WESTINGHOUSE (NON-PROPRIETARY) CLASS 3

WCAP-14597

SG-96-03-010

LASER WELDED ELEVATED TUBESHEET SLEEVES
FOR
WESTINGHOUSE MODEL F STEAM GENERATORS

Generic Sleeving Report

March 1996

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ABSTRACT

This report provides the technical basis for licensing the use of the Westinghouse Laser Welded Sleeve (LWS) technique to return an 11/16 inch diameter tube with indications of degradation to an operable condition. This report summarizes the generic design, structural, thermal-hydraulic, materials and inspection analyses and corrosion and mechanical tests, as well as installation processes of an elevated tubesheet sleeve. It addresses a tubesheet sleeve for Westinghouse Model F steam generators which utilize 11/16 inch outside diameter tubes.

The Westinghouse LWS technique has been licensed previously for use within 7/8 inch and 3/4 inch diameter steam generator tubing, has been installed and is in operation. This document covers installation in 11/16 inch tubes which are installed in the tubesheet by a hydraulic expansion process. That technology base and the technology base for the hybrid expansion joint (HEJ) technique for sleeving are utilized herein, with the described evaluations to form the technical basis for the LWS technique for 11/16 inch diameter tubing.

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1.0 INTRODUCTION

Under Plant Technical Specification requirements steam generator (SG) tubes are periodically inspected for degradation using non-destructive examination techniques. If established inspection criteria are exceeded, the tube must be removed from service by plugging or the tube must be brought back into compliance with the Technical Specification Criteria. Tube sleeving is one technique used to return the tube to an operable condition. Tube sleeving is a process in which a smaller diameter tube or sleeve is positioned to span the area of degradation. It is subsequently secured to the tube, forming a new pressure boundary and structural element in the area between the attachment points.

This report presents the technical bases developed to support licensing of the laser welded sleeve installation process for use in 11/16 inch diameter tubing. One sleeve type is addressed, a tubesheet sleeve. This sleeve type extends over approximately one-third of the tube length within the tubesheet, is joined to the tube approximately 15 inches above the tubesheet bottom and is referred to as the elevated tubesheet sleeve (ETS). This type of sleeve allows large radial coverage of the bundle, i.e., installation close to the bundle periphery. The ETS is appropriate for all plants with SG tubes which have degradation at the top of the tubesheet, and/or within a distance of several inches above and below the top of the tubesheet.

This technical basis for laser welded sleeves is applicable to Westinghouse Model F steam generators; these SGs utilize 11/16 inch OD tubing.

1.1 Report Applicability

Each Model F SG tube bundle contains U-shaped tubes that are Alloy 600 and have a nominal OD of 11/16 inch and a nominal wall thickness of 0.040 inch. The SGs of one plant (Callaway) have both mill annealed (MA) and thermally treated (TT) tubes. The Model F SGs of all other plants have only TT tubes.

Data are presented to support the application of one tubesheet sleeve design. The sleeve characteristics include:

- 12 inch long ETS
- upper weld joint with post weld heat treatment
- lower joint with hard roll

The sleeves described herein have been designed and analyzed to meet the service requirements of the Model F SGs through the use of conservative and enveloping thermal boundary conditions and structural loadings. Previous testing of sleeve lower mechanical joints of sleeves for 3/4 inch OD tubes has been utilized. It has been determined that the results of these tests are applicable to the lower mechanical joints of sleeves for the 11/16 inch OD tubes in this report, provided that confirmatory leak tightness tests at room temperature are performed. The technical approach for licensing the remaining two parts of this design in advance of completion of the qualification work, i.e., the weld process qualification report/procedure specification and the lower joint qualification, is discussed in Sections 2.3.1 and 4.3, respectively.

Similarly, previous testing of upper laser welds and of the lower mechanical joints of sleeves for 7/8 inch OD tubes has been performed. The results of that program are also applicable to the corresponding joints of the sleeves for the 11/16 inch OD tubes in this report. The test data for the laser welded sleeves for 7/8 inch OD tubes are provided here as bases in addition to the analytical bases for the upper laser weld of this sleeve.

The structural analysis and mechanical performance of the sleeves are based on installation in the hot leg of the steam generator. [

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1.2 Sleeving Tube Access Boundary

Tubes to be sleeved will be selected by radial location, tooling access (due to channelhead geometric constraints), sleeve length, and eddy current analysis of the extent and location of the degradation.

The boundary is determined by the amount of clearance below a given tube, as well as tooling and robot delivery system constraints. At the time of application, the exact sleeving boundary will be developed. Owing to the constant development of tooling, designs and processes, essentially 100 per cent coverage of the tubesheet map is expected.

2.0 SLEEVE DESCRIPTION AND DESIGN

2.1 Sleeve Design Description

Tube sleeves can effectively restore a degraded tube to a condition consistent with the design requirements, i.e., the strength and pressure retaining capabilities of the original tube. The design of the sleeve and sleeve weld is predicated on the design rules of Section III, Subsection NB, of the American Society of Mechanical Engineers Boiler & Pressure Vessel Code (ASME Code). Also, the sleeve design addresses dimensional constraints imposed by the tube inside diameter and installation tooling. These constraints include variations in tube wall thickness, tube ovality, tube to tubesheet joint variations and runout/concentricity variations.

The elevated tubesheet sleeve (ETS) is illustrated in Figure 2-1. It is applicable to the steam generators in which the tubes were installed in the tubesheet by the hydraulic expansion process, as is the case for Model F SGs. The ETS upper joint is identical to other free span joints, i.e., the upper joint of the full length tubesheet sleeve (FLTS) and the tube support sleeve (TSS). The ETS lower joint is fabricated by the same Hybrid Expansion Joint (HEJ) process which is used to fabricate the FLTS lower joints, i.e., hydraulic expansion and roll expansion. The preferred approach to design of the lower joint is direct fabrication on the tube with no preparatory roll expansion. However, in case the tube in the location of the ETS lower joint requires preparation before sleeving such as "truing" or making an interference fit with the tubesheet hole surface, it may be locally roll expanded. It is expected that, although essentially no crevice exists between the tube outside surface and the tubesheet hole surface, the tube may not have had an interference fit with the hole when it was expanded in the factory. Preparatory roll expansion of the tube over at least the approximately two inch axial length of the roll expansion of the sleeve joint will be performed, if needed, to provide adequate axial anchorage of the tube and sleeve at the lower joint. The ETS is similar to the FLTS in that it is designed to address tube degradation in the tube free span and in the vicinity of the tubesheet top. However, unlike the FLTS, it is limited to this application and is not designed to address degradation in the remainder of the tube within the tubesheet.

The lower sleeve-to-tube joint is approximately 15 inches above the tube end. The FLTS and TSS joints are discussed because previous sleeves in 3/4 and 7/8 inch tubes have been of these types and that experience is applicable to ETS installation in Model F SGs.

2.2 Sleeving of Previously Plugged Tubes

Previously plugged tubes must meet the same requirements as sleeving candidates for never-plugged, active tubes. An example of this requirement is that the minimum distance, as measured along the tube axis between degradation and the location of the sleeve welds, is the same in both cases. Another example is that the tube deplugging process performed by Westinghouse as part of the sleeving process is designed to leave the tube in a condition to be returned to service unsleeved, excluding the degradation which

a,c,e

Figure 2-1

Tubesheet Elevated Laser Welded Sleeve
Installed Configuration

caused the tube to be plugged in the first place. The deplugging process is designed to leave the tube-to-tubesheet weld and tube portion adjacent to the weld in a condition to perform the pressure boundary function without any added integrity from the sleeve-to-tube lower joint.

2.3 Sleeve Design Documentation

The sleeves are designed and analyzed according to the 1989 edition of Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, as well as applicable United States Nuclear Regulatory Commission (USNRC) Regulatory Guides. (As of the date of this report, the 1989 edition is the latest edition approved by the NRC.) The associated materials and processes also meet the rules of the ASME Boiler and Pressure Vessel Code. Specific documents applicable to this program are listed in Table 2-1. The sleeving codes, i.e., IWB-4300, first approved in the Section XI Div. 1, 1989 Addenda, dated March 1990 are used in this evaluation as guidelines.

2.3.1 Weld Qualification Program

All of the laser welding processes have been qualified, used in the field and have produced structures which are now operating, for [ ]^{a,c,e} sleeves for 7/8 inch OD tubes and for [ ]^{a,c,e} sleeves for FSGs. The laser welding processes used to install [ ]^{a,c,e} nominal OD sleeves in 7/8 inch nominal OD tubes, (a.k.a., the "7/8 inch sleeves") was qualified per the guidelines of the ASME Code. The laser welding processes used to install [ ]^{a,c,e} nominal OD sleeves in the 3/4 inch nominal OD tubes of the FSGs was also qualified per the guidelines of the ASME Code. These requirements specify the generation of a procedure qualification record and welding procedure specification. The processes for the larger-diameter sleeve/tube joints required requalification for the smaller-diameter sleeve/tube joints because of a change in two of the essential variables, in excess of limits as defined in ASME Code Section XI, IWB-4313.1. The welding processes for Model F SGs are being qualified separately.

Specific welding processes are generated for:

- Sleeve weld joints made outside of the tubesheet
- Sleeve weld joints made outside of the tubesheet with thermal treatment
- Repair or rewelding of sleeve joints

Representative field processes are used to assemble the specimens to provide similitude between the specimens and the actual installed welds. The laser welded joints are representative in length and diametral expansion of the hydraulic-expansion zones. The sleeve and tube materials are consistent with the materials and dimensional conditions representative of the field application. Essential welding variables, defined in ASME Code Section IX, Code Case N-395 and Section XI, IWB-4300 are used to

Table 2-1
ASME Code Rules and Regulatory Requirements

Item	Applicable Criteria	Requirement
Sleeve design	Section III	NB-3000 Design
	Operating Requirements	Analysis Conditions
	Reg. Guide 1.83	SG Tubing Inspectability
	Reg. Guide 1.121	Plugging Limit
Sleeve Material	Section II	Material Composition
	Section III	NB-2000, Identification, Tests and Examinations
	Code Case N-20-3	Mechanical Properties
Sleeve Joint	10CFR100	Predicted Steam Line Break Leak Rate
	Technical Specifications	Operating Primary-to-Secondary Leak Rate
	Section IX	Weld Qualification
	Code Case N-395/Section IX/ Section XI	Laser Welding Essential Variables, procedure qualification record, sleeving procedure specification, certified design report, etc.

develop the weld process. [

]^{a,c,e}

The documentation specified by ASME Section XI (sleeving codes - '89 Addenda) may be provided at any reasonable time before the actual sleeving job. This weld qualification documentation is typically submitted to the customer no later than the date of submission of the field procedures.

2.3.2 Weld Qualification Acceptance Criteria

For the qualification of the process, the acceptance criteria specify that the welds shall be free of cracks and lack of fusion and meet design requirements for weld throat and minimum leakage path. The welds shall meet the liquid penetrant test requirements of NB-3530.

3.0 ANALYTICAL VERIFICATION

This section of the report provides the analytical justification for the laser welded sleeves. Section 3.1 deals with the structural justification, Section 3.2 considers the effect of tubesheet rotations on sleeve contact pressures, Section 3.3 provides the thermal/hydraulic justification, and Section 3.4 addresses flow induced vibration concerns for laser welded sleeving.

3.1 Structural Analysis

Section 3.1 summarizes the structural analysis of laser welded elevated tubesheet sleeves for 11/16 inch diameter tubes for use in plants with Model F steam generators. The loading conditions considered in the analysis represent an umbrella set of conditions, based on the applicable design specifications, References 3-1, 3-2, and 3-3. The analysis includes development of the finite element models, a heat transfer analysis to obtain thermal stresses, a primary stress intensity evaluation, a primary plus secondary stress range evaluation, and a fatigue evaluation for mechanical and thermal conditions. Calculations are also performed to establish minimum wall thickness requirements for the sleeve. Finally, the structural analysis calculates the effect of tubesheet rotations on the changes in contact pressure between the sleeve, tube, and tubesheet at the roll expanded section.

3.1.1 Component Description - Elevated Tubesheet Sleeve

The installed elevated tubesheet sleeve is illustrated in Figure 2-1. [

]^{a,c,e}

The lower tube/sleeve interface, inside the tubesheet, consists of a section [

]^{a,c}

At the upper end, the sleeve consists of a section that [

]^{a,c} Figure 3-1 shows a schematic of the sleeve to tube interfaces and the various [ ]^{a,c}

3.1.2 Summary of Material Properties

Reference 3-1 specifies the material of construction for the 11/16 inch tubes in Model F steam generators to be nickel based Alloy 600 in a thermally treated (TT) condition, which meets the 40 ksi minimum yield strength requirements of Reference 3-5. The sleeve material is also a nickel based alloy, thermally treated Alloy 690, which meets the strength requirements of Reference 3-4. Summaries of the applicable mechanical, thermal, and strength properties for the tube and sleeve materials, assumed in this evaluation,

a,c,e

Figure 3-1

Schematic of Laser Welded Elevated Tubesheet Sleeve Configuration.

are provided in Tables 3-1 and 3-2, for Alloy 600 and 690, respectively. The weld is evaluated at the lower strength properties of Alloy 600 in Table 3-1. Note that the Alloy 600 tube strength data, used in the evaluation and listed in Table 3-1, are for a minimum ambient yield strength of 35 ksi, which is lower than the 40 ksi specified for Alloy 600 in Reference 3-5. One Model F plant contains both mill annealed (MA) and thermal treated Alloy 600 tubes. For the MA tubes of that plant, Callaway, the structural evaluation applies directly; for the TT tubes of that plant and all other plants, the structural evaluation is conservative.

The fatigue curves used in the analysis of the sleeve, tube, and laser weld are the ASME Code fatigue design curves for nickel-chromium-iron (Alloys 600 and 690) given in Figures I-9.2.1 and I-9.2.2 of Appendix I of Reference 3-4.

The sleeve evaluation also includes the influence of the tubesheet, channel head, and cylinder shell which are constructed of SA-508 Class 2a, SA-216 WCC, and SA-533 Grade A Class 2 steels, respectively. A summary of the applicable properties for these materials is provided in Tables 3-3 to 3-5.

3.1.3 Applicable Criteria

The applicable criteria for evaluating the sleeves is defined in the ASME Code, Section III, Subsection NB, 1989 Edition, Reference 3-4. The welded section, between the Alloy 690 sleeve and the Alloy 600 tube, is included in the analysis and is conservatively evaluated to the ASME Code criteria as a structural weld assuming the smaller strength properties of Alloy 600. In establishing minimum wall requirements for plugging limits, the ASME Code minimum values for the material properties are used. A summary of the applicable stress and fatigue limits for the sleeve and tube is given in Tables 3-6 through 3-9. Again, these limits are conservative for the TT tubes and respective welds. The limits apply directly for the MA tubes and respective welds.

3.1.4 Loading Conditions Considered

The loadings considered in the structural analysis represent an umbrella set of conditions as defined in References 3-1, 3-2, and 3-3. The analysis considers a full duty cycle of events that includes design, normal, upset, faulted, emergency and test conditions. A summary of the applicable transient conditions is provided in Table 3-10. This duty cycle considers all specified relevant transients for Model F steam generators in a standard four-loop plant for a 40 year fatigue design life. The applicable temperatures and pressures are based on the specified design transients for the primary reactor coolant and secondary steam side of the steam generators given in References 3-1, 3-2, and 3-3. The uprated, V-5 fuel, 15% plugging parameters, specified in Reference 3-3, are conservatively assumed. Umbrella pressure loads for Design, Faulted, Emergency and Test conditions are summarized in Table 3-11.

Table 3-1
Summary of Material Properties
Alloy 600 Tube Material

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus (psi x 1.0E06)	31.00	30.20	29.90	29.50	29.00	28.70	28.20
Coefficient of Thermal Expansion (in/in/°F x 1.0E-06)	6.90	7.20	7.40	7.57	7.70	7.82	7.94
Density (lb-sec^2/in^4 x 1.0E-04)	7.94	7.92	7.90	7.89	7.87	7.85	7.83
Thermal Conductivity (Btu/sec-in-°F x 1.0E-04)	2.01	2.11	2.22	2.34	2.45	2.57	2.68
Specific Heat (Btu-in/lb-sec^2-°F)	41.2	42.6	43.9	44.9	45.6	47.0	47.9

STRENGTH PROPERTIES (ksi)							
Sm	23.30	23.30	23.30	23.30	23.30	23.30	23.30
Sy	35.00	32.70	31.00	29.80	28.80	27.90	27.00
Su	80.00	80.00	80.00	80.00	80.00	80.00	80.00

Table 3-2
Summary of Material Properties
Sleeve Material
Thermally Treated Alloy 690

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus (psi x 1.0E06)	30.30	29.70	29.20	28.80	28.30	27.80	27.30
Coefficient of Thermal Expansion (in/in/°F x 1.0E-06)	7.76	7.85	7.93	8.02	8.09	8.16	8.25
Density ($lb\text{-}sec^2/in^4$ x 1.0E-04)	7.62	7.59	7.56	7.56	7.54	7.51	7.51
Thermal Conductivity (Btu/sec-in-°F x 1.0E-04)	1.62	1.76	1.9	2.04	2.18	2.31	2.45
Specific Heat ($Btu\text{-}in/lb\text{-}sec^2\text{-}°F$)	41.7	43.2	44.8	45.9	47.1	47.9	49.0

STRENGTH PROPERTIES (ksi)							
Sm	26.60	26.60	26.60	26.60	26.60	26.60	26.60
Sy	40.00	36.80	34.60	33.00	31.80	31.10	30.60
Su	80.00	80.00	80.00	80.00	80.00	80.00	80.00

Table 3-3
Summary of Material Properties
Tubesheet Material
SA-508 Class 2a

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus (psi x 1.0E06)	29.20	28.50	28.00	27.40	27.00	26.40	25.30
Coefficient of Thermal Expansion (in/in/°F x 1.0E-06)	6.50	6.67	6.87	7.07	7.25	7.42	7.59
Density (lb-sec^2/in^4 x 1.0E-04)	7.32	7.3	7.29	7.27	7.26	7.24	7.22
Thermal Conductivity (Btu/sec-in-°F x 1.0E-04)	5.49	5.56	5.53	5.46	5.35	5.19	5.02
Specific Heat (Btu-in/lb-sec^2-°F)	41.9	44.5	46.8	48.8	50.8	52.8	55.1

Table 3-4
Summary of Material Properties
Channel Head Material
SA-216 Grade WCC

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus (psi x 1.0E06)	29.50	28.80	28.30	27.70	27.30	26.70	25.50
Coefficient of Thermal Expansion (in/in/°F x 1.0E-06)	5.53	5.89	6.26	6.61	6.91	7.17	7.41
Density (lb-sec^2/in^4 x 1.0E-04)	7.32	7.3	7.29	7.27	7.26	7.24	7.22

Table 3-5
Summary of Material Properties
Cylinder Shell Material
SA-533 Grade A Class 2

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus (psi x 1.0E06)	29.20	28.50	28.00	27.40	27.00	26.40	25.30
Coefficient of Thermal Expansion (in/in/°F x 1.0E-06)	7.06	7.25	7.43	7.58	7.70	7.83	7.94
Density (lb-sec^2/in^4 x 1.0E-04)	7.32	7.3	7.29	7.27	7.26	7.24	7.22

Table 3-6
Criteria for Primary Stress Intensity Evaluation
Sleeve - Alloy 690

CONDITION	CRITERIA	LIMIT (KSI)
DESIGN	$P_m \leq S_m$ $P_1 + P_b \leq 1.5\ S_m$	$P_m \leq 26.60$ $P_1 + P_b \leq 39.90$
FAULTED	$P_m \leq .7\ S_u$ $P_1 + P_b \leq 1.05\ S_u$	$P_m \leq 56.00$ $P_1 + P_b \leq 84.00$
TEST	$P_m \leq 0.9\ S_y$ $P_1 + P_b \leq 1.35\ S_y$	$P_m \leq 36.00$ $P_1 + P_b \leq 54.00$
EMERGENCY	$P_m \leq S_y$ $P_1 + P_b \leq 1.5\ S_y$	$P_m \leq 40.00$ $P_1 + P_b \leq 60.00$
ALL CONDITIONS	$P_1 + P_2 + P_3 \leq 4.0\ S_m$	$P_1 + P_2 + P_3 \leq 106.4$

Notes: P_i (i=1,2,3) = Principal stresses.

Some of the allowables are temperature dependent and may vary from the values shown.

Table 3-7
Criteria for Primary Stress Intensity Evaluation
Tube - Alloy 600

CONDITION	CRITERIA	LIMIT (KSI)
DESIGN	$P_m \leq S_m$ $P_1 + P_b \leq 1.5\ S_m$	$P_m \leq 23.30$ $P_1 + P_b \leq 34.95$
FAULTED	$P_m \leq .7\ S_u$ $P_1 + P_b \leq 1.05\ S_u$	$P_m \leq 56.0$ $P_1 + P_b \leq 83.88$
TEST	$P_m \leq 0.9\ S_y$ $P_1 + P_b \leq 1.35\ S_y$	$P_m \leq 31.50$ $P_1 + P_b \leq 47.25$
EMERGENCY	$P_m \leq S_y$ $P_1 + P_b \leq 1.5\ S_y$	$P_m \leq 35.00$ $P_1 + P_3 \leq 52.5$
ALL CONDITIONS	$P_1 + P_2 + P_3 \leq 4.0\ S_m$	$P_1 + P_2 + P_3 \leq 93.20$

Notes: P_i (i=1,2,3) = Principal stresses.

Some of the allowables are temperature dependent and may vary from the values shown.

Table 3-8
Criteria for Primary Plus Secondary Stress Intensity Evaluation
Sleeve - Alloy 690

CONDITION	CRITERIA	LIMIT (KSI)
NORMAL, UPSET, and TEST	$P_l + P_b + Q \leq 3\ S_m$*	$P_l + P_b + Q \leq 79.8$
NORMAL, UPSET, and TEST	Cumulative Fatigue Usage	1.0

* Limit applies to the range of primary plus secondary stress intensity.

Table 3-9
Criteria for Primary Plus Secondary Stress Intensity Evaluation
Tube - Alloy 600

CONDITION	CRITERIA	LIMIT (KSI)
NORMAL, UPSET, and TEST	$P_l + P_b + Q \leq 3\ S_m$*	$P_l + P_b + Q \leq 69.9$
NORMAL, UPSET, and TEST	Cumulative Fatigue Usage	1.0

* Limit applies to the range of primary plus secondary stress intensity.

Table 3-10
Summary of Transient Events

CLASSIFICATION	CONDITION	OCCURRENCES
		a, c, e
Normal		
Upset		

Table 3-10 (continued)
Summary of Transient Events

a, c, e

CLASSIFICATION	CONDITION	OCCURRENCES
Upset		
Test		

Table 3-11
Umbrella Pressure Loads for Design, Faulted, and Test Conditions

	PRESSURE LOAD, PSIG	
CONDITIONS	PRIMARY	SECONDARY
Design		
Design Primary		
Design Secondary		
Primary to Secondary Boundary		
Secondary to Primary Boundary		
Faulted(1)		
Reactor Coolant Pipe Break		
Feedline Break		
Steam line Break		
RC Pump Locked Rotor		
Control Rod Ejection		
Test		
Primary Side Hydrostatic Test		
Secondary Side Hydrostatic Test		
Tube Leak Test A		
Tube Leak Test B		
Tube Leak Test C		
Tube Leak Test D		
Primary Side Leak Test		
Secondary Side Leak Test		
Emergency		
Small LOCA		
Small SLB		
Complete Loss of Flow		

b,c

NOTE: (1) The Safe Shutdown Earthquake (SSE) results in negligible stresses in the sleeve, tube, and weld compared to the pressure stresses for the listed faulted events.

3.1.5 Analysis Methodology

The analysis of the laser welded elevated sleeve designs utilizes both conventional and finite element analysis techniques. Several finite element models are used for the analysis. The main axisymmetric model of the sleeve and tube spans the full length of the sleeve plus the distance above the sleeve to the flow distribution baffle (FDB). The tubesheet ligament simulation in this model incorporates the stiffness of a [$]^{a,c}$ in the tubesheet. The analysis considers both [

$]^{a,c}$ Since the tube can be either fixed or free at the FDB, both possibilities are considered. Consideration of the tube as fixed at the FDB is judged to be very conservative for a Model F SG with stainless steel support plates and brooched holes. Therefore, four independent combinations of tube status (intact or severed) and boundary condition (B.C.) constraints at the FDB (fixed or free) are considered in the evaluation as follows:

Combo 1:	Tube Status: INTACT	B.C. @ FDB: FIXED,
Combo 2:	Tube Status: INTACT	B.C. @ FDB: FREE,
Combo 3:	Tube Status: SEVERED	B.C. @ FDB: FIXED,
Combo 4:	Tube Status: SEVERED	B.C. @ FDB: FREE.

An end cap axial load is applied for pressure cases when the boundary condition at the FDB is free. For thermal cases, when the boundary condition at the FDB is fixed, the sleeved tube is conservatively assumed to be adjacent to a stay rod and the axial interactions with the stay rods and spacer pipes are included in the sleeved tube model.

In addition to the axisymmetric sleeved tube model discussed above, a separate axisymmetric global model of the tubesheet, channel head, and lower cylinder shell was developed and used to calculate tubesheet rotations under combined pressure and temperature loadings. The resulting maximum tubesheet rotations were then applied to a beam model of the tube and sleeve spanning from inside the tubesheet to the FDB. These models were used to assess the tubesheet rotational effect on the stresses in the sleeve, tube, and weld, as discussed in Section 3.1.7. (See Section 3.2 for more details on the tubesheet, channel head, lower cylinder shell model.)

In all cases, the tolerances used in simulating the sleeve and tube geometry are such that [

$]^{a,c}$ Based on previous laser welded joints, the nominal width (interfacial axial extent) of the laser weld joining the tube and sleeve is expected to be about [$]^{a,c}$ However, qualification tests for the weld process are expected to show that the welds may be as small as [$]^{a,c}$ Thus, in performing this analysis, a weld width of [$]^{a,c}$ was considered. Therefore, the stress and fatigue results reported later in Sections 3.1.8 and 3.1.9, respectively, are for the limiting weld geometry of [$]^{a,c}$ in width.

3.1.6 Heat Transfer Analysis

Based on previous thermal analyses of sleeved tubes, relatively large heat transfer coefficients on both the primary and secondary sides of the sleeve and tube are expected [

]^{a,c}

These high external surface heat transfer rates, when coupled with thin walls and the relatively high thermal conductivity of the metal compared to the thermal impedance of the gaps between the tube and sleeve, would suggest that, in the limit, the metal walls of the tube and sleeve tend to instantaneously follow the fluid temperatures. Figure 3-2 shows the resulting conservative temperature distribution in the sleeve and tube that follows from these assumptions. The sleeve temperature is assumed to always follow the primary fluid temperature, T_p. The tube has essentially three temperature zones. First, inside the perforated tubesheet, the tube will follow the primary fluid temperature, T_p. Second, directly across from the sleeve, due to the high thermal impedance of the gap which acts like an insulator, the tube will follow the secondary fluid temperature, T_s. The third zone is above the sleeve, where the tube is exposed to both the primary and secondary fluids, which have relatively large heat transfer coefficients, implying that the metal will be at approximately the average of the fluid temperatures, or $\frac{1}{2}(T_p + T_s)$. The assumed temperature distribution in the sleeve and tube shown in Figure 3-2 conservatively imposes the maximum thermal discontinuity stresses on the weld. Since most of the transients listed in Table 3-10 are relatively slow and the heat transfer rates at the surfaces and in the metal walls are high, the through wall gradient stresses are much smaller than the thermal discontinuity stresses.

3.1.7 Tubesheet / Channel Head / Shell Influence

The results from the tubesheet / channel head / shell model and the beam model of the sleeve and tube show that the maximum tubesheet rotations [

]^{a,c} (Note that Section 3.2 discusses the tubesheet rotation effect on the contact pressure between the sleeve, tube, and tubesheet which is a different and distinct evaluation from the tubesheet rotational effect on stresses in the critical locations of the sleeve, tube, and weld discussed in this section.)

3.1.8 Stress Analysis

In performing the stress evaluation using the axisymmetric sleeve and tube model, [

]

a,c

Figure 3-2

Temperature Distribution Assumed in Laser Welded Elevated Tubesheet Sleeve Structural Evaluation

a,c,e

Figure 3-3

Boundary Condition for Unit Primary Pressure

[ ]^{a,c,e} $P_P > P_S$

a,c,e

Figure 3-4

Boundary Condition for Unit Primary Pressure

[$]^{a,c,e}$ $P_P < P_S$

a,c,e

Figure 3-5

Boundary Condition for Unit Primary Pressure
[ ]^{a,c,e} $P_P > P_S$

a,c,e

Figure 3-6

Boundary Condition for Unit Primary Pressure
[ ]^{a,c,e} $P_P < P_S$

[

]^{a,c}

a,c,e

Figure 3-7

Boundary Condition for Unit Secondary Pressure

[ ]^{a,c,e} $P_P > P_S$

a,c,e

Figure 3-8

Boundary Condition for Unit Secondary Pressure

[ ]^{a,c,e} $P_P < P_S$

a,c,e

Figure 3-9

Boundary Condition for Unit Secondary Pressure

[ ]^{a,c,e} $P_P > P_S$

a,c,e

Figure 3-10

Boundary Condition for Unit Secondary Pressure

[$]^{a,c,e}$ $P_P < P_S$

3.1.9 ASME Code Evaluation

The ASME Code evaluation was performed for specific analysis sections (ASN's) through the finite element model. [

]^{a,c} Stress limits are evaluated by the ratio of calculated stress intensity to allowable stress intensity at each analysis section. This ratio must be less than or equal to one to satisfy the limit. Fatigue is evaluated by the cumulative usage factor summed over all specified normal, upset, and test loads. The cumulative usage factor must also be less than or equal to one to meet the fatigue limit. The evaluations were performed at each analysis section in Figure 3-11, for each Code limit in Tables 3-6 to 3-9, for all of the specified pressure and temperature loads in Tables 3-10 and 3-11, for all combinations of tube status (intact or severed), FDB boundary conditions (fixed or free), and considering the effect of relative magnitudes of the primary and secondary pressure loads on the sleeve to tube interfaces.

The umbrella loads for the primary stress intensity evaluation have been given previously in Table 3-11. The largest magnitudes of the [

]^{a,c}

Note that in evaluating fatigue usage due to the seismic stresses for the OBE, [

]^{a,c,e}

The results for maximum range of primary plus secondary stress intensity and fatigue are summarized in Table 3-13. [

a,c

Figure 3-11

Analysis Section Number (ASN) Locations
Laser Welded Elevated Tubesheet Sleeve

Table 3-12
Summary of Maximum Primary Stress Intensity
Laser Welded Elevated Tubesheet Sleeves
Sleeve/Tube Weld Width of [ ]^{a,c}

a, c, e

Table 3-13
Maximum Range of Primary plus Secondary Stress Intensities and Maximum Fatigue Usage Factors Laser Welded Elevated Tubesheet Sleeves Sleeve/Tube Weld Width of [ ]^{a,c}

a,c

]^{a,c} The analysis results show the ASME Code limits for the maximum primary plus secondary stress range and for fatigue are satisfied at all analysis sections for all of the specified normal, upset, and test loads listed in Table 3-10.

3.1.10 Minimum Required Sleeve Wall Thickness

In establishing the safe limiting condition of a sleeve in terms of its remaining wall thickness, the effects of loadings during both the normal operation and the postulated accident conditions must be evaluated. The applicable stress criteria are in terms of allowables for the primary membrane and membrane-plus-bending stress intensities. Hence, only the primary loads (those necessary for equilibrium) need be considered.

For computing t_{min}, the pressure stress equation NB-3324.1 of the Code is used. That is,

$$t_{min} = \frac{\Delta P_i \times R_i}{P_m - 0.5 (P_i + P_o)}$$

Normal/Upset Operation Loads

The limiting stresses during normal and upset operating conditions are the primary membrane stresses due to the primary-to-secondary pressure differential ΔP_i across the tube wall. The limits on primary stress, P_m, for a primary-to-secondary pressure differential ΔP_i, are as follows:

Normal: $P_m < S_u/3$
Upset: $P_m < S_y$

Accident Condition Loadings

LOCA + SSE

The dominant loading for LOCA and SSE loads occurs [

]^{a,c}

FLB/SLB + SSE:

The maximum primary-to-secondary pressure differential occurs during a postulated feedline break (FLB) accident. Again, [ ]^{a,c} the SSE bending stresses are small. Thus, the governing stresses for the minimum wall thickness requirement are the pressure membrane stresses. For the FLB + SSE transient, the applicable pressure loads are [ ]^{a,c} The applicable criterion for faulted loads is:

$$P_m < \text{lesser of } 0.7\ S_u \text{ or } 2.4\ S_m$$

A summary of the resulting minimum required wall thicknesses are given in Table 3-14.

3.1.11 Determination of Plugging Limits

The minimum acceptable wall thickness and other recommended practices in Regulatory Guide 1.121 (Reference 3-6) are used to determine a plugging limit for the sleeve. The Regulatory Guide was written to provide guidance for the determination of a plugging limit for steam generator tubes undergoing localized tube wall loss and can be conservatively applied to sleeves. Tubes with sleeves which are determined to have indications of degradation of the sleeve in excess of the plugging limit, would have to be repaired or removed from service.

As recommended in paragraph C.2.b of the Regulatory Guide, an additional thickness degradation allowance must be added to the minimum acceptable tube wall thickness to establish the operational sleeve thickness acceptable for continued service. Paragraph C.3.f of the Regulatory Guide specifies that the basis used in setting the operational degradation allowance include the method and data used in predicting the continuing degradation and consideration of NDE measurement errors and other significant eddy current testing parameters. An NDE measurement uncertainty value of [ ]^{a,c} of the sleeve wall thickness is applied for use in the determination of the operational sleeve thickness acceptable for continued service and thus determination of the plugging limit.

Paragraph C.3.f of the Regulatory Guide specifies that the bases used in setting the operational degradation analysis include the method and data used in predicting the continuing degradation. To develop a value for continuing degradation, sleeve experience must be reviewed. To date, no degradation has been detected on Westinghouse designed mechanical joint sleeves and no sleeved tube has been removed from service due to degradation of any portion of the sleeve. This result can be attributed to the changes in the sleeve material relative to the tube and the lower heat flux due to the double wall in the sleeved region. Sleeves installed with the laser weld joint are expected to experience the same performance. As a conservative measure, the conventional practice of applying a value of [ ]^{a,c} of the sleeve wall, applied as an allowance for continued degradation, is used in this evaluation.

Table 3-14
Summary of Minimum Wall Thickness Calculations Laser Welded Elevated Tubesheet Sleeves For Use in 11/16 inch Tubes

a,c,e

In summary, the operational sleeve thickness acceptable for continued service includes the minimum acceptable sleeve wall thickness, and the combined allowance for NDE uncertainty and operational degradation [ ]^{a,c}. A summary of the resulting plugging limits as determined by Regulatory Guide 1.121 recommendations are given in Table 3-15.

3.1.12 Application of Plugging Limits

Sleeves which have eddy current indications of degradation in excess of the plugging limits must be repaired or plugged. Those portions of the sleeve for which indications of wall degradation must be evaluated are summarized as follows:

1) [ ]^{a,c}

2) [ ]^{a,c}

3) [ ]^{a,c}

4) [ ]^{a,c}

5) [ ]^{a,c}

3.1.13 Structural Evaluation Conclusions

Based on the results of this structural analysis and evaluation, the design of the laser welded elevated tubesheet sleeve is concluded to meet the requirements of the ASME Code. The applicable plugging limit for the sleeves is [ ]^{a,c} the nominal wall thickness.

3.2 Effect of Tubesheet Rotations on ETS Contact Pressures

The sleeves are to be installed in the upper half of the tubesheet, where tubesheet bow during operation tends to increase the diameter of the holes drilled in the tubesheet. This diameter increase will result in a decrease in the contact pressures between the sleeve/tube and tube/tubesheet produced by system pressures and differential thermal expansions among the sleeve, tube, and tubesheet. This section determines the effect of tubesheet rotations on the sleeve/tube and tube/tubesheet contact pressures.

Table 3-15
Summary of Recommended Plugging Margins
Laser Welded Elevated Tubesheet Sleeves
For Use in 11/16 inch Tubes

a,c,e

Loads are imposed on the sleeve as a result of tubesheet rotations under pressure and temperature conditions. A 2-D axisymmetric finite element analysis of a Model F tubesheet, channel head, and lower shell has been performed. The model is shown in Figure 3-12. This yields displacements throughout the tubesheet for two pressure and three thermal unit loads. The three temperature loadings consist of applying a uniform thermal expansion to each of the three component members, one at a time, while the other two remain at ambient conditions.

Previous calculations performed with a 3-D finite element model of this region of a Model D-4 steam generator showed that the displacements at the center of the tubesheet when the divider plate is included are 0.76 of the displacements without the effect of the divider plate (Reference 3-7). Although the reduction in the displacement components throughout the tubesheet is a more complex function of the reduction in the vertical displacements at the center due to the divider plate, applying the same 0.76 factor to all the displacement components is a reasonable approximation since all displacement components will decrease when the maximum displacement decreases. This is supported by the 3-D analysis of the Model E channel head complex. The radial displacements produced by the thermal unit loads are unaffected by the divider plate.

The radial deflection at any point within the tubesheet is found by scaling and combining the unit load radial deflections at that location according to:

$$\begin{aligned} U_R \quad &= (0.76)(U_R)_{Prim}(\text{Primary Pressure}/1000) \\ &+ (0.76)(U_R)_{Sec}(\text{Secondary Pressure}/1000) \\ &+ (U_R)_{Tubesheet}\{(\text{Tubesheet Temperature} - 70)/500\} \\ &+ (U_R)_{Shell}\{(\text{Shell Temperature} - 70)/500\} \\ &+ (U_R)_{Channel\ Head}\{(\text{Channel Head Temperature} - 70)/500\} \end{aligned}$$

This expression is used to determine the radial deflections along a line of nodes at a constant axial elevation (e.g. top of the tubesheet) within the perforated area of the tubesheet.

The expansion of a hole of diameter D in the tubesheet at a radius R is given by:

Radial: $\Delta D = D\ \{dU_R(R)/dR\}$
Circumferential: $\Delta D = D\ \{U_R(R)/R\}$

U_R is available directly from the finite element results. dU_R/dR may be obtained by numerical differentiation.

a,c,e

Figure 3-12

Finite Element Model of Channel Head/Tubesheet/Stub Barrel of Model F SG

The maximum expansion of a hole in the tubesheet is in either the radial or circumferential direction. Typically, these two values are within 5% of each other. Since the analysis for calculating contact pressures is based on the assumption of axisymmetric deformations with respect to the centerline of the hole, a representative value for the hole expansion must be used that is consistent with the assumption of axisymmetric behavior. A study was performed to determine the effect of hole out-of-roundness on the contact pressures between the sleeve and tube, and between the tube and tubesheet. The equation used for the hole ΔD is:

$$\Delta D = (SF)(\Delta D_{max}) + (1 - SF)(\Delta D_{min})$$

where SF is a scale factor between zero and one. For the eccentricities typically encountered during tubesheet rotations, SF is usually between [$]^{a,c}$.

This hole expansion includes the effects of tubesheet rotations and deformations caused by the system pressures and temperatures. It does not include local effects produced by interactions between the sleeve, tube, and tubesheet hole. Thick shell equations from Reference 3-8 in combination with the hole expansions from above are used to calculate the contact pressures between the sleeve and tube, and between the tube and tubesheet.

For a given set of primary and secondary side pressures and temperatures, the above equations are solved for selected elevations in the tubesheet to obtain the contact pressures as a function of radius between the sleeve and tube and the tube and tubesheet. The elevations selected were the neutral axis of the tubesheet and three elevations spanning the section from the bottom of the ETS to two inches from the top surface of the tubesheet.

Normal Operation

The temperatures and pressures for normal operating conditions at Callaway are:

Primary Pressure	=	2235 psig
Secondary Pressure	=	924 psig
Primary Fluid Temperature (T_{hot})	=	620 °F
Secondary Fluid Temperature	=	537 °F

For this set of primary and secondary side pressures and temperatures, the contact pressures between the sleeve and tube and the tube and tubesheet are obtained as functions of radius for selected elevations in the tubesheet for both intact tubes and tubes separated above the tubesheet.

Faulted condition

The temperatures and pressures for the limiting faulted condition are:

Primary Pressure = 2635 psig
Secondary Pressure = 0 psig
Primary Fluid Temperature (T_{hot}) = 503 °F
Secondary Fluid Temperature = 212 °F

For this set of primary and secondary side pressures and temperatures, the contact pressures between the sleeve and tube and the tube and tubesheet are obtained as functions of radius for selected elevations in the tubesheet for both intact tubes and tubes separated above the tubesheet.

Summary of Results

The contact pressures between the sleeve and tube, and between the tube and tubesheet are plotted versus radius in Figures 3-13 through 3-15. Results from these figures are summarized in the table below:

a,c,e

[

]^{a,c,e}

a,c,e

Figure 3-13

Contact Pressures for Normal Conditions with an Intact Tube

a,c,e

Figure 3-14

Contact Pressures for Normal Conditions with a Separated Tube

a,c,e

Figure 3-15

Contact Pressures for Faulted Condition with an Intact or Separated Tube

3.3 Thermal Hydraulic Analysis

3.3.1 Safety Analyses and Design Transients

From the standpoint of system effects, safety analyses and system transients, steam generator tube sleeving has the same effect as tube plugging. Sleeves, like plugs, increase both the flow resistance and the thermal resistance of the steam generator.

Each NSSS is analyzed to demonstrate acceptable operation to a level of plugging denoted as the plugging limit. When the steam generators include both plugs and sleeves, the total effect must be shown to be within the plugging limit. To do this, an equivalency relationship between plugged and sleeved tubes needs to be established. The following section derives a hydraulic equivalency number. This number represents the number of sleeved tubes which are hydraulically equivalent to a single plugged tube. It is a function of various parameters including 1) the number and location of sleeves in a tube, 2) the steam generator model, and 3) the operating conditions. Conservative bounding values are determined so that a single number applies to a given steam generator model and tube sleeve configuration.

Once the hydraulic equivalency number is established, the equivalent plugging level of a steam generator and NSSS can be determined. This equivalent plugging level must remain within the plugging level established for the plant.

3.3.2 Equivalent Plugging Level

The insertion of a sleeve into a steam generator tube results in an increase in flow resistance and a reduction in primary coolant flow in that tube. Furthermore, the insertion of multiple sleeves (tubesheet) will lead to a larger flow reduction in the sleeved tube compared to a nominal unsleeved tube. The flow reduction through a tube due to the installation of one or more sleeves can be considered equivalent to a portion of the flow loss due to a plugged tube. A parameter termed the "hydraulic equivalency number" has been developed which indicates the number of sleeved tubes required to result in the same flow loss as that due to a single plugged tube.

The calculation of the flow reduction and equivalency number for a sleeved tube is dependent upon: 1) the tube geometry, 2) the sleeve geometry, and 3) the steam generator primary flow rate and temperature. These parameters are used to compute the relative difference in flow resistance of sleeved and unsleeved tubes operating in parallel. This difference in resistance is then used to compute the relative difference in flow between sleeved (W_{slv}) and unsleeved (W_{unslv}) tubes. The hydraulic equivalency number is then simply:

a,c,e

[ ]

The hydraulic equivalency number can be computed for both normal operating conditions and off-normal conditions such as a LOCA. For LOCA conditions, the equivalency number is established using flow rates consistent with the reflood phase of a post-LOCA accident when peak clad temperatures exist. The equivalency number for normal operation is independent of the fuel in the reactor. In all cases, the hydraulic equivalency number for normal operation is more limiting than for postulated LOCA conditions.

As a result of the flow reduction in a sleeved tube and the insulating effect of the double wall at the sleeve location, the heat transfer capability of a sleeved tube is less than that of an unsleeved tube. An evaluation of the loss of heat transfer at normal operating conditions indicated that the percentage loss of heat transfer capability due to sleeving is less than the percentage loss associated with the reduction in fluid flow. In other words, the heat transfer equivalency number is larger than the hydraulic equivalency number. Thus, the hydraulic equivalency number is limiting.

The specific LOCA conditions used to evaluate the effect of sleeving on the analysis occur during a portion of the postulated accident when the analysis predicts that the fluid in the secondary side of the steam generator is warmer than the primary side fluid. For this situation, the reduction in heat transfer capability of sleeved tubes would have a beneficial reduction on the heat transferred from secondary to primary fluids.

Hydraulic Equivalency Calculation

The goal of the calculations described below is to develop conservative values of hydraulic equivalency to bound all possible sleeve configurations that might be considered for Model F steam generators with 11/16 inch tubes. Hydraulic equivalency numbers are generated for a tube with each of the following tubesheet sleeve configurations.

1) One tubesheet sleeve on the hot leg
2) One tubesheet sleeve on the cold leg
3) Two tubesheet sleeves, on both hot and cold leg

In addition, the installed sleeve has tolerances on the diametral dimensions. Table 3-16 shows the diametral range expected for each length segment of the sleeve and tube. Hydraulic equivalency is calculated for both sets of values in the table.

Table 3-16
Sleeve I.D.'s and corresponding lengths (inches)

Axial Segment	I.D. (min)	I.D. (max)	Length

a,c,e

Operating conditions, though their effect is small, were also evaluated. Consistent with other studies, high values of primary flow or T_{hot} and low values of T_{cold} give the most conservative values of hydraulic equivalency. The values of these parameters in Table 3-17 were selected for a conservative case and a case to check sensitivity.

<u>Hydraulic Equivalency Results and Sensitivity</u>

Calculated values of hydraulic equivalency are presented in Table 3-18. The case with the set of minimum diametral dimensions and maximum flow and temperature yields the lowest, most conservative, values of hydraulic equivalency. These values are bounding for all operating conditions and the full range of 12" sleeve dimensions. As can be seen from the table, the diametral dimensions have the dominant effect and the operating conditions are secondary. Also noteworthy is that the difference between the bounding hydraulic equivalency value and the least conservative value is insignificant in terms of the number of equivalent plugs. For example, 1000 hot leg sleeves is equivalent to 30 plugged tubes using the minimum equivalency, 33.1 in Table 3-18. Using the maximum equivalency, 35.6, results in 28 equivalent plugs, a benefit of only two tubes.

The total equivalent number of plugged tubes is the sum of the equivalent number of plugs associated with sleeving (number of sleeves divided by the hydraulic equivalency number) and the actual number of plugged tubes. The method and values of hydraulic equivalency and flow loss per sleeved tube outlined above can be used to represent the equivalent number of sleeves by the following formula:

$$P_e = P_a + \sum\left(\frac{S_i}{N_{hyd,i}}\right) + P_c$$

where:

P_e = Equivalent number of plugged tubes
P_a = Number of tubes actually plugged
S_i = Number of active tubes with a sleeve combination "i"
$N_{hyd,i}$ = Hydraulic equivalency number for a sleeve configuration "i"
P_c = Equivalent number of plugged tubes due to other sleeve designs

3.3.3 Fluid Velocity

As a result of tube plugging and sleeving, primary side fluid velocities in the steam generator tubes will increase. The effect of this velocity increase on the sleeve and tube has been evaluated assuming a limiting condition in which 20 per cent of the tubes in a steam generator are plugged.

Using the conservatively high primary flow rate defined previously, with 20 per cent of the tubes plugged, the fluid velocities through an unplugged and unsleeved t[illegible] [ ]^{a,c,e}. For a tube with a single tube sheet sleeve, the maximum local velocity in the sleeve region is computed to be [ ]^{a,c,e}. These

Table 3-17
Operating Conditions Used for Hydraulic Equivalency Calculations

a,c,e

	Parameter Values	
Parameter	**Conservative Case**	**Sensitivity Case**
Primary Flow - GPM		
Primary T_{hot} - °F		
Primary T_{cold} - °F		

Table 3-18 Hydraulic Equivalency Values, 11/16" Tube

	Primary Conditions		Sleeve Configuration		
Sleeve Diametral Set	Flow gpm	T_{hot} °F	HL	CL	HL+CL

a,c,e

velocities are smaller than the inception velocities for fluid impacting, cavitation, or erosion-corrosion for Alloy 600 and 690 tubing. As a result, the potential for tube degradation due to these mechanisms is low.

3.4 Sleeved Tube Relative Flow Induced Vibration Assessments

The purpose of this section is to provide the bases, methodology overview, salient parameters and results which demonstrate acceptability of tube modifications implicit with installation of laser welded sleeves in terms of tube flow induced vibration (FIV) and wear potential. The two viable tube vibration mechanisms in steam generator tube bundles are due to cross flow turbulence and fluidelastic excitations. It is noted that the mechanisms of axial flow turbulence and vortex shedding are not considered viable as major causative mechanisms based on field experiences and, hence, are not addressed further.

Results from these assessments show that the limiting cases of a tube modification caused by laser welded sleeves do not cause significant potential field issues with respect to FIV responses. These results, along with the experience that FIV problems have not occurred in the straight leg regions of Model F SGs in the field, are intended to provide adequate assurance that laser welded sleeves are acceptable for vibration considerations.

3.4.1 Flow Induced Vibration Evaluation Methodologies

Westinghouse capabilities and methodologies for the evaluations of flow induced vibrations are under continuous development (see References 3-9 through 3-17). To perform the subject evaluations, a relative analysis method is used. This relative method is described below.

The first case considers a laser welded sleeve to be installed in a tube and, at the same time, the tube is conservatively assumed to be severed through 360 degrees of arc at some location within bounds of the length of the sleeve. The second, reference case, is that of the unmodified (nominal) tube. Ratios of the vibration responses for these cases provide the desired relative results, which are then put into perspective relative to actual field and test operating experiences to provide the required demonstration of acceptability.

In this relative evaluation, it is necessary to establish all vibration response related parameters which vary between the two cases being compared. A sleeved and separated tube produces physical changes in the structural tube system, relative to the nominal case, such that the length of that system may be increased and/or its cross-sectional properties decreased. Each of these effects results in both reduced natural frequencies and changed mode shapes. Because damping is known to be a strong function of frequency, it too must be considered.

Linear system vibration responses for both the turbulence and fluidelastic mechanisms are obtained with a Westinghouse proprietary computer code. Initial separate evaluations are typically performed, as in this case.

A finite element program provides for the generation of a finite element model of the tube and tube support system in the form of a linear superelement. The finite element model provides the vehicle to define the mass and stiffness matrices for the tube system. This information is used to determine the modes (eigenvalues) and mode shapes (eigenvectors) for the linearly supported tube being considered. Table 3-19 provides the tube and sleeve cross sectional properties used in the creation of the superelements. A schematic of the superelement showing the tube, tube support elevations and node designations is provided in Figure 3-16.

Inputs to the vibration analysis are the mass and stiffness matrices, the secondary fluid flow velocity and density distributions, a set of pre-determined permissible boundary conditions for each tube (or tube span) in the bundle to be evaluated, the fluidelastic constant, beta, and damping appropriate to the flow, boundary conditions, and the lower limit value to the reduced velocity parameter.

The secondary side fluid velocity and density distributions used for the present evaluations were derived from three-dimensional flow studies for the Model F SG. In order to include the hydrodynamic mass effect of the secondary fluid on the tube, density as a function of elevation was extracted from the results in a region of the hot leg near the periphery of the bundle. The density distribution provides conservative evaluation results, as it has the highest values for the hot leg region of the bundle at the selected full power operating conditions. The density distribution is given in Table 3-20, along with the associated equivalent tube density profiles. It is these latter profiles which are input to the superelement models to form the tube mass matrices.

Specific boundary conditions considered for each tube location are typically obtained on the basis of results from the application of Monte Carlo methods. However, in this present evaluation, the boundary conditions considered are conservatively chosen as up to two missing tube supports at the four lowest (true) tube supports, a.k.a., TSPs on the hot leg side. Included in these conditions are: 1) all supports active, 2) any one support inactive, 3) any two supports inactive, including the conservative case of two consecutive supports inactive. In all cases the fifth and higher supports are assumed to provide pinned tube support and the flow distribution baffle is assumed to provide no support.

Output from the vibration evaluation is comprised of the fluidelastic stability ratio and the root-mean-square turbulence vibration amplitude. Because these are relative evaluations, the outputs (results) presented herein are ratios of appropriate stability ratios and root-mean-square turbulence vibration amplitudes. These results can be presented in many different forms. Generally, it is instructive to produce maps showing the worst case boundary condition result at each tube location considered in the tube bundle. Since these relative evaluations are being performed on a conservative "worst expected case tube condition" basis, there is only one evaluation result for each of two mechanisms and boundary conditions evaluated. Thus, the presentation format chosen for these evaluations is a table. This table is presented and discussed below.

Table 3-19
Model F Sleeved Tube Relative FIV Evaluation
Tube and Sleeve Cross Sectional Properties

a,c,e

a,c,e

Figure 3-16

Model F Sleeved Tube Superelement Geometry and Nodes

Table 3-20
Sleeved Tube Relative FIV Evaluation
Tube Density Distribution

a,c,e

3.4.2 Effects of Damping on Relative Evaluations

Tube damping plays the very important role of establishing tube vibration and stress magnitudes for both the fluidelastic and turbulence mechanisms, once all other system and forcing function parameters are established. For these relative evaluations, damping is important because of the change in frequencies brought about by the introduction of the sleeve, and the conservative assumption of a severed tube, with their associated, but independent, changes in effective tube system geometry.

In order to establish the magnitude of the effects of damping on the FIV evaluation results and the difference in these damping effects given different damping relations associated with different SG straight-leg conditions, a parametric evaluation has been performed in prior LWS evaluations (Reference 3-18). This evaluation was performed independent of the final relative evaluations for other LW sleeves and was intentionally made independent of the mode shape integral effects. [

]^{a,c} For the present evaluation, a frequency-dependent damping relationship originally developed specifically for a Model F SG straight-leg evaluation is used in all laser welded sleeve and nominal tube configuration cases. Based on physical considerations associated with the various tube / sleeve configurations, it is expected that this damping relation is relevant and conservative for laser welded sleeve configurations and relevant for the nominal configurations.

3.4.3 Flow Induced Vibration Results and Conclusions

The subject laser welded sleeve FIV evaluation results are provided in Table 3-21. Both fluidelastic and turbulence results are presented for all the boundary conditions considered. The boundary conditions are varied between pinned and open at the four lowest true tube support plates. Again, each individual result is the ratio of the sleeved and severed tube's predicted response for the vibration mechanism indicated at the top of the columns to the predicted response for the nominal tube configuration subjected to the same mechanism and conditions.

Fluidelastic Stability

Table 3-21 shows that there is only one support configuration for which the ratio of a sleeved and severed tube to nominal tube stability ratio exceeds [ ],^{a,c} which implies a [ ]^{a,c} increase for the sleeved/severed configuration over nominal. No support configurations exceed a ratio of [ ].^{a,c}

Because there are no known unacceptable cases of straight-leg fluidelastic vibration and wear conditions in any of the field units with Model F SGs, the fluidelastic stability ratio increases implied by the results discussed above and presented in Table 3-21 are expected to be acceptable.

Table 3-21
Relative Flow Induced Vibration Evaluation Results for Model F Laser Welded Sleeve Configuration with Various Tube Support Plate Boundary Conditions

a,c,e

Turbulence Response

The turbulence response results, given in the final column of Table 3-21. show that the sleeved and severed to nominal tube turbulence amplitude ratios for the various support conditions range from [ ].^{a,c} However, it is well known on the bases of both tests and field results that the absolute turbulence response for the nominal condition case for the hot leg in any of the feedring SG models is quite small, on the order of ten mils or less (Reference 3-13). Thus, it is fully expected that there would be no real vibration and wear issues introduced if the turbulence amplitudes were increased by the largest ratio in the table, which is about [ ].^{a,c} It is also expected that, at these higher amplitudes, the turbulence response would remain below the endurance limit and, therefore, would not change the tube/sleeve system fatigue evaluation outcome relative to the nominal case.

3.5 References for Section 3

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3-2 Design Specification 413A35, Rev. 0, "Elevated Tubesheet Application of Sleeves for 11/16 Inch O.D. Tubes in Westinghouse Model F Steam Generators," February 28, 1996. (Westinghouse Proprietary)

3-3 Design Specification 953291, "Standardized Nuclear Power Plant System - Reactor Coolant System - Model F Steam Generator," December 12, 1976, Rev. 6, June 8, 1989. (Westinghouse Proprietary)

3-4 ASME Boiler and Pressure Vessel Code, Section III, "Rules, For Construction of Nuclear Power Plant Components," The American Society of Mechanical Engineers New York, NY, 1989.

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3-7 WNET-142, Volume 8 "Model D4-2 Steam Generator Stress, Report Divider Plate Analysis", Westinghouse Tampa Division, September, 1977.

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3-12 "Extraction of Turbulence Generated Input Forces Acting on a Steam Generator Tube," Kendig, R.P., Frick, T.M., Noise-Con 87, 1987, pps 77-82.

3-13 "Tube Vibration Measurements on a Feedring Steam Generator," Curlee, N.J. Jr., Frick, T.M., Mabon, I.D., 1985 ASME WAM, Conference on Thermal Hydraulics and Effects on Nuclear Steam Generators and Heat Exchangers, HTD Vol. 51, pps 43-55.

3-14 "Flow Induced Vibrations and Wear of Steam Generator Tubes," Connors, H.J., Nuclear Technology, Vol. 55, November 1981, pps 311-331

3-15 "Methodologies for the Computation of Steam Generator Tube Wear with Applications for Turbulence in the U-Bend Region," R. Waisman and T.M. Frick, Joint ASCE/ASME Mechanics, Fluids Engineering, and Biomechanics Conference, San Diego, CA, July 9-12, 1989.

3-16 "U-Bend Shaker Test Investigation of Tube/AVB Wear Potential," H.J. Connors and F.A. Kramer, International Conference on Flow-Induced Vibrations, Proceedings of the Institution of Mechanical Engineers, May 1991.

3-17 "Simulation of Flow-Induced Vibration Characteristics of a Steam Generator U-Tube," E.R. France and H.J. Connors, International Conference on Flow-Induced Vibrations, Proceedings of the Institution of Mechanical Engineers, May 1991.

3-18 "Laser Welded Sleeves for 3/4 Inch Diameter Tube Feedring Type and Westinghouse Preheater Steam Generators," Generic Sleeving Report, WCAP-13698, Revision 1, May 1993.

4.0 MECHANICAL TESTS

Mechanical tests are used to provide [

]^{a,c,e}

Mechanical testing was previously applied to both HEJ (lower joint) and laser welded (free span and lower joint) sleeving to confirm analyses that evaluated the interaction between the sleeve and tube. Mechanical testing is primarily concerned with leak resistance and joint strength, including fatigue resistance. A consistent characteristic observed in the testing of HEJ, a.k.a. mechanical interference fit (MIF) lower joints for sleeves, is that leakage, when observed, is generally higher at room temperature (RT) for normal operation, steamline break (SLB) and greater-than-SLB pressure differential conditions than at elevated temperatures. This result obviates the need for all of the combined or separate elevated temperature leakage resistance and applied-load types of tests and permits qualification of these 11/16 inch MIF lower joints on the basis of the RT leak resistance test and the previous testing.

Sections 4.1 and 4.2 summarize previous mechanical tests and results for HEJ 3/4 and 7/8 inch tube sleeves, respectively. The 3/4 and 7/8 inch sleeve results show the adequacy of obtaining the required strength of the roll expanded portion of the HEJ, based on optimal roll thinning of the sleeve. This same method is used to achieve the required strength of the roll expanded portion of the HEJ for the 11/16 inch sleeves. Confirmatory RT leakage resistance tests are needed to confirm the 11/16 inch sleeve MIF joints (see Section 4.3).

Section 4.2 also summarizes previous mechanical tests and results for 7/8 inch laser welded joints. These data were provided to show that tests corroborated the analyses for those joints. Therefore, verification by analysis is sufficient for the 3/4 and 11/16 inch laser welded sleeve joints.

In previous testing, some of the 3/4 and 7/8 inch tube sleeve HEJ lower joint specimens were also subjected to cyclic thermal and mechanical loads, simulating plant transients. [

]^{a,c,e} Other specimens were subjected to tensile and compressive loads to the point of mechanical failure. These tests demonstrate that the required joint strength exceeded the loading the sleeve joint would receive during normal plant operations or accident conditions.

Note: In the test portions of this report, the units of primary-to-secondary side differential pressures are listed simply as "psi," rather than "psid." The secondary side pressures were zero psig.

4.1 Tubesheet HEJ Tests – 3/4 Inch Tube Sleeves

4.1.1 Case No. 1 - Feedring Steam Generator (FSG)

The mechanical tests of the tubesheet lower joint (HEJ), provided for a non-Westinghouse feedring, 3/4 inch OD (nominal) tube, steam generator (FSG) are applicable to the 3/4 inch OD (nominal) Westinghouse Preheat Steam Generator (PSG) tubes and generically applicable to other non-Westinghouse FSGs. The test conditions are listed in Table 4-1 and the generic, allowable, primary-to-secondary leak rates are listed in Table 4-2. The test results are provided in Table 4-3. As discussed earlier, the HEJs are formed in [

]^{a,c,e}

4.1.1.1 Acceptance Criteria - 3/4 Inch Tube HEJ Sleeve (FSG)

For push-out and pull-out tests, all joints shall exhibit loads for initial slip, where observable, or loads for start of non-linear load-deflection, above the 0 to 2200 lb. push/release effective axial loads that were applied during the fatigue tests. The leak rate criteria are based on typical Technical Specifications and Regulatory requirements. Table 4-2 shows the leak rate criteria for the FSGs and PSGs.

4.1.1.2 Results of Verification Tests - 3/4 Inch Tube HEJ Sleeves (FSG)

The test results for the HEJ (lower joint) specimens are presented in Table 4-3. For normal operating conditions, i.e., 1485 to 1600 psi at RT and 600°F, [

]^{a,c,e}

In the case of the fatigue testing, this number of cycles (30,000) represents the number of cycles expected yearly multiplied by a suitable factor to achieve an accelerated test condition. On that basis the test results provide data which are conservative in nature and exceed the actual operating conditions. The other parameters associated with the thermal cycle test, for example, such as temperature ramp, hold time and temperature gradient. are accelerated to achieve meaningful test results within an acceptable time frame. Consequently, the test results obtained and discussed are those of accelerated conditions designed to test the sleeve at the endurance limit. The results do not imply that after a specific length of operating time the sleeves will begin to leak. Rather they demonstrate that under extreme accelerated test conditions leakage is small or zero, providing assurance that in the actual operating case the sleeves will perform at an essentially zero leakage base. Additionally, by using that same test series for all sleeve designs it is possible to measure consistency in process modification and/or small changes in the overall design to facilitate an assessment of the effect on total sleeve performance.

Table 4-1
Case No. 1 - Feedring Steam Generator
Mechanical Test Program Summary
Tubesheet HEJ Tests - 3/4 Inch Tube Sleeves

a,c,e

Table 4-2
Typical Bounding Maximum Allowable Leak Rates for 3/4 Inch Tube, Feedring - Type and Preheater Steam Generators

		Allowable Leak Rate			
Condition	Plant	*Most Limiting Sleeved SG, gpm (gpd)			Allowable Leak Rate per Sleeve**
		Model D	Model E	FSG	
Normal Operation	1.0 gpm	0.105 (150)	0.105 (150)	0.105 (150)	[ ]^{d,e}
Postulated Accident Condition	1.0 gpm 3.78 ml/min.				[ ]^{d,e}

* Typical administrative leakage limit for steam generators containing sleeves.

** Based on installation of 500 tubesheet sleeves with non-welded lower joints - for a steam generator in a four-loop plant (2000 sleeves in the plant).

a,c,e

a,c,e

a,c,e

a,c,e

Table 4-3 (Page 5 of 5)
Verification Test Results - Lower Joint (HEJ)
Alloy 690 Full Length Tubesheet Sleeve for 3/4 Inch Tube (FSG)
Notes to Table 4-3

a,c,e

a,c,e

Figure 4-1

Full Length Tubesheet Sleeve Lower Joint Test Specimen

[

]^{a,c,e}

The conclusions reached as a result of the test program are:

A consistent characteristic observed in the testing of mechanical joints is that the leakage, when observed, is generally higher at room temperature (RT) conditions. This characteristic has led to the increased use of the room temperature hydrostatic test in process, tooling, personnel, procedure and demonstration phases.

For the lower joint, initial leak rates, both at room temperature and at 600°F, [

]^{a,c,e} As stated earlier in this report, if the FSGs or PSGs of individual plants require minor modifications to the qualified HEJ processes, due to environmental or other conditions, these needs will be addressed in the specific preparations for the repair project. Any additional qualifications will be documented separately. Note: Leak rate measurement is based on counting the number of drops leaking during a 10-20 minute period. Conversion to volumetric measure is based on assuming 19.8 drops per milliliter.

Thermal cycling between 120°F and 600°F, for the lower joint, had no detectable adverse influence on joint leak rate. The leak rate after testing remained at [ ]^{a,c,e}

Fatigue tests of the HEJ had no discernable adverse effect on joint leak resistance or structural integrity. [ ]^{a,c,e}

For push-out and pull-out tests, all joints tested exhibited loads for initial slip, where observable, or loads for start of non-linear load-deflection, above the effective axial loads that were applied during the fatigue tests.

The leak rates observed during a simulated steam line break test were well below the acceptance criteria.

The leak rates observed during a simulated LOCA remained at [ ],^{a,c,e} which is far below the acceptance limit.

4.1.2 Case No. 2 - Feedring Steam Generator

The verification based on mechanical tests of the tubesheet lower joint (HEJ) previously performed for an FSG [

]a,c,e

The test conditions are listed in Table 4-4.

4.1.2.1 Acceptance Criteria - 3/4 Inch HEJ Sleeve (FSG)

The acceptance criteria for these strength tests were the same as for those listed for Case No. 1. The leak rate criteria for these tests are also listed in Table 4-2.

4.1.2.2 Results of Verification Tests - 3/4 Inch Tube HEJ Sleeves (FSG)

From the test results obtained for Case No. 2 (Table 4-5), the following conclusions were reached:

a,c,e

a.

b.

c.

d.

Table 4-4
Case No. 2 - FSG
Mechanical Test Program Summary
Tubesheet HEJ Tests - 3/4 Inch Full Length Tubesheet Sleeves

a,c,e

Table 4-5 (Page 1 of 5)
Verification Test Results - Lower Joint (HEJ)
Alloy 690/625 Bimetallic Full Length Tubesheet Sleeve for 3/4 Inch Tube (FSG)

b,c,e

Specimen No.
VBL-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20

Table 4-5 (Page 2 of 5)
Verification Text Results - Lower Joint (HEJ)
Alloy 690/625 Bimetallic Full Length Tubesheet Sleeve for 3/4 Inch Tube (FSG)

Specimen No.
VBL-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20

b,c,e

Table 4-5 (Page 3 of 5)
Verification Test Results - Lower Joint (HEJ)
Alloy 690/625 Bimetallic Full Length Tubesheet Sleeve for 3/4 Inch Tube (FSG)

b,c,e

Specimen No.
VBL-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20

Table 4-5 (Page 4 of 5)
Verification Test Results - Lower Joint (HEJ)
Alloy 690/625 Bimetallic Full Length Tubesheet Sleeve for 3/4 Inch Tube (FSG)

b,c,e

Specimen No.
VBL -1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20

Table 4-5 (Page 5 of 5)
Verification Test Results - Lower Joint (HEJ)
Alloy 690/625 Bimetallic Full Length Tubesheet Sleeve for 3/4 Inch Tube (FSG)
(Notes to Table 4-5)

a,b,c,e

1.
2.
3.
4.
5.
6.
7.
8.

4.1.3 Case Number 3 - Elevated Alloy 690 Sleeve-FSG

A sleeve elevated in the tubesheet (ETS) is shown in Figure 2-1. The lower joint of this sleeve is a mechanical, non-welded joint known as a mechanical interference fit (MIF) joint. Sleeve pullout resistance and leakage resistance at this lower joint are a direct result of the interference fit radial contact pressure (CP) between the tube inside surface or "diameter" (ID) and sleeve outside surface or diameter (OD). Changes to the as-installed CP of the structure result from the four types of loading conditions, normal operation (N.Op.), faulted, upset and test.

The ETS for this FSG consists of a 0.630 inch (nom.) x 0.038 inch (nom.) wall thickness, Alloy 690 sleeve, installed in a 3/4 inch (nom.) outside diameter x 0.048 inch (nom.) wall thickness, Alloy 600 tube, explosive expanded in the tubesheet in the factory.

Leakage and Pullout Resistance Tests

It has been determined that for ETS MIF lower joints, the room temperature (RT) leakage resistance test, a contact pressure (CP) test and previous testing are sufficient to qualify new ETS lower joint configurations. The pullout resistance calculated for the qualification of new ETS configurations requires the determination of the CP between the sleeve OD and tube ID in the as-installed condition. In conjunction with an appropriate coefficient of friction, from previous pullout tests involving the same materials and other conditions, the sleeve pullout resistance can be calculated. After determination of the as-installed interference fit pressure, the changes from that condition, both increasing (beneficial) and decreasing (detrimental) to joint integrity are calculated, based on tubesheet deformation and temperature and fluid pressure changes.

Previous tests have shown that if a MIF joint passes the RT leak test at prototypical pressure differentials, it will pass the elevated temperature (prototypical) leak test. Accordingly, leak tests were performed for this case at RT at three Delta P's: 1900, 2650 and 3110 psi. The 1900 psi Delta P condition was conservative to the 1450 psi normal operating condition and the 1500 psi design condition. The 2650 psi was used to exceed the plant SLB Delta P of 2520 psi and the 3110 psi differential also enveloped the 2520 psi SLB condition.

Similar to the method used in the pullout resistance calculation, the changes from the as-installed CP were also used to project leakage for the RT leak test. The result of the beneficial and detrimental changes to the as-installed CP were used to bound the projected leakage at elevated temperatures.

4.1.3.1 Acceptance Criteria

Primary-to-Secondary Leakage

The acceptance criterion for average leakrate at normal operating conditions was 0.25 drops per minute (dpm) per sleeve. This was based on a fraction of the Administrative permissible leakrate of 50 gpd per SG. A similar limit for faulted conditions was not specified. (Note: There are approximately 75,000 drops in one gallon.)

Pullout Resistance - Normal Operation

A pullout resistance of three times the maximum primary-to-secondary pressure differential, times the tube cross sectional area, i.e., the "endcap" load, for normal operation has been used as the requirement for sleeve MIF lower joints and it is consistent with the ASME B&PV Code. Based on this approach, the limiting required resistance to pullout, upward, for the FSG in this case was 1605 lbs. for the most stringent case, 1500 psi pressure differential, at the design condition, and the largest tube ID, resulting from installation of a tube in the largest hole in the tubesheet.

Pullout Resistance - Faulted Condition

A pullout resistance of 1.43 times the "endcap" load for the corresponding primary-to-secondary pressure differential, for the limiting faulted condition, SLB, was used as the requirement for sleeve MIF lower joints and it is consistent with the ASME Code. For the FSG in this case, the maximum pressure differential for the limiting faulted condition was 2520 psi; the largest tube ID, resulting from installation of a tube in the largest hole in the tubesheet was 0.674 inch. This load was calculated to be 1286 lbs.

Pullout Resistance - Upset and Test Conditions

These conditions had been bounded by normal operation and SLB conditions in previous evaluations and it was assumed that the same was true for this case.

Pullout Resistance Limiting Condition - Conclusion

The limiting axial load for the joint design is the greater of the "3 Delta P" endcap load for the normal operation condition and the "1.43 times the largest faulted endcap load". In this case, the normal operation condition endcap load, 1605 lbs. caused the largest load and was the limiting condition.

4.1.3.2 Results and Conclusions of Verification Tests

Leakage Resistance - Normal Operation

[

]^{a,c,e}

Table 4-6 (Page 1 of 3)

Verification Test Results - Mechanical Interference Fit Lower Joint

Elevated Tubesheet Sleeve

Alloy 690 Sleeve for 3/4 Inch Tube (Feedring SG)

Sample Identification								Room Temp. Leak Rate (dpm) Sleeve I.D. Pressure, PSI		
Collar	Tube	Sleeve	Collar I.D.	Slv. Lgn. in.	Roll Len. in.	Torque in. #	AWT* %	1900	2650	3100

a,c,e

*AWT = Apparent Wall Thinning

Table 4-6 (Page 2 of 3)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Feedring SG)

Sample Identification								Room Temp. Leak Rate (dpm) Sleeve I.D. Pressure, PSI		
Collar	Tube	Sleeve	Collar I.D.	Slv. Lgn. in.	Roll Len. in.	Torque in. #	AWT* %	1900	2650	3100

a,c,e

*AWT = Apparent Wall Thinning

Table 4-6 (Page 3 of 3)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Feedring SG)

Sample Identification								Room Temp. Leak Rate (dpm) Sleeve I.D. Pressure, PSI		
Collar	Tube	Sleeve	Collar I.D.	Slv. Lgn. in.	Roll Len. in.	Torque in. #	AWT* %	1900	2650	3100

a,c,e

*AWT = Apparent Wall Thinning

4.1.4 Case Number 4 - Elevated Alloy 690 Sleeve-PSGs

Two previous interference fit, ETS lower joints have been developed for sleeves for Westinghouse 3/4 inch diameter tube steam generators (SGs).

One of these is the Westinghouse Model E configuration which consists of the same sleeve and tube as the second configuration, the Model D4, ETS lower joint, i.e. a 0.640 inch (nominal) outside diameter x 0.038 inch (nom.) wall thickness, Alloy 690 sleeve, installed in a 3/4 inch (nom.) outside diameter x 0.043 inch (nom.) wall thickness, Alloy 600 tube, roll expanded at the factory. The tubesheet unit cells are also the same for the Model E and Model D4 SGs. The sleeve lower joint fabrication, including the roll expansion and hydraulic expansion processes, roll expander type and torque are the same for sleeves for the two SGs. However, the Model E sleeve installation sequence was slightly different from the Model D4 sequence; it was a roll-first (weld-last) process; the Model D4 is a roll-last sequence.

The roll-last ETS lower joint was also developed for the 3/4 inch tube FSGs, Case No. 3 above. The roll-last sequence involves performing welding and all heat treatment prior to final expansion of the lower joint. It reduces the tensile far field stresses on the tube above the weld for cases involving locking or suspected locking of the tube at the first support.

Leakage and Pullout Resistance Tests

The same tests used to qualify the ETS MIF lower joints in Case 3 were used to qualify the lower joints in Case 4. This included the RT leakage resistance test, the CP test and previous testing. Additionally, elevated temperature leak tests and RT pullout resistance tests were also performed.

The objective of the leak tests was to determine potential primary-to-secondary side leakage for the rare case where the tube became completely degraded within the sleeve length. (The upper joint, the laser weld, was taken as leaktight in this and in all cases.) Leak tests were performed for this case at RT at three Delta P's: 1900, 2650 and 3110 psi. The 1900 psi Delta P condition was conservative to the 1270 psi normal operation condition and the 1600 psi design condition. (The 1900 psi was a typical pressure previously used in elevated temperature testing; it was adequately above the saturation pressure to ensure that liquid, rather than a two-phase flow was entering a potential leakage path in the joint. Although no phase change issues were involved in RT testing, the higher pressure was used for comparison with the results of the previous elevated temperature test programs.). The 2650 psi was used to approximate the plant FLB Delta P of 2750 psi and the 3110 psi differential enveloped the 2750 psi FLB condition. As stated earlier RT leak tests had been found to be adequate in comparison with elevated temperature testing due to the net results of the beneficial and detrimental effects in going from the as-installed/RT condition to the elevated temperature/deformed tubesheet/pressurized conditions for the bounding tube/sleeve in the bundle. Therefore, leakage testing at the prototypical temperature was unnecessary. However in this, PSG case, it was performed for completeness and Engineering Information.

In the pullout resistance related test, the sleeve-to-tube as-installed interference fit contact pressure (CP) was first determined by the secondary-to-primary side pressure test. The test was based on the fact that the roll expanded interface between the sleeve and tube without axial or helical scratches will leak only when the fluid pressure in the sleeve-to-tube annulus exceeds the sleeve-to-tube CP. The CPs for given, i.e., normal operation and FLB conditions, were then determined by adding or subtracting the respective CP change to the as-installed CP. Accordingly, the CP change due to tubesheet upward bow, in the part of the bundle where the bow effect caused the maximum reduction in CP, was subtracted. However, the beneficial changes, due to the differential growth mismatch between the sleeve and tube-tubesheet structure and the "differential pressure tightening", were added to the as-installed CP. The net effect at the radius from the tubesheet vertical centerline where the tubesheet deformation caused the largest reduction in the as-installed CP, was positive for both normal operation and FLB conditions. This CP for normal operation, FLB or any other condition, acting over the effective area of contact between the sleeve and tube, along with an appropriate coefficient of friction determined the pullout resistance at that condition.

For the sake of completeness, actual pullout tests were also performed at room temperature and unpressurized conditions. Due to the net effect of increased CP at all elevated temperature and pressure conditions, for all radii in the tubesheet, results of pullout tests at RT bounded all elevated temperature/pressure results.

4.1.4.1 Acceptance Criteria

Primary-to-Secondary Leakage

The acceptance criterion for average leakrate per sleeve at normal operation conditions was not listed specifically for this PSG site. However, in the absence of an Administrative Leak limit in this non-domestic plant, a typical value would be 500 gpd per SG divided by the total number of sleeves in the SG, to arrive at the average per-sleeve leakage. In this 100 percent sleeving case, this provided a guideline of approximately 5.4 dpm per sleeve. No special limit was available for faulted conditions either. However, use of the typical domestic limit of 1.0 gpm for the plant, or, considering the line break in only one SG, the guideline of approximately 5.4 dpm also applies to this condition.

Pullout Resistance - Normal Operation

As discussed previously, a pullout resistance of three times the normal operation tube endcap load has been used as the requirement for sleeve MIF lower joints. Based on this approach, the limiting required resistance to pullout, upward, for the PSG in this case was 1784 lbs. for the most stringent case, 1600 psi pressure differential, at the design condition, and the largest tube ID, resulting from installation of the minimum wall thickness tube in the largest hole in the tubesheet.

Pullout Resistance - Faulted Condition

The corresponding pullout resistance at the most stringent faulted condition, FLB, was calculated to be 1461 lbs. for the Delta P of 2750 psi.

Pullout Resistance - Upset and Test Conditions

These conditions had been bounded by normal operation and the most limiting faulted conditions in previous evaluations and it was assumed that the same was true for this PSG case.

Pullout Resistance Limiting Condition - Conclusion

The limiting axial load for the joint design was the greater of the "3 Delta P" endcap load for the normal operation condition and the "1.43 times the largest faulted endcap load. In this case the normal operation condition endcap load, 1784 lbs.,was the limiting condition..

4.1.4.2 Results and Conclusions of Verification Tests

Refer to Table 4-7.

Leakage Resistance - Normal Operation

Reference to Table 4-7 shows that, for the 20 samples, no leakage was observed at RT or the normal operation temperature of 626^{0}F. The permissible leakage guideline (criterion) of 5.4 dpm per sleeve was met.

Leakage Resistance - FLB

The same 20 sleeve/tube/tubesheet simulant samples used for the N.Op. testing were also used for FLB testing at Delta P's of 2650 and 3110 psi. No leakage was observed for any sample for any of these pressures at RT or 626^{0}F. The permissible leakage guideline (criterion) of 5.4 dpm per sleeve was met.

Pullout Resistance Related Test

As stated above, the objective of the secondary-to-primary side pressure testing was to determine the sleeve-to-tube interference fit CP. The pressure at which the leakage became significant was a conservative measurement of the contact pressure; the actual contact pressure was higher than the leakage initiation pressure. The test pressures were far above pressures found in the SG, over twice as high as the highest pressure differential for any condition. Based on seven of the samples used in the previous primary-to-secondary testing discussed above, the as-installed CP was determined to be a minimum of 6,000 psi for each of six samples and 4,500 psi for the seventh sample. Considering the 4,500 psi data point as an "outlier", the average CP, as well as the 95 percent/95 percent lower tolerance limit (LTL) was

Table 4-7 (Page 1 of 5)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Preheater SG)

a,c,e

*See table Page 5 for footnotes.

Table 4-7 (Page 2 of 5)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Preheater SG)

a,c,e

*See table Page 5 for footnotes.

Table 4-7 (Page 3 of 5)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Preheater SG)

a,c,e

*See table Page 5 for footnotes.

Table 4-7 (Page 4 of 5)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Preheater SG)

a,c,e

*See table Page 5 for footnotes.

Table 4-7 (Page 5 of 5)
Verification Test Results - Mechanical Interference Fit Lower Joint
Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 3/4 Inch Tube (Preheater SG)

a,c,e

6,000 psi. Using the 6,000 psi as the CP, the calculated minimum pullout resistance for the shortest (axially) roll expansion, 1.50 inches, the smallest diameter tube and a coefficient of friction of 0.2, from previous testing, was approximately 3852 lbs. This resistance exceeded the required resistance of 1784 lbs. by a factor of 2.2.

Table 4-7 also lists the results of actual sleeve pullout tests. The "initial slip" values ranged from 3400 to 5120 lbs. The average force was 4,339 lbs.; the 95 percent/95 percent LTL value for these data was 2959 lbs. The latter force exceeds the required resistance to pullout of 1784 lbs. by a factor of 1.7.

4.2 Tubesheet HEJ, Free Span and Tubesheet LWS Tests – 7/8 Inch Tube Sleeves

4.2.1 Test Plan - 7/8 Inch Tube Sleeves

The same type of testing as shown for the 3/4 inch sleeve HEJs was performed for 7/8 inch nominal OD tube sleeves (Reference 4-1) and are applicable. The 7/8 inch sleeves were installed previously and are in successful operation. The 7/8 inch tube Westinghouse steam generators are very similar in design and manufacture to the FSGs and PSGs. Therefore, all of the 7/8 inch free span and tubesheet LWS testing, as well as the tubesheet HEJ testing, applies to the respective areas of the 3/4 inch sleeves of the FSGs and PSGs as well as the Model F sleeves. All of the applicable results of the 7/8 inch sleeve testing are included here.

It has been pointed out earlier in this report that sleeve-to-tube welds are verified by analysis and that no laboratory testing is required. However, considerable weld testing was also performed for the previous, 7/8 inch sleeve program. The applicable results of that program are provided here as additional bases for the Model F sleeve weld. [

]^{a,c,e}

[

]^{a,c,e} As pointed out earlier in this report, if the sleeving of Model F SGs requires minor modifications to the qualified HEJ processes due to environmental or other unique conditions and this entails testing, these needs and potential tests at RT conditions will be addressed and documented separately.

The test conditions summarized in Table 4-8 (specific test conditions displayed in data tables) may vary due to evolution of the testing process. Test parameters have also been modified slightly over time as more refined analysis of plant loading conditions are applied.

The generic, allowable, primary-to-secondary leak rates are listed in Table 4-2 and the results are provided in Tables 4-9 through 4-14. The test samples were fabricated per Figure 4-1.

Table 4-8
Mechanical Test Program Summary
Tubesheet HEJ Tests - 7/8 Inch Tube Sleeves

a,c,e

Table 4-9
Verification Test Results for HEJ Lower Joints - 7/8 Inch Sleeves

a,c,e

Table 4-10
Verification Test Results for HEJ Lower Joints with Exceptional Conditions for Tube and Sleeve - 7/8 Inch Sleeves

a,c,e

NOTES:

1. The long sleeve end of RT 3 buckled prematurely during the room temperature compression test. Sleeve lengths for all subsequent sleeves were shortened.
2. The weld between the sleeve and the test end cap of RT 2 failed prematurely.

Table 4-11
Additional Verification Test Results for HEJ Lower Joints with Exceptional Conditions for Tube and Sleeve - 7/8 Inch Sleeves

a,c,e

Table 4-12

HEJ Lower Joint Test Results (with Seal Weld) - 7/8 Inch Sleeves

a,c,e

Specimen Number
M1
M2
M3
M4
M5
M6
M7
M8
M9

(Leak rate in drops per minute)

a,c,e

SPECIMEN NUMBER	COMPRESSIVE LOAD (lbs.)	TENSILE LOAD (lbs.)
M1		
M2		
M4		
M6		
M7		
M9		

Table 4-13
Free Span Joint Maximum Stress Relief Temperature - 7/8 Inch Sleeves

a,c,e

Specimen Number	Maximum Temperature (°F)
L-536	
L-540	
L-543	
L-544	
L-546	
L-548	
L-550	
L-551	
L-552	
L-555	

Table 4-14
Free Span Joint Leak Rate and Loading Data - 7/8 Inch Sleeves

a,c,e

Specimen Number
L-536
L-540
L-543
L-544
L-546
L-548
L-550
L-551
L-552
L-55

Leak rate is in drops per minute.

4.2.2 Acceptance Criteria - 7/8 Inch Tubesheet HEJ Sleeves

The leak rate criteria that have been established are based on typical Technical Specifications and Regulatory requirements. Table 4-2 shows the generic leak rate criteria for the Series 44 and 51 steam generators.

While the laser weld joint is hermetic and exhibits no leakage, in practice the lower joint of a tubesheet sleeve may be installed with or without a seal weld. In the case where a seal weld is not applied, the leakage characteristics must be evaluated. The values of the fabrication parameters of the HEJ are independent of the plan to weld or not to weld the sleeve.

[ ]^{a,c,e} indicate acceptable joint performance.

4.2.3 Results of Testing HEJ Lower Joint - 7/8 Inch Tube Sleeves

[

]^{a,c,e}

4.2.3.1 No Seal Weld

The test results for the Series 44 and 51 lower joint specimens are presented in Table 4-7. The specimens [

]^{a,c,e}

For the tests the following joint performance was noted:

> Specimen MS-2: Initial leak rates at all pressures and at normal operating pressure following thermal cycling were [
>
>]^{a,b,c,e}
>
> Specimen MS-3: [
>
>]^{a,b,c,e}

Specimen MS-7: [

]^{a,b,c,e}

4.2.3.2 Description of Additional Test Programs - HEJ Lower Joint With Exceptional Conditions and No Seal Weld

Additional test programs were performed to verify acceptable performance of the sleeve lower mechanical joint to accommodate exceptional conditions which may exist in the steam generator tubes and conditions which may be encountered during installation of sleeves.

These exceptional conditions in steam generator tube characteristics and sleeving operation process parameters included:

- shorter lengths of roller expanded lower tube joints
- shorter lengths of roller expanded lower sleeve joints

The specific exceptional tube conditions and changes to the sleeving process parameters tested in the first program, are shown in Table 4-10.

Each process operation and sequence of operations employed in fabricating each test sample was consistent with those specified for sleeves to be installed by field procedures. In addition, the exceptional tube conditions and changes to the sleeving process parameters described in Table 4-11 were included in the assembly of tube and collar subassemblies.

4.2.3.3 Lower Joint Testing with Seal Weld

Nine specimens were fabricated in [

]^{a,c,e}

4.2.4 Results of Testing, Free Span Joint Mechanical Testing - 7/8 Inch Tube Sleeves

Free span joints are representative of the tubesheet sleeve upper joint and both joints of the tube support sleeves. This joint configuration, where there is no tubesheet backing the tube, is simulated using a test specimen as shown in Figure 4-2.

a,b,e

Figure 4-2

Free Span Laser Weld Joint Test Specimen

Eleven free span weld specimens were fabricated using representative field parameters. All specimens were then stress relieved to account for the mechanical property effects resulting from thermal treatment. All free span test specimens were given a stress relief heat treatment in the range of [ ]^{a,c,e} The temperature source was a radiant heater installed inside the sleeve which was centered on the weld. The maximum temperature attained by the tube was measured by thermocouple attached to the tube outer surface and summarized in Table 4-13. The temperature was ramped up [ ]^{a,c,e} Following stress relief the thermocouple attachments were filed off.

4.2.4.1 Free Span Joint Test Results

The welds were subjected to leak testing [ ]^{a,c,e}

Two welds were metallurgically examined following fatigue testing (L-552 and L-555). Based on this examination [ ]^{a,c,e}

Compressive test specimens L-540 and L-543 were examined following testing and [ ]^{a,c,e} under design loading conditions.

4.2.4.2 Impact of Tube Fixity on Free Span Weld Performance

Under certain conditions tubes may become locked to the support plate structure of the steam generator, normally during operation at full temperature (approximately 600°F). Upon cool down, differential thermal expansion rates between the sleeve and steam generator structure can induce tensile loads in the tube. [ ]^{a,c,e}

[ ]^{a,c,e}

4.2.4.3 Results of Fixed Tube Free Span Welding

[ ]^{a,c,e}

[

]^{a,c,e}

4.3 Confirmatory Testing for Model F Lower Joint

As discussed for the MIF lower joints developed for 3/4 inch and 7/8 inch tube sleeves, confirmatory tests, i.e., room temperature leakage resistance tests, a contact pressure test and previous testing are sufficient to qualify the ETS lower joint for the Model F steam generator. It is required that the leakage resistance test meet the leakage criteria listed in Table 4-15. The pullout resistance required of the Model F ETS lower joint is calculated based on the greater of the "3-Delta P" normal operation pullout force and the "1.43-Delta P" faulted pullout force. The pullout resistance of the joint depends on 1) the CP between the sleeve OD and tube ID for the respective SG condition, 2) an appropriate coefficient of friction, from previous pullout tests involving the same materials and other conditions and, 3) the roll length over which the CP acts.

4.4 References for Section 4

4-1 WCAP-13088, Rev. 3, "Westinghouse Series 44 and 51 Steam Generator Sleeving Report (Laser Welded Sleeves)," 1/93 (Westinghouse Proprietary Class 2)

Table 4-15
Typical Bounding Maximum Allowable Leak Rates for Model F Steam Generators

		Allowable Leak Rate	
Condition	Plant	Most Limiting Sleeved SG, gpm (gpd)	Allowable Leak Rate per Sleeve**
Normal	1.0 gpm	0.105*	[ ]^{d,e}
Postulated	1.0 gpm		[ ]^{d,e}

* Typical administrative leakage limit for steam generators containing sleeves.

** Based on installation of 500 tubesheet sleeves with non-welded lower joints - for a steam generator in a four-loop plant (2000 sleeves in the plant).

5.0 STRESS CORROSION TESTING OF LASER WELDED SLEEVE JOINTS

The Alloy 690 TT (thermally treated) sleeve material exhibits exceptional resistance to stress corrosion cracking in steam generator environments (Ref. 5-1). Based on all available corrosion test results, Alloy 690 TT appears resistant to stress corrosion cracking in primary water (PWSCC), and offers substantial advantage over other candidate SG tube alloys in faulted secondary side environments. For this reason it has been the preferred alloy for heat transfer tubing in new and replacement SGs since approximately 1988; its use for sleeving extends back as far as 1984.

The resistance, therefore, of the laser weld-repaired sleeve joint is dictated by the resistance of the Alloy 600 tubing at the repair elevation. Hence, the major threat to the operational integrity of laser welded sleeve repairs is the magnitude of the stresses residual to the sleeve installation process. These stresses are the combined results of: (a) the hydraulic expansion of the sleeve and tube, (b) the stresses associated with the welding process, and (c) the far-field stresses that develop during post-weld thermal stress relief.

The purpose of the thermal stress relief operation is to reduce the peak residual stresses in the fusion weld and, for certain installation geometries, the peak stresses in the upper (free-span) hydraulic expansion transitions. However, under conditions where the tubes are axially restrained by locking and/or denting at the tube support plates, the thermal stress relief can elevate substantially the far-field stresses that develop in the tubing. These stresses would be additive to any remaining unrelaxed stress at the laser weld/hydraulic expansion locations. As discussed in subsequent paragraphs of this section, the role of these stresses on the corrosion resistance of tube-sleeve assemblies has been recognized and an attempt made to evaluate their effects.

In view of the role played by the stress level in determining the service performance of weld-repaired SG tubing, a discussion is presented in the next subsection of the influence of the LWS process parameters and SG design variables on stress. A subsequent section reviews briefly the effects of thermal stress relief on stress levels and is followed by a summary of the results of corrosion tests performed to evaluate the resistance to PWSCC of laser welded sleeve-repaired tube mockups. Included in this summary are the results of tests on as-welded mockups (i.e., without post-weld stress relief), mockups tested under conditions without applied axial loads, and mockups tested under conditions believed to reflect the conditions which might exist under conditions of axial restraint. The laser welding processes used to prepare the test specimens are representative of the field processes using the neodymium-YAG (Nd:YAG) pulsed laser currently in use by Westinghouse for sleeve welding.

5.1 LWS Process and SG Design Variables

The influence of the sleeve process parameters and steam generator design features or tube conditions on stress levels is summarized in Table 5-1.

Table 5-1
Summary of Impact of Laser Welded Sleeve Operations on Stresses

a,c,e

As installed, i.e., prior to thermal stress relief or final hard rolling, the far-field stresses are generally low, on the order of a few ksi. The peak residual stresses at the laser weld, however, are quite high; they have been estimated as approaching 80 - 85% of the tensile yield strength of the sleeve-tube assembly. [

]^{a,c,e}

The residual stresses at the upper hydraulic expansion are somewhat lower - estimated as ~ 35 ksi (however, this region may also be subject to relatively early corrosion failures if these stresses are not reduced).

The most practical means to relax these peak residual stresses is by thermal stress relief. For conditions in which the tube is free to expand axially, i.e., no fixity or restraint at the support plate locations, stress relief is an efficient process, and has a negligible impact on far-field stresses. However, recent experience with operating steam generators suggests this condition may not always exist, and it is useful to assume for conservatism that the tubes may in fact be locked at the tube support plate(s); most recent corrosion tests have thus been performed under the more conservative assumption, i.e., under conditions of applied axial stress.

The consequence of a locked tube condition is that thermal stress relief, while lowering peak residual stresses at the laser weld and at the hydraulic expansion, may increase the far-field axial stresses in the tube and may lead to bulging distortion of the tube at and above the elevation of the weld. Since this response is a consequence of the thermal expansion of the tube, the higher the stress relief temperature or the greater the axial extent of the region being stress relieved, the greater the axial far-field stresses.

Hence, the thermal stress relief process must be carefully tailored to achieve a trade-off between reduction of the peak stresses at the weld and hydraulic expansion transition while at the same time minimizing the far-field stresses.

In view of the influence of the tube-tube support plate span length on the magnitude of the far-field stresses, optimization of the sleeve installation and stress relief process must be defined on a plant (or SG design)-specific basis.

5.2 Residual Stresses vs. Stress Relief Temperature in LWS Sleeve Repairs

Table 5-2 summarizes the expected range of far-field stresses that result as a function of the stress relief process. These are conservative stress values from strain gage measurements above and below the laser weld location and are for temperatures measured at the weld and upper hydraulic expansions of sleeve mockups; the values shown are appropriate to Model D preheat SGs [

].^{a,c,e} Specific values for Model F SGs such as those at Callaway have not yet been measured, but have been estimated from the available experience; these are used in Subsection 5.7 to estimate the service performance of laser weld-repaired tubes in Callaway.

Table 5-2
Far-field Stress as a Function of Stress Relief Temperature

a,c,e

These data show the substantial reduction of far-field stress that can be realized in LWS-repaired SG tubing by controlling the stress relief temperature to be in the lower portion of the allowable range.

5.3 Corrosion Test Description

Since approximately 1988, Westinghouse has used the doped steam corrosion test to evaluate the resistance of test mockups or repair assemblies to primary water stress corrosion cracking (PWSCC). This test is conducted in dense steam in an autoclave operating at 750°F (400°C). The steam is doped with 30 ppm each of fluoride, chloride and sulfate ions in addition to 11 psig of dissolved hydrogen. For test mockups of the type considered here, the doped steam, at a pressure of 3000 psig, is in contact with the ID surfaces; the environment on the OD surfaces is pure steam at 1500 psig.

This test provides an extreme acceleration of the corrosion process relative to that which occurs in an operating steam generator. In some respects, the doped steam test can be viewed as a stress-indexing test; failure times in the doped steam test can generally be analyzed in terms of the stresses (residual and pressure) present in the test articles. In view of the dominant role stress plays in PWSCC of Alloy 600, this is a particularly valuable feature of the test.

The acceleration of the corrosion process provides the opportunity to evaluate the corrosion resistance of configurations appropriate to the repair process of interest, and avoids the need to rely on such stress-indexing tests as the stainless steel-$MgCl_2$ or Alloy 600-sodium tetrathionate tests which require surrogate materials or nonrepresentative microstructures.

As mentioned above, corrosion tests have been performed on tube-sleeve mockups in the as-welded condition, and for conditions representing weld stress relief with and without the addition of axial loading.

Generally, two types of specimen have been tested. The first of these, illustrated in Figure 5-1, has been used to test laser weld joints in the as-welded condition, or in the condition following thermal stress relief of the joint, but without additional axial load.

The second configuration is somewhat more complex. In this mockup test, the specimen is fabricated using a test stand as shown in Figure 5-2. The purpose of the test stand is to permit the sleeve installation, hydraulic expansion, welding, and post weld thermal stress relief under locked tube conditions. The nominal span length between supporting plates is varied to simulate the appropriate values for the SG model/design of interest (the value in Figure 5-2 is not accurate for a Model F SG). The stresses that result from the several stages of fabrication are measured by placing strain gages above and below the weld location. Temperatures are recorded throughout the stress relief process.

Following all specimen fabrication steps, the specimens are unloaded and prepared for corrosion testing. The configuration of the test assembly used for these tests is shown in Figure 5-3. The specimen is loaded axially in a tensile machine to the strain values noted in the fabrication sequence. By means of the threaded end fitting at the top of the assembly and the compression cylinder, the axial load is established and maintained on the sleeve joint throughout the corrosion test.

To facilitate interpretation of the corrosion test results and to provide verification of the aggressiveness of the test environment, roll expansion transition mockups, prepared of Alloy 600 tubing with known low resistance to cracking, are included in the test autoclaves.

5.4 Corrosion Resistance of Free-Span Laser Weld-Repaired Tubes - As-Welded Condition

Corrosion tests have been performed on laser weld-repaired tube assemblies prepared using both the CO_2 and the Nd:YAG laser processes. The former process is no longer of interest and will likely not be used for field operations; hence, data are presented here only for the Nd:YAG process.

The corrosion tests on as-welded mockups have been performed on specimens of the configuration shown in Figure 5-1, i.e., without added axial load. The doped steam test results are summarized in Table 5-3. (Table 5-3 also includes some data for stress-relieved Nd:YAG welds.) [

]^{a,c,e}

A limited number of as-welded 3/4 inch tube-sleeve mockups have also been tested (ca. 1994) to support a field sleeving campaign. [

]^{a,c,e}

a,c,e

Figure 5-1

Accelerated Corrosion Test Specimen for Welded Joint Configuration

a,c,e

Figure 5-2

Test Stand for Fabrication of LWS Mockups Under Locked Tube Conditions

a,c,e

Figure 5-3

LWS Mockup Corrosion Sample Test Assembly

Table 5-3
Results of 750°F Doped Steam Tests for Nd:YAG Laser Weld-Repaired Mockups

a,c,e

Figure 5-4 is a micrograph showing the typical failure location in these test specimens. The failures invariably occurred in the Alloy 600 base metal adjacent to the weld. The cracking is intergranular, typical of PWSCC, and is circumferential in orientation. This failure mode has been observed in essentially all laser weld-repair mockups tested - irrespective of whether or not the specimen was stress relieved, or subjected to additional axial load during the test.

5.5 Corrosion Resistance of Free-Span Laser Weld-Repaired Tubes - with Post Weld Stress Relief

In addition to the results presented in Table 5-3 referred to in the previous subsection, doped steam corrosion tests were performed on 3/4 inch tube-sleeve mockups to support the 1994 field sleeving campaign. These specimens were tested without the imposition of axial loading. One of the objectives of this test program was to evaluate the effectiveness of the post weld thermal stress relief over the temperature range 1275 - 1675°F (for the relevant sleeving campaign, the process specification was 1400 - 1600°F). The results of these doped steam tests are presented in Table 5-4.

These tests were, for the most part, terminated at 200 - 227 hours, a time period agreed upon with the utility as sufficient to demonstrate adequate resistance to in-service degradation through the remaining service performance of the steam generators. All specimens were post-test destructively examined by splitting and flattening. [

]^{a,c,e}

5.6 Corrosion Resistance of Free-Span Laser Weld-Repaired Tubes - with Post Weld Stress Relief and Conditions of Axial Load During Test

Experience related to a field sleeved tube inspection campaign indicated that restraint to axial expansion due to locking of the tube at the tube support plate (TSP) elevations could lead to "bulging" of the tube above the sleeve, and the introduction of large axial "far-field" stresses. This provided the incentive to include conditions of restraint both during fabrication of mockups for testing and during corrosion testing.

The degree of axial restraint varies (see discussion in Subsections 5.2 and 5.3) with span length (e.g., the distance from tubesheet to TSP) and installation/fabrication parameters - in particular, the thermal stress relief. Hence, most recent tests have used conditions which recognize these factors for the specific plant or sleeve application of interest.

Doped steam corrosion tests have recently been performed on 3/4 inch tube LWS-repaired mockups prepared to simulate sleeving installations for two different models of operating steam generators. A summary of the fabrication parameters, pertinent measurements made during the mockup fabrication, and the results of corrosion tests is provided in Table 5-5.

a,b,e

Figure 5-4

IGSCC in Alloy 600 Tube of YAG Laser Welded Sleeve Joint After 109 Hours in 750°F Steam Accelerated Corrosion Test

Table 5-4
Doped Steam Corrosion Test Results for Tube-Sleeve Mockups Tested Without Axial Load

a,c,e

[

]

For each of these mockups, only the laser weld regions were stress relieved. This minimizes the increase in far-field axial stress while providing a more efficient field installation process by avoiding the need to separately stress relieve the upper hydraulic expansion (UHE) transitions. This is only practical, however, when the distance between the weld and the UHE is sufficiently small that the stress relief of the weld provides a measure of stress relief to the UHE as well. [

]$^{a.c.e}$

Table 5-5
Summary of Fabrication Parameters, Temperatures, Stresses and Corrosion Test Results for 3/4 inch Sleeve Mockups Tested With Applied Axial Load

a,c,e

A consequence of this difference can be seen in the corrosion test results for these specimens, Table 5-5. All failures in the CAE set of specimens occurred at the UHE locations, whereas the failures for the MHE specimens occurred equally at the weld and UHE elevations, at longer times than for the CAE specimens.

The axial stresses imposed on these specimens during testing were determined from strain gage measurements made during specimen fabrication. The variation seen for the four CAE specimens reflects the fact that CAE-001 and -003 experienced a maximum temperature of 1520 - 1530°F, whereas for CAE-002 and -004 the maximum temperature was approximately 1355°F. The lower stresses in the MHE mockups reflects the use of a slightly lower weld stress relief temperature range and the substantially greater span length relative to the CAE mockups (47 inches vis-a-vis 36.7 inches).

The experience accrued in the fabrication and testing of tube-sleeve mockups has been used to optimize the field sleeving process so as to minimize field installation time while at the same time arriving at a configuration in which the local weld stresses and far-field tube stresses are controlled so as to maximize field service performance of the sleeve repairs. This optimization involves modifying the equipment such that the distance between the laser weld and the UHE is kept to a practical minimum, thereby permitting effective stress relief of both regions at the same time. [

]^{a,c,e}

<u>Note: Current Field-Installed Laser Welded Sleeves</u>

The performance of laser welded sleeve repairs in operating steam generators has been excellent. Tubesheet and TSP sleeves have been in service in a domestic nuclear power plant for four years with no indications of degradation. These sleeves are in tubes known to have some degree of lock-up at the TSPs; [ ]^{a,c,e} Stress relief was limited to the weld region and was performed at approximately 1400°F.

In a non-domestic plant approximately 5 years of operation were attained with LWS-repaired tubes at the time the repaired SGs were replaced, again with no incidents of degradation. In another non-domestic plant, over 11,000 elevated tubesheet sleeves have been in service for approximately 18 months. After approximately 10 months of operation, NDE of all sleeved tubes and destructive examination of ten pulled tube-sleeve assemblies revealed no in-service corrosion degradation of the laser welds, the hydraulic expansion regions, or the tube bulges that resulted from stress relief under locked tube conditions.

In the following subsection an estimate is provided of the service performance that might reasonably be expected for sleeve installations in Model F SGs such as those at Callaway.

5.7 Estimated Sleeve Performance at Callaway

Three conditions were considered. These were: (a) the tubes are completely free to expand axially upon sleeving and thermal stress relief; (b) the tubes are rigidly fixed at the first tube support plate (TSP); and (c) the tubes are rigidly fixed at the flow distribution baffle plate elevations.

The secondary side of each of the Callaway steam generators was cleaned by chemically-enhanced pressure pulse cleaning in the spring 1995 outage. Visual inspections suggested the cleaning was effective; hence, it is judged unlikely that deposits sufficient to axially restrain the tubes at either the TSP or FDB elevations exist at the present time, or at the time of the next outage (October 1996). However, in the event that sleeving will not be performed until some number of cycles in the future, it was judged prudent to consider also the possibilities of cases (b) and (c) above.

In performing the following estimates, the operating temperature of Callaway ($T_{inlet} \approx 618°F$) is taken into consideration. It is also recognized that the tube-tubesheet expansions at Callaway were effected by hydraulic expansion. These will be characterized by residual stresses lower than those of the roll transition mockups used to benchmark the accelerated corrosion tests. The corrosion test results were adjusted accordingly.

All estimates of sleeve performance were based on stresses measured in prototypic mockups for which the laser weld stress relief region experienced five minute exposures at 1350°F. Stress relief of the upper hydraulic expansion transitions is not anticipated to be necessary.

Tubes Free to Expand Axially

In this case, following thermal stress relief of the laser weld region, the primary stresses acting on the tube-sleeve assembly are the remaining residual weld stress and the operating pressure stress. [

]^{a,c,e}

These tests were performed using Alloy 600 SG tubing archived from the manufacture of the SGs and for which field performance was known. This permitted direct benchmarking of the results. [

]^{a,c,e}

Tubes Fixed at the First Tube Support Plate

In the Callaway Model F steam generators, the first TSP is at an elevation 39 inches above the top of the tubesheet. For fixed conditions at this elevation, the far-field stresses after thermal stress relief of the weld will be in the range of 8 to 10 ksi.

Corrosion testing of mockups under this condition of stress, again from comparison with roll transition mockups exposed at the same time, indicates degradation-free sleeve performance for periods greater than twenty times those required to initiate PWSCC in roll transitions. Adjusting these results to the case of Callaway, with hydraulically expanded tubes, provides an estimate of 24 years of service for the laser welded sleeves.

Tubes Fixed at the Flow Distribution Baffle Plate

The FDB is at an elevation 20 inches above the top of the tubesheet. [

]^{a,c,e}

Interpolating the results of corrosion tests performed on mockups under loads above and below this value, indicates a probable mean failure time in 750°F doped steam of approximately 280 hours. This corresponds to service times on the order of 10 times those of roll transitions. [

]^{a,c,e}

A summary of the estimates for the service performance of laser welded sleeve-repaired tubes at Callaway, for the three different conditions assumed for tube fixity, is provided below.

a,c,e

[

]

5.8 Outer Diameter Surface Condition

Because the sleeving involves operations only on the primary side, no aspect of the sleeve installation directly involves the tube OD surfaces. In operating SGs, however, the OD surfaces undergo surface corrosion and may collect deposits. These are typically oxides or related minerals in the thermodynamically stable form of the constituent elements; in PWR secondary water, magnetite is the most prominent oxide that forms. At the temperatures experienced during sleeve welding and thermal stress relief, these compounds are stable and do not thermally decompose. All such compounds have crystal structures that are too large to permit diffusion into the lattice of the Alloy 600. Reactions between these stable oxides and minerals and the alloying elements of Alloy 600 are thermodynamically unfavorable. Consequently, their presence during sleeve installation is not expected to produce deleterious tube-sludge/scale interactions.

This judgment has been evaluated by installing and laser welding sleeves into tubes removed from operating plants. Following the sleeving operations, microanalytical examinations were performed to verify the lack of interactions. Prior to welding, the tubes had oxide deposits which contained Cu, Ti, Al, Zn, P and Ca as measured by EDAX analyses on an SEM. Following welding and stress relief the maximum penetrations of the OD surfaces were on the order of 7 to 8 μm (less than a grain depth).

Additional evaluations were performed on three areas of an Alloy 600 U-bend section which was coated with sludge and heat treated in air for 10 minutes at 1350°F. The sludge was a simulant of SG secondary side sludge (Fe_3O_4, Cu, CuO, ZnO, $CaSO_4$ and $MgCl_2$) and was applied to the U-bend using acrylic paint as a binder. Post-thermal exposure evaluations indicated no general or intergranular corrosion had occurred.

5.9 Reference for Section 5

5-1 "Alloy 690 for Steam Generator Tubing Applications", EPRI Report NP-6997-SD, Final Report for Program S408-6, October 1990.

6.0 INSTALLATION PROCESS DESCRIPTION

The following description of the sleeving process pertains to current processes used. Westinghouse continues to enhance the tooling and processes through development programs. As enhanced techniques are developed and verified they will be utilized. Use of enhanced techniques which do not materially affect the technical justification presented in this report are considered to be acceptable for application. Section XI, Article IWB-4330 (Reference 6-1), of the ASME Code is used as a guideline to determine which variables require requalification.

The installation processes described in this section were developed and used for the installation of 7/8 inch and 3/4 inch sleeves. In the cases where sleeve/tube configuration diameters would require it, the corresponding processes will be requalified for the 11/16 inch sleeves.

The sleeves are fabricated under controlled conditions, serialized, cleaned, and inspected. They are typically placed in polyethylene sleeves, and packaged in protective styrofoam trays inside wood boxes. Upon receipt at the site, the boxed sleeves are stored in a controlled area outside containment and as required moved to a low radiation, controlled region inside containment. Here the sealed sleeve box is opened and the sleeve removed, inspected and placed in a protective sleeve carrying case for transport to the steam generator platform. The sleeve packaging specification is extremely stringent and, if unopened, the sleeve package is suitable for long term storage.

Sleeve installation consists of a series of steps starting with tube end preparation (if necessary) and progressing through tube cleaning, sleeve insertion, hydraulic expansion at both the lower and upper joint, welding the upper joint hard rolling the lower tubesheet joint locations, visual inspection and eddy current inspection. The sleeving sequence and process are outlined in Table 6-1. These steps are described in the following sections. More information on the currently used equipment can be obtained from References 6-2, 6-3, and 6-4.

6.1 Tube Preparation

There are two steps involved in preparing the steam generator tubes for the sleeving operation. These consist of rolling at the tube mouth and tube cleaning. Tube end rolling is performed only if necessary to insert a sleeve.

6.1.1 Tube End Rolling (Contingency)

If gaging or inspection of tube inside diameter measurements indicate a need for tube end rolling to provide a uniform tube opening for sleeve insertion, a light mechanical rolling operation will be performed. This is sufficient to prepare the mouth of the tube for sleeve insertion without adversely affecting the original expanded tube or the tube-to-tubesheet weld. Tube end rolling will be performed only as a contingency.

Table 6-1

Sleeve Process Sequence Summary

TUBE PREPARATION	1)	Light Mechanical Roll Tube Ends (if necessary)
	2)	Clean Tube Inside Surface
SLEEVE INSERTION	3)	Insert Sleeve/Expansion Mandrel Assembly
	4)	Hydraulically Expand Sleeve Top and Bottom Joints
WELD OPERATION	5)	Weld Upper Tubesheet Sleeve Joints
STRESS RELIEF	6)	Post Weld Stress Relief Sleeve Welds
INSPECTION	7)	Ultrasonically Inspect Sleeve Welds (Free span welds only on a sample plan)
TUBESHEET LOWER JOINT FORMATION	8)	Roll Expand Tubesheet Lower Sleeve End
INSPECTION	9)	Baseline Eddy Current Sleeves

Testing of the rolling of the tube weld has been performed and has been confirmed to be acceptable based on mechanical considerations. Westinghouse has performed tube end rolling of this weld type in the field.

6.1.2 Tube Cleaning

The sleeving process includes cleaning the inside diameter area of tubes to be sleeved to prepare the tube surface for the upper and lower joint formation by removing boric acid, frangible oxides and foreign material. Evaluation has demonstrated that this process does not remove any significant fraction of the tube wall base material. Cleaning also reduces the radiation shine from the tube inside diameter, thus contributing to reducing person-rem exposure.

The interior surface of each candidate tube will be cleaned by a [ ]^{a,c,e} The hone brush is mounted on a flexible drive shaft that is driven by an pneumatic motor and carries reactor grade deionized flushing water to the hone brush. The hone brush is driven to a predetermined height in the tube that is greater than the sleeve length in order to adequately clean the joint area. [ ]^{a,c,e} The Tube Cleaning End Effector mounts to a tool delivery robot and consists of a guide tube sight glass and a flexible seal designed to surround the tube end and contain the spent flushing water. A flexible conduit is attached to the guide tube and connects to the tube cleaning unit on the steam generator platform. The conduit acts as a closed loop system which serves to guide the drive shaft/hone brush assembly through the guide tube to the candidate tube and also to carry the spent flushing water to an air driven diaphragm pump which routes the water to the radioactive waste drain.

6.2 Sleeve Insertion and Expansion

When all the candidate tubes have been cleaned, the tube cleaning end effector will be removed from the tool delivery robot and the Select and Locate End Effector (SALEE) will be installed. The SALEE consists of two pneumatic camlocks, dual pneumatic gripper assemblies, a pneumatic translation cylinder, a motorized drive assembly, and a sleeve delivery conduit.

The tool delivery robot draws the SALEE through the manway into the channel head. It then positions the SALEE to receive a sleeve, tilting the tool such that the bottom of the tool points toward the manway and the sleeve delivery conduit provides linear access. At this point, the platform worker pushes a sleeve/mandrel assembly through the conduit until it is able to be gripped by the translating upper gripper.

The tool delivery robot then moves the SALEE to the candidate tube. Camlocks are then inserted into nearby tubes and pressurized to secure the SALEE to the tubesheet.

Insertion of the sleeve/mandrel assembly into the candidate tube is accomplished by a combination of SALEE's translating gripper assembly and the motorized drive assembly which pushes the sleeve to the desired axial elevation. For tubesheet sleeves, the sleeve is positioned by use of a positive stop on the delivery system.

At this point, the sleeve is hydraulically expanded. The bladder style hydraulic expansion mandrel is connected to the high pressure fluid source, the Lightweight Expansion Unit (LEU), via high pressure flexible stainless tubing. The Lightweight Expansion Unit is controlled by the Sleeve/Tube Expansion Controller (S/TEC), a microprocessor controlled expansion box which is an expansion control system previously proven in various sleeving programs. The S/TEC activates, monitors, and terminates the tube expansion process when proper expansion has been achieved.

The one step process hydraulically expands both the lower and upper expansion zones simultaneously. The computer controlled expansion system automatically applies the proper controlled pressure depending upon the respective yield strengths and diametrical clearance between the tube and sleeve. The contact forces between the sleeve and tube due to the initial hydraulic expansion are sufficient to keep the sleeve from moving during subsequent operations. At the end of the cycle, the control computer provides an indication to the operator that the expansion cycle has been properly completed.

When the expansion is complete, the mandrel is removed from the expanded sleeve by reversing the above insertion sequence. The SALEE is then repositioned to receive another sleeve/mandrel assembly.

6.3 General Description of Laser Weld Operation

Welding of the upper tubesheet sleeve joint will be accomplished by a specially developed laser beam transmission system and rotating weld head. This system employs a Nd:YAG laser energy source located in a trailer outside of containment. The energy of the laser is delivered to the steam generator platform junction box through a fiber optic cable. The fiber optic contains an intrinsic safety wire which protects personnel in the case of damage to the fiber. The weld head is connected to the platform junction box by a prealigned fiber optic coupler. Each weld head contains the necessary optics, fiber termination and tracking device to correctly focus the laser beam on the interior of the sleeve.

The weld head/fiber optic assembly is precisely positioned within the hydraulic expansion region using the SALEE (described earlier) and an eddy current coil located on the weld head. At the initiation of welding operations, the shielding gas and laser beam are delivered to the welding head. During the welding process the head is rotated around the inside of the tube to produce the weld. A motor, gear train, and encoder provide the controlled rotary motion to deliver a 360 degree weld around the sleeve circumference. As the weld is being made, infrared detectors monitor the weld pool to assure consistent delivery of laser energy and weld pool formation.

The welding parameters, qualified to the rules of the ASME code, are computer controlled at the weld operators station. The essential variables per Code Case N-395 are monitored and documented for field weld acceptance.

6.4 Rewelding

Under some conditions, the initial attempt at making a laser weld may be interrupted before completion or determined to be unsatisfactory, based on the infrared feedback. Also, the ultrasonic test (UT) examination of a completed initial weld may be indeterminate resulting in the weld being rejected. In these cases, an additional weld, having the same nominal characteristics as the initial weld, will be made close to and inboard of the initial weld. If a perforation of the sleeve is suspected in the initial weld area, the repair weld will be located inboard of the initial weld (see Figure 6-1). If the sleeve/tube were perforated during interruption of the initial weld, the tube would be removed from service.

6.5 Post-Weld Heat Treatment

Based on the results of corrosion tests of as-welded laser weld-repaired mockups, it has been clearly established that optimum resistance to corrosion requires the use of a post-weld thermal stress relief. The effect of the stress relief is to reduce the high peak stresses at the laser weld and hydraulic expansion locations while minimizing the far-field stresses that may develop in the parent tube. These effects, and means to minimize them, were discussed in Section 5. The data presented there clearly supports the prudence of post-weld thermal stress relief.

The following is a brief summary of the tooling used by Westinghouse to perform the post-weld stress relief.

The field tooling consists of four items:

a. A fiber optic probe
b. A heater (production) probe
c. A pop-up end effector
d. A production end effector

The fiber optic probe is used in conjunction with the pop-up end effector. The end effector places a probe within the proper zone to perform the stress relief operation. [

]^{a,d} This is done by using the ROSA robotic arm and the SALEE to sequentially place production probes at the proper welded sleeve/tube interfaces, including reweld locations, followed by application of the stress relief process.

a,c,e

Figure 6-1

Laser Welded Sleeve with Reweld

This equipment has been used routinely and consistently for all recent field sleeving campaigns. Improvements in positioning and temperature control has been continuous. The field worthiness and reliability of this process have been proven to be extremely high.

6.6 Lower Joint (Elevated Tubesheet Sleeves)

In the tubesheet, the sleeve is joined to the tube by a hard roll (following the hydraulic expansion) performed with a roll expander [

]^{a,c,e} Control of the mechanical expansion is maintained through [

]^{a,c,e}

6.7 Inspection Plan

In order to verify the final sleeve installation, inspections will be performed on sleeved tubes to verify installation and to establish a baseline for future eddy current examination of the sleeved tubes. Specific NDE processes are discussed in Section 7.0.

If it is necessary to remove a sleeved tube from service as judged by an evaluation of a specific sleeve/tube configuration, tooling and processes are available to plug the tube.

6.8 References for Section 6

6-1 ASME Boiler and Pressure Vessel Code, Section XI, Article IWB-4300, 1989 Edition, 1989 Addenda.

6-2 Boone, P. J., "ROSA III, A Third Generation Steam Generator Service Robot Targeted at Reducing Steam Generator Maintenance Exposure," CSNI/UNIPEDE Specialists Meeting on Operating Experience with Steam Generator, paper 6.7, Brussels, Belgium, September 1991.

6-3 Wagner, T. R., VanHulle, L., "Development of a Steam Generator Sleeving System Using Fiber Optic Transmission of Laser Light," CSNI/UNIPEDE Specialists Meeting on Operating Experience with Steam Generators, paper 8.6, Brussels, Belgium, September 1991.

6-4 Wagner, T. R., "Laser Welded Sleeving in Steam Generators," AWS/EPRI Seminar, Paper IID, Orlando, Florida, December 1991.

7.0 NDE INSPECTABILITY

The welding parameters are computer controlled at the weld operator's station. The essential variables, per ASME Code Case N-395, are monitored and documented to produce repeatability of the weld process. In addition, two non-destructive examination (NDE) capabilities have been developed to evaluate the success of the sleeving process. One method is used to confirm that the laser welds meet critical process dimensions related to structural requirements. The second method is then applied to provide the necessary baseline data to facilitate subsequent routine in-service inspection capability.

7.1 Inspection Plan Logic

The basic tubesheet sleeve inspection plan shall consist of:

A. Ultrasonic Inspection (Section 7.2) [ ]^{a,c,e} or alternate methods (Section 7.4).

   1. Verify minimum required weld width.

B. Eddy current examination (Section 7.3) [ ].^{a,c,e}

   1. Demonstrate presence of upper and lower hydraulic expansions.
   2. Demonstrate lower roll joint presence.
   3. Verify weld is located within the hydraulic expansion.
   4. Verify Presence of a post weld heat treatment as applicable.
   5. Record baseline volumetric inspection of the sleeve, the sleeve/tube joint, and the parent tube in the vicinity of the welded sleeve joint for future inspections.

C. Weld Process Control [ ]^{a,c,e}

   1. Demonstrate weld process parameters comply with qualified weld process specification.

7.2 General Process Overview of Ultrasonic Examination.

The ultrasonic inspection process is based upon field proven techniques which have been used on laser welded sleeves for 3/4" and 7/8" OD tubing installed by Westinghouse.

The inspection process developed for application to the laser welds uses the transmission of ultrasound to the interface region (the sleeve OD /tube ID boundary) and analyzing the amount of reflected energy from that region. An acceptable weld joint should present no acoustic reflectors from this interface above a predetermined threshold.

Appropriate transducer, instrumentation and delivery systems have been designed and techniques established to demonstrate the ability to identify welds with widths below the structural requirements. The entire weld interface (100 per cent of the axial and circumferential extent) will be examined. Acceptance of welds is based upon application of criteria which are qualified by destructive examination of marginal welds.

7.2.1 Principle of Operation and Data Processing of Ultrasonic Examination.

The ultrasonic examination of a laser-weld is schematically outlined in Figure 7-1. An ultrasonic wave is launched by application of an electrical pulse to a piezoelectric transducer. The wave propagates in the couplant medium (water) until it strikes the ID of the sleeve. Ultrasonic energy is both transmitted and reflected at the boundary. The reflected wave returns to the transducer where it is converted back into an electrical signal which is amplified and displayed on the UT display.

The transmitted wave propagates in the sleeve until it reaches the sleeve OD. If fusion between the sleeve and tube exists, the wave continues to propagate through the weld joint into the tube. This wave then reaches the outer wall (backwall) of the tube and is reflected back to the transducer. The resulting UT display from a sound weld joint is a large signal from the sleeve ID, followed by a tube backwall "echo" spaced by the time of travel in the sleeve-tube-weld assembly ($T_{1,2,3}$). If no fusion between the sleeve and the tube exists, another pattern is observed with a large signal from the sleeve ID followed by a reflection from the sleeve OD. The spacing of these echoes depends on the time of travel in the sleeve alone ($T_{1,2}$). Additional reflections after the sleeve OD reflections are considered "multiples" of the sleeve OD reflection. These are caused as the sound energy reflected off the sleeve OD bounces back and forth between the sleeve ID and OD, and decays over time.

[

]^{a,c,e}

Criteria for the acceptance of a laser weld is based upon combination of the observed ultrasonic response at the at the weld surface, the sleeve/tube interface, and the tube OD.

An automated system is used for digitizing and storing the UT wave forms (A-Scans). [

]^{a,c,e} The ultrasonic response from the weld is then digitized for each pulse. A typical digitized

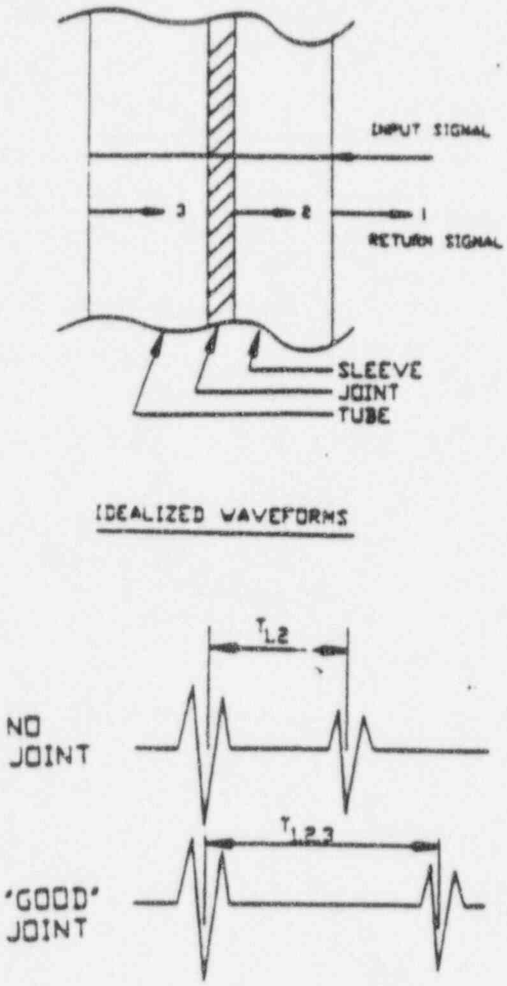

Figure 7-1

Ultrasonic Inspection of welded Sleeve Joint

A-scan is shown in Figure 7-2. Time intervals known as "gates" are set up over the signals of interest in the A-Scan so that an output known as a "C-Scan" can be generated. The C-Scan is a developed view of the inspection area which maps the amplitude of the signals of interest as a function of position in the tube. A combined C-scan which shows the logical combinations conditions of signals in two gates with respect to predetermined threshold values can also be displayed. Figure 7-3 shows the A, B, C, and combined C-scan display for a weld in a calibration standard.

7.2.2 Laser Weld Test Sample Results

Ultrasonic test process criteria are developed by [

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Field application requires calibration to establish that the system essential variables are set per the same process which was qualified. Elements of the calibration are to:

- Set system sensitivity (gain).
- Provide time of flight reference for sleeve ID, OD and tube OD signals.
- Verify proper system function by examination of a workmanship sample.

Figure 7-4 depicts a calibration standard for the sleeve weld UT exam. (This figure shows the standard for a 3/4 inch sleeve; a corresponding standard will be made for the 11/16 sleeve)

7.2.3 Ultrasonic Inspection Equipment and Tooling

The Probe is delivered with the Westinghouse ROSA III zero entry system. The various subsystems include the water couplant, UT, motor control, and data display/storage.

The probe motion is accomplished via rotary and axial drives which allow a range of speeds and axial advances per 360° scan of the transducer head (pitch). The pitch provides a high degree of overlapping coverage without sacrificing resolution or sensitivity.

The controls and displays are configured for remote location in a trailer outside of containment. The system also provides for periodic calibration of the UT system on the steam generator platform.

a,c

Figure 7-2

Typical Digitized UT Waveform

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Figure 7-3
A, B, C, and Combined C-Scan Display for Weld in UT Calibration Standard

a,c,e

Figure 7-4

UT Calibration Standard

7.3 Eddy Current Inspection

Upon conclusion of the sleeve installation process, a final eddy current inspection is performed on every installed sleeve to meet the process verification and baseline inspection requirements outlined in Section 7.1 B. The combined Cecco-5/bobbin probe is utilized towards this end to provide an enhanced baseline inspection without sacrificing data acquisition speed. The bobbin probe provides the inspection to verify the presence and location of the expansions, as well as weld location. The Cecco-5 probe provides baseline examination of the sleeve and tube.

7.3.1 Cecco-5/Bobbin Principles of Operation

The standard bobbin probe configuration consists of two circumferentially wound coils which are displaced axially along the probe body. The coils are connected in the differential mode; that is, the system responds only when there is a difference in the properties of the materials surrounding the two coils.

The Cecco-5 (C5) design operates as a transmit-receive probe. The C5 configuration is designed to provide detection of both circumferential and axial degradation. There are two bracelets of coils, each consisting of an array of transmit-receive sets. Each bracelet is capable of achieving 50 percent coverage of the circumference of the tube. This is due to the fact that there is no coverage directly underneath the coils of a transmit receive probe. For this region, the second bracelet is offset relative to the first to achieve full coverage.

Transmit-receive probes are, by nature of their operational principles, less sensitive to lift-off effects than a comparable impedance coil. By virtue of this feature, probes can be designed in such a fashion that the coils do not have to ride the surface of the tube in order to achieve a reasonable level of detectability in a region of geometric change. The coupling of the probes with instrumentation and software designed to take advantage of their specific design features makes transmit-receive probes an attractive technology for the inspection of sleeved tubes.

The calibration standard used for Cecco 5 sleeve inspection includes various axial and circumferential notches as depicted on Figure 7-5 (This figure shows the standard for 7/8 and 3/4 inch sleeves; a corresponding standard will be made for the 11/16 sleeve). Notches are located in the expansion transitions as well as in the tube and sleeve freespan. Figure 7-6 depicts a 20 channel strip chart plot of the calibration standard. The analysis software allows the data from the two bracelets and the bobbin coil to be displayed in an aligned fashion. The channels may be selected so that data from each sensing point is viewed, enabling viewing of an entire tube circumference on a single screen.

Figures 7-7 and 7-8 show the response of the Cecco 5 probe to [60% through-wall axial and circumferential OD]^{a,c,e} notches in the parent tube at the sleeve expansion transition.

a,c,e

Figure 7-5
Cecco-5 Sleeve Calibration Standard

a,c

Figure 7-6
Strip Chart Display for Cecco/Bobbin Data

a,c,e

Figure 7-7
Response of Cecco-5 Probe to 60% OD Axial Notch in Parent Tube
Located at Expansion Transition

a,c,e

Figure 7-8
Response of Cecco-5 Probe to 60% OD Circumferential Notch in Parent Tube Located at Expansion Transition

Cecco-5 Probes have been previously qualified to EPRI Appendix H requirements for detection in 3/4 inch and 7/8 inch sleeved tubing. A qualification will be performed to show equivalent detection performance in 11/16" sleeved tubing by comparing responses to equivalent EDM notches.

7.4 Alternate Post Installation Acceptance Criteria

Ultrasonic or volumetric inspection is the prime method for post-installation weld quality evaluation, with eddy current examination being used as the prime in-service examination technique. However, there are cases, due [

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[

]^{a,c,e}

In support of accepting UT indeterminate welds, several alternate strategies will be applied, as agreed to by the implementing utility and Westinghouse. While this summary is not meant to preclude other methods, it is included to provide an indication of the rigor of the alternate methods.

7.4.1 Bounding Inspections

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[

]^{a,c,e}

7.4.2 Workmanship Samples

[

]^{a,c,e}

7.4.3 Other Advanced Examination Techniques

As other advanced techniques become available and are proven suitable, Westinghouse may elect, with utility concurrence, to alter its post-installation inspection program. [

]^b

[

]^b

In summary, Westinghouse proposes to apply alternate inspection techniques with utility concurrence as they become available. It is intending that this licensing report not preclude the use of these inspections as long as they can be demonstrated to provide the same degree or greater of inspection rigor as the initial use methods identified in this report.

7.5 Inservice Inspection Plan for Sleeved Tubes

The need exists to perform periodic inspections of the supplemented pressure boundary. The inservice inspection program will consist of the following:

a.The sleeve will be eddy current inspected upon completion of installation to obtain a baseline signature to which all subsequent inspections will be compared.

b.Periodic inspections will be performed to monitor sleeve and tube wall conditions in accordance with the inspection section of the individual plant Technical Specifications.

The inspection of sleeves will necessitate the use of an eddy current probe that can pass through the sleeve ID. For the tube span between sleeves, this will result in a reduced fill factor. The possibility for tube degradation in free span lengths is extremely small. Plant data have shown that this area is less susceptible to degradation than other locations. Any tube indication in this region will require further inspection by alternate techniques (i.e., surface riding probes) prior to acceptance of that indication. Otherwise the tube shall be removed from service by plugging. Any eddy current indication in the free span, sleeve or sleeve/tube joint region which can't be dispositioned by standard dual-analyst review will require further inspection by alternate techniques, i.e., surface riding probes, prior to acceptance of that indication. Otherwise the tube containing the sleeve in question shall be removed from service by plugging.

7.6 References for Section 7

7-1Stubbe, J., Birthe, J. Verbeek, K., "Qualification and Field Experience of Sleeving Repair Techniques: CSNI/UNIPEDE Specialist Meeting on Operating Experience with Steam Generators, paper 8.7, Brussels, Belgium, September 1991.