WCAP-11174

ROW 1 AND ROW 2 HEAT TREATMENT

FOR

COMANCHE PEAK UNIT 1

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ROW 1 and 2 U-BEND HEAT TREATMENT LICENSING REPORT FOR COMANCHE PEAK UNIT 1

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1.0 INTRODUCTION

Primary water stress corrosion cracking (PWSCC) of mill annealed Nickel Chromium Iron Alloy 600 steam generator tubing has been identified as having a potential effect on the operation of steam generators. PWSCC appears to occur in areas of high residual stress of steam generator tubes, such as the U-bend region of small radius tubes and the roll and roll transition zones within the tubesheet. As part of an ongoing steam generator PWSCC preventative measure program, Westinghouse has developed a process that provides additional margin against inner diameter (ID) PWSCC that may occur in the U-bend region of some row 1 and row 2 steam generator tubes by reducing residual tensile stress at or near the inner surface of the tube through the application of a thermal stress-relief cycle.

The concept of the U-bend heat treatment process and system design is based on observations to date indicating that PWSCC appears to develop in the U-bend region of steam generator tubes at the tangent points of the transition between the straight and U-bend sections of the tube and at or near the apex of the U-bend. The latter appears to occur only in cases with substantial ovality or denting. Examination of tubes with leaks in the U-bend region that were removed from operating plants has shown that the leakage occurred at ID initiated, generally short, tight (low leakage) axially oriented cracks through the tube wall. The examinations indicated that the cracks were initiated and propagated by intergranular stress corrosion. Because no specific contaminant in the reactor coolant has been identified as the corrodant, the reactor coolant water itself is assumed to be the corrodant in a manner similar to pure water.

The process and tooling system for thermal stress relief have been developed and qualified by Westinghouse for application on the Model D-4 steam generators at Comanche Peak Unit 1. This report presents a discussion of the development and qualification of the U-bend heat treatment program and its beneficial affect of enhancing resistance to PWSCC. More importantly, a safety evaluation is provided where it is demonstrated that the application of the U-bend heat treating PWSCC preventive measure process to the ID of a steam generator tube does not represent a potentially unreviewed safety question as defined in 10 CFR 50.59 (a) (2).

2.0 U-BEND HEAT TREATMENT OBJECTIVES AND PROCESS DESCRIPTION

2.1 Objectives

The objective of the U-bend heat treatment program at Shearon Harris Unit 1 is to provide a means of reducing the residual stresses that appear to contribute to PWSCC on the ID of small radius U-bends of steam generator tubing. This is achieved through the reduction of residual tensile stresses at or near the inner surface of the tube by heating the U-bend areas of Row 1 and 2 heat transfer tubes. Stress relief from the in situ thermal treatment process has been demonstrated in the laboratory to beneficially reduce primary water initiated stress corrosion cracking in the U-bend region.

One hundred percent (100%) of row 1 and row 2 active steam generator tubes will be thermally treated in the U-bend area. Thermal treatment will be accomplished by insertion of a [ ]^{a,c,e} heater from the tubesheet to the U-bend area and heating at the optimum time and temperature cycle. The heating system is to include the [

]^{a,c,e} Process optimization involves rapid tool insertion and removal, and selection of the most efficient [ ]^{a,c,e} to achieve the desired stress relief that is beneficial in reducing PWSCC.

2.2 Process Description

The U-bend heat treat objective is to heat a U-bend section extending between [

]^{a,c,e}

[

(3)

(4)

]^{a,c,e}

The heat treatment process and tooling system is described in greater detail in Section 3 of this report.

2.3 U-Bend Heat Treatment Time/Temperature Range

The current U-bend stress relief temperature and time parameters were developed under programs partially funded by the Electric Power Research Institute (EPRI) in which the emphasis was on exploring the minimum temperature and time that would provide additional margin of resistance to PWSCC in the [ ]^{a,c,e} Initial studies were done using reverse U-bend tubing sections in 680°F water. This program has been extended to quantify additional resistance to PWSCC using prototypically heated and stressed U-bends that have been evaluated in 750°F superheated steam. The continuing thermal stress-relief program shows an extension of life of over [ ]^{a,c,e} A description and data presentation of test programs that resulted in the establishment of the reference specification parameters is included in Section 4 of this report.

3.0 U-BEND HEAT TREATMENT TOOLING SYSTEM DESCRIPTION AND QUALIFICATION

3.1 Tooling System Description

The tooling system description for effecting the heat treatment of the Row 1 and Row 2 U-bends of the Shearon Harris Unit 1 Model D4 steam generators consists of a:

A. Channel head end effector
B. Heater insertion mechanism
C. Temperature detection system
D. Heater and cable assembly including power supply and control system

Briefly, as noted previously, the underlying concept of the U-bend heat treatment program is to provide a heater which is inserted into the Row 1 and 2 tube to a known depth [

]^{a,c,e} This insertion depth positions the heater in a location that provides the required heat to effect heat treatment to an area bounded [

]^{a,c,e}

3.1.1 Channel Head End Effector

For the U-bend heat treatment of the Shearon Harris Unit 1 Row 1 and 2 steam generator tubes, a channel head end effector is [ ]^{a,c,e} positioned under the designated tube prior to insertion of the heater. The system is illustrated in Figure 3-1. [

]^{a,c,e} Operation of the end effector is controlled from a point outside the channel head in the Control Area.

3.1.2 Heater Insertion Mechanism

The heater cable assembly is an integrally designed unit with a suitable outer sheath to withstand the insertion loads required by the mechanism. [

]a,c,e

Two techniques have been developed and evaluated for verifying the as-built tangent point location in Row 1. [

]a,c,e

The backup technique for locating U-bend [

]a,c,e Both techniques are acceptable for field work. The insertion probe is the reference system.

3.1.3 Temperature Determination System

[

]a,c,e

[

][a,c,e]

3.1.4 Heater and Flexible Insertion Conduit Assembly

A [ ][a,c,e] heater is used as the heat source for the U-bend heat treatment process. [

][a,c,e]

[

][a,c,e] is inert at temperatures reached during the heat treatment process and, most importantly, does not sinter or fuse to itself at those temperatures, which would render the heater assembly inflexible and brittle after a single heating cycle.

The structural core of the heater [

][a,c,e]

A 1/2 inch diameter [ ][a,c,e] tube is used as the heater insertion conduit. A combination of braided and solid stainless steel sections at the conduit to heater interface provide a standoff distance of approximately [

][a,c,e]

[

]a,c,e

3.2 Process Controls

Row 1 and Row 2 heat treatment process control is provided by [

]a,c,e When a tube is heated by applying a voltage across the heater located within the tube, the tube wall temperature starts to rise. The tube, in turn, loses heat to its surroundings by conduction, convection, and radiation heat transfer mechanisms. At low temperature, the heat loss from the tube wall is small compared to the heat input from the heater and hence, tube wall temperature continues to increase. At higher temperatures, the heat loss approaches the heat input. Finally, an equilibrium temperature is achieved where the heat input is equal to heat loss. The numerous tests conducted in the laboratory have shown that equilibrium is achieved approximately [ ]a,c,e after commencement of the heating cycle. [

]a,c,e

[

]a,c,e

This [
]a,c,e resultant temperature distribution through the U-bend has been confirmed and defined by many lab tests employing continuous monitoring [

]a,c,e

[

]a,c,e The purpose is to furnish another verification of the lab data and demonstrates there are no anomalous conditions in the actual steam generator tubing that would affect the temperatures obtained. For this reason the field procedure includes performing an abbreviated heating cycle [

]a,c,e

[

]a,c,e.

[

]a,c,e

3.3 Process Qualification Effort

A thorough test and qualification program was undertaken to verify the adequacy of the Row 1 and Row 2 U-bend heat treatment process. Functional requirements were determined prior to the qualification program. These requirements were then used during qualification to demonstrate that the U-bend heat treatment process is a viable PWSCC margin enhancement technique and that the tooling system (i.e., heater assembly, insertion mechanism, channel head manipulator, etc) can fulfill its intended function by meeting or exceeding established design criteria. A brief summary of the Shearon Harris Unit 1 qualification program follows:

A. The tooling system (heater assembly, insertion mechanism, etc) was tested to verify acceptance of the process parameters. Initial checkout and mechanical tests were performed on a test stand and in the field to verify the adequacy of the heater assemblies in performing their designed objective.

B. [

]a,c,e

C. [

]a,c,e

D. [ ]a,c,e resultant U-bend temperature control has been verified. [

]a,c,e

E. Full Height U-bend Insertion and Heating testing were conducted to check full system capability. Heater life tests were also conducted in this manner.

F. Straight leg pop-up optical temperature measurements were made in the vertical tube cluster for various emissivity conditions. The testing was utilized to verify straight leg pop-up as steam generator emissivity radiation factor calibration.

G. Moisture Condensation Testing was conducted as a measure of the process capability to accommodate a moisture film on the steam generator tube secondary side. A black Row 1 tube cluster was spray soaked with water and run through a nominal heating cycle. No difference was observed in comparison to a dry cluster.

H. Runaway heater test was conducted in Row 1 heaters to a maximum temperature before heater failure in a shiny U-bend- 1732°F (achieved with careful power ramping to prevent premature failure).

3.4 Additional Qualification Test Data

3.4.1 [ ][a,c,e] Cycle Determination

A series of U-bend [ ][a,c,e] mockup tests were performed
[ ][a,c,e]

[

][a,c,e]

[

][a,c,e]

3.4.2 [ ][a,c,e]

[

][a,c,e]

[

]a,c,e

TABLE 3-1

U-BEND TUBE TEMPERATURE DEVIATION FROM MEAN TEMPERATURE IN [ ][a,c,e] TEMPERATURE RANGE

ROW ONE U-BEND, SHINY AND AUTOCLAVE TUBE (NON-OPERATING)

TEST	DURING SOAKING		AT 7'30"			RANGE		MAX. DIFFERENCE
NO.	VOLTAGE	AMPERAGE	MAX	MIN	AVG	MAX-AVG	AVG-MIN	MAX-MIN

a,c,e

[ ]

TABLE 3-1 (Cont.)

ROW TWO U-BEND, SHINY & AUTOCLAVE TUBE (NON-OPERATING)

TEST NO.	DURING SOAKING VOLTAGE	AMPERAGE	MAX	AT 7'30" MIN	AUG	DEVIATION MAX-AUG	AUG-MIN	MAX. DIFFERENCE MAX-MIN

a,c,e

TABLE 3-2

TYPICAL HEATER CORRELATION DATA

HEATER	HEATER	SOAKING		FIBER OPTIC READING		AVERAGE TEMPERATURE		TEMPERATURE DIFFERENCE	
NO.	RESISTANCE	CURRENT	VOLTAGE	AT 6'00"	AT 9'45"	AT 6'00"	AT 9'45"	AT 6'00"	AT 9'45"

a,c,e

a,c,e

Figure 3-1 Systems Concept

[ ]a,c,e

Figure 3-2 Heater Assembly Schematic

a,b,c,e

Figure 3-3 Voltage vs Temperature Curve For Row 1, Autoclave

a,b,c,e

Figure 3-4 Current vs Temperature Curve For Row 1, Autoclave

a,b,c,e

Figure 3-5 Voltage vs Temperature Curve For Row 2, SHINY

a,b,c,e

[ ]

Figure 3-6 Current vs Temperature Curve For Row 2, SHINY

a,b,c,e

Figure 3-7 Row 2 Test Minimum Power

a,b,c,e

Figure 3-8 Row 2 Test Average Power

a,b,c,e

Figure 3-9 Row 2 Test Maximum Power

a,b,c,e

Figure 3-10 Dry Run Test Using Production Heater

a,b,c,e

Figure 3-11 Comparsion of Predicted Tube Wall Temperature
With Measured Data

4.0 U-BEND HEAT TREATMENT PROCESS VERIFICATION

4.1 Process Parameter Development

A range of potential process parameters of temperature and time was examined in accelerated stress corrosion cracking (SCC) tests conducted by Westinghouse in programs in concert with the Electric Power Research Institute (EPRI). Selected parameters from those programs were then applied to Row 1 U-bends using field-prototypical electrical resistance heaters in a separate feasibility program, also partially funded by EPRI. In an extension of the latter program, a second set of parameters was also applied to Row 1 U-bends, and both sets of Row 1 U-bends, representing the two sets of selected heat treatment parameters, were subjected to accelerated SCC tests. These accelerated SCC tests of the heat treated U-bends demonstrated the effectiveness of both sets of process parameters in providing additional SCC resistance of the U-bends. Finally, metallurgical studies were performed to assess the effects of the selected process parameters, and parameters outside of the process range, on the microstructure and mechanical properties of heat treated U-bends.

This section summarizes the initial parameter selection data base, the SCC performance of heat treated U-bends, and the metallurgical studies.

4.1.1 Stress Relief Data Base

The accelerated SCC tests examined a wide range of potential heat treatment parameters as defined by heat treatment temperature and time at temperature. Highly susceptible Alloy 600 split-tube, axially strained "reverse U-bend" (RUB) specimens were used in this phase. These were bolt-loaded across the "legs" of the bend and stress relieved in this stressed condition. [

]^{a,c,e} The samples, together with non-stress relieved "controls", were exposed in stainless steel autoclaves to recirculating, pressurized high-purity water containing a typical dissolved hydrogen content of ~ 45 cc (STP)/kg water. The test temperature was 680°F (360°C). These conditions accelerate the kinetics of primary water SCC (PWSCC) by at least an order of magnitude over those at the inlet temperature of a steam generator tube bundle; the acceleration is even greater when the U-bend temperature is considered.

All heat treatments [ ]a,b,c,e were found to prolong the integrity of these highly susceptible RUB samples compared to the non-heat treated controls. [

]a,b,c,e

Subsequent tests were later initiated on RUB samples [
]a,b,c,e These later tests used RUB's made from one of the two heats that were tested as a full-size Row 1 U-bend. The tests consisted of prolonged exposures at 680°F to lithiated, borated water containing dissolved hydrogen, as a simulant to the reactor coolant environment. This test series also contained RUB's having lower temperature/longer time stress relief cycles. After extensive exposure to the simulated reactor coolant, during which no PWSCC was observed, all of the samples were transferred to an environment of 3000 psig superheated steam at 750°F (400°C) with 11 psia hydrogen. The superheated steam test exhibits PWSCC kinetics that are at least 2 orders of magnitude faster than those at the U-bend temperature. No PWSCC occurred in any stress relieved sample in over 2000 hours in this very accelerated steam test. Table 4-1 summarizes these data from the simulated reactor coolant/superheated steam exposures.

4.2 PROCESS PARAMETER VERIFICATION

4.2.1 Preparation and Testing of Row 1 U-bend Tubes

From the preceding sets of extensive tests, a minimum temperature [ ][a,b,c,e] was selected as the stress relief temperature for the tangent point regions of Row 1 U-bends. This selection was based in part upon the field implementation criterion [

][a,b,c,e] These were subjected to a post-heat treatment differentially applied strain that simulated the hot leg and cold leg difference in axial growth at steam generator U-bend operational conditions. Two samples of each of the two heat treatment durations, together with two differentially strained non-heat treated "control" samples, were exposed to the reference 3000 psig, 750°F superheated steam test with hydrogen present in the steam. The test was further accelerated in that the full 3000 psi internal steam pressure also constituted the differential pressure across the tube wall. This test differential pressure was accordingly about twice the normal steam generator primary-to-secondary operational differential pressure.

In the earlier feasibility program, a heat treatment [ ][a,b,c,e] was selected and applied to Row 1 U-bends of both 7/8 in. OD and 3/4 in. OD. The 7/8 in. OD tubes were of the same heat as that used for the [ ][a,b,c,e] heat treatment, the 3/4 in. OD tubes were of a second heat. The heat treatment was applied with a developmental model of the flexible ID electrical resistance heaters that were finally adopted for field implementation. The initial PWSCC evaluation of this heat treatment [ ][a,b,c,e] used as an ID test environment recirculating, pressurized, high purity water containing about 25 cc hydrogen (STP)/kg water at 680°F and 3000 psig. The OD surfaces were exposed to 1500 psig superheated steam. For each U-bend size, two non-stress relieved "controls" and two heat treated samples were exposed with the imposed differential hot leg/cold leg strain. The exposure to pressurized water conditions was for 4944 hours during which time both non-heat treated 7/8 in. OD U-bends developed typical axial throughwall PWSCC near the extrados of the tangent point of the irregular transitions. No other leakage events occurred. The 3/4 in. OD U-bends in the [ ]a,b,c,e stress-relief condition and in the non-stress-relief condition were then transferred to the 750°F superheated steam test.

4.2.2 Accelerated Test Results for Row 1 U-bend Tubes

The aggressiveness of the superheated steam test environment as a PWSCC test medium and the effectiveness of the stress-relief cycles [ ]a,b,c,e are demonstrated by these observations.

- Both non-stress relieved 7/8 in. OD bends developed typical throughwall PWSCC at the tangent point in 25-26 hours.

- No leakage occurred on any of the four [ ]a,b,c,e tested 7/8 in. OD bends in over 1000 hours in test, an increase in the longevity of a factor of greater than 40.

- One 3/4 in. OD stress relieved U-bend with 4944 hours exposure to 680°F water developed throughwall PWSCC at the tangent point after 144 hours in steam.

- Neither [ ]a,b,c,e 3/4 in. OD bend developed leakage after 600 hours in the steam test.

Table 4-2 summarizes the PWSCC testing of heat treated and non-heat treated Row 1 U-bends.

[

]a,b,c,e U-bends with this stress relief have displayed no PWSCC in exposures that are more than 50 times longer than those that led to PWSCC of untreated U-bends in the same test medium.

4.3 Process Parameter Selection and Definition

[

]a,b,c,e This upper limit is based on extensive microstructural characterization tests and hardness determinations that have been conducted specifically for the U-bend heat treatment program. These studies of the response of mill annealed Alloy 600 U-bends to the heat treatment cycles have shown that no exaggerated grain growth occurs [ ]a,b,c,e and that the hardness of U-bends heat treated [ ]a,b,c,e remains above the hardness of the unbent straight legs, confirming that the yield strength in the bends remains acceptable. The upper limit on temperature is fixed by the observation that treatment [ ]a,b,c,e produces some exaggerated grain growth and a significant reduction in hardness in the bend section. This indicates that the yield strengths in the bend may be compromised at [ ]a,b,c,e. At the specified maximum temperature of [ ]a,b,c,e for the U-bend heat treatment process, these microstructural studies showed that no changes occurred during short [ ]a,b,c,e exposures at temperature; however, the beginnings of exaggerated grain growth and hardness reductions were observed (in one of two test heats) after [ ]a,b,c,e maximum temperature.

In summary, stress relief that is beneficial against SCC occurs at [ ]a,b,c,e and above, and no significant recrystallization, grain growth or hardness changes occur below [ ]a,b,c,e. Therefore, the acceptable and optimum temperature range for the field process is defined as [ ]a,b,c,e

TABLE 4-1

ADDITIONAL RESULTS ON STRESS RELIEVED ALLOY 600
REVERSE U-BENDS

Heat	Treatment	No. RUBS SCC/No. RUBS Tested 680°F RCS[a]		750°F Steam[b]
	a,b,c,e			
2650		0/2, 8500 hr.	->	0/2, 2250 hr.
2650		Not in test		0/3, 2250 hr.
2650		Not in test		0/3, 2250 hr.
2650		0/2, 8500 hr.	->	0/2, 2550 hr.
2650		0/2, 8500 hr.	->	0/2, 2000 hr.
2650		0/2, 8500 hr.	->	0/2, 2250 hr.
2650		0/2, 8500 hr.	->	0/2, 1550 hr.
2650		0/2, 8500 hr.	->	0/2, 2250 hr.
2650		2/2, 500 hr.		5/5, 100 hr.[c]
				5/5, 650 hr.[d]
1019		Not in test		0/3, 2250 hr.
1019		Not in test		0/3, 2250 hr.
1019		Not in test		2/3, 250 hr.
				3/3, 700 hr.

a. RCS = Lithiated, borated, Reactor Coolant System chemistry with hydrogen

b. Steam at 3000 psi + H_2 at 11 psia

c. Set 1

d. Set 2 (with 1/5 in 100 hr., 4/5 in 400 hr.)

TABLE 4-2

PERFORMANCE OF STRESS RELIEVED, DIFFERENTIALLY STRAINED ROW 1 U-BENDS IN ACCELERATED PWSCC TEST ENVIRONMENTS

	Sample Number, Condition, and Exposure Time	
	High Purity Water 680°F 1500 psi ΔP 25cc H_2/kg H_2O	3000 Psig Steam 750°F 3000 psi ΔP 3 psia H_2
7/8 in. OD Bends		
[ ] a,b,c,e	No. 1 = SCC, 1300 hr.	No. 3 = SCC, 25 hr.
	No. 2 = SCC, 2950 hr.	No. 4 = SCC, 26 hr.
	---	No. 1 = OK, 1400 hr.
	---	No. 2 = OK, 1400 hr.
	---	No. 1 = OK, 1400 hr.
	---	No. 1 = SCC, 1082 hr.
	No. 1 = OK, 4944 hr.	---
	No. 2 = OK, 4944 hr.	---
3/4 in. OD Bends		
[ ] a,b,c,e	No. 1 = OK, 4944 hr.	No. 1 = SCC, 144 hr.*
	No. 2 = OK, 4944 hr.	No. 2 = OK, 144 hr.*
	No. 1 = OK, 4944 hr.	No. 1 = OK, 600 hr.*
	No. 2 = OK, 4944 hr.	No. 2 = OK, 600 hr.*

* Exposed to steam after the 4944 hour water test

[ ]a,b,c,e

Figure 4-1 Short Duration Stress Relief Treatments at Higher Temperatures are Effective Against SCC

5.0 EDDY CURRENT RESPONSE TO U-BEND HEAT TREATMENT

Eddy current testing was conducted to determine the effect of heat treatment on the inspectability of the U-bend region of steam generator tubing. The objective of the testing was to determine whether the heat treatment process, designed to reduce residual stresses in inner row U-bends, introduces additional signals or alters the existing baseline signature of the steam generator tubing [ ]a,c,e

5.1 Description of Eddy Current Test Program

Eddy current testing was conducted on two sets of tubes. Laboratory testing was performed using two mill-annealed 7/8 inch outer diameter, 0.05 in. wall thickness Row 1 U-bends. One U-bend sample had been heat treated whereas the other was in its as-manufactured condition. In-generator eddy current testing was conducted on two Row 1 U-bends during a plant demonstration of the heat treatment process. For the field test, the tube diameter was 3/4 in. OD with a 0.043 inch wall thickness.

Laboratory eddy current tests were conducted using a [ ]a,b,c diameter probe and a [ ]a,b,c instrument. Test frequencies of [ ]a,b,c were used. The in-generator testing was conducted using a [

]a,b,c,e

5.2 Eddy Current Test Results

5.2.1 Laboratory Tests

Two different U-bends were examined. A comparison of the eddy current signatures for the two U-bends, one heat treated and one as-manufactured, showed no discrete signals attributable to the heat treat process. [
]a,b,c,e

[

]a,b,c,e

5.2.2 Field Tests

Tube R1-C1 was eddy current tested before and after heat treatment within the straight section of the bend. R1-C50 was eddy current tested only after heat treatment, within the straight section of the bend. Small amplitude permeability signals were observed between the 6th and 7th support plates of the hot leg side of both tubes. The maximum amplitude of a permeability signal was approximately one-fourth the magnitude of a normal support plate signal. See Figure 5-2.

5.3 Eddy Current Inspectability Summary

Laboratory eddy current testing of as-manufactured and heat treated U-bends shows no significant difference in eddy current response. [

]a,b,c,e It is concluded that heat treating the U-bend region of SG tubing does not impede the performance of standard eddy current inspection systems.

a,b,c,e

A

B

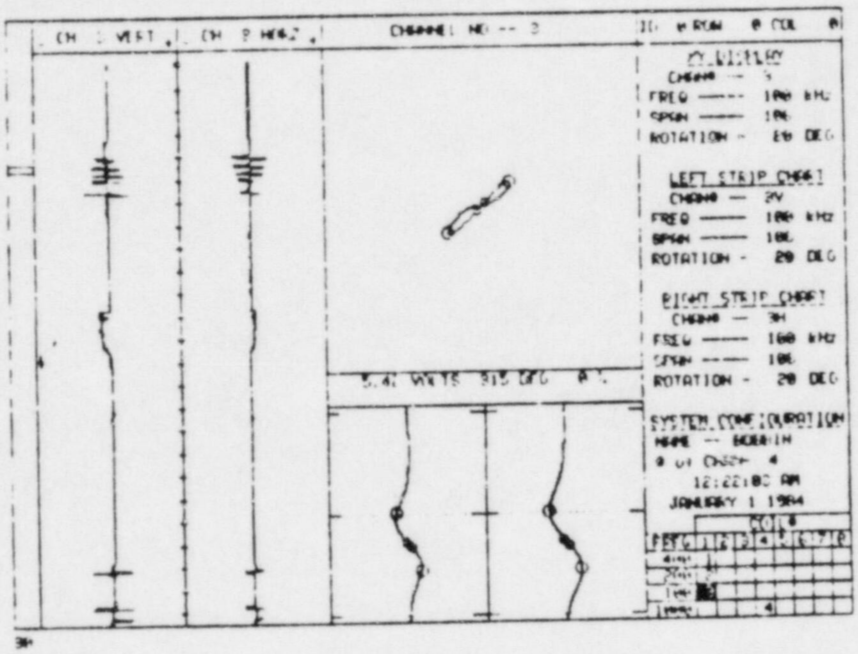

Figure 5-1 Eddy Current Results for: A) Heat Treated Tube
B) 40% Through Wall Tube
ASME Std.

a,b,c,e

Figure 5-2 Eddy Current Results After Heat Treatment

6.0 SAFETY EVALUATION

6.1 Introduction

Primary water stress corrosion cracking (PWSCC) of mill annealed Alloy 600 steam generator tubing has been identified as having a potential impact on the operation of steam generators. Regions of the steam generator tubing that may be affected are; some Row 1 (possibly Row 2) U-bends at the tangent points (transition from curved to straight portions of the tube), at or near the apex of the U-bend, and at the roll and roll transition zones within or near the top of the tubesheet. The in situ thermal stress-relief process discussed herein addresses U-bend region PWSCC only.

Examination of tubes removed from service with leaks in the U-bend region has revealed that the leakage occurred at inner-diameter-initiated through wall cracks that are generally short, tight (low leakage), and axially oriented. The examinations indicated that cracks were initiated and propagated by intergranular stress corrosion cracking.

Laboratory experiments have established that the factors contributing to the occurrence of PWSCC in service are: high operating temperatures, susceptible tubing microstructure, and high local stress-strain conditions. Each of these factors may be present in varying degrees in operating steam generators. An effective means for minimizing the potential for PWSCC is to reduce or modify the residual stress in the region of the tube that may have less resistance to PWSCC.

Westinghouse has developed a process to provide additional margin against inner diameter (ID) PWSCC occurring in the Row 1 and 2 U-bends at both tangent points and at or near the apex of the U-bend within the steam generator. This is achieved through the reduction of residual tensile stresses in the tube wall by a thermal stress-relief cycle. Procedures have been developed and qualification tests performed for the insertion of an [

]a,c,e

[

]a,c,e

The following safety evaluation is provided to demonstrate that the application of the in situ U-bend heat treatment process to the Comanche Peak Unit 1 Row 1 and 2 steam generator tubes does not compromise steam generator tube bundle integrity and therefore does not represent a potentially unreviewed safety question. The weight loss from the heater insulation material and impact on the primary system are also evaluated.

6.2 Tube Bundle Integrity Evaluation

In situ U-bend heat treatment process qualification was performed under Westinghouse Quality Assurance (QA) surveillance. Prototypical heat treatment testing and qualification has been performed to establish temperature distributions for the tubes and top support plate during heat treatment. In addition, tests were performed for tube support plate geometries both with and without cutouts along the central axis of the plate. The elements of the field procedures have been developed and tested to meet field operation requirements. Field procedures provide direction for all crew and site activities and serve as the documented QA verification method for field implementation of the heat treatment process.

The impact of the U-bend heat treatment process on steam generator tube integrity and the top tube support plate in the Comanche Peak Unit 1 steam generators is addressed below. The evaluation of both of these components utilized a combination of finite element model analysis and conventional analysis techniques. The applied temperature distributions were determined from prototypic heat treatment tests or from conservative estimates of component temperatures when test results were not available.

The current U-bend stress-relief temperature and time parameters were developed by Westinghouse in concert with EPRI partially funded programs. Emphasis was placed on exploring the minimum temperature and time that would provide additional margin to resistance to PWSCC in the Row 1 and 2 U-bend tangent point area. Accelerated tests (in 680°F water) on split tube reverse U-bend samples showed that heat treatment temperatures [ ]^{a,b,c,e} eliminated PWSCC over the full test duration of 16,000 hours. Row 1 U-bends of 3/4 in. OD tubing that were stress relieved [ ]$^{a,b,c,e]}$ and subjected to superheated steam tests at 750°F and 3000 psi internal pressure have not resulted in a leakage event in approximately 6 times longer than that of a non-stress relieved sample in the same test. These 3/4 in. Row 1 U-bends had all been previously exposed to accelerated tests in 680°F pressurized water with hydrogen for approximately 5000 hours. For 7/8 in. Row 1 U-bends, 2 samples that were stress relieved [ ]^{a,b,c,e} have resisted PWSCC in the superheated steam for 64 times as long as the exposure that cracked 2 non-stress relieved 7/8 Row 1 bends. One sample of 7/8 in. Row 1 U-bends with [ ]^{a,b,c,e} stress relief developed tangent point leakage in superheated steam after an exposure of 42 times that required for SCC in the non-stress relieved samples. These observations on actual Row 1 U-bends in these highly aggressive accelerated test environments confirm that stress relief, which is beneficial against PWSCC, occurs [ ]^{a,b,c,e} Separate studies have shown that no significant recrystallization, exaggerated grain growth or hardness reductions occur [ ]^{a,b,c,e}

6.2.1 Steam Generator Tube Integrity Evaluation

For the steam generator tubes, an analysis has been completed that considered the potential for increasing the residual stresses in the tube away from the area at issue during initial heatup, and also evaluated the resulting stresses in terms of overall fatigue. For the top tube support plate, an analysis determined the maximum stresses resulting from the heat treatment process and compared the results to the ASME Code guideline for maximum stress to preclude gross deformation of the plate, which could potentially result in tubes being pinched.

The tube evaluation considered three separate loading conditions. The first loading condition considered the resulting heat treatment temperature distribution. The tube temperature distribution resulting from the heat treatment process was evaluated to determine whether additional residual stresses are introduced into the Row 1 and 2 tubes during initial heatup, and to determine if the cyclic (fatigue) stresses that the tubes experience are acceptable. [

]^{a,b,c,e} was considered. The second loading condition considered the stresses introduced into the tube as a result of the axial variation in temperature that exists at the end of the heater. The third loading condition examined the stresses in the tube resulting from the heating of the straight portion of the tube between the top two support plates, which is performed to establish tube emissivity characteristics.

Pertaining to the first loading condition, an analysis was completed to determine if the heat treatment process would result in increased residual stress elsewhere in the U-bend, particularly at the apex. [

]^{a,b,c,e} Analysis results revealed that the maximum induced moment was less than the elastic restoring moment (which exists during the initial bending of the tube), and that the heat treatment process results in only elastic cycling of the tube; therefore, tube residual stresses will not be increased. [

]a,b,c,e

For the second loading condition, a finite element model analysis was used to evaluate the stresses in the tube. The axial variation in temperature at the end of the heater assembly was shown by test to be a [ ]a,b,c,e reduction in temperature over a 1 inch length. The maximum tube stress for this loading was determined to be 5.9 ksi, occurring at the end of the tube hot region. This stress occurs in the vicinity of the tube support plate, where tube bending stresses resulting from the heat treatment are low.

In evaluating the third loading condition, heating of the straight portion of the tube between the top two support plates, the tube was permitted to expand freely in the axial direction. The active heater region was assumed to have a temperature of [ ]a,b,c,e. Above and below the heater for the majority of the straight length portion, the tube temperature was assumed to be [ ]a,b,c,e, which was judged to be conservative based on test results that show a [ ]a,b,c,e reduction in temperature over a one inch tube length. The resulting elastically calculated stress is 83.9 ksi and occurs at the tangent point of the tube. This stress determination is considered conservative since it incorporates a tube flexibility factor as determined for the U-bend region away from the straight length of the tubing. The subsequent U-bend thermal stress-relief cycle would reduce any residual stresses generated at the tangent point by the heating of the straight leg portion of the tube to below the threshold level necessary for initiation of PWSCC. Work is still in progress to justify straight-leg heating for conditions where the tube is unable to expand axially between the top two support plates. Because the applied loading is displacement controlled, it is anticipated that limited lateral deflection of the tube will relieve the applied load. The scenario where a tube is unable to expand axially due to constraints of denting in the support plate area is not expected to occur at the non operating plant.

In evaluating the structural response of the tubes to the above loadings, consideration has been given to the material response as a functon of time at temperature. Three response mechanisms are considered in the analysis; cyclic fatigue, thermal creep, and time to rupture. Thermal creep and time to rupture effects have been shown to be negligible. The remaining criterion is to show that the resulting fatigue usage is less than 1.0, and the analysis results show that the fatigue usage for the tubes is 0.011.

[

]a,b,c,e

[

]a,b,c,e

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test data has revealed no significant differences in the signal responses observed using conventional bobbin coil examination practices. The heat treated tubing remained fully inspectable.

6.2.2 Tube Support Plate Analysis

During the heating of any single tube, the portion of the plate that is influenced by the heat treatment is quite small in comparison with the overall plate diameter; therefore, the general stress in the heated region was approximated as [ ]^{a,b,c,e} The effects of the plate perforations in the [ ]^{a,b,c,e} stresses were determined using a finite element model of a typical ligament. The analysis also accounted for the increased plate stiffness in regions where the cutouts along the central plate axis do not exist. The plate temperatures used for this analysis were based on test results that utilized a heat treatment temperature of [ ]^{a,b,c,e} A summary of the resulting plate stresses, which includes results for a plate with and without a central cutout, respectively, has revealed that the allowable stresses, which were based on the ASME Code limit of $3S_m$ (3 times ASME Code allowable stress intensity for design) for the maximum range of primary plus secondary stresses, are within acceptable limits. In order to limit the heat introduced into the plate from the heating of adjacent tubes, heat treatment cycles will be performed on every third tube.

Calculations were also performed to determine if buckling of the heated region of the top tube support plate is an issue. Calculations reveal a critical elastic plate stress significantly in excess of the maximum induced plate stress generated due to the U-bend heat treatment process; therefore, buckling of the plate in the heated region is not expected to occur.

6.3 Primary Side Impact of the U-Bend Heat Treatment Process

To measure possible introduction of foreign material from the breakdown of the [ ][a,c,e] fiber used as the high temperature electrical insulation for the heater wire, sensitive weight loss measurements were made on a prototypical heater during full height extension into the U-bend, including a heating cycle for each insertion.

The [ ][a,c,e] heater assembly used in the in situ heat treatment program has been both cold and hot tested to assure that residual amounts of fiber left in the Inconel 600 tubing are within acceptable limits. The insulating material [ ][a,c,e] selected for the heater contains high concentrations of SiO_2 and Al_2O_3. This fiber material loses some weight during use; therefore, the potential that the residual fiber could exceed the specification limits for either silica or aluminum in the primary water was evaluated. The specifications for these materials are stringent to limit deposition on the fuel rods.

A production heater of the exact design intended for use in the planned field heat treatment of Row 2 U-bends was cycled [

][a,b,c,e]

6.4 Conclusion

The application of the in situ heat treatment process in the Row 1 and Row 2 U-bend region of the Comanche Peak Unit 1 steam generators has been demonstrated to provide a significant increase in margin to PWSCC while not adversely affecting steam generator tube bundle integrity. Briefly summarizing relative to steam generator tube integrity, analyses have shown that: the U-bend heat treatment program does not result in the introduction of additional stresses in the tubes, fatigue usage in tubes resulting from the combined loadings of U-bend heat treatment [ ]^{a,c,e} is minimal, heat treatment of a tube at a temperature [ ]^{a,c,e} introduces negligible creep strains in the tube, and the effect of air formed oxides due to the stress relief process on corrosion resistance of the U-bends is not detrimental to the long term corrosion resistance of stress relieved Inconel 600. Relative to steam generator top tube support plate integrity, plate stresses generated during the heat treatment process were found to be acceptable for a heat treatment of [ ]^{a,c,e} (which bounds the U-bend heat treatment process parameters) and buckling of the plate in the heated region was determined not to be an issue. Also, the weight change due to loss of fiber insulation, measured from cycling the U-bend heater, does not deleteriously affect the water chemistry specification for both aluminum and silica in the primary side of the Comanche Peak Unit 1 plant after heat treating all Row 1 and 2 U-bends without cleanup. Additionally, per recommendations in RG 1.83 "Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes", the application of the U-bend heat treatment process does not interfere with periodic in-service inspection and interpretation to assess tube structural and leaktight integrity. The U-bend heat treatment process procedures and inherent quality assurance checks further substantiate that the application of the heat treatment process to the Comanche Peak Unit 1 steam generators does not represent an unreviewed safety question pursuant to 10 CFR 50.59 criteria (a) (2).