same procedure was used for the carbon steel tubes, but in some cases the surface of these tubes were initially machined to obtain the required fit and to remove the inside diameter weld bead.

3. <u>Bonding Conditions</u>

The selection on bonding conditions was based on determining those conditions which would give maximum bond strength while minimizing stainless carburization. Since the bulk diffusion of carbon is much more temperature dependent than an interface bonding reaction, the selection was made on the basis of defining the lowest temperature giving adequate bond strength and then selecting the shortest time compatible with this temperature. In the pack test bond strength study this optimum condition was 945°C for 3 hours, and in the gas pressure bonding study it was 899°C for 2 hours. These temperatures and times were in a range giving reasonably limited carburization for the Type 304L stainless and AISI 1010 carbon steel material combination. Bonding conditions were therefore selected to be: 899°C (1750°F), 3 hours at temperature, pressure of 103 MPa (15,000 psi).

TABLE II-1. Carburization in Cold Roll Bond Composites

Composite Number	Materials	Depth of Carbon Penetration 3 Hours at 954°C
8	Type 304:0.01% C Steel	0.15 mm* (.0059 in.)
13	Type 304:0.035% C Steel	0.15 mm* (.0059 in.)
4	Type 304:0.10% C Steel	0.15 mm* (.0059 in.)
24	Type 304L:0.01% C Steel	0.025 mm (.00098 in.)
16	Type 304L:0.035% C Steel	0.064 mm (.00252 in.)
22	Type 304L:0.10% C Steel	0.076 mm (.00299 in.)

* Complete carbon penetration of the 0.15 mm (0.006 in.) thick Type 304 layer.

TABLE II-2. Carburization in Compression Pack Bond Experiments Bonds Formed at 954°C - 1 Hour - Applied Stress of 6.89 MPa

Bond Code	Materials	Depth of Carbide Penetration in Stainless: 1010°C Anneal[a]	1010°C Anneal - 593°C Sensitize[b]
A-C	Type 304 0.10% Carbon Steel	0.122 mm (.00480 in.)	0.180 mm (.00709 in.)
B-C	Type 304L 0.10% Carbon Steel	0.048 mm (.00189 in.)	0.144 mm (.00567 in.)

Bonded coupons were treated as follows:

[a] Annealed at 1010°C for 3 minutes and water quenched.
[b] Annealed at 1010°C for 3 minutes, water quenched and sensitized at 593°C for 5 minutes.

TABLE II-3. Pack Test Bond Strength Results

Code	Applied Finish		Load (Kg) Required to Separate Bonded Components After Indicated Pack Bonding Treatment*		
	Stainless Steel	AISI 1010 Carbon Steel	954°C for 3 hrs	954°C for 7 hrs	1066°C for 3 hrs
24	Pickled	Wire Wheel	8.2	7.3	20.4
25	Pickled	Pickled	6.8	7.3	34.9
26	Pickled	240 Grit	8.2	10.9	19.1
28	Pickled	Ni Plate	6.8	6.8	17.2
14	Wire Wheel	Wire Wheel	9.5	12.7	20.0
15	Wire Wheel	Pickled	8.7	10.9	-
16	Wire Wheel	240 Grit	7.3	12.7	25.4
34	240 Grit	Wire Wheel	8.2	7.3	12.7
35	240 Grit	Pickled	9.1	6.8	11.8
36	240 Grit	240 Grit	7.7	10.0	10.9

* All packs were bolted together using a constant torque of 27.02 J (20 ft/lb) prior to vacuum treatment.

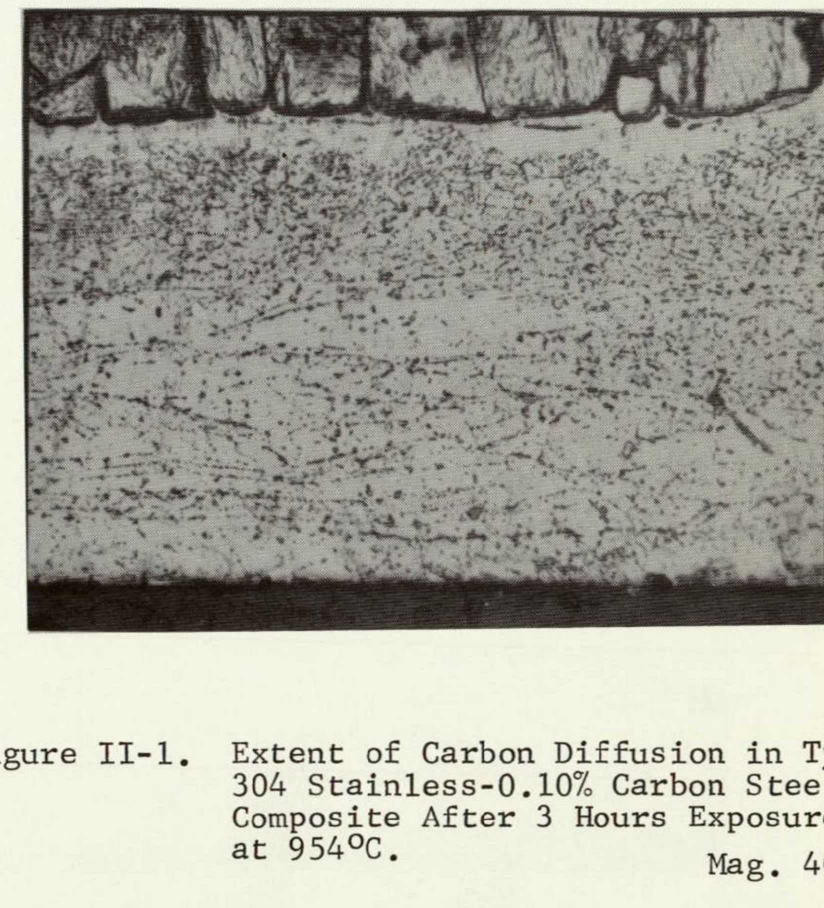
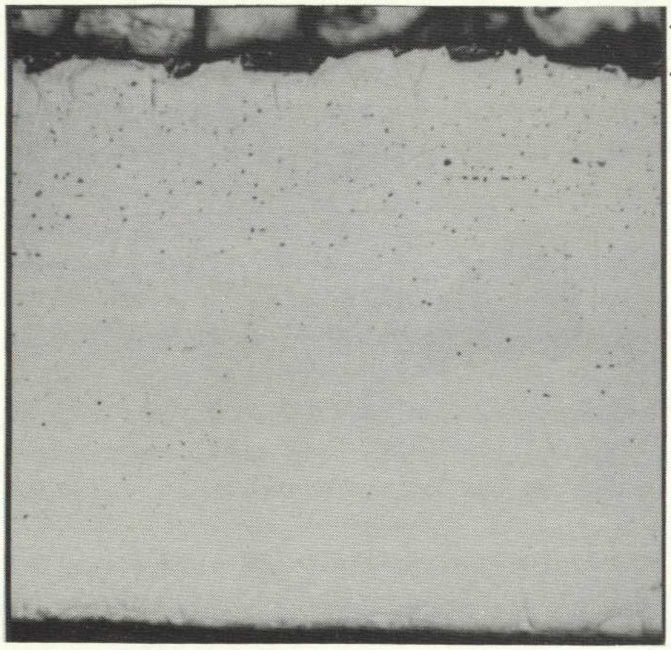
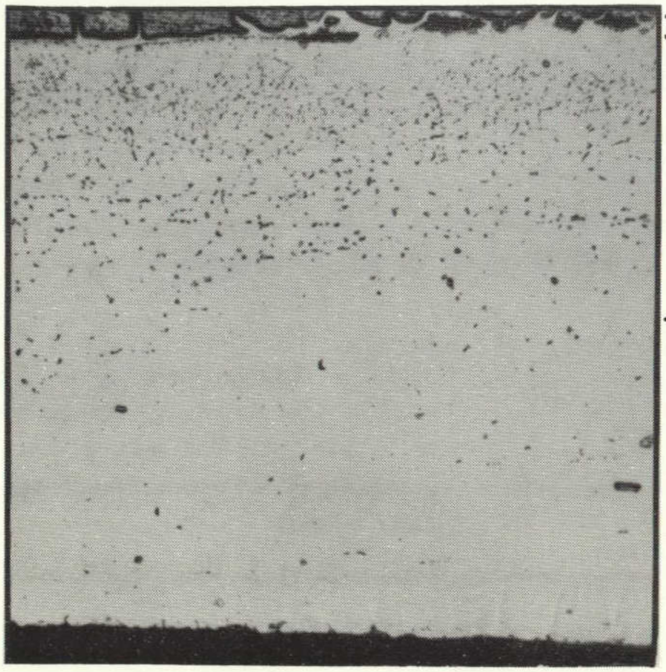


Figure II-1. Extent of Carbon Diffusion in Type 304 Stainless-0.10% Carbon Steel Composite After 3 Hours Exposure at 954°C.

Mag. 400X



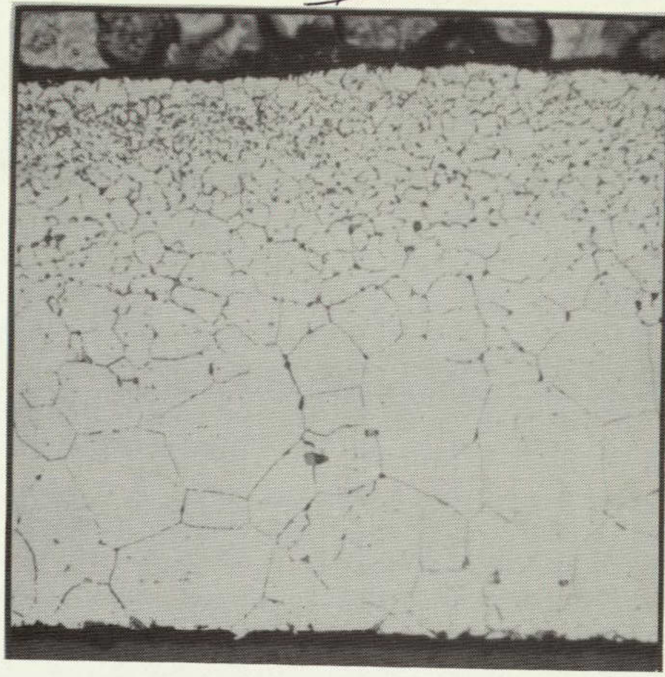
0.01% C



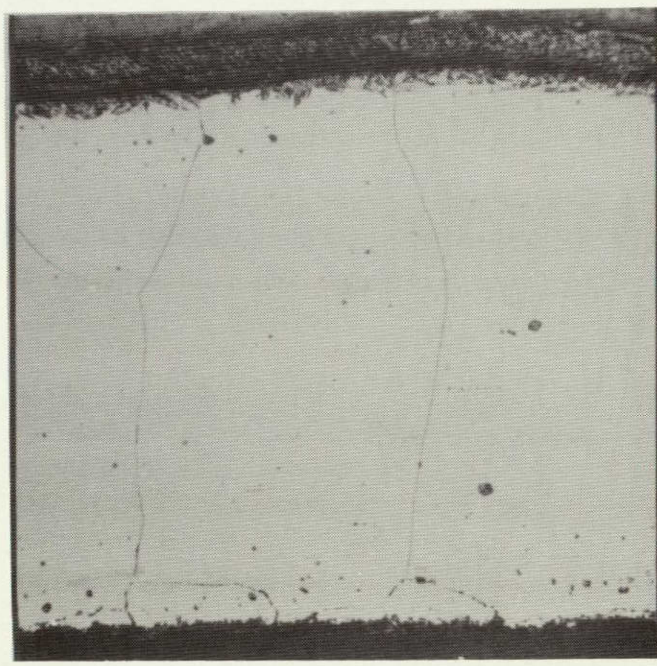
0.10% C

Figure II-2. Effect of Carbon Steel Carbon Content on the Extent of Carbon Diffusion in Type 304L Stainless-Carbon Steel Composites After 3 Hours Exposure at 954°C.

Mag. 400X



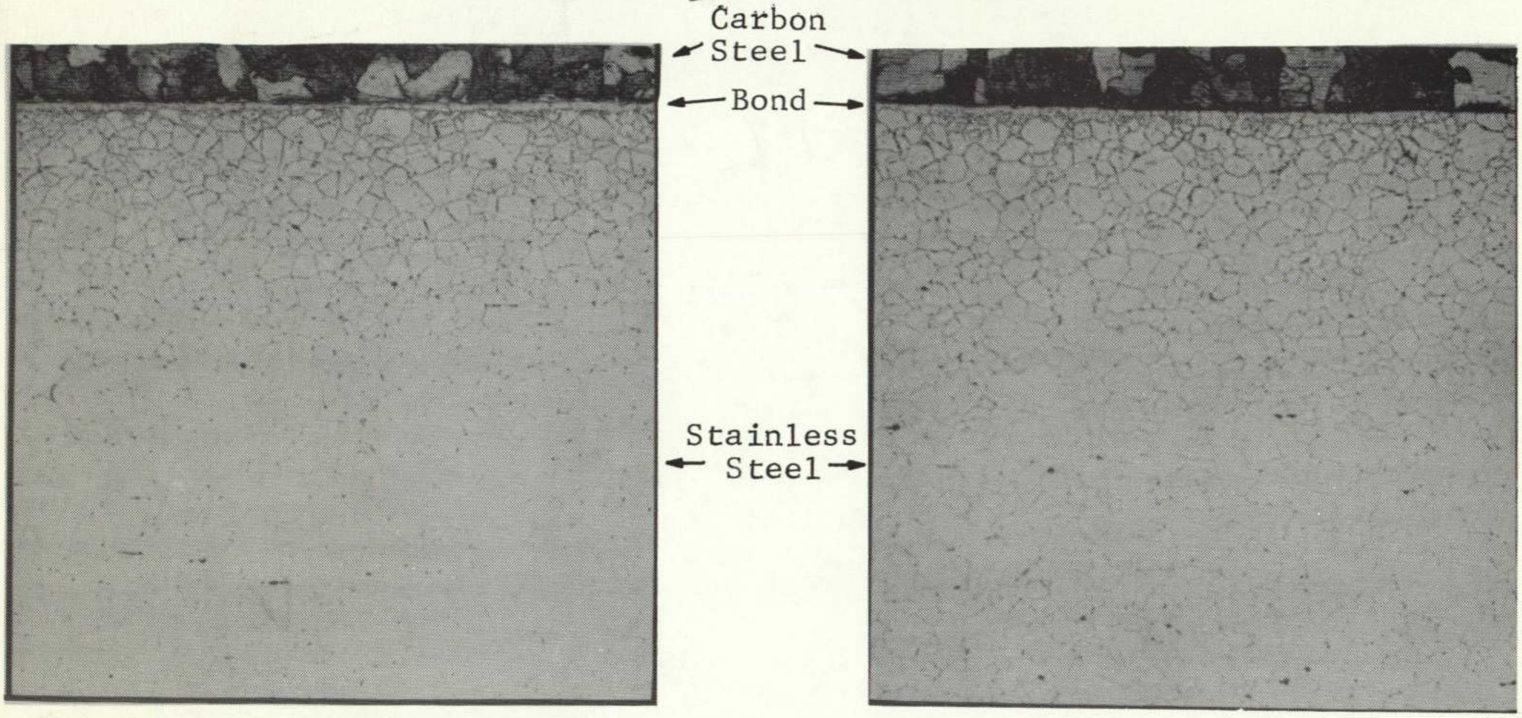
954°C - 3 Hours



1177°C - 3 Hours

Figure II-3. Effect of Exposure Temperature on Carbon Diffusion in Type 304L:0.10% Carbon Steel Composites. Exposure Time Was 3 Hours. Samples Were Sensitized at 677°C for 5 Minutes to Delineate Grain Boundaries.

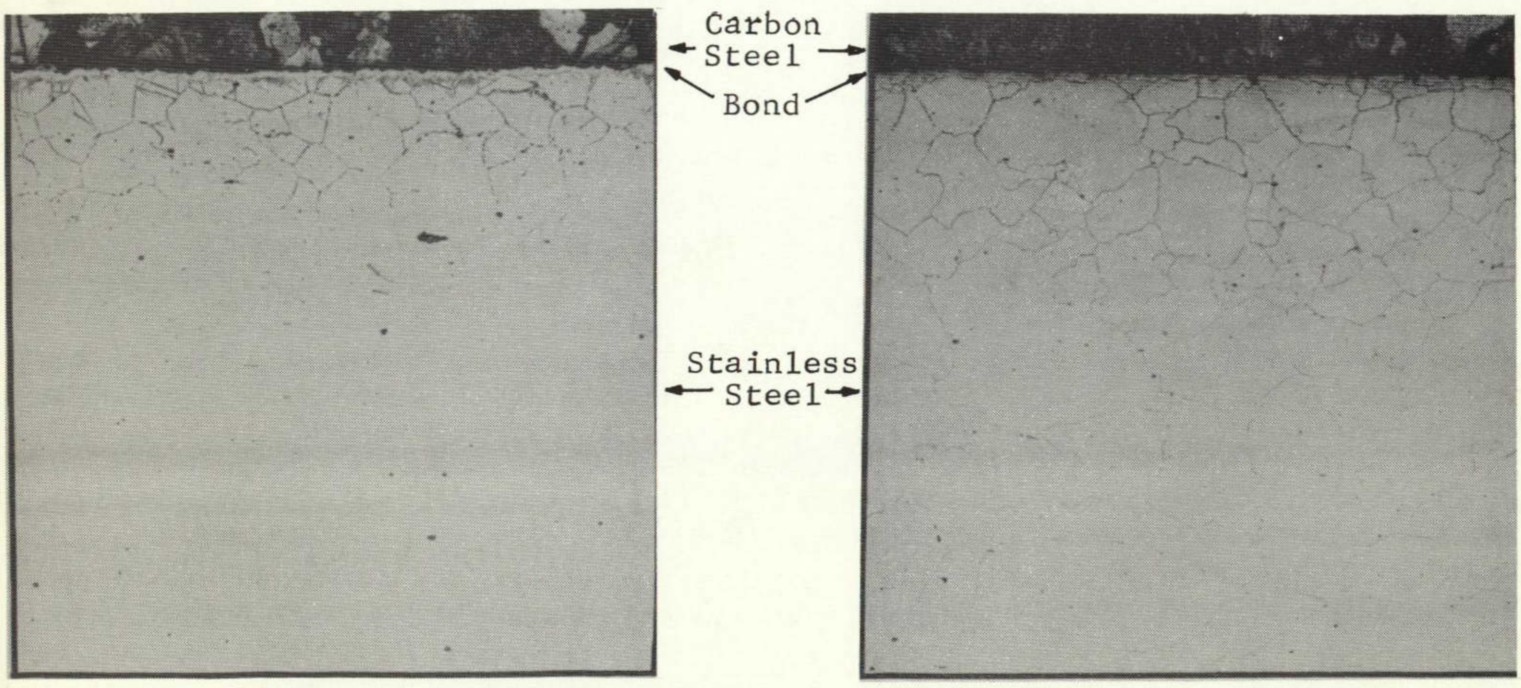
Mag. 400X



Bonded and reannealed at 1010°C for 3 minutes.

Bonded, reannealed and sensitized at 593°C for 5 minutes.

Type 304:0.10% Carbon Steel Bonds



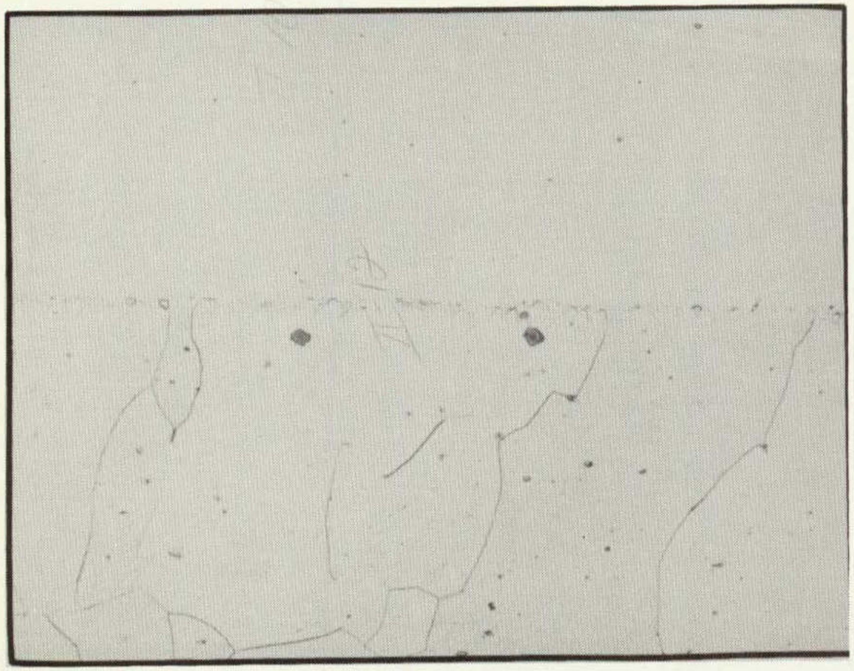
Bonded and reannealed at 1010°C for 3 minutes.

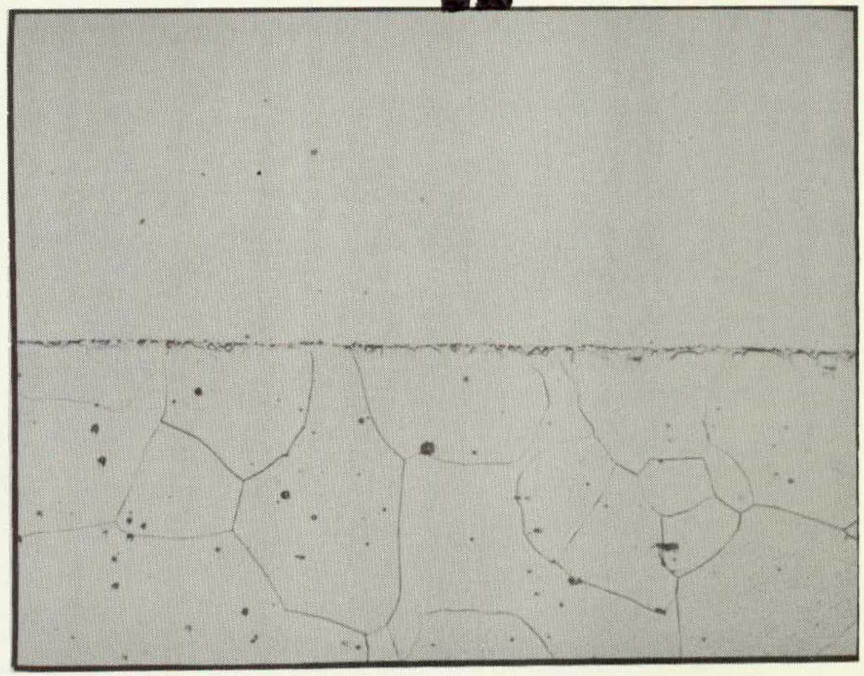
Bonded, reannealed and sensitized at 593°C for 5 minutes.

Type 304L:0.10% Carbon Steel Bonds

Figure II-4. Extent of Carbon Diffusion in Compression Pack Tests Simulating Gas Pressure Bonding. Samples Were Bonded at 954°C for 1 Hour Under an Applied Stress of 6.89 MPa.

Mag. 200X



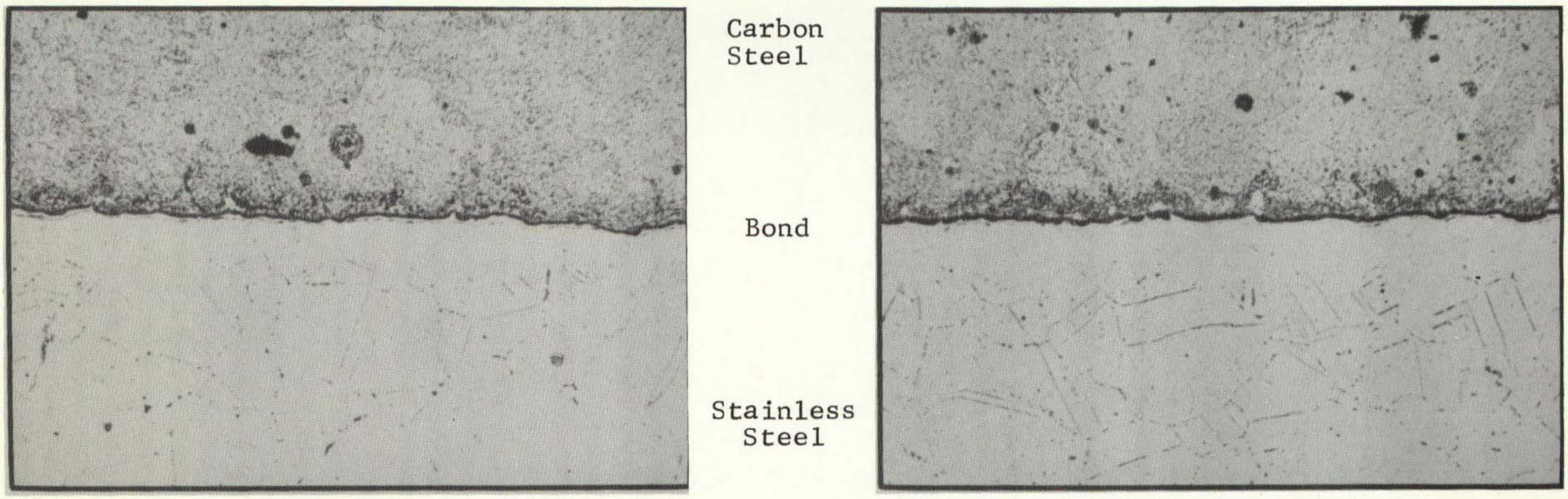


Sample a) Bonding between finished surfaces

Sample b) Bonding between carbon steel and adjacent oxidized stainless spacer

Figure II-5. Typical Bond Interface Between Type 304L and AISI 1010 Carbon Steels Produced During Gas Pressure Bonding at 899°C (1650°F).

Etchant: 5% Nital - Grain Boundaries Delineated on Carbon Steel Mag. 200X



Type 304L:0.04% Carbon Steel

Type 304L:0.10% Carbon Steel

Figure II-6. Extent of Carbon Diffusion in Type 304L:Carbon Steel Composites (240 Grit Finish) During Gas Pressure Bonding at 899°C. Samples were annealed at 1066°C for 10 minutes after bonding.

Etchant: 10% Oxalic Acid - Electrolytic

Mag. 400X

III. Fabrication of Stainless Steel Clad Tubing

A. Materials

The tube fabrication and evaluation phases of this program were conducted in two sequential tasks. Task I consisted of the fabrication of only 25.4 mm (1.0 inch) diameter-20 percent stainless wall tubes which were then thoroughly evaluated before proceeding to the second task. Task II consisted of the fabrication of all four tube sizes in sufficient quantity for limited evaluation and to provide enough tubes to meet the delivery requirement. Since the materials and fabrication methods used were generally the same for both tasks, they will be discussed together in this section.

The starting tubes were obtained in the form of welded tubing from commercial vendors. The source of the tubing and its chemical composition is given in Table III-1. In all cases the composition of the Type 304L tubing conformed to the AISI grade composition limits. The carbon steel tubing was purchased as AISI Grade 1010 carbon steel. However, in three cases we were able to select from the vendor a low carbon heat that actually conformed to 1006 carbon steel specifications. In the fourth case the carbon content was higher than the 1010 specification, but the tubing was retained in the program to explore the extent of carburization difficulties that might be encountered with a higher carbon steel.

B. Tube Preparation and Gas Pressure Bonding

The first step in fabrication was to prepare tubesets with the closest dimensional compatability to minimize possible distortion during the bonding operation. This was done by measuring the diameters of all tubes and then matching the best sizes for each tubeset. In some cases outside diameter metal removal was required on the carbon steel to obtain a good fit, and was accomplished by surface grinding. In all cases the inside diameter carbon steel weld flash had to be removed and this was accomplished with a shaving tool. All surfaces were then finished with 240 grit abrasive belts and then cleaned with chloroform. An illustration of the finished tubes and an assembled tubeset is given in Figure III-1. The typical starting tube sizes for each of the four final stainless clad sizes is given in Table III-2.

For gas pressure bonding, groups of five tubes each were placed in 25.4 cm (10-inch) diameter steel cans which were then filled with a sand pressure transfer medium. The tubes were first coated with a glass coating to minimize sand imbedment on the surfaces and to prevent sand from penetrating between layers from the tube ends. An illustration showing a loaded can partially filled with the pressure transfer medium is provided in Figure III-2. After filling, the cans were vibrated to maximize the density of the pressure transfer medium, and an end plate containing an evacuation tube was welded to the end to complete the can assembly as shown in Figure III-3. The cans were then evacuated to a pressure 10 μm and sealed.

Gas pressure bonding of the Task I tubes was conducted in an autoclave located at Kennametal, Latrobe, Pa. Bonding conditions as measured inside the autoclave were: temperature - 899°C (1750°F), time at temperature - approximately 3 hours, pressure - 103 MPa (15,000 psi). The Task II tubes were bonded in the large autoclave located at Battelle Memorial Institute. Bonding conditions employed for these tubes were the same as those used for the Task I tubes. The appearance of the tubes after gas pressure bonding was quite good in terms of straightness and roundness, and in this regard the quality was quite adequate for subsequent cold drawing operations. The general surface smoothness also was good, but some of the Task II tubes contained surface defects. An illustration of an as-bonded Task I tube showing good roundness and surface condition is provided in Figure III-4. Examples of the Task II tube surfaces illustrating the range of surface conditions encountered are provided in Figure III-5.

C. Final Fabrication by Cold Drawing and Annealing

Processing of the gas pressure bonded tubes to final size was accomplished by a double cold draw-anneal sequence commonly used commercially to finish welded stainless steel tubing. This work was conducted using production facilities and by methods routinely used to produce stainless tubing at the Trent Tube Division of Colt Industries. The only special procedures followed related to close control of annealing to minimize carburization, and close control of pickling to minimize attack on the very thin stainless surfaces layers. These controls consisted of restricted times and temperatures for both operations. A complete process schedule for each set of tubes is given in Table III-3.

This processing was generally successful in that all of the as-bonded tubes which were free of surface defects could be cold drawn with no difficulty. The only cold drawing difficulty encountered was with the Task II-a tubes which contained surface defects in the as-bonded condition. These defects produced delamination on the inside stainless layer during the end pointing operation required to gain entrance to the die. These delaminated areas then interferred with the plug and breakage resulted. As a consequence, only a few short lengths of the Task II-a tubes were successfully produced. Another problem was encountered in pickling the Task II-c tubes. These tubes were designed with an extremely thin stainless layer thickness, 0.178 mm (0.0071 inches) in the as-bonded condition, which evidently was severely carburized after the intermediate annealing operation. As a consequence, the surfaces reacted very rapidly with the pickling bath. In spite of careful observation during pickling, the outer stainless layer was completely removed before the operation could be halted.

The net successful production of tubes then was as follows: five Task I tubes, five Task II-b tubes, and four Task II-d tubes. These tubes had an average length of about 2.5 meters (8 feet) and are shown in Figures III-6 and III-7.

Experience from the fabrication phase of the program indicates that stainless steel clad carbon steel tubing can be successfully produced by the gas pressure bonding process. While a large number of steps are required, with the exception of the autoclave, none of these steps require specialized production equipment or special procedures that do not lend themselves to a normal manufacturing operation. Thus the production of such tubes on a commercial basis would seem feasible providing the material supply, demand and economic factors were favorable; and that the quality and properties of the clad tubing were adequate for potential applications. The quality and properties of this tubing is considered in the next section of this report.

TABLE III-1. Chemical Composition of Starting Tubes Used for Clad Stainless Tube Fabrication

Task	Grade	C	Mn	P	S	Si	Ni	Cr	Mo	Cu
I	1010*	0.049	-	-	-	-	-	-	-	-
I	304L	0.026	1.67	0.032	0.020	0.63	9.86	18.30	0.38	0.22
II-a	1010*	0.073	-	-	-	-	-	-	-	-
II-a	304L	0.020	1.25	0.012	0.010	0.44	9.80	18.60	0.02	0.03
II-b	1010*	0.049	-	-	-	-	-	-	-	-
II-b	304L	0.026	1.67	0.032	0.020	0.63	9.86	18.30	0.38	0.22
II-c	1010*	0.049	-	-	-	-	-	-	-	-
II-c	304L	0.020	1.25	0.012	0.010	0.44	9.80	18.60	0.02	0.03
II-d	1010*	0.187	-	-	-	-	-	-	-	-
II-d	304L	0.020	1.25	0.012	0.010	0.44	9.80	18.60	0.02	0.03

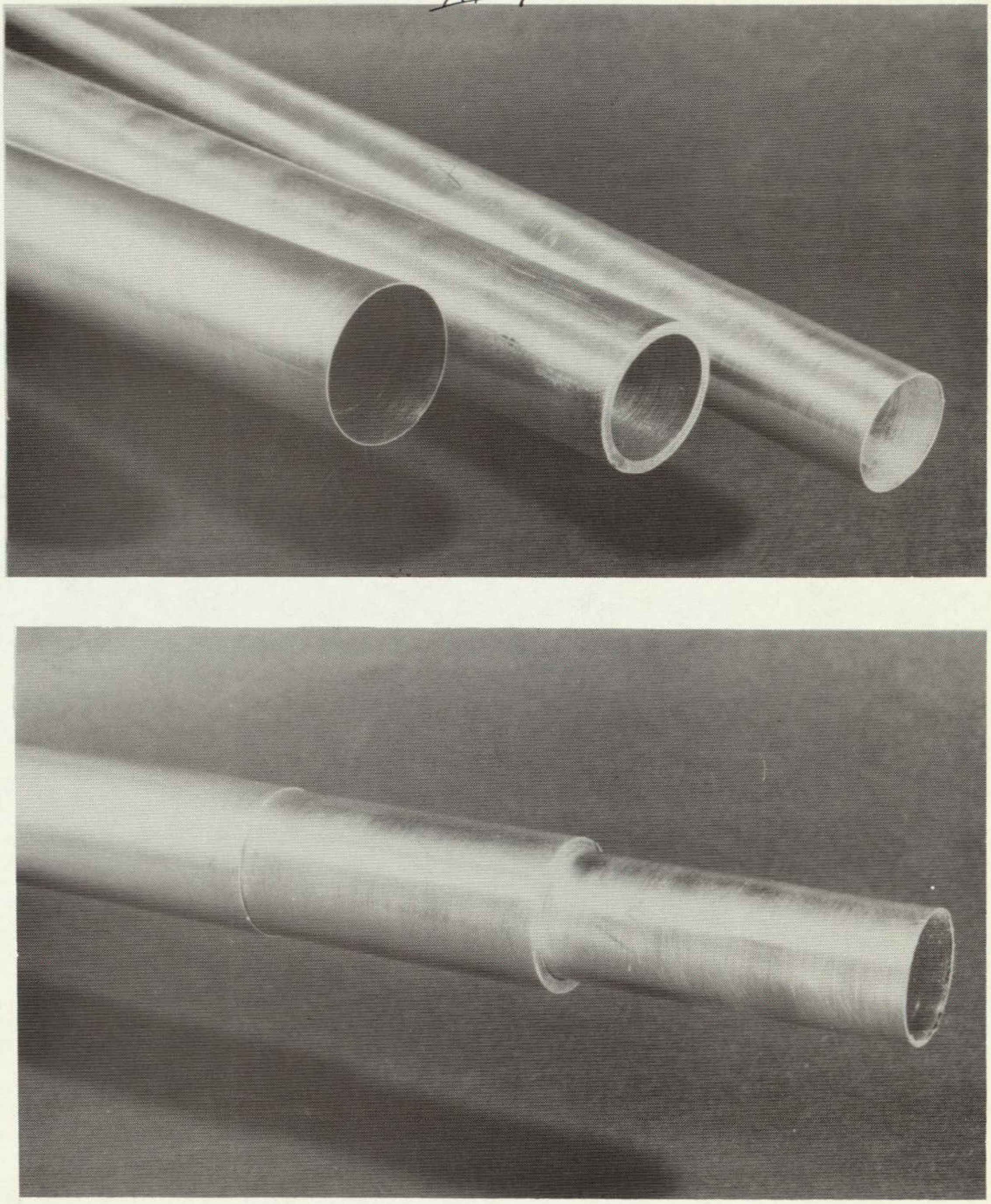
* Material supplied by Keystone Tubular Service Corp.

TABLE III-2. Stainless and Carbon Steel Component Tube Sizes and Final Clad Carbon Steel Tube Sizes Produced by Gas Pressure Bonding

	Starting Tube Sizes					Final Stainless Clad Carbon Steel Tube Size				
	Component	Diameter		Wall		Diameter		Wall		Stainless Steel Clad
		mm	in.	mm	in.	mm	in.	mm	in.	
Task II (a)	Carbon Core	57.15	2.250	1.575	.062					
	Inner Stainless Clad	53.34	2.100	0.203	.008					
	Outer Stainless Clad	57.78	2.275	0.203	.008					
	CLAD BONDED TUBE	57.56	2.266	1.981	.078	44.45	1.75	1.651	.065	20%
Task II (b)	Carbon Core	30.99	1.220	2.59	.102					
	Inner Stainless Clad	25.40	1.000	0.33	.013					
	Outer Stainless Clad	31.75	1.250	0.33	.013					
	CLAD BONDED TUBE	31.65	1.246	3.25	.128	25.4	1.0	2.413	.095	20%
Task II (c)	Carbon Core	31.75	1.250	3.048	.120					
	Inner Stainless Clad	25.40	1.000	0.178	.007					
	Outer Stainless Clad	32.38	1.275	0.178	.007					
	CLAD BONDED TUBE	32.13	1.265	3.404	.134	25.4	1.0	2.413	.095	10%
Task II (d)	Carbon Core	54.10	2.130	3.988	.157					
	Inner Stainless Clad	45.59	1.795	0.508	.020					
	Outer Stainless Clad	55.37	2.180	0.508	.020					
	CLAD BONDED TUBE	55.12	2.170	5.004	.197	44.45	1.75	3.404	.134	20%

TABLE III-3. Cold Draw - Anneal Process Schedule Used for Clad Stainless Tubing

Operation		Task I Tubes	Task II-a Tubes	Task II-b Tubes	Task II-c Tubes	Task II-d Tubes
Initial Tube Size	- Dia.	31.6 mm	57.8 mm	31.6 mm	32.1 mm	55.1 mm
	- Wall	3.25 mm	1.98 mm	3.25 mm	3.40 mm	5.00 mm
Clean Tubes		Shot Blast Pickle	Shot Blast Pickle	Shot Blast Pickle	Shot Blast Pickle	Shot Blast Pickle
Cold Draw - Size	- Dia.	27.9 mm	Broke in Draw	27.9 mm		49.7 mm
	- Wall	2.97 mm		2.79 mm		4.14 mm
- Reduction		18%	(discontinued)	23%		25%
Air Anneal		1066°C - 5 min	-	1066°C - 5 min	1066°C - 5 min	1066°C - 5 min
Nitric - HF Acid Pickle		15 min	-	15 min	10 min stainless removed (discontinued)	15 min
Cold Draw - Size	- Dia.	25.4 mm	-	25.4 mm	-	44.5 mm
	- Wall	2.41 mm		2.41 mm		3.40 mm
- Reduction		25%		21%		26%
Air Anneal		1066°C - 5 min	-	1066°C - 5 min	-	1066°C - 5 min
Nitric - HF Acid Pickle		15 min	-	15 min	-	15 min
Number of Tubes		5	0	5	-	4



Outer Stainless   Carbon Steel   Inner Stainless

Figure III-1. Task I Tube Assemblies Prior to Gas Pressure Bonding.

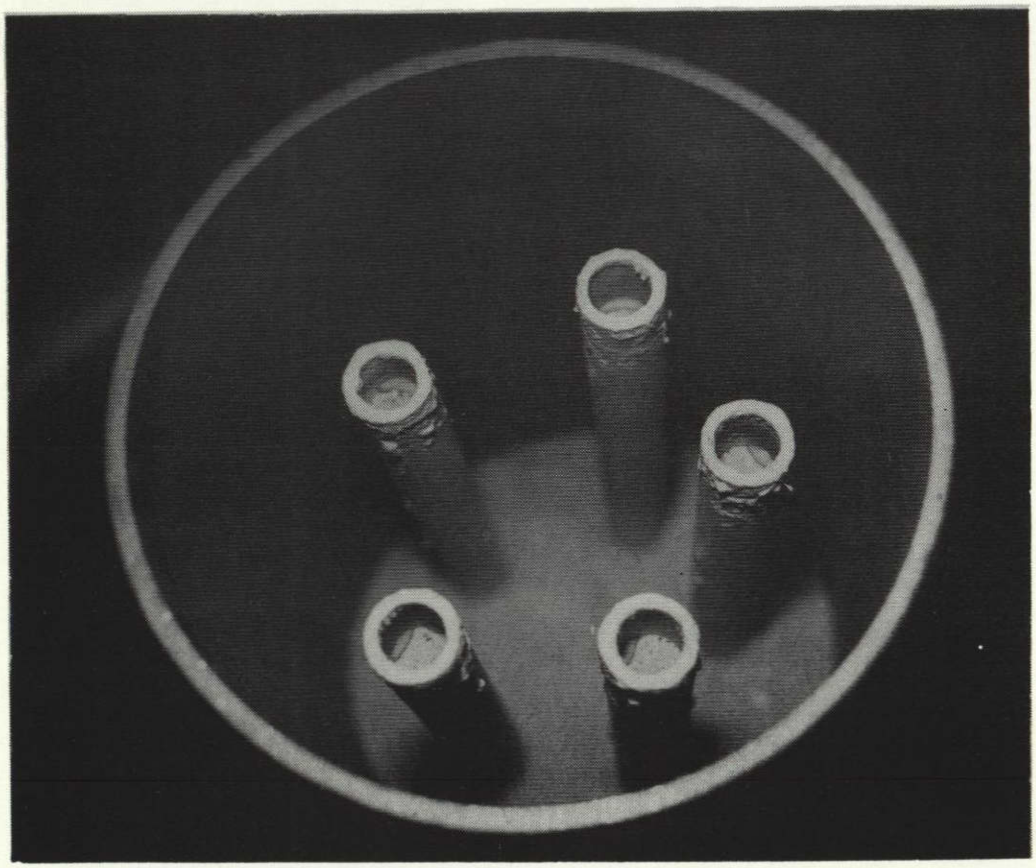


Figure III-2. Interior View of Can and Assembled Tubes Prior to Gas Pressure Bonding Task I Tubes.

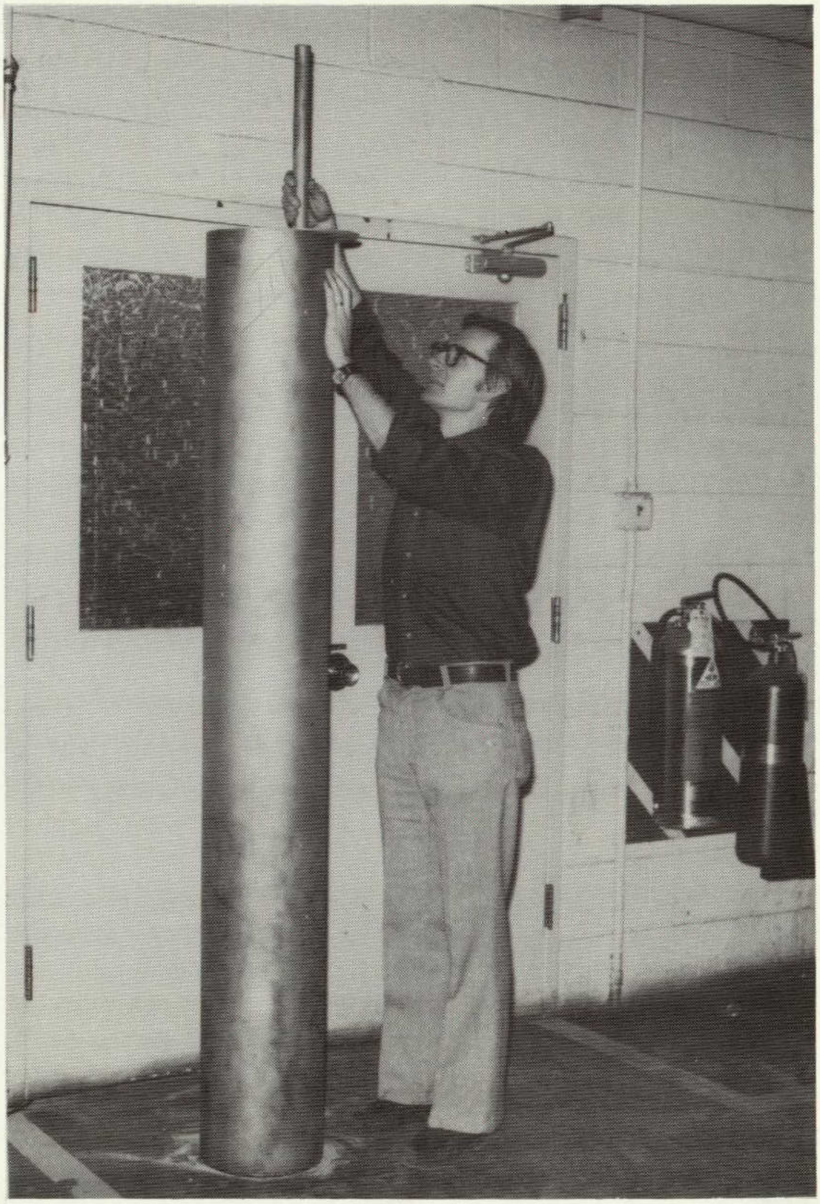


Figure III-3. Can Assembly Used for Gas Pressure Bonding.

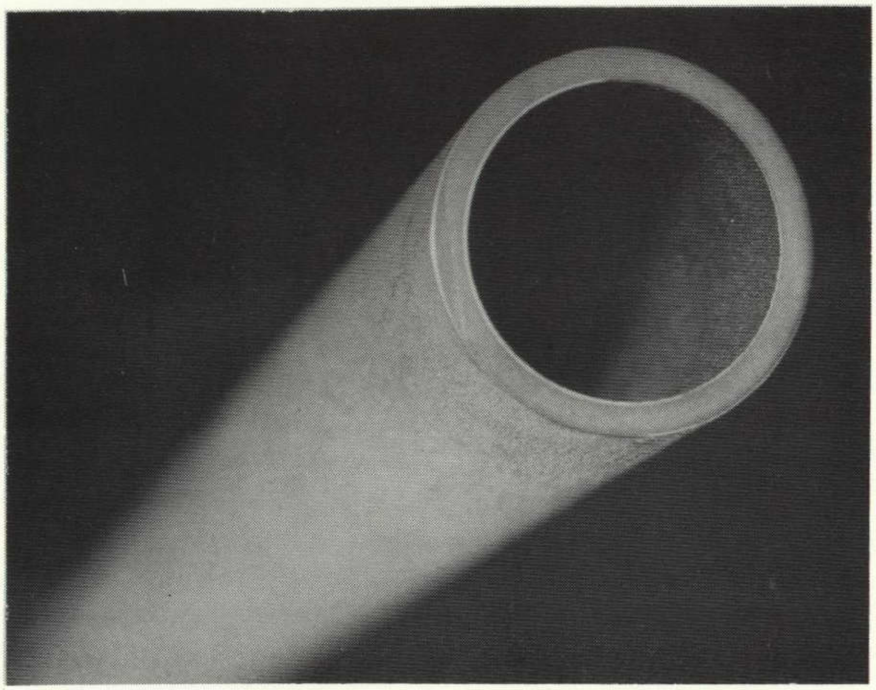


Figure III-4. Appearance of a Task I Tube After Gas Pressure Bonding.

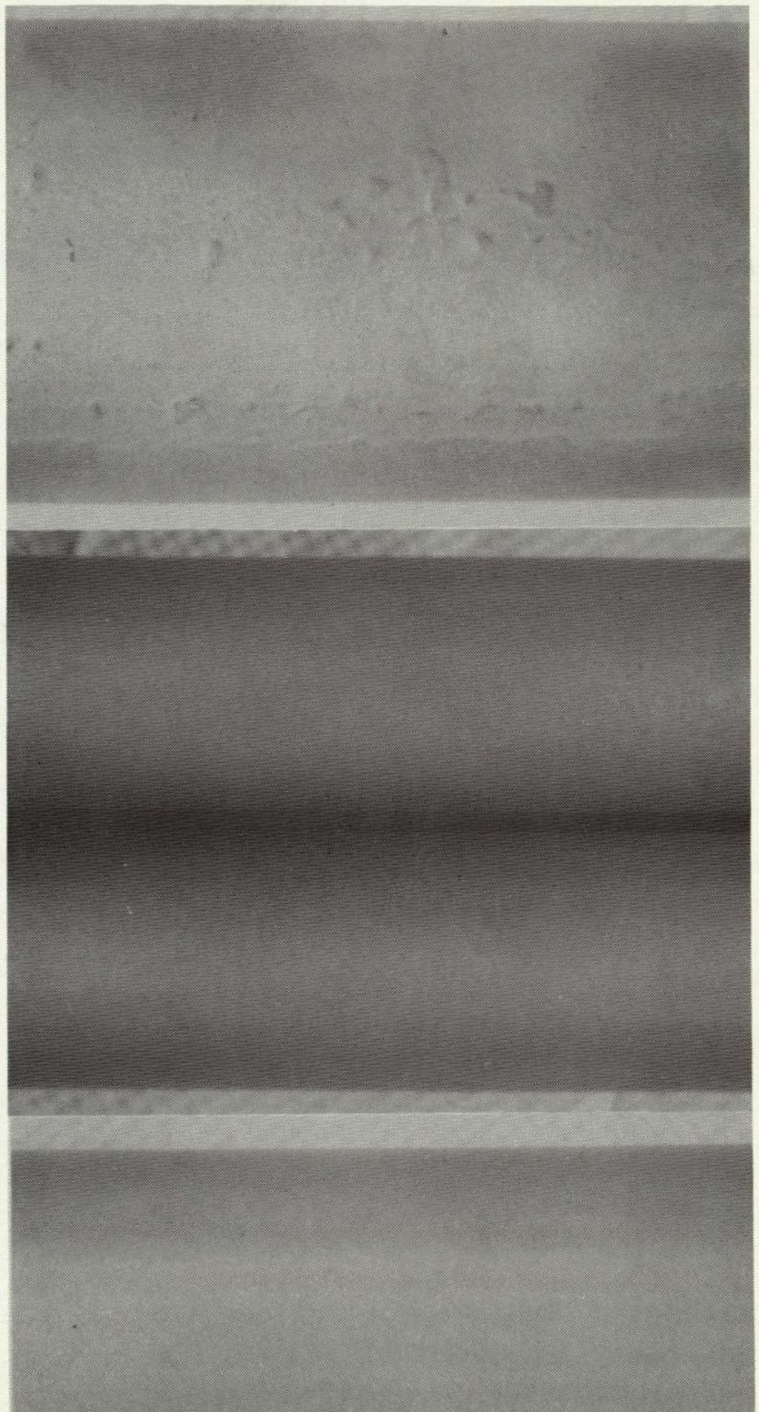


Figure III-5. Surface Appearance of Task II Tubes After Gas Pressure Bonding Showing Good and Non-uniform Surface Conditions. Mag. 1X

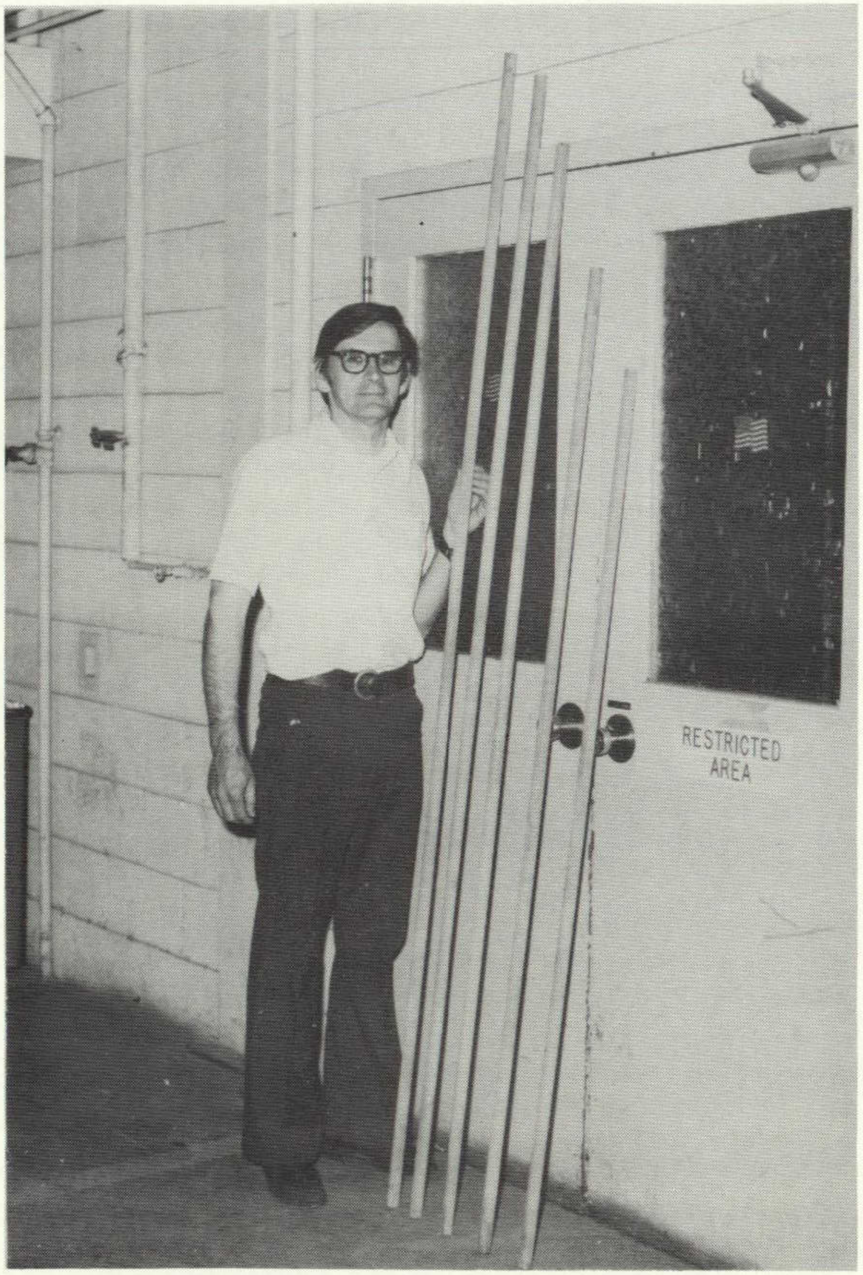


Figure III-6. Completed Task I Tubing.

Figure III-7. Completed Task II Tubing.

IV. Tubing Evaluation

A. Bond Integrity and Carburization of As-Bonded Tubes

Sections of as-bonded tubes were evaluated by metallographic methods for bond integrity and degree of carburization. In all sections examined the stainless-carbon steel interfaces displayed a complete metallurgical bond as illustrated in Figure IV-1 for the Task I tube and Figures IV-2-5 for the Task II tubes. The only abnormalities noted were occasional oxide particles on the interface which could have been caused by residual surface contamination.

Substantial carburization of the stainless steel developed in all of the tubing as illustrated in Figure IV-1 and Figures IV-6-9. The amount of carbon enrichment did not exceed the austenite solubility limit at 1066°C (1950°F) beyond a depth of 0.178 mm (0.007 inches) as determined by an annealing experiment on the Task I tube shown in Figure IV-1b. This degree of carburization approaches the planned final wall thickness of the tubing. Therefore, anticipating further carbon diffusion during annealing, the possibility of outer stainless surface sensitization in the finished tubing was expected.

B. Stainless Uniformity and Integrity in Finished Tubing

The bond integrity of those tubes which were successfully cold drawn to final size appeared to be good on the basis of metallographic examination (Figures IV-10 and 11 for Task I tubing and Figures IV-12-16 for Task II tubing). However, the amount of oxide particles on the interface appeared to be greater in finished tubing compared to as-bonded tubing. Also, voids were present on some interfaces (Figures IV-13 and 14) suggesting that cold drawing can initiate void formation, possibly on oxides initially present at the interface.

The stainless clad layer was very uniform in thickness on tubing that retained a smooth surface in the pickling operations. However, many of the tubes were severely pickled producing stainless non-uniformity on micro-scale. This severe pickling was obviously caused by surface intergranular sensitization as demonstrated by the intergranular nature of the pickling attack shown in Figures IV-11, 15 and 16. While there was some variation in degree of surface attack, there was no apparent trend of reduced attack in the thicker stainless wall Task II-d tubes. Therefore, carburization penetrated as far as the 0.33 mm stainless wall of the Task II-d tubes.

C. Mechanical Properties and Formability

Standard tension tests were conducted on two Task I tubes and a Type 304 monolithic stainless tube of similar size. The results, given in Table IV-1, show that the yield strength of the clad tubing is comparable to that of monolithic Type 304 and it is considerably higher than that expected for AISI 1010 carbon steel. Tensile strength of the clad tubing is greater than that of AISI 1010 but substantially lower than that of Type 304 stainless. The ductility of the clad tubing was comparable to that of AISI 1010 and it was considerably lower than that of Type 304 stainless. Thus, the yield strength of the clad tubing favors that of the higher strength stainless while the other tensile properties favor those of carbon steel which constitutes 80 percent of the clad wall thickness. This behavior is normal for clad materials in general. The tubes did not show any evidence of delamination of fracture, and the fracture was normal for a tubular tensile specimen having ductile fracture as shown in Figure IV-17.

Samples of the Task I and Task II-d tubes were successfully flared to a 37^{o} angle using SAE Specification T533b (Flares for Tubing) as a standard. In these tests the clad tubes were deburred and flared to a minimum flare opening of 30.48 mm (1.200 inch). No evidence of disbonding or localized fracture was observed on the flared surface or tube end as shown in Figures IV-18 and 19. Metallographic examination of the flare specimens also showed no evidence of disbonding or localized fracture as shown in Figures IV-20 and 21.

In bend testing, samples of Task I tubes 1, 4 and 5 were successfully bent to a 90^{o} angle over an 8.89 cm (3-1/2 inch) radius with no visual evidence of clad fracture as shown in Figure IV-21. The Task II-d tubes were also bent but these tubes showed evidence of clad stainless disbonding on the inside bend radius as shown in Figure IV-22.

D. Corrosion and Burst Test Evaluation

Copper-accelerated acetic acid salt spray (CASS) test (ASTM B368) were conducted to compare the corrosion resistance of clad tubing with that of monolithic Type 304 tubing. Clad Task I tubes 2 and 4 were used for CASS testing. A 240 grit finish was applied to all CASS test samples to provide a relatively smooth and uniform finish. This was necessary since excessive oxidation and aggressive pickling attack during final tube processing resulted in a very rough final clad tube finish. A 240 grit finish was also applied to monolithic Type 304 CASS test samples.

Prior to corrosion testing, the cut ends of each clad tube sample were masked with a protective neoprene primer coating in efforts to prevent carbon steel core corrosion and subsequent rust rundown over the OD stainless surface being evaluated. Six samples of each clad tube were prepared in the manner. In the course of CASS testing, it was apparent that the protective edge coating began to break down after about one week exposure causing rust rundown. To minimize the effect, all samples were removed after two weeks exposure, their cut edges cleaned and recoated.

CASS tests were conducted by initially placing all clad and monolithic stainless samples in the salt spray cabinet and removing one sample from each tube at one week intervals. Each sample was rated for rust staining on both front and back surfaces in the as-tested (uncleaned) condition and after a light cleaning with a soft paper towel to remove edge rundown effects. The results of six weeks of CASS testing are given in Table IV-1. Due to rust rundown from the front surfaces as well as the coated tube ends, the back surfaces displayed heavier staining. As indicated in Table IV-2, light cleaning removes a large percentage of the rust staining observed on both the front and back surfaces. An unusual pit-type condition developed on the composite tubes after being exposed for two weeks and the number of pits increased with exposure time. The monolithic stainless tube did not display any type pitting and was less corroded in general. Figures IV-23 through IV-25 show the appearance of the test specimens after one through six weeks exposure to CASS testing.

Samples of Task II tubes were also evaluated by the same procedures in the CASS corrosion test except that no surface conditioning was employed prior to the test. These tubes developed substantial rust staining after 15 and 30 days exposure as shown in Figures IV-26-29 and summarized in Table IV-3. This poor performance is obviously due to the rough pickled surfaces and intergranular sensitization present in these tubes.

The Task I corrosion test specimens were burst tested and the results are summarized in Figure IV-30. In general, the burst pressure for the clad tube decreases with increased CASS test exposure time but the maximum loss in burst strength is slightly less than 10 percent. We also noted that all of the failures occurred in the thinnest portion of the wall.

E. Clad Tubing Quality in Comparison to Monolithic Tubing

From the viewpoint of bond integrity and overall mechanical quality, these results show that stainless clad tubing produced by the gas pressure bonding process is similar to monolithic tubing. The tubing can withstand normal forming operations without any mechanical degradation. The only mechanical differences in comparison to monolithic tubing are those related to the inherent strength and ductility characteristics of the component materials. In regard to corrosion resistance this is not the case in view of the decidedly inferior corrosion resistance of the clad tubing. This poor corrosion resistance has been shown to be caused by excessive carburization of the stainless surface layers by the carbon steel core. A number of possibilities exist for solving this problem which include: the optimization of bonding conditions in relation to carburization, the use of thicker starting stainless clad layers, revising processing schedules to minimize the need for annealing, and the use of a low carbon or stabilized carbon steel core perhaps with nickel plating or other carburization barrier.

TABLE IV-1 Tensile Properties of Stainless Clad Carbon Steel Tubing*

	Tensile Strength MPa	Tensile Strength (psi)	Yield Strength .2% Offset MPa	Yield Strength .2% Offset (psi)	Elongation in 2 inches (%)
Tube 4	372	(53,900)	255	(37,000)	26.0
Tube 4	405	(58,800)	281	(40,700)	24.0
Type 304 Stainless	623	(90,300)	251	(36,400)	74.5
AISI 1010 (Hot Rolled)[1]	331	(48,000)	172	(25,000)	28.0

* Nominally 25.4 mm (1 in.) diameter by 2.413 mm (.095 in.) wall.

TABLE IV-2. Results of Copper-Accelerated Acetic Acid Salt Spray (CASS) Corrosion Test Conducted on Task I Stainless Clad Tubing

	1 Week Run #1			2 Weeks Run #2			3 Weeks Run #3			4 Weeks Run #4			5 Weeks Run #5			6 Weeks Run #6		
	% Area Affected		No. of Pits	% Area Affected		No. of Pits	% Area Affected		No. of Pits	% Area Affected		No. of Pits	% Area Affected		No. of Pits	% Area Affected		No. of Pits
	Not Cleaned	Cleaned		Not Cleaned	Cleaned		Not Cleaned	Cleaned		Not Cleaned	Cleaned		Not Cleaned	Cleaned		Not Cleaned	Cleaned	
Monolithic 304 Stainless Front	0	0	0	0	0	0	27	5*	0	5	1*	0	5	1*	0	5	1*	0
Back	35	15*	0	40	15*	0	50	10*	0	60	15*	0	55	15*	0	65	16*	0
Composite Tube 2 Front	18	7	0	25	7	0	45	8	7	60	15	11	65	15	20	75	17	20
Back	75	15	0	80	14	6	70	15	20	80	22	22	75	20	31	85	25	24
Composite Tube 4 Front	5	2	0	35	4	4	65	8	17	50	10	17	65	11	25	80	14	29
Back	75	12	0	80	10	3	60	15	18	75	24	28	75	22	32	80	25	38

Exposed surface areas, front and back, 61.3 cm^2 (9.5 $in.^2$) each.

* very light staining.

Tested surfaces had a 360 grit finish.

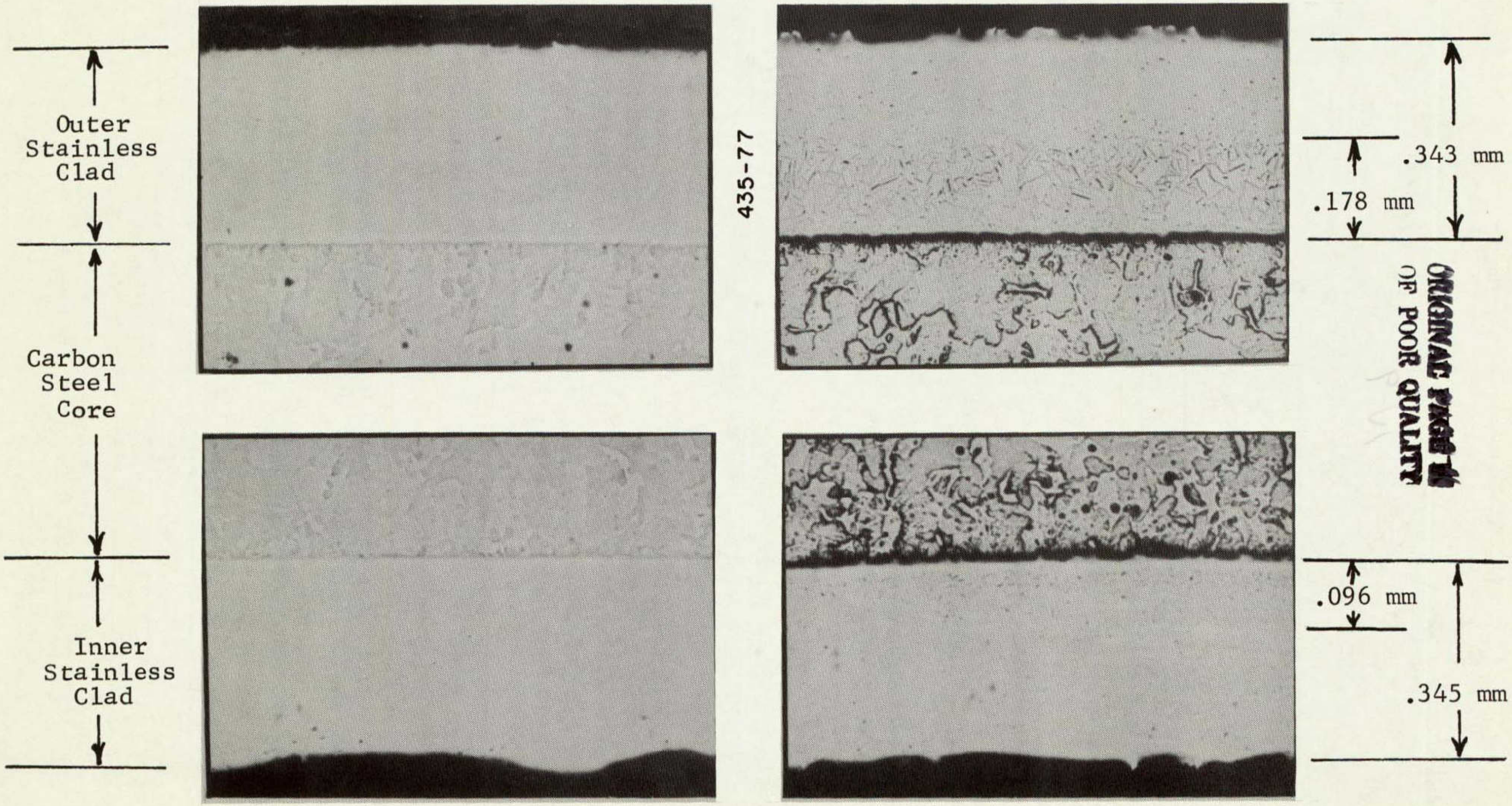
TABLE IV-3. Results of Copper-Accelerated Acetic Acid Salt Spray (CASS) Corrosion Test Conducted on Task II Stainless Clad Tubing

	Evaluation at 15 Days % Affected Area	Evaluation at 30 Days % Affected Area
Monolithic 304 Stainless A		
Front	2*	10*
Back	8*	35*
Monolithic 304 Stainless B		
Front	5*	7*
Back	15*	35*
Composite Tube II-a A		
Front	75	95
Back	75	98
Composite Tube II-a B		
Front	60	95
Back	70	99
Composite Tube II-d A		
Front	30	65
Back	60	90
Composite Tube II-d B		
Front	60	95
Back	60	95

Exposed Surface Areas
Monolithic 304 Stainless and Tube II-a, Front and Back, 61.3 cm^2 (9.5 $in.^2$) each,
Tube II-d, Front and Back, 106 cm^2 (16.5 $in.^2$) each.

Tested surface had an as-processed finish (cold drawn, annealed and pickled).

* Very light staining.



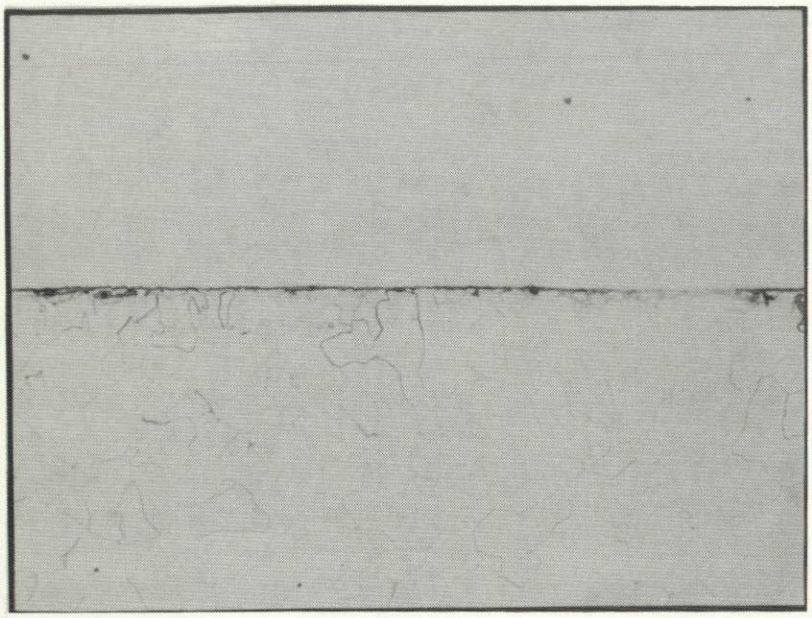
(a) As Gas Pressure Bonded

As Polished

(b) Bonded and Annealed at 1066C (1950F)

Etchant: Ammonium Persulfate - Electrolytic

Figure IV-1. Bond Integrity and Extent of Carbon Diffusion in Typical Task I As-Bonded Tubing. Mag. 100X



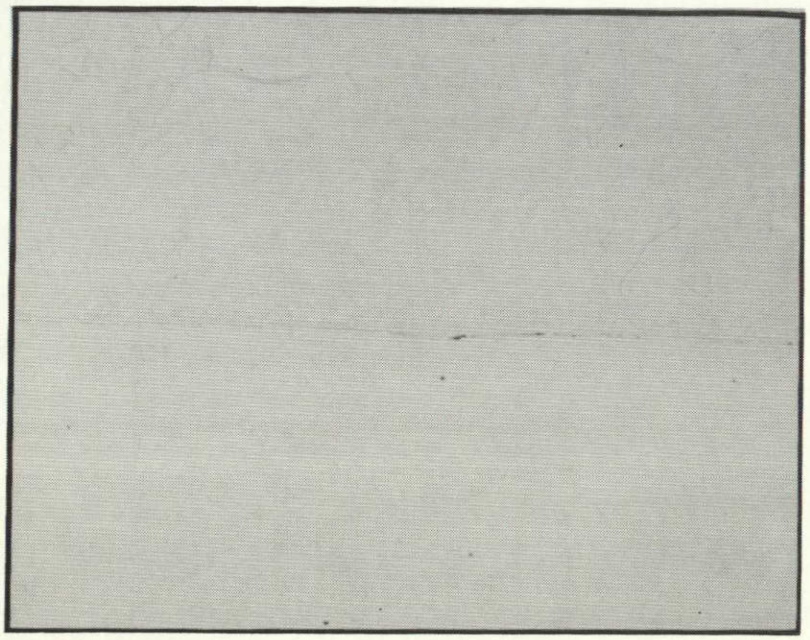
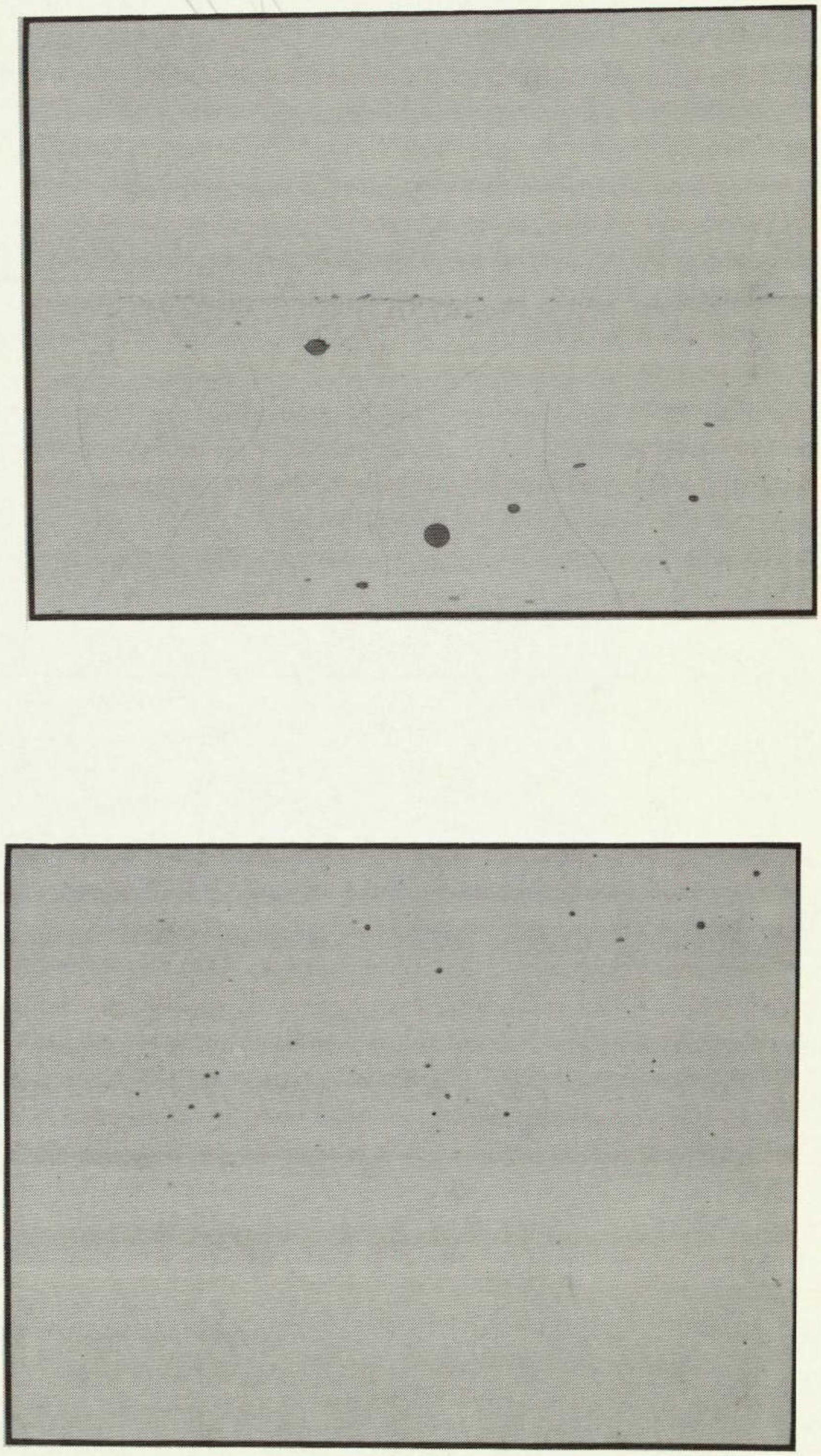


Figure IV-2. Longitudinal Section of Task II-a Tube Showing Bond Line Integrity in the As-Bonded Condition.

Etchant - Light Nital Mag. 200X



Outer Clad

Bond Line

Carbon Steel Core

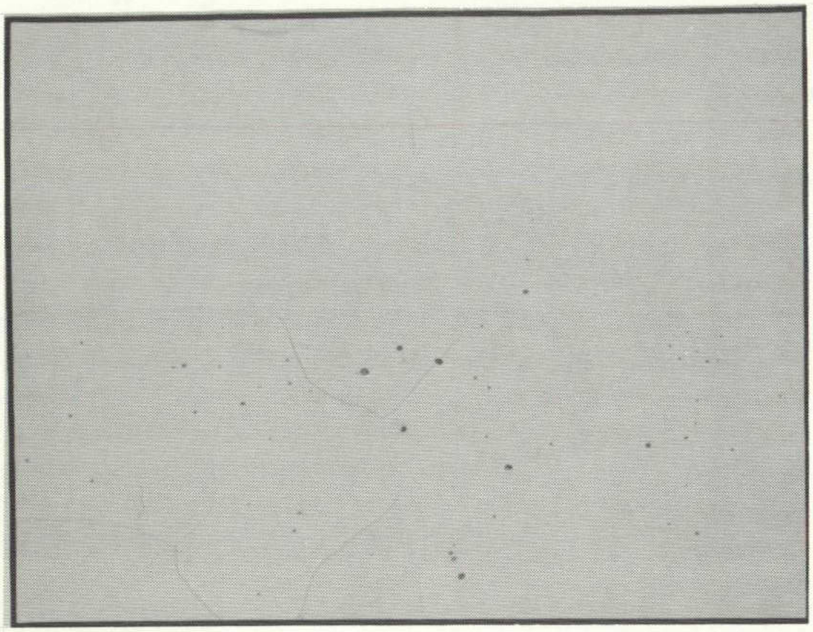
Carbon Steel Core

Bond Line

Inner Clad

Figure IV-3. Longitudinal Section of Task II-b Tube Showing Bond Line Integrity in the As-Bonded Condition.

Etchant: Light Nital Mag. 200X



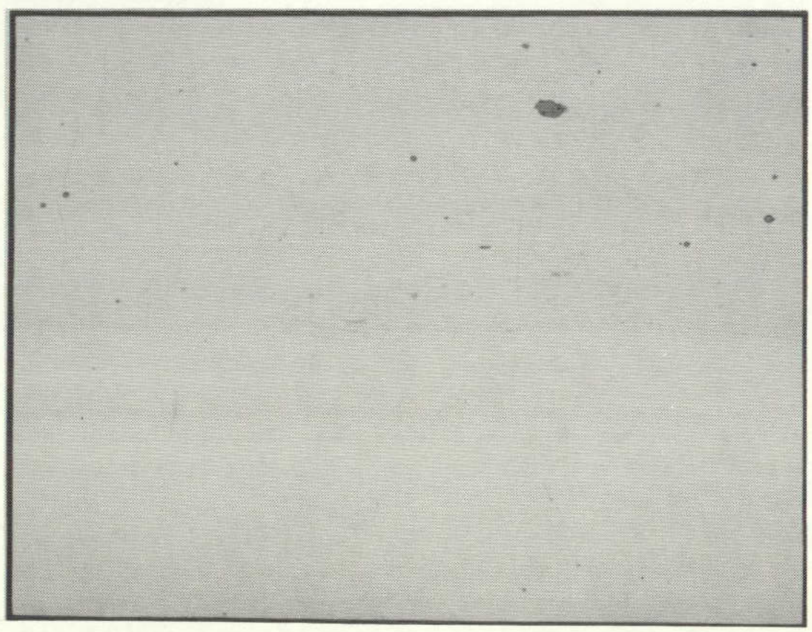
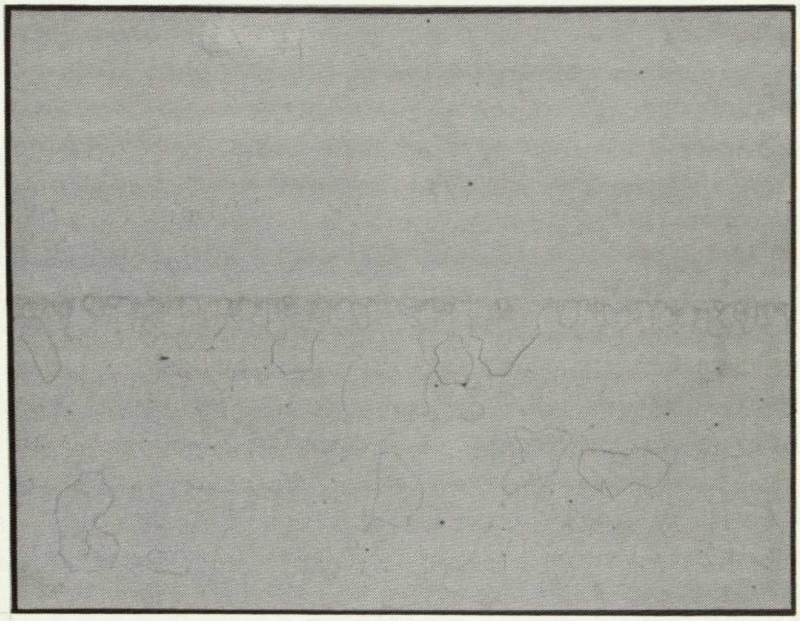


Figure IV-4. Longitudinal Section of Task II-c Tube Showing Bond Line Integrity in the As-Bonded Condition.

Etchant: Light Nital Mag. 200X



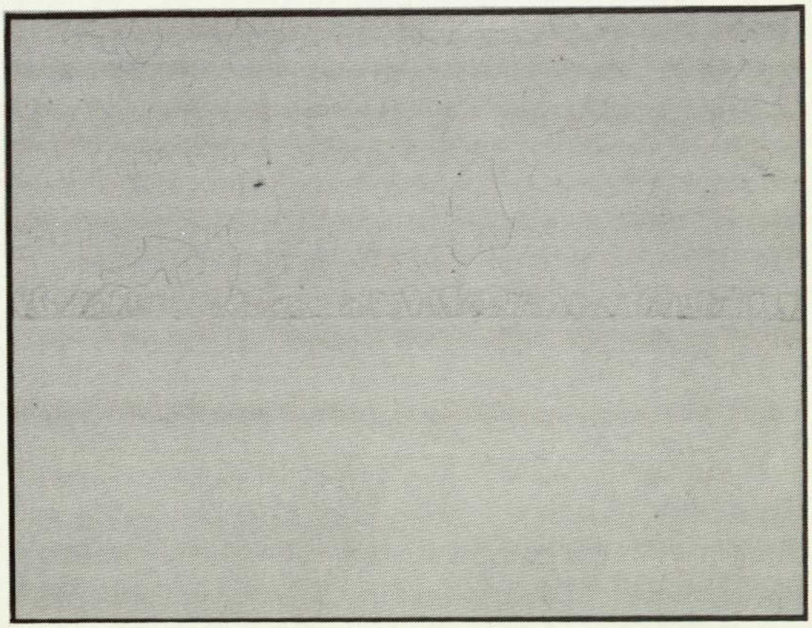


Figure IV-5. Longitudinal Section of Task II-d Tube Showing Bond Line Integrity in the As-Bonded Condition.

Etchant: Light Nital Mag. 200X

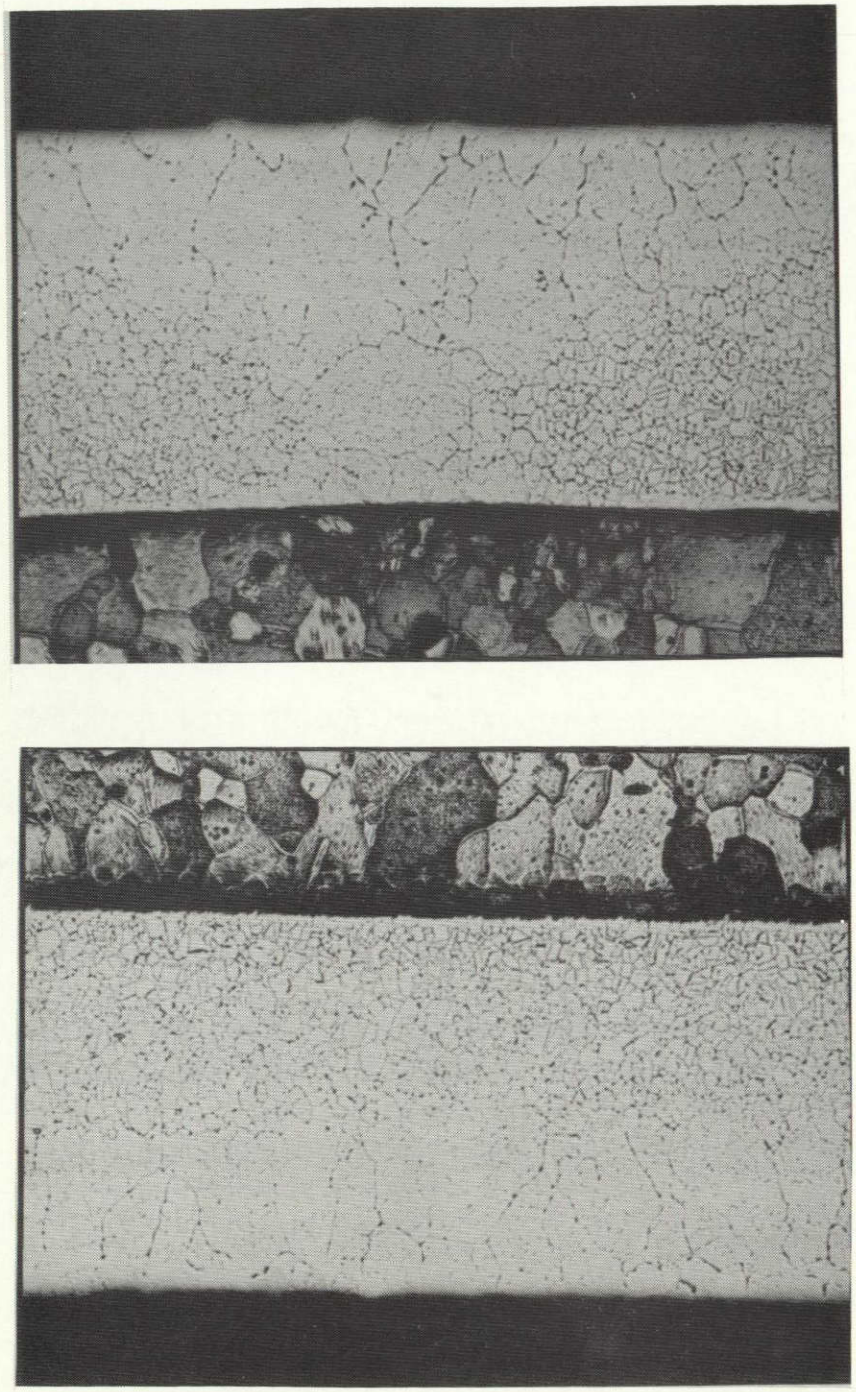
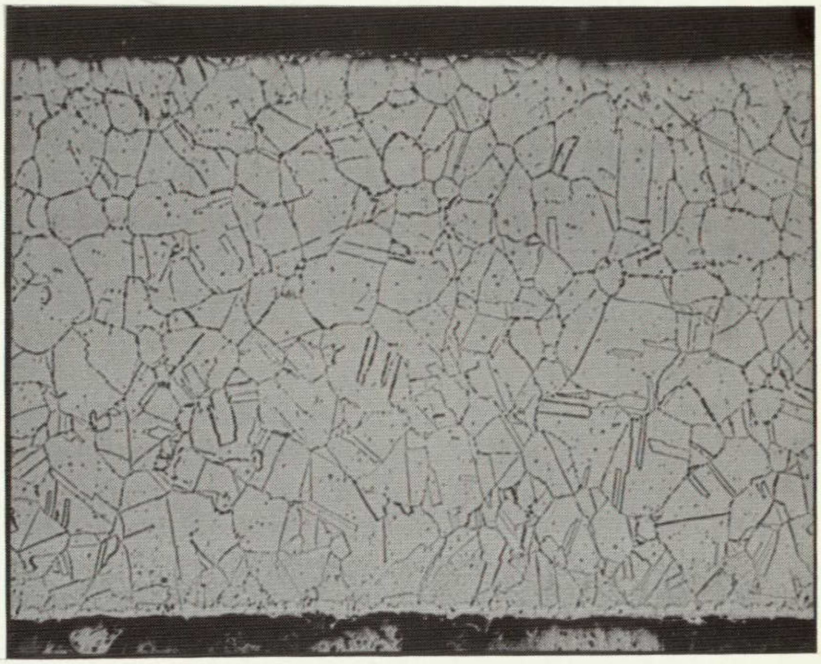


Figure IV-6. Longitudinal Section of Task II-a Tube Showing Extent of Carbon Penetration in the As-Bonded Condition.

Etchant: Ammonium Persulfate - Electrolytic   Mag. 200X

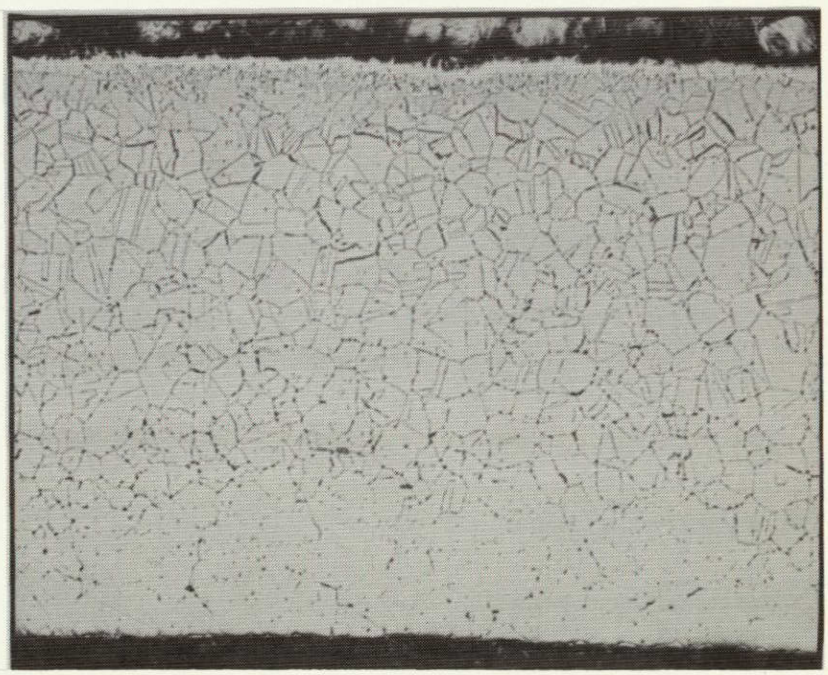


Outer Clad

Bond Line
Carbon Steel Core

Carbon Steel Core

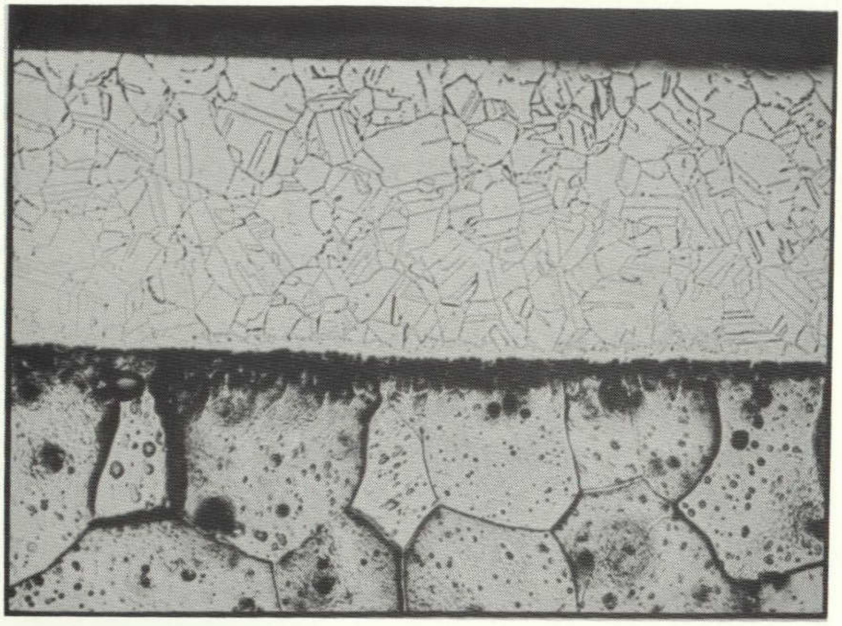
Bond Line



Inner Clad

Figure IV-7. Longitudinal Section of Task II-b Tube Showing Extent of Carbon Penetration in the As-Bonded Condition.

Etchant: Ammonium Persulfate - Electrolytic Mag. 200X



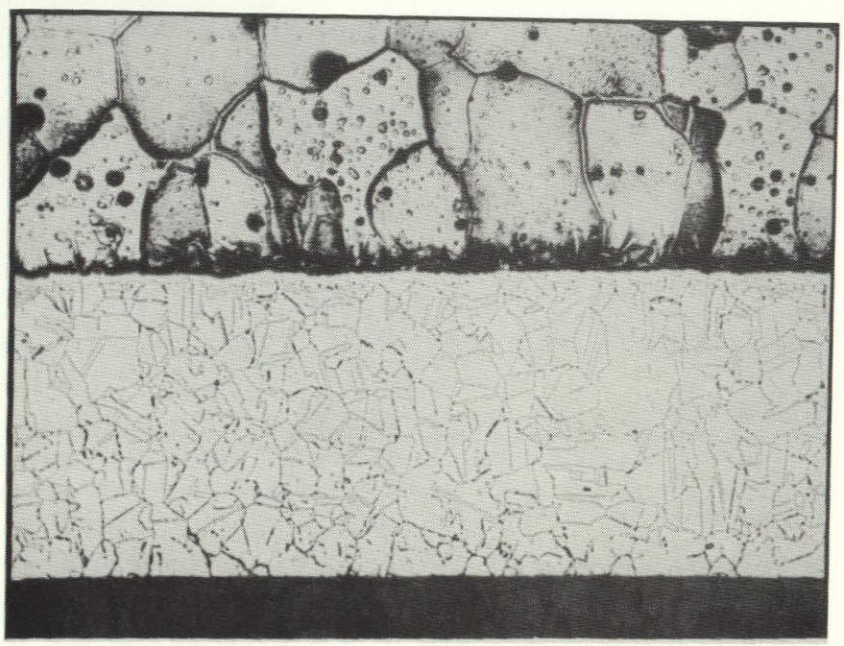
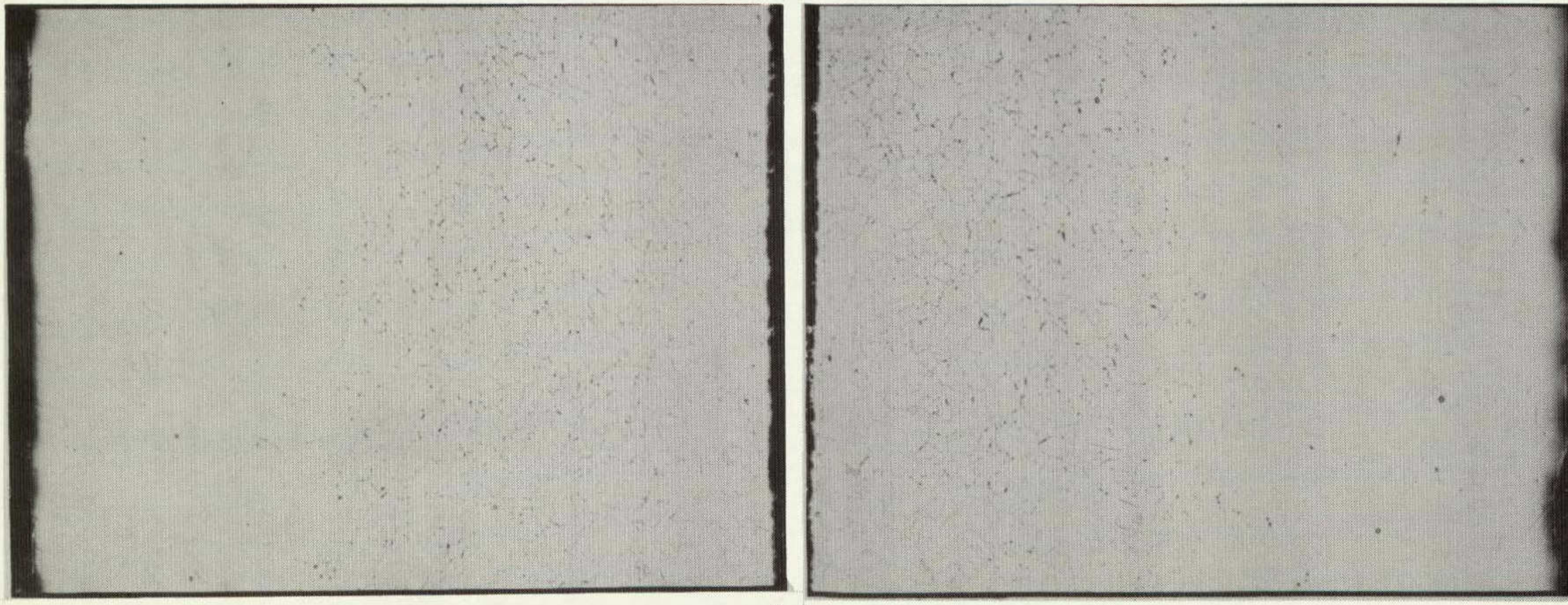


Figure IV-8. Longitudinal Section of Task II-c Tube Showing Extent of Carbon Penetration in the As-Bonded Condition.

Etchant: Ammonium Persulfate - Electrolytic Mag. 200X



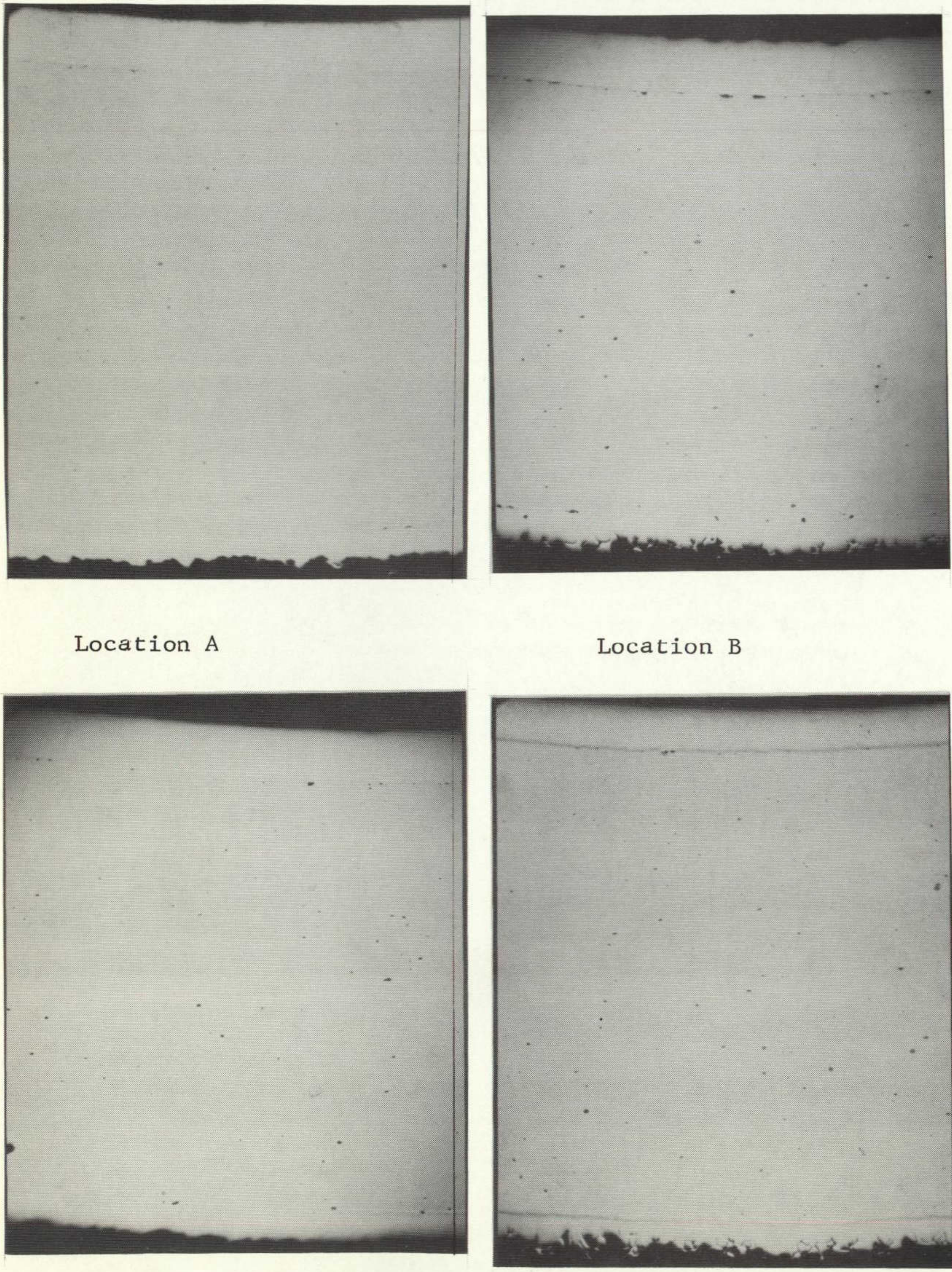
Outer Clad

Bond Line

Inner Clad

Figure IV-9. Longitudinal Section of Task II-d Tube Showing Extent of Carbon Penetration in the As-Bonded Condition.

Etchant: Ammonium Persulfate - Electrolytic Mag. 200X



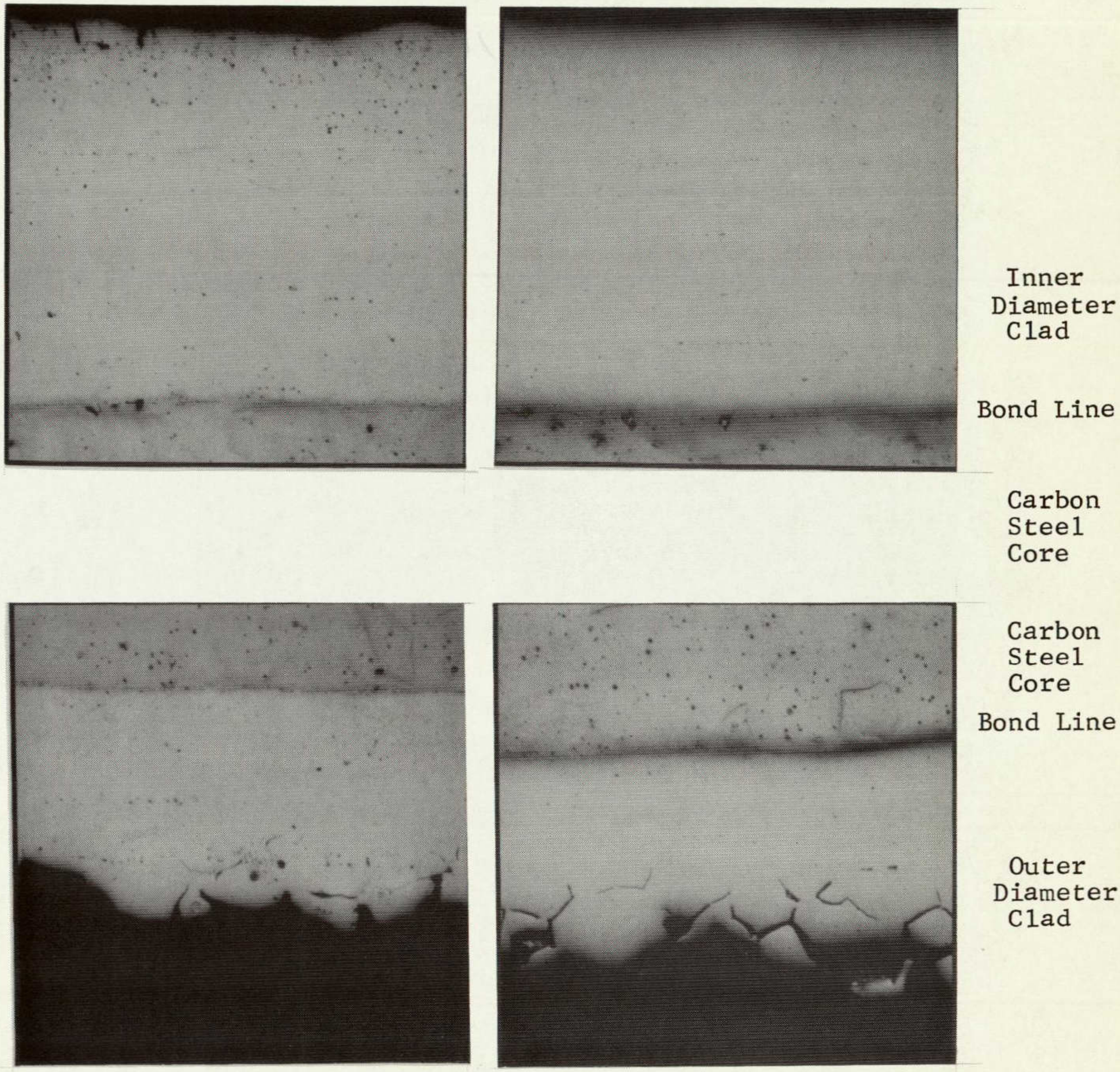
Location A

Location B

Location C

Location D

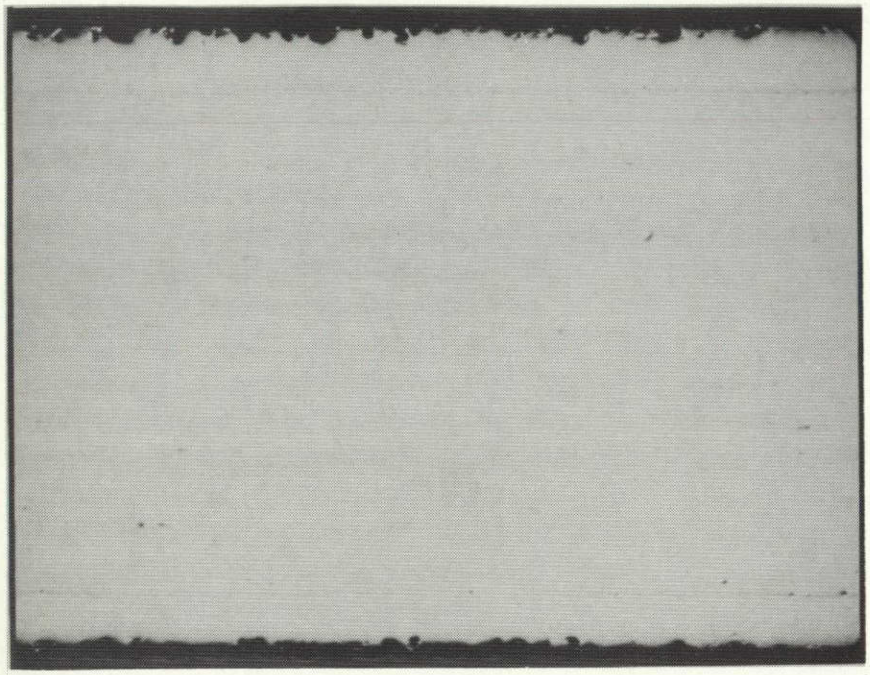
IV-10. Transverse Sections of Task I Tubes Showing Stainless Clad Uniformity --- Tube I-2. Mag. 45X



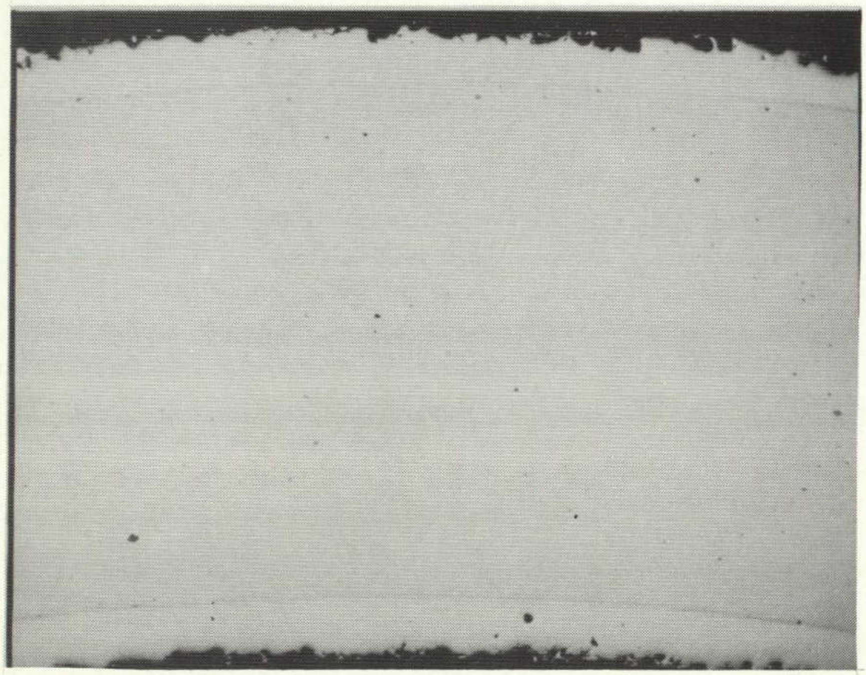
Tube I-2 Location C | Tube I-2 Location B

Figure IV-11. Longitudinal Sections of Task I Tubes Showing Bond Line Integrity and Stainless Clad Uniformity.

Etchant: Ammonium Persulfate - Electrolytic Mag. 250X



Longitudinal Section



Transverse Section

Figure IV-12. Section of Task II-bl Tube Illustrating Uniformity of the Stainless Clad Layers.

Mag. 35X

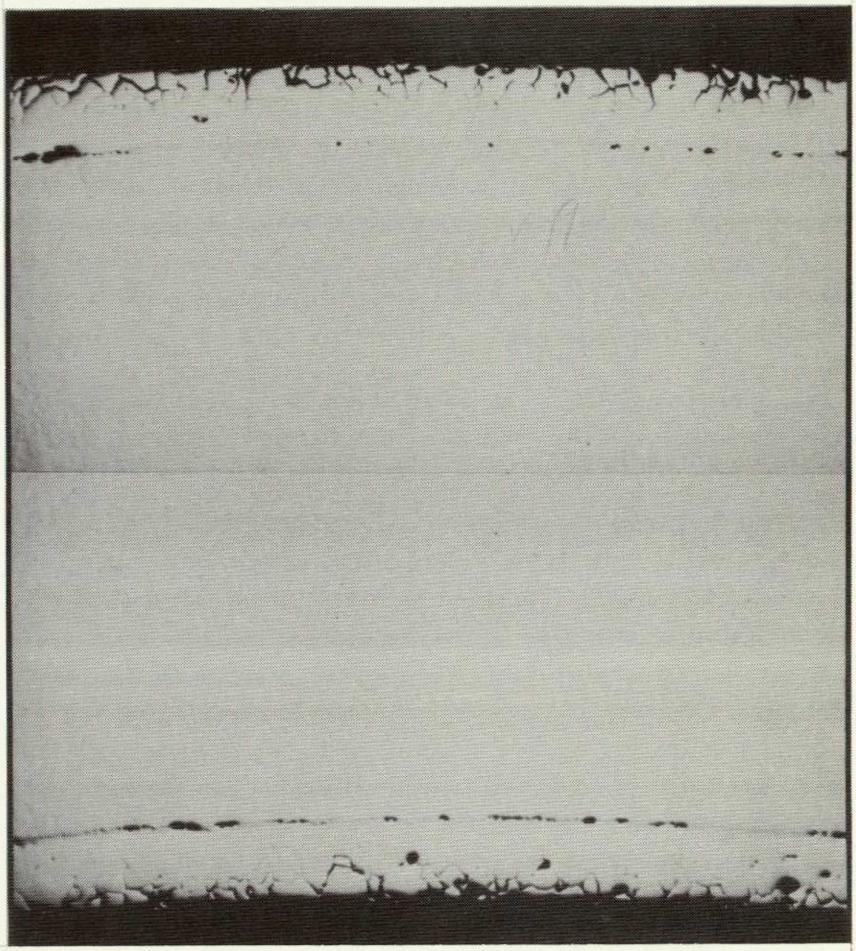


Figure IV-13. Transverse Section of Task II-d2 Tube Illustrating Uniformity of the Stainless Clad Layers. Mag. 35X

IV-21

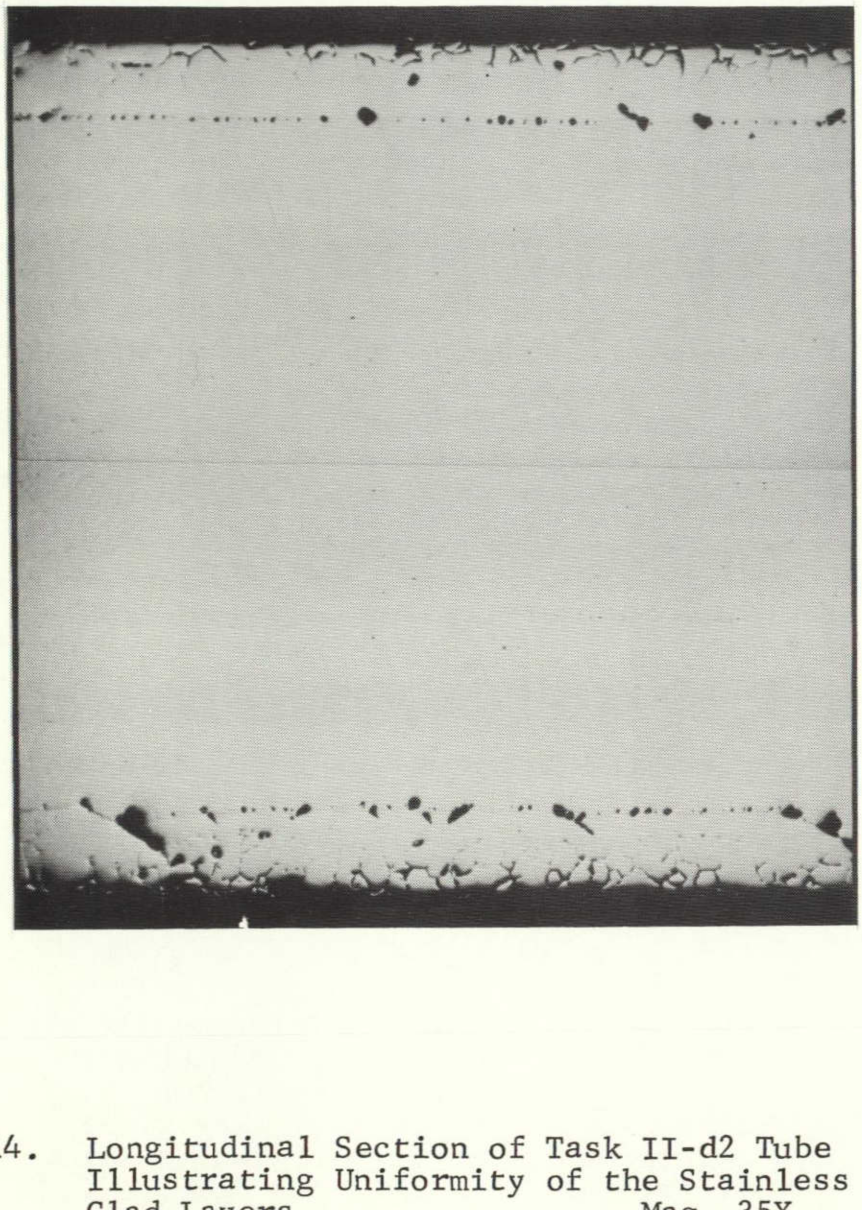


Figure IV-14. Longitudinal Section of Task II-d2 Tube Illustrating Uniformity of the Stainless Clad Layers. Mag. 35X

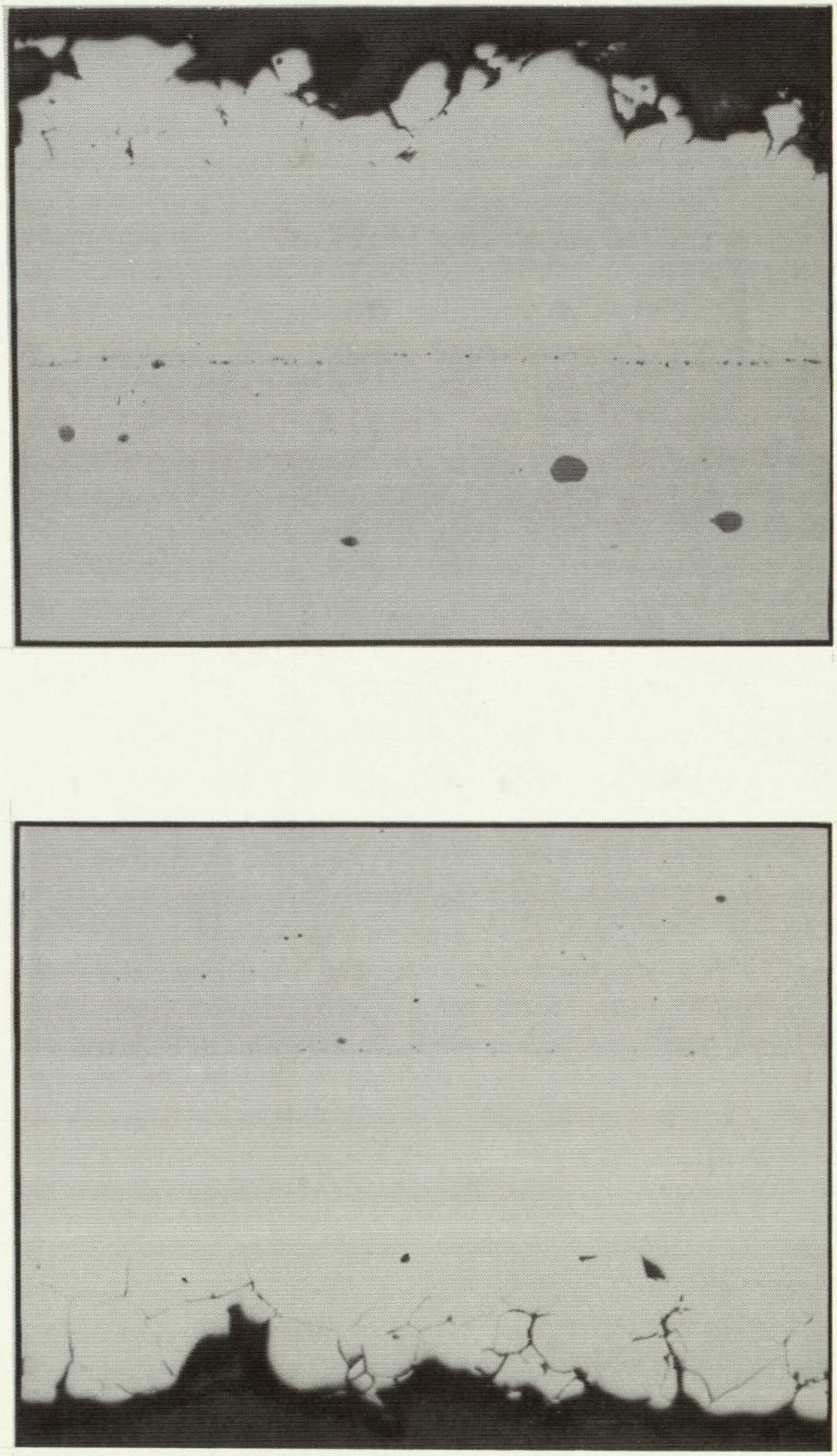
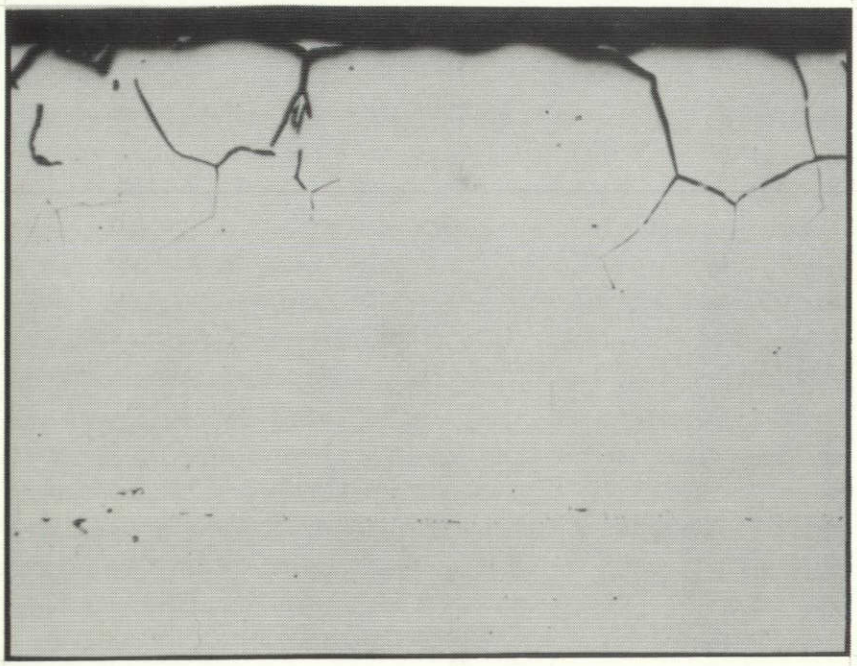


Figure IV-15. Transverse Section of the Task II-b1 Tube Showing Integrity of the Bond Line and Stainless Surface. Mag. 200X



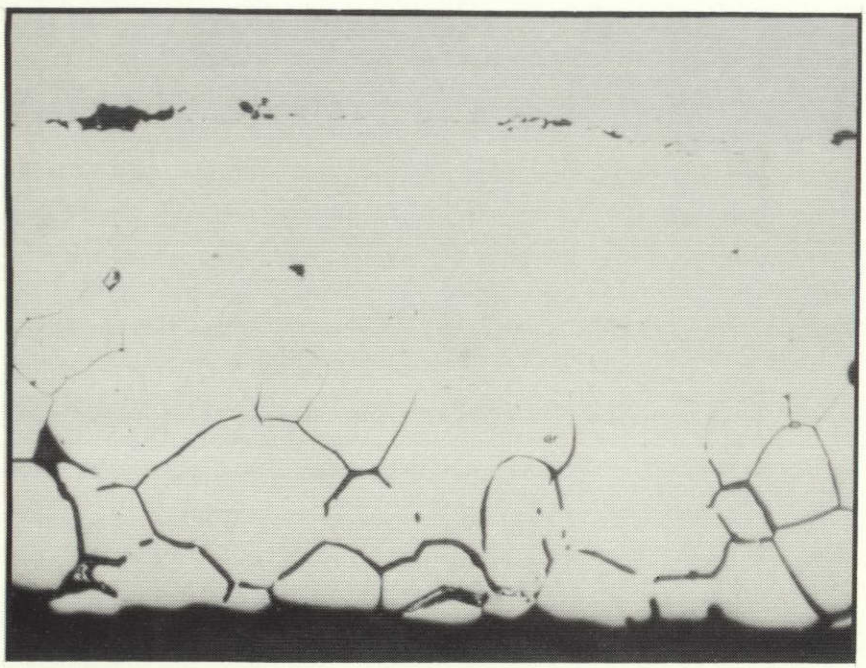


Figure IV-16. Transverse Section of the Task II-d2 Tube Showing Integrity of the Bond Line and Stainless Surface. Mag. 200X

IV-35

IV-24

ORIGINAL PAGE IS OF POOR QUALITY

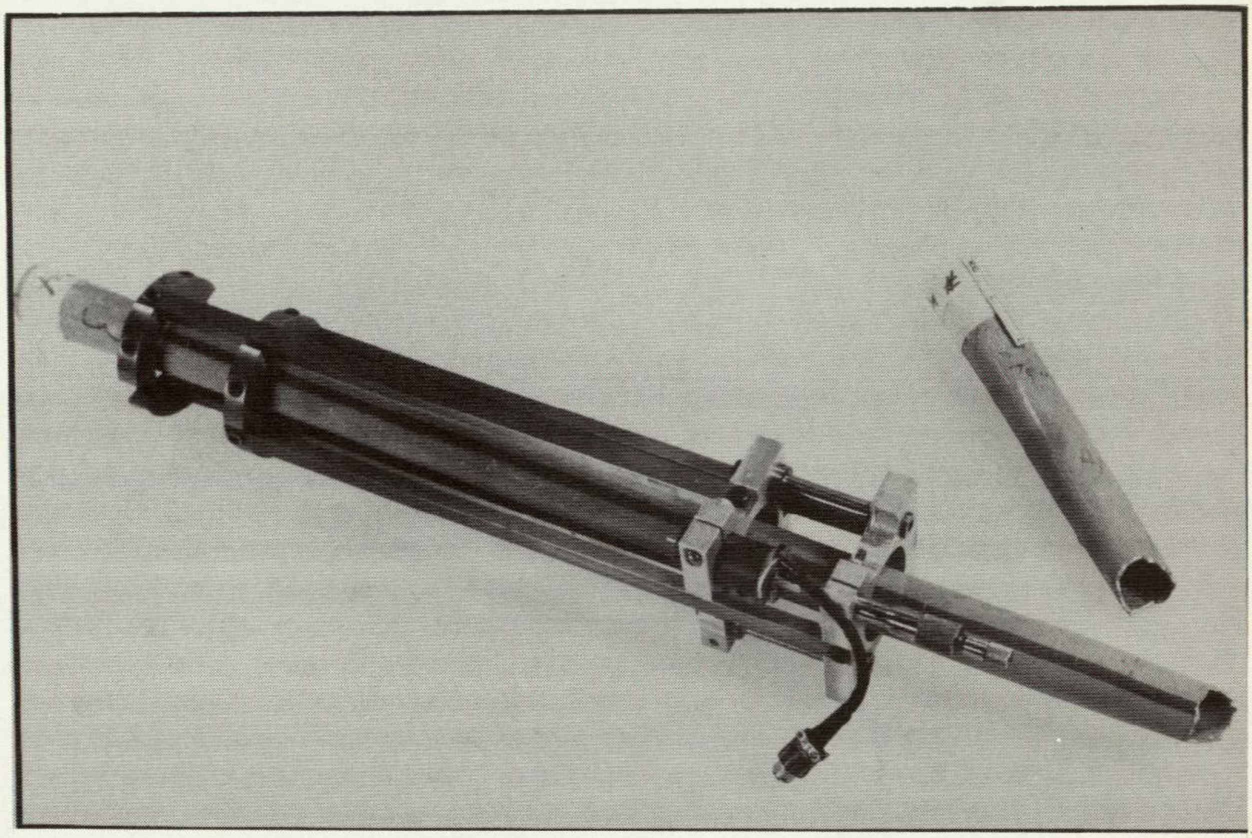


Figure IV-17. Tubular Extensometer and Tested Task I Tensile Specimen Showing Fracture Appearance.

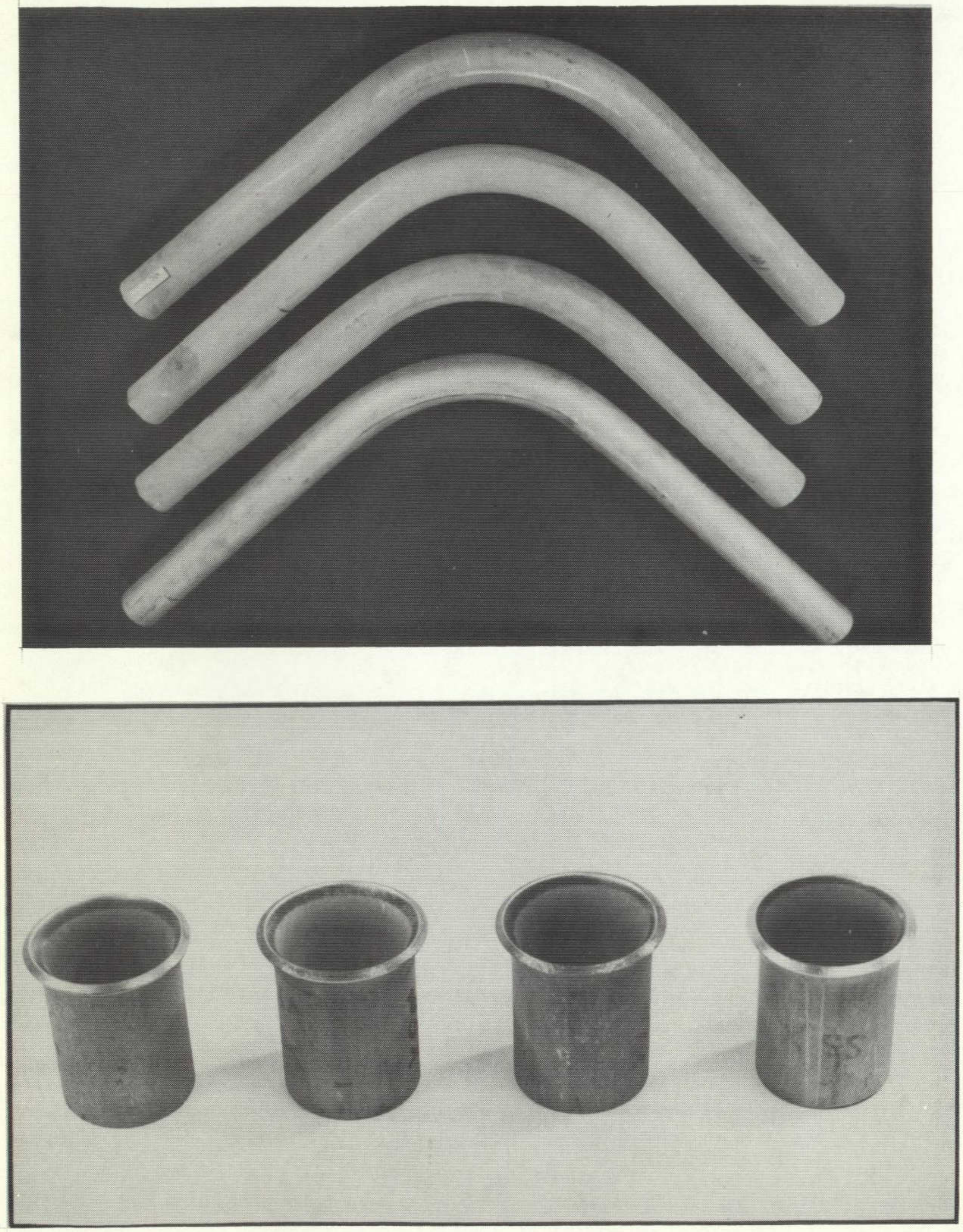


Figure IV-18. Appearance of Task I Tubes After Bend and Flare Testing.

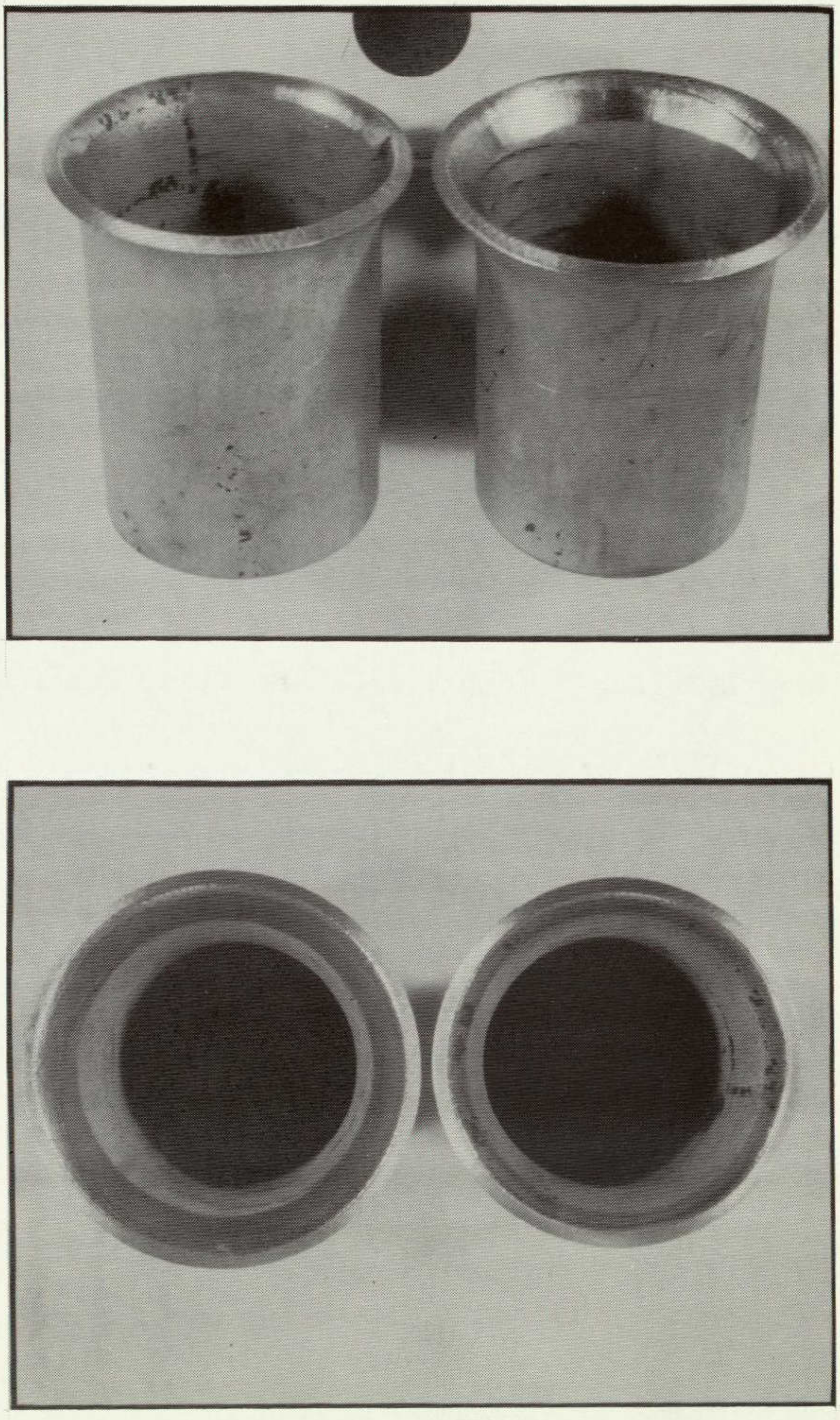
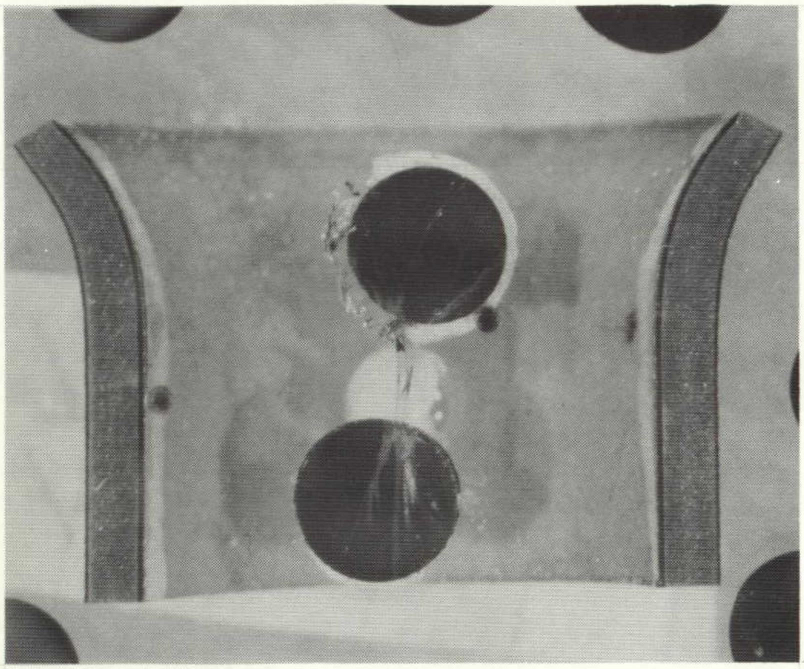
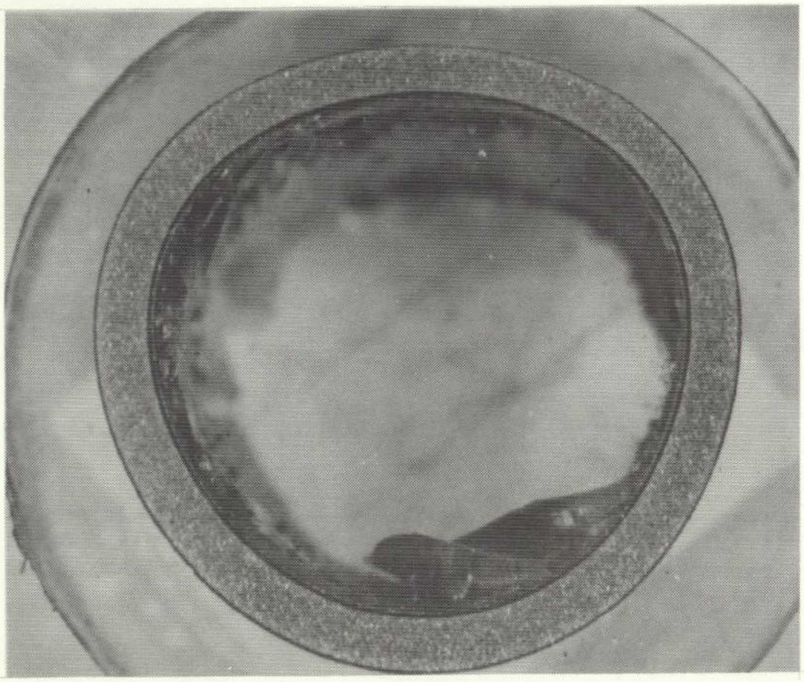


Figure IV-19. Appearance of Task II-d Tubes After Flare Testing.

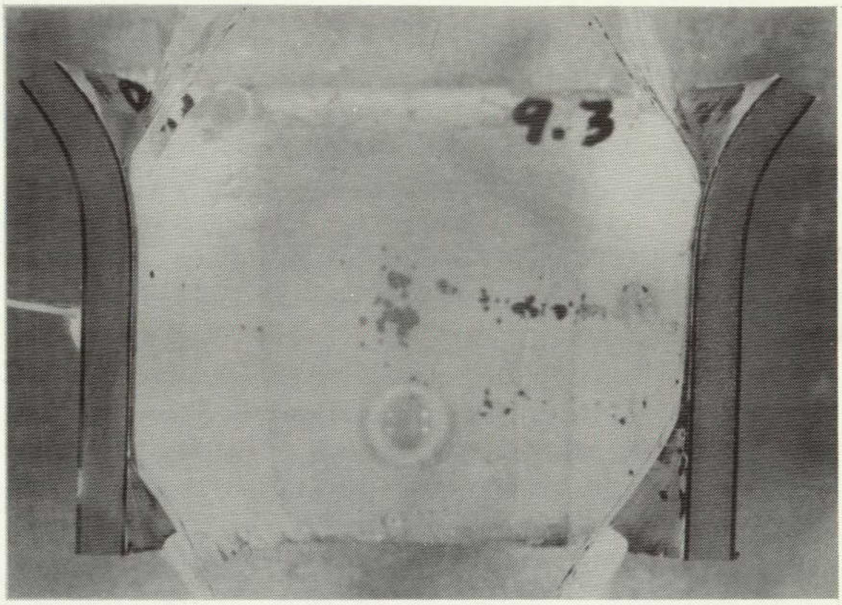


Tube I-3, Longitudinal Section, Flare Test

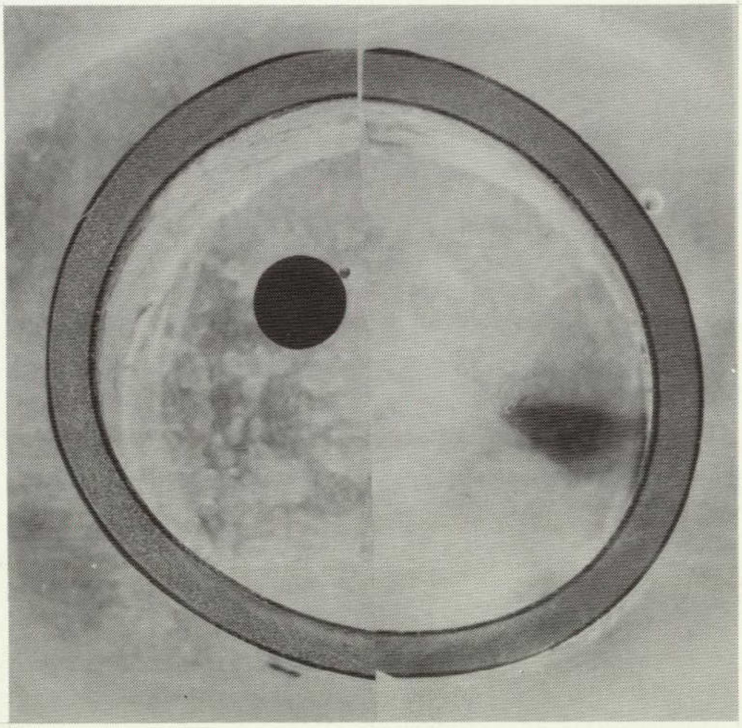


Tube I-3, Longitudinal Section, Bend Test

Figure IV-20. Sections of Task I Tube Flare and Bend Test Specimens Showing Maintenance of Bond Integrity. Mag. 3.5X

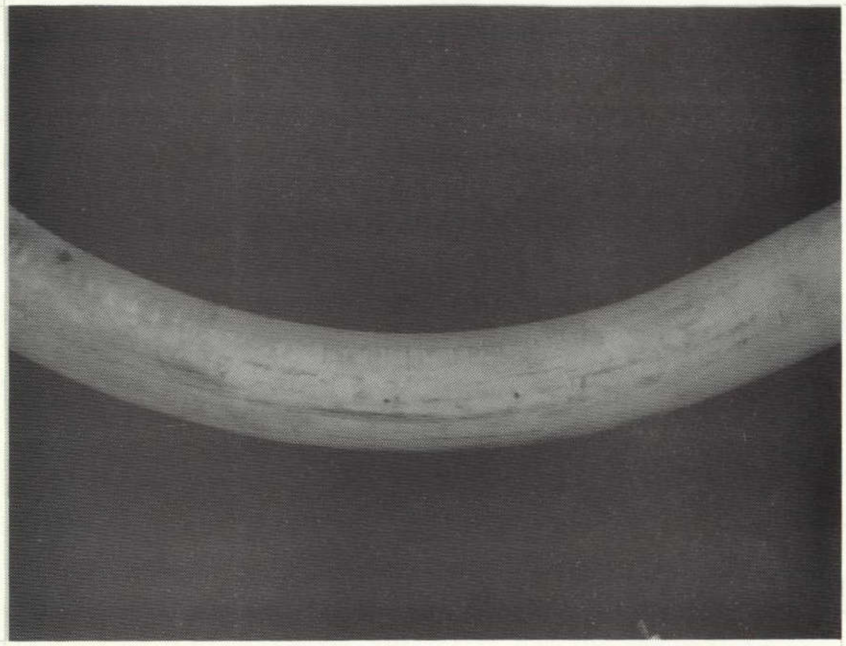


Tube II-d2, Longitudinal Section, Flare Test

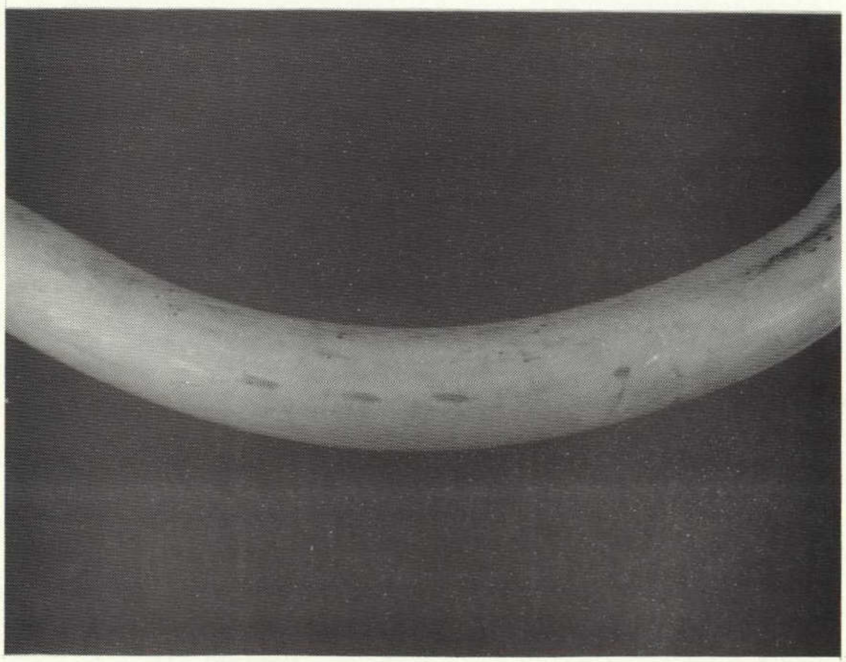


Tube II-d2, Transverse Section, Bend Test

Figure IV-21. Sections of Task II Tube Flare and Bend Test Specimens Showing Maintenance of Bend Integrity. Mag. 2X

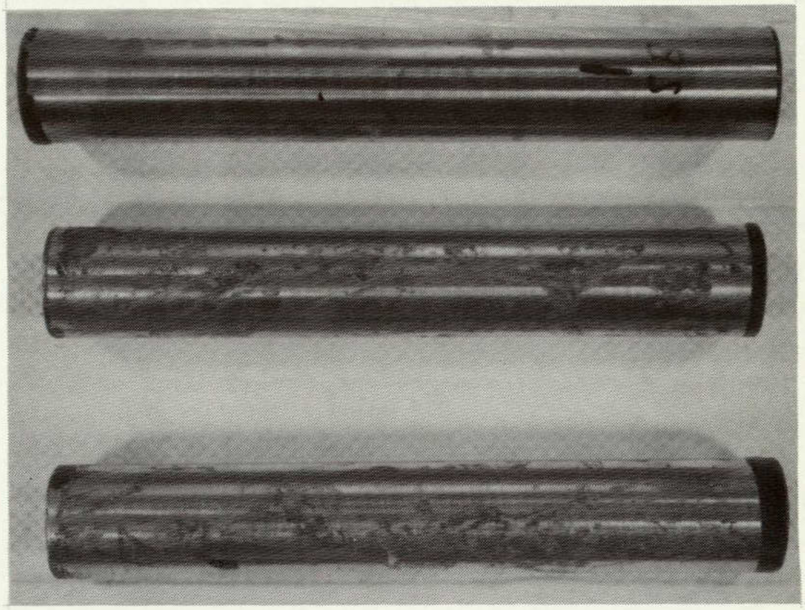


Side A



Side B

Figure IV-22. Appearance of Task II-d Tubes After Bend Testing.



Type 304

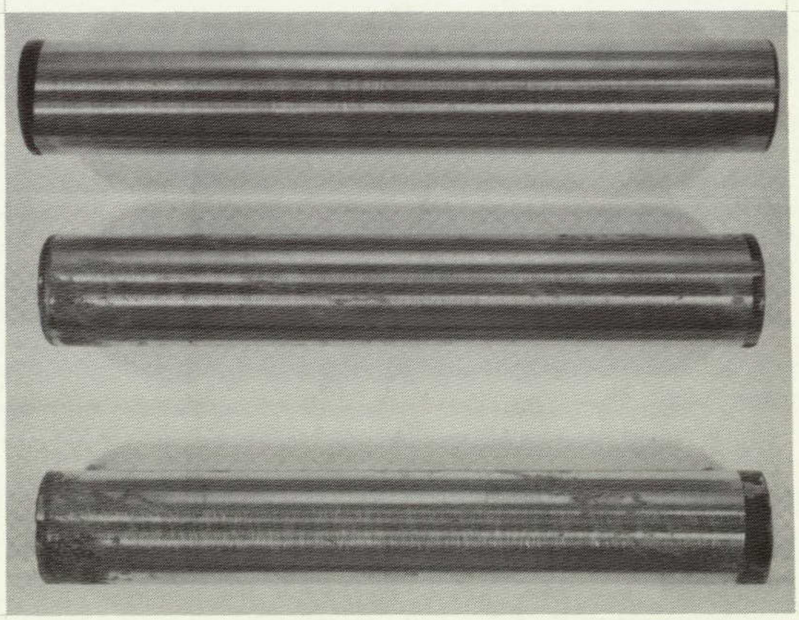
Tube 2

Tube 4

Top Bottom

Back Surface

511-77



Type 304

Tube 2

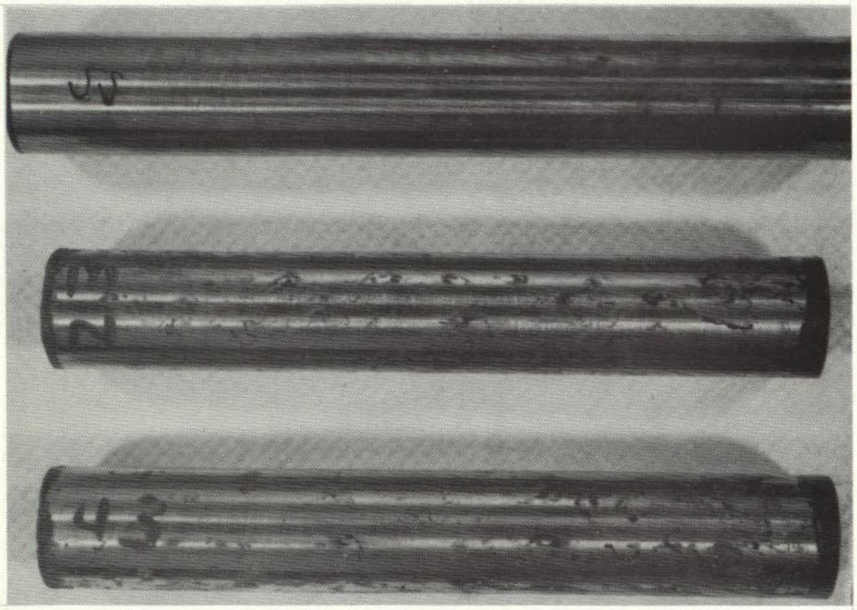
Tube 4

Top Bottom

Front Surface

Figure IV-23. Appearance of Tube Specimens After One Weeks Exposure in CASS Corrosion Tests.

Reduced approximately one-third.



Type 304

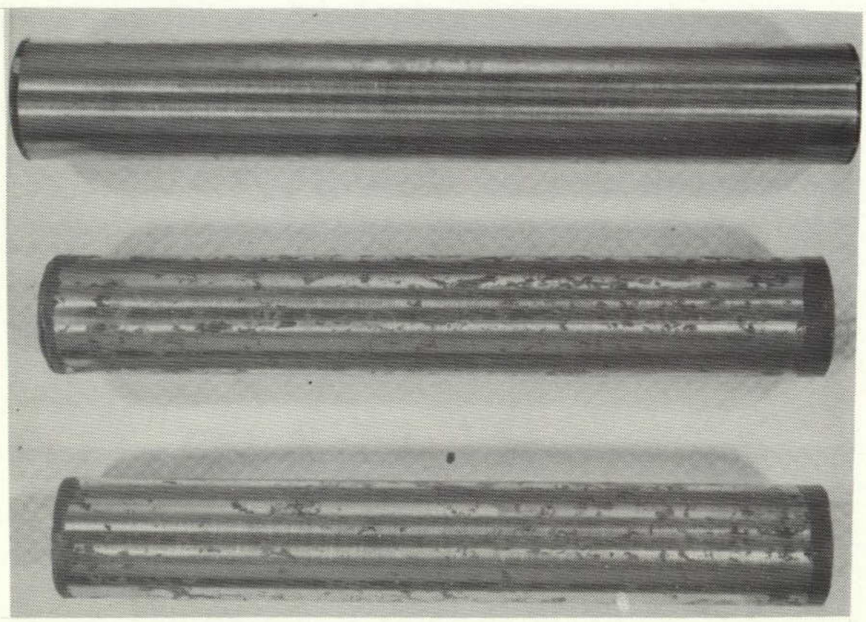
Tube 2

Tube 4

Bottom Top

Back Surface

513-77



Type 304

Tube 2

Tube 4

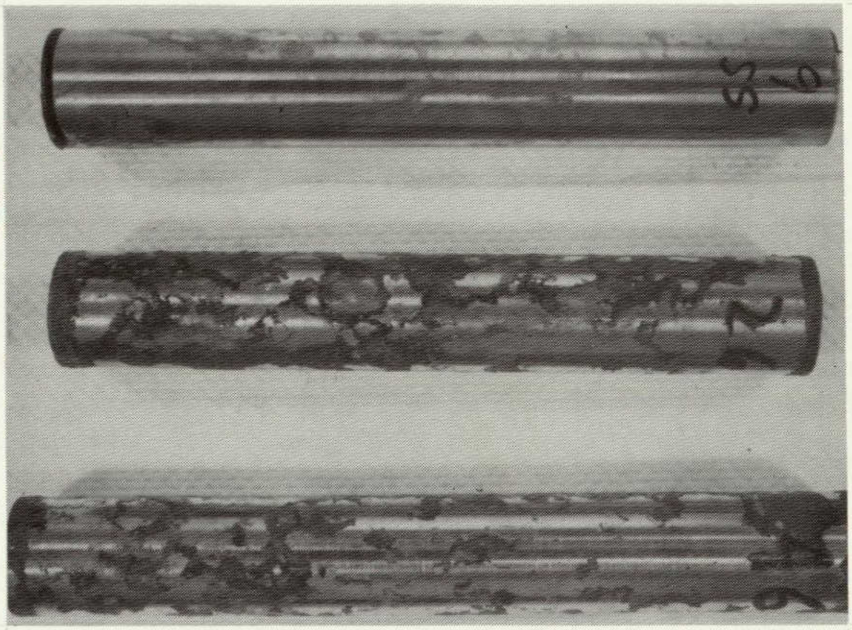
Bottom Top

Front Surface

Figure IV-24. Appearance of Tube Specimens After Three Weeks Exposure in CASS Corrosion Tests.

Reduced approximately one-third.

563-77



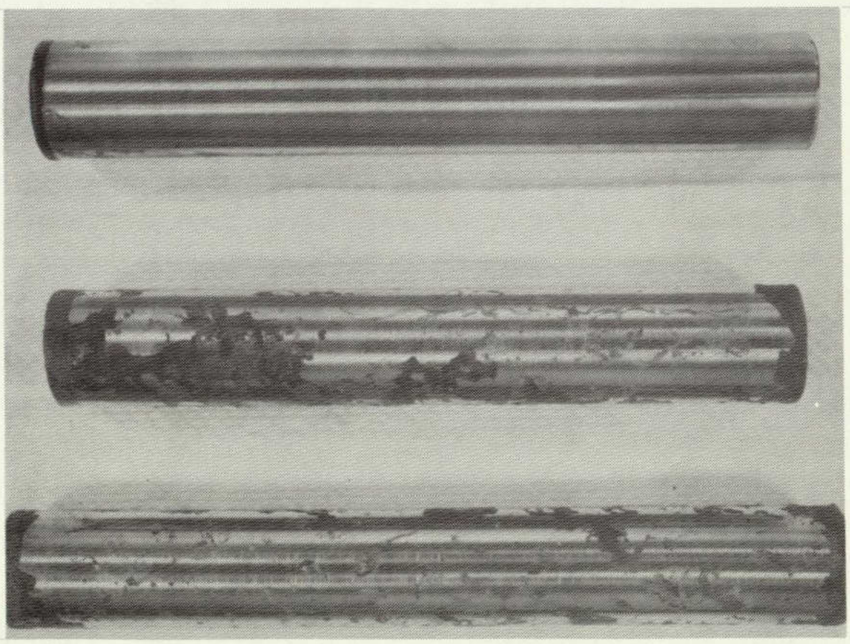
Type 304

Tube 2

Tube 4

Top Bottom

Back Surface



Type 304

Tube 2

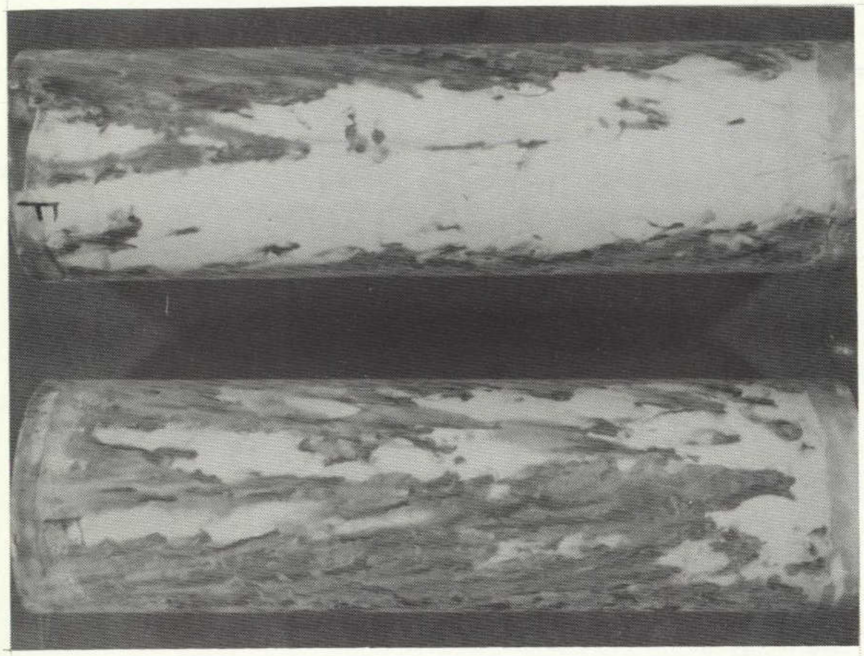
Tube 4

Top Bottom

Front Surface

Figure IV-25. Appearance of Tube Specimens After Six Weeks Exposure in CASS Corrosion Tests.

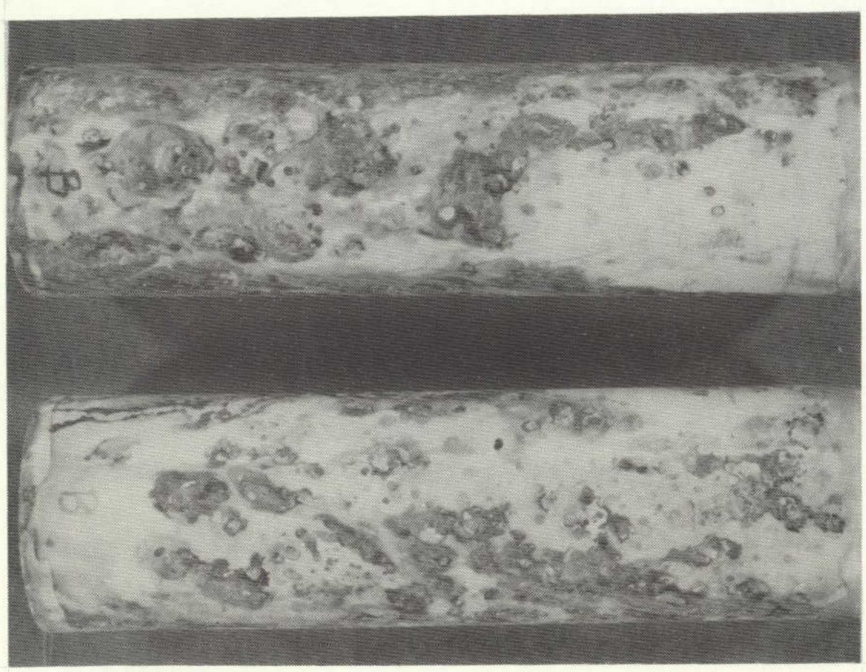
Reduced approximately one-third.



Sample A

Sample B

Bottom Front Side Top

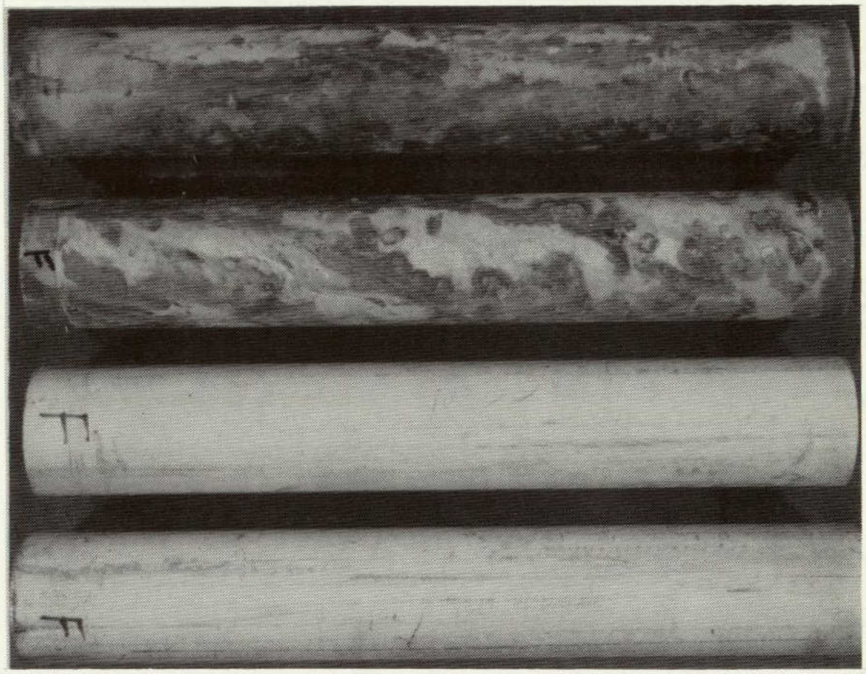


Sample A

Sample B

Bottom Back Side Top

Figure IV-26. Appearance of Task II-d1 Tube Specimens After 15 Days Exposure in CASS Corrosion Test.



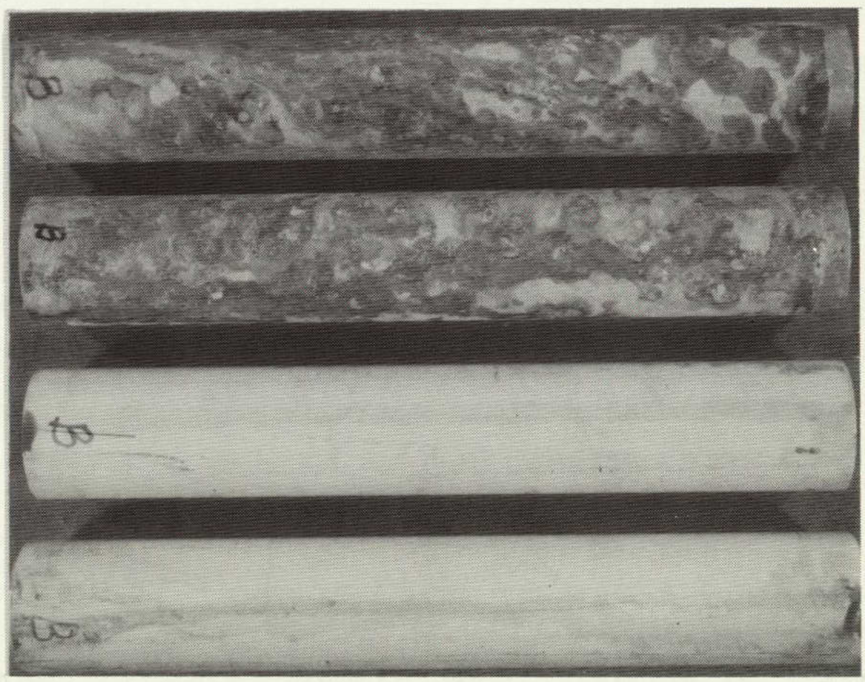
Tube II-b1
Sample A

Tube II-b1
Sample B

T-304
Sample A

T-304
Sample B

Bottom   Front Side   Top



Tube II-b1
Sample A

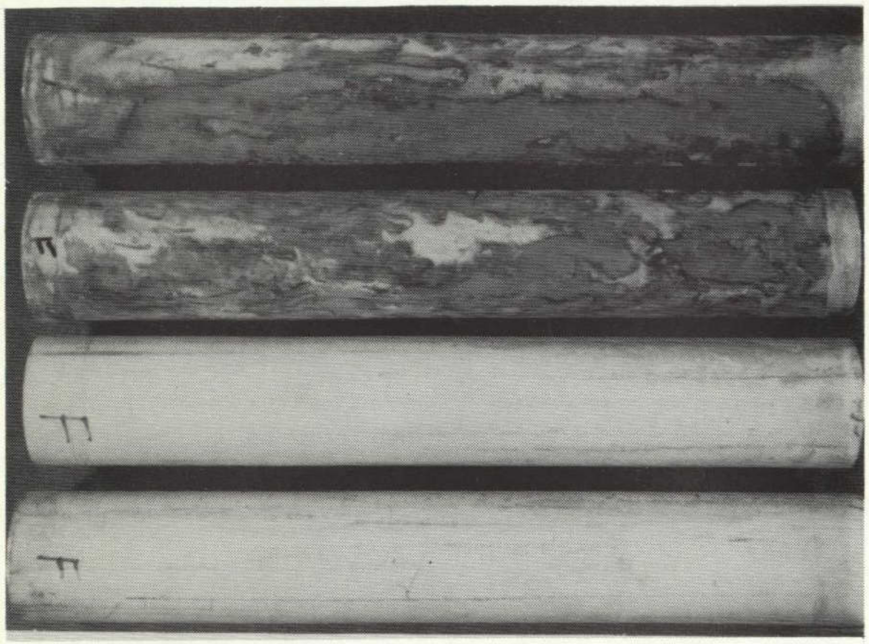
Tube II-b1
Sample B

T-304
Sample A

T-304
Sample B

Bottom   Back Side   Top

Figure IV-27. Appearance of Task II Tube Specimens After 15 Days Exposure to CASS Corrosion Test.



Tube II-b1
Sample A

Tube II-b1
Sample B

T-304
Sample A

T-304
Sample B

Bottom Front Side Top

Tube II-b1
Sample A

Tube II-b1
Sample B

T-304
Sample A

T-304
Sample B

Bottom Back Side Top

Figure IV-28. Appearance of Task II Tube Specimens After 30 Days Exposure to CASS Corrosion Test.

REFERENCE

Section IV

1. ASM Metals Handbook, 8th Edition, Volume 1, 1961, Editor - Taylor Lyman, Ohio

Sample A

Sample B

Bottom — Front Side — Top

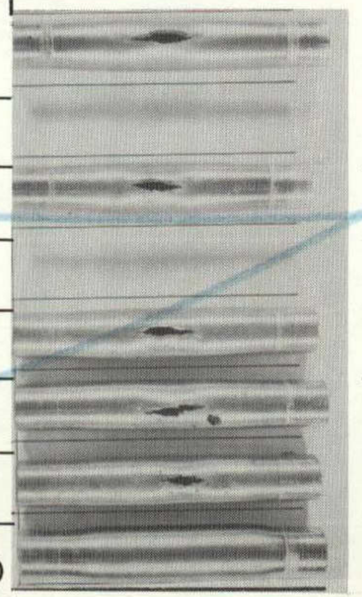
Sample A

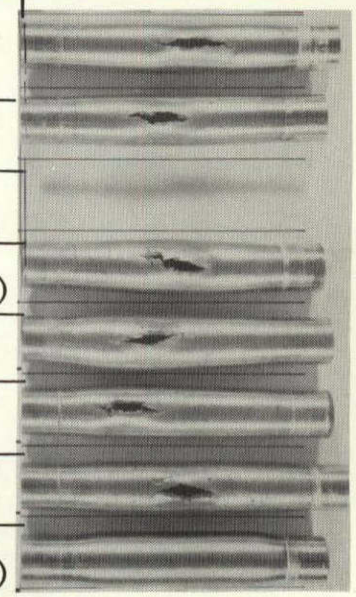
Sample B

Bottom — Back Side — Top

Figure IV-29. Appearance of Task II-d1 Tube Specimens After 30 Days Exposure in CASS Corrosion Test.

Burst Test

Code	CASS Testing Exposure Time (Weeks)	Burst Pressure MPA (psi)	Sample
2-0	0	81.4 (11,800)	
2-1	1	Test Malfunction	
2-2	2	79.3 (11,500)	
2-3	3	Test Malfunction	
2-4	4	75.8 (11,000)	
2-5	5	74.5 (10,800)	
2-6	6	73.8 (10,700)	
SS-6	6	96.5 (14,000)(1)	

Code	CASS Testing Exposure Time (Weeks	Burst Pressure MPA (psi)	Sample
4-0	0	76.5 (11,100)	
4-1	1	76.5 (11,100)	
4-2	2	Test Malfunction	
4-3	3	78.6 (11,400)(1)	
4-4	4	71.0 (10,300)	
4-5	5	73.1 (10,600)	
4-6	6	73.1 (10,600)	
SS-6	6	96.5 (14,000)(2)	

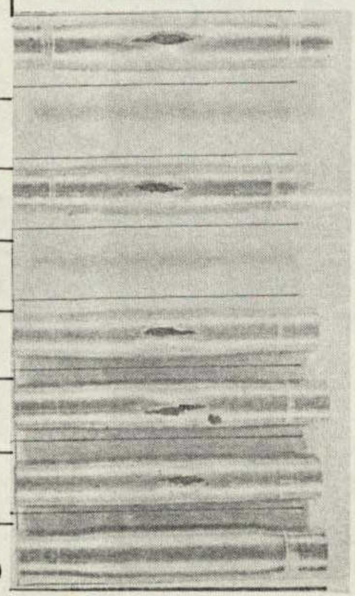
(1) Maximum pressure capabilities.

(1) Cold worked-reloaded several times before failure.

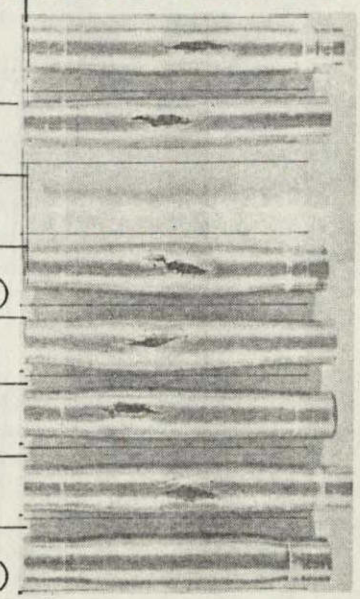
(2) Maximum pressure capabilities

Figure IV-30. Task I Burst Test Specimens Showing Fracture Appearance. Clad Tubing Coded 2-0/6 and 4-0/6, Monolithic Type 304 Stainless Coded SS-6.

Burst Test

Code	CASS Testing Exposure Time (Weeks)	Burst Pressure MPA (psi)	Sample
2-0	0	81.4 (11,800)	
2-1	1	Test Malfunction	
2-2	2	79.3 (11,500)	
2-3	3	Test Malfunction	
2-4	4	75.8 (11,000)	
2-5	5	74.5 (10,800)	
2-6	6	73.8 (10,700)	
SS-6	6	96.5 (14,000)(1)	

(1) Maximum pressure capabilities.

Code	CASS Testing Exposure Time (Weeks	Burst Pressure MPA (psi)	Sample
4-0	0	76.5 (11,100)	
4-1	1	76.5 (11,100)	
4-2	2	Test Malfunction	
4-3	3	78.6 (11,400)(1)	
4-4	4	71.0 (10,300)	
4-5	5	73.1 (10,600)	
4-6	6	73.1 (10,600)	
SS-6	6	96.5 (14,000)(2)	

(1) Cold worked-reloaded several times before failure.

(2) Maximum pressure capabilities

Figure IV-30. Task I Burst Test Specimens Showing Fracture Appearance. Clad Tubing Coded 2-0/6 and 4-0/6, Monolithic Type 304 Stainless Coded SS-6.

V. Nondestructive Defect and Gaging Evaluations

A. Survey of NDE Methods

Preliminary NDE method evaluations were conducted at Battelle Memorial Institute to survey a number of potential test methods. The materials used in this survey were two-layer clad flat strip samples. These samples were made at CMRC by roll bonding methods. Regions of disbondment and thickness variations were intentionally made in these samples to allow for evaluation of the NDE test methods.

Eddy Current: Two samples were examined at 500 khz. for thickness of the clad using samples which were known to have good bonding between the outside clad and carbon steel substrate. The tests were manually run and there were variations in scanning speed. The chart of the first sample appeared to show a change in thickness of cladding from edge to center, as indicated by a peak in the center of the chart which corresponds to the middle of the sample.

The clad thickness of the second sample was intentionally varied by inserting an additional strip in the roll bond assembly. The corresponding chart shows a dip in the center, which is believed to correspond to the added strip. Frequencies of 10 and 120 khz. were also tried. Neither specimen was uniform from end to end, and this non-uniformity became most predominant at 10 khz. At 10 khz., variations in the chemical and magnetic properties of the carbon steel substrate became more noticeable due to the increased depth of penetration of the eddy current signal of 0.414 cm (0.163 in.), as compared with 0.119 cm (0.047 in.) at 120 khz., and 0.058 cm (0.0229 in.) at 500 khz. Also, at 10 and 120 khz., the intentional thickness variation of the clad was not detected.

Infrared Radiometry: The specimens were heated from the inside with a quartz lamp, and the outside surface was examined with a high resolution infrared camera. There were no anomalous heat patterns found. The specimens were then painted black, for increased heat absorption, but again, no unusual heat patterns were detected.

Ultrasonics: The sample with intentional delamination was tested using the through-transmission technique at a frequency of 5 mhz., with a water path of 2.540 cm (1 inch) between the receiving transducer and pipe, and transmitting transducer and pipe. This test was based on the assumption that defects caused by poorly bonded or disbonded areas would attenuate the transmitted pulse of ultrasonic energy. The waviness of the specimen caused the pulse to drop out when diverged past the receiving transducer. However, an area about 1.8 cm (7 in.) from the marked end appeared to attenuate the pulse due to discontinuities in the material. It was felt that this technique had good possibilities as a method of detecting flaws and delamination, and should be explored in greater depth.

Acoustic Impact: It was decided that this method should be regarded as a last resort, since it is not a state-of-the-art method of evaluation for tubular configurations.

B. NDE Method Evaluation Using Clad Tube

In follow-up to the preliminary evaluations conducted at Battelle, further method evaluation was carried out at CMRC using clad tube produced under Task I of the program. The samples were 45.72 cm (18 in.) long sections taken from tubes number 2, 4 and 5. These tubes have an outside diameter of 2.54 cm (1 in.).

Ultrasonics: Two samples of the clad tubing were inspected for thickness and disbonding using an ultrasonic thickness gage and a 15 mhz. 0.64 cm (0.25 in.) delay transducer. Seventeen readings were taken down opposite sides of each sample, and were spaced approximately 2.54 cm (1 in.) apart. The rough surface of both samples caused difficulty in obtaining stable readings, therefore, the areas on each side of the tube were sanded lightly with 240 grit paper. It was shown from the readings obtained from sample #2 NDE that side A decreased in total wall thickness from 0.25 cm (0.099 in.) to 0.23 cm (0.090 in.) (Figure V-1) and that side B increased in total wall thickness from 0.21 cm (0.084 in.) to 0.23 cm (0.091 in.) (Figure V-2). Readings were consistently obtained on both sides of sample #2 NDE. Sample #5 NDE appears to have areas of poor bonding of the outer wall. Side A decreased in total wall thickness from 0.25 cm (0.099 in.) to 0.24 cm (0.093 in.) (Figure V-3). However, no readings were obtained from points 4 to 8. Side B appears to have areas of poor bonding also, only four thickness readings could be taken, these being at points 3, 4, 11 and 12 (Figure V-4).

The samples were then inspected using a high resolution flaw detector and a 10 mhz. 0.64 cm (0.25 in.) diameter transducer. The relative height of the first received echo from the back wall of the tube was recorded for every spot where thickness readings were taken. This data was tabulated with the thickness data and plotted. The back reflection amplitude readings (Figures V-1 and V-2) showed some change for sample #2 NDE on sides A and B but the correlation between back reflection height and loss of thickness readings can be clearly seen on the charts from sample #5 NDE (Figures V-3 and V-4). At points 3 to 8 on side A of sample #5 NDE, no thickness readings could be obtained. The dramatic decrease in back reflection amplitude can be seen in this area simultaneously. The variations in back reflection amplitude for side B of sample #5 NDE also relate to the areas of no thickness readings. In the case of the ultrasonic thickness gage, we felt that in these areas the returning signal was of insufficient amplitude to actuate the electronic gating circuitry of the instrument to give a thickness reading. Therefore, the use of the thickness gage as a means of gaging the wall thickness would also be useful in providing a means of detecting delaminations and flaw detection. Thus, one instrument would serve as both a means of flaw detection and metrology.

In experiments with ultrasonics, it was possible to inspect the tube for total thickness and disbonding from the exterior. It would not be feasible to utilize ultrasonics to inspect from the inside of the tube for disbonding of the inner clad surface, nor did it seem possible to measure the thickness of the clad itself using any known method of ultrasonic testing.

Magnetic Gaging: After studying the possibilities of using magnetic gaging, we determined that this technique would provide an accurate and repeatable method of determining the thickness of the inside and outside of stainless cladding. A manufacturer of equipment which is specifically designed with the capability of performing this type of measurement, agreed to assist us in solving this problem with their line of magnetic gaging instrumentation.

Eddy Current: Readings were also taken at the same points on the tubing with an eddy current instrument, which gave a reading of a relative number, that can be related to Rockwell hardness and conductivity of known test standards. No correlation was seen to exist between these readings and the data obtained by ultrasonic testing, but possibly a relationship could be found with data obtained from the magnetic gaging technique.

C. Summary of NDE Method Evaluations

For flaw detection we determined that the ultrasonic method would be the first method used. Magnetic gaging would also provide flaw detection capability. For thickness gaging a combination of ultrasonics and magnetic methods would give information on total and individual clad layer thickness. Thus, two basic NDE evaluation methods, ultrasonic and magnetic, were used to evaluate the clad tubing.

D. Stainless Clad Tubing Defect and Gaging Evaluations

Evaluation Procedure: The primary method planned for evaluating the thickness of the stainless steel layers was magnetic gaging. The clad thickness on both the inside and outside of the tubing was measured with an "Accuderm" instrument which utilizes magnetic amplification to determine the coating thickness of a nonmagnetic material on a magnetic substrate. The signal from a transducer is converted to a digital readout displaying the measured thickness of the nonmagnetic stratum in thousandths of an inch.

The CP-4 probe with the CPC guide was used to obtain clad thickness readings on the outer surface of the samples. Inside measurements were taken using the HP-2 probe and the EH extension handle.

Outer clad thickness readings were taken on sides "A" and "B" of each tube, these locations being 180° apart. For the long sections of large and small diameter tubing, measurements were taken every 2.54 cm (1 in.) for a distance of 61.0 cm (2 ft.) on sides "A" and "B" from the ends of the tube, on both the top and bottom of each sample. Ouside thickness measurements were taken for a distance of 30.5 cm (1 ft.) on each end of the tube for the two short sections of small diameter tubing.

Inside clad thickness readings were also taken at 2.54 cm (1 in.) intervals on sides "A" and "B" for a distance of 30.5 cm (1 ft.) from both ends of the tube.

The large and small diameter bent samples were measured at approximately 2.54 cm (1 in.) intervals for the total length of sides "A" and "B", on the outside. Inside measurements were taken at 2.54 cm (1 in.) intervals as far into the samples as possible, this distance being limited by the radius of the bend. Clad thickness measurements were marked on the samples at the locations taken.

The primary method planned for defect evaluation was by ultrasonics using a high resolution flaw detectors with a 0.635 cm (0.25 in.) diameter transducer. Flaw detectors of 5 or 15 mhz. were used depending on the tube size. In this procedure, the undetected RF signal from the amplifier of the Automation Industries G2 thickness gage was displayed on a Tektronix T922 oscilloscope. The amplitude of the first received echo after the initial pulse was recorded for each tube. The amplitude of the back reflection is directly proportional to the ease of sound penetration through the outer clad interface. It was shown in previous tests that sample areas where the back reflection amplitude fell below the average for the tube have fine inclusions of debris and oxide in the outer clad/substrate interface. An example of a tube containing defects at the bond layer that were located by the ultrasonic method is shown in Figure V-5.

We had initially also planned to use magnetic gaging for secondary defect detection by correlating apparent non-uniformities in clad layer thickness with ultrasonic defect indications. However, the stainless clad layers displayed excellent thickness uniformity and thus no correlations could be developed with defect indications. Also, we had planned to conduct thickness gaging with an ultrasonic thickness gage and a 15 mhz. - 0.635 cm (0.25 in.) delay transducer. However, excessive surface roughness on some of the tubes, and the need to optimize the testing parameters for defect detection, made ultrasonic gaging impractical and it was therefore discontinued.

Results: The gaging and defect data for the Task I and Task II tubes are tabulated according to location on the tube in Tables V-1 and V-2. In these tables the location number begins at both the top and bottom end of the tubes and extends toward the center on 2.54 cm (1 in.) intervals, for a distance up to 61.0 cm (24 in.). The thickness of the stainless layers is relatively uniform along the tube length with most measurements within $\pm$0.01 mm (0.003 in.) of the mean thickness. The thickness of the outside stainless layer on the Task I-3 tube is considerably less than the inside layer, however, there is little difference in thickness among inner and outer layers for the Task II tubes. Average thickness data for all of the tubes determined by the magnetic method, and metallographic measurement on the ends, are summarized in Tables V-3 and V-4. There is good agreement between the two methods of thickness gaging. The percent of the total wall thickness which is quite close to the objective of 20 percent for these tubes.

The ultrasonic values for defect detection also generally display good uniformity along the tube length indicating general freedom from defects. There are locations on some of the Task II tubes, however, where the ultrasonic values is zero or near zero indicating that internal defects are present at these locations.

Data from the nondestructive evaluation of bend test samples are given in Tables V-5 and V-6. There is no significant change in the thickness measurements along the length of the bends. For the Task I-1 tube the ultrasonic values are also uniform along the bend showing that bending did not produce disbonding. However, the Task II-dl tube produced only zero ultrasonic values throughout the length of the bend on both the inside and outside surfaces indicating complete disbondment. Surface irregularities did develop on the inside surface which were suggestive of disbonding as shown in Figure V-5.

E. Summary of the Defect and Gaging Evaluations

In regard to stainless clad layer thickness and uniformity, the nondestructive evaluations indicate that the gas pressure bonding clad tube fabrication method can produce good uniformity observed relate primarily to excessive pickling encountered with the sensitized stainless layers. It should be possible to improve performance by better control of sensitization. Overall, the tubing is relatively free of defects at the bond line whether in the as-produced condition or after forming. The size and frequency of bond defects which were encountered probably would not effect tube performance in many applications.

TABLE V-1. Nondestructive Evaluation of Task I Stainless Clad Tubing by Accuderm and Ultrasonic Inspection

• Tube I-3

Location	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	.15	4.0	17	5 0	.17	3 5	18	3 0	15	21	23	25
2	14	3 8	.18	4.4	18	4.0	.20	4 0	.14	20	22	24
3	15	3 5	.18	4 4	15	4.0	19	4 0	18	20	22	25
4	16	4 4	.17	5.0	18	4 8	.18	4 0	19	20	.22	25
5	17	4 0	17	5 0	.18	4.0	18	4.6	19	.20	.23	25
6	17	4 5	17	4 5	18	4 0	17	5 0	20	20	.24	25
7	16	4 0	18	5 5	.17	4 0	18	4 5	19	20	24	25
8	16	3.8	16	5 0	17	4 3	17	4 5	20	20	23	25
9	15	3 5	16	5 0	17	5 0	18	4 5	20	20	23	25
10	16	3 6	17	4 5	17	4 3	19	5.5	20	20	23	25
11	15	3 5	17	4 5	15	6.0	.19	4 5	20	21	23	25
12	16	3 0	16	4 0	16	4 0	18	4 0				
13	16	3.5	15	4 2	15	4 5	18	4 0				
14	15	3 0	16	4 0	17	5 5	19	4.0				
15	15	3 8	16	4 0	18	5 0	17	4 0				
16	15	3 3	16	4 5	18	4 2	.16	4.0				
17	15	4.0	15	4.0	18	4 5	16	4 0				
18	15	4 0	16	4 5	18	4 5	18	4 2				
19	.16	4.5	17	3 5	15	3.5	18	4 5				
20	.16	4 5	15	3 5	17	3.0	.15	3 0				
21	17	4 5	14	3.0	18	4 0	17	4 0				
22	.15	5.0	13	3.5	.16	3 8	17	3 0				
23	17	4.0	15	2 5	16	3 5	18	4 0				
24	.16	4.0	15	2 0	17	3 5	.16	3 0				

Note Measurements were taken at 25 4 mm intervals

V-8

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TABLE V-2. Nondestructive Evaluation of Task II Stainless Clad Tubing by Accuderm and Ultrasonic Inspection

Tube II-b1

	Top Outside				Bottom Outside				Top Inside Stainless Thickness mm		Bottom Inside Stainless Thickness mm	
	Side A		Side B		Side A		Side B					
Location	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	20	2.5	.23	4 5	.21	2.0	22	2 5	.20	.19	.21	22
2	20	3.5	22	4 5	21	2.5	22	2 5	19	.20	22	22
3	20	3 5	23	4 0	21	2 5	22	3 0	20	21	22	23
4	20	1 5	.21	5.0	.22	2.5	.23	2.5	.20	.20	22	23
5	.20	4.0	.23	4.5	.22	3.0	.23	2.0	.20	21	21	23
6	20	4 5	.21	4 5	.22	2 0	21	1 5	.20	22	.22	23
7	20	3 7	22	3 5	22	2.0	.22	2 0	.21	.20	.20	23
8	20	2 5	21	5.0	.21	1.5	.22	2 7	.15	21	.22	23
9	.20	3.0	.22	2.5	.22	2.0	.21	1.5	.16	22	22	23
10	21	3.3	.22	3 5	.22	2 0	22	2 0	21	23	22	.24
11	21	3 0	.23	3 5	22	2.5	.22	2 5	23	23	22	24
12	.20	3.0	22	3 5	21	2.7	.21	3 2				
13	.20	3.0	.23	3 5	21	2 7	.22	2 7				
14	20	3.0	.22	2 5	21	3.5	.22	3.0				
15	20	3 3	22	3.0	.21	2 5	.22	3.2				
16	21	3 0	22	2 5	21	2.5	.21	2 8				
17	.21	3 0	21	3 0	21	2 5	.22	3 0				
18	.21	3 7	.21	3 0	.21	2.5	.21	4 0				
19	.21	3 0	.22	2 8	22	2 5	21	2.8				
20	20	3 0	.22	2 5	22	2 0	21	3.2				
21	20	3.0	21	3 5	22	2.5	.21	3 0				
22	.21	2.5	.22	2.5	.21	3.0	.21	3 7				
23	21	2 5	.21	2.5	21	2.3	21	3.8				
24	20	3 0	22	2 5	21	2 7	21	3 8				

Note. Measurements were taken at 25 4 mm intervals

Tube II-b2

	Top Outside				Bottom Outside				Top Inside Stainless Thickness mm		Bottom Inside Stainless Thickness mm	
	Side A		Side B		Side A		Side B					
Location	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side
1	.21	3 8	.21	3 5	.22	4 0	.21	4 0	24	22	20	.20
2	20	4 2	.20	5 5	.21	5 2	.22	5.4	.25	24	.20	.22
3	21	5.0	20	4.5	.20	4 2	21	5 5	24	24	.20	21
4	.21	4.5	20	4 5	.21	4 5	21	5 5	24	24	.22	21
5	21	4.5	21	5 0	22	6 5	21	5.3	24	24	.22	22
6	21	5.0	.20	4.8	21	5.8	.20	5.3	.24	.24	23	23
7	21	4 5	.20	5 0	21	4 5	21	5.0	24	.24	22	23
8	19	4 0	20	4 5	21	5 0	20	4.7	.24	24	23	24
9	.21	3 5	20	2 5	.21	5.5	20	4.5	.24	24	23	24
10	.20	2.5	18	1.5	.20	4 4	21	5 3	.24	24	23	.24
11	21	1.5	21	2.0	20	4.4	.21	5 0	24	24	24	24
12	19	1.5	19	3.0	21	4.5	.20	5 2				
13	20	1 5	.22	1.5	.22	5.4	20	5.0				
14	21	1 0	21	2.5	21	5.8	21	5 0				
15	.21	0 0	18	3 5	22	5 0	21	5.2				
16	.20	2.0	.21	1.0	.21	5 0	.20	5.3				
17	20	2.5	.21	2.0	.22	5 5	.21	5 8				
18	21	3.0	.20	2.5	21	5 5	.21	5 8				
19	20	3.0	21	2.5	20	6.2	.22	5.3				
20	21	3.0	20	2.5	.20	5.2	.21	6.0				
21	.20	3 0	20	2 5	.22	6.5	20	6.0				
22	21	3 0	20	2 0	.20	5 5	21	5 0				
23	20	2.5	.21	2.2	.19	4.0	21	5.0				
24	.19	2.5	.20	2.0	.20	4 5	.20	5 4				

Note· Measurements were taken at 25.4 mm intervals

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TABLE V-2. (Cont'd) Nondestructive Evaluation of Task II Stainless Clad Tubing by Accuderm and Ultrasonic Inspection

Tube II-b3

	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
Location	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	.25	2.0	23	3 0	.23	3.0	.23	2 0	25	20	.20	23
2	25	2.0	23	2 2	23	2 0	25	2.5	25	20	20	20
3	25	2.0	.25	2.8	23	2.8	23	3 0	23	20	20	.20
4	25	1.5	25	2 8	23	2 0	.25	2 5	23	20	.20	23
5	.25	1.5	25	2 5	.25	2.4	.25	2 5	23	20	23	20
6	25	2.0	.25	2.5	23	2.0	.25	1.5	.23	.20	.20	20
7	25	2 2	.23	1 5	.18	1 5	.25	2 0	23	.20	20	20
8	.25	2 2	23	2.0	25	1.5	.23	1 5	.23	.20	20	.20
9	.25	2.2	.23	1.7	.23	2 0	.23	1.5	.23	.20	.20	.20
10	.25	2 2	23	1.3	25	1 5	.25	2 0	.23	20	20	20
11	.25	1 8	23	2.0	.25	1.5	.23	1 5	.23	.20	20	.23
12	25	1 8	23	2 0	25	2 0	25	2.0				

Note: Measurements were taken at 25.4 mm intervals.

Tube II-b4

	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
Location	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	18	3 5	.20	2.5	13	2 0	20	2 0	23	20	20	23
2	20	2 0	.18		18		.18		.30	20	20	23
3	.20	2 0	18		18		.20		23	18	18	20
4	.20	2 5	.20		18		.20		23	20	.20	20
5	.20	2 2	.20		20		.20		25	.23	.20	.23
6	20	2 2	20		.20		.20		.23	.25	20	.20
7	20	2 2	20		.18		20		.25	23	.23	.20
8	20	2 7	20		.20		20		.23	25	23	20
9	.20	2 8	20		.20		18		.25	25	23	20
10	.20	2 0	20		.20		20		.25	.20	23	23
11	.20	2.0	.23		20		20		25	20	23	20
12	.20	3.0	.20		18		20					

Note: Measurements were taken at 25.4 mm intervals.

TABLE V-2. (Cont'd) Nondestructive Evaluation of Task II Stainless Clad Tubing by Accuderm and Ultrasonic Inspection

Tube II-b5

Location	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	.20	6.2	20	4 5	.20	5 0	.22	4 5	24	21	22	22
2	21	5.0	.18	5.0	.21	6 0	.22	5.0	21	.28	22	22
3	19	5 5	.19	4 0	20	5 0	.22	4 5	22	21	23	.22
4	19	4.0	.20	4.3	20	5 2	.21	3 5	21	22	22	22
5	.21	5.0	21	5.0	20	3.5	22	3 5	20	22	22	22
6	21	4 5	19	4 5	21	3.7	21	4 0	.24	22	22	22
7	21	4.0	20	5.0	.20	3.0	21	3.0	.22	.22	.22	22
8	21	4.3	.20	4.5	.21	2.0	.22	3 7	.21	22	.22	22
9	21	4.2	.20	4 5	.20	2.0	.22	3 0	36	22	22	23
10	22	4 2	20	4 5	21	3 0	21	3 5	.36	22	20	23
11	21	3.5	21	4.4	20	1.0	.22	3.0	20	23	19	.23
12	.21	5.3	21	3 5	.20	1.5	23	2.5				
13	.21	4 0	21	4 5	.19	1 5	22	2 5				
14	.22	3 5	19	4 0	.21	1 5	22	2 5				
15	20	4 0	21	4 5	.20	3 5	.22	3 0				
16	21	4 7	.20	4.0	.20	3.0	.22	4 0				
17	21	4.0	20	4.0	.22	3.0	.22	4 2				
18	.21	4 0	20	4 0	.21	3 0	.21	3 0				
19	21	4 5	20	4 0	.21	3 0	21	4 0				
20	20	5.0	20	4.0	.21	2 5	.21	4.0				
21	.21	4.0	20	3 5	.21	2 7	.20	2.5				
22	.21	3.7	.20	3 5	.22	2 5	.20	3.5				
23	19	3 5	21	4 0	.20	3 0	.22	4 0				
24	20	3 3	20	3.8	15	2 5	.22	3.0				

Note· Measurements were taken at 25 4 mm intervals.

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TABLE V-2. (Cont'd) Nondestructive Evaluation of Task II Stainless Clad Tubing by Accuderm and Ultrasonic Inspection

Tube II-d1

Location	Top Outside				Bottom Outside			
	Side A		Side B		Side A		Side B	
	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values
1	.30	4.3	33	2 4	30	2 4	.30	1 7
2	.30	3 3	33	2.0	.30	3.7	.30	2 7
3	30	3.6	33	2 0	30	2.7	.30	3.0
4	30	4 5	33	1.3	30	3 5	30	2.5
5	30	4 5	33	1.4	30	3 5	.30	2.5
6	33	4 4	33	1 5	30	4 5	30	3 1
7	33	4.8	.30	2.0	30	3 5	30	4.0
8	33	4 5	.30	2.0	30	3 5	.30	4.0
9	30	4.7	30	2.0	30	4 0	.30	3 1
10	33	4 5	.30	1.8	.30	4.0	30	2 7
11	.33	4 2	.30	1 7	.30	4 5	30	3 8
12	30	1.5	.30	2.0	.30	4 8	.30	4 5
13	.33	2.2	.30	1 4	30	4.5	.30	4.2
14	.30	2.7	30	1 4	30	4 5	30	3 5
15	30	2 7	30	1 0	30	4.0	.30	2 3
16	33	3 0	30	1 2	30	4 6	30	3 5
17	30	4.5	30	1 4	30	4.8	30	3 4
18	30	4 5	30	2 0	30	5.0	.30	4 6
19	.33	2.2	30	1 5	30	4.8	30	4.2
20	.33	2.5	30	1 4	30	4.8	30	4.6
21	.33	2.5	30	2.8	30	4.4	.30	4 8
22	.30	1.0	.30	2.5	.30	4.4	.30	5 0
23	30	1 2	.30	2 0	.30	4.6	.30	4.5
24	.30	0.0	33	2.7	30	4 5	30	4 5

Note Measurements were taken at 25.4 mm intervals.

Tube II-d2

Location	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	30	2 0	30	1 8	.30	4.3	33	4 4	30	.28	20	.25
2	.30	2.1	.30	1 8	.30	4.3	30	4.7	28	.25	23	.23
3	30	1 9	.30	2 5	30	4 0	30	4 7	.28	25	23	.25
4	30	1 8	30	2 2	30	5.0	.30	4.6	28	28	25	23
5	30	2 0	30	1 8	30	4.4	.30	5.0	28	.28	25	.25
6	30	1 2	30	1 8	30	4 8	.30	5 0	28	28	25	25
7	30	2 0	.33	2.6	30	4.8	.33	5 0	.30	28	25	25
8	30	1 7	.30	2.6	30	4 8	.30	5.0	28	.28	25	25
9	.30	1.8	.30	2.4	.30	4 8	30	5.0	.28	.28	25	25
10	.30	1.8	.30	2.0	.30	4.8	30	4.6	.30	.28	.25	25
11	30	2 0	30	2.3	30	4 7	30	3 0	.28	28	25	25
12	.30	2.7	.30	2.8	30	4.8	30	2 0				
13	.30	2.4	30	3 2	30	4.6	30	4 0				
14	30	2.4	.30	2.4	30	5.0	30	5 0				
15	30	2 5	.30	3 0	30	4.8	30	4 2				
16	30	2 5	33	2 7	30	5.0	30	3 0				
17	.30	2 6	.30	3.0	30	4 8	.30	0 0				
18	30	2 8	30	3 7	30	4.8	.30	4 5				
19	.30	2 4	30	3.0	.30	5 0	.30	4.3				
20	.30	2 5	30	2.8	.30	4.8	30	4.4				
21	.30	2.9	.30	2 6	.30	4 8	30	4.2				
22	.30	2.7	.30	3.2	.30	4 8	30	3 8				
23	30	1.7	.30	1.2	30	5 0	.30	3 0				
24	30	1.5	.30	1.7	30	4.8	30	3 0				

Note: Measurements were taken at 25.4 mm intervals

TABLE V-2. (Cont'd) Nondestructive Evaluation of Task II Stainless Clad Tubing by Accuderm and Ultrasonic Inspection

Tube II-d3

	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
Location	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	.33	5 8	33	0.0	33	1.5	.33	2.2	.25	.28	33	30
2	.33	5 3	33	0.0	33	2 2	33	2 2	.25	28	.30	30
3	.33	5 0	36	0.0	33	1.5	33	0.0	.25	28	.30	.30
4	33	3 6	33	4.6	33	1.6	33	1.0	.28	.28	30	.33
5	33	4 8	33	4 8	33	2.0	33	1 5	28	28	30	33
6	.33	4 0	33	3 8	33	2.0	33	1.2	.28	.28	33	30
7	33	4 0	33	4.8	33	2 5	33	0 0	.28	28	33	33
8	33	4 2	.33	4.8	33	1 2	33	0 0	.25	28	33	33
9	33	4 8	33	4.7	33	1.0	30	1 5	.28	28	30	30
10	33	4 7	33	4 7	33	2.0	33	1 2	.28	28	30	30
11	33	4 8	33	4 7	33	2.2	30	1 0	.28	28	30	30
12	.33	5 0	.33	4.7	33	1 5	33	1.0				
13	33	4.8	33	5.0	33	2 0	33	1 5				
14	.33	3.8	.33	4.7	33	1 5	33	0.0				
15	33	4.7	.33	4.8	33	1.0	33	1.2				
16	33	4.8	33	4 8	33	2 5	33	2 0				
17	33	4.8	33	4.8	33	1 8	33	1.3				
18	.33	4.2	.33	4.9	33	1.0	30	0.0				
19	.33	5 0	.33	4 8	33	2 0	33	2 2				
20	33	5.0	.33	4.9	33	2 4	33	1 5				
21	.33	4.5	.33	4.8	.33	2 0	.33	1 0				
22	33	4.5	33	4 3	33	1 6	33	1 5				
23	33	4.7	.33	4.2	33	2 0	.33	2.0				
24	33	4.5	.33	4.4	33	1 6	.33	1 5				

Note. Measurements were taken at 25 4 mm intervals.

Tube II-d4

	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
Location	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	30	1 5	30	2.5	30	5 0	30	3.4	25	30	23	28
2	30	1.5	30	2 2	30	4 7	.30	4 5	.25	30	.25	28
3	30	1 6	30	1 2	30	4 8	.30	4 5	25	28	28	30
4	.30	1.5	.30	2.5	30	4.7	.30	5.0	25	30	25	28
5	.30	1 5	.30	1.3	.30	5.0	30	4 8	25	30	25	28
6	30	1 2	30	2.3	30	5 2	30	5 0	28	30	.25	28
7	.30	0 0	.30	2.0	30	5 2	30	5 0	28	.28	.25	.25
8	30	1.2	30	1 2	30	5 2	.30	5.0	.25	28	.28	.25
9	30	2 0	30	1 5	30	5 0	28	5 0	25	28	25	30
10	30	2.0	.30	2 0	.30	5.0	.28	4.5	25	25	28	.25
11	30	2.5	30	2 0	.30	5.2	28	4.5	25	.28	28	28
12	30	1.5	30	2.5	30	5 0	28	4 8				
13	.30	1 9	30	2.2	30	5 0	30	4.5				
14	.30	2 2	.30	2.5	30	5 0	30	4.8				
15	.30	1 0	28	2 4	30	5 0	30	4 8				
16	30	1 0	30	2 2	30	5.2	.30	3.3				
17	30	1 5	30	1 5	30	4.8	30	3 2				
18	30	1.4	30	1.2	.30	5.0	30	4 0				
19	30	2.0	28	1.4	30	4.0	30	3 5				
20	.30	1.8	30	1.5	30	4 2	30	3 0				
21	.30	2 4	.30	1.5	30	4 7	.30	3 8				
22	.30	2 5	.30	1.3	30	4.8	.28	3.5				
23	30	2 4	28	1 7	30	4.5	28	2 8				
24	.30	2.2	30	1 5	.30	4.8	28	2 7				

Note Measurements were taken at 25 4 mm intervals

TABLE V-3. Dimensions of Completed Task I Stainless Clad Tubing

Tube No.	Diameter		Wall Thickness		Clad Thickness					Stainless Steel Clad
					Method*	Outer Clad		Inner Clad		
	mm	in.	mm	in.		mm	in.	mm	in.	
I-1	25.3	.996	2.324	.0915	M	.140	.0055	.242	.0095	16.4%
I-2	25.3	.996	2.365	.0931	M	.156	.0061	.250	.010	17.3%
I-3	25.3	.996	2.339	.0921	M A	.140 .165	.0055 .0065	.250 .216	.010 .0085	16.8% 16.3%
I-4	25.3	.996	2.339	.0921	M	.150	.0059	.250	.010	17.2%
I-5	25.3	.996	2.332	.0918	M	.150	.0059	.240	.0094	16.7%

* M - Thickness determined by microscope measurement on metallographic specimens from tube ends.
A - Thickness determined by the Accuderm measurements along tube length.

TABLE V-4. Dimensions of Completed Task II Stainless Clad Tubing

Tube No.	Diameter		Wall Thickness		Clad Thickness					Stainless Steel Clad
						Outer Clad		Inner Clad		
	mm	in.	mm	in.	Method*	mm	in.	mm	in.	
II-b1	25.40	1.000	2.31	.091	M	.21	.0082	.22	.0086	18.5%
					A	.21	.0083	.21	.0084	18.4%
II-b2	25.40	1.000	2.36	.093	M	.17	.0066	.25	.0098	17.7%
					A	.21	.0081	.23	.0091	18.5%
II-b3	25.40	1.000	2.62	.103	M	.24	.0094	.22	.0086	17.5%
					A	.24	.0096	.22	.0085	17.6%
II-b4	25.40	1.000	2.31	.091	M	.15	.0059	.24	.0094	16.9%
					A	.19	.0076	.22	.0087	17.7%
II-b5	25.40	1.000	2.36	.093	M	.17	.0066	.25	.0098	17.7%
					A	.21	.0081	.23	.0089	18.3%
II-d1	44.32	1.745	3.41	.134	M	.33	.0129	.30	.0118	18.4%
					A	.31	.0122	.30	.0118**	17.9%
II-d2	44.32	1.745	3.33	.131	M	.32	.0125	.30	.0118	18.5%
					A	.31	.0120	.26	.0104	17.1%
II-d3	44.32	1.745	3.34	.132	M	.33	.0129	.30	.0118	18.7%
					A	.33	.0130	.29	.0115	18.6%
II-d4	44.32	1.745	3.38	.133	M	.33	.0129	.30	.0118	18.6%
					A	.30	.0119	.27	.0108	17.1%

* M - Thickness determined by microscope measurement on metallographic specimens from tube ends.
A - Thickness determined by the Accuderm measurements along tube length.

** - Accuderm data not available, thickness assumed the same as from microscope measurement.

TABLE V-5. Nondestructive Evaluation of Task I Stainless Clad Tubing Bend Test Specimen by Accuderm and Ultrasonic Inspection

Tube I-1 Bend Test

Location	Top Outside				Bottom Outside				Top Inside		Bottom Inside	
	Side A		Side B		Side A		Side B		Stainless Thickness mm		Stainless Thickness mm	
	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Stainless Thickness mm	Ultrasonic Values	Side A	Side B	Side A	Side B
1	.14	2.5	.15	1.8	.14	5.0	.14	2.0	.26	.21	.21	.19
2	.13	2.5	.15	2.5	.15	5.0	.14	2.5	.23	.20	.21	.19
3	.13	3.8	.15	2.5	.13	5.0	.15	2.5	.22	.20	.21	.18
4	.14	3.8	.12	2.5	.12	3.8	.14	3.8	.22	.20	.21	.18
5	.14	2.5	.13	2.5	.15	4.0	.16	4.0	.22	.20	.21	.19
6	.14	3.8	.14	3.8	.14	2.5	.17	5.0	.21	.24		
7	.16	2.5	.13	3.8	.16	1.0	.16	5.0	.21	.24		
* 8	.13	1.8	.13	3.8	.17	0.6	.16	5.0				

* Center of Bend

Note: Measurements were taken at 25.4 mm intervals.

TABLE V-6. Nondestructive Evaluation of Task II Stainless Clad Tubing Bend Test Specimen by Accuderm and Ultrasonic Inspection

Tube II-d1 - Bend Test

Location	Top Outside				Bottom Outside				Top Inside Stainless Thickness mm		Bottom Inside Stainless Thickness mm	
	Side A		Side B		Side A		Side B					
	Stainless Thickness mm	* Ultrasonic Values	Stainless Thickness mm	* Ultrasonic Values	Stainless Thickness mm	* Ultrasonic Values	Stainless Thickness mm	* Ultrasonic Values	Side A	Side B	Side A	Side B
1	.36		.30		.30		.33		.30	.30	.28	No Readings Taken
2	.36		.30		.30		.33		.30	.30	.28	
3	.36		.30		.30		.33		.30	.30	.25	
4	.38		.30		.30		.33		.30	.30	.28	
5	.33		.30		.30		.30		.30	.33	.28	
6	.30		.30		.30		.30		.33		.28	
7	.30		.30		.33		.30				.28	
8	.33		.33		.33		.30				.30	
9	.30				.33						.38	
10	.33				.30							

Note: Measurements were taken at 25.4 mm intervals.

* Although metallography indicated good bonds over substantial areas, the ultrasonic signals were too weak to valid data.

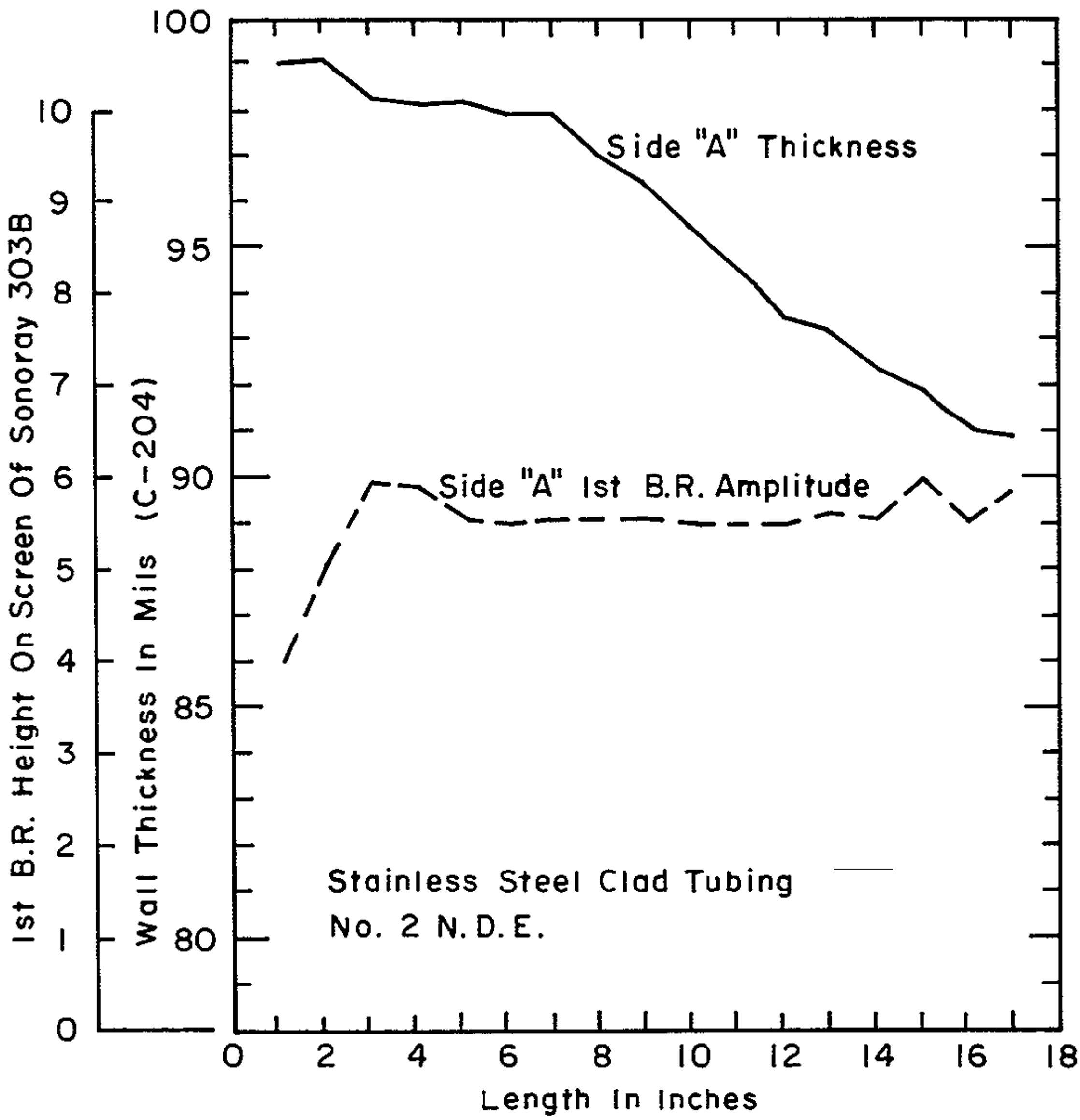

Figure V-1. Ultrasonic Evaluation of Stainless Steel Clad Tube Sample Task I-2 NDE - Side A.

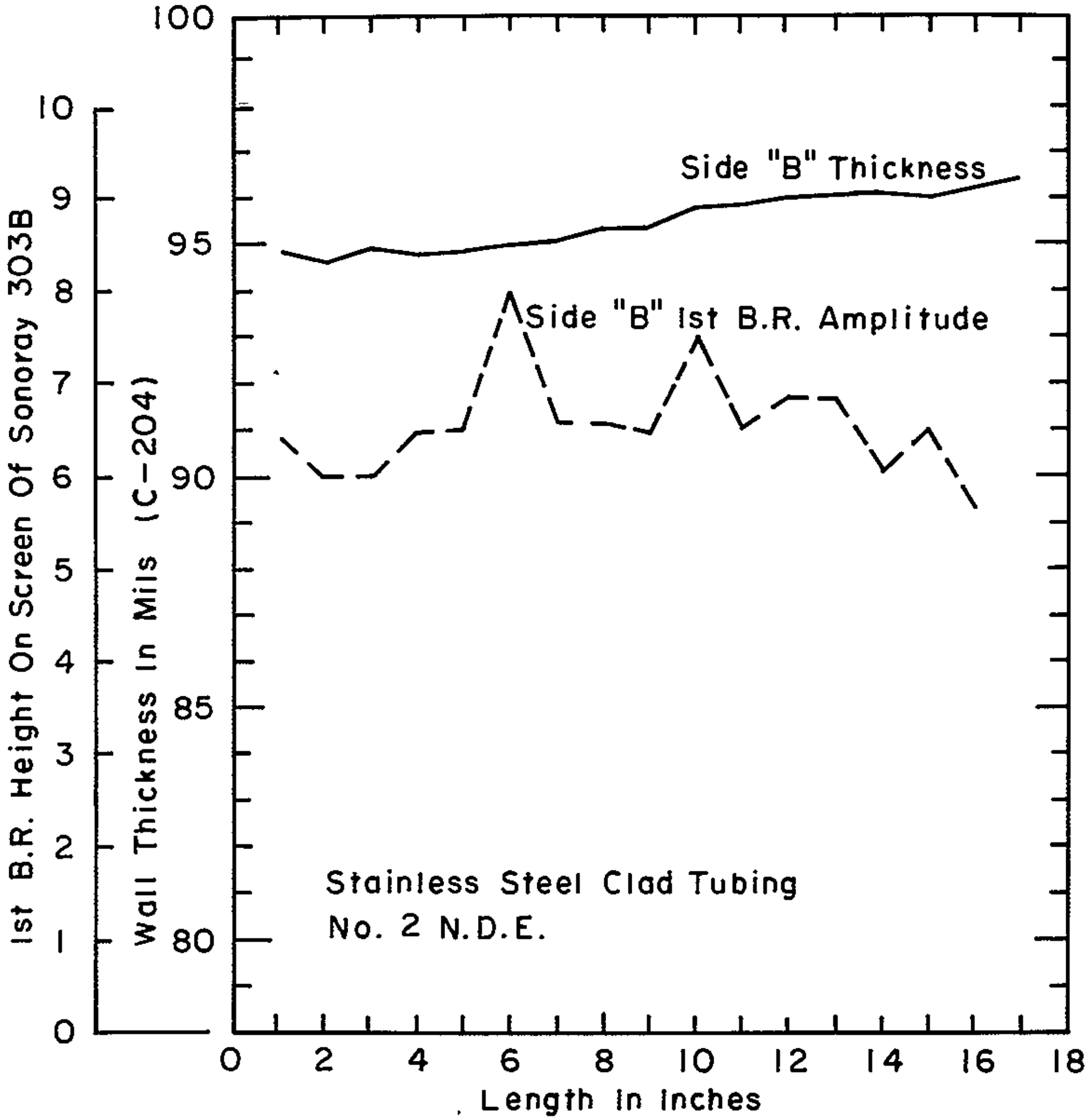

Figure V-2. Ultrasonic Evaluation of Stainless Steel Clad Tube Sample Task I-2 NDE - Side B.

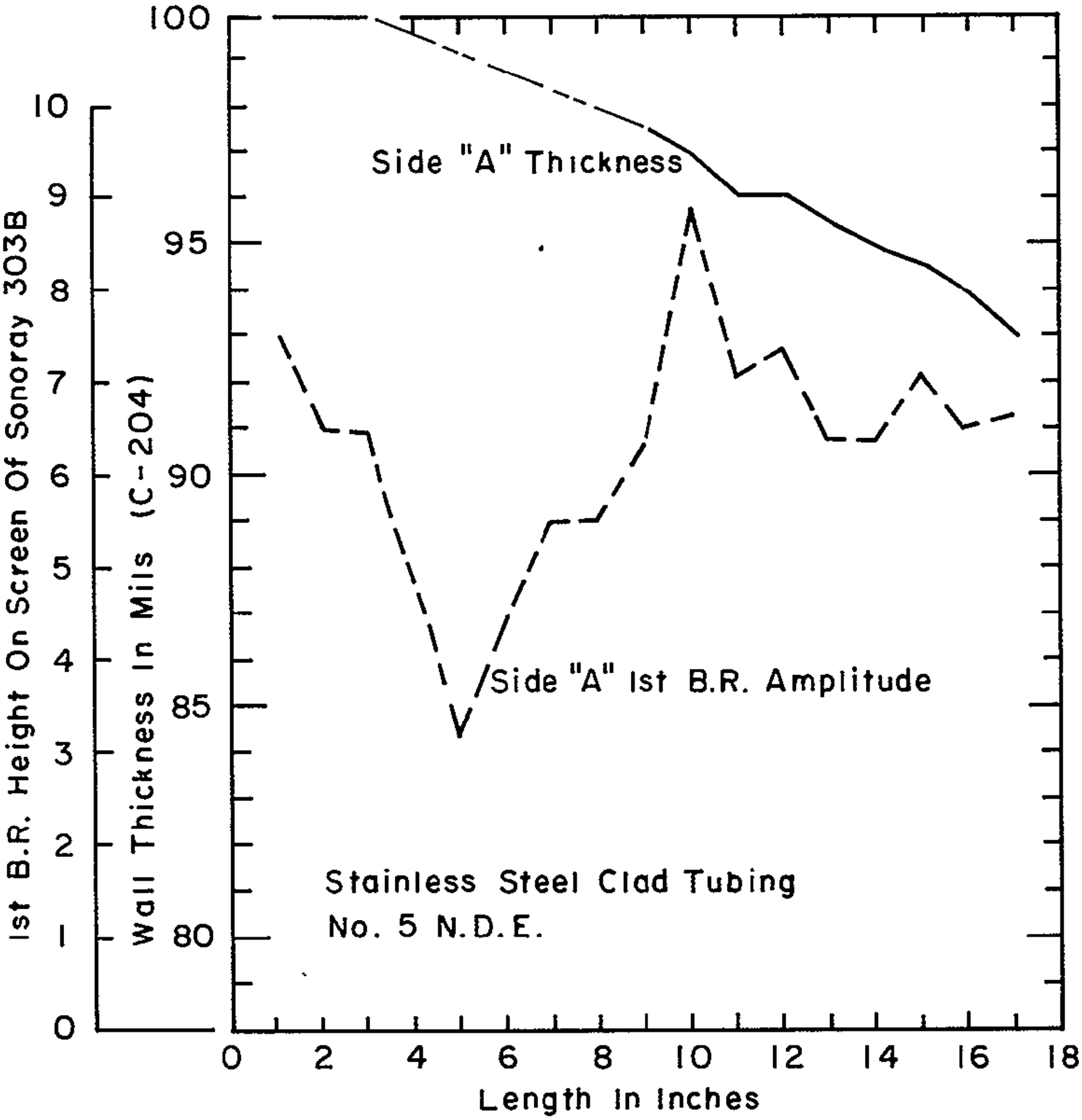

Figure V-3. Ultrasonic Evaluation of Stainless Steel Clad Tube Sample Task I-5 NDE - Side A.

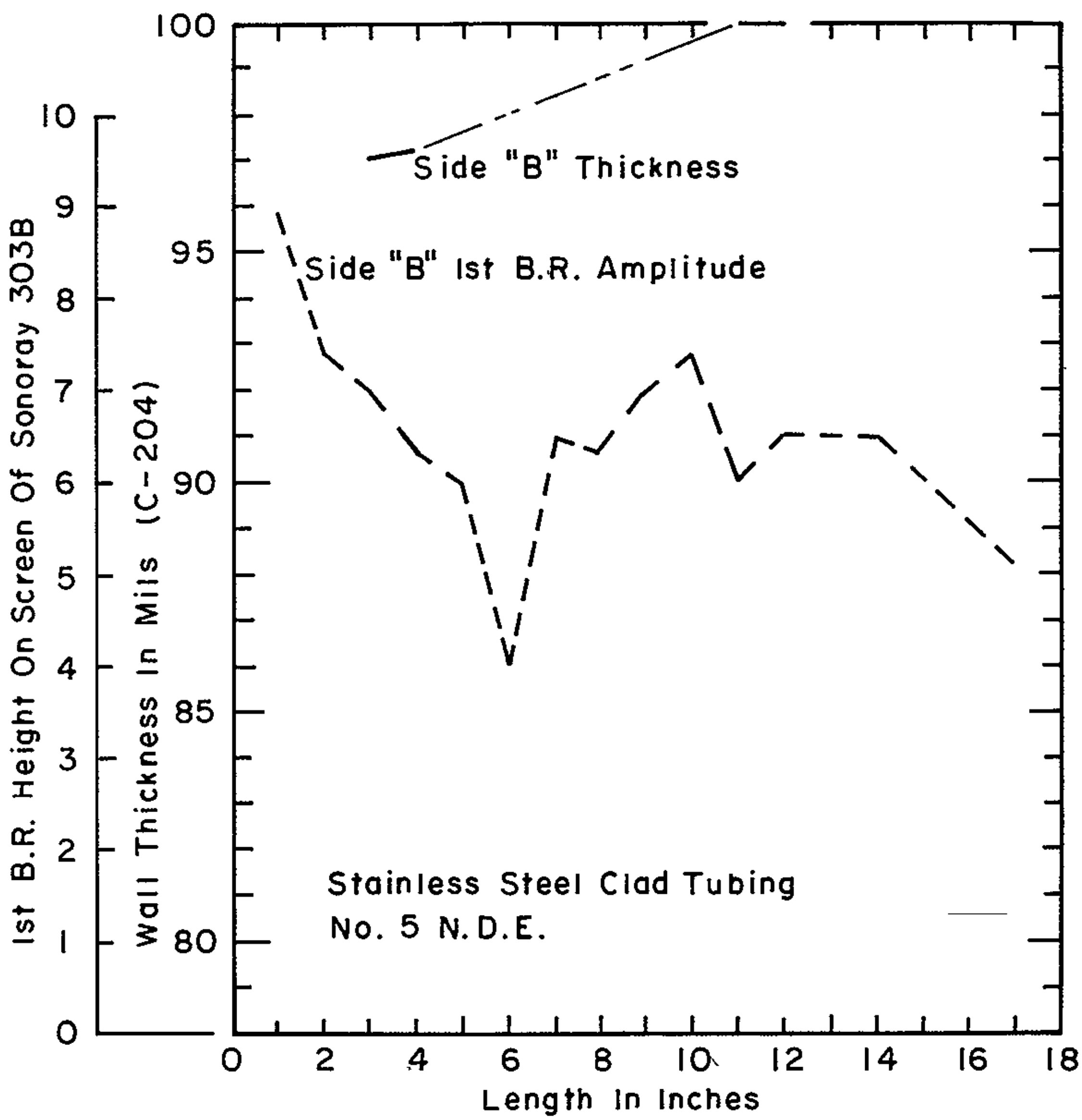

Figure V-4. Ultrasonic Evaluation of Stainless Steel Clad Tube Sample Task I-5 NDE - Side B.

Ultrasonic Defect Indication   No Ultrasonic Defect Indication

Figure V-5. Transverse Section of Task I-4 Tube Illustrating Correlation of Ultrasonic Indications with Bond Line Defects. Mag. 35X

VI. Estimate of Manufacturing Costs

A. Materials

An estimate of the manufacturing costs for the fabrication of stainless clad carbon steel tubing was developed based on the fabrication methods used in the tube production phase of this program, and on technical information developed in the program, which suggested an optimum product from the standpoint of cost and quality. Where possible, cost data were taken from similar commercial operations, but in many cases estimates had to be made based only on our laboratory experience. The manufacturing processes were modeled on an individual-discontinuous operation basis which is typical of production procedures used commercially for the manufacture of high quality stainless steel tubing.

The clad tube product selected for this study was 2-1/2 inch Schedule 80 pipe with 20% Type 304L stainless clad. The 20% clad was selected primarily to allow sufficient stainless thickness to avoid carburization problems. The relatively heavy Schedule 80 wall thickness also allows for a greater stainless thickness to avoid carburization, and provides for a greater weight tube giving minimum costs through the gas pressure bonding stage of manufacture. (The cost of fabricating thinner wall-smaller diameter tubes can be derived from the 2-1/2 inch Schedule 80 cost analysis by including additional cold draw-anneal sequences in final manufacture.)

The starting tubeset size was designed to provide a single cold draw-anneal sequence after gas pressure bonding. This serves to minimize carburization from repetitive anneals and also to minimize costs. The starting size also utilized a standard 3-inch Schedule 40 carbon steel pipe to minimize cost. The stainless requirement for this size, and most sizes of interest for clad tubing, is not optimum from a cost standpoint. The large diameter-thin wall requirement does not allow the use of an economical continuous welded tube mill product. Such tubing must be made by press form and welding, or by cold drawing which substantially add to the material cost. The starting tube and initial tubeset sizes are given in Table VI-1, and the cost of these tubes were based on purchase from vendors.

B. Manufacturing Sequence

The manufacturing sequence modeled for this cost analysis initiates upon the receipt of starting tube blanks and ends with the completion of cleaned tubesets which have been gas pressure bonded. This model includes the operations required in sequence, equipment, and materials needed. The autoclave operation was not detailed in the model because the analysis is based on purchasing this service from an outside vendor. A production rate of 56 finished tubes per day was used for the model to match a 1 cycle per day autoclave production rate. The autoclave used was the large capacity unit located at Battelle Memorial Institute. A capacity of 56 tubesets per day is possible based on using 8 cans per cycle each containing seven - 213 cm (7 ft.) long tubesets. The equipment requirements were based on the capacity needed to match this 56 tubesets per day production requirement. In most cases only 1 or 2 machines are needed to maintain this production rate. The exception is the surface preparation operations needed for the stainless and carbon steel tube blanks. Twenty-four turning machines are required with associated labor which produces a substantial cost increment at this stage. Studies to determine if surface polishing could be eliminated might produce a substantial cost reduction. The only significant material requirements beyond initial tube blanks are pipe for can fabrication and the sand pressure transfer medium. The model assumes two time use of cans and sand, and this might be extended with special decanning and sand reclaimation techniques.

C. Manufacturing Cost Estimate

The completed estimate of manufacturing costs is provided in Table VI-2. For this estimate a labor rate of $10 per hour has been used and equipment has been depreciated over ten years of one shift per day operation. Final tube drawing and annealing costs are based on experience with the commercial production of stainless tubing. Overhead costs for plant, administration and selling are not included because such costs will vary greatly depending upon particular circumstances.

The cost estimate shows that the direct manufacturing cost of stainless clad carbon steel 2-1/2 inch Schedule 80 pipe is about $86/m ($26/ft.) or $7.70/kg ($3.5/lb.) This cost is about three times the manufacturing cost of monolithic welded-cold finished Type 304 stainless tubing of the same size. Substantial elements of these costs arise from the starting tube blanks, intensive labor, and the high cost of the gas pressure bonding operation. While economies should be achievable through refinement of this new process, it is unlikely that costs could be reduced to a level competitive with monolithic stainless tubing. The costs, however, are within the realm of commercial practicality if chromium shortages make the use of stainless clad tubing a necessity. Such tubing also might compete economically with monolithic tubing manufactured from more expensive alloys.

TABLE VI-1. Description of Starting Tubes and Initial Tubeset Used for a Cost Analysis for the Fabrication of 20% Stainless Clad Carbon Steel - 2-1/2 inch Schedule 80 Pipe

Material	Actual Tubing Size				Nominal Size	Weight kg/m (lb./ft.)
	Dia.		Wall			
	cm	in.	cm	in.		
T-304L - Outside Stainless	8.89	3.50	0.076	0.030	3.5 inch x 0.030 inch Tube	1.65 (1.1)
1010 - Carbon Steel	8.73	3.44	0.610	0.240	3 inch Schedule 40 Pipe	12.3 (8.2)
T-304L - Inside Stainless	7.52	2.96	0.076	0.030	3 inch x 0.030 inch Tube	1.5 (1.0)
Initial Tubeset	8.89	3.50	0.760	0.300	3.5 inch Schedule 80 Pipe	15.5 (10.3

TABLE VI-2. Summary of Direct Manufacturing Costs for the Fabrication of 20% Stainless Clad Carbon Steel - 2-1/2 inch Schedule 80nPipe

	Cost per Tubeset ($)
Individual Costs	
Starting Tube Blanks (purchased)	58.80
Tubeset Fabrication	
Labor	60.10
Supplies	33.00
Utilities	-
Equipment Depreciation	0.50
Gas Pressure Bonding (purchased)	71.40
Final Tube Drawing, Annealing, Pickling (93% Yield)	5.00
Total Cost	
Direct Manufacturing Cost per Tubeset (93% Yield)	245.16
Direct Manufacturing Cost per foot	26.19
Direct Manufacturing Cost per pound	3.42
Production Rate	
Finished 2.6 m (8.4 ft.) long tubes per day - 1 shift operation	56

VII. Conclusions

A. Tube Fabrication

This program has demonstrated that stainless clad carbon steel tubing can be successfully fabricated by the gas pressure bonding of tubeset assemblies prepared from conventional stainless and carbon steel tubing of appropriate sizes to give the desired clad-substrate thickness ratio. Such gas pressure bonded tubing can be further processed to a variety of finish sizes by conventional cold draw-anneal-pickle procedures used in the commercial stainless steel tubing. The production methods necessary for tube fabrication represent no unusual departure from conventional production procedures with the exception of the actual gas pressure bonding operation. While this is a new technology, it is beyond the development stage and is being employed successfully for other purposes on a commercial basis. Good quality tubes were produced by this process without the need for unusually stringent quality control. Thus, the process would appear to be feasible to consider for a normal industry manufacturing operation.

B. Tube Quality

The only significant tube quality problem which developed in this program was that of stainless carburization from the carbon steel core. Fortunately, the mechanism of this carburization is well understood and so it should be possible to solve the problem with some further relatively straightforward development work. Possibilities for minimizing carburization include: use of a stabilized low-carbon steel core, the use of lower temperature - lower time gas pressure bonding cycles, and specifying some minimum stainless clad thickness based on the expected depth of carburization. Unfortunately, the use of a very thin stainless clad layer would appear to be unfeasible for this process because some carburization is always to be expected. For the conditions employed in this study the minimum stainless clad thickness appears to be at least 0.33 mm (0.013 inch).

Other quality aspects of clad tubing produced by this process appear to be excellent. The bond strength is sufficiently high to allow conventional cold draw final tube processing, and for the tubing to withstand flaring and bending operations. The mechanical properties essentially represent the relative thickness integrated average of those anticipated for monolithic clad and substrate materials.

C. Tube Fabrication Cost

There are a number of factors in this method of clad tube fabrication which produce final costs at least three times greater than production costs for monolithic stainless tubing. These include: the need for expensive large diameter/wall ratio starting stainless tube blanks, the labor - intensive tubeset preparation and assembly that is required, and high gas pressure bonding costs which result from the low production rate capability of this type of process. While it is likely that some economies can be achieved, it is unlikely the cost of Type 304 stainless clad carbon steel tubing produced by this process could be cost-competitive with monolithic stainless tubing. The production cost of this clad tubing, however, is not so high as to make it impractical for replacement of monolithic stainless tubing in the event of a serious chromium shortage.