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JOINING REFRACTORY/AUSTENITIC BIMETAL TUBING

Supplemental Report

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J. N. Kass

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Prepared for

National Aeronautics and Space Administration

Lewis Research Center

Space Power Systems Division

Under Contract NAS 3-7621

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FOREWORD

This program, Supplement to Contract NAS 3-7621, "Joining of Refractory/Austenitic Bimetal Tubing", was performed for the NASA-Lewis Research Center. The evaluation was conducted in support of the SNAP-8 mercury boiler being developed by Aerojet General Corporation for NASA. The authors gratefully acknowledge the realistic guidance and support given by P. Stone, the NASA-technical project manager, throughout the contract performance.

The authors thank those whose technical assistance aided in the successful performance of the program. These include J. Sedlock for physical measurements, material control, and overall assistance; E. Vandergrift and J. Lesczynski for helium leak testing and other non-destructive testing; J. Lott and K. Galbraith for metallography; P. Gaal, for thermal expansion measurements; and M. Demcyzk for ultrasonic testing.

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ABSTRACT

Bimetal tubing produced by four manufacturing processes was evaluated on the basis of bond integrity, dimensional control, and surface condition. The bimetal tubing, consisting of a stainless steel clad on a tantalum or columbium inner liner, was fabricated by: co-extrusion and drawing; explosive bonding and drawing; explosive bonding to size; and chemical vapor deposition. The primary evaluation criterion was the best bimetal bond quality obtainable as determined by ultrasonic inspection and metallography.

The section of extruded and drawn tubing which was evaluated displayed the best combination of bond quality and dimensional control. Explosively bonded to size tubing had inherent defects at the "standoff" dimples required for explosive bonding. This tubing displayed the best control of bimetal layer dimensions. Other dimensional properties such as out of roundness were average. The explosively bonded and drawn tubing displayed unbond areas coupled with bondline voids and poor dimensional control. The tubing produced by chemical vapor deposition was of very poor quality. The refractory metal component was severely contaminated with carbon producing complete unbonding and a very brittle inner liner. The evaluation conducted in this program does not fully reflect the potential of the various process techniques; because either very small quantities of tubing were produced or in the one case where adequate quantities were produced, only a limited sample was evaluated. Although limited in both scope and sample size, this evaluation serves as a guide to future, more complete application orientated evaluations.

I. INTRODUCTION

In the fall of 1966, a program was begun to evaluate bimetal tubing made by several manufacturing processes. This tubing was required to provide satisfactory corrosion resistance in the SNAP-8 mercury boiler. The tubing was austenitic stainless steel with an interior liner of columbium or tantalum refractory metal. A metallurgical bond between the layers was required for good heat transfer properties. Tubing made by the following manufacturing processes was evaluated.

1. Co-extruded and drawn
2. Explosively bonded and drawn
3. Explosively bonded to size
4. Chemically vapor deposited

The program at Westinghouse was principally intended to evaluate the bond quality produced by the various processes; however, dimensional properties and bond endurance were also of interest.

Considerable difficulty was experienced in producing bimetal tubing by the chemical vapor deposition process, in which tantalum is deposited on the inner surface of 321 stainless steel tubing. The problems included poor bonding and interstitial contamination. A more detailed description of this tubing is included in Section IIA of this report. As a result of these fabrication problems chemically vapor deposited tubing was excluded from all but a cursory inspection procedure.

By early 1967 the basic evaluation of the four types of prototype tubing was underway. However; the late delivery of the prototype tubing, coupled with a concurrent and pressing need for producing tubing to fabricate a SNAP-8 boiler, forced initiation of work on production tubing before the evaluation phase could be completed. Since a reliable bimetal tubing fabrication process had not been developed, three different types of production tubing were made to insure the construction of at least one successful boiler. To evaluate the production quantities of tubing, an evaluation program (Contract NAS 3-10601) was begun at WANL.

Since the prototype evaluation program could not serve the original purpose of determining the optimum tubing fabrication techniques and much of the work would be covered in the production quantity evaluation, the prototype evaluation was terminated. At the termination point, physical measurements, chemical analysis, and characterization of as-received bond quality for three types of tubing (extruded/co-drawn, exploded/drawn, and exploded to size) were completed and the coefficient of thermal expansion for exploded to size tubing was also completed.

II. MATERIAL & EXPERIMENTAL PROCEDURES

A. BIMETAL TUBING

Extruded and Drawn Bimetal Tubing

The extruded and drawn bimetal tubing was provided by Nuclear Metals Corporation in 1964 and was composed of 316 stainless steel lined with columbium. The tube received for inspection was 20 feet long with the following nominal dimensions:

O D = 0.510"	316 SS = 0.035" wall
I D = 0.400"	Cb Liner = 0.025" wall

The manufacturing process consisted of the hot co-extrusion of stainless steel and columbium tube hollows canned in mild steel. Although information on the detailed manufacturing process is not available the extrusion temperature was about 1800°F. Following extrusion, the tubing was dejacketed by pickling and cold drawn to final size with intermediate vacuum anneals as required. An appreciable quantity of this tubing was made in 1964 with bond quality ranging from less than 50% to near 100% as determined by ultrasonic inspection by the supplier.

Explosively Bonded and Drawn Bimetal Tubing

The explosively bonded and drawn tubing was produced jointly by DuPont de Nemours and Superior Tubing Inc. DuPont at Gibbstown, N. J. explosively bonded the 321 SS and columbium tube hollows. The resultant bonded tube hollow was cold drawn to final size by Superior Tubing at Norristown, Pennsylvania. In general terms, the explosive bonding is accomplished as follows:

A refractory metal tube hollow is placed inside a stainless steel tube hollow. The hollows are sized such that a small, uniform, standoff distance is maintained between them. The refractory metal hollow is filled with a solid medium to prevent deformation and a layer explosive charge is placed around the stainless steel hollow. The explosive charge is ignited from one end and the traveling shock wave bonds the two metals. The bonded tube hollow is then cold drawn to final size.

Intermediate vacuum anneals were used during the cold drawing operation. The piece received for inspection was 5 feet 5-1/2 inches long with the following nominal dimensions:

O D = 0.520"	321 SS = 0.043" wall
I D = 0.400"	Cb = 0.020" wall

Explosively Bonded to Size Bimetal Tubing

The explosively bonded to size tubing was produced by Aerojet-General at their Chino, California facility. The explosive bonding operation is similar to that previously described. The major exception being that final size tubing was bonded instead of heavy wall tube hollows. Small dimples in the refractory metal liner provide the concentrically spaced standoff distance and the dimple area did not bond. The bimetal tubing was made of 316 stainless steel with a tantalum liner. The piece received for inspection was 24 inches long with the following nominal dimensions:

O D = 0.800"	316 SS liner = 0.090" wall
I D = 0.580"	Ta liner = 0.020" wall

The stainless steel wall was much thicker than required because it was the only matching size of stainless steel tubing readily available for the development program.

Chemically Vapor Deposited Tubing

This tubing was coated in the form of a small sized heat exchanger. Figure 1 shows the completed heat exchanger comprised of three, 20 inch long bimetal tubes. Some distortion occurred during the coating process due to a pressure build-up in the protective can. The coating processing sequence was as follows:

> Deposit approximately 0.001 inch Cb on 321 SS
>
> Deposit approximately 0.020 inch of Ta on Cb using $TaCl_5$ reduced by hydrogen at 1850°F. The deposition process was followed by a 10 minute flush with argon at 1850°F to remove dissolved hydrogen.

The heat exchanger was sectioned and the initial evaluation indicated very poor bonding and very high hardness in the vapor deposited tantalum. Figure 2 indicates the lack of bonding shown by longitudinally sectioning the tubing. Chemical analyses were made of the tantalum layer which indicated very high carbon content of nearly 0.5%. The hardness measurements and chemical analyses are shown in Table 1.

Because of the poor quality of the vapor deposited tubing, further evaluation of this item was discontinued.

TABLE 1 - Chemical Analyses of Vapor Deposited Tubing

	Chemical Analyses of Tantalum Liner (ppm by wt.)					
	C	O_2	N_2	Cl	H_2	Hardness* (DPH)
Inlet Side	5300	190	23	---	6	253
Outlet Side	3900	340	28	25	12	321
	---	---	---	---	---	320**

* 10 kg load, average of 5 readings.
** Following vacuum annealing 2 hrs. at 700°C(1300°F) at 10^{-5} torr.

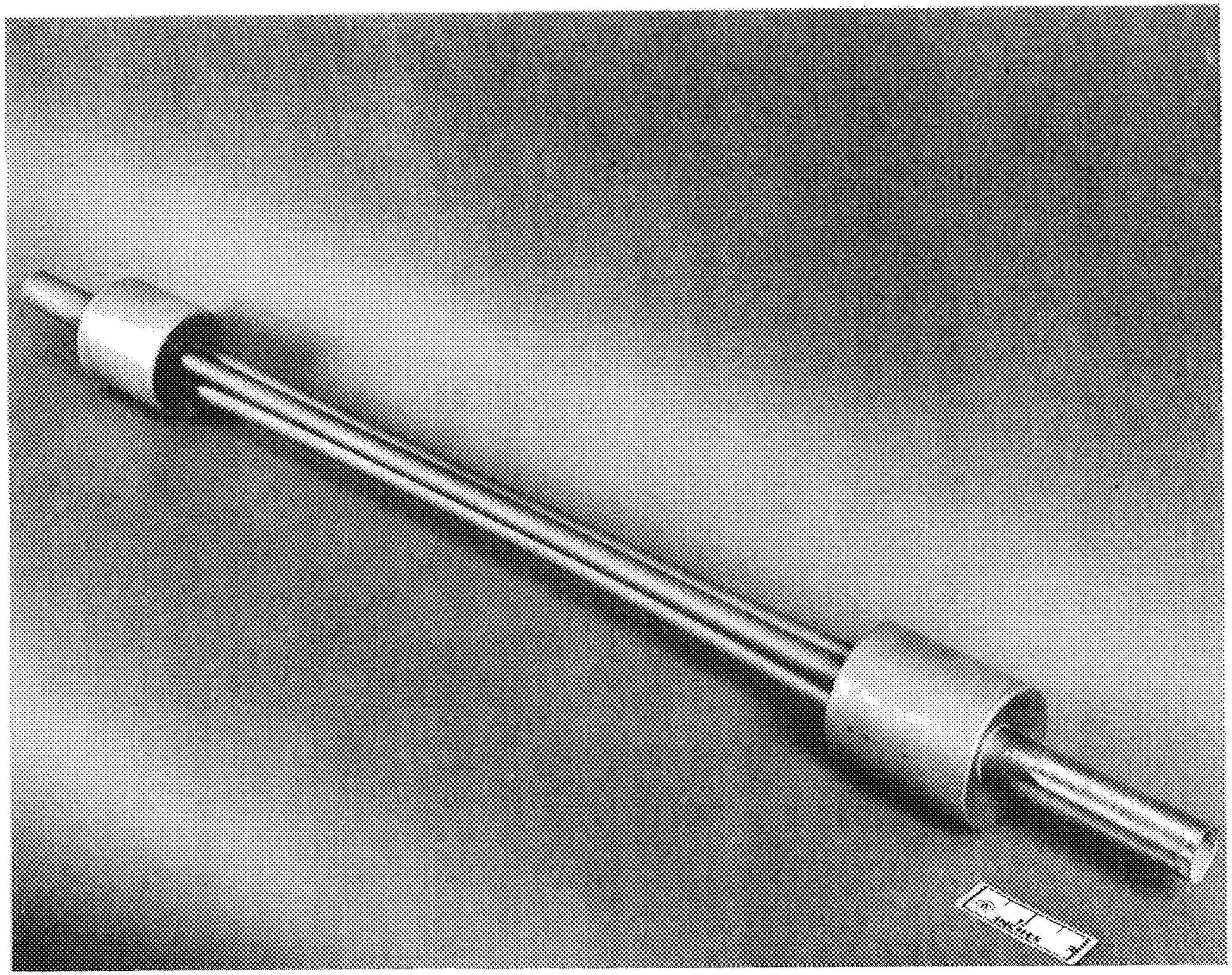

FIGURE 1 - Bimetal Tubing Heat Exchanger

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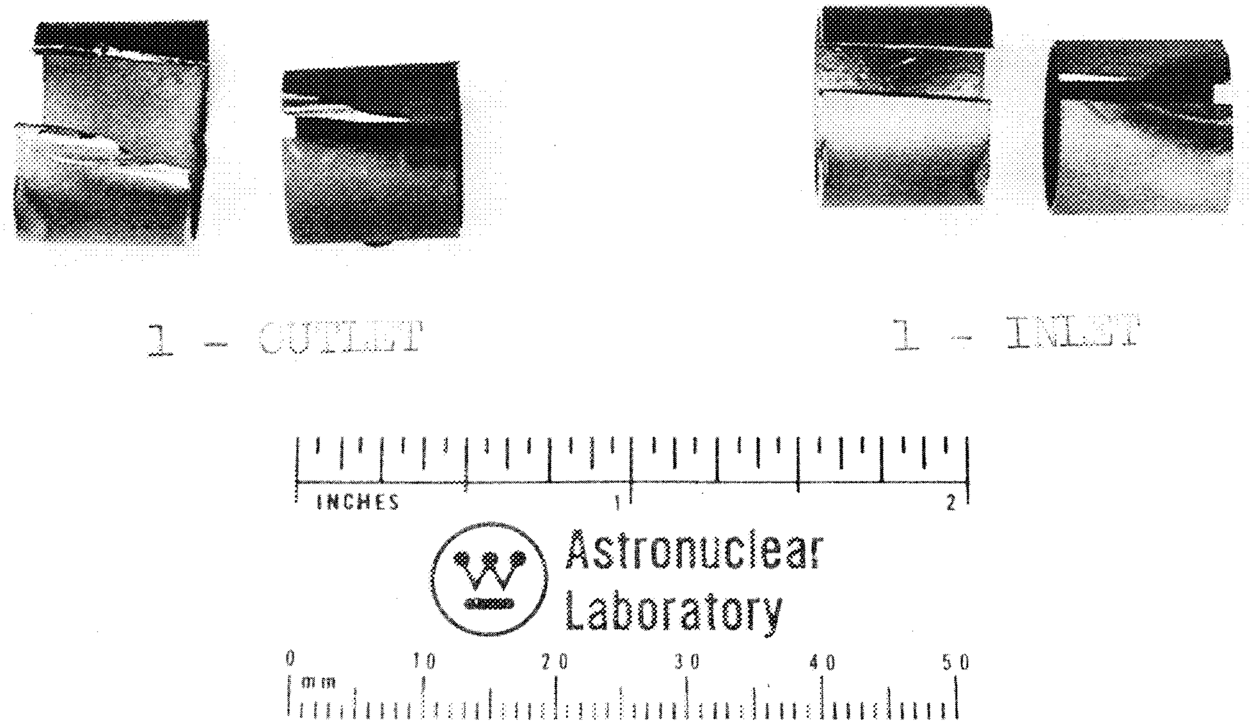


FIGURE 2 - Chemically Vapor Deposited Tubing

B. DIMENSIONAL MEASUREMENTS

Outside and inside diameter measurements were made with micrometers. Transverse sections were measured optically for tube wall and clad dimensions.

C. BOND CHARACTERIZATION

Several techniques were used to determine the bond characteristics of the three types of tubing. The basic evaluation was "through transmission" ultrasonic inspection which was verified by metallographic sectioning. In addition, a helium leak test and liquid penetrant test were used to measure discontinuities of the bond interface. Radiography was used to measure gross defects and fabrication oriented patterns in the bimetal layer thickness.

Helium Leak Test Technique

The helium leak test is capable of determining interconnected unbonding from end to end in bimetal tubing. The test is run by inserting one end of a bimetal tube into a leak detector, plugging the inside diameter at the opposite end and passing helium over it at this point. Continuous longitudinal unbonding provides a leak path for the helium. Figure 3 is a schematic of the helium leak test. The test is quite sensitive and 1% of the most sensitive range of the meter represents a leak of 1.25×10^{-3} cc/sec.

Ultrasonic Testing Technique

A through transmission longitudinal technique was developed to handle bimetallic tubes up to 24 inches in length. The focused transmitting crystal, mounted on a 15 inch long x 0.3 inch diameter tube was assembled to WANL specifications to facilitate insertion into small diameter tubing. The transmitting transducer had a working area 1/8 inch in diameter and was fitted with a hypodermic needle-type focusing mechanism. A yoke was designed to position the transmitting and receiving crystals for optimum focusing and to maintain alignment with the test piece.

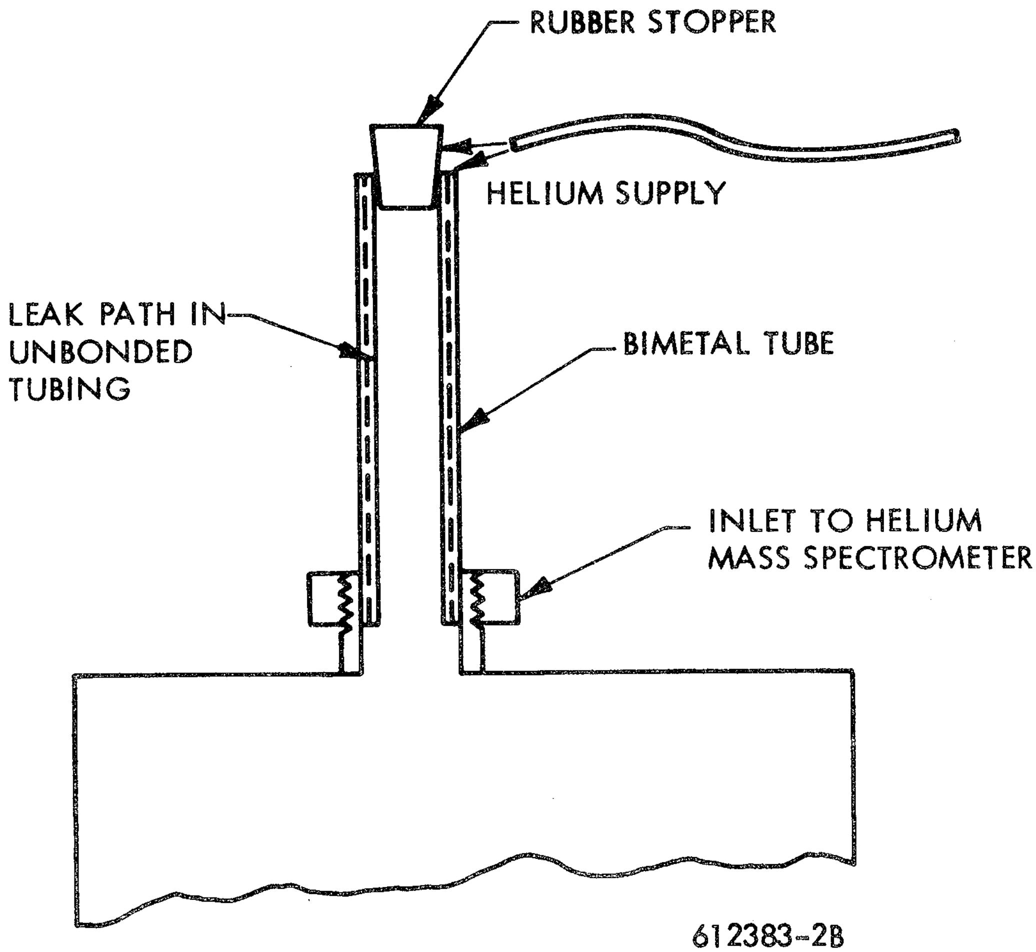


FIGURE 3 - Helium Leak Test

The system, shown in Figure 4 includes a variable speed and reversible driven turntable which rotates the water tank, chuck, and tube being tested. Also, shown are the electrosensitive recording pen and paper, reversible vertical drive mechanism, transducer yoke and associated microswitches.

As the tank rotates with the tube being tested, sound signals are transmitted through the tube wall and are displayed on the reflectoscope screen. The gated signal height is established for a known good bond area and a voltage is applied to the electrosensitive paper by the spring loaded pen, thereby producing an autographic trace of the bond quality. Discriminator level of the display is adjusted so that in an unbonded area the signal drops to set level and the voltage at the pen disappears and the recording is blank. For each rotation of the tank, a microswitch is triggered automatically, which in turn longitudinally moves the transducer yoke assembly and recording mechanism a predetermined amount.

The uniqueness of the system is that the tank which holds the water for the coupling of the sound also acts as the recording drum; in this way the orientation of the defective area can easily be identified. The problem of synchronizing the rotation of the test piece with the recording is thereby eliminated. Also, the recording is magnified by the ratio of the diameter of the tube to the diameter of the tank, this case being 20:1 (1/2 inch diameter tube and 10 inch diameter tank). A 1/16 unbond would produce a 1-1/4 inch void or no print on the trace.

Radiography Testing Technique

The source of radiation was a 300 KVP Isovolt X-ray machine and the recording medium, extra-fine grain Industrial X-ray film.

Two views were exposed at 90 degrees apart along the entire axis of the tubes. Due to the small diameter of the tubes, a double wall technique was used. Appropriate penetrameters were employed to determine radiographic sensitivity. Figure 5 shows a sketch of the method employed.

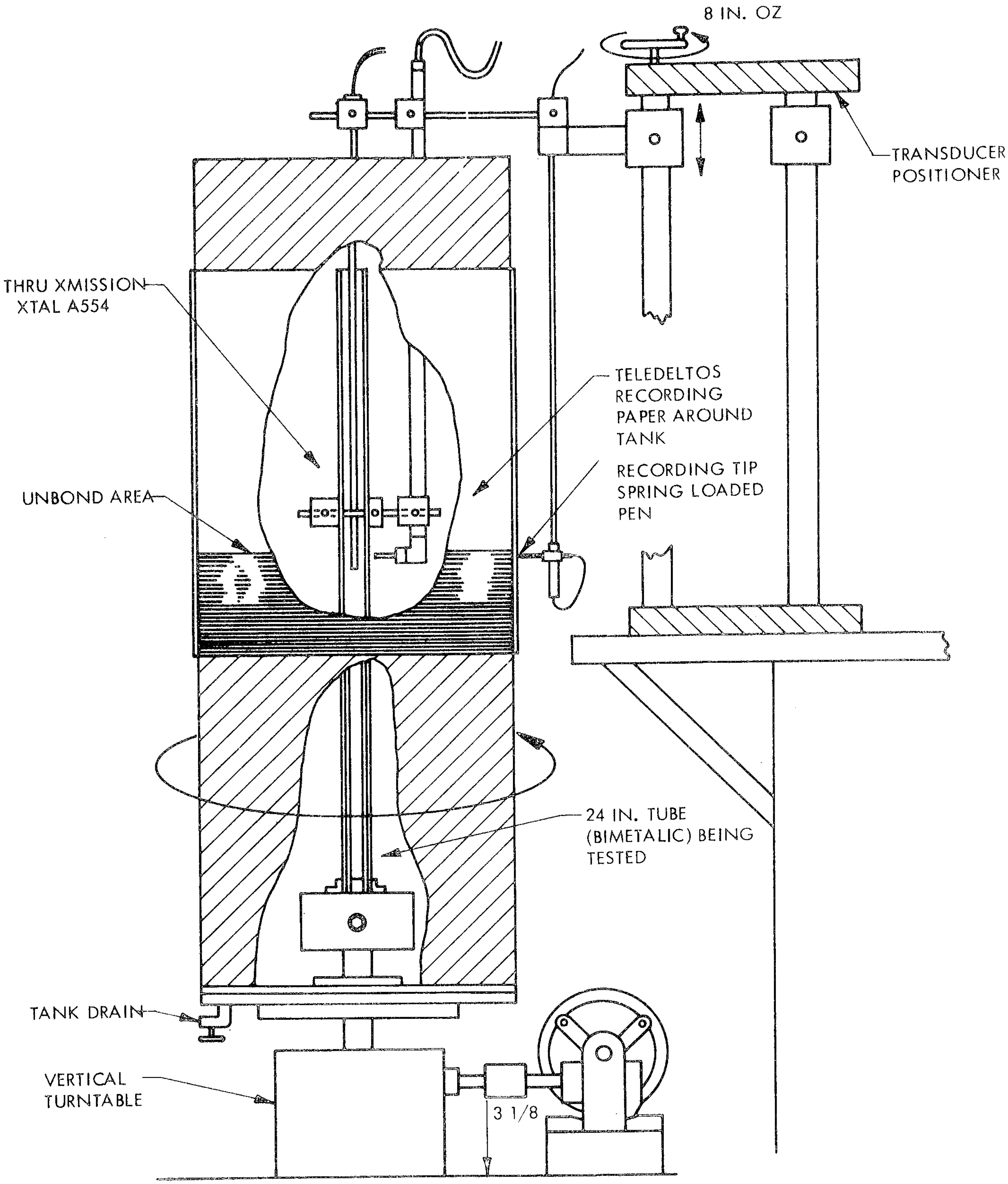


FIGURE 4 - Ultrasonic Test Equipment

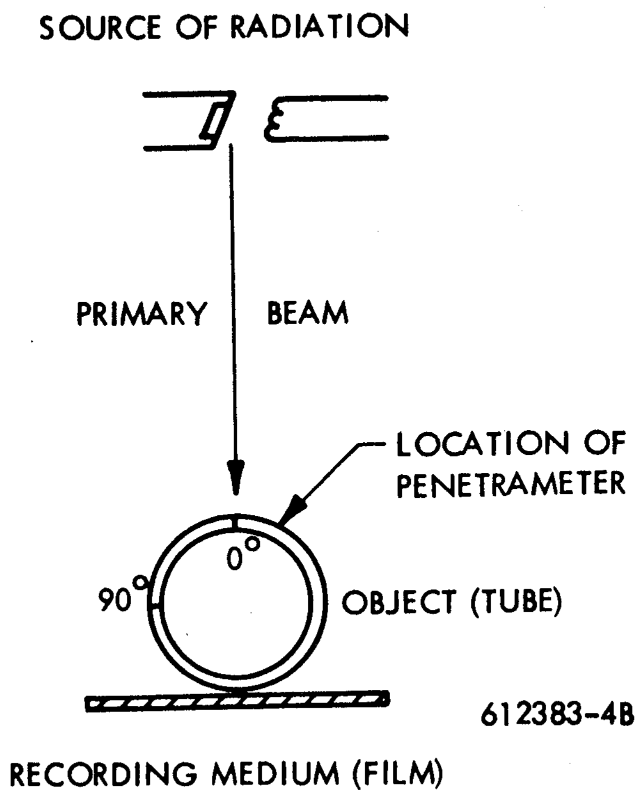


FIGURE 5 - Schematic of Transmission Radiography System for Bimetal Tubing

Liquid Penetrant Inspection

The liquid penetrant inspection was performed according to a standard Westinghouse specification. The tubing was first degreased with acetone and then the penetrant, VP 31 Type II, was dipped or brushed on. The penetrant was allowed to stand on the surface for 20 minutes and then the excess was wiped off with a clean cloth. Type E 50 emulsifier was used as the remover in a 10 second dip. The tubing was then dried. Type Met L Check D-70 developer was then sprayed on with 15 minutes allowed for developing to take place.

D. CHEMICAL ANALYSIS

1. X-ray fluourescence was used to verify the composition of the stainless steel and refractory metal layers. Oxygen content was found by vacuum fusion and nitrogen content by the Kjeldahl technique.

E. THERMAL EXPANSION

1. The apparatus used to perform the measurements is shown in Figure 6. Since the thermal expansion was measured from room temperature to 1350°F, the apparatus is enclosed in a vacuum chamber to prevent atmospheric contamination of the refractory metal component above 500°F. The diffusion pumped test chamber was maintained at a vacuum of 10^{-6} torr.

The unit utilizes a modified form of the standard quartz push rod and tube (See Figure 6.). A vertical quartz tube with a flat polished upper end and a slit forms the pedestal. The quartz push rod is formed into a ring to surround and contact the tubular specimen opposite the pedestal. The change in specimen diameter is thus transferred directly to push rod motion. Push rod motion is measured and recorded by an electro-mechanical transducer.

The transducer employed is a linear variable differential transformer with the chopper, oscillator, and demodulator integrated into the transducer, requiring only a stable DC input while providing a high level (~1V) output for its ±0.050 inch, full-scale deflection. The furnace was fitted with a loose fibrous quartz thermal insulator to help provide temperature uniformity.

The support section is mounted on a large base plate and the whole instrument is enclosed in a bell jar. The measurements were performed in a vacuum of 10^{-6} torr.

The overall accuracy of the measurements is estimated to be on the order of ±2% for the average case. This figure was substantiated by measuring the expansion of a copper sample and comparing the results to those found in the literature.

FIGURE 6 - Thermal Expansion Measurement Apparatus

III. INSPECTION RESULTS

A. PHYSICAL MEASUREMENTS

Dimensional Properties

The results of the dimensional measurements are summarized in Table 2.

TABLE 2 - Tubing Dimensions

		ID (in)	OD (in)	Wall (in)	SS Layer (in)	Cb Layer (in)	Eccentricity ID max-min	Eccentricity OD max-min
Co-extruded and Drawn	Ave.	0.3971	0.5102	0.0567	0.0355	0.0211	0.00096	0.00057
	3σ	0.0016	0.0008	0.0036	0.0030	0.0030		
Exploded and Drawn	Ave.	0.3964	0.5226	0.0630	0.0431	0.0199	0.0011	0.0006
	3σ	0.0025	0.0011	0.0026	0.0033	0.0033		
Explosively bonded to size	Ave.	0.5851	0.8091	0.1150	0.0924	0.0225	0.0021	0.005
	3σ	0.0042	0.0054	0.0060	0.0036	0.0027		

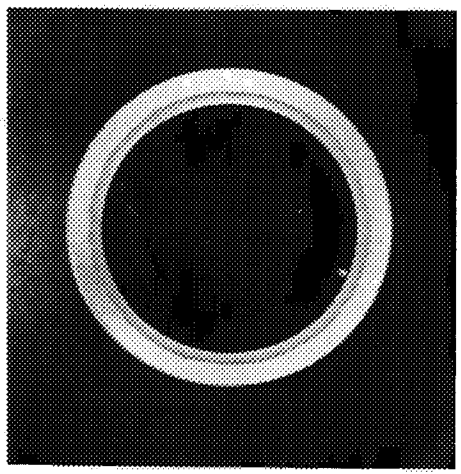
The above measurements for all three types of tubing compared well to commercial tolerances on seamless stainless steel tubing. The commercial tolerances for this size range tubing are:

OD	±0.005"
Eccentricity	±0.010"
Wall Thickness	±10%
Camber	0.01" per foot

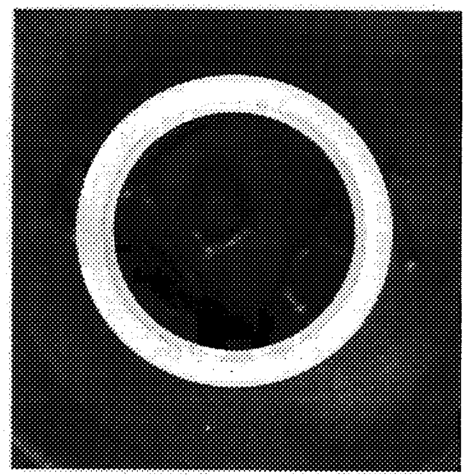
The eccentricity or "out of roundness" of the explosively bonded tubing was much greater than the tubing finished by drawing, reflecting the greater degree of dimensional control which can be achieved by a final drawing operation.

The camber was acceptable for the extruded/drawn, and explosively bonded/drawn tubing. The camber of the explosively bonded to size tubing was not accurately determined because of the short length of tubing supplied (24 inch).

Cross sections of the co-extruded and drawn and explosively bonded and drawn tubing are shown in Figure 7. The explosively bonded and drawn tubing occasionally shows severe variations in refractory liner thickness which are not reflected in the variations shown in Table 2. The explosively bonded to size tubing, not shown in section view, had the least variation in refractory clad thickness.



a. Extruded and Drawn



b. Explosively Bonded and Drawn

FIGURE 7 - Transverse Tube Sections

Hardness

The results of bimetal interface hardness traverses are shown in Figure 8. The explosively bonded to size tubing is significantly different than the other tubing in that the stainless steel is much harder through the entire cross section and the hardness of both the tantalum liner and the stainless steel builds up to a maximum at the bimetal interface. This behavior is typical of explosively bonded material and has been previously observed. The stainless steel is severely work hardened by the explosive bonding operation. Several annealing steps were used in producing the explosively bonded and drawn tubing, thus lowering the hardness to the values shown. Since the co-extruded product is extruded at ~1800°F and the tubing is also annealed between the drawing operations, a moderate hardness in the stainless steel results.

Liquid Penetrant Tests

The exterior surfaces of all the tubing were examined for crevices using liquid penetrant. None were found on any of the three types of tubing. Liquid penetrant was also used to inspect the tube ends for unbonding and no defects were found.

Chemical Analyses

Chemical analyses were made of the tubing to positively identify the bimetal components and to check for interstitial contamination in the refractory metal. X-ray fluourescence was used to identify the major bimetal components; the characteristic emission from molybdenum identified 316 stainless steel and that from titanium identified 321 stainless steel. All components were as stated.

The bimetal components were analyzed for interstitial composition to determine if the refractory metal was contaminated. Table 3 shows the interstitial analyses obtained. The oxygen and nitrogen levels were slightly higher than those for the starting materials, thus indicating some minor contamination during processing.

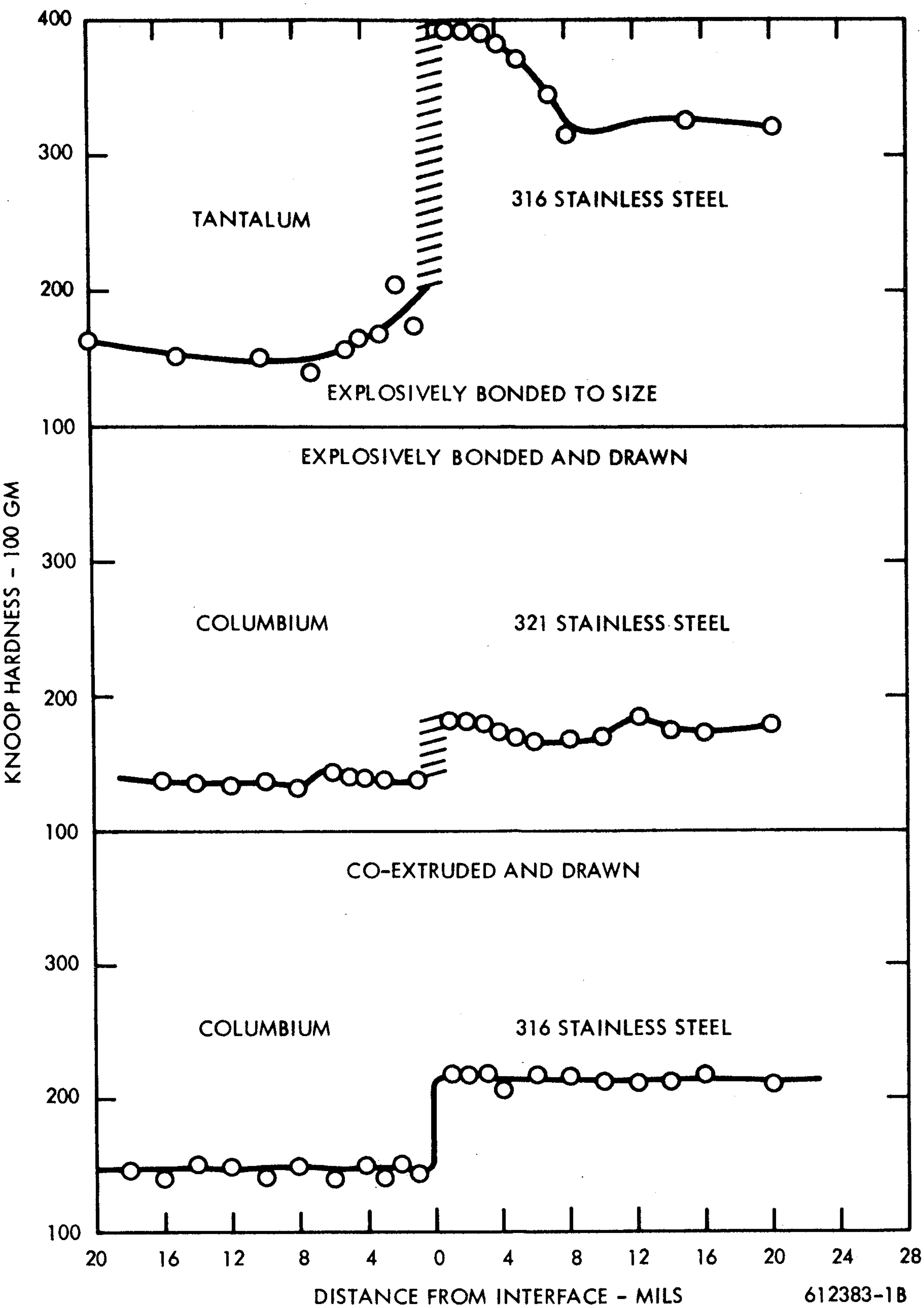


FIGURE 8 - Bimetal Interface Hardness Traverses

TABLE 3 - Interstitial Levels in Bimetal Components

Type of Tubing	Composition (ppm)	
	O_2	N_2
Explosively Bonded to Size		
316 SS	59	360
Tantalum	81	24
Explosively Bonded & Drawn		
321 SS	34	64
Columbium	160	7
Extruded & Drawn		
316 SS	74	820
Columbium	190	9

Helium Leak Test

Helium leak tests as previously described in Section II of this report were run on the three types of tubing to determine interconnected unbonding. No defective tubes were found.

Thermal Expansion

The thermal expansion of explosively bonded bimetal tubing in the longitudinal and radial direction was determined from room temperature to 1350°F. To determine the contribution of the tantalum and 316 stainless steel to the overall thermal expansion rate, respective layers were removed and the individual components were measured. The results are shown in Table 4. The results show that stainless steel is the dominant component as would be expected from the 4:1 thickness ratio of the stainless steel to tantalum. No significant difference was observed between the axial and radial expansion tests.

TABLE 4 - Coefficient of Linear Thermal Expansion for Explosively Bonded to Size Bimetal Tubing

Sample	Furnace Run	Direction	α in/in	
			°C(RT-735°C)	°F(RT-1350°)
1	1	radial	22.2	12.3
1	2	axial	19.6	10.9
1(Ta removed)	3	axial	19.6	10.9
1(Ta removed)	4	radial	19.6	9.8
2	1	axial	(1)	(1)
2	2	axial	18.6	10.3
2	3	radial	18.5	10.3
2(316 SS removed)	4	radial	7.4	4.1
2(316 SS removed)	5	axial	6.3	3.5
316 SS	handbook	axial	19.3	10.7
Ta	citation	axial	6.8	3.8

(1) No test due to alignment problems

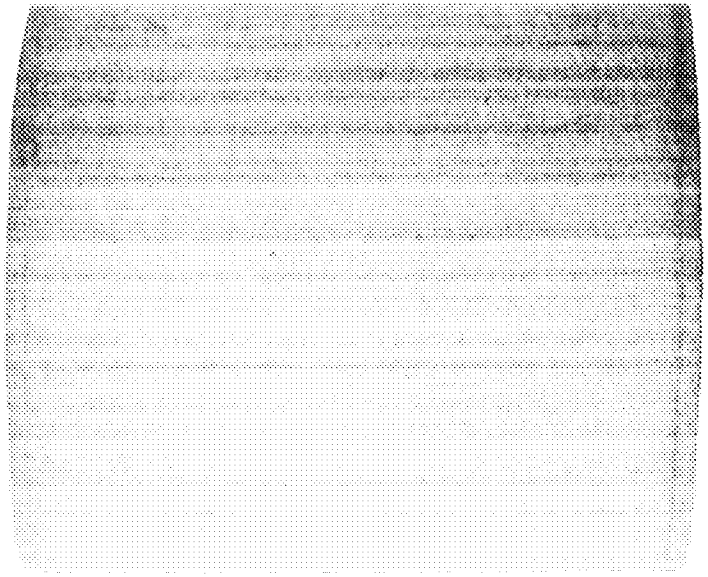
B. BOND CHARACTERIZATION - ULTRASONIC, RADIOGRAPHIC, METALLOGRAPHIC

Co-extruded and Drawn Tubing

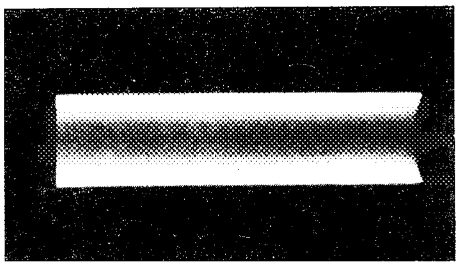
The co-extruded and drawn tubing displayed excellent bimetal bonding as inspected non-destructively by through transmission ultrasonic testing and destructively by metallographic section. Three feet of tubing were ultrasonically inspected and 12 metallographic sections were obtained from the original 20 foot length of bimetal tubing.

Interface Shape

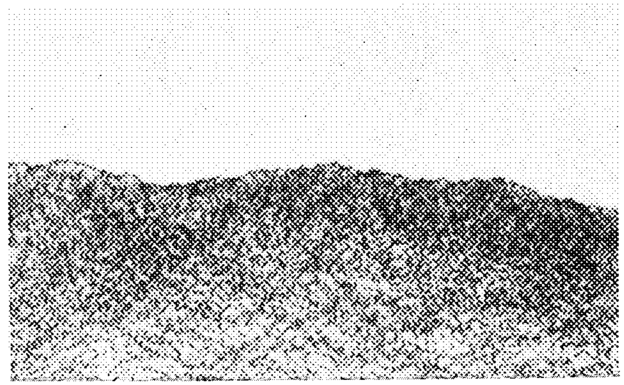
Figure 9a shows the interface configuration. The stainless steel layer was chemically removed with concentrated HCl and H_2O_2 permitting visual inspection. Figure 9b shows the information obtained by radiography. The longitudinal shading fluctuations are produced by the striations shown in Figure 9a. Figure 9 c shows the interface line obtained from this manufacturing process. Figure 9d shows the interface at 500X.



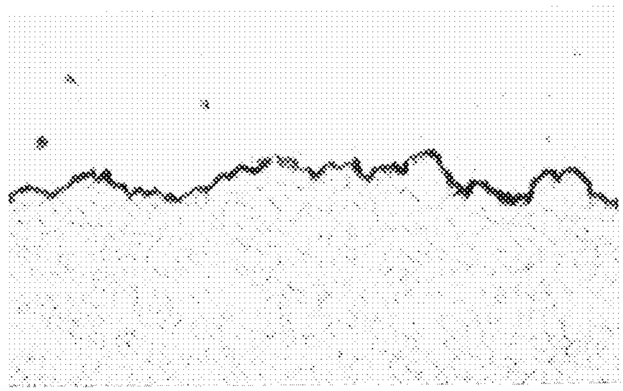
(a) Co-extruded and Drawn Bimetal Tubing Interface with SS Layer Chemically Removed to Reveal Interface



(b) Radiograph of Co-extruded and Drawn Tubing (Print - Light areas are thicker) Longitudinal Striations shown in (a) are Shown



(c) Co-extruded and Drawn Bimetal Tubing Interface 100X



(d) Co-extruded and Drawn Bimetal Tubing Interface 500X

FIGURE 9 - Co-extruded and Drawn Bimetal Tubing

Explosively Bonded and Drawn

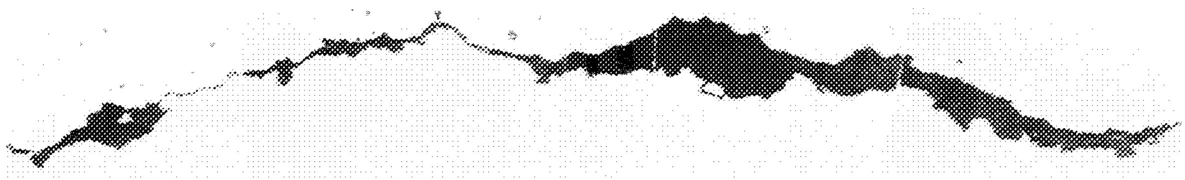
Three feet of this tubing was ultrasonically inspected and a distinct longitudinal unbond area was found. Metallographic sectioning confirmed the existence of a crevice, and Figure 10a is a transverse section showing its transverse length and width. Other sectioning showed that the axial or transverse length of the crack was equal to that shown by the ultrasonic traces. Additional metallographic sectioning was performed to investigate the large fluctuations in layer thickness that were occasionally found. Figure 10b is a typical transverse section. Figure 10c is an example of a well bonded interface.

Figures 11a and 11b show the rough interface where thickness variations and voids occur at the interface. These voids were not identified by other non-destructive inspection techniques.

Radiography results are shown in Figure 11c which indicate columbium layer thickness fluctuations but in an unusual pattern.

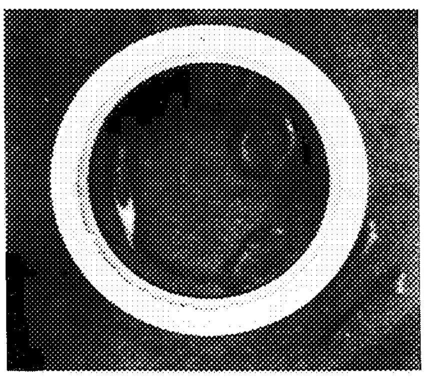
The stainless steel was chemically removed to reveal the columbium layer and a pattern was revealed identical to the radiographic results as shown in Figure 12. The deep grooves show clearly why sudden large columbium layer thickness fluctuations are found by transverse sectioning.

Several other metallographic sections were taken from this type of tubing and in each case, small voids such as those shown in Figure 11 were found. It seems quite probable that these defects are produced concurrently with the deep grooving during the manufacturing process, and that there are many of these defects throughout all the tubing inspected.



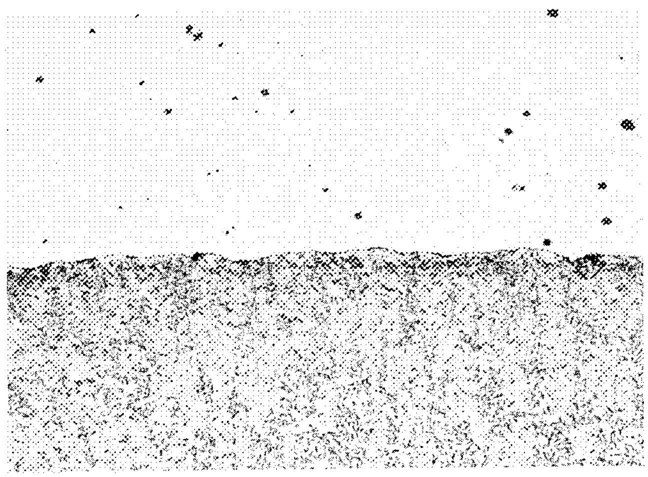
130X

(a) Transverse Section of Explosively Bonded and Drawn Tubing Showing Unbond



3X

(b) Transverse Section Showing Typical Interface Found in Explosively Bonded and Drawn Tubing



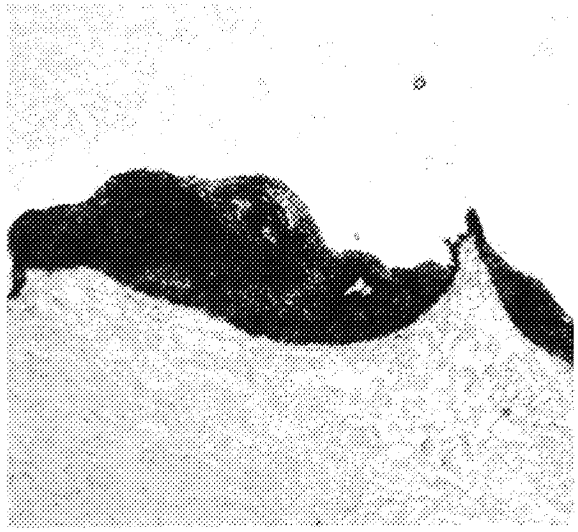
400X

(c) Transverse Section Showing Well Bonded Interface in Explosively Bonded and Drawn Tubing

FIGURE 10 – Explosively Bonded and Drawn Tubing

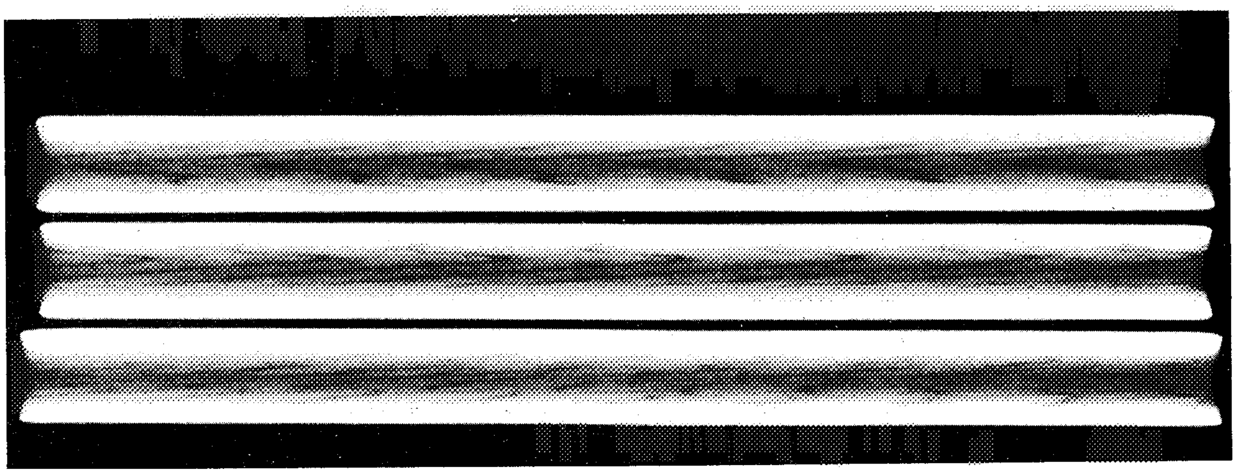
100X

(a) Transverse Section Showing Rough Interface Found Quite Frequently in Explosively Bonded & Drawn Bimetal Tubing.



400X

(b) Small Interface Void Found by Metallographic Sectioning



(c) Radiograph of Explosively Bonded and Drawn Tubing (Print-Light Areas are Thicker) Shading Fluctuations Indicate Probable Interface Irregularity.

FIGURE 11 - Explosively Bonded and Drawn Tubing

3X

Stainless steel layer was removed with concentrated HCl acid and H_2O_2. Small voids such as those shown in Figure 9c are a result of this interface and probably occur at deep grooves denoted by arrow.

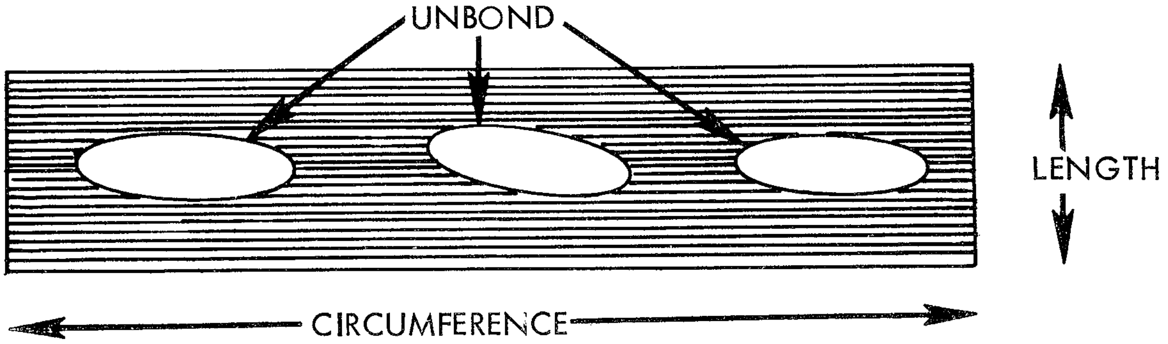
FIGURE 12 - Explosively Bonded and Drawn Bimetal Tubing Interface

It is important to note that the small voids shown in Figure 11b were not identified by ultrasonic testing. The defect shown in Figure 11b is approximately 5 mils long and about 1 mil wide. The ultrasonic crystal used for inspection is about 1/8 inch in diameter, much larger than the defect. The signal produced is an average of the interface that the crystal covers and defects smaller than 1/32 inch in diameter cannot disrupt enough of the overall signal to indicate unbonding. This type of defect could probably be identified by ultrasonic techniques involving a smaller diameter crystal and a correspondingly slower inspection speed. The smaller signal diameter may be appreciably disturbed by the rough bimetal interface however, and thus produce spurious signals or a "noisy" background. The development of an ultrasonic inspection technique for small defects would involve considerable time and expense and was beyond the scope of this study.

Explosively Bonded to Size Tubing

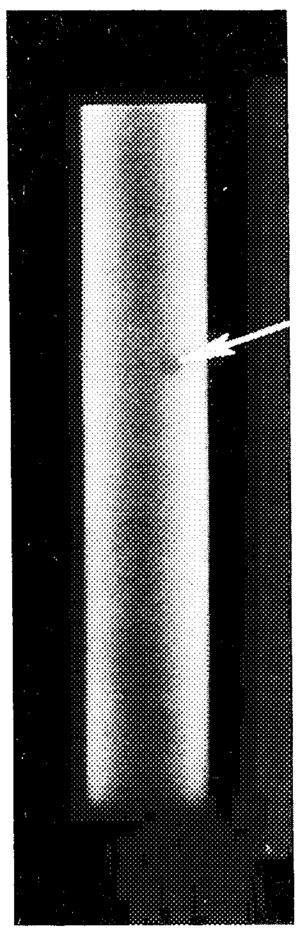
Bond Quality — The 2 feet section of tubing received was ultrasonically inspected. The tubing was well bonded except at the dimples required to stand off the Ta tube. The three dimples observed were equally spaced at 10 inch intervals along the length. At the dimple contact area, no separation is possible and defective bonding is produced.

The unbond area is described in Figure 13 which includes an ultrasonic trace and a radiograph print of series of "dimples". The unbond areas appear as a slightly thinner region on the radiograph. Figure 14c and d shows metallographic sections of a "dimple" unbond. Adequate bimetal bonding is maintained in the area adjacent to the dimples as shown in Figure 14b The bimetal interface is very smooth in explosively bonded to size tubing as is observed in Figure 15. The smooth interface is also shown in Figure 16 which shows the outer surface of the tantalum liner with the stainless steel chemically removed.



Ultrasonic Trace of Explosively Bonded Tubing

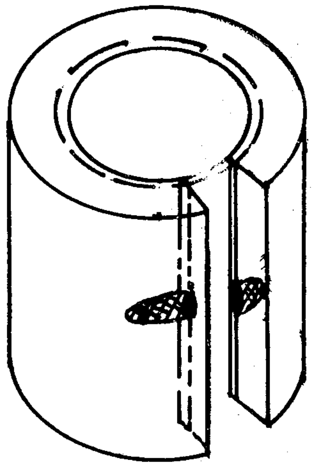
(Radiograph - Print-Light areas are thicker)



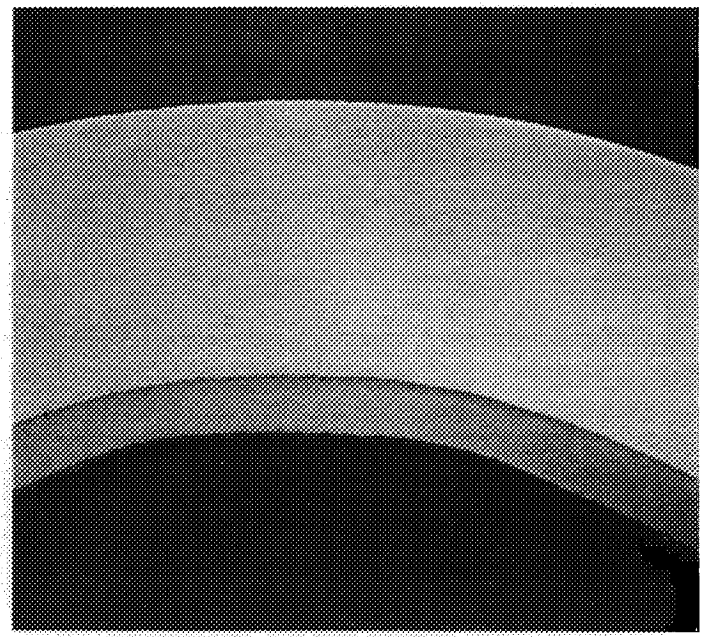
Unbond indications on ultrasonic trace. "Standoff" Dimples for explosive bonding

Radiograph of Explosively Bonded Tubing

FIGURE 13 - Ultrasonic Trace and Radiograph of Unbonded "Dimples"

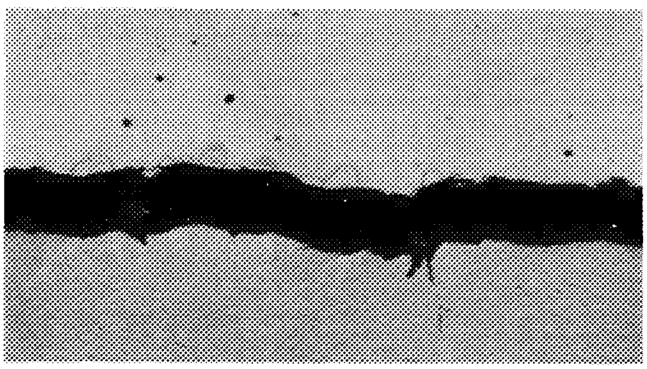


(a) Schematic of unbonding caused by dimpling in exploded to size tubing



7X

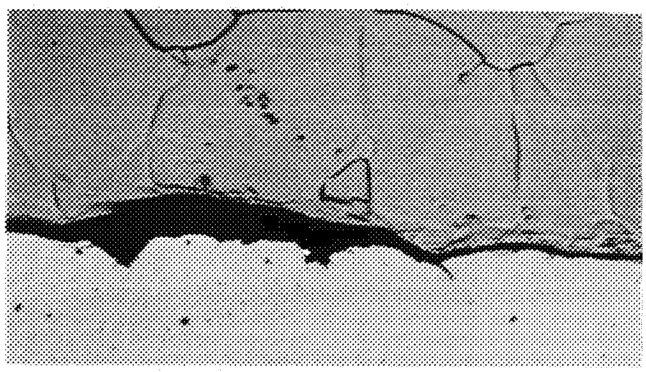
(b) Transverse section taken slightly above unbond region



100X

(c) Unbond at center of dimple width 2.5 mils

Transverse Section

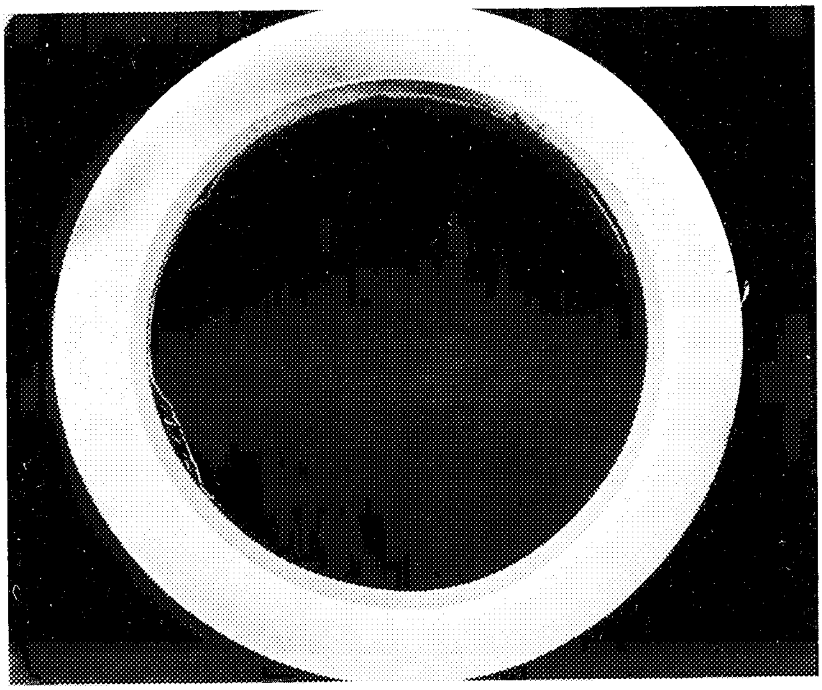


100X

(d) Unbond found at longitudinal extremity of dimple. Length 5 mils width 1 mil

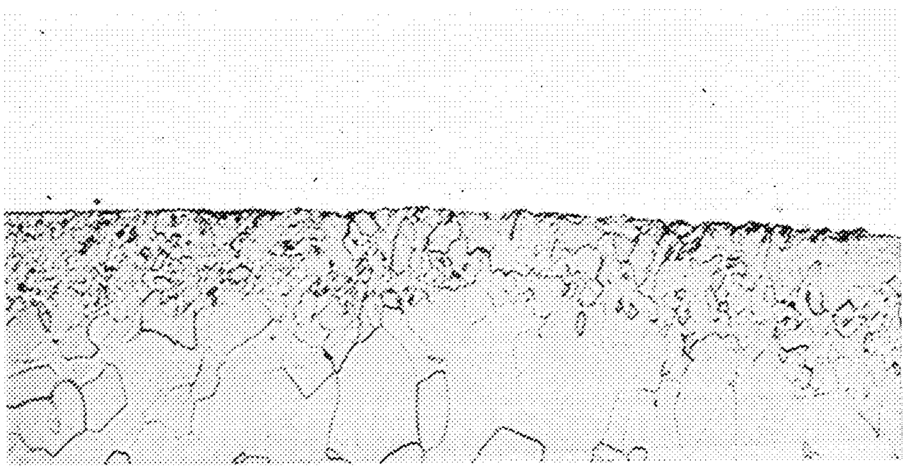
Transverse Section

FIGURE 14 - Metallographic Sections of Unbond Dimples



3-1/2X

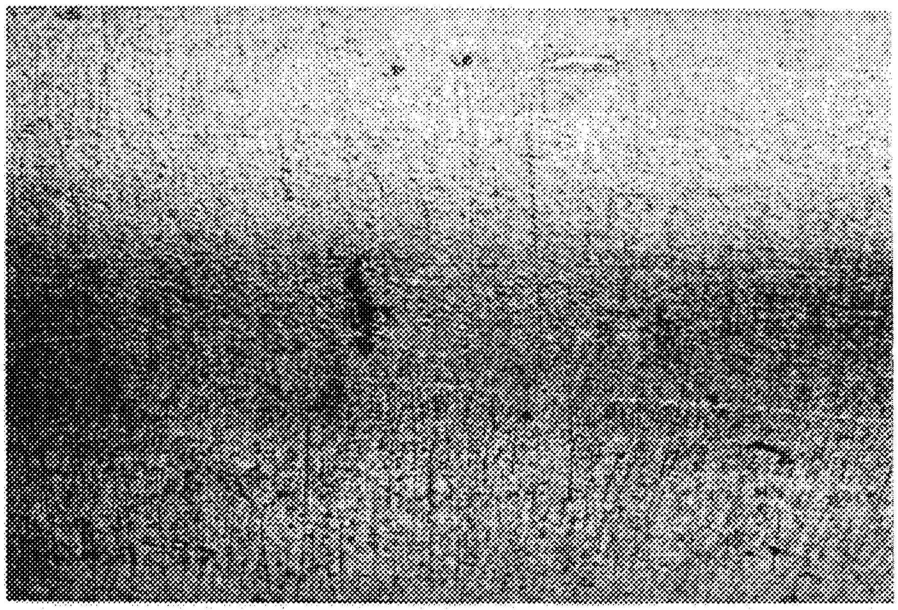
(a) Transverse section of exploded to size bimetal tubing from dimple showing uniform layer thickness and well bonded interface



100X

(b) Transverse section showing acceptable metallurgical bonding

FIGURE 15 - Good Bonding Beyond Immediate Vicinity of Dimples



3X

FIGURE 16 – Explosively Bonded to Size Tubing Bimetal Interface

IV. SUMMARY AND CONCLUSIONS

Bimetal refractory stainless steel tubing manufactured by four competing processes was evaluated in terms of dimensional properties and bimetal bond quality. Although the evaluation was limited in scope and in adequate process sampling, some general observations can be made of the state-of-the-art of bimetal tubing fabrication.

Co-extruded and Drawn Tubing

The extruded and drawn tubing was by far the best quality with no bond defects found in the entire 20 foot section either by destructive or non-destructive techniques. Considering the interface produced by this process there does not seem to be any inherent limitation to the eventual development of production quantities of bimetal tubing. Other sections of tubing from this same lot of material, however, were found in independent investigations to have appreciable unbonding, so that further development is required.

Explosively Bonded to Size Tubing

The explosively bonded to size tubing ranked second in bond quality except at the "standoff" dimples required for explosive bonding. The dimpling is inherent to the process and thus there will always be small regions of unbonding in this type of tubing. Work by Aerojet General Corporation has indicated that the "dimple" unbonding propogates under thermal cycling. Therefore the dimples may serve as nucleation sites for general unbonding at the interface.

Explosively Bonded and Drawn Tubing

The sample of explosively bonded and drawn tubing had a poor quality interface. The interface seems to be characterized by voids, crevices, and layer thickness fluctuations.

Chemically Vapor Deposited Tubing

The bimetal tubing made by chemical vapor deposition for this evaluation was apparently improperly made and was of too poor quality to be evaluated. For this reason no information was obtained on the relative quality of chemically vapor deposited tubing.

In summary, although none of the bimetal tubing evaluated was clearly indicative of high reliability tubing, sufficient promise is shown in co-extruded and drawn tubing and explosively bonded to size tubing to warrant further development. In this respect, large quantities, (300 feet) of bimetal tubing are being fabricated for a combination process-component evaluation.