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FABRICATION AND INSPECTION OF TUBING, TUBESHEETS, AND TUBE-TO-TUBESHEET WELDS OF THE CRBRP STEAM GENERATORS

by

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ABSTRACT

The rationale for the technical details leading to the selection of tubing and tubesheet specifications and inspection techniques was based upon the desire to optimize the chances of success for the CRBRP steam generators. Fabrication processes, especially welding for the tube-to-tubesheet joints were recognized as critical. Thus, heavy emphasis was placed upon the development of reliable welding techniques as well as inspection methods using the most accurate and sensitive tools available.

Accomplishments to date include: a) the procurement of the tubing and tubesheets, to the desired specifications; b) validation that the design base properties of VAR and ESR wrought products are well within the Code acceptable levels; and, c) development of welding and tube-to-tubesheet inspection methods to provide satisfactory levels of quality.

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1.0 INTRODUCTION

It was recognized from the onset that one of the primary causes of failures in steam generators is material related. In an effort to optimize the chances of success in the CRBRP steam generators, extreme care was made in the selection and testing of the tube and tubesheet materials and the selection of suppliers of these projects. The material selected for construction was 2-1/4Cr-1Mo. This choice was made primarily because of this alloy's resistance to stress corrosion cracking. Once the material was selected, meetings were held with potential fabricators of tubes and tubesheets to discuss what limits of control could reasonably be achieved on these products with a state of art technology. In addition, methods of melting and the advantages and disadvantages thereof as well as methods of heat treatment were discussed.

After extensive discussion with potential suppliers, specifications were drafted by the General Electric Company, Sunnyvale, California, with major input from Westinghouse, the Lead Reactor Manufacturer (LRM), the Project Office (PO), Oak Ridge National Laboratories (ORNL), Atomics International (AI), and the potential suppliers of the finished product forms before they were formally imposed on potential product suppliers. Specifications were prepared for Vacuum Arc Remelt (VAR) and for Electro Slag Remelt (ESR) tubesheets and tubing. Standard melting practice was used for the shell plate material. In general, the requirements for the balance of the materials for the steam generators were ASME Boiler and Pressure Vessel Code specifications with added restrictions as necessary. The reason that strict emphasis was placed on the tubing and tubesheet material is because the tube-to-tubesheet welds were considered to be the most probable source of failure within the CRBRP steam generators.

Emphasis was placed on providing metallurgically clean, consistent quality materials with low impurity levels in order to achieve high integrity welds. A decision was made to require VAR or ESR tubesheets rather than weld overlay partially because of the length of the spigots which are machined from these tubesheets. These long spigots are required to permit the tube-to-tubesheet weld to be inspectable by radiography and other means and to permit individual post weld heat treatment of these welds with subsequent radiography.

The importance in the selection of vendors and the placement of the purchase orders for the tubes and tubesheets were recognized. The major problem encountered in purchasing the tubing was to find a vendor who could deliver tubes approximately 20M (65') long in an annealed condition, and a vendor who could vacuum melt or electro slag remelt and forge the tubesheet to the specification requirements.

A great amount of technical effort was expended by the vendors to follow the materials during the production and testing cycles. Pacific Tube Company, Commerce, California was selected as the vendor for the tubing, and Cameron Iron Works in Houston, Texas was selected for the melting and forging and inspection of the tubesheets. The other critical items were plates for the shell, nozzles, forgings, sweepolets and steam heads. Suppliers were selected among vendors such as Lukens Steel, Bonner Forge, Crane Company, etc.

This report deals with the rationale for the choice of specifications, process methods and inspection techniques for the materials and welding processes critical to the CRBRP steam generators. Testing results are given which were necessary to qualify tubing and tubesheets and to validate their suitability as regards to Code criteria.

2.0 GENERAL DISCUSSION

2.1 Tubing and Tubesheet Properties

Metallurgical refining was specified for starting materials destined for steam generator tubing and tubesheets. These specifications were considered necessary in order to reduce the potential for: (a) inclusions which could interfere with tube/tubesheet welding and contribute to tubewall or tubesheet spigot defects, and (b) embrittlement phenomena, usually the result of impurity element content.

Industrial applications of this alloy have been almost exclusively through the use of air melted grade, thus manufacturing experience and data base for the ESR and VAR grades had been very limited. It was necessary to select specifications which were proper for the critical sodium/water pressure boundary application, but also within the available or potentially achievable state of the art within the steel industry. Once initial heats of ESR and VAR materials became available, a test program was initiated to determine if the properties of the refined alloy differed from those of the air melt variety used to establish ASME Code criteria. Initially, available material yielded test results which compared favorably with Code accepted values. The results showed that strength property values for material without post weld heat treatment tends to lie toward the lower region of the data band, but still well above the lower bounds for the data in ASME Code Case 1592.(1) At this time, it was also realized that the Code values did not include the effects of post weld heat treatment as a separate category.

There were over 200 lots of tubing which will be used for fabricating all CRBR steam generators.[2] Nine of these lots were selected for further testing and comparison with the preliminary data and the data base for the ASME Code (Table 1). For the tubesheet evaluation, one large forging was selected out of the 22 ordered for the test and evaluation (Table 2).[3] Short term mechanical properties testing for the forgings has been completed and long range tests (10,000 hours creep and beyond) are now in progress.

The requirements of the initial specifications for both tubing and tubesheet have been met. It was, therefore, demonstrated that high quality wrought products made by the electroslag refining (Figure 1) and vacuum arc processes, meet the Code. Initial fears of high rejection rates because of tight specifications did not materialize and the resultant tubing and tubesheets have been delivered to the manufacturer of the steam generators at reasonable costs.

2.1.1 Tubing Characterization

To ensure that the production tubing met the specified requirements, 9 lots of tubing were selected from the initial 23 and were tested in detail to determine chemical composition, microstructural features, physical dimensions, and short term mechanical properties. As with initial tests, the results indicate that the production tubing met the technical requirements and intent of the original specification. Chemical composition was held within very tight limits and the microstructure, hardness, and tensile properties were extremely reproducible from lot to lot (Table 3). Tensile and burst tests up to temperatures of 600°C showed that a very tight control of chemical content and final heat treatment produces homogeneous structures. The wall thickness was held within the specified tolerance of 10%. Statistical analysis of results from ultrasonic examination indicated a probability of .01 that a flaw greater than 3% of the wall exists in any given tube length examined.

2.1.2 Specification Requirements - Tubing

Comparison of CRBR specification with ASME standards are shown in Table 1. Significant differences are the size of permissible tube wall flaw, inclusion content, heat treatment, restricted chemical composition, tighter dimensional control, decarburization layer limit, the inclusion of liquid penetrant and surface finish.

It was decided to use a heat treatment which produces the most stable microstructure so as to obtain stable long term mechanical properties. The desired heat treatment was isothermal anneal, austenitized at 1700°F for one hour, cooled to 1300°F and held for 2 hours to permit isothermal transformation and yield a maximum amount (80%) of polygonal ferrite. Variations of carbon content from lot to lot can change the location of pearlite phase field, but within the carbon ranges of the CRBR tubing, the carbides formed are expected to produce acceptable degree of variation in the tubing mechanical impurities.

The actual heat treatment for tubing was slightly different than the theoretical case, the heating and cooling schedules were modified to accomodate available furnaces at the vendors facilities. Austenitize at 900°C-955°C (1652-1750°F) for 15 minutes minimum, 30 minutes maximum, cool at $\leq$500°F/hr to 720 ±28°C (1328 ±82°F) and hold for a minimum of 85 minutes. Extensive testing prior to and following the production run was necessary to qualify the furnace at the vendors shop. Familiarization with all requirements by the tube producers was essential to obtain an agreement regarding all aspects of the specification. The delivered costs per foot were a factor of two over the cost of commercial tubing, well worth the premium when the intended purpose is taken into account.

2.1.3 Results of Testing Production Tubing - Chemical Composition

Table 3 shows the results obtained compared with specification requirements in the same Table. Analysis was performed by two laboratories and overcheck at Atomics International confirmed the results.

2.1.4 Physical Dimensions

Measurements obtained from 52 feet (16 meters) of tubing selected from the initial lot indicate the outside and inside diameters were very uniform, varying from 0.06 mm (0.0023 in.) on the OD and 0.05 mm (0.0017 in.) on the ID. Wall thickness measured with an ultrasonic method, exhibited a variation of 0.23 mm (0.0091 in.). The nominal dimensional requirements for the reference CRBR tubing are: outside diameter $15.9\,\mathrm{mm}\ {}^{+\,.13\,\mathrm{mm}}_{-\,0.0}$ $(0.625\ {}^{+\,.005}_{-\,0.0}$ in.), wall $2.8\,\mathrm{mm}\ {}^{+\,.25\,\mathrm{mm}}_{-\,0.0}$ $(0.109\ {}^{+\,0.010}_{-\,0.0}$ in.), 69 feet in length.

The requirements for ultrasonic testing of the CRBRP steam generator tubing are ASME E-213 as modified by GE "Ultrasonic Inspection Procedure for Tubing Using a Twelve-Notch Standard," Revision 3 (Table 4, Figure 2).

The test system is qualified by running a statistically significant sample under defined conditions. The mean response is determined and the ability to control the mean is established by calibration standards, with notch characteristics shown in Table 5. There is a product test required to establish with 95% probability that a flaw equivalent to a 3% or larger standard notch will be detected.

A comparison between the UT requirements of the Code, RDT M3-33T, and the original specification is made in Table 4. The procedures, detection levels required and method of test control imposed by the reference specification constituted an advance in the industrial state of the art for production testing of tubing of this size. These more stringent requirements were imposed to achieve the highest possible tubing quality commensurate with the critical application in the steam generator units of CRBRP.

The objective of this added complexity is to allow a statistical calculation of the minimum probability of detecting defects. A defect is a flaw that will return an echo equal to, or greater than, an echo from the 3% notch of the standard used in Qualification and Calibration. The GE Specification set the minimum probability for detecting a defect as 95%.

Tubing produced has satisfied these requirements. As an independent test, a rigorous inspection was carried out in the GE Nondestructive Test Laboratories using a small sample of tubing selected from the initial quantities produced. Fifty-nine pieces 1.5 meters (5 ft.) in length were examined from 10 independent lots. Analysis of results showed no flaws over 2.8% of wall thickness to exist in the 90 meters of the tubing examined. A thorough audit made of the tube production process by the Project Quality Assurance organizations found that the vendors processes met or exceeded the specifications.

2.1.5 Metallographic Examination

Ferritic grain size was uniform from lot to lot with an ASTM grain size of 7-1/2. All cross sections exhibited (a) high ferrite content and minimum amounts of transformation product, (b) hardness values were 71 to $76R_b$, both conditions indicative of complete isothermal transformations during heat treatment. Microstructure cleanliness exceeded the specifications; the longest inclusion found was 0.002" long.

2.1.6 Mechanical Property Tests

Room temperature tensile tests at the vendors laboratory and the overchecks at GE show close agreement, and results met the ASME Code minimum requirements. Elevated temperature tensile tests (up to 600°C) show yield strength to decrease with increasing temperature beyond 200°C. The mean values of the CRBR tubing exceed the ASME Code Case 1592 minimum expected yield stress below 300°C.* However, above 300°C, the CRBR tubing yield values are below minimum expected Code value and this fact must be taken into account when the design stress analysis is being done.* Standard deviation comparison show 7% for yield, 3% in ultimate, and 12% in percent elongation which suggests little difference in tensile properties from lot to lot.

Burst tests were performed on tubing specimens at temperatures of 25° to 600°C (77° to 1112°F), using a pressure rate controlled apparatus at 6.89 MPa (1000 psi) per minute. Gas pressure and diameter were recorded during the tests. Little variation in burst test results was detected from heat to heat, as evidenced from standard deviation values of 7%, 3%, and 12% for yield, ultimate, and reduction in area, respectively.

2.2 Characterization of CRBR Steam Generator Tubesheet Forgings

Vacuum arc remelting was chosen, to minimize spigot flaws and provide assurance of defect-free tube/tubesheet welds. Full anneal heat treatment chosen for the forgings will yield metallurgical structures (ferritic/pearlitic) similar to the isothermally annealed tubing and, thus provide stable long term creep-rupture properties. Post weld heat treatment will ensure minimum embrittlement at the heat affected zones and weld metal.

Once the VAR forgings were available, it was thought prudent to verify that the reference forgings met the guidelines of the ASME Boiler & Pressure Vessel Code as well as the CRBR specifications. Test specimens used for this work were cut from a tubesheet forging 5880 lbs. weight, 12.75 inches thick, 48 in. diameter, which was part of the CRBRP order. Forging reduction was 3 to 1 and annealed at 1700°F ±25°F, then held for 1 hour per inch of thickness, not to exceed 4 hours, but not less than 1 hour, followed by cooling at rates of 100°F/hr. to 600°F, then room temperature.

Microstructural evaluation was necessary to determine the type of carbides resulting from the annealing and post weld heat treatment. For the purposes of maintaining stable mechanical properties, it was preferred

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*With post weld heat treatment

that MO_2C carbide be retained for the maximum time, and this can be accomplished if the microstructure is mostly ferrite. The specified post weld heat treatment promotes the formation of a stable microstructure at the weld such as the precipitation of relatively stable $M_{23}C_6$ and cementite. Cross sections taken from the forging show that the desired microstructure was achieved. Hardness values ranged from Rockwell B scale 70-72 and the ferrite grain size ranged from ASTM 5-1/2 to 4-1/2. The worse inclusion field found at the spigot side of the tubesheet had dimensions less than .002". With this cleanliness, flow lines in the forging have less significance than would be the case if a large number of inclusions were present.

Results of chemical analysis show that the vendor check and repeated tests by GE are consistent (Table 6). The uniformity of composition was in agreement with the observation that non-metallic inclusions were very infrequent. The tubesheet met all of the desired specifications.

2.2.1 Mechanical Properties

Mechanical properties evaluation included tensile testing (Figure 3), Charpy impact, drop weight, creep rupture, and continuous fatigue. As with the case of ESR tubing, VAR forging also shows a drop in high temperature yield, below the Code Case 1592. This has to be taken into account by design. (Note that CC 1592 curves do not take PWHT into account, and results here contain PWHT.) The drop weight test is used to establish the temperature below which brittle fracture may occur in structural steels. Fracture toughness testing is required by the ASME Code. Drop weight tests were performed for a material in the fully annealed and post weld heat treated condition and also for material given heat treatment, but with an additional 1000 hour aging embrittlement*. Testing was performed according to ASTM Standard E-208 to establish nil ductility temperature. Drop weight testing by the forging vendor and confirmed by GE through further testing showed the nil ductility temperature to be at 30°F, and by definition, the lowest hydrostatic test or in-service temperature for the tubesheet is 90°F.

Charpy V-Notch impact testing was also performed as a function of temperature to augment the results obtained by drop weight tests. All specimens, regardless of location within the forging, showed that the 0.89 mm (35 mils) lateral expansion and the 67.85 (50 ft-lb) energy absorption requirement was met at a lower temperature than required by NB-2300 subsection of the ASME Code (Fig. 4).

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*Performed for information purposes only.

Creep-rupture tests were performed to determine effects of remelting (VAR) and heat treatment upon creep properties of primary importance; time to tertiary creep, time to 1% strain, minimum creep rate and time to rupture. Test temperatures were 454, 510 and 566°C (850, 950 and 1050°F), specimen geometry was according to ASTM E-139, 6.35 mm (0.250 in.) diameter and 25.40 mm (1.00 in.) gauge length. The results are tabulated below:

Parameter	Comparative Curve	Comments
Time to Tertiary Creep	ASME Code Case 1592	All the data fall above the Code curve.
Minimum Creep Rate	Nuclear Systems Materials Handbook (NSMH)	All data fall above the lower tolerance limit.
Time to 1% Strain	Hobson Creep Equation (using only data on remelted, annealed material)	Hobson equation incorporates measured UTS. Most data fell between two curves calculated using the maximum and minimum observed UTS.
Time to rupture	CC1592 Expected Minimum Value and the NSMH Lower Tolerance Limit	Only short term (<1000 hours) data for post weld heat treated material fell below these curves.

Time to rupture results fell below the Code Case 1592, but these specimens included post weld heat treatment whereas Code Case 1592 data do not take PWHT into account.

Fatigue testing was done at 538°C (1000°F) at frequencies of 2 Hertz and strain rates of $4x10^{-3}$/sec. (strain controlled) (Figure 5). All data fell at or slightly below the best fit curve of air melt material data with carbon contents of 0.12, 0.13, and 0.14%, and not PWHT. Thus, it is consistent that the VAR specimens which had carbon content of 0.088% and had PWHT would be expected to fall slightly below the best fit curve.

Thus, the VAR forging was found to be homogeneous, within the specified chemistry, microstructurally very clean and almost completely isotropic (sample orientation and location in forging show negligible differences in mechanical properties). Furthermore, the toughness was found high and the ductility transition temperatures were sufficiently low so as to allow room temperature hydrostatic testing of the assembled steam generators.

2.3 Tube-to-Tubesheet Welding

2.3.1 Joint Design

The joint is an autogenous butt weld, made with an internal bore welding head. As shown in Figure 6, the tube is welded to a 1-3/4 in. projection, or nipple, which is machined out of the tubesheet forging. To achieve a close fit between these two parts, the internal bore of both the tubesheet nipple and the tube are machined too, within ±.0005 in. and a close fitting removable mandrel is used to align the two parts. The faces of both the tubesheet nipple and the tube must be accurately perpendicular to their centerlines, within a tolerance of ±.0005 in.

2.3.2 Welding Equipment

The system used for tube-tubesheet welding consists of the following major equipment items:

1) Welding power supply
2) In-bore weld head
3) Purge gas control panel
4) External purge gas manifold

The welding power supply chosen for this application is manufactured by the Dimetrics Company and provides an adjustable pulsed output, a high-frequency pulse of 16 kHz, four adjustable current levels during the weld cycle, and a variable current upslope and downslope. These features were found necessary to make a consistent, reproducible weld.

The in-bore weld head (Figure 7) is inserted through the tubesheet and is centered in the tubesheet nipple by means of the silicon nitride gas cup. The copper electrode holder grips the tungsten electrode tightly by means of a nut which is screwed onto a tapered shoulder. This permits easy electrode replacement. Purge gas for the interior of the weld is introduced through the center of a copper tube into which the electrode holder can be positioned. The copper tube also carries the welding current. Slots in the electrode holder channel the purge gas to the weld area. The gas cup is resistant to thermal shock and has been used for 300 welds and more with no discernable deterioration. As a consequence, cooling, such as with water, is not required. The result is a simple system which can be replicated at low cost.

The weld head is rotated by a DC motor and current is introduced to it via copper slip rings. Overall electrical resistance of the head assembly is low and reproducible, after the first weld is made with a new electrode. Since the electrode gradually erodes during welding, it is replaced, as a precaution, every seven welds.

As a means of weld geometry control, the purge gas control panel measures the pressures and gas flows on the internal and external diameter of the weld and maintains a preset difference in pressure between the inside and outside of the weld during the weld cycle. This partially nullifies the effect of gravity, minimizing weld "sag" and concavity, since the weld is made in the horizontal position.

An external purge gas manifold is clamped around the joint and serves the multiple functions of holding the tube in alignment with the tubesheet nipple, maintaining a flow of inert gas over the external weld surface and providing for weld preheat using electrical cartridge heaters within the manifold.

2.3.3 Welding Procedure

To make the tube-tubesheet weld, both the tube and tubesheet nipple are first cleaned using a detergent solution (trade name Alconox), then rinsed with ammoniated water of pH about 9. Prior to welding, the mating surfaces are polished to an 8 rms finish using a slowly rotating spot facing tool.

The tube and tubesheet are then aligned with the aid of an internal close-fitting mandrel inserted through the tubesheet. A specially designed clamp forces the tube against the tubesheet nipple with about 30 lb. of force.

The external purge gas manifold is then clamped in place around the joint, and the internal mandrel is removed. Any lack of freedom of motion of the mandrel is an indication of misalignment at the weld joint.

The weld head is then inserted and clamped in place. A precheck prior to joint fitup assures exact positioning of the electrode relative to the joint. It has been found that the electrode must be displaced .045 in. toward the tubesheet side of the weld joint to equalize the fusion of its tube and the spigot.

Purge gas flow on both the ID and OD is then initiated and the joint is preheated to 430°F utilizing the external purge gas manifold with electric heaters installed.

The weld sequence is then initiated. The typical current values as a function of electrode rotation are shown in Figure 8.

Visual examination of the completed weld after disassembly of the external manifold may then be performed. The visual examination, although qualitative, can usually establish in a preliminary way that the weld is geometrically acceptable.

2.3.4 Weld Characteristics

Engineering calculations have established that concavity of up to .010 in. on either the inside diameter (ID) or the outside diameter (OD) is acceptable. Thinning of the weld is also acceptable provided it does not exceed .010 in. Figure 9 is a plot of measured concavity on both the ID and OD of 50 welds made in succession. All welds had acceptable concavities.

Figure 10 shows measured wall thinning of the same 50 welds. The number of measurements shown in Figure 10 were obtained at several positions around the weld circumference. All welds are acceptable.

2.3.5 Weld Examination

Particular emphasis was placed on the inspection of the tubes and the tube-to-tubesheet joint. The small inside diameter of the tubes, about 10mm (0.400") restricted the means to radiograph these welds to isotopic sources and a rod annode x-ray. The rod annode x-ray was proven to be far superior to isotopic sources in sensitivity.[4] Four of these machines, manufactured by Technish Physische Dienst, Delft, Netherlands, were ordered for the inspection of the tube-to-tubesheet joints on the eleven steam generators. In this device, a small tungsten target is positioned with the tube at the centerline of the weld. This target is bombarded by an accurately focused electron beam. The entire device is inserted through the steam holes in the tubesheet. The film is wrapped around the outside of the weld. The target end of the device is shown schematically in Figure 11.

The small geometric source of the x-rays permits resolution of very fine detail. Under ideal conditions, pores in the weld as small as 2 to 3 mils can be registered on the x-ray film. Even under production conditions and using automatic film processing, pores as small as 5 mils can be readily discerned.

Preliminary work was performed at ORNL in conjunction with Atomics International Development Program and General Electric Company (FBRD) to establish criteria, techniques and methods of interpretation for the tube-to-tubesheet weld. This effort helped establish the requirements of the four rod anode x-ray machines, and establishment of the joint acceptance and inspection criteria.

The rod anode microfocus x-ray machine can be made sufficiently sensitive to show up "linear indications" which resemble cracks, but which are in fact minute oxide inclusions about .0005 in. in diameter. These have been reduced almost to zero in the weld by careful design of the external purge gas manifold to exclude oxygen from the immediate vicinity of the weld bead. In any event, they are not cause for rejection of the weld.

Weld porosity received a great deal of attention in the development of the joint preparation process. It was found that low porosity could consistently be achieved by detergent cleaning, rinsing with a weak ammonia solution, and (the most important step) polishing of the mating surfaces mechanically with a spot facing tool to a finish of approximately 8 rms. The resultant statistical occurrence of porosity is shown in Figure 12. The porosity "figure-of-merit", for simplicity, is simply the sum of the diameters of all pores .005 in. or over, detected by the highly sensitive rod anode x-ray machine. All welds would have been considered completely pore-free if examined using conventional radioisotope techniques.

CONCLUSIONS

Experimental verification shows that steam generator tubing and tubesheet forgings have been successfully produced in large quantities using melt-refining techniques, electro slag (tubing) and vacuum arc (forgings). Samples taken from several of the heats show the products to have mechanical properties which satisfy the ASME Code. In all other respects, the materials were within all provisions of the original specifications, which in many respects were much tighter than existing commercial standards.

The welding development program to produce reliable procedures for the tube-to-tubesheet weld is in its last stages of completion. The application of a special, sensitive x-ray apparatus has been adopted for inspection of welds, yielding extremely sharp radiographic images which show weld imperfections with a high degree of reliability.

References

1. Spalaris, C.N., Challenger, K.D., Ring, P.J., and Day, R.A., "Material for Steam Generators", International Conference on Liquid Metal Technology in Energy Production, Seven Springs, PA, May 3, 1976.

2. Total tubing requirements for CRBR is 551,000 feet (104 miles) ASME Code requirements SA-213, Grade T22 were upgraded to RDT Standard M3-33T February 1975. Vendor: Pacific Tube Company, Commerce City, CA. Tube Hollows Babcock & Wilcox, Beaver Falls, PA.

3. Forging specifications: ASME Code SA-336 Class F22a and Article NB-2000 Section III, Division I (1974 Winter addenda) as amended by Code Case 1592 (Class I, Elevated Temp. Services). SA-336 was upgraded by RDT Standard M2-19T, February 1975. Vendor: Cameron Iron Works, Houston, TX.

4. McClung, R.W., Slaughter, G.M., Spalaris, C.N., and Lillie, A.F., "Fabrication and Inspection Development for CRBRP Steam Generators", J. Nuclear Tech., Vol. 28, P. 374, March 1976.

TABLE 1

ORDERING SPECIFICATIONS FOR CRBRP STEAM GENERATOR TUBING

ITEM	ASME CODE SECTION III CLASS 1	MODIFIED RDT M3-33
1. Basic Specification	ASME SA-213	ASME SA-213
2. Melt Practice	Electric Furnace	VAR or ESR
3. Inclusion Rating for Tube Hollows	Not Specified	ASTM E45, Method D < 1½ Thin < 1 Heavy
4. Manufacture	Seamless Cold Drawn	Seamless Cold Drawn or Cold Reduced
5. Heat Treat	Slow Cooling thru A_3 - A_1 or Normalized + Temper (≥ 675C)	926±28C/15-30 minutes + 717±28C/80-100 minutes Temper at 726±19C/1 hr min
6. Chemical Composition	SA-213 Grade T22	SA-213 Grade T22 + closer control of C, P, Si, S, Ni, Ti, V, Cu
7. OD Tolerance, mm (in.)	+0.10 (+0.004) -0.10 (-0.004)	+0.13 (+0.005) -0 (-0)
8. Wall Tolerance, mm (in.)	+0.51 (+0.02) -0 (-0)	+0.25 (+0.010) -0 (-0)
9. Total Decarburization mm (in.)	Not Specified	5% Wall 0.14 (0.0055)
10. Ultra. Test, Wall	Not Specified	ASME SE-113
11. Ultra. Test, Defects mm (in.)	ASME SE-213 5% Wall 0.14 (0.0055)	ASME SE-213 3% Wall 0.08 (0.0033)
12. Liquid Penetrant	Not Specified	ASME SE-165 A2, A3, B2, or B3
13. Hydro. Test, MPa (ksi)	6.89 (1000)	31.0 (4500)
14. Helium Leak Check	Not Specified	ASME Code Section V
15. Surface Finish	Not Specified	63 rms
16. Tensile Properties		
Y.S., MPa (ksi)	207 (30) min.	207 (30) min.
UTS, MPa (ksi)	414 (60) min.	414-586 (60-85)
Elong.	30% min.	30% min.
17. Hardness	85 R_b max.	85 R_b max.
18. Quality System	ASME Code NA-3700	ASME Code NA-3700

TABLE 2

ORDERING SPECIFICATION FOR CRBRP STEAM GENERATOR TUBESHEET FORGING

ITEM	ASME CODE SECTION III CLASS 1	RDT M2-19
1. Basic Specification	ASME SA-336	ASME SA-336
2. Melt Practice	Open-hearth, basic oxygen or Electric Furnace	VAR or ESR
3. Inclusions	Not Specified	<1 1/2 Thin <1 Heavy
4. Manufacture	2:1 Reduction	2:1 Reduction
5. Heat Treatment	Annealed or Normalized + Temper at ≥ 1250F	1700F/1 hr./in. of thkns.to 1700F/4 hrs., cool at ≤100F/1 hr. to 600F, cool in air
6. Chemical Composition	SA-336 Grade F22A	SA-336, Grade F22A +C, P, Si, S, Ni, Ti, V, Cu
7. Liquid Penetrant	NB-2540	NB-2540 >0.020 in. long (info.) for spigot area
8. Ultrasonic Test Defects	SA-388 Entire Volume <5% Full Scale	SA-388 Entire Volume 1/2" Dia. F.B. Hole Spigot Area { 1/16" Dia. F.B. Hole 1/32" Dia. S.D. Hole (info.) }
9. Surface Finish	Machined	≤250✓
10. Tensile Properties		
Y.S.	35 ksi, min.	35 ksi, min.
U.T.S.	60 - 85 ksi	60 - 85 ksi
Elong.	20% min.	20% min.
Red. in Area	35% min.	35% min.
11. Hardness	Not Specified	<85 R_b
12. Impact Tests		
Drop Wgt. Test	RT_{NDT}	RT_{NDT}
C_v	@ $<RT_{NDT}+60°F$, E≥50 ft.-lb., Lat.Exp.≥35 mils	@ $<RT_{NDT}+60°F$, E 50≥ft.-lb., Lat. Exp.≥35 mils
13. Weld Repair	NB-2539	NB-2539 Purchaser's Permission Required
14. Quality System	ASME Code NA-3700	ASME Code NA-3700
15. Grain Size	McQuaid-Ehn 1 - 5	McQuaid-Ehn 3 - 5

TABLE 3

CHEMICAL COMPOSITION OF CRBRP STEAM GENERATOR TUBING

Parent ht. No.[1] ESR No.[2]	PATCO Product Lot No.[3]	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cu	Ti
		Composition in % By Weight of Each Element										
RDT M3-33 as Modified by PO		0.07 to 0.12	0.30 to 0.60	0.015 max	0.015 max	0.10 to 0.40	0.25 max	1.90 to 2.60	0.87 to 1.13	0.03 max	0.35 max	0.03 max
C1005												
91154		.09	.42	.008	.011	.22	.18	2.26	.96	<.01	.10	<.01
	183	.09	.46	.012	.005	.16	.20	2.25	.94	<.01	.09	<.01
C1088		.09	.41	.015	.006	.30	.06	2.31	1.00	<.01	.07	<.01
91232		.09	.42	.015	.009	.28	.06	2.32	.99	<.01	.07	<.01
	430	.085	.37	.012	.001	.18	.06	2.38	.99	<.01	.06	<.01
91234		.08	.41	.015	.006	.31	.06	2.30	.99	<.01	.07	<.01
	442	.105	.36	.012	<.001	.15	.03	2.30	.95	<.01	.01	<.01
91235		.09	.42	.015	.007	.31	.09	2.36	.99	<.01	.07	<.01
	439	.085	.41	.015	<.001	.31	.06	2.36	1.02	<.01	.04	<.01
C1089		.10	.33	.014	.009	.30	.12	2.07	.96	<.01	.07	<.01
91240		.10	.32	.013	.010	.24	.12	2.07	.95	<.01	.07	<.01
	644	.095	.34	.014	.002	.22	.17	2.08	.98	<.01	.06	<.01
91242		.10	.32	.012	.008	.23	.12	2.08	.96	<.01	.07	<.01
	657	.095	.32	.015	.004	.23	.14	2.13	.99	<.01	.07	<.01
91243		.11	.32	.013	.013	.22	.12	2.09	.96	<.01	.06	<.01
	655	.095	.32	.015	.006	.23	.15	2.18	.99	<.01	.07	<.01
C1012		.10	.43	.009	.010	.25	.10	2.11	.98	<.01	.10	<.01
91160		.11	.42	.011	.007	.27	.11	2.13	.97	<.01	.10	<.01
	650	.085	.40	.013	.002	.26	.12	2.08	.98	<.01	.09	<.01
C1073		.10	.50	.011	.008	.38	.08	2.36	1.02	<.01	.08	<.01
91210		.09	.47	.010	.007	.31	.07	2.33	.99	<.01	.08	<.01
	429	.095	.52	.012	<.001	.36	.05	2.35	1.08	<.01	.08	<.01

1 Heat analysis shown in line with parent Heat No. (B&W Analysis)
2 ESR ingot analysis shown in line with ESR No. (B&W Analysis)
3 Final Product Check Analysis shown in line with Lot No. (PATCO Analysis)

TABLE 4
COMPARISON OF TUBING SPECIFICATION
FOR LOCATING FLAWS

	GE Specification 22A3634, Rev. 3	ASME Code NB 2552	RDT M3-33T Feb. 1975
Rejectable Nominal Notch Size in sq. in., (Normalized degree of severity)	0.0008 (1.0)	0.0055 (6.9)	0.0001 (1.3)
Calibration Interval, Hours	1/2	4	4
Number of times the notch must be detected (pitch of test)	3	Not Specified	3
Probability of Defect Detection	95% **	Not Specified	Not Specified
Statistical Control	Required	Not Required	Not Required
Qualification (detailed error analysis)	Required*	Not Required	Not Required

* Qualification is required initially and whenever the equipment is changed in any substantial way.

** Intent of Revision 3 Specification

TABLE 5

CALIBRATION AND SET-UP STANDARDS FOR TUBING

LOCATION	LONGITUDINAL NOTCHES	TRANSVERSE NOTCHES
O.D. SURFACE	.0022" (2%) .0033" (3%) .0055 (5%)	.0022" (2%) .0033 (3%) .0055 (5%)
I.D SURFACE	.0022" (2%) .0033" (3%) .0055" (5%)	.0022" (2%) .0033" (3%) .0055" (5%)

CALIBRATION AND SET-UP STANDARD
OF O.D. AND I.D. EDM NOTCHES
(NOTCH DEPTH TOLERANCE = $\pm$ .0002")
(NOTCH LENGTH 0.25")

TABLE 6
CHEMICAL ANALYSIS OF 2¼Cr-1Mo STEEL

		Tubesheet Forging - Heat VAR 56448					RDT M2-19	
Element	Ingot*	Top Edge (Spigot Side)	Bottom Edge	Bottom Center	Top Center (Spigot Side)	Estimated Accuracy	Minimum	Maximum
Aluminum		0.002%	0.002%	0.002%	0.002%	±0.01%		
Antimony		<0.002%	<0.002%	<0.002%	<0.002%	±0.005%		
Arsenic		0.006%	0.009%	0.007%	0.005%	±0.005%		
Carbon		0.087%	0.091%	0.088%	0.088%			
Carbon	0.10%	0.086%	0.090%	0.088%	0.089%	±0.005%	0.070%	0.110%
Carbon		0.090%	0.087%	0.087%	0.089%			
Chromium	2.14%	2.18%	2.17%	2.17%	2.18%	±0.01 or 1%	1.90%	2.60%
Cobalt		0.007%	0.007%	0.007%	0.007%	±0.01 or 1%		
Copper	0.09%	0.10%	0.11%	0.11%	0.10%	±0.02 or 2%		0.35%
Hydrogen		0.0002%	0.0002%	0.0001%	0.0003%	±0.0002%		
Manganese	0.54%	0.52%	0.58%	0.59%	0.59%	±0.02 or 1%	0.30%	0.60%
Molybdenum	1.01%	0.98%	0.99%	0.99%	0.99%	±0.02 or 2%	0.87%	1.13%
Nickel	0.15%	0.14%	0.14%	0.15%	0.14%	±0.01 or 1%		0.25%
Nitrogen		0.005%	0.005%	0.005%	0.005%	±0.001%		
Oxygen		0.001%	0.002%	0.001%	0.002%	±0.001%		
Phosphorus	0.010%	0.013%	0.013%	0.013%	0.014%	±0.003 or 3%		0.015%
Silicon	0.26%	0.28%	0.30%	0.30%	0.30%	±0.02 or 2%	0.20%	0.40%
Sulfur	0.006%	0.006%	0.006%	0.006%	0.007%	±0.003 or 2%		0.015%
Tin		<0.002%	<0.002%	<0.002%	<0.002%	±0.01%		
Titanium	0.01%	<0.002%	<0.002%	<0.002%	<0.002%	±0.01%		0.03%
Vanadium	0.01%	0.004%	0.005%	0.004%	0.005%	±0.01%		0.03%

* Vendor's Analysis - Average of 4 Values

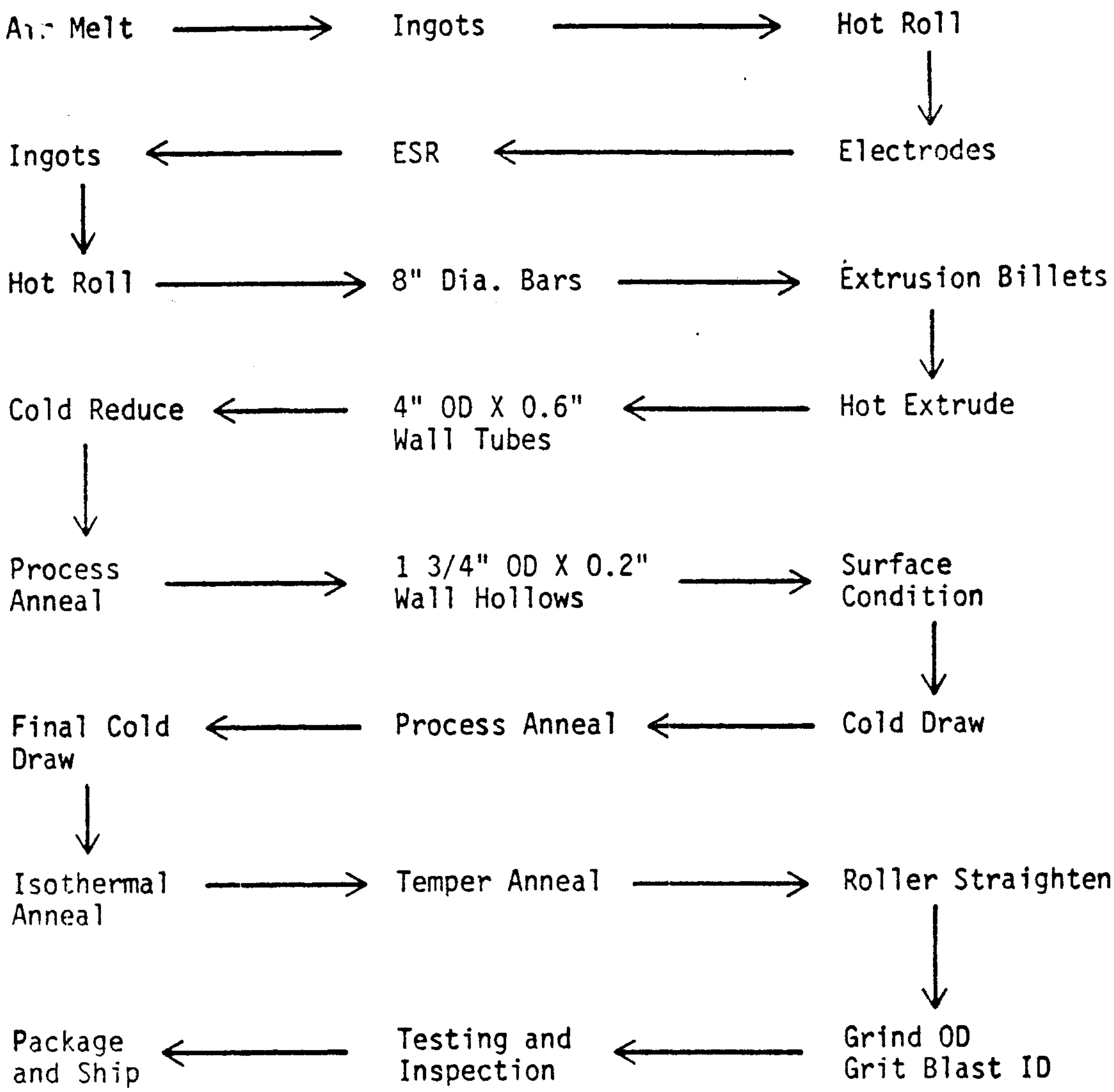
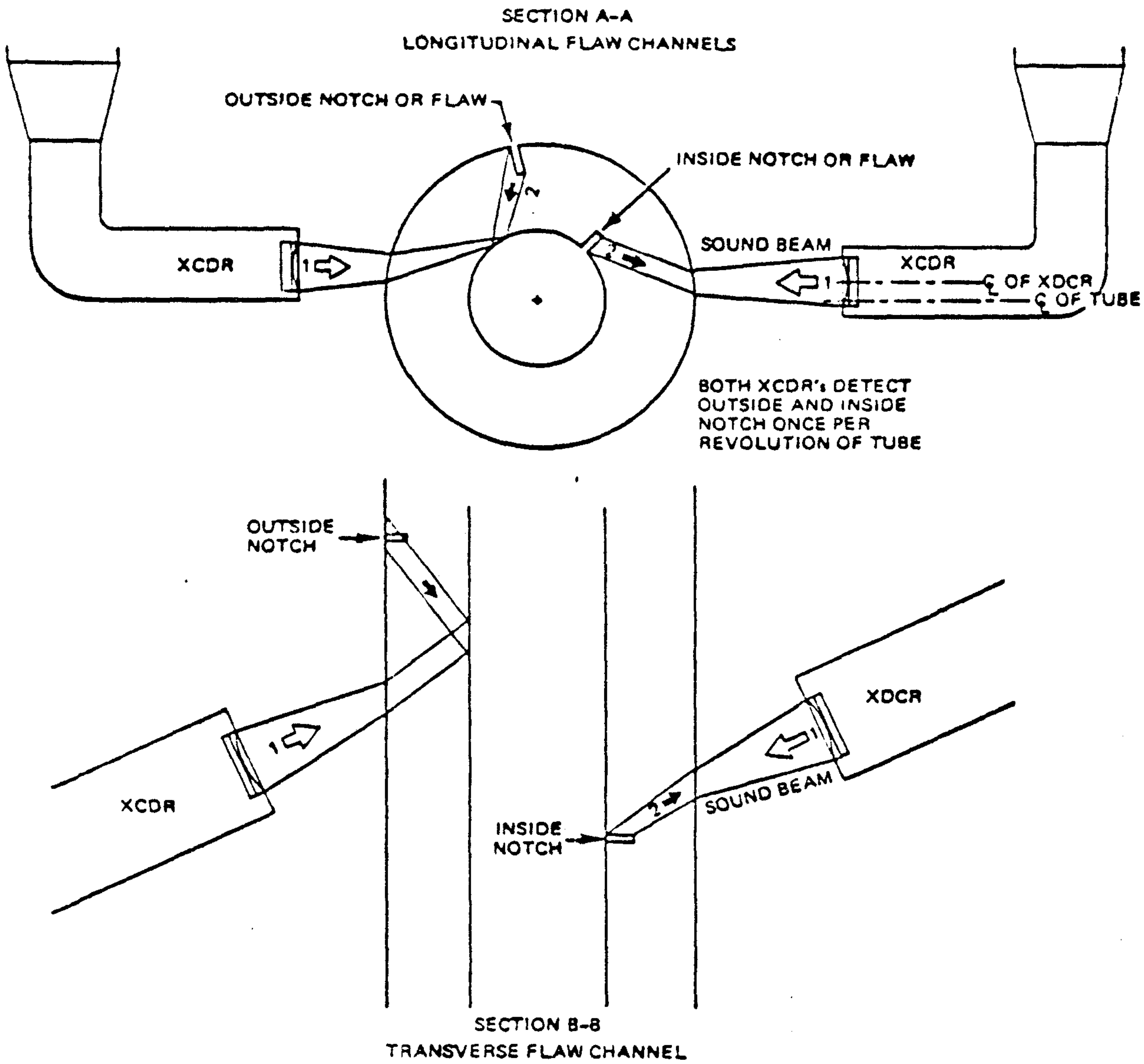


Figure 1 Flow Plan Illustrating Fabrication Sequence for Producing CRBRP Steam Generator Tubing



NOTE: Transmitted pulse (1) of sound travels from transducer (XDCR) into the tube wall and returns along the same path when reflected from the notch (2). Pulses reflected from the outer surface of tube are separated out electronically while the pulse from the flaw is converted to a signal on a strip chart recorder.

Figure 2. Sound paths to determine tube quality

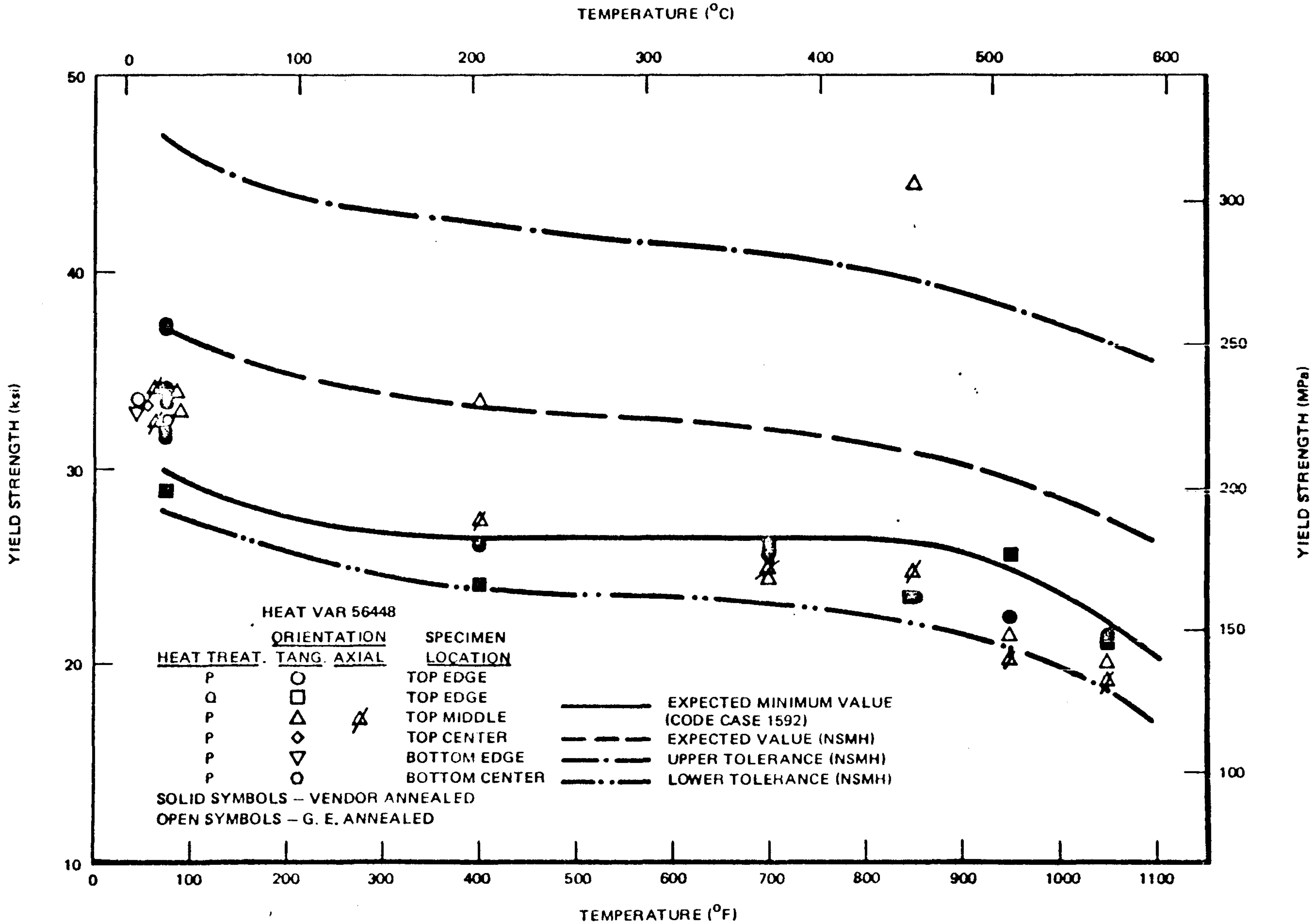


Figure 3 Variation of 0.2% Offset Yield Strength with Temperature

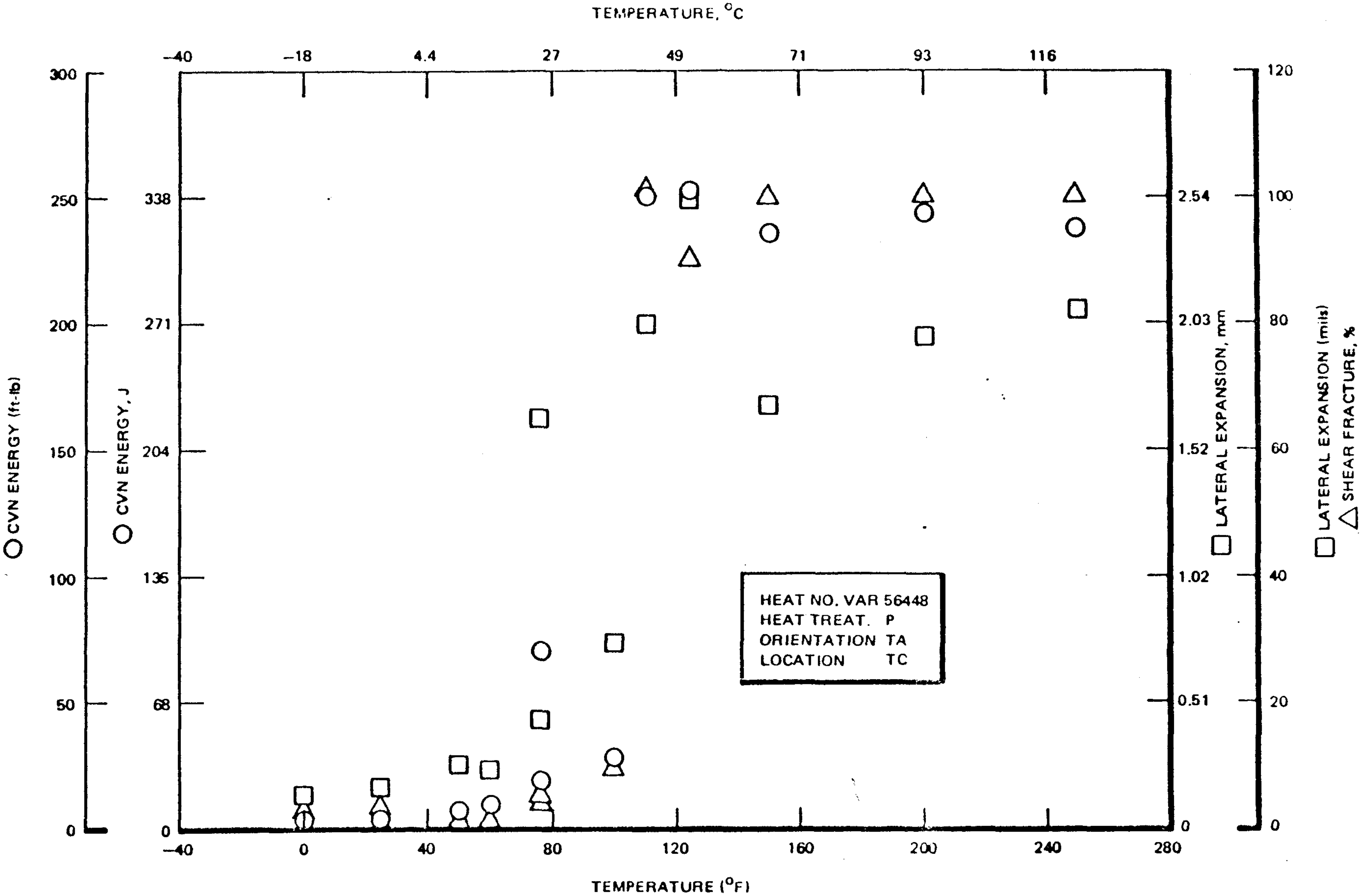


Figure 4 Variation of Charpy Impact Toughness Properties with Temperature in the Top Center Location

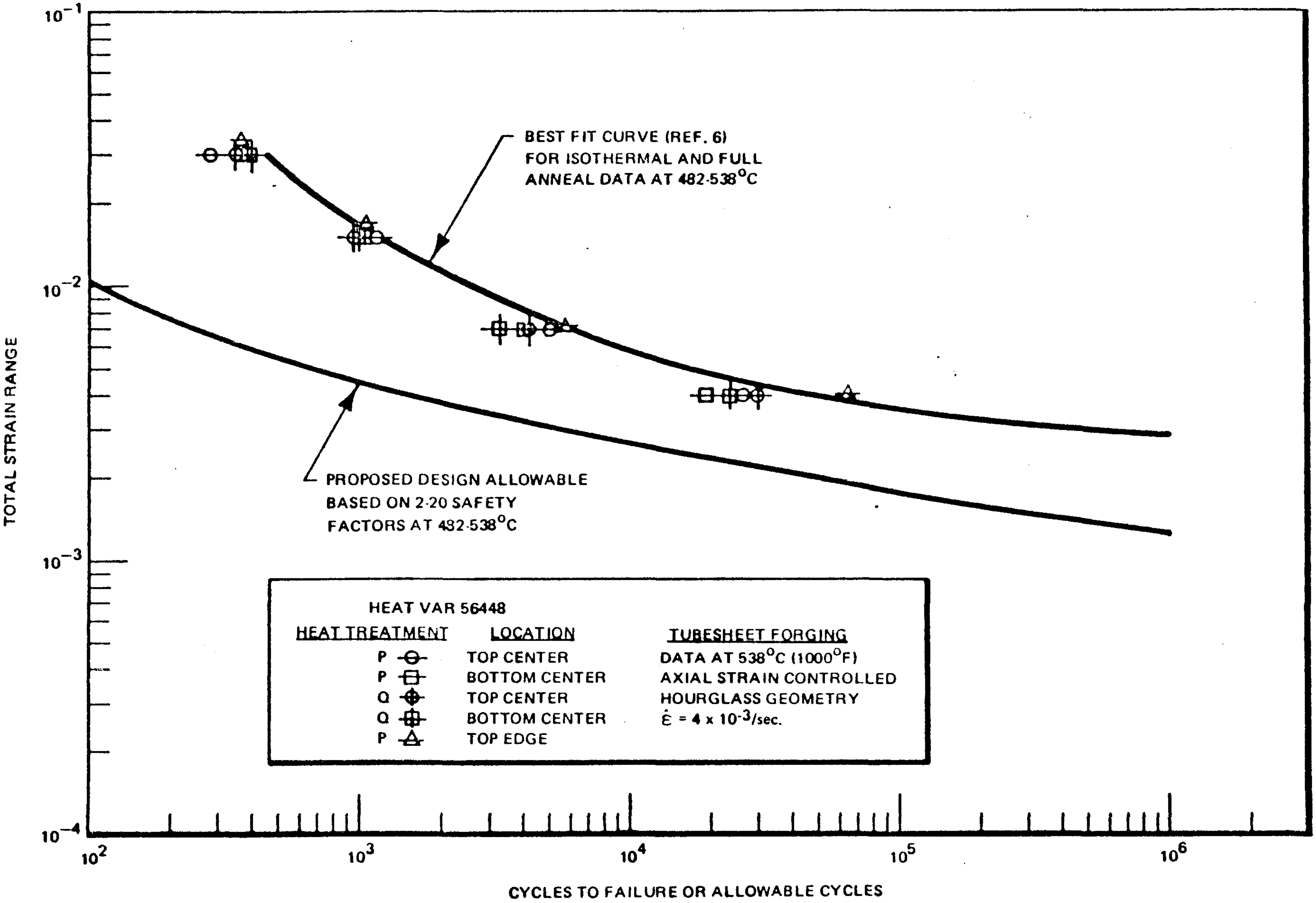
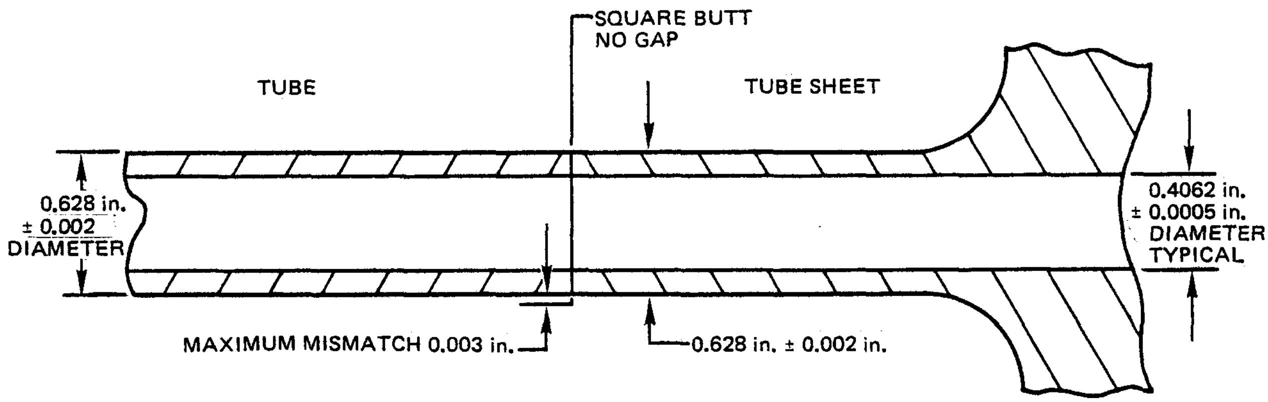


Figure 5 Variation of Cycles to Failure or Allowable Cycles with Total Strain Range



TUBE-TO-TUBESHEET JOINT TOLERANCES

Figure 6 Tube-to-Tubesheet Joint Tolerances

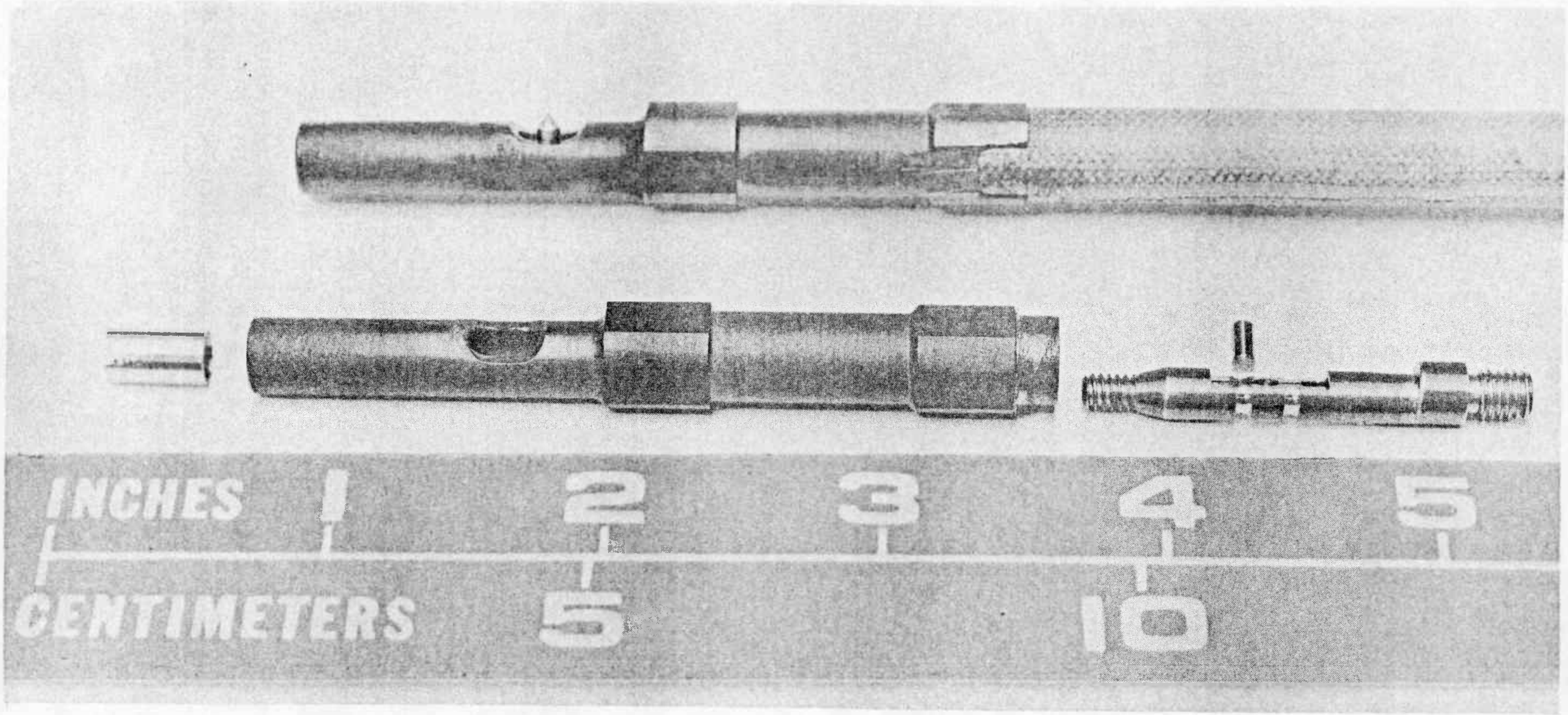


FIGURE 7. ELECTRODE DETAILS

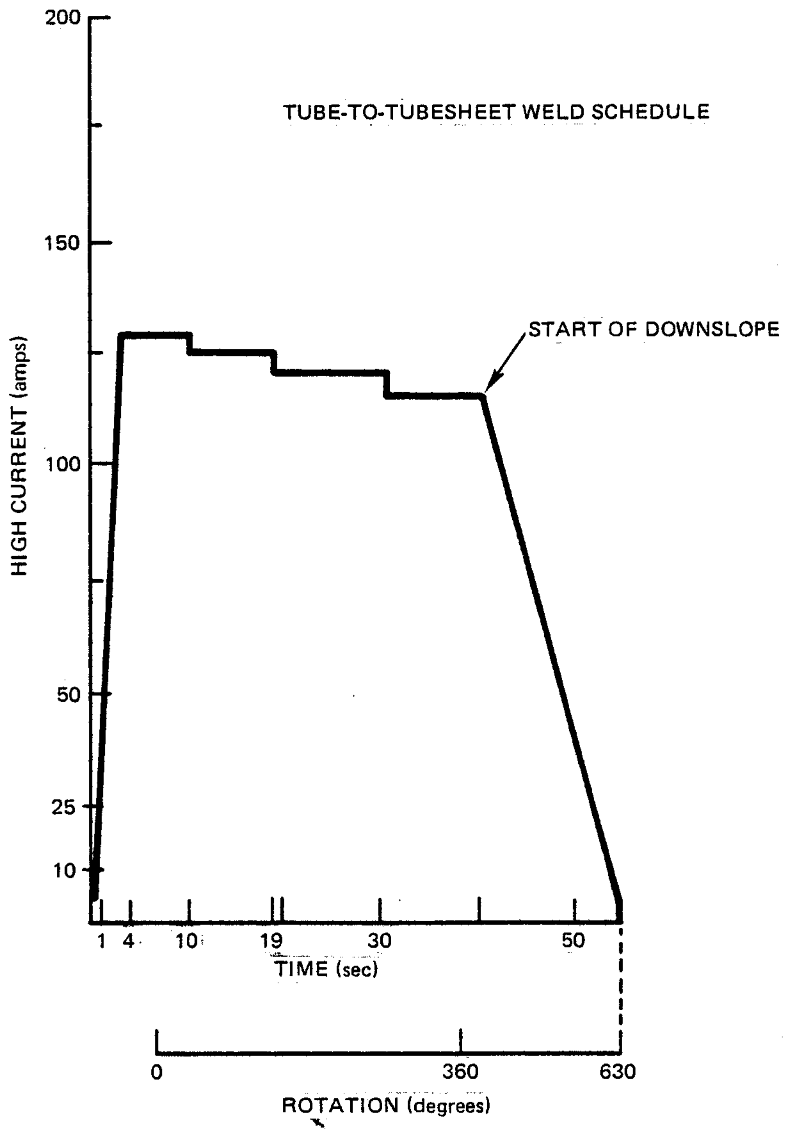


Figure 8 Tube-to-Tubesheet Weld Schedule

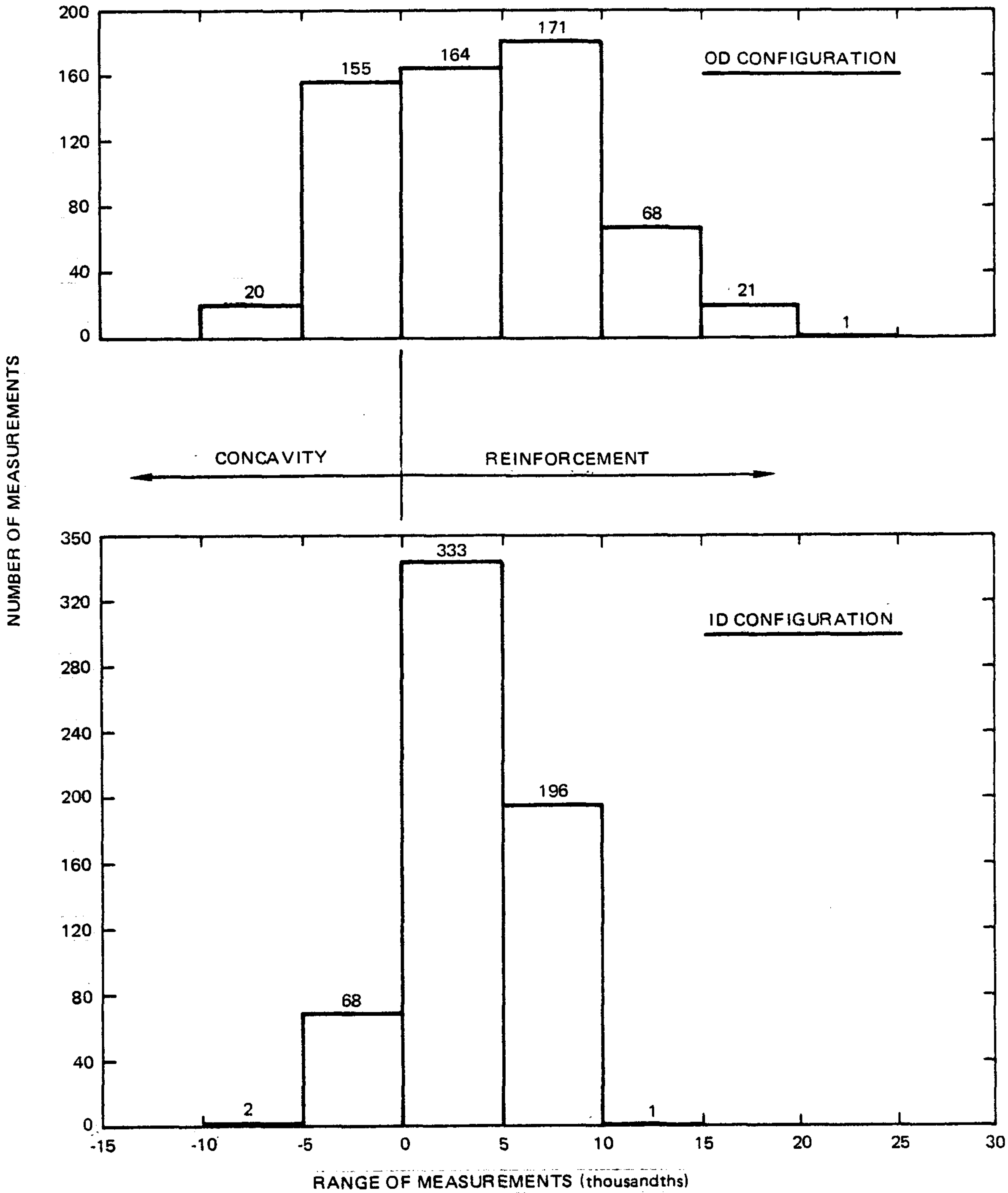


Figure 9 Process Demonstration Series, Tube-to-Tubesheet Weld Measurements

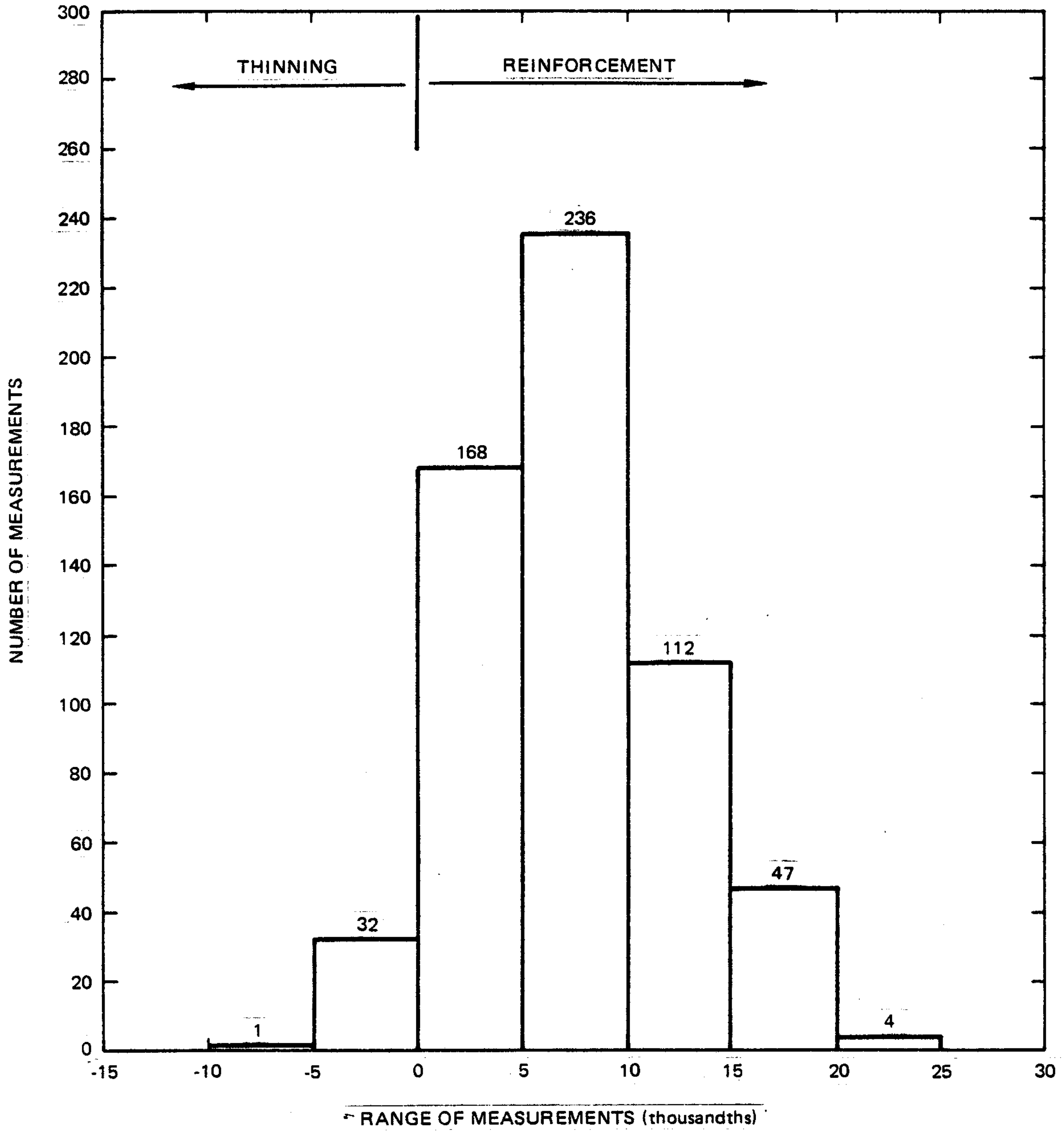


Figure 10 Process Demonstration Series, Tube-to-Tubesheet Weld Thickness Measurements

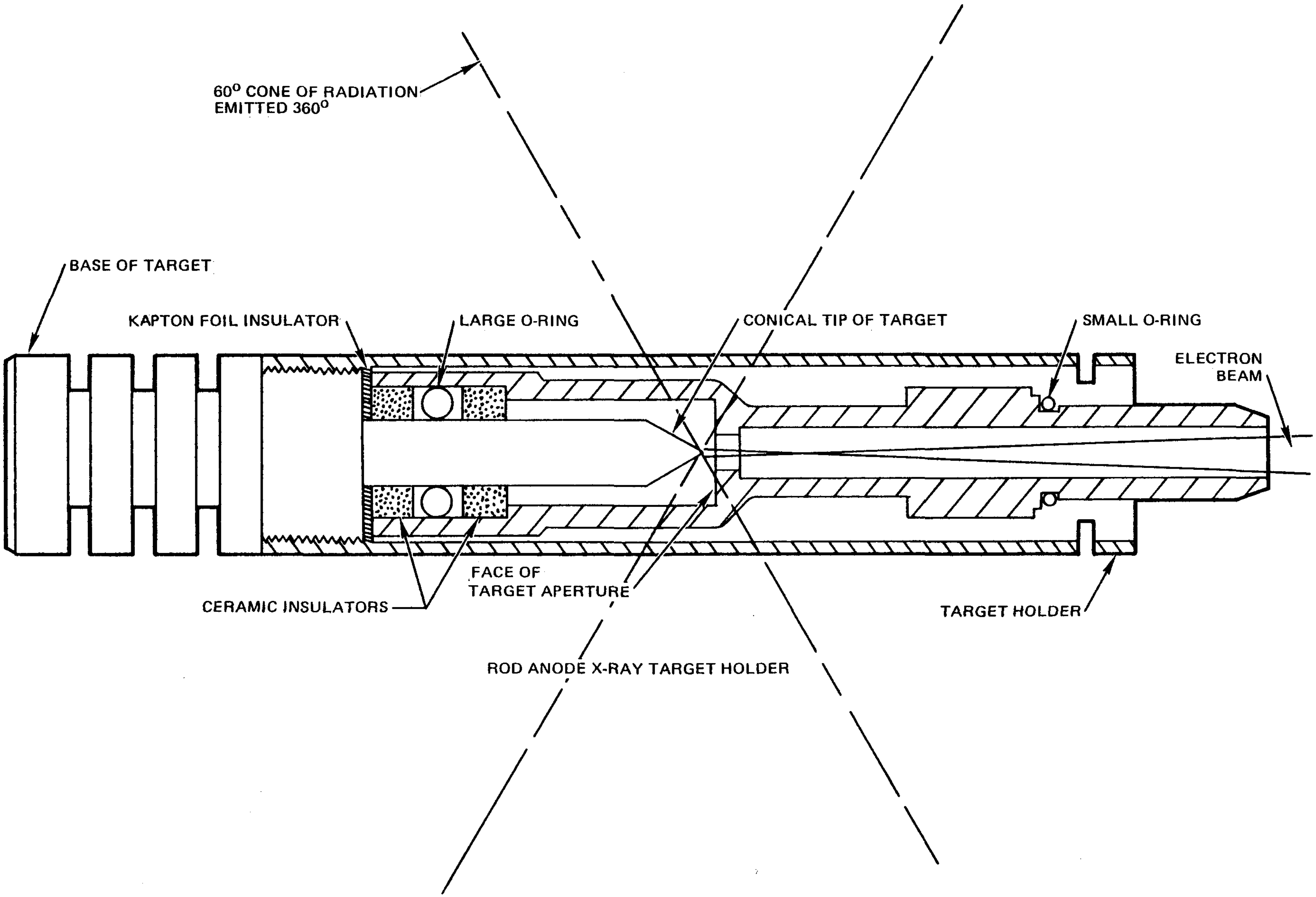


Figure 11 Rod Anode X-Ray Target Holder

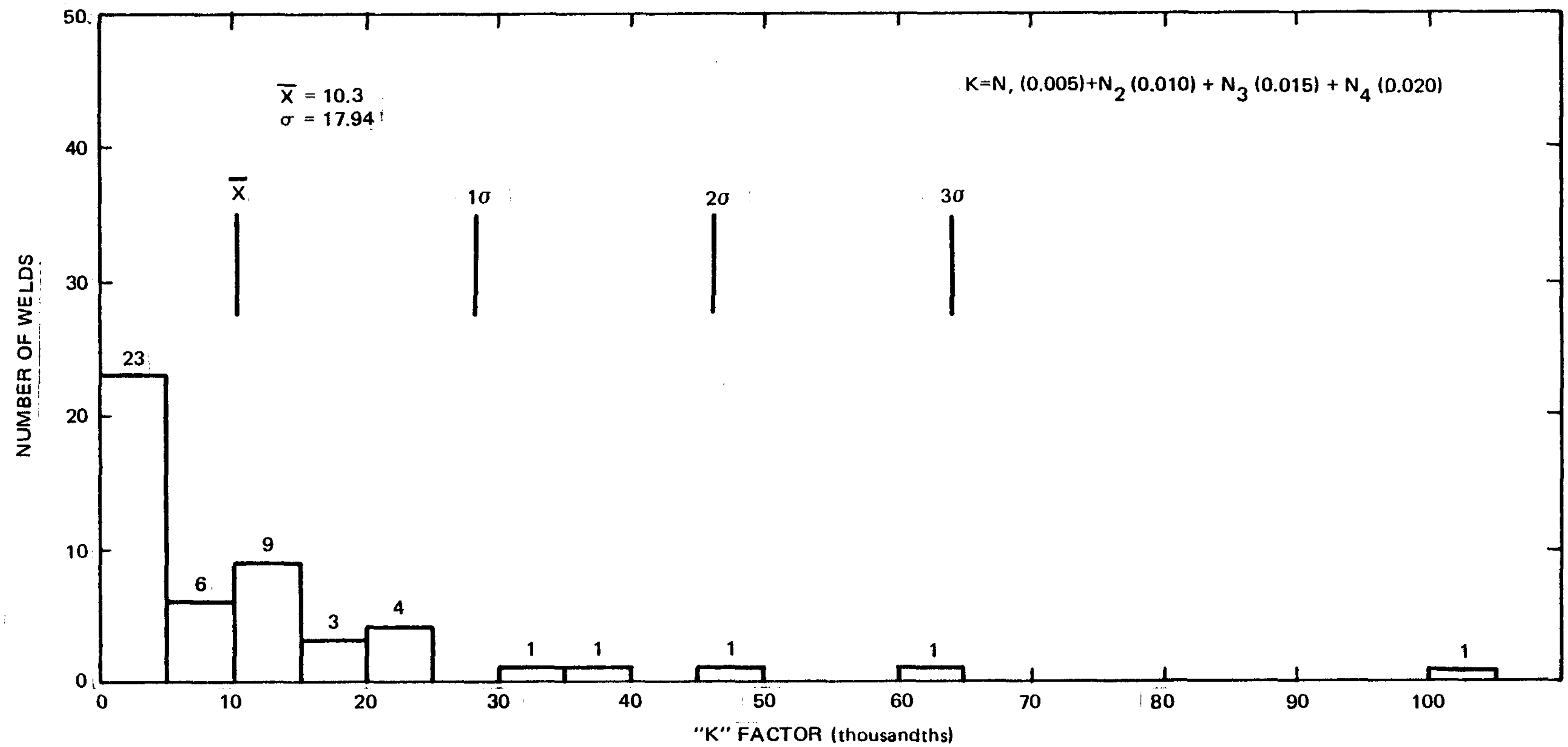


Figure 12 Process Demonstration Series, Tube-to-Tubesheet Weld Porosity, Al Rod Anode X-Ray Machine Examination of 50 Welds