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TITLE: Development and Production of Explosively Bonded 316SS/Tantalum Tubing

ABSTRACT

Explosively bonded 316SS/tantalum tubing was developed and produced to support the bimetal-tube concept for the SNAP-8 boiler. It appears that the explosive tube-bonding fabrication process can produce tubing of adequate bond quality for a 40,000 hour boiler life. The pre-existing bond quality influences the debonding tendency during simulated SNAP-8 boiler exposure.

No correlation was found between the thermal exposure sequence and the debonding of explosively bonded tubing. It appears that debonding during simulated SNAP-8 boiler exposure virtually stops after 1400-hour incubation period. The 316SS/tantalum bond is therefore sufficient to withstand the tube deformation to be encountered in boiler fabrication without adverse effects. The ratio of 316SS bonding to tantalum bonding increased as experience in explosive-bond tube fabrication progressed. However, the effects of explosive bonding on the microstructure of 316SS compromises the use of this fabrication procedure.

Simulated boiler testing indicates that the boiler no. 5 bimetal tube-butt joint is inadequate for boiler use. The preferred parameters for producing the most complete and the strongest bond between the 316SS and the tantalum are a 0.020 in. stand-off, a 7.8 grams/in.^{3} explosive density, and a one to 1/4 inch explosive thickness.

KEY WORDS: 316 stainless steel, tantalum, explosive bonding, bimetal tube butt joint

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NOTE: The information in this document is subject to revision as analysis progresses and additional data are acquired.

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I. SUMMARY

This report covers the development and production of explosively bonded 316 SS/Ta tubing, an effort initiated to support the bimetal tube concept for the SNAP-8 boiler. The following conclusions resulted from this effort.

A. Correlation of extrapolated test data and the SNAP-8 boiler operation requirements indicates the probability that the explosive tube bonding fabrication process can produce tubing of adequate bond quality for 40,000 hour boiler life.

B. During simulated SNAP-8 boiler exposure, no correlation was found between thermal exposure sequence, i.e., various combinations of continuous 1350°F exposure and continuous 250-1350°F cycling, and debonding of 316 SS/Ta explosively bonded tubing.

C. The preexisting bond quality of explosively bonded tubing influences the debonding tendency during simulated SNAP-8 boiler exposure.

D. It appears that debonding during simulated SNAP-8 boiler exposure virtually stops after an incubation period of about 1400 hours maximum.

E. The 316 SS/Ta bond is sufficient to withstand the tube deformation to be encountered in boiler fabrication without adverse effect.

F. The effects of explosive bonding on the microstructure of 316 SS compromises the use of this fabrication procedure.

G. Simulated boiler testing indicates that the Boiler #5 bimetal tube butt joint is inadequate for boiler use.

H. The percentage of 316 SS to Ta bonding achieved increased with increased experience in explosive bond tube fabrication.

I. The preferred parameters for producing the most complete and strongest bond between the 316 SS and the Ta are .020 inch stand-off, 7.8 grams/inch^3 explosive density, and 1-1/4 inch explosive thickness.

II. INTRODUCTION

SNAP-8 Boiler Development has included, in the past, Haynes 25 alloy, and 9M steel as the boiler mercury containment material. Haynes 25 exhibited excessive aging embrittlement at the boiler operating temperature, 1100-1300°F, and insufficient mercury corrosion resistance for 10,000 hours required boiler life. The 9M steel exhibited excessive decarburization of the NaK exposed surface and excessive corrosion in mercury. The need for obtaining a satisfactory boiler mercury containment material which will be exposed to both NaK and mercury led to a program for producing a bimetal containment tube with tantalum (resistant to mercury) on the inside diameter and a 300 series austenitic stainless steel (resistant to NaK) on the outside diameter. The clad protection of the tantalum was deemed necessary to protect against highly probable interstitial gas and carbon pickup by tantalum which would otherwise be exposed to the flowing NaK.

316 SS was selected as the clad material for SNAP-8 refractory bimetal boiler-tube application. 316 SS exhibits sufficient strength to carry the induced tube wall stress at the maximum boiler operating temperature, up to 1350°F, for required boiler life, at least 10,000 hours. The selection of 316 SS was also based on the apparent superior resistance of 316 SS to sigma formation compared to 321 SS and 347 SS, see Ref. 1. Sigma phase formation in austenitic stainless steels can cause loss of ductility and detrimentally affect other mechanical properties.

This program was initiated to develop a procedure for metallurgically bonding the tantalum and 316 SS using explosives and to fabricate sufficient tubing for boilers and subscale single tube tests.

III. EXPLOSIVE BONDING FABRICATION PROCEDURE

The explosive bonding fabrication sequence is outlined in Figure 1. In preparation for explosive bonding, a Ta tube is placed inside an oversize 316 SS tube, producing a uniform 0.020 inch clearance (standoff) between the Ta O.D. and the 316 SS I.D. Stand-off is maintained by dimples spaced on the Ta tube. Dimples are small spherical areas made by expanding the Ta I.D. The Ta tube is filled with a low melting point alloy to provide support against tube collapse during bonding. A layer of explosive charge is placed around the 316 SS tube O. D. and ignited from one end of the tube. The explosive force compresses the cladding tube onto the O.D. surface of the liner tube with sufficient impact velocity to effect a bond between the two, Figure 2. The dimple areas do not bond because there is no stand-off at these areas.

IV. 316 SS/Ta TUBE FABRICATION

A. PRELIMINARY EXPERIMENTS

The fabrication parameters for bonding 316 SS to Ta were originally unknown. Five experiments were conducted on short tubes (6 to 12 inch lengths) to establish process parameters. The parameters selected produced a bond resistant to severe mechanical deformation (180° bends about a radius equal to twice the bimetal wall thickness) without bond failure. A series of experiments was then performed, during the time period January - May, 1967, on bonding of tubes of various lengths. As a result of these tests, 8 feet was selected for the production of tubes for a full size SNAP-8. Subsequently, three 8-ft tube lengths were successfully explosively bonded. Ultrasonic inspection indicated these tubes were bonded 87 to 98% of the interface area. Without additional criteria for judgment it was decided that the procedure was adequate for initiation of production. Subsequent subscale and full scale boiler tests was expected to provide additional data for a review of the adequacy of these criteria at a later date.

B. PRODUCTION TUBING FOR BOILER NO. 5 AND SUBSCALE TESTS

The following lengths were fabricated during the time period June - August, 1967, using the developed production techniques.

No.	Length (ft)	Scheduled Use	
		Test Section	Test Facility
1	4	4C-9	CL-4
1	4	4E-1	CL-4
4	8	SF-1A	SSL
36	8	Blr #5	PCS-1
3	8	4E	CL-4
1	3	4E	CL-4

C. EXPERIMENTAL LONG LENGTHS

Experiments were conducted to extend the explosively bonded tube length production capability from 8 ft to 34 ft. The intent was to produce a single tube length sufficient for use in the then-current 32 ft long SNAP-8 boiler design. Joining of shorter lengths was deemed necessary for first generation boiler designs but was not considered sufficiently reliable for the ultimate, and optimum, boiler configuration. Nine tubes were bonded during the time period August 1967 - February 1968. One was 15 ft, two were 22 ft, and the remaining six were 34 ft long. The three shorter length tubes were 93 to 98% bonded. The six 34 ft long tubes were inconsistent in bond percentage indicating undetected loss of control of important processing parameters.

V. EVALUATION OF 316 SS/Ta TUBING

A. ACCEPTANCE TESTING

Acceptance of explosively bonded 316 SS/Ta tubing was based upon the degree and quality of bonding achieved. The degree of bonding was determined by ultrasonic inspection of the circumferential bond area of each tube. The bond quality was determined by mechanical bend tests of selected areas along the length of experimental tubing and from the ends of production tubing.

1. Ultrasonic Bond Inspection

Ultrasonic bond inspection employed the pulse-echo, immersion, longitudinal wave technique, Figure 3a. Data presentation (C-scan method) was a permanently recorded plan view of unbond area. The ultrasonic bond inspection technique developed was validated by metallographic examination, Figure 4. The equipment calibration test standard contained simulated unbond areas represented by three eloxed, 1/8 inch dia. holes on the Ta I.D. with depths of .010, .020, and .030 inch. Using this standard, the ultrasonic equipment was calibrated to record all defects parallel to the 316 SS/Ta interface between .010 inch and .030 inch from the Ta surface. The balance of the bimetal tube wall thickness scan was electronically obliterated. The 316 SS/Ta interface is a nominal .020 inch distance from the Ta I.D. surface. Therefore the scan depth concentrated on the bond region only. Total unbond of each tube was obtained by measuring the C-scan unbond areas with a compensating polar planimeter.

The degree of bonding for all explosively bonded lengths (4 ft or greater in length) as determined by ultrasonic inspection is shown in Figure 5. The unbond percentages included 1% of introduced dimple unbond on each tube. An indication of control of the process attainable is provided by the history of percentage of bonding determined during the production run of forty 8 ft lengths fabricated for Boiler #5 and SF-1A. The average unbond percentage decreased from 4.2% unbond in the first twenty tubes fabricated to 2.0% in the last twenty tubes fabricated, Figure 6.

2. Mechanical Bend Testing

Sections from all experimental lengths were mechanically tested by bending and flattening to qualitatively compare bend strength to ultrasound test results. Bend specimens were longitudinal tube elements that were bent around a 7/16-inch diameter pin with the Ta either in compression or tension. Flattening specimens were transverse tube elements that were flattened in a vise.

Results of mechanical bend testing were found to correlate with ultrasonic bond inspection results. Sections representing bonded areas were flattened and bent, with the Ta either in tension or compression without bond separation, Figure 7. In contrast, mechanical tests of specimens taken from unbonded, or of questionable bond, based on ultrasonic test results, failed at the 316 SS/Ta interface.

The extent of tubing deformation in the qualitative bond integrity tests greatly exceeds the tube deformation to be encountered in boiler fabrication (boiler coiled to a 30 inch diameter) without adversely affecting the 316 SS/Ta bond integrity. Therefore, the bond adherence of an explosively bonded tube should not be adversely affected by boiler fabrication procedures.

B. DIMENSIONAL ANALYSIS

Dimensional analysis of forty 8 ft 316 SS/Ta explosively bonded tubes fabricated for Boiler #5 and the SF-1A subscale test revealed I.D. variation of .018 inch maximum, Figure 8, and O.D. variation of .022 inch maximum, Figure 9.

The large tolerance range in the finished bimetal tube dimensions resulted from an accumulation of starting material tolerances plus sizing tolerances. The average finished inside diameter is .008 in. greater than the original I.D. due to sizing of the tantalum tubing during the dimpling operation and also from the expansion caused by 0.6% linear growth of the cast cerrobend support material. The bimetal O.D. is related to the before bonding tantalum O.D. since any irregularities in the tantalum O.D. were transferred to the SS surface of the bimetal tube.

The effect of accumulating starting material tolerances and sizing tolerances can be eliminated in future bimetal tube production by expanding all the tantalum material to a uniform diameter during the sizing operation. Since 0.5% of the linear growth of the cerrobend support material occurs during the first 24 hours after casting and only 0.1% occurs during the next 21 days, tube bonding between 1 and 22 days after casting will introduce a maximum diameter variation of 1 mil.

It is postulated that future bimetal tubing produced by explosive bonding at Chino can be controlled to ± .005 inch on the I.D. dimension. This tolerance must be imposed because of the 1 mil variation in Ta tube diameter due to cerrobend growth in addition to the original SS and tantalum wall thickness tolerance. Tantalum tubing of .648 in. minimum I.D. should be purchased to fabricate a bimetal tube with a $.652 \begin{smallmatrix} + .010 \\ - .000 \end{smallmatrix}$ I.D. The tantalum I.D. will expand .004 in. due to dimpling and cerrocasting.

C. THERMAL TESTING OF 316 SS TO Ta BONDING

In a bimetal boiler, the explosively bonded 316 SS/Ta tubing will be exposed to thermal cycling as a result of system startups and shutdowns. Also, during steady state operation a temperature gradient across the tube wall, as high as 100°F in the high heat flux area, will exist. Under these conditions, debonding of 316 SS/Ta tubing which would cause decreased heat transfer is possible. Initial experiments on experimental 316 SS/Ta explosively formed tubing, Table 1, showed the following thermal exposure effects:

1. Unbonding at tube ends,
2. Growth of previous areas of unbond, and
3. Unbonding at previous areas of complete bonding.

An evaluation of heat transfer requirements in the SNAP-8 system, Ref. 2, indicated that uniformly distributed debonding progressing up to 14% during the boiler life time cannot significantly affect the boiler performance in any vapor quality region. Higher debonding values can be tolerated in the film boiling and vapor superheat region. Evaluation of the debonding potential during boiler operation is necessary to establish reliability for 40,000 hour service.

Thermal cycling was performed on specimens taken from both 8 and 34 ft long, explosively bonded tubing, Ref. 3. This investigation evaluated the debonding tendency of 316 SS/Ta tube specimens under a simulated boiler operating environment of thermal exposure at 1350°F in combination with slow thermal cycling between 250 and 1350°F to determine bond reliability for extended time, 1350°F service. Six (four 15-inch long, two 17-inch long) 316 SS/Ta explosive bond specimens were prepared, Figure 10. Specimen identification and the overall bond quality of the parent tube in the as-fabricated condition is shown in Table 2. The 15 inch minimum specimen length was selected to meet two requirements. First, the test specimen length was sufficient to eliminate potential excessive stresses on the bond due to tube and effects. Stress calculations show that high thermal stresses at tube ends decrease to a constant minimum level within .25 inch from the end. Second, the explosive bond tube specimens were to contain more than one complete dimple pattern to be representative of typical tubing bond quality.

The tube specimens contained 316 SS I.D. support bushing at the tube ends, Figure 10. Bushings were an integral part of the boiler design to support the Ta, thus minimizing tube end debonding due to differential thermal expansion between the Ta liner and the 316 SS clad during thermal cycling[(1)]. One bushing in the test specimen was solid, forming an end cap. The other tube end was sealed by electron beam welding a flat 316 SS disc to the bimetal tube 316 SS clad, Figure 10. Electron beam closure welding results in a vacuum of approximately 10^{-4} torr inside the tube serving two purposes. First, the Ta

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(1) Thermal Expansion Coefficients, 75 to 1300°F are 4.0×10^{-6} and 10.6×10^{-6} in./in.-F° for Ta and 316 SS, respectively.

liner was protected against oxidation during elevated temperature exposure. Second, a simulation is produced of the vacuum conditions imposed on the Hg containment tube during boiler hot outgassing in preparation for system startup.

All thermal exposure was performed in a vacuum furnace at 10^{-5} torr for redundant (over the protection afforded by enclosing the Ta in a 316 SS capsule) tantalum liner protection against oxidation. The purpose of thermally exposing the two 17-inch specimens was to evaluate the effect of pre-existing tube bond quality on the propensity toward debonding. One 17-inch specimen (4.3% unbond) was removed from a very poorly bonded tube (60% bonded) and the other (1.6% unbond) from a tube which was very well bonded (99%).

The specimens were thermally exposed, Table 2, and periodically ultrasonic C-scan inspected for bond quality and Ta liner cracking. The last ultrasonic inspection was performed after the specimens had accumulated up to 3443 hours at 1350°F, including 56 slow and 92 fast cycles. The specimens were evaluated for cracking by the ultrasonic, pulse-echo, immersion, shear wave technique, Figure 3b, to establish the condition of the Ta liner. A permanently recorded plan view (C-scan) of defect locations was made. For ultrasonic equipment calibration, the test standard had two 1/4-inch long .005 inch deep notches eloxed on the Ta I.D. surface. One notch was parallel and the other notch was transverse to the bimetal tube axis. Ultrasonic equipment was calibrated to show all Ta I.D. defects with depths equal to or greater than .005 inches. Axial and radial shear scans were performed in two opposite directions each because of the presence of laminar 316 SS/Ta unbond (dimple areas), which prevent shear wave penetration from the 316 SS into the Ta both beneath the unbond area and on the periphery of the unbond area away from the scan direction. Scanning in two opposite directions therefore gave complete inspection of the Ta liner on the periphery of laminar unbond. No defects were detected.

The bond percentage between the Ta liner and the 316 SS clad was quantitatively determined using the ultrasonic longitudinal wave technique previously described, paragraph V.A.1 and Figure 3a. Debonding due to thermal effects is presented only as a function of exposure time, Figure 11, since there does not appear to be a correlation between thermal cycling and debonding, Ref. 3. The pre-existing quality of explosive bond tubing appears to influence the debonding tendency. A tube specimen of high bond percentage appears to possess a bond of higher strength than a tube specimen of lower bond percentage. This is illustrated by comparison of the two 17-inch specimens which were exposed to an identical test sequence, Figure 11. The D50 specimen (4.3% initial unbond) had a significantly higher debonding rate than the D40 specimen (1.6% initial unbond). This higher debonding rate of specimen D50 may be due to the presence of initial non-dimple unbond. Specimen D40 had only dimple unbond (1.6%) present before testing whereas specimen D50 had non-dimple unbond (2.9%) interspersed between regularly spaced dimple unbond (1.4%). This suggests that the unbond growth rate increases if non-dimple unbond is present. The introduction of unbond between regularly spaced dimples reduces the mean distance between defects which results in a higher average stress concentration per unbond area.

The debonding rate of each specimen, with exception of the obvious fabrication reject specimen D50, appears to decrease after an initial incubation period of varying duration up to about 1400 hours, Figure 11, indicating an approach to cessation of debonding. Extrapolation of the debonding expected at 40,000 hour exposure, Table 3, indicates that of the five specimens from apparently well-bonded tubes, the three specimens with the least amount of original unbond (0.8 to 1.6%) show a factor safety of 1.8 minimum when applied to vapor region boiler operation. The two specimens with slightly greater original unbond (2.1 and 2.3%) show an average extrapolated unbond of 14%, the maximum allowable unbond in the vapor region without significantly affecting boiler performance. It therefore appears that the explosive tube bonding fabrication process can produce tubing of adequate bond quality for 40,000 hour boiler life.

D. MICROSTRUCTURAL CHARACTERISTICS

The 316 SS/Ta interface profile varies from a wave-type to a planar configuration, Figure 12a. Waviness at the interface probably results from material build-up ahead of the fast moving collision point (10,000 ft/sec) between the 316 SS and Ta surfaces. A non-continuous, hard (67 R_c) layer of approximately .0005 inch thickness is present at the 316 SS/Ta interface. Electron beam microprobe analyses by Westinghouse, Ref. 4, showed that the interface layer is a complex intermetallic compound containing Ta, Fe, Cr and Ni.

Other than the intermetallic formation, no interdiffusion of Ta, Fe, Cr and Ni was detected. This intermetallic is formed by the melting which occurs intermittently along the wavy interface during bonding, and is apparently associated with the material build-up ahead of the collision point. Cooling of this melt layer results in occasional shrinkage voids extending across the layer transverse to the tube axis from the 316 SS to the Ta, Figure 12b. These shrinkage voids act as crack initiation areas during bending of the 316 SS/Ta tubing, Figure 13. This localized cracking does not cause bond failure, as bond integrity is maintained during bending in areas where the intermetallic layer is absent.

The hardness of both the 316 SS and Ta increased due to explosive bond fabrication, Figure 14, with the greatest hardness increases adjacent to the 316 SS/Ta interface, the region of highest absorbed energy from the explosive shock impact. Visible strain hardening of the 316 SS is apparent, Figure 15, but no visible microstructural changes are apparent in the Ta.

VI. PROCESS OPTIMIZATION STUDY

Between November 1966 and October 1967, AGC-Downey demonstrated that the Ta/316 SS explosive bonding process for producing bimetal tubing (316 SS clad over a Ta liner) in 8 ft lengths was well controlled and also demonstrated significant progress in producing tubing lengths up to 22 ft. Bimetal tubing was fabricated using the set of process variables which had been selected based upon satisfactory mechanical tests of experimental short lengths. However, satisfactory mechanical test results are not necessarily indicative that tubing quality is sufficient to withstand the SNAP-8 boiler operating conditions for up to 40,000 hour life.

In preparation for extending the explosive bonding process to the production of 34 ft lengths, a process parameter study was made, Ref. 5. The purpose of this study was to determine the optimum combination of explosive bonding process parameters for producing the most complete and strongest bond between the Ta liner and 316 SS clad.

The most important parameters in explosive bonding are the type and mass of explosive, mechanical properties of the cladding metal, and the distance through which the cladding metal is accelerated (standoff distance) before it collides with the base metal. For this study, the type of explosive and the cladding metal were not considered as variables. AGC-Downey's previous experience with explosive bonding indicated the preferred use of one type of explosive powder. The cladding metal (316 SS) as well as the base metal (Ta) were specified by SNAP-8 requirements. The mass of the explosive is related to the explosive density and also to the thickness of explosive packing. Therefore, three parameters were considered as primary in this study; explosive density, explosive thickness and standoff distance.

Evaluation of explosively bonded specimens was made by ultrasonic C-scan bond inspection, bond tensile testing, and by thermal cycle testing. A significant statistical relationship was found between the percentage of bonding and the combination of primary process parameters, explosive density and explosive thickness. The range of variables studied in the process parameter specimens had no determinable influence upon the thermal debonding resistances except in the specimen with the highest levels of both explosive thickness and density which exhibited a lower thermal debonding resistance. The bond tensile strength test data was inconclusive, and metallographic examination is required to determine if accurate data could be obtained by additional testing. But it was determined that thermal exposure test data, and not tensile test data, is required for selecting optimum parameters for explosive bonding. It is concluded that .020 inch stand-off, 7.8 grams/inch^3 explosive density, and 1-1/4 inch explosive thickness be used to obtain optimum bond properties.

VII. JOINT DEVELOPMENT

Due to the long length of the bimetal tubes required for Boiler No. 5, joints were necessary that would provide the needed physical and mechanical properties as well as the compatibility criteria for NaK exposure externally and for mercury internally. The SNAP-8 Program Office requested the Materials Technology Section, Research and Technology Department to design, fabricate and evaluate joints for the Boiler No. 5 bimetal tubes, Ref. 6.

Many combinations of welding and brazing various configurations were considered. Of these, five bimetal tube joint designs were selected for fabrication and evaluation. These are shown in Figure 16 and vary in joint preparation and joining as follows.

Joint No. 1 was designed with an EB welded Tantalum liner joint plasma arc sprayed on the O.D. of the exposed tantalum and enclosed with recessed split ring of Type 316 stainless steel EB welded to fully enclose the tantalum.

Joint No. 2 was designed similarly to Joint No. 1 except that the stainless steel split rings were brazed over the spray coating rather than EB welded and a doubler sleeve, 0.6 in. long and 0.040 in. wall thickness, was GTA welded over the brazed split rings to completely protect the braze.

Joint No. 3 design is the same as Joint No. 2 except that the plasma arc sprayed coating over the exposed tantalum was replaced with a braze alloy overlay, hereafter referred to as pre-braze.

Joint No. 4 design is a combination of EB weld of the tantalum joint, plasma arc spray of the exposed tantalum, then gas tungsten arc weld over the spray coating using 316 SS filler wire to fill the circumferential groove.

Joint No. 5 design is a combination of EB welding and brazing. The EB welded tantalum liner is coated with braze alloy (pre-braze). Recessed split rings are then brazed over the pre-braze which had been machined to be concentric. This joint is then machined again extending 0.36 inches in length further than the original brazed split ring length and to a depth sufficient to permit stainless steel backup for the final closure EB welds. Partially recessed split rings are EB welded, circumferentially and longitudinally, to complete the joint.

The joint design selected for the SNAP-8 Boiler No. 5 was joint No. 5, Figure 16. The fabrication consisted of removal of the stainless steel from the tantalum liner by machining and using an internal expanding mandrel to minimize distortion of the tantalum caused by the cutting tool pressure. Again the stainless steel was removed 0.170 in. from the ends of the tantalum liner which was machined square and the remaining stainless steel cladding on the tantalum removed by hand filing and chemically. The tube ends were fixture internally, then placed into the weld chamber, and the tantalum liner joint was welded, Figure 17. The tantalum welded butt joint was then dye penetrant inspected and X-rayed prior to applying pre-braze to the exposed tantalum at the joint. Measurements of the tantalum joint were taken prior to pre-brazing. After pre-brazing the braze was machined concentric to allow a minimum of 0.005 in. braze cladding to remain on the tantalum. Internal mandrel support was used during machining. Split rings were machined to mate with the pre-brazed machined surface. The rings were machined to allow braze flow clearance of 0.006 in. on the length and diameter. A completed brazed joint is shown in the lower view of Figure 17. After completion of the split ring braze operation the groove was cut $0.700 {}^{+.002}_{-.000}$ in. wide and $0.750 {}^{+.000}_{-.002}$ in. in diameter. Split rings were machined to mate with the groove having dimensions $0.698 {}^{+.000}_{-.002}$ in. long and $0.748 {}^{+.002}_{-.000}$ in. in diameter. The machined brazed joints were again radiographically inspected. The split rings and the tube joint areas as shown in the upper view of Figure 18 were cleaned with alcohol prior to assembling. The split rings were positioned around to tube by rotating the longitudinal joints 90 degrees from the braze split ring longitudinal joints, then GTA weld tacked. The joint was positioned in the EB weld chamber and electron beam welded. A completed EB welded joint is shown in the lower view of Figure 18. The electron beam welding sequence and schedule developed was as follows. The longitudinal joints were welded first using 14-9 K.V., 20 ma, 2.8 focus current 6 IPM for the first pass. The second pass was welded with 19.5-11.25 K.V., 28 ma, 2.8 focus current, 6 IPM. The girth welds were also made in two passes. The first pass settings were 14-9 K.V., 20 ma, 2.8 focus current, 6 IPM. The second pass settings were 20-12.5 K.V., 35 ma, 3.0 focus current at 6 IPM. Cross sections of completed joints are shown in Figure 19. The top view shows a joint with complete weld penetration. In the center view weld suck-up is present in both welds. The weld penetration is marginal in the lower view.

One bimetal tube butt joint was fabricated and then tested in the Seventh Scale Loop at San Ramon in the SF-1A boiler, Ref. 7. Both the braze alloy and the Ta electron beam weld in the joint failed. Failure of the braze layer was attributed to insufficient ductility of the braze alloy to withstand the differential thermal expansion stresses generated by the 316 SS and Ta.

The failure of the Ta electron beam weld was attributed to fabrication defects. Redesign of the butt joint is required before additional testing is performed.

VIII. TUBE WELD MECHANICAL PROPERTIES

A. INTRODUCTION

Tensile tests at 70, 500, and 1300°F were made on parent and electron beam weld Ta tubing to obtain mechanical property data for stress analysis of Boiler #5. The intent was to establish relative properties of electron beam weld Ta based on parent Ta properties. Design mechanical properties for parent Ta were selected previous to this study, Ref. 8. The electron beam weld Ta tube joint tested represented the Ta butt weld scheduled for use in Boiler #5.

B. PROCEDURE

Parent metal, unwelded Ta tensile specimens and electron beam welded[(1)] Ta tensile specimens, Figure 20, were prepared from surplus, Boiler #5 Ta tubing, .652 inch I.D. x .020 inch wall. The tensile specimens were representative of both heats of tubing used for Boiler #5 fabrication, Figure 21. The welds of the electron beam weld specimens were approximately 0.10 inch wide with an approximate 0.07 inch wide heat affected zone on each side. Weld build-up was approximately .004 inch, Figure 21, and was not removed for tensile testing, thus representing a boiler fabrication weld.

Tensile tests at 70°F were run in air. Tensile tests at 500°F and 1300°F were run in a Satec tube furnace, Figures 22 and 23. The specimens were protected against elevated temperature oxidation by continuously purging with helium[(2)]. All tests were conducted using a type C extensometer and a Tinius Olsen test machine. Autographic load-strain curves were recorded up to 0.1 percent strain for each test and were used for calculating elastic limits and 0.1 percent offset yield strengths. The testing cross-head speed was 0.02 inch per minute to the 0.1 percent yield point and 0.2 inch per minute to fracture. Elongation was calculated from the extension of 1.0 and

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(1) Weld machine: 30 KV Electron Beam
Weld schedule: 18/13 KV, 26 ma, 2 in. arc length

(2) Helium gas flow rate: 15 ft^3/hr

2.0 inch gage lengths for weld specimens and parent specimens, respectively. Reduction of area was calculated for each specimen. The original area of each weld specimen was measured with a micrometer before electron beam welding.

C. TEST RESULTS

The parent Ta mechanical properties are higher than those of the electron beam welded Ta, Table 4 and Figure 24. The curves, Figure 24, distinguish between parent and weld material from the same heat of tubing to permit relative comparison of parent and weld properties.

All weld tensile specimens failed in the Ta electron beam weld. Elongation of the welded specimens was restricted to the width of the electron beam weld (0.1 inch), whereas, the parent specimens elongated throughout the 2.0 inch gage length, Figure 25.

D. DISCUSSION

The mechanical property curves, Figure 26, show the relative efficiency of weld to parent Ta tube material. The lower strength of electron beam welded Ta over parent Ta is attributed to grain growth during welding, as coarse structures tend to have lower strengths than fine structures. When plastically strained, each grain experiences a more uniform stress system the smaller it is. Increasing the grain size increases the magnitude of the stress concentration and favors the nucleation of cracks at lower nominal stresses than are required to cause yielding of adjacent grains. The single grain thickness in the electron beam weld specimens makes a single crack catastrophic.

Offset yield strengths are not reported for the weld specimens due to non-homogeneous Ta yielding within the gage length. Offset yield strengths are based on the entire gage length, but since strain occurred only in approximately 1/10 of the gage length, higher than actual weld stress values were obtained for each plastic strain value. The "apparent" lower elongation of welded Ta over parent Ta is attributed to non-homogeneous Ta structure within the gage length. The gage lengths of weld specimens consisted of both parent and weld grain structure. Due to the lower strength of weld over parent material, plastic strain was confined to the weld area, Figure 25.

E. RECOMMENDATIONS

1. Use the mechanical property curves, Figure 26, to predict the relative efficiency of Ta tube electron beam welds.

2. In future mechanical testing of tube welds, use an extensometer gage length which spans the weld width only (0.1 inch) to allow direct comparison of weld strain to parent material strain.

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8. SNAP-8 design Manual, H-100, Section IV-3, "Properties of Structural Materials."

TABLE 1

HISTORY OF SHORT TIME THERMAL EXPOSURE OF 316 SS/Ta EXPLOSIVELY BONDED TUBING

Configuration[1]	No. of Cycles	Rate[2]	Dwell Time at 1350°F	Results
3 in. Tube	100	A-Fast	2 min.	Unbond increased from 15 to 25%
3 in. Tube	100	A-Fast	2 min.	Unbond increased from 1 to 54%
3 in. Tube	100	A-Fast	2 min.	Unbond increased from 1% to 40%
1 in. Tube	15	C-Slow	$\frac{1}{4}$ hr. min.[3] 62 hr. max.	.04 in. end debonding
3-3/4 in. Tube	26	C-Slow	$\frac{1}{4}$ hr. min.[3] 62 hr. max.	.06 in. end debonding
3 in. Tube 1 end square and 1-4° taper end	25	A-Fast	2 min.	No unbonding
3 in. Tube	100	A-Fast	2 min.	a. No unbonding at 4° taper end
1 sq. end and 1-4° taper end				b. .10 in. unbonding at sq. end
3 in. Tube	25	A-Fast	2 min.	a. No unbonding at 4° taper end
1 sq. end and 1-4° taper end				b. .06 in. unbonding at sq. end
1 ft Tube	50	D-Slow	None	a. Unbond growth at dimples
				b. 2 new unbond areas (3/4 in.^{2} total)
				c. No unbond at ends
4 ft Tube coiled into 16 in. dia. single turn coil	100	D-Slow	None	Dimple area unbond increased from 1% to 5%. No new areas of unbond.
1 ft Tube	50	D-Slow	None	a. Unbond growth at dimples and previous unbond areas.
				b. 2 new unbond areas (1/4 in.^{2} total)
				c. No unbond at ends
3 in. Tube 1 end fix	25	A-Fast	2 min.	a. Dimple unbond growth of 335%
				b. Sq. end, .01 in. unbonding

Configuration[1]	No. of Cycles	Rate[2]	Dwell Time at 1350°F	Results
3 in. Tube 1 end fix	1	D-Slow	25 hrs	a. Dimple unbond growth of 600% b. Sq. end, .25 in. unbonding
3 in. Tube 1 end fix	25	B-Fast	2 min.	a. Unbond growth of 645% b. Sq. end, .12 in. unbonding
3 in. Tube 1 end fix	1	D-Slow	5 hr	a. Dimple unbond growth of 82% b. Sq. end, .01 in. unbonding
3 in. Tube 1 end fix	1	D-Slow	100 hr	a. Unbond growth of 525% b. Sq. end, .25 in. unbonding
3 in. Tube 1 end fix	25	D-Slow	5 hr	a. Dimple unbond growth of 940% b. Sq. end, .015 in. unbonding

(1) Where not indicated, ends of tube were cut square in perpendicular plane to tube axis. Degree of taper refers to included angle of Ta end at 316 SS interface. End fix denotes use of prototype pressed bushing inside Ta liner at end of tube specimen.

(2) Definition of cycle rate:

Heating rate: 200 to 1350°F
1-4 min.
B-8 min.
C-12 min.
D-15 min.

Cooling rate: Fast - 1350 to 200°F in 4 to 12 min.
Slow - 1350 to 200°F in $2\frac{1}{2}$ hrs.

(3) Specimens cycled by on-off hand switch control of furnace time of 1350°F dwell depended on convenience of task engineer going to furnace and throwing switch.

SPECIMEN				EXPOSURE PERIOD	HOURS AT 1350°F PER EXPOSURE PERIOD	NO. OF CYCLES PER EXPOSURE PERIOD *	PERCENT UNBOND (1)
IDENT.	LENGTH (IN.)	PARENT TUBE HISTORY S/N	PARENT TUBE HISTORY TOTAL BOND, %				
GG	15	D52	85	PRE-TEST 1 2 3 4 5 6	— 95 125 100 663 1034 1026	— 1(a) 25(b) 1(a) 51(d) 6(e) 2(f)	1.1 2.0 3.4 3.9 5.4 5.8 6.1
QQ	15	D52	85	PRE-TEST 1 2 3 4 5 6	— 95 125 100 663 1034 1026	— 1 (a) 25 (b) 1 (a) 51 (d) 6 (e) 2 (f)	0.8 1.1 1.6 2.1 2.3 2.4 2.7
FF	15	D52	85	PRE-TEST 1 2 3 4 5 6	— 125 95 125 663 1034 1026	— 25 (b) 1 (a) 25 (b) 51 (d) 6 (e) 2 (f)	2.3 6.7 — 9.3 12.0 12.1 12.5
HH	15	D52	85	PRE-TEST 1 2 3 4 5 6	— 125 95 125 663 1034 1026	— 25 (b) 1 (a) 25 (b) 51 (d) 6 (e) 2 (f)	2.1 5.8 — 11.0 12.8 13.0 13.5
D50	17	D50	60	PRE-TEST 1 2 3 4 5 6 7 8 9	— 50 50 155 240 125 100 663 1034 1026	— 1 a 1 a 31 b 30 c 25 b 1 a 51 d 6 e 2 f	4.3 13.2 16.1 18.5 — 25.0 26.9 30.9 32.7 33.1
D40	17	D40	99	PRE-TEST 1 2 3 4 5 6 7 8 9	— 50 50 155 240 125 100 663 1034 1026	— 1 (a) 1 (a) 31 (b) 30 (c) 25 (b) 1 (a) 51 (d) 6 (e) 2 (f)	1.6 1.9 2.2 2.4 — 3.4 3.5 4.4 4.5 4.5

* CYCLE DESCRIPTION: LEGEND

	CYCLE TIME (HRS.)		
	250 TO 1350°F	1350°F DWELL	1350 TO 250°F
a	1/2	AS NOTED	2 1/2
b	1/2	5/CYCLE	2 1/2
c	1/2	5 FOR 29 CYCLES, 95 FOR 1 CYCLE	2 1/2
d	4 1/2	13/CYCLE	6 1/2
e, 1 2 3 4 5 6	7 1 1/2 7 7 3 1/2 4	53 1/2 8 164 58 1/2 314 436	8 13 ↕ 13
f	7	380 1/2/1 CYCLE, 645 1/2/1 CYCLE	12

(1) PERCENT UNBOND DETERMINED FROM ULTRASONIC C-SCAN INSPECTION.

HISTORY OF EXTENDED TIME THERMAL EXPOSURE OF 316SS/Ta EXPLOSIVELY BONDED TUBING

TABLE 2

TABLE 3

EXTRAPOLATION TO 4×10^4 HRS OF DEBONDING RATE AT 1350°F OF EXPLOSIVE BONDED TUBE SPECIMENS

Specimen[1]	Pre-Exposure Debond	Debond at End of Incubation Period[2]		Extrapolated Debond Percentage after 4×10^4 Hrs
	(%)	No. Hrs	%	
HH	2.1	450	12.3	15.0
FF	2.3	1000	12.0	13.0
GG	1.1	1000	5.4	7.8
D-40	1.6	1400	4.4	4.7
QQ	0.8	310	2.0	3.0

(1) See Figure 11 for specimen identification correlation

(2) From Figure 11

TANTALUM CONDITION	ASTM GRAIN SIZE NO. (b)	MATERIAL SOURCE (c)	TEST TEMP, °F	TENSILE STRENGTH, KSI	YIELD STRENGTH, KSI		ELONGATION, % (d)	AREA REDUCTION, %
					ELASTIC LIMIT	0.1% OFFSET		
UNWELDED, 100% RE-CRYSTALLIZED STRUCTURE	5	FANSTEEL	70	43.4	17.8	27.2	50.0	43
	7	KAWECKI	70	43.9	(e)	(e)	57.5	52
	5	FANSTEEL	500	39.1	12.5	14.9	(g)	31
	7	KAWECKI	500	42.3	13.4	16.4	(g)	50
	7	KAWECKI	500	42.4	(f)	(f)	(g)	38
	5	FANSTEEL	1300	19.3	3.9	4.8	54.5	42
	7	KAWECKI	1300	22.6	6.0	8.3	—	60
ELECTRON BEAM WELDED	00 (5)	FANSTEEL	70	30.5	(f)	–	14.0	33
	00 (5)	↑	70	28.6	13.1	–	12.0	29
	00 (5)		500	28.9	(f)	–	9.0	26
	00 (5)	↓	500	30.4	8.0	–	10.0	24
	00 (5)	FANSTEEL	500	29.3	(f)	–	10.0	24
	0 (7)	KAWECKI	1300	20.1	4.8	–	18.0	26
	0 (7)	KAWECKI	1300	21.2	4.8	–	26.0	26

NOTES:

a. .652 INCH I.D. X .020 INCH WALL.

b. NUMBER IN PARENTHESIS INDICATES PARENT GRAIN SIZE.

c. TUBE PRODUCT ANALYSIS (ppm)

	O	N	H	C
FANSTEEL, G.S. NO. 5	90	<50	5	250
KAWECKI, G.S. NO. 7	130	<50	5	26
KAWECKI, G.S. NO. 0	50	–	–	–

d. 1.0 AND 2.0 INCH GAGE LENGTHS FOR WELDED AND UNWELDED SPECIMENS, RESPECTIVELY.

e. PRE-LOADED BEYOND YIELD POINT.

f. EXTENSOMETER MALFUNCTION

g. FAILED OUTSIDE GAGE MARKS

MECHANICAL PROPERTIES OF UNWELDED AND ELECTRON BEAM WELDED TANTALUM TUBING

TABLE 4

NOTES:

(1) Dimpling (introducing shallow, spherical, raised areas of less than 1/4 inch dia. on the Ta tube O.D.) was accomplished by internal hydraulic pressurization of the Ta tube causing selected, localized, .020 inch expansion of the Ta wall into a die cavity. Four dimples were formed with each dimpling operation to constitute one dimple pattern. The four dimples in each pattern are circumferentially distributed over a five inch length. The pattern is repetitive through the full tube length.

(2) Ta tube was held vertically in a casting tower to fill I.D. with liquid Cerrobend Alloy (50% Bi, 26.7% Pb, 13.3% Sn, 10% Cd). Casting temperatures were monitored (thermocouples were spaced each six inches along tube length with temperature read-out on a multi-point recorder). Freezing rate was controlled by varying water flow in the cooling jacket of the casting tower. Solidification temperature of Cerrobend is 158°F.

(3) X-ray exposure was 60 sec. at 100 KV. Voids in the Cerrobend greater than 0.010 inch were rejected. Void-free condition of cerrobend required to prevent I.D. collapse during explosive bonding.

(4) Press-straightened to .005 inch/ft. TIR.

(5) Sanded and chemically etched.

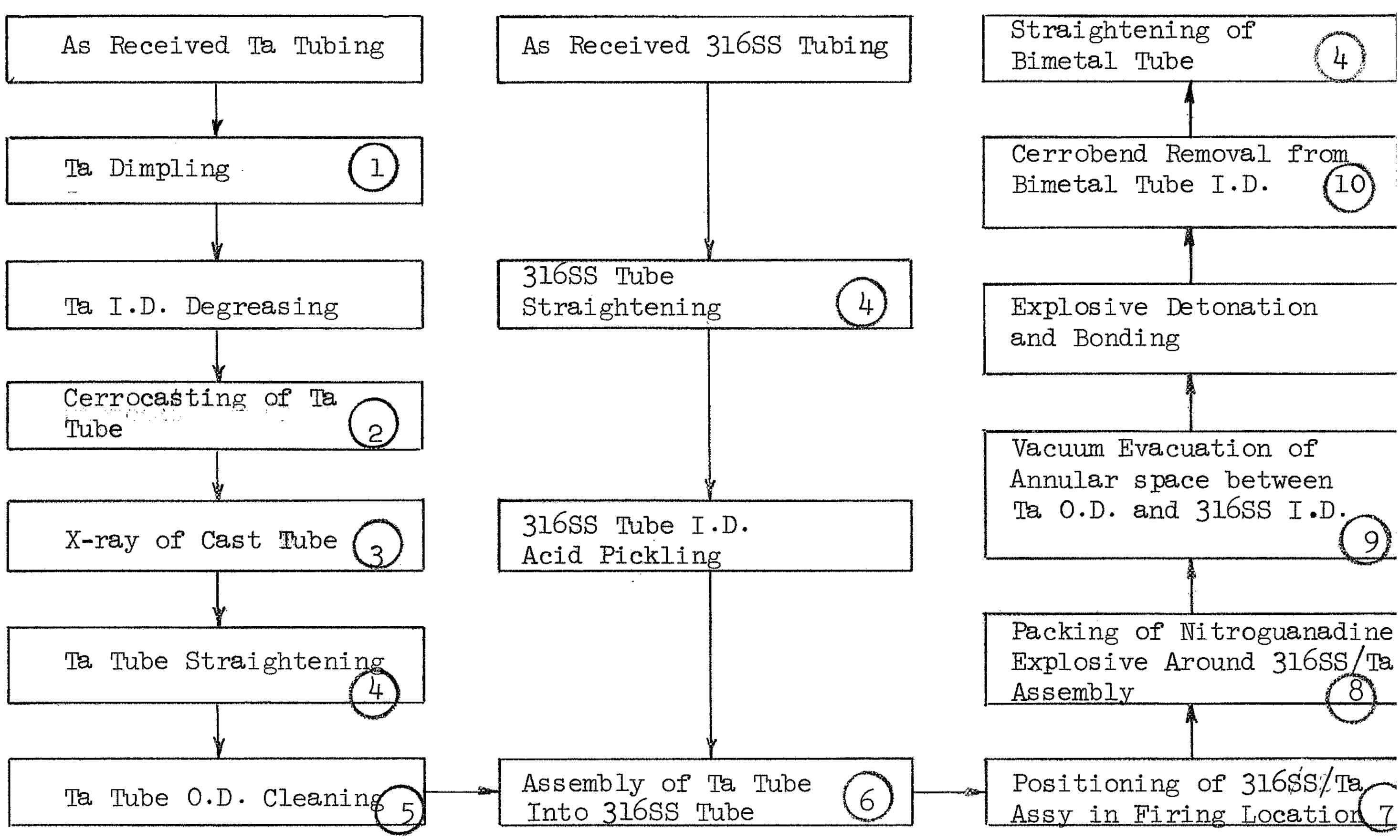
(6) Vertical assembly performed by lowering the Ta tube into the 316SS tube with dimples centrally locating the Ta tube. The annular space between the Ta O.D. and the 316SS I.D. was sealed at the tube ends using threaded fittings.

(7) 316SS/Ta assembly positioned vertically in the center of a 3 1/2 inch dia. cardboard tube inside an empty oil drum assembly inside either a firing tank or a drilled earth hole.

(8) Nitroguanadine powder explosive was packed to a 7 gram per cubic inch density around the 316SS/Ta assembly inside of the cardboard tube.

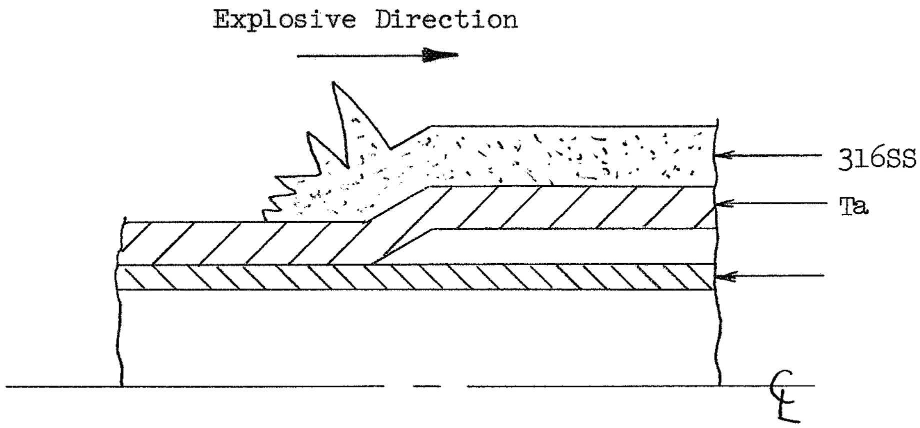
(9) Annular space evacuated to 29 in. of Hg pressure 1 hour prior to and during explosive bonding.

(10) Tube heated with hot water (>158°F) to melt cerrobend.

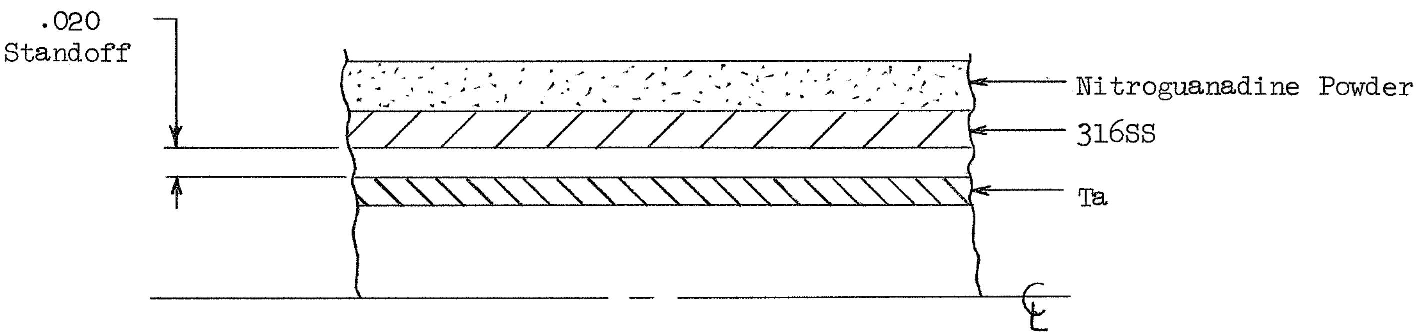


FABRICATION PROCEDURE FOR EXPLOSIVELY BONDED 316SS/Ta TUBING

Figure 1



b. Explosive Bonding



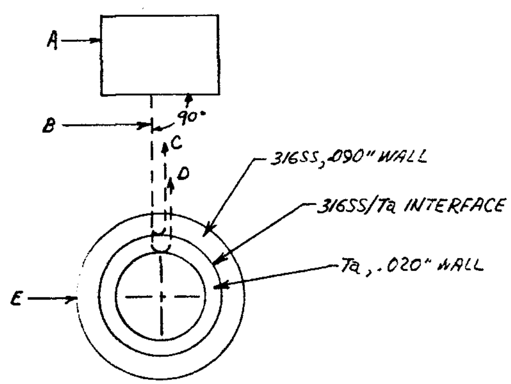
a. Pre-Detonation Assembly

EXPLOSIVE BONDING OF 316SS TO TANTALUM

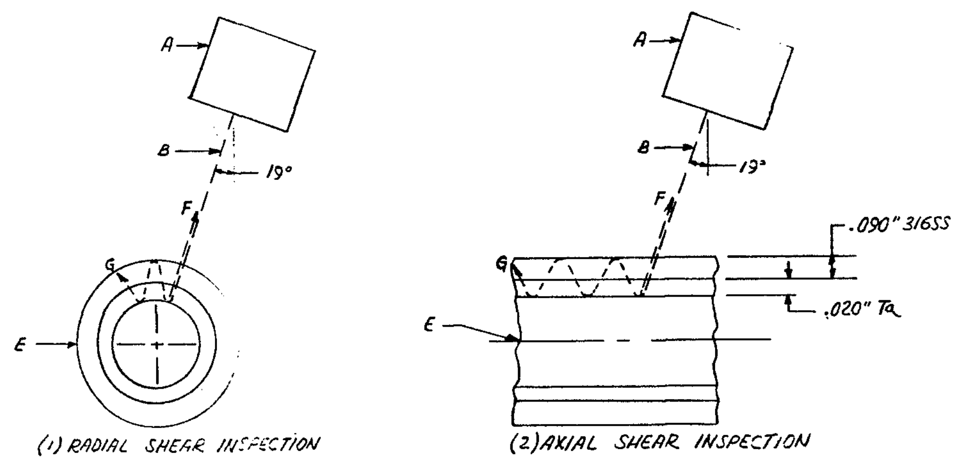
Figure 2

LEGEND

A. ULTRASONIC SEARCH UNIT (MOVEMENT PARALLEL TO TUBE AXIS) SENDS AND RECEIVES SOUND ENERGY.
B. PULSE-ECHO SOUND ENERGY IN WATER MEDIUM.
C. PATH OF REFLECTED SOUND BEAM WHEN 316SS/Ta UNBOND EXISTS, INDICATED AS UNBOND ON C-SCAN RECORDING.
D. PATH OF REFLECTED SOUND BEAM WHEN 316SS/Ta BONDING EXISTS.
E. 316SS/Ta TUBE ROTATED 4 DEGREES AFTER EACH SCAN OF THE SEARCH UNIT
F. PATH OF REFLECTED SOUND BEAM IF CRACK DEFECT EXISTS, INDICATED AS DEFECT AREA ON C-SCAN RECORDING.
G. PATH OF REFLECTED SOUND BEAM IF I.D. IS DEFECT FREE, SOUND CONTINUES IN SHEAR THROUGH TUBE WALL.



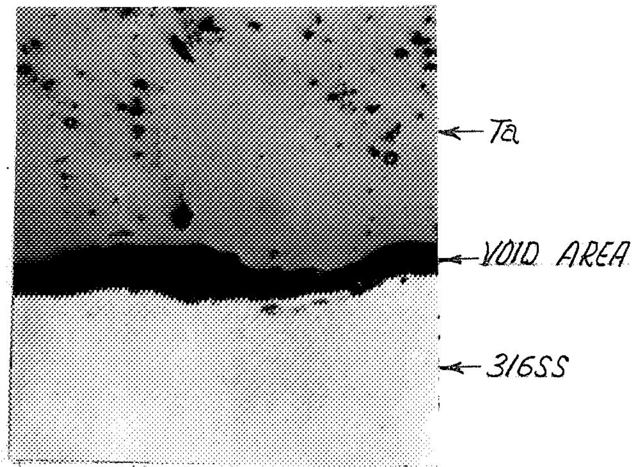
a. Ultrasonic Technique Used for Bond Inspection



b. Ultrasonic Technique Used for Ta Liner Inspection

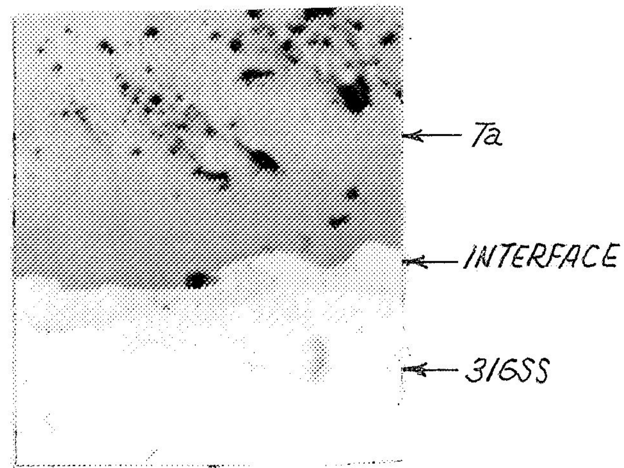
ULTRASONIC INSPECTION OF 316SS/Ta EXPLOSIVELY BONDED TUBING

Figure 3



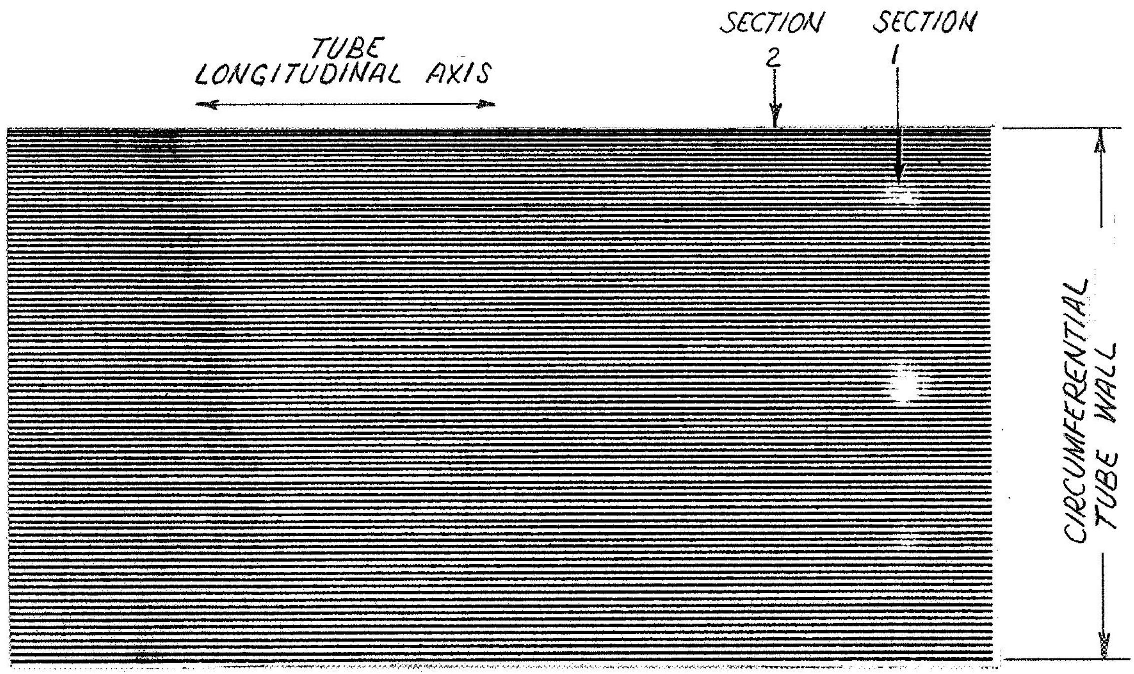
L-425 UNETCHED 1000X

b. UNBONDED AREA CORRESPONDING TO LIGHT AREA IN SECTION 1 BELOW



L-424 UNETCHED 1000X

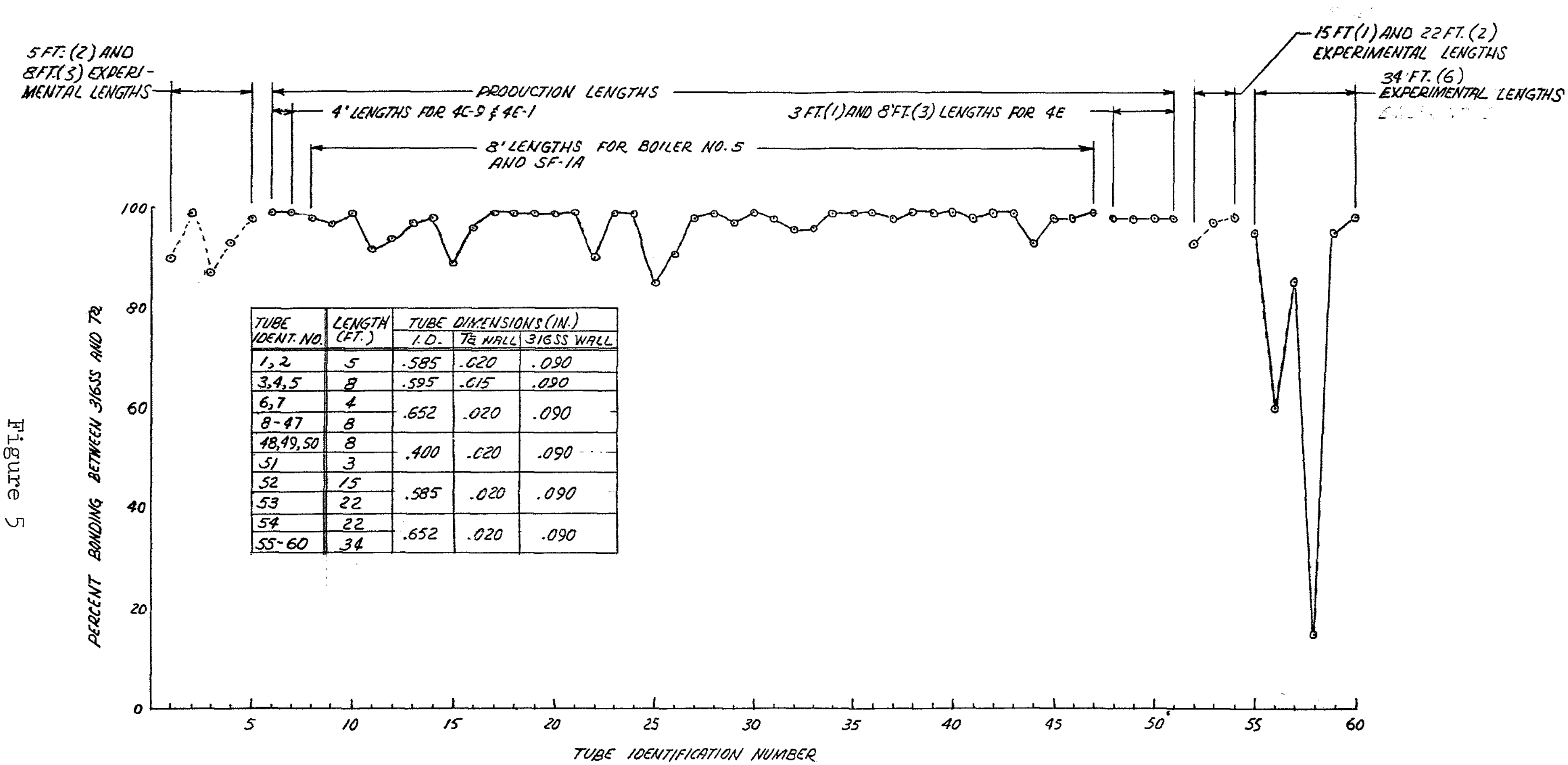
c. BONDED AREA CORRESPONDING TO SECTION 2 BELOW



a. ULTRASONIC "C" SCAN RECORDING OF EXPLOSIVELY BONDED 316SS/Ta TUBING SHOWING BOND (DARK) AND UNBOND (LIGHT) AREAS

VALIDATION BY METALLOGRAPHIC EXAMINATION OF ULTRASONIC "C" SCAN BOND RECORDINGS OF EXPLOSIVELY BONDED 316SS/Ta TUBING

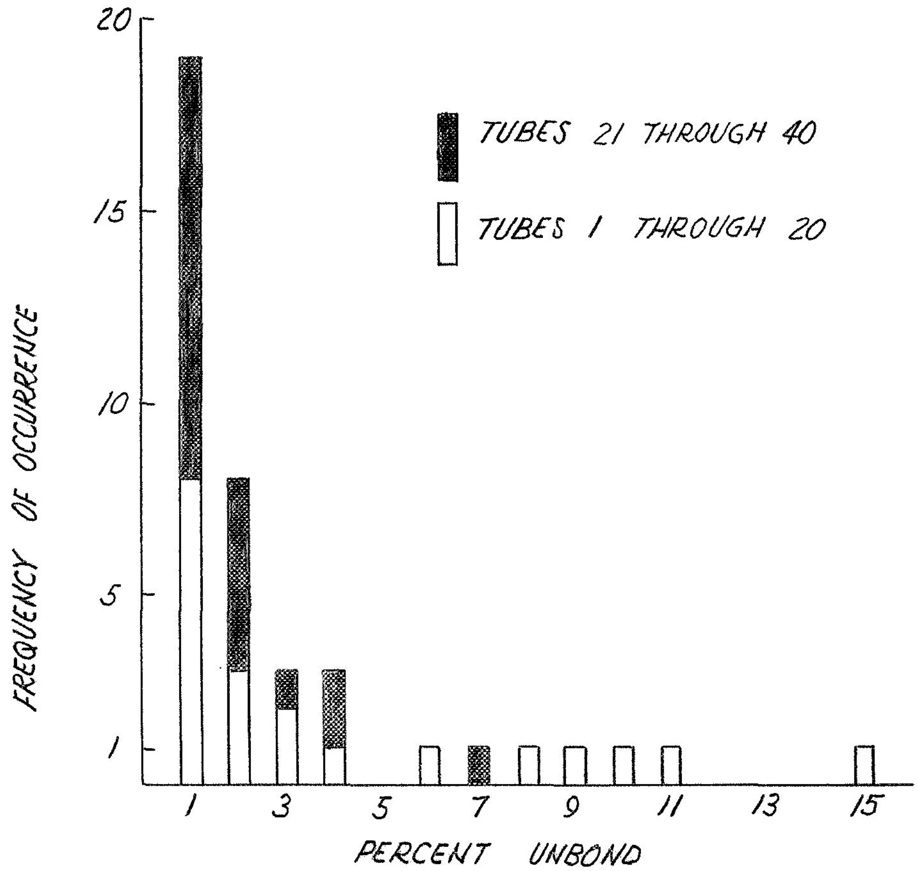
FIGURE 4



TUBE IDENT. NO.	LENGTH (FT.)	TUBE DIMENSIONS (IN.) I.D.	Ta WALL	316SS WALL
1, 2	5	.585	.020	.090
3, 4, 5	8	.595	.015	.090
6, 7	4	.652	.020	.090
8-47	8			
48, 49, 50	8	.400	.020	.090
51	3			
52	15	.585	.020	.090
53	22			
54	22	.652	.020	.090
55-60	34			

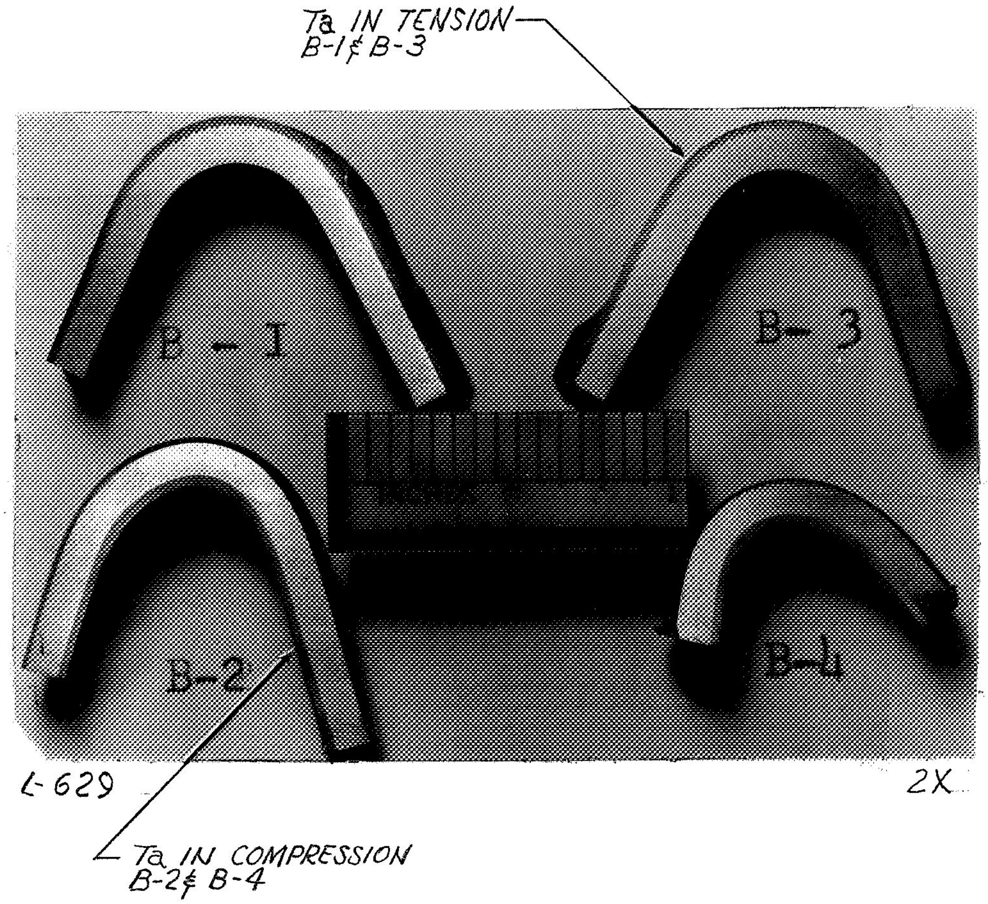
BONDING OF 316SS/Ta BIMETAL TUBING

Figure 5



ULTRASONIC INSPECTION RESULTS OF FORTY 8FT. 316SS/Ta EXPLOSIVELY BONDED TUBES

FIGURE 6



MECHANICAL DEFORMATION SPECIMENS FROM EXPLOSIVELY BONDED 316SS/Ta TUBING

FIGURE 7

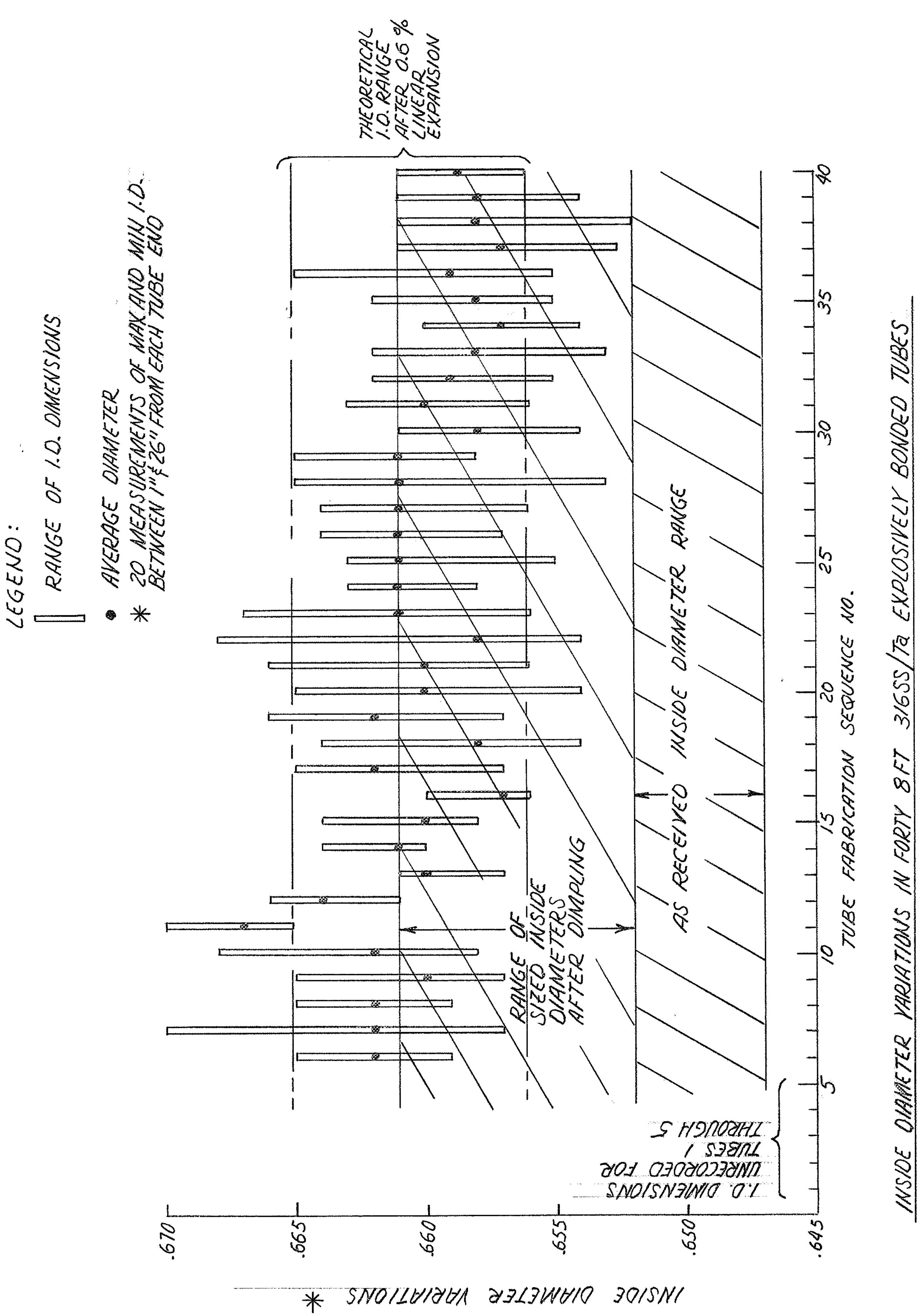

LEGEND:
RANGE OF I.D. DIMENSIONS
AVERAGE DIAMETER
20 MEASUREMENTS OF MAX AND MIN I.D. BETWEEN 1" & 26" FROM EACH TUBE END
THEORETICAL I.D. RANGE AFTER 0.6 % LINEAR EXPANSION
RANGE OF SIZED INSIDE DIAMETERS AFTER DIMPLING
AS RECEIVED INSIDE DIAMETER RANGE
I.D. DIMENSIONS UNRECORDED FOR TUBES 1 THROUGH 5
.670
.665
.660
.655
.650
.645
5
10
15
20
25
30
35
40
TUBE FABRICATION SEQUENCE NO.
INSIDE DIAMETER VARIATIONS *
INSIDE DIAMETER VARIATIONS IN FORTY 8 FT 316SS/Ta EXPLOSIVELY BONDED TUBES

Figure 8

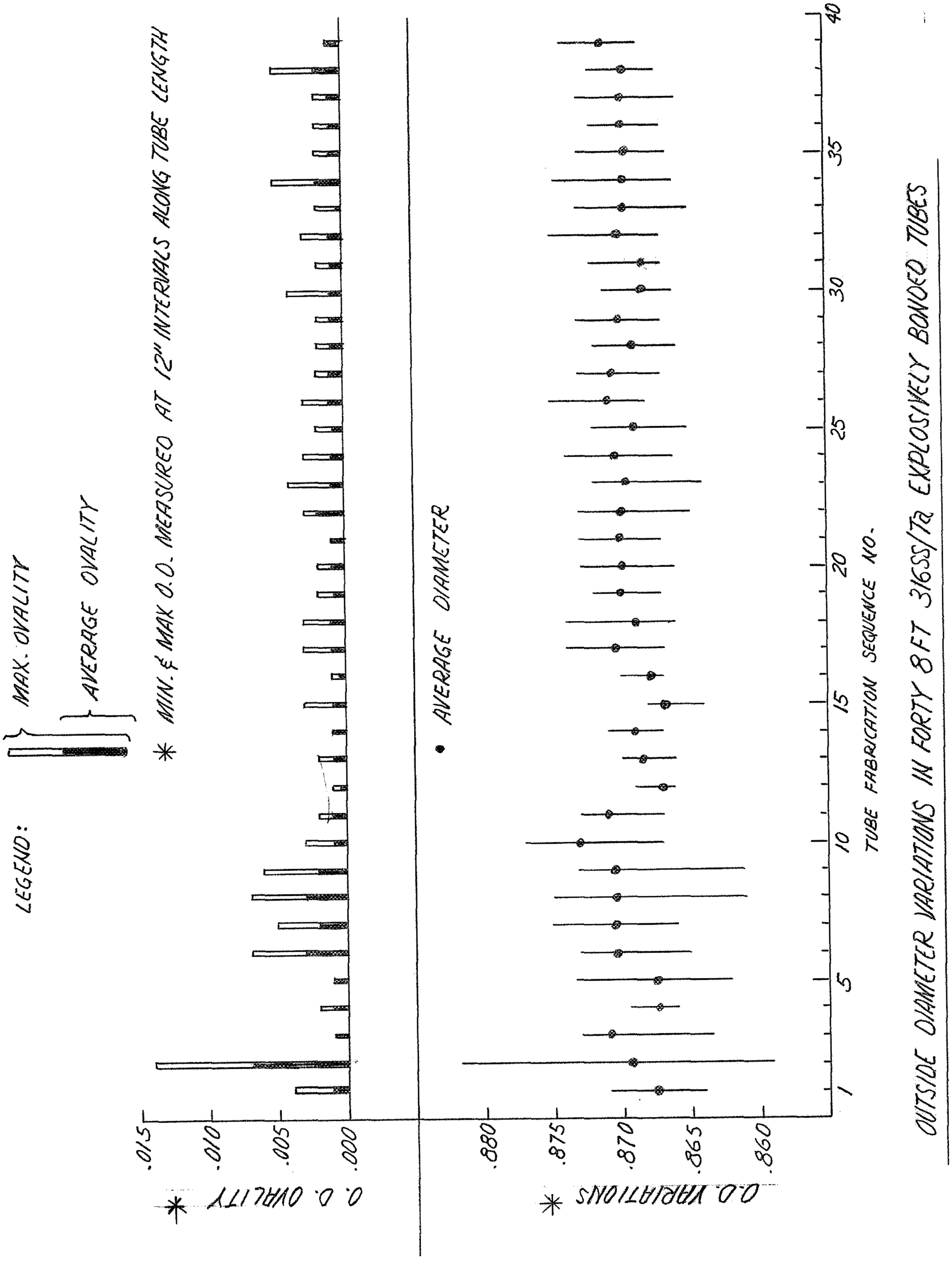
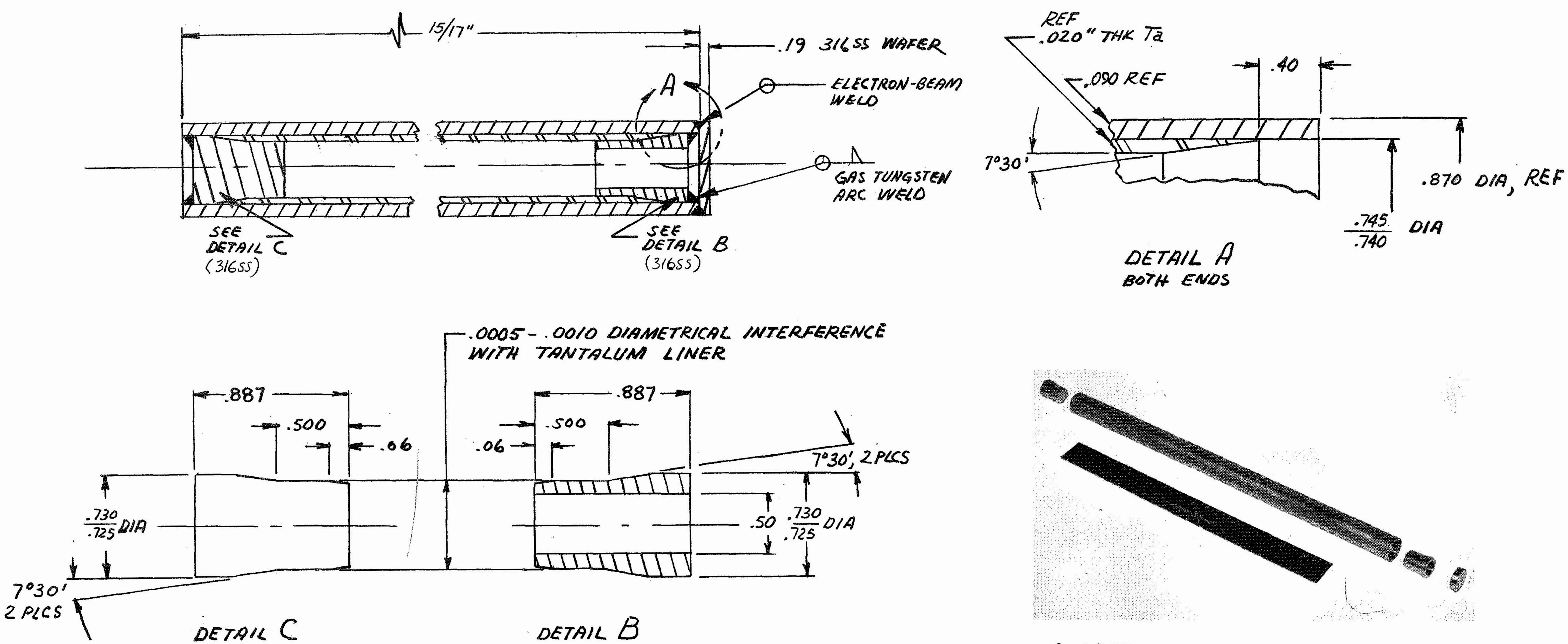


Figure 9

Figure 9



L468 575

316SS/Ta EXPLOSIVELY BONDED TUBE THERMAL EXPOSURE SPECIMEN

FIGURE 10

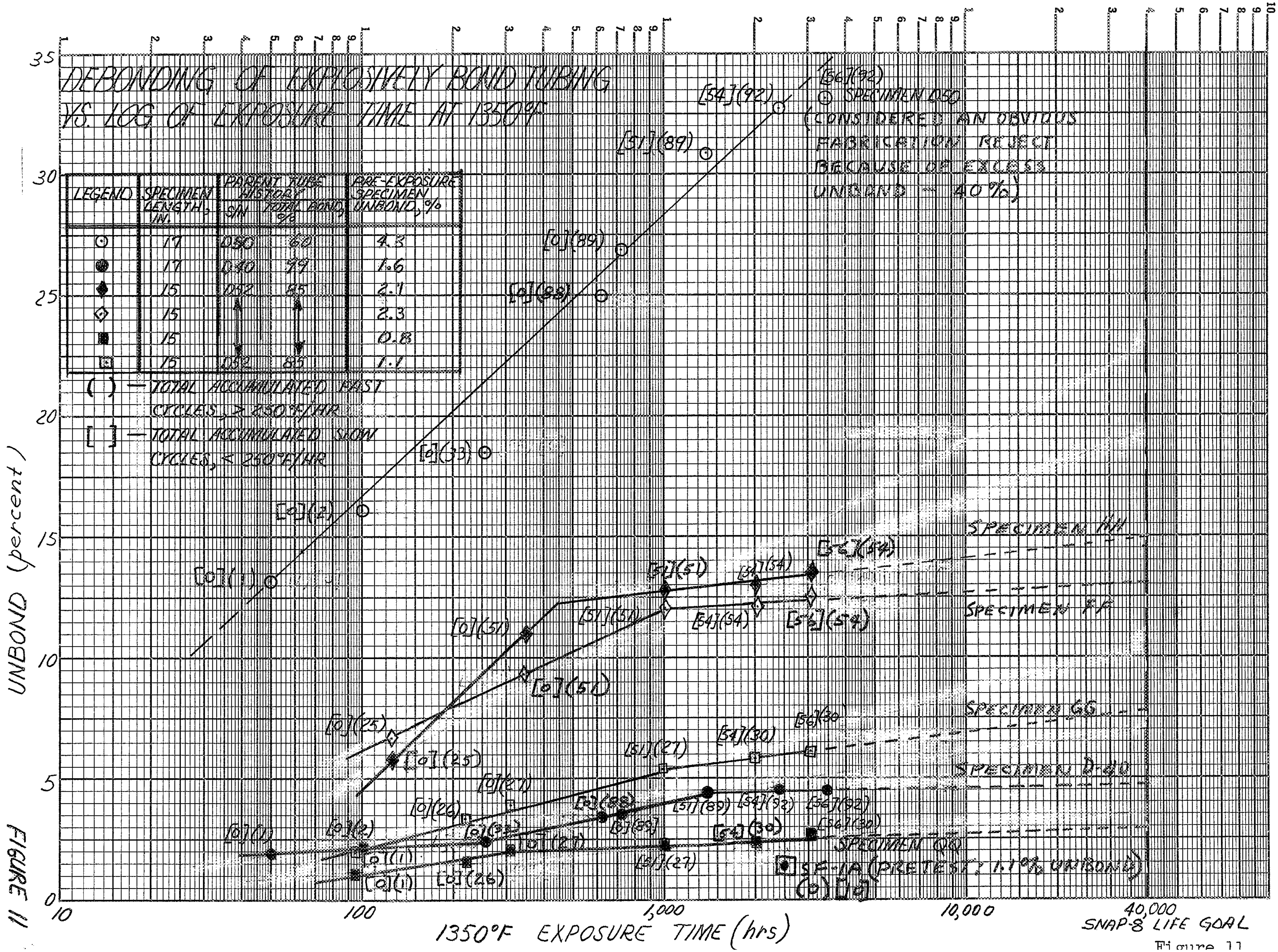
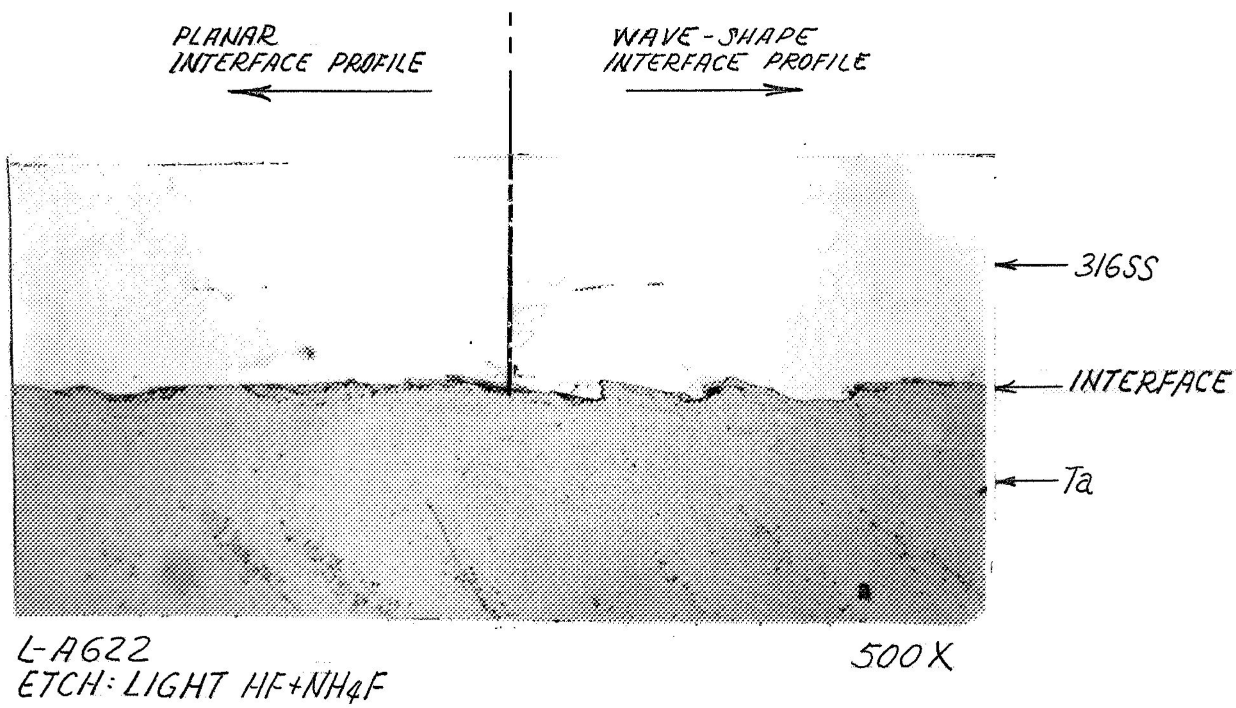
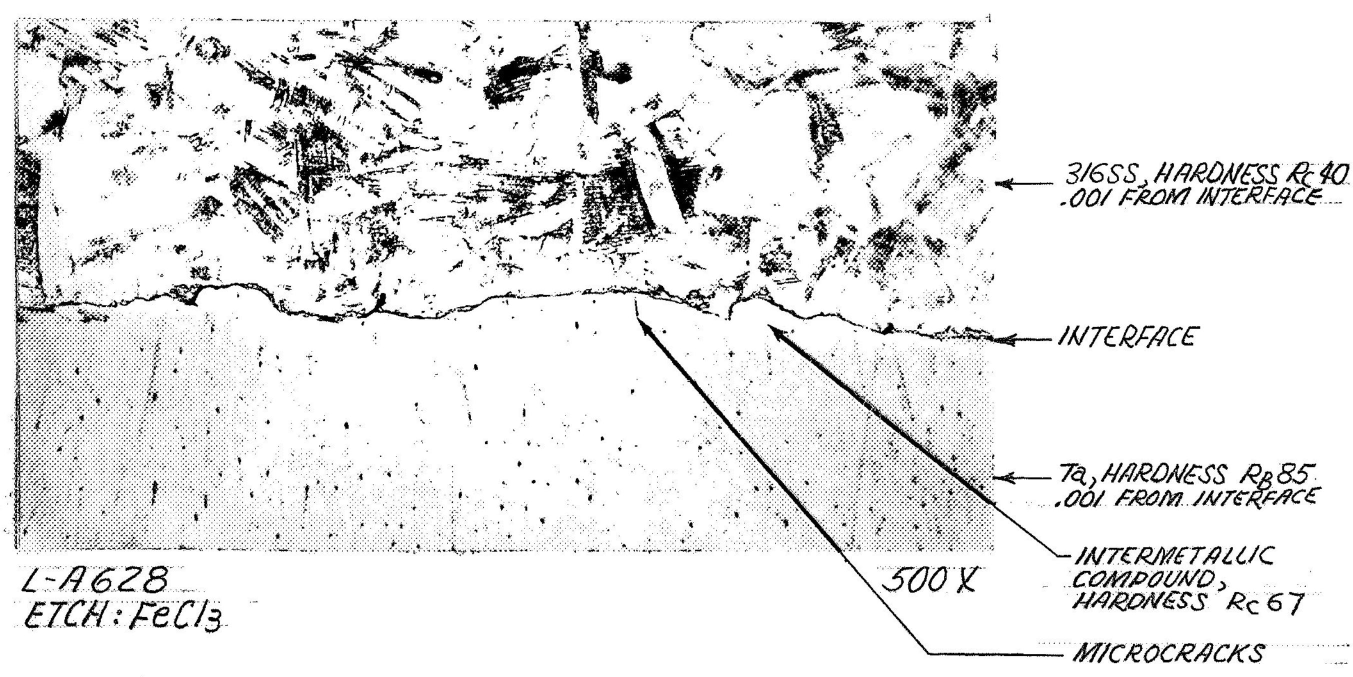


FIGURE 11

Figure 11



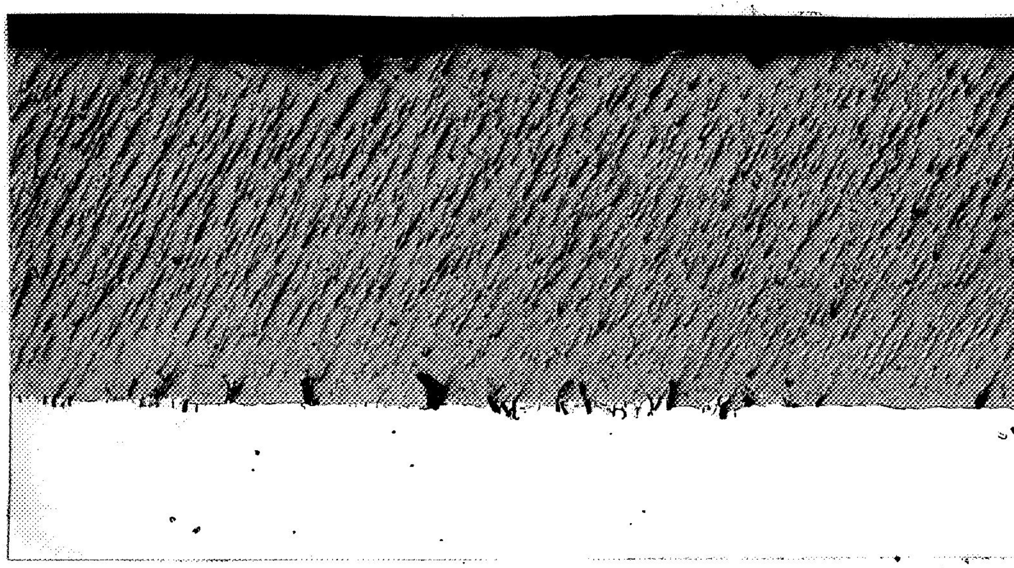
a. BOND LINE PROFILES



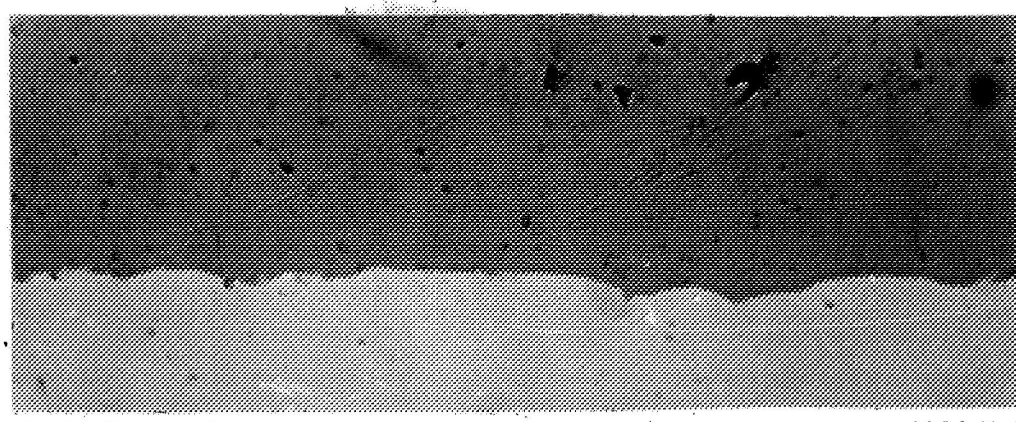
b. INTERMETALLIC COMPOUND AT BOND LINE

BOND INTERFACE BETWEEN 316SS AND Ta IN EXPLOSIVELY BONDED TUBING

FIGURE 12



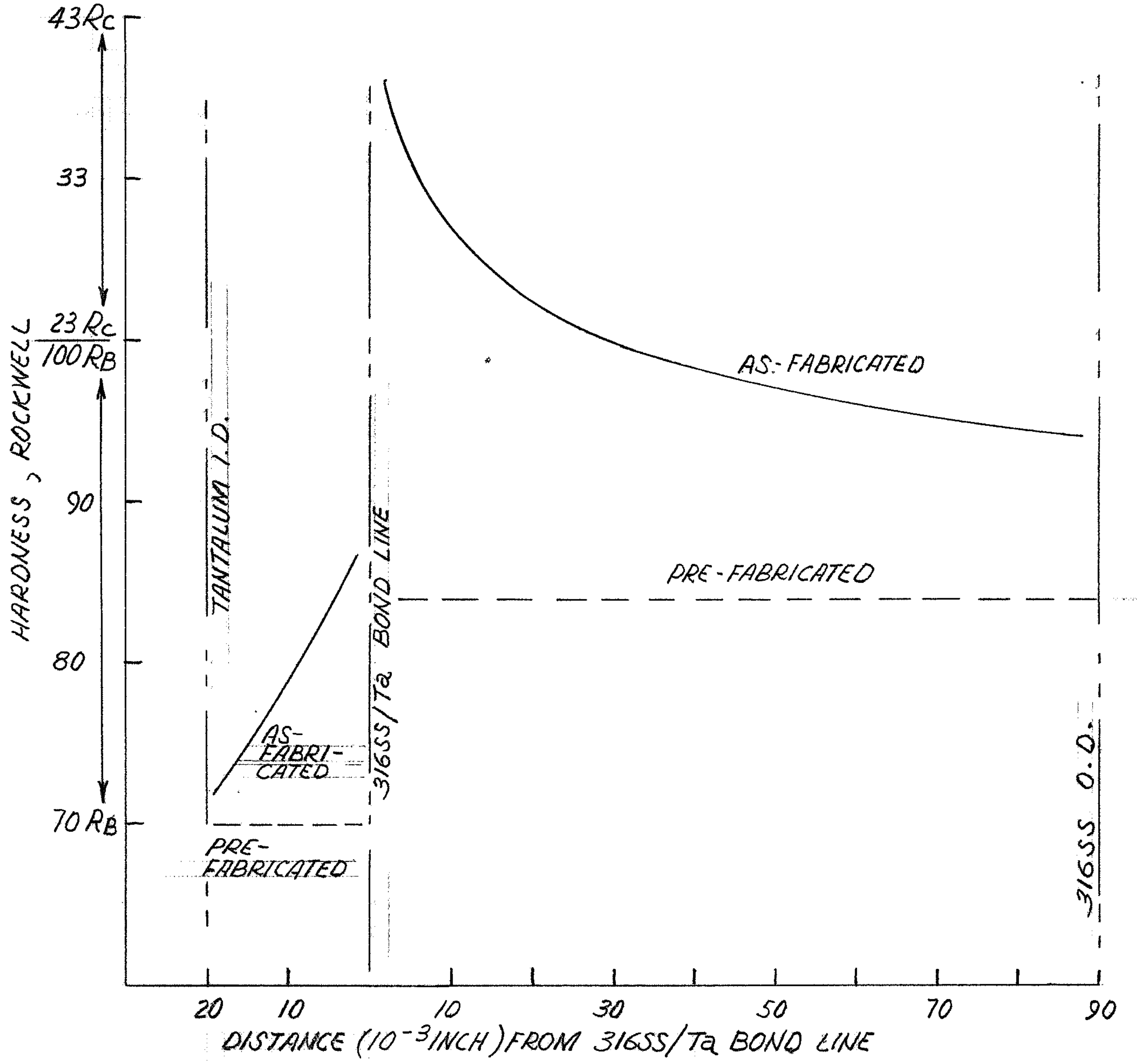
a. LOCALIZED BRITTLE FAILURE INITIATED AT SHRINKAGE MICROCRACKS IN THE INTERMETALLIC REGION



b. BOND INTEGRITY MAINTAINED AT INTERMETALLIC-FREE INTERFACE REGION DURING FLATTENING TEST

MICROSTRUCTURE OF 316SS/Ta INTERFACE AFTER FLATTENING

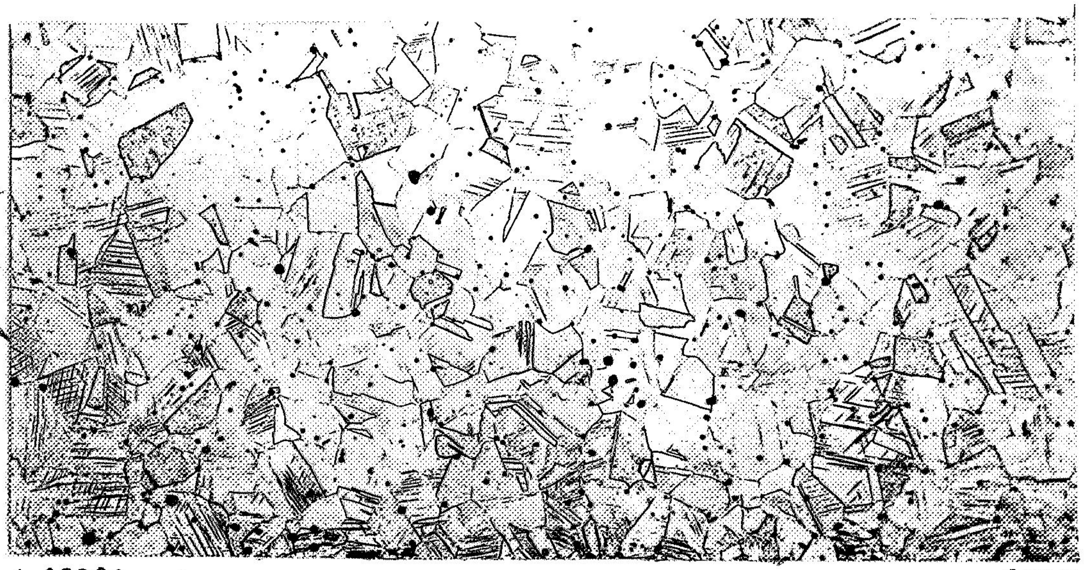
FIGURE 13



HARDNESS TRAVERSE OF EXPLOSIVELY BONDED 316SS/Ta TUBING

FIGURE 14

STRAIN LINES CAUSED BY EXPLOSIVE BONDING



L-A3390
ETCH: 10% $(NH_4)_2S_2O_8$

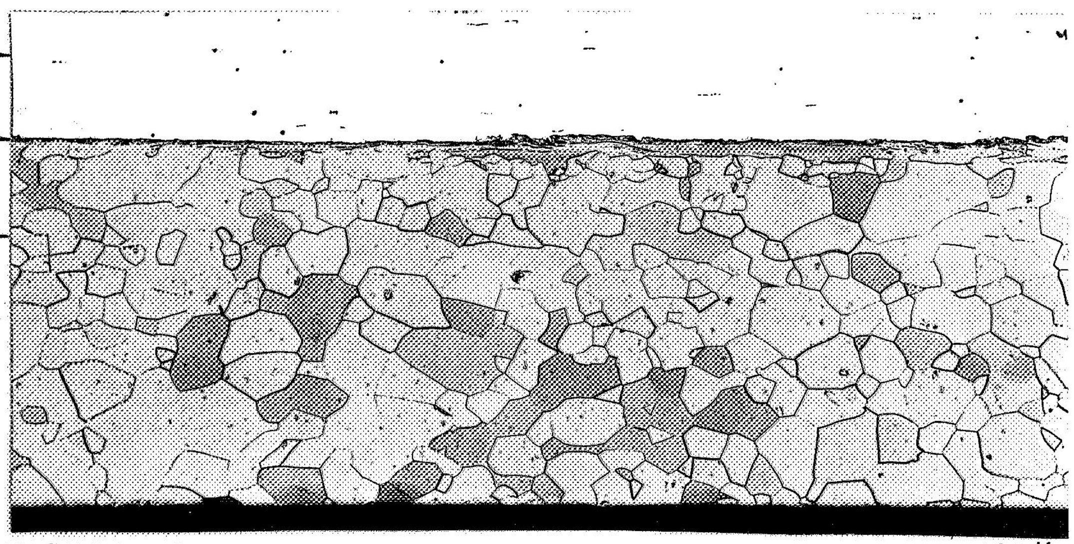
250X

a. 316SS

316 SS

INTERFACE

Ta, NO CHANGE IN MICROSTRUCTURAL APPEARANCE CAUSED BY EXPLOSIVE BONDING



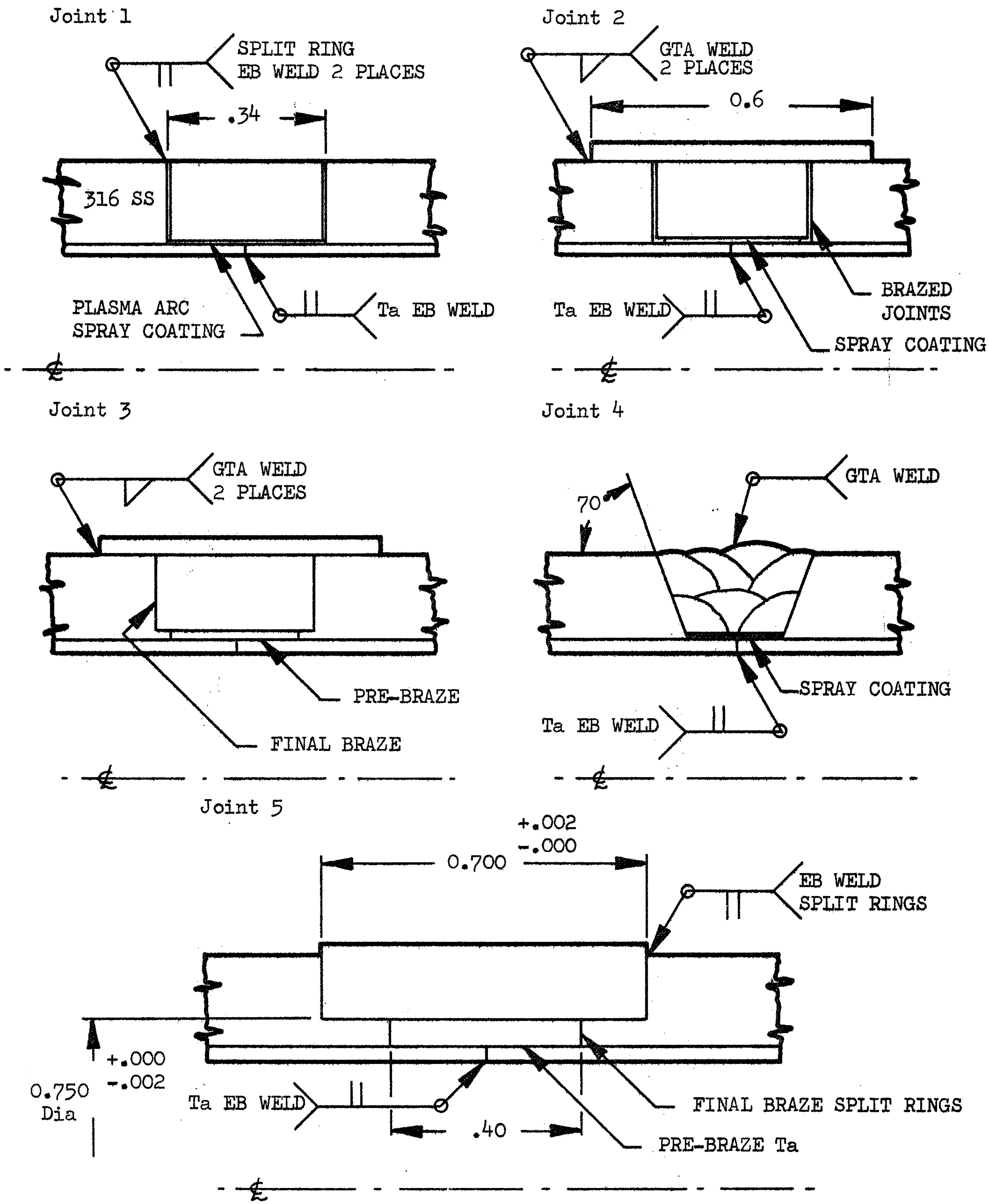
L-0085
ETCH: GLYCEREGIA + HNO_3 + HCl

100 X

b. TANTALUM

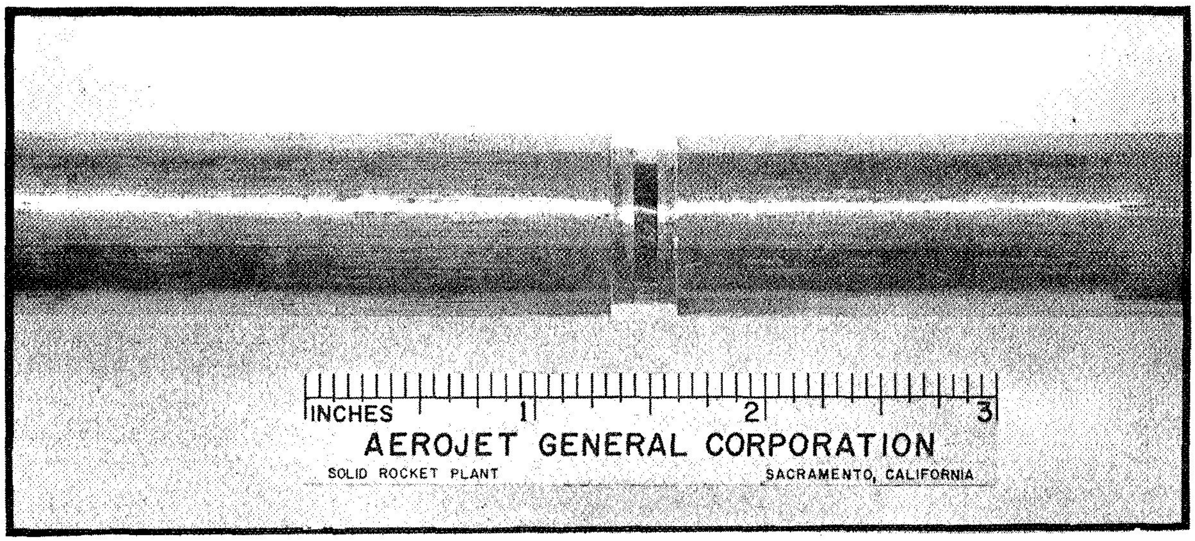
MICROSTRUCTURE OF 316SS AND TANTALUM AFTER EXPLOSIVE BONDING

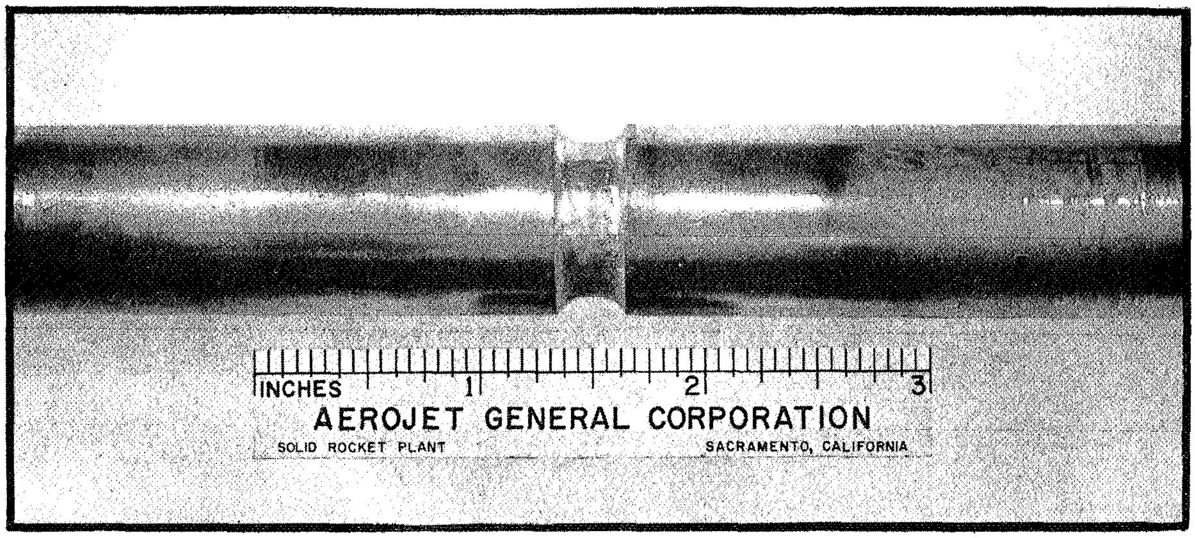
FIGURE 15



Bimetal tube joint designs selected for evaluation.

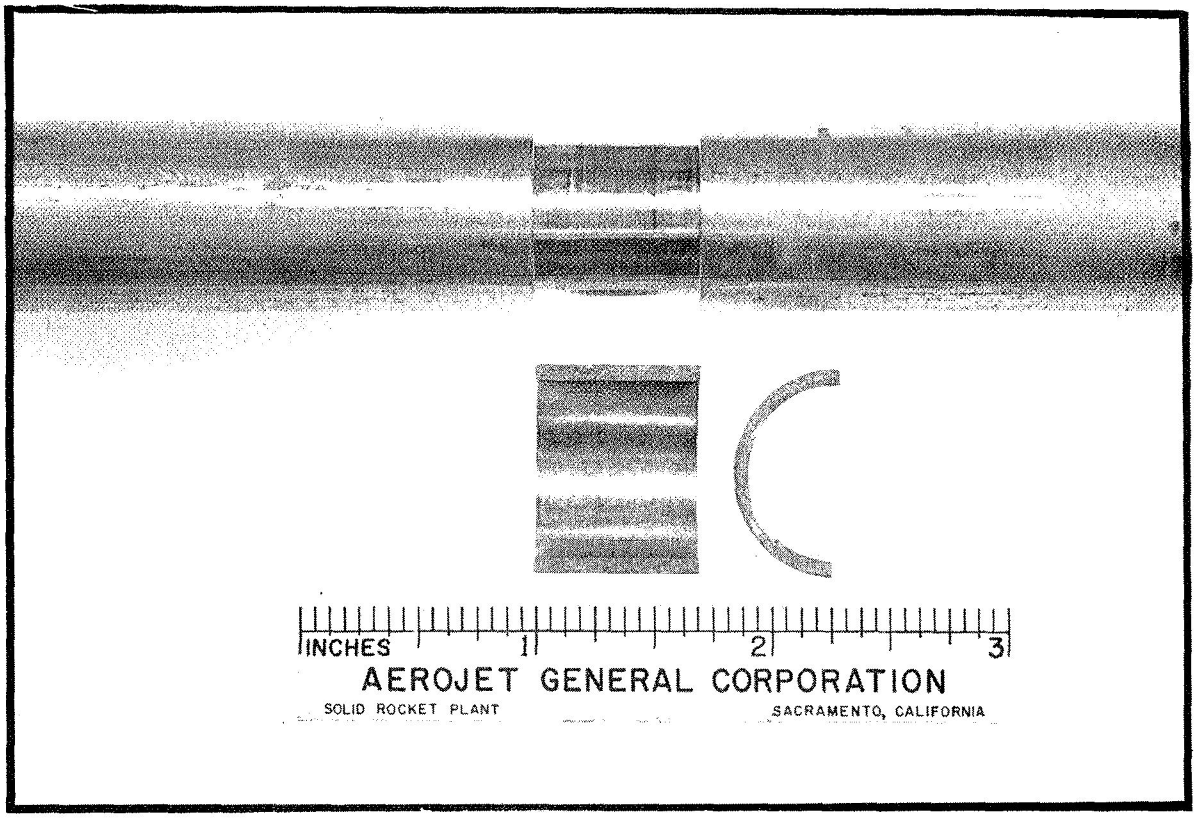
FIGURE 16

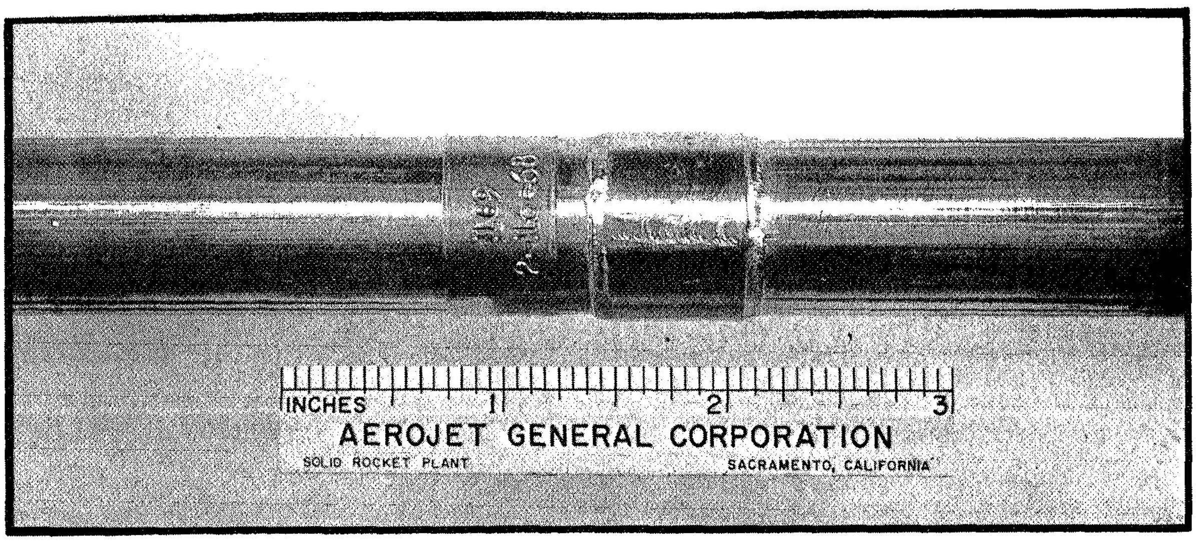




The top view shows a completed electron beam tantalum butt joint. The lower view shows a completed brazed joint overlay prior to final machining for the EB weld closure rings.

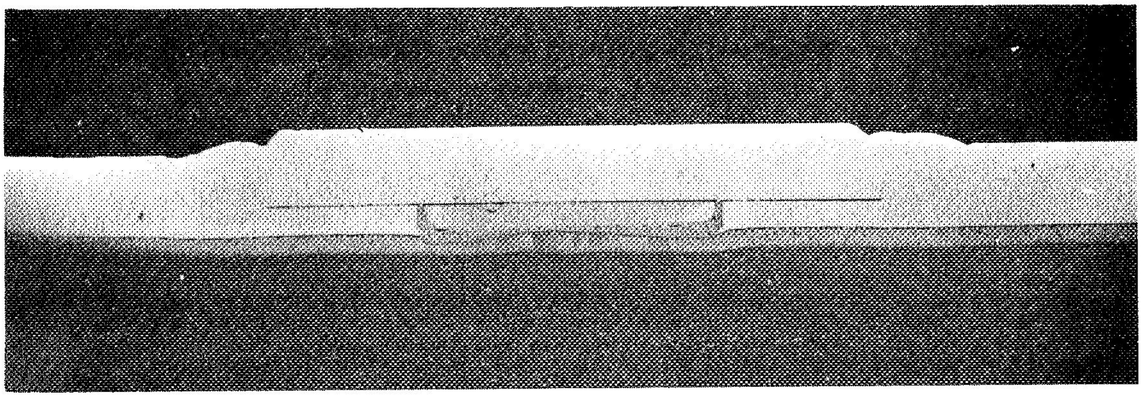
FIGURE 17



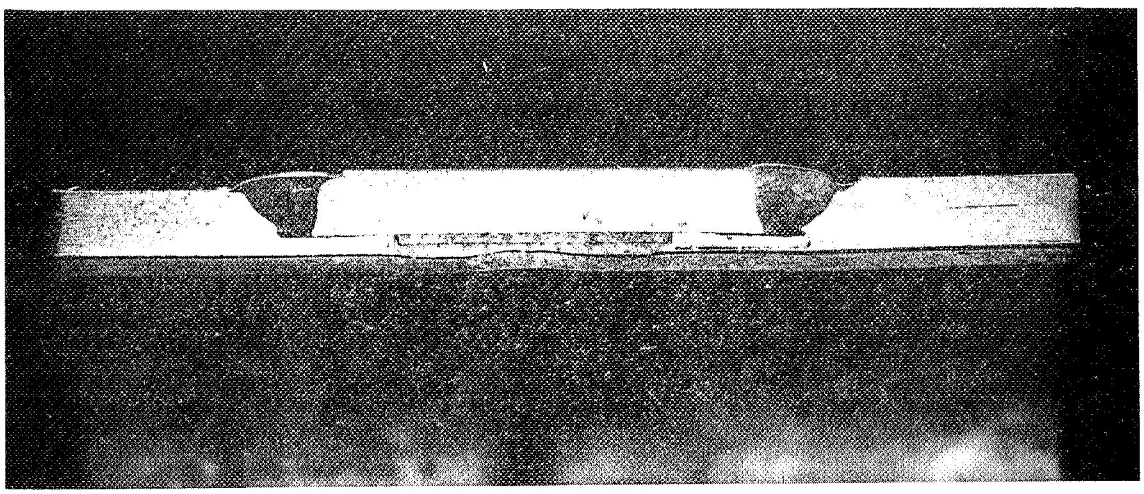


The top view shows a brazed joint with the groove machined to accept the split rings for EB welding. A completed electron beam welded joint is shown in the lower view. The joint number and data of radiographic inspection is embossed on the lead tape.

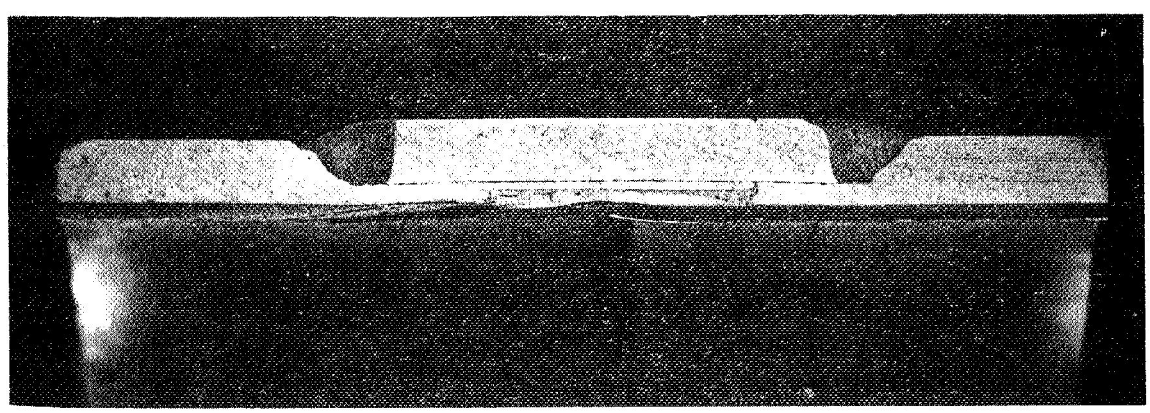
FIGURE 18



Mag: 5X



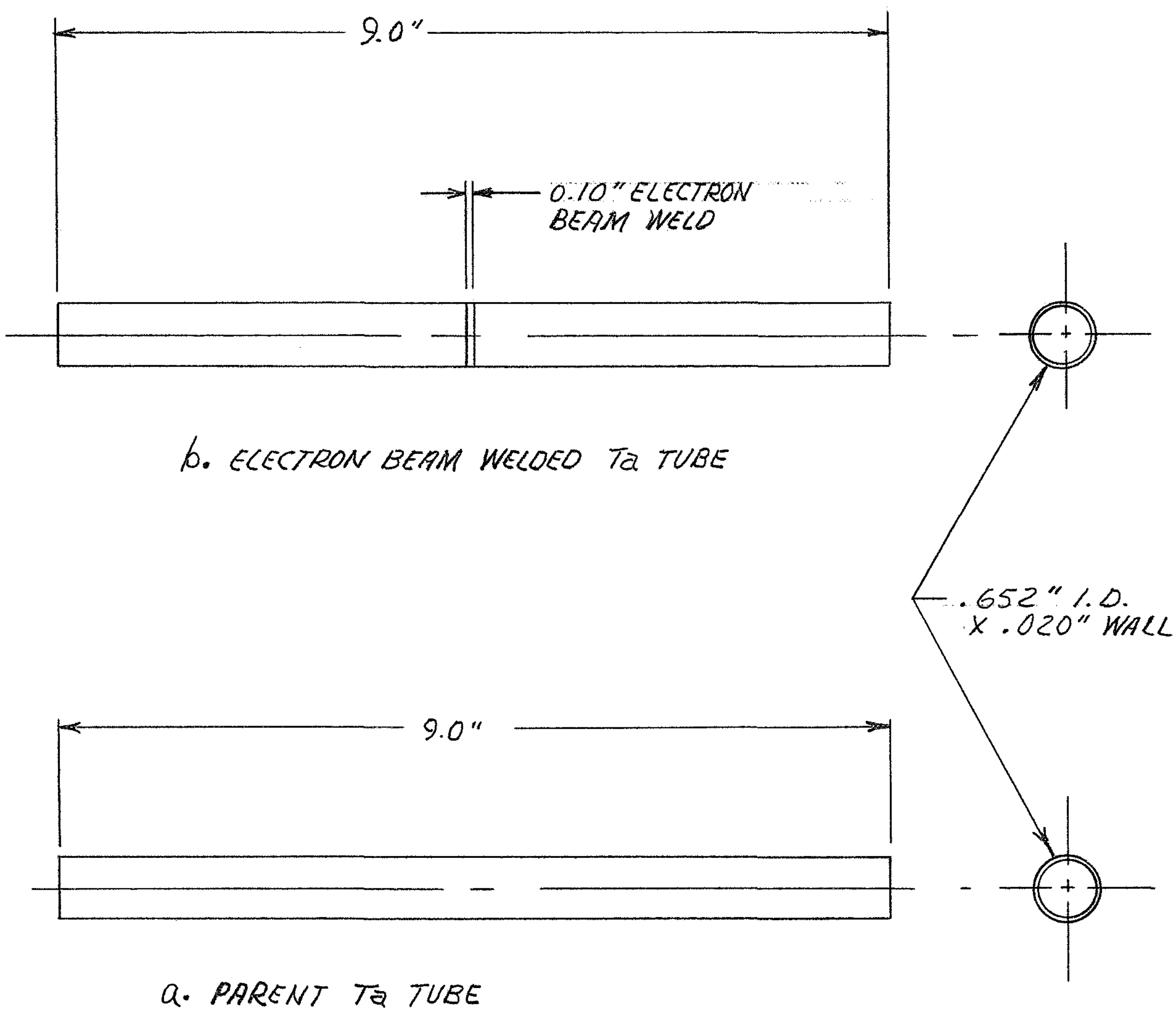
Mag: 4X



Mag: 4X

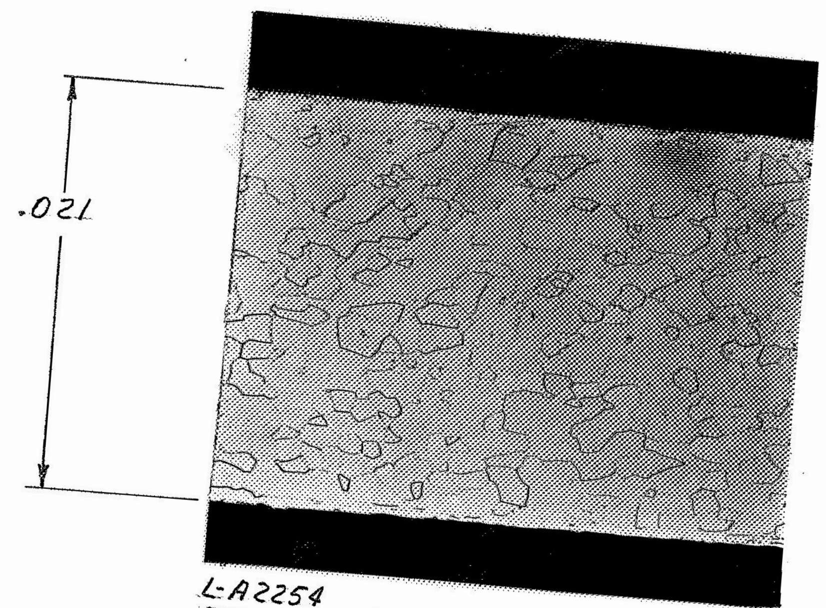
Three cross sections of completed joints of Joint No. 5 showing variations in the depth of weld penetration due to the electron beam spiking effect.

FIGURE 19

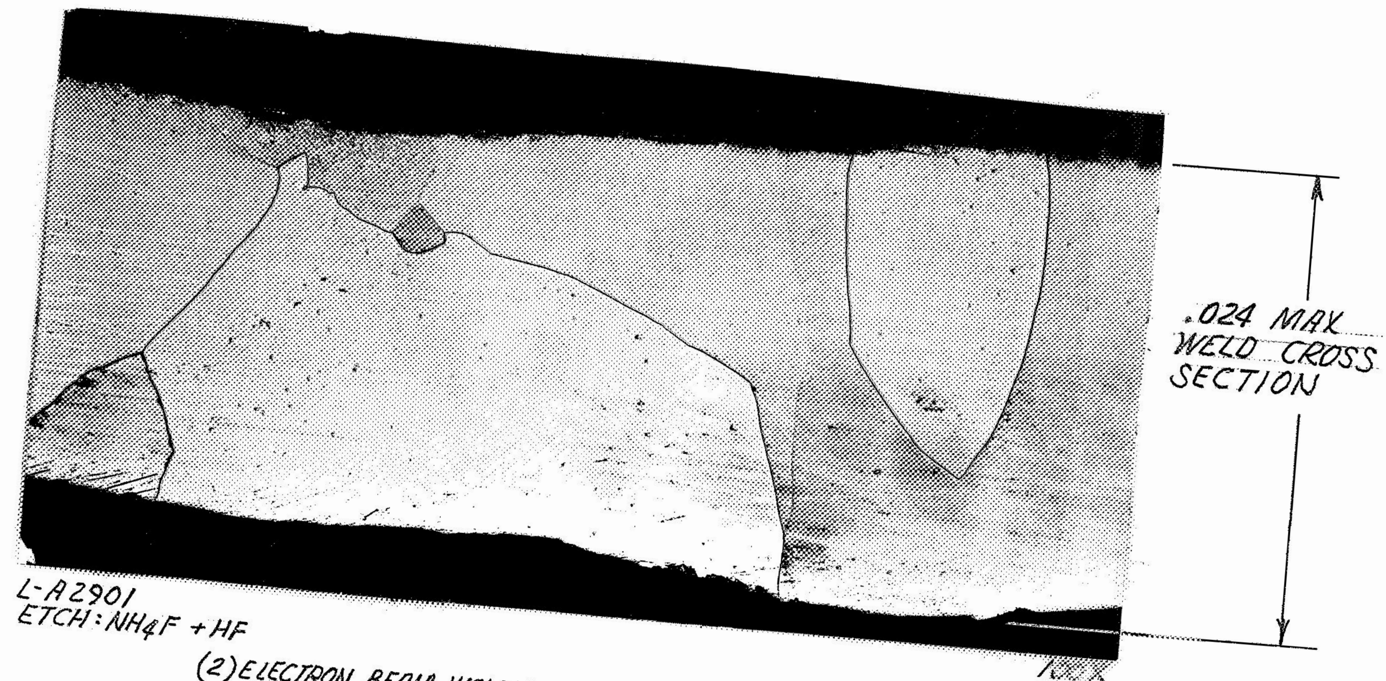


PARENT AND ELECTRON BEAM WELDED TANTALUM TUBE TENSILE SPECIMENS

FIGURE 20

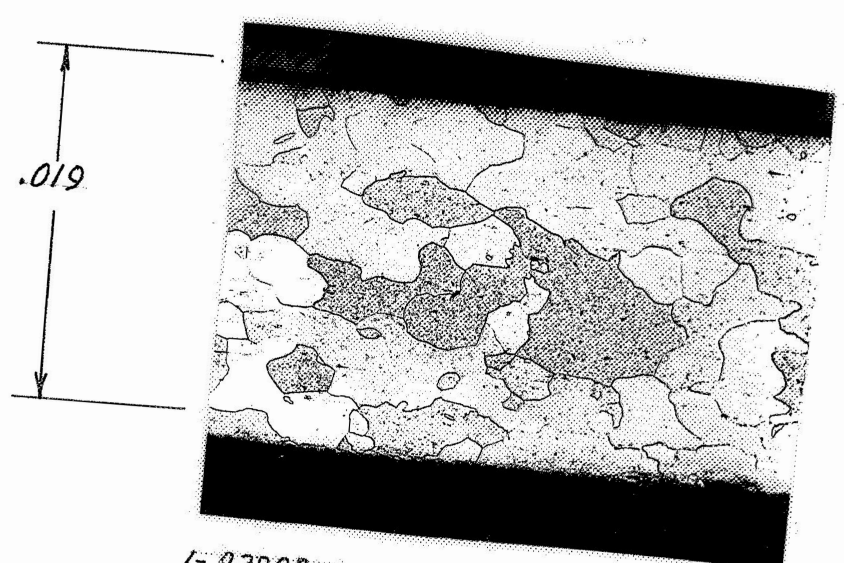


L-A2254
ETCH: $NH_4F + HF$ 100 X
(1) PARENT, ASTM GRAIN SIZE NO.7



L-A2901
ETCH: $NH_4F + HF$ 100 X
(2) ELECTRON BEAM WELDED, ASTM GRAIN SIZE 0

b. KAWECKI SUPPLIED MATERIAL



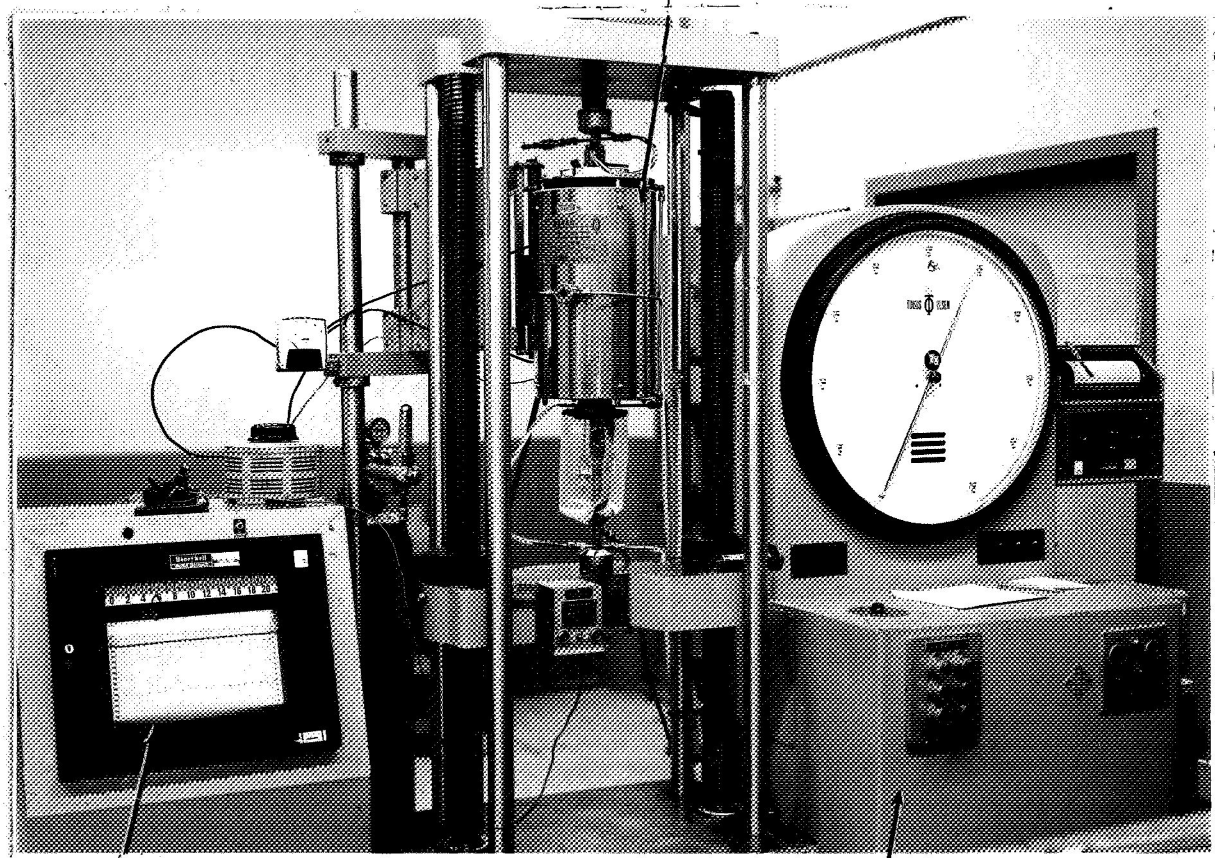
L-A2903
ETCH: $NH_4F + HF$ 100 X
(1) PARENT, ASTM GRAIN SIZE NO.5

L-A2902
ETCH: $NH_4F + HF$ 100 X
(2) ELECTRON BEAM WELDED, ASTM GRAIN SIZE 00

a. FANSTEEL SUPPLIED MATERIAL

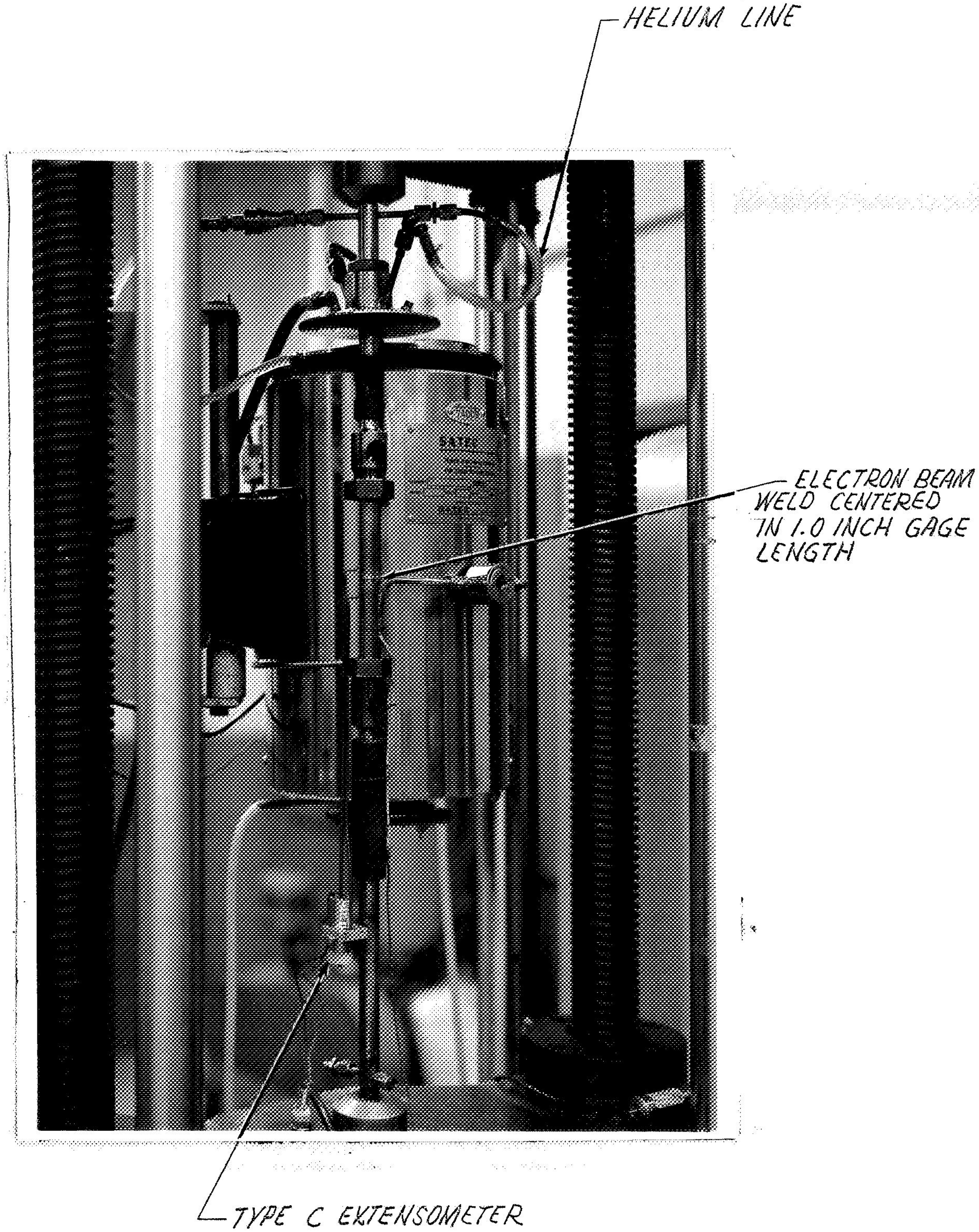
MICROSTRUCTURES OF PARENT AND ELECTRON BEAM WELDED TANTALUM TUBING

FIGURE 21



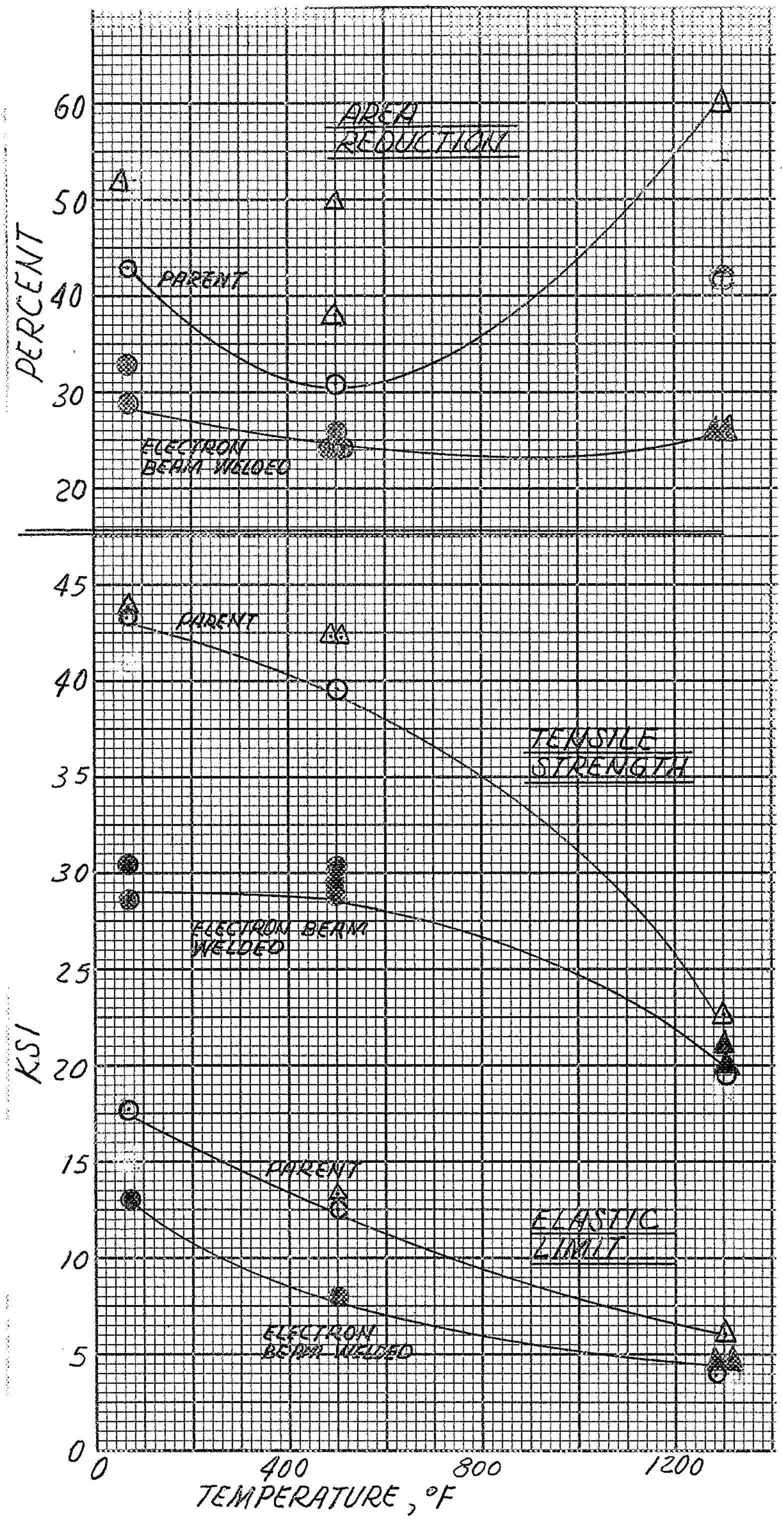
TEST SET-UP FOR ELEVATED TEMPERATURE TENSILE TESTING OF TANTALUM

FIGURE 22



Ta TUBE JOINT FIXTURED FOR TENSILE TESTING

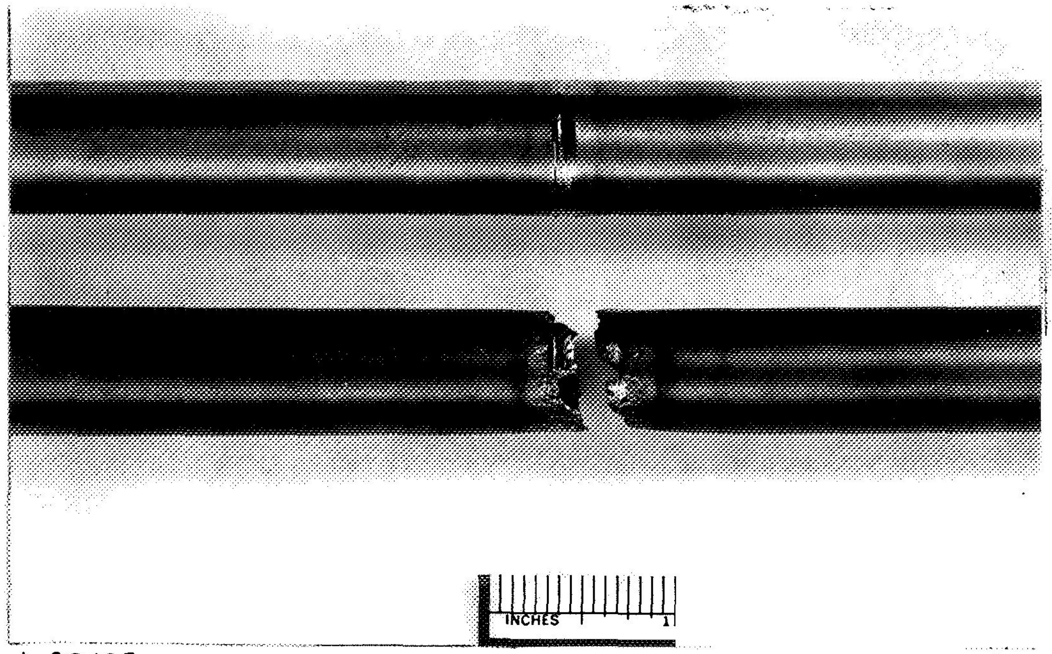
FIGURE 23



LEGEND			
PARENT		ELECTRON BEAM WELDED	
SYMBOL	ASTM GRAIN SIZE NO.	SYMBOL	ASTM GRAIN SIZE NO.
○	5	●	00
△	7	▲	0

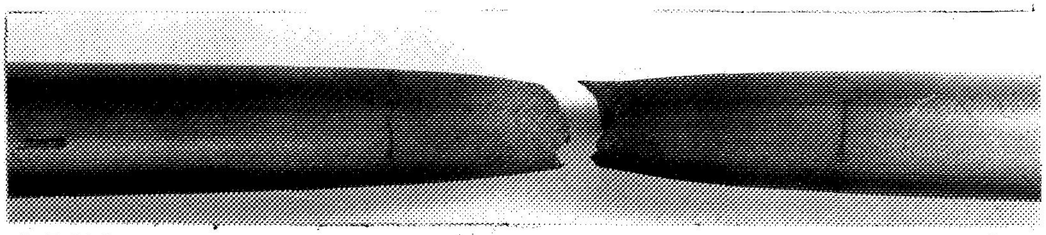
MECHANICAL PROPERTIES OF PARENT & ELECTRON BEAM WELDED .652 I.D. X .020 WALL TANTALUM TUBING

FIGURE 24



L-A2633 1X

b. ELECTRON BEAM WELD PRE-TEST (TOP) AND POST-TEST (BOTTOM) SPECIMENS

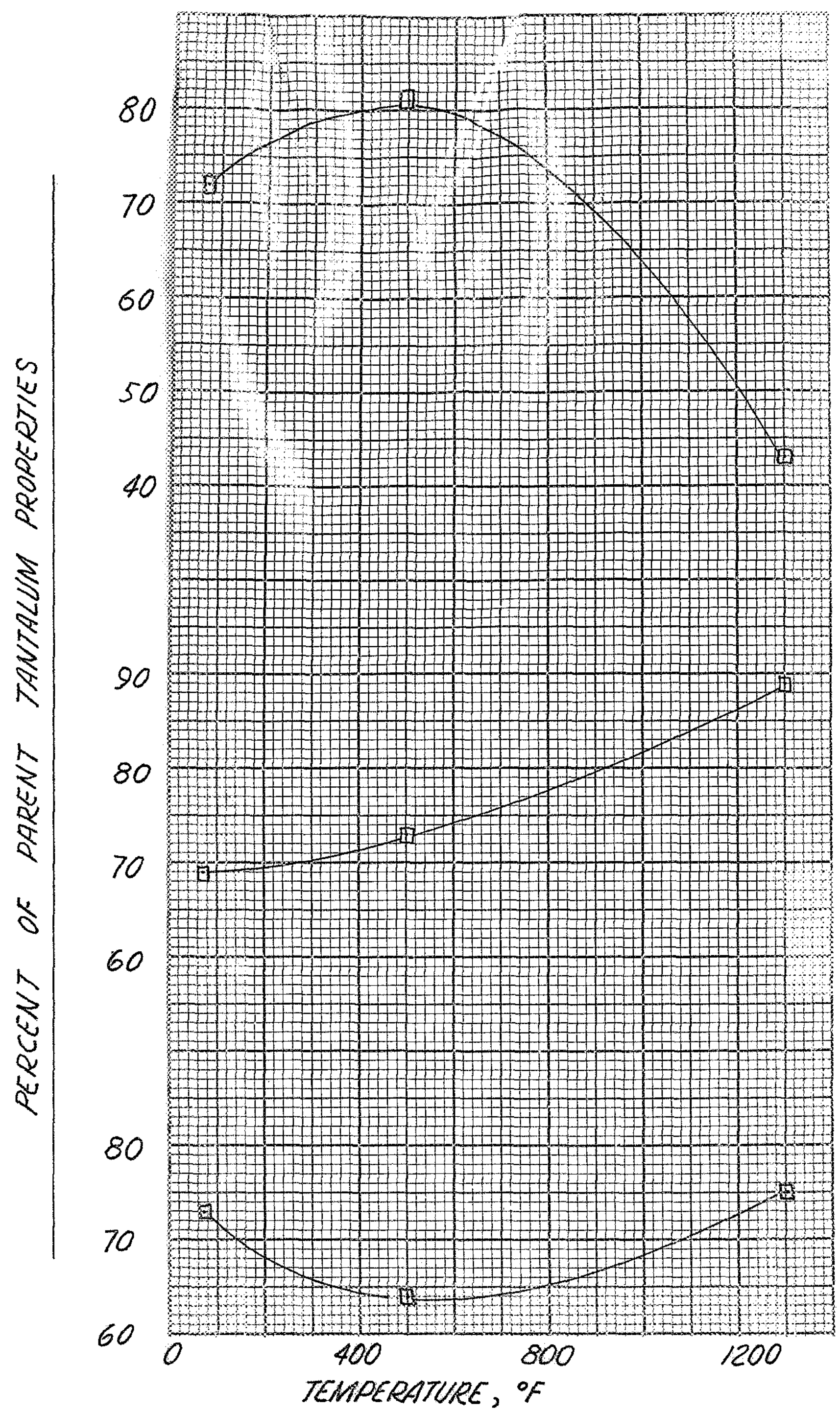


L-A2635 1X

a. PARENT SPECIMEN

Ta TUBE PARENT AND ELECTRON BEAM WELD TENSILE FRACTURE SPECIMENS

FIGURE 25



EFFICIENCY OF Ta ELECTRON BEAM TUBE WELDS

FIGURE 26