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Welding for the CRBRP steam generators

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MASTER

The rationale for selecting weld design, welding procedures and inspection methods was based upon the desire to obtain the highest reliability welds for the CRBRP steam generators. To assure the highest weld reliability, heavy emphasis was placed on the control of material cleanliness and composition substantially exceeding the requirements of the ASME Code for 2-1/4Cr-1Mo. The high tube/tubesheet weld quality was achieved through close material control, an extensive weld development program and the selection of high reliability welding equipment. A pre-production run involving 300 welds demonstrated the ability of the manufacturing team to work with the methods and tools provided during the development stage. Prior to the initiation of manufacturing, control of the process and equipment was demonstrated by a 52 weld qualification run.

Shell and nozzle weld fabrication using TIG, MIG, and submerged arc procedures are also being controlled through precise specifications, including preheat and postheat programs, together with radiography and ultrasonic inspection to ascertain the weld quality desired.

Details of the tube/tubesheet welding and shell welding are described and results from the weld testing program are discussed.

INTRODUCTION

1. The material of construction for the Clinch River Breeder Reactor Plant Project steam generators is unstabilized 2-1/4Cr-1Mo. The basis for the selection of this material and the associated care in the specification requirements are covered in references 1, 2 and 3.

2. The importance of high integrity welds was recognized in the formulation of the specifications for tubes, tubesheets, shell plates and forgings which formed the critical sodium to water boundary as well as the sodium to air boundary. Metallurgical cleanliness was obtained through the use of Vacuum Arc Remelt (tubesheets) and Electroslag Remelt (tubing) techniques. The primary objectives in specifying melt refining practices were to (a) reduce the size and quantity of inclusions as well as porosity that could lead to a sodium/water leak path in the tubesheet stubs, (b) minimize the occurrence of defective tube/tubesheet welds and (c) reduce residual impurities in 2-1/4Cr-1Mo alloy that are likely to induce post weld embrittlement (ref. 2 and 4).

3. To establish optimum welding parameters for the tube/tubesheet (T/TS) joint, an extensive weld development program was performed, followed by a preproduction run of 300 welds from which the final welding parameters and acceptance criteria were established. Extensive use of the rod anode x-ray was utilized in the inspection of these welds. The preproduction run was followed by a procedure qualification of 52 consecutive acceptable welds.

4. Careful evaluation of time and temperature for the post weld heat treatment of the tube/tubesheet was made in order to optimize this cycle. Time was an important element because these welds were post weld heat treated and radiographed as they were fabricated to permit repair or replacement of defective welds.

5. Weld repair procedures that permitted localized grinding and manual rewelds of the T/TS joints were established as well as a tube plugging procedure.

6. Material specifications for shell plates, nozzles and headers were modifications of ASTM standards with changes to provide cleaner and more uniform chemical requirements. Special equipment was developed to weld, inspect and postweld heat treat these joints.

7. Testing of completed tube/tubesheet welds was performed to validate the weld integrity, using materials taken from CRBRP heats, welded under prototypical manufacturing conditions during the 300 and 52 weld runs. Tests were necessary to ascertain the effect of post weld heat treatment upon the metallurgical, corrosion, decarburization and mechanical properties of the welds. The accuracy and calibration of the radiographic technique was established by extensive metallographic work, which included quantitative measurements of porosity as well as identification of oxide inclusions when revealed by radiography.

PROCESS DEVELOPMENT AND INSPECTION

Tube-to-tubesheet welding

8. Joint design. As shown in Fig. 1, the steam generator tubes are joined to tubesheet

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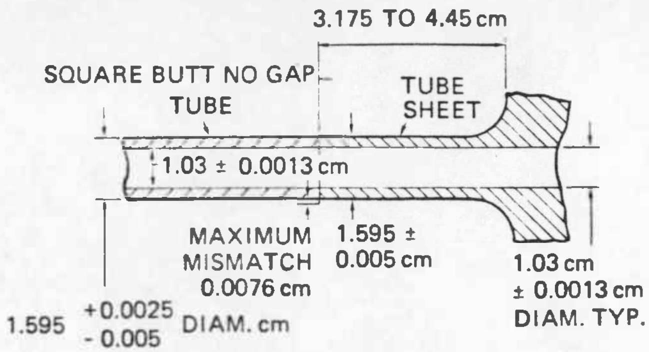


FIG. 1 TUBE-TO-TUBESHEET JOINT

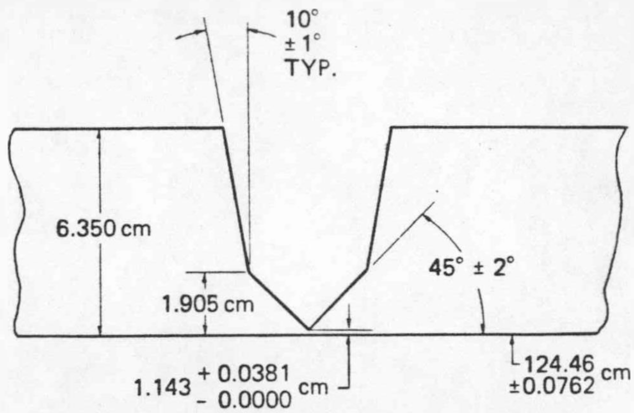


FIG. 4 TYPICAL SHELL WELD CONFIGURATION

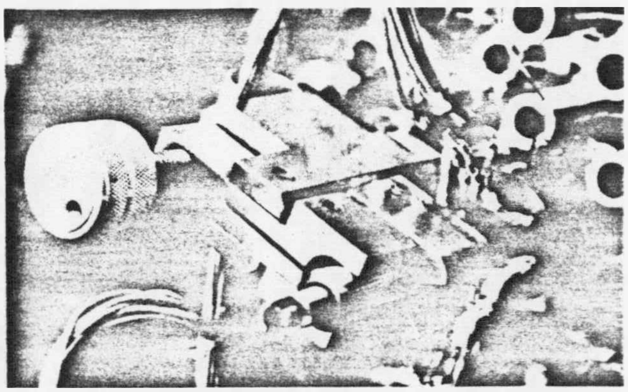


FIG. 2 BACKFACE OF TUBESHEET SHOWING HEATING MANIFOLD AND HOLD DOWN CLAMP

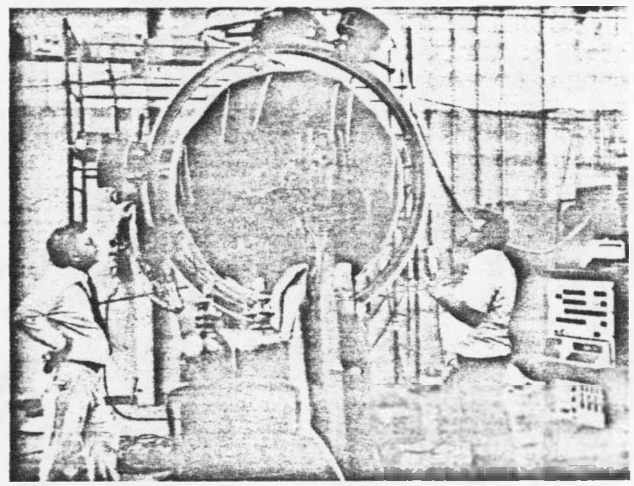


FIG. 5 SHELL WELDING EQUIPMENT

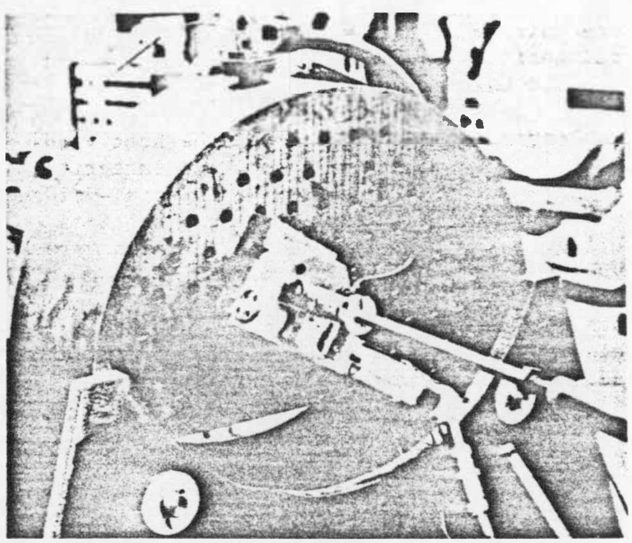
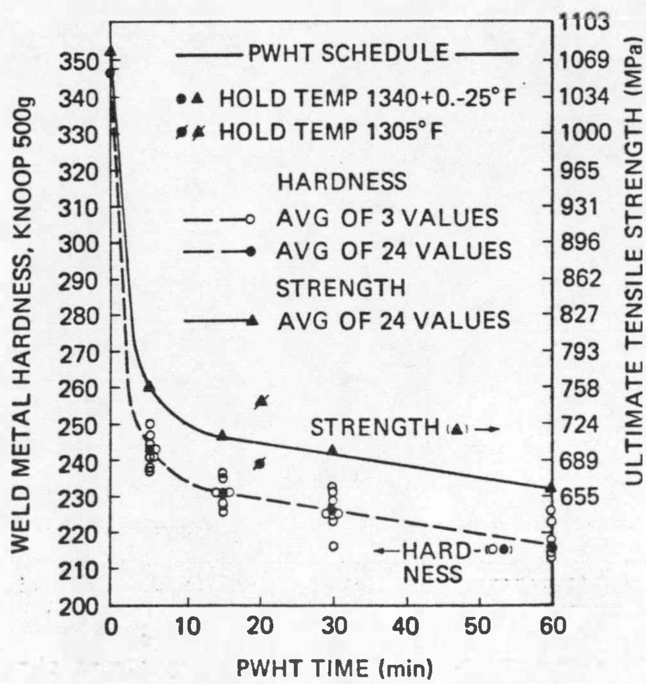


FIG. 3 FRONT FACE OF TUBESHEET SHOWING WELDING TOOLING



NOTE: Heating Time and Cooling Time = 12-15 min.

FIG. 6 EFFECT OF PWHT TIME AND TEMPERATURE ON TUBE/TUBESHEET WELD METAL projections, or nipples, machined out of the tubesheet forging. The tolerances indicated for the tubing and tubesheet were established during the weld development program and were found to be practical for the manufacturing process. A close fitting removable mandrel is used to align each tube with its mating tubesheet stub. After alignment, accurate positioning of the tube on the stub is maintained by axial pressure, applied by means of a spring-loaded clamp. No inserts are used in the weld joint.

9. Welding equipment. The welding system is made up of a highly accurate and stable welding power supply, a specially designed in-bore weld head, a purge gas control panel, and an external purge gas manifold (which also provides electrical preheat). Variations in output current or pulse frequency, innocuous in other welding applications, were found to be deleterious in achieving welds with a high statistical probability of meeting weld shape acceptance criteria. The welding power supply chosen provides an adjustable pulsed output, a high frequency pulse, four adjustable current levels during the weld cycle, and a variable current upslope and downslope.

10. The key design feature of the in-bore head inserted through the tubesheet and rotated by a DC motor, is the silicon carbide gas cup, which channels the flow of purge gas to the weld area, and centers the electrode holder. The gas cup material is highly resistant to thermal shock, thereby eliminating the need for auxiliary cooling. The tungsten electrode is held in the upper electrode holder by means of a nut which screws onto a tapered shoulder, permitting easy electrode replacement. Welding current and purge gas for the interior of the weld are introduced via a copper tube which positions the electrode holder. Slots in the electrode channel the purge gas to the weld area.

11. The purge gas control is extremely important in achieving acceptable weld geometry, by maintaining a preset difference in pressure between the inside and outside of the weld during the weld cycle. Pure purge gas (75% Helium-25% Argon) with no significant aspiration of oxygen from the atmosphere is provided by the external gas manifold. Electrical cartridge heaters within the manifold provide for weld preheat (Fig. 2).

12. Welding procedure. Cleanliness and smoothness of the weld mating surfaces were found to be of paramount importance in achieving welds with the extremely low porosity levels desired. Prior to welding, the mating surfaces are cleaned with detergent, rinsed, dried, and then mechanically polished.

13. The tube and tubesheet nipple are aligned, using an internal close fitting mandrel inserted through the tubesheet. The tube is clamped and loaded against the nipple, the external purge gas manifold is then clamped in place around the joint and the mandrel is removed (Fig. 2). The weld head is then inserted and clamped in place as shown in Fig. 3, and the joint is preheated to 430°F ±25°F (221°C ±14°C). The automatic weld cycle, which requires about 545 angular degrees of rotation, is then initiated. After welding, all equipment is removed and the completed weld is visually examined before proceeding to the next weld. If satisfactory, a special post weld heat treat manifold is installed around the weld and, with the aid of an additional cartridge heater, installed in the bore of the tube and in a pure Argon atmosphere the weld joint temperature is raised to 1340°F ±35°F (727°C ±19°C) at 60 to 160°F (16 to 71°C) per minute. After at least 20 minutes at 1340°F (727°C), the weld is allowed to cool. An infrared temperature sensing device is used in lieu of a contact thermocouple to measure the temperature of the joint. It has been determined experimentally that 20 minutes at 1340°F (727°C) decreases the hardness of the weld to an acceptable value.

14. Weld inspection. Each weld is subjected to visual examination of the exterior, dye-penetrant inspection, and helium leak checking. Each weld is radiographed using a rod anode x-ray source, inserted into the bore of the weld through the tubesheet. The x-ray film is wrapped around the exterior of the weld joint.

15. Standards stricter than the ASME Code have been established for acceptable porosity in the weld. The rod anode technique is capable of imaging pores as small as two thousands of an inch (0.051mm) in diameter under optimum conditions. In the entire weld, the total pore count must be such that the sum of diameters of all pores visible is less than 0.010 inches (2.54mm), e.g., four pores each 0.015 inches (0.381mm) and four 0.010 inch (0.254mm) pores would be just acceptable. In addition, other criteria are placed on local concentrations (clusters) of pores. For example, the total pore count of all pores in a 1/8 inch (3.175mm) circle anywhere in the weld must be such that the sum of their diameters is less than 0.025 inches (0.635mm). Any single pore with a diameter greater than 0.022 inches (0.559mm) is cause for rejection and repair of the weld. These standards have been consistently achieved in weld qualification runs by careful control of the entire weld process, including joint preparation.

16. Weld shape must meet certain geometrical requirements which have been established by detailed stress analysis. No more than 0.010 inches (0.254mm) concavity is allowed on either side of the weld surface, and wall thinning must also be less than 0.010 inches (0.254mm). Exterior concavity is measured with a dial gauge. Wall thinning and interior concavity are checked ultrasonically utilizing an instrument built specifically for this purpose.

Shell welding

17. The hockey stick configuration of the steam generator makes it impractical to perform all of the shell welds by rotating the unit itself under the weld head. For those shell welds performed in advance of the tube bundle assembly,

however, such rotation is feasible and the welds are accomplished using conventional welding equipment and techniques (gas-tungsten arc welding, gas-metal arc welding, and submerged arc welding).

18. The typical shell weld joint design and tolerances shown in Fig. 4 have proven practical to machine, thereby permitting automatic gas tungsten arc welding of the root.

19. All shell welds are preheated to a temperature between 400°F (204°C) and 600°F (316°C), and the temperature is maintained within ±50°F (28°C). Highly restrained welds are taken to post weld heat treat temperature immediately after welding, without dropping preheat temperature.

20. For unrestrained welds, stress analysis has shown that it is permissible to allow the weld to cool to ambient temperature any time after 3/4 inch (19mm) of weld metal has been deposited. This must be done under controlled cooling rates. This procedure, although not currently industry practice, has been done in production with no adverse consequences to the weld (such as cracking). Cooldown in this manner permits interim examination to uncover defects before the weld is finished.

21. The final closure welds and welds in the bend region of the "hockey stick" are made using gas-metal arc weld heads which travel on a circular track. As shown in Fig. 5, two of these heads may be mounted on one track to speed up the welding process. Utilization of advanced welding equipment with automatic seam tracking, proximity control, and pulsed output has permitted excellent welds to be made in all positions with deposition rates in excess of 5 lbs. per hour per head used, a uniform weld head pattern produced by this process. All shell welds are heat treated at 1340° ±35°F (727 ±19°C) for a length of time prescribed by the ASME Boiler and Pressure Vessel Code. Subsequent to post weld heat treatment, welds are subjected to liquid penetrant, ultrasonic, and x-ray examination per the Code.

TESTING OF WELDS AND EVALUATION

22. A series of tests were undertaken to verify the high reliability of the welding process. Welds taken from the development program and from the 300 weld qualification run are being subjected to (a) bend tests to identify susceptibility to brittleness, (b) hardness tests to determine the effectiveness of post weld heat treatments, (c) stress corrosion cracking tests to evaluate caustic stress corrosion susceptibility under faulted conditions, (d) flexural fatigue tests (to characterize the effects of the weld geometry, metallurgical structure and allowable porosity), and (e) stress rupture and burst tests to evaluate the weld mechanical efficiency under biaxial stress, relative to the tubing strength. To maintain prototypicality, 100 of the welds tested were made with tubing and tubesheet materials from the lots specifically procured and are a part of the CRBRP order. For comparison, a smaller number of specimens were included in the tests which originated from air melted heats of 2-1/4Cr-1Mo. The 150 welds have been or are currently being examined, 100 are from the 300 weld qualification series and can be considered fully prototypic.

23. To ensure the tube/tubesheet welds are adequately characterized, a group of repair welds are being tested. Evaluation of the repair welds is expected to be particularly informative in the case of the remelt welds, where grain growth and a type of "zone refinement" is present in the heat affected zone, because of the migration of trace elements. Trace elements such as P, Sb, Sn, and As can increase susceptibility to temper and creep embrittlement and may play a part in stress corrosion susceptibility; however, this risk has been minimized by the use of controlled composition remelt material.

Nondestructive testing

24. Nondestructive examination techniques included the microfocus rod anode radiography (90-100Kev) fluorescent magnetic particle examination, color contrast liquid penetrant, high sensitivity fluorescent liquid penetrant, and mechanical profilometry.

25. No evidence of insufficient penetration was encountered in the qualification welds. Pinhole indications less than 17 microns in diameter were observed on several welds, but further evaluation showed the pinholes to be inconsequential. Profilometry measurements for concavity, convexity, and wall thickness around the circumference of the welds indicated that while the regions of maximum convexity were typically 0.35mm to 0.60mm for the bore and outer diameter respectively, the areas of maximum concavity were typically in the region of 0.25mm. For six remelted specimens examined, however, the bore concavity was greater than 0.25mm, although none had wall thicknesses less than 0.277mm.

Metallography

26. Optical microscopy was performed on several tube/tubesheet weld longitudinal sections to determine the weld microstructure and heat affected zone (HAZ) size and structure. Due to the high cleanliness of the VAR and ESR material, no large inclusions were observed in the base or weld metal. A small number of fine pores was observed to exist randomly distributed through the weld metal. No buildup of inclusions or porosity was detected in the weld tail-off region of the five welds sectioned.

Post weld heat treatment of tube/tubesheet welds and the effects on weld hardness

27. Four welds without post weld heat treatment (PWHT) were slit to produce 12 equal sectors. Eight of the 12 sectors were given a 1 hour 727°C (1340°F) post weld heat treatment. Knoop 500g microhardness profiles were taken before and after PWHT across polished surfaces of the weld regions shown in Table 1. Each value in Table 1 represents the average of at least 36 readings. The values of UTS are important since weld metal and HAZ cracking and embrittlement

resistance are considered optimum when the strength or hardness of the weld is reduced below 655MPa (ref. 4). The average Knoop 500g of the tubing and tubesheet, unaffected by the welding operation, was 171.

Table 1. Weld and HAZ hardness (Knoop 500g) and UTS (MPa) average values - one hour PWHT

	Tubesheet Heat Affected Zone(HAZ)		Weld Metal		Tubing Heat Affected Zone(HAZ)	
	Hardness	UTS	Hardness	UTS*	Hardness	UTS
As-welded	297	894	346	1073	306	966
After PWHT	201	616	222	682	199	609

*Converted from hardness values using the Rockwell Table.

Effect of PWHT temperatures and hold times

28. To determine the effect of fast heating and cooling rates (ten to fifteen minutes to heatup or cooldown) and variable hold times (1 hour or less) during post weld heat treatment, an additional series of heat treatments was conducted. Eight specimens were heat treated in argon for each of the time periods shown in Fig. 6 at 727°C (1340°F). Three Knoop 500g microhardness measurements were made on each of the three zones of interest (HAZ/weld/HAZ) on each sample and the weld metal values are presented graphically in Fig. 6, along with the ultimate tensile strength values obtained by hardness conversion. Irrespective of hold times, the weld metal retained the highest hardness and corresponding UTS value.

29. The automatic control for the localized post weld heat treatment procedure is programmed to switch off when the temperature reaches 727°C (1340°F) rather than switching off at a lower temperature and coasting to 727°C. For this reason, a temperature overshoot is more likely than an undershoot. Nevertheless, since the specification permits a temperature minimum of 708°C (1305°F), the adequacy of a post weld heat treatment at this temperature was investigated. Eight tube/tubesheet weld sections were post weld heat treated at 708°C for 20 minutes. The average weld metal hardness was reduced to Knoop 500g load 239.0, which converts to 744MPa (107.9 ksi) UTS, equivalent values (after a 727°C (1340°F) heat treatment would be expected to be Knoop 230 and tensile strength 703MPa). These 708°C (1305°F) data, along with the 727°C (1340°F) data, were plotted as a function of hold time in Fig. 6. As can be seen from the figure, the hardness and corresponding tensile strength of the weld metal (the hardest and strongest part of the weld region) are reduced the greatest amount during the first 15 minutes at temperature. To produce a microstructure least susceptible to cracking, the heat treatment should ideally be continued for a full hour. However, the continual balance between cost and benefit, which is always present in a fabrication campaign, dictated that the advantage gained did not merit the additional production time cost. It was decided that a 20 minute post weld heat treatment was adequate.

Ductility and toughness tests

30. Constrained U-bend tests were performed on sixteen (16) ninety degree sectors taken from tube/tubesheet welds. Root and face bend tests (ASTM E-190) were performed on specimens in the as-welded condition and in the post weld heat treated condition (1 hour-727°C). No cracking was observed in any of the specimens either by visual examination or high sensitivity fluorescent magnetic particle examination.

31. Subsize Charpy V-notch impact toughness tests were performed on a number of tube/tubesheet welds in an attempt to determine the effect of post weld heat treatment on the weld region. The difficulties of this type of test on small thin section specimens are well known, but it was considered worth the effort to obtain this information.

32. Specimens were fabricated according to ASTM Standard E-23 with a standard width and length, 2.79 x 10 x 55mm, notch, 0.61mm deep, and a subsize thickness (approximately 3mm), with the weld positioned across the full specimen width. Despite the reduction in cross-sectional area and the stress triaxiality at the notch, the specimens bent without cracking in the un-notched base metal at temperatures as low as -73°C (-100°F). At -101°C (-150°F), brittle fracture occurred in the notched HAZ. Typical results were as follows:

Temperature °C	CVN Energy (J)
25	10.8[1]
-18	10.8[1]
-46	14.2[1]
-73	15.6[1]
-186	0.7[2]
-101	3.4[2]

[1]No fracture specimen bent in the un-notched base metal.

[2]Fracture in the heat affected zone.

33. Although the results are very favorable (and most probably due in part to the use of remelt material and correct heat treatments), the specimen thickness confounds the results since we consider that a condition of high plane stress rather than nearly plane strain exists at the notch tip. This condition would make brittle fracture unlikely at temperatures above 0°C.

Stress corrosion tests

34. Stress corrosion tests were performed in 10% and 20% (by weight) sodium hydroxide solution at 232°C (450°F), conditions chosen to simulate CRBR shutdown and requalification following a sodium intrusion into the water side of the steam generator. Both tube/tube and tube/tubesheet welds were evaluated. Sixteen (16) tensile samples with the weld centered in the gage section were fabricated as illustrated in Fig.7 and tested under constant load. The original weld combinations included air melt tubing

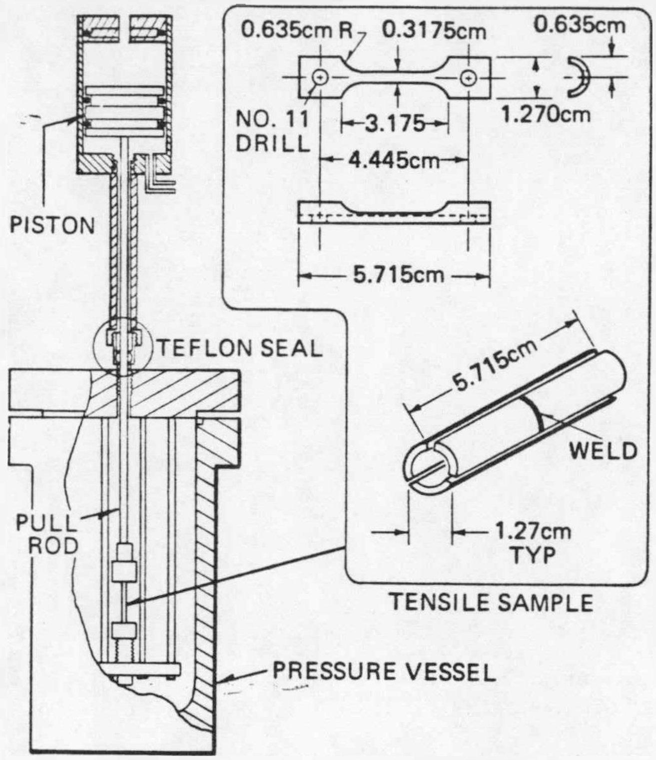


FIG.7 TUBE/TUBESHEET WELDS: STRESS CORROSION APPARATUS. (ABOVE CYLINDER AND LOAD TRAIN IS ONE OF TWELVE)

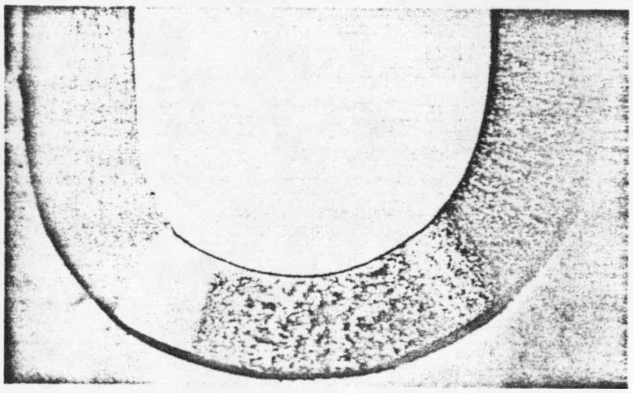


FIG.8 CONSTRAINED U-BEND TUBE/TUBESHEET WELD TESTED IN 20% NaOH AT 232°C (450°F) SHOWING CRACKING IN WELD METAL (SPECIMEN No. 1079A)

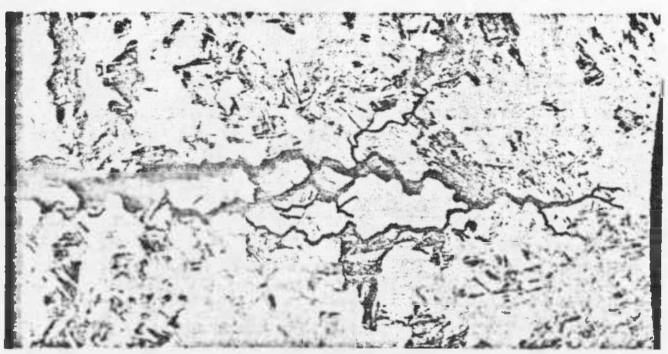


FIG.9 SAME SPECIMEN AS ABOVE SHOWING BRANCHED, INTERGRANULAR NATURE OF CRACK PROPAGATING THROUGH WALL THICKNESS, MAGNIFICATION ~ 34X

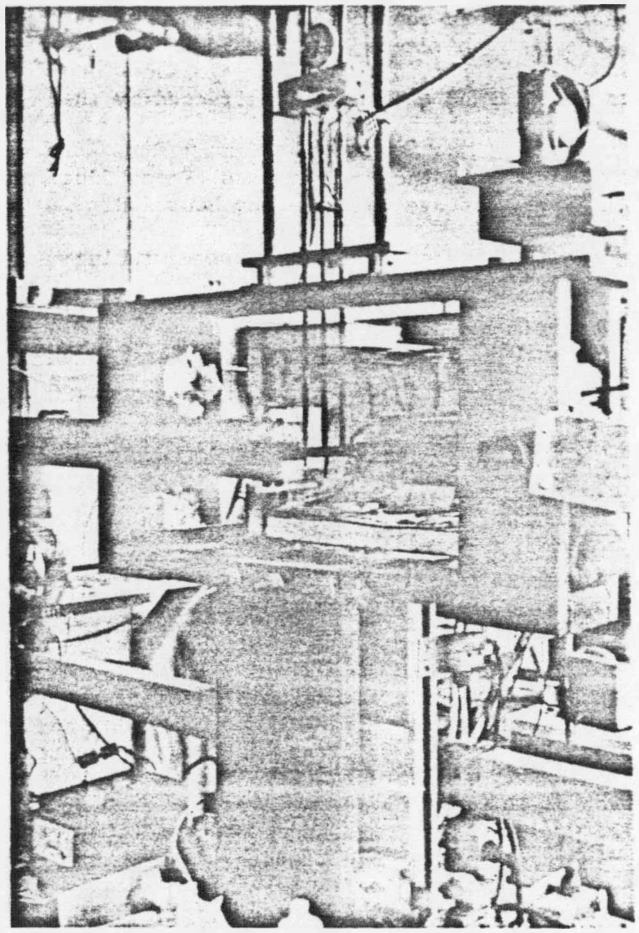


FIG.10 FLEXURAL FATIGUE TEST APPARATUS

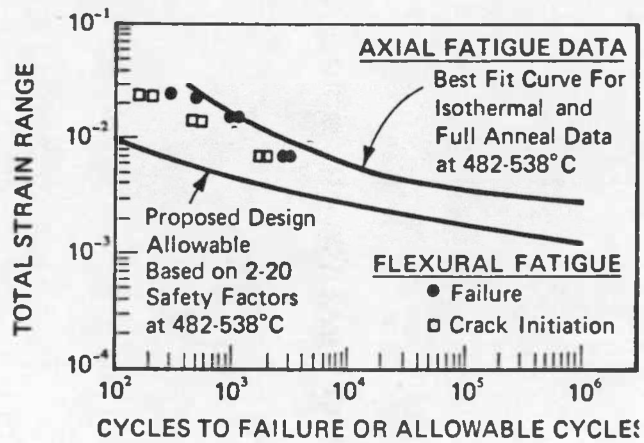


FIG.11 TUBE/TUBESHEET WELDS FLEXURAL FATIGUE DATA COMPARED WITH AXIAL FATIGUE DATA FOR 2-1/4Cr-1Mo

welded to air melt tubing, vacuum arc remelt (VAR) to VAR tubing, and electroslag remelt (ESR) to VAR combinations. In addition, a number of welds from each of the above combinations were post weld heat treated for one hour at 727°C (1340°F). Thus, six metallurgical conditions were evaluated.

35. The first group of specimens were tested in 10% sodium hydroxide at 232°C (450°F). Three specimens failed after less than 1 hour of testing (Table 2); all had been fabricated from air melt material. Examination of the fracture surfaces showed all failures were initiated by intergranular stress corrosion cracking in the weld center. Some plastic deformation had occurred in the unfailed samples, but none of these showed any indications of cracking. It should be noted that all of the air to air melt weldments had some degree of porosity, but although these flaws could have affected the initial cracking location and growth rate, they would not predetermine the cracking mechanism, i.e., stress corrosion. Apparently the weld metal itself was extremely susceptible to stress corrosion cracking since no cracking occurred in the mechanically weaker base metal.

36. Testing continued on the unfailed samples in run two when two additional samples failed in less than 2 hours. One failed sample was fabricated from VAR tubing welded to ESR tubing and the other from air melt welded to air melt. The fracture mode was identified as a combination of intergranular fracture and ductile tearing. The area percentages of these fracture modes which existed as separate, rather than intermixed regions, were approximately 60-70% intergranular and 30-40% ductile tearing, respectively. It is encouraging to note that most of the specimens did not fail after 1248 hours in this aggressive environment, even though stressed at values close to the weld metal yield point. Testing was continued on the unfailed specimens in run three with 10 additional samples added and the NaOH strength increased to 20%. These specimens, in run 3, were the first fully prototypical welds taken from the 300 weld qualification series. The test temperature remained the same 232°C (450°F), which is considered to be in the region of maximum susceptibility to stress corrosion attack for this alloy (ref. 5). One specimen failed (a specimen without PWHT) by stress corrosion cracking after approximately 10 minutes testing. The fracture location was determined to be in the heat affected zone along prior austenite grain boundaries. A second specimen, also without PWHT, failed after approximately 378 hours with the same fracture mode. <u>None of the tensile specimens with PWHT failed</u>.

<u>U-bend stress corrosion tests</u>

37. Sixteen constrained U-bend specimens were tested in 20% sodium hydroxide solution at 232°C for a total test duration of 1607 hours. The specimens were prepared as described previously under ductility and toughness tests. Eight of the U-bend specimens were tested in the as-welded condition, and eight were tested in the post weld heat treated condition (1 hour). Half of each group were face bend, the other half were root bend. Six of the eight as-welded specimens failed, whereas none of the post weld heat treated specimens failed. The U-bend test conditions and results are shown in Table 3. Figures 8 and 9 show the macrostructure and microstructure of a U-bend as-welded specimen which failed in the weld metal at the fusion line.

38. An evaluation of the data resulting from the stress corrosion tests leads to some interesting conclusions:

1. The air melt material appeared to be more susceptible to stress corrosion cracking than the remelt material, either VAR or ESR, in that air melt weld specimens, stressed near the yield point in 10% sodium hydroxide at 232°C, cracked whether post weld heat treated or not.
2. <u>None</u> of the post weld heat treated electroslag remelt or vacuum arc remelt specimens cracked during the stress corrosion testing, but 80% of the ESR/VAR specimens cracked if not post weld heat treated.
3. There are strong indications that both VAR and ESR materials are more resistant to stress corrosion cracking than air melt material based on the tests performed. Vacuum arc remelt material appears to be superior to electroslag remelt material in this respect. None of the welds made solely with VAR material cracked whether post weld heat treated or not.

39. The ESR process is more effective in removing phosphorus, the major deleterious element as regards embrittlement. The material specifications for VAR and ESR grades both required phosphorus levels below 0.015% and examination of the analyses of both groups of materials shows, in fact, very comparable phosphorus levels; but, the VAR process also removes arsenic, tin, hydrogen, and nitrogen, apparently benefiting the VAR grade in terms of resistance to caustic stress corrosion cracking.

<u>Stress rupture tests</u>

40. Internally pressurized stress rupture tests are being performed at 510°C (950°F) and 566°C (1050°F) on tube/tubesheet welds in the as-welded post weld heat treated and post weld heat treated and aged conditions (aging temperature 510°C for 1000 hours). The specimens are machined and internally bored, reamed and honed to reduce the wall thickness and produce a smooth external and internal surface. The final wall thickness in the gage region is one millimeter. No results are currently available.

<u>Fatigue testing</u>

41. The Clinch River Breeder Reactor (CRBRP) steam generator is the hockey stick type (ref. 2). Thermal expansion stresses, due to temperature differences between the shell and the tubing, as well as regions within the tube bundles, are mitigated by flexing at the tube bends. Fatigue stressing of the tubesheet welds at least at the upper tubesheet, will therefore be flexural.

42. The tube/tubesheet welds are being tested in

Table 2. Constant load stress corrosion tests
Temperature: Run Nos. 1,2, and 3 232°C
Time: Run No. 1: 1 hour; Run No. 2: 1248 hours; Run No. 3: 1607 hours
Sodium hydroxide concentration: Run Nos. 1 and 2: 10%; Run No. 3: 20%

Sample Number	Stress MPa	Material Combination[1]	Heat Treatment[2]	Product Form[3]	Total Exposure Run No.	Total Exposure Total Hours	Failure Time, Hrs.
1529	413.7	AA	AW	TT	1&2	1249	1.8
1530	413.7	AA	AW	TT	1	1	<1
1531*	413.7; 310.3; 379.2*	AA	AW	TT	1,2&3	2856	No Failure
1538	413.7	EV	AW	TT	1&2	1249	1.6
1539	413.7	EV	AW	TT	1&2	1249	No Failure
1560	379.2	EV	AW	TF	2	1607	No Failure
1563	379.2	EV	AW	TF	3	1607	.067
1566	379.2	EV	AW	TF	3	1607	No Failure
1540	379.2	EV	AW	TT	1,2&3	2856	No Failure
1528	379.2	VV	AW	TT	1,2&3	2856	No Failure
1526	379.2	VV	AW	TT	1&2	1249	No Failure
1527	379.2	VV	AW	TT	1&2	1249	No Failure
1533	379.2	AA	PWHT	TT	1,2&3	2856	1627
1534	379.2	AA	PWHT	TT	1	1	<1
1532	413.7	AA	PWHT	TT	1	1	<1
1541	379.2	EV	PWHT	TT	1,2&3	2856	No Failure
1542	379.2	EV	PWHT	TT	1,2&3	2856	No Failure
1555	379.2	EV	PWHT	TF	3	1607	No Failure
1556	279.2	EV	PWHT	TF	3	1607	No Failure
1558	379.2	EV	PWHT	TF	3	1607	No Failure
1561	379.2	EV	PWHT	TF	3	1607	No Failure
1562	379.2	EV	PWHT	TF	3	1607	No Failure
1564	379.2	EV	PWHT	TF	3	1607	No Failure
1565	379.2	EV	PWHT	TF	3	1607	No Failure
1543	344.7	EV	PWHT	TT	2	1248	No Failure
1536	344.7	VV	PWHT	TT	2	1248	No Failure
1535	379.2	VV	PWHT	TT	1&2	1249	No Failure
1537	379.2	VV	PWHT	TT	1&2	1249	No Failure

[1]Material combinations: V=Vacuum arc remelted; E=Electroslag remelted; A=Air melted
[2]Heat treatments: AW=As-welded; PWHT-1 hour 727°C (1340°F), or as noted.
[3]Product form: T=Tubing; F=Forging spigot
*The stress for specimen 1531 was varied for each test run, i.e., Run No. 1: 413.7MPa; Run No. 2: 310MPa; Run No. 3: 377.2MPa.

Table 3. U-bend caustic stress corrosion test
20% NaOH, 232°C (450°F)
Exposure time: 1607 hours

Weld No.	Bend Type*	Heat Treatment**	Failure Location
1079A	Root	AW	Weld
1081A	Root	AW	HAZ
1083A	Root	AW	None
1082A	Root	AW	None
1086A	Face	AW	HAZ
1088A	Face	AW	HAZ
1092A	Face	AW	HAZ
1087A	Face	AW	HAZ
1081B	Root	PWHT	None
1083B	Root	PWHT	None
1082B	Root	PWHT	None
1079B	Root	PWHT	None
1088B	Face	PWHT	None
1086B	Face	PWHT	None
1092B	Face	PWHT	None
1087B	Face	PWHT	None

*Weld Root is tube OD. Weld Face is tube ID.
**Heat treatments: AW-As-welded; PWHT=1 hour, 727°C (1340°F)

two different flexural modes--four point bending and cantilever bending. The specimens are constructed with a heavy grip region machined out of the tubesheet material at one end of the specimen. At the other end, the tube end, a heavy bolster is welded on to form the grip. A 6.35mm diameter tube connects the bore of the test specimen with a helium supply. Failure of the weld is established by detection of helium passing through the tube wall. Both four point and cantilever tests are performed in the same test facility (Fig. 10).

43. As can be seen, the loading apparatus penetrates the walls of the furnace. For four point bending, both flexural arms apply vertical oscillatory motion. For the cantilever test, one arm is fixed. Load cells are used to calibrate each flexural arm. Specimen strain is determined by three free floating rods linked to Linear Variable Transformers (LVDT's). This LVDT system is in turn calibrated cold against resistance strain gages at three locations on the specimen.

44. The test program calls for flexural fatigue tests at 510°C and 10^2, 10^3, 10^4, 10^5, and 10^6 cycles. To obtain a clear baseline, plain tubing will be tested along with the tube/tubesheet welded sections. Welds with the highest level of porosity will be compared with welds free from porosity. Repair welds are being tested to evaluate the effect of the repair operation and repeated remelting, other specimens were given an aging treatment at 510°C for 1000 hours following post weld heat treatment. Aging at this temperature promotes diffusion of trace elements to the grain boundaries; if any embrittlement is likely to occur at 510°C (the approximate CRBR operating temperature), the majority of it will occur within the first 1000 hours.

45. In Fig. 11, the results are evaluated against the proposed design allowable curve for axial strain controlled data. This curve is based on the safety factors of 2 on strain, and 20 on cycles to failure. In addition, the best fit curve is plotted for the data from which the design curve was derived.

46. All available data to date falls above the design curve, but generally below the best fit curve. No firm conclusions can be drawn until data are obtained at higher numbers of cycles. It is, however, noteworthy that none of the failures has yet occurred in the welds.

TESTING OF HEAVY SECTION WELDS

47. Welded test sections will be fabricated, using methods and materials prototypic to steam generator units. The planned testing of these specimens includes fracture toughness, tensile and drop weight, long term creep fatigue, and creep rupture tests.

CONCLUSIONS

48. The welding process for tube/tubesheet welds for the Clinch River Breeder Reactor steam generators was established by means of a well controlled pre-production manufacturing campaign. The results verified earlier expectations for a high quality weld needed for this project.

49. A comprehensive weld testing program is now underway to confirm the structural integrity of the tube-to-tubesheet welds, through detailed and specialized testing methods. The results obtained to date indicate that the welds made are of high integrity. Initial fatigue testing results show the welds to exceed design requirements.

50. A noteworthy feature of the weld test program is the strong indication of high resistance of ESR and VAR grades to stress corrosion cracking, under highly corrosive conditions. We believe that specifying remelt refining for the tubing and tubesheets has enhanced the reliability of the steam generators over air melted steel. Examples are as follows:

1. The high yield of pore-free tube/tubesheet welds during the 300 weld statistical run.
2. Increased resistance to stress corrosion cracking.
3. Increased resistance to decarburization (ref. 1).

The modest incremental costs incurred for specifying remelt refining are believed more than offset by higher yields and lower weld repair rates during the manufacture of the steam generators.

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