WESTINGHOUSE CLASS 3 (Non-Proprietary)

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WCAP-13089
Rev. 1

WESTINGHOUSE SERIES 44 AND 51 STEAM GENERATOR GENERIC SLEEVING REPORT

Laser Welded Sleeves

January 1993

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ABSTRACT

Under Plant Technical Specification requirements, steam generator 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. This report summarizes a generic structural analysis of two distinct types of sleeves for Series 44 and 51 steam generators, a tubesheet sleeve and a support plate sleeve.

The analysis includes 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 requirements for the sleeve and a corresponding plugging limit for tubes where sleeves have been installed.

Based on the results of this analysis, the design of the laser welded tubesheet sleeve and the tube support plate sleeve are concluded to meet the requirements of the ASME Code. The lower bound, applicable plugging limit for the sleeve is 32% of the initial wall thickness. Comparing the critical crack length for burst under FLB conditions to the critical crack length for leakage, the maximum permissible leak rate under normal operation is 340 gpd per steam generator. Thus, based on leak-before-break criteria, plants where sleeves are to be installed should maintain a leak rate limit under normal operation at or below 340 gpd per steam generator.

Mechanical tests were used to provide additional information related to sleeve joint performance. This testing was concerned with joint leak resistance and strength. Prototypical sleeve-to-tube joints were subjected to cyclic thermal and mechanical loads, simulating plant transients. Other joint test specimens were subjected to loads to the point of failure, beyond the bounding loads which result from normal operation and accident conditions.

The resistance of the laser welded sleeve joint to in-service corrosion was evaluated by an accelerated primary water stress corrosion cracking (PWSCC) test. Free-span as-welded and post weld heat treated joints were tested, in comparison with an Alloy 600 tube roll transition, a structure which is potentially susceptible to PWSCC. The as-welded joints generally exhibited times for throughwall SCC that were 1.3 to 1.6 times longer than the times for the roll transition. No PWSCC or other corrosion was noted on the Alloy 690 portion of the joint. The post weld heat treated joint exhibited an improvement of over 10 times, compared to the as-welded joint. Similar corrosion testing of the as-welded laser welded lower joint were performed and a minimum of 3 to 4 time life increase over the control specimens.

The entire sleeve process, from sleeve manufacturing through installation and nondestructive examination (NDE), was detailed. The installation NDE involves eddy current test (ECT) and ultrasonic test (UT). The baseline NDE involves ECT and the inservice NDE will require alternate techniques if the inservice ECT exhibits changes from the baseline inspection.

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1.0 INTRODUCTION

Under Plant Technical Specification requirements steam generator 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 document was prepared to summarize the technical information developed to support licensing of the laser welded sleeve installation process. This document is not intended to describe the detailed installation verification steps; those steps are in the installation procedures. The principles of the eddy current test and ultrasonic test nondestructive examinations for installation and inservice are defined.

This report addresses two distinct types of sleeves - a tubesheet sleeve and a support plate sleeve. Each of these sleeve types has several installation options which can be applied. The tubesheet sleeve is appropriate for all plants which have degradation at the top of the tubesheet, and/or within the tubesheet above the lower joint since the lower joint is formed at the bottom of the tubesheet. The tube support plate (TSP) sleeve may be installed to bridge degradation located at tube support plate locations or in the free span section of the tube.

Installation and inspection options will be selected in advance of performing the field campaign. This determination will be made based on degradation history, current degradation rates, utility steam generator maintenance strategy, schedule, and cost. Thus, the application can be optimized to utility needs by applying the proper combination of 'modular' sleeve-tube joint options.

This report serves as the "reference" design basis for laser welded sleeves for plants with Series 44 and 51 steam generators. However, changes in plant operating parameters can occur as a result of system or operating modifications. Therefore, prior to installation of laser welded sleeves at any plant with Series 44 or 51 steam generators, a supplementary plant specific review of the applicable operating parameters at the time of sleeve installation relative to the design basis parameters will be performed. This review will be documented in a separate report, and the two reports will together form the plant specific design basis for the laser welded sleeves.

1.1 Report Applicability

This report is applicable to Westinghouse Series 44 and 51 steam generators. These steam generators are U-tube heat exchangers with mill annealed Alloy 600 heat transfer tubes which have a 0.875 inch nominal outside diameter (OD) and 0.050 inch nominal wall thickness.

Data are presented to support the application of two sleeve designs; tubesheet and tube support plate. Moreover, with each design, several utility selectable application options are provided. The sleeve size and options are:

Tube support plate sleeve

- 12 inch long
- welding with post weld heat treatment
- welding without post weld heat treatment

Tubesheet sleeve

- 27 inches to 36 inches long [ ]b
- straight or bowed (enhanced for peripheral coverage)
- upper weld joint with post weld heat treatment
- upper weld joint without post weld heat treatment
- lower joint with seal weld
- lower joint without seal weld

The sleeves described herein have been designed, analyzed, or tested to meet the service requirements of the Series 44 and 51 steam generators through the use of conservative and enveloping thermal boundary conditions and structural loadings. The structural analysis and mechanical performance of the sleeves are based on installation in the hot leg of the steam generator. [ ]c

1.2 Sleeving 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. For reference purposes, a typical Series 51 Rosa III sleeving coverage map for 12 inch long support plate sleeves is shown if Figure 1-1.

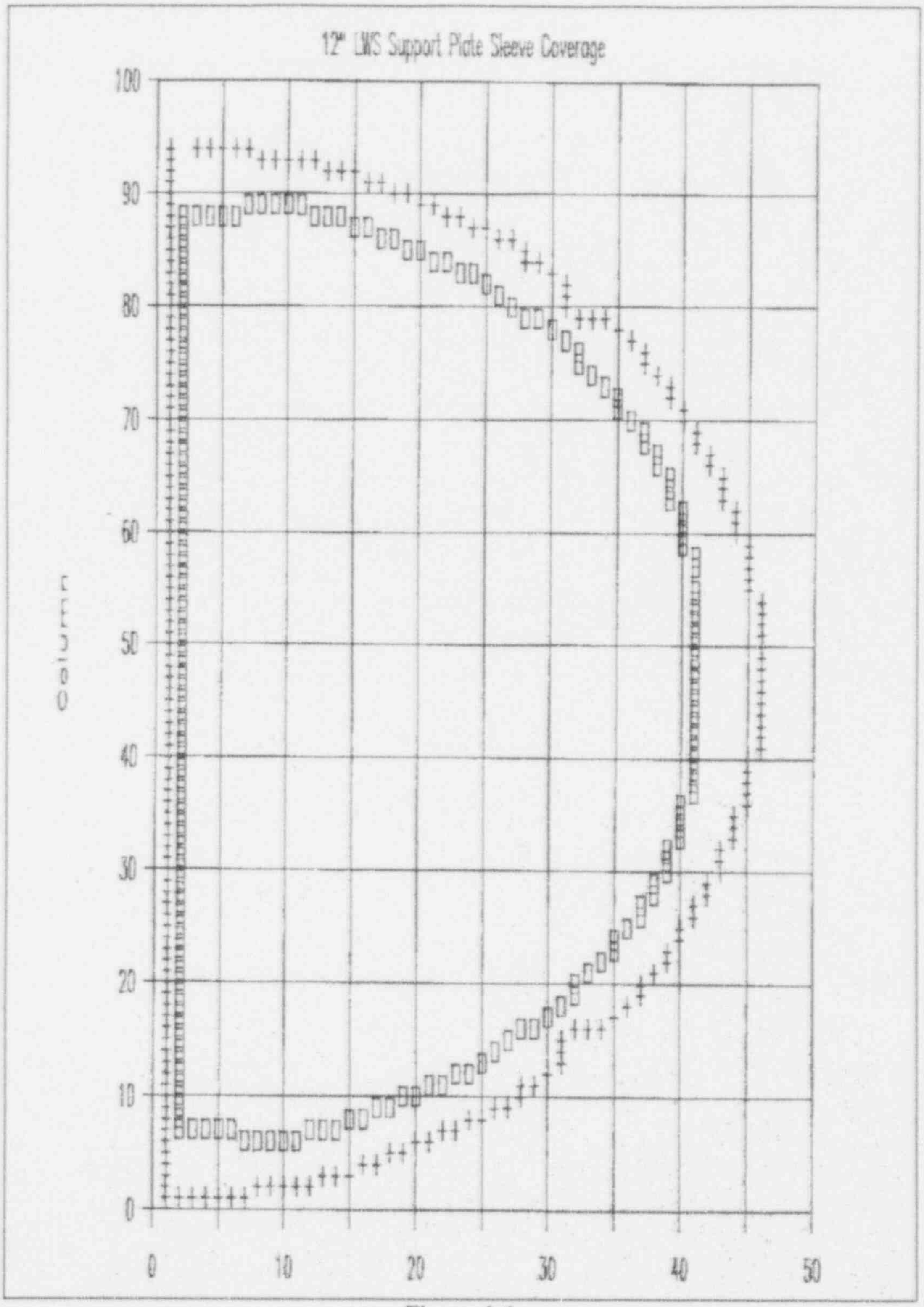

Figure 1-1

Example 12-inch Support Plate Sleeve Coverage in a Series 51 Steam Generator

WP0321-1.CL3:1b/011493

2.0 SLEEVE DESCRIPTION AND DESIGN

2.1 Sleeve Design Description

Tube sleeves effectively restore a degraded tube to a condition consistent with the design requirements of the tube. The design of the sleeve and sleeving process is predicated on the design rules of Section III, Subsection NB, of the 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 inside diameter, tube to tube sheet joint variations and runout/concentricity variations created during tubesheet drilling or misalignment of tubesheet and support plate holes.

2.1.1 Tubesheet Sleeve

The reference design of the tubesheet sleeve, as installed, is illustrated on Figure 2-1. At the upper end, the sleeve configuration consists of a section which is hydraulically expanded. The hydraulic expansion of the upper joint brings the sleeve into contact with the parent tube to achieve the proper fitup geometry for welding. Following the hydraulic expansion, an autogenous weld is made between the sleeve and the tube using the laser welding process. This joint configuration is known as a laser welded joint (LWJ).

The tubesheet sleeve extends from the tubesheet primary face to above the tube degradation. In the process of sleeve length optimization and allowing for axial tolerance in locating degradation by eddy current inspection, the guideline is that the welds are to be positioned a [

]^{a,c,e}.

The upper joint is located so as to provide [

]^{a,c,e}.

At the lower end, the sleeve configuration consists of a section which is [

]^{a,c,e}

2.1.2 Tube Support Plate Sleeve

The support plate sleeve is shown in Figure 2-2. Each end of the sleeve has a hydraulic expansion region within which the weld is placed. The weld configuration is the same for both upper and lower joints and is the same as the upper weld in the tubesheet sleeves. Tube support sleeves are qualified for the second-from-highest support plate elevation through the lowest elevation for both series of steam generators. (Qualification of the sleeve at the top support plate would require a small structural evaluation and minor modifications to the tooling. The hydraulic equivalency and flow reduction calculations have already been made for support plate sleeves at all evaluations for both series of steam generators and are reported in Section 3.) [

]^{a,c,e}.

[

]^{a,c,e}

The sleeve material, thermally treated Alloy 690, was selected to provide additional resistance to stress corrosion cracking.

2.1.3 Sleeving of Previously Plugged Tubes

Previously plugged tubes must meet the same requirements as sleeving candidates as 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 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.

2.2 Sleeve Design Documentation

The sleeves are designed and analyzed according to the 1986 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. 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.

2.2.1 Weld Qualification Program

The laser welding process used to install [ ]^{a,c} nominal OD sleeves into 0.875 inch nominal OD tubes was qualified per the guidelines of the ASME Code which specify the generation of a procedure qualification record and welding procedure specification.

Specific welding processes were 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

- Sleeve weld joints made within the tubesheet

These processes address the weld joints necessary for installation of the tubesheet and support plate types of sleeves discussed earlier.

To provide similitude between the specimens and the actual installed welds, representative field processes are used to assemble the specimens. The laser welded joints are representative in length and diametral expansion of the hydraulic expansion zone. 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 Case N-395, are used to develop the weld process. [

]^{a,d,e}

2.2.2 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.

Table 2-1

ASME CODE AND REGULATORY REQUIREMENTS

Item	Applicable Criteria	Requirement
Sleeve design	Section III	NB-3200, Analysis NB-3300, Wall Thickness
	Operating Requirements	Analysis Conditions
	Reg. Guide 1.83	SG Tubing Inspectability
	Reg. Guide 1.121	Plugging Margin
Sleeve Material	Section II	Material Composition
	Section III	NB-2000, Identification, Tests and Examinations
	Code Case N-20	Mechanical Properties
Sleeve Joint	10CFR100	Predicted Steam Line Break Leak Rate
	Technical Specifications	Operating Primary to Secondary Rate
	Section IX	Weld Qualification
	Code Case N-395/Section IX	Laser Welding Essential Variables

a,c,e

Figure 2-1

Tubesheet Laser Welded
Sleeve Installed Configuration

a,c,e

Figure 2-2

Support Plate Laser Welded
Sleeve Installed Configuration

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, and Section 3.2 provides the thermal/hydraulic justification.

3.1 Structural Analysis

Section 3.1 summarizes the structural analysis of the tubesheet and tube support plate laser welded sleeves for plants with Series 44 and 51 steam generators. The loading conditions considered in the analysis represent an umbrella set of conditions based on the applicable design specifications, and are defined in Reference (1). The analysis includes finite element model development, a heat transfer and thermal stress evaluation, 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 requirements for the sleeve. Finally, the analysis addresses a number of special considerations as they affect the adequacy of the sleeve designs.

3.1.1 Component Description

3.1.1.1 Tubesheet Sleeve

The design of the tubesheet sleeve, as installed, is illustrated in Figure 2-1. The sleeve extends from the tubesheet primary face to above the tube degradation zone. In order to allow for eddy current uncertainty in defining the degradation zone, the sleeve length is such that it extends a minimum of [ ]^{a,c,e} above the tube degradation zone.

At the lower tube/sleeve interface, the sleeve configuration consists of a section [

]^{a,c}

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

]^{a,c} A schematic of the tube / sleeve interfaces and the various [ ]^{a,c} is provided in Figure 3-1.

3.1.1.2 Tube Support Plate Sleeve

The installed configuration of the tube support plate sleeve is shown in Figure 2-2. The sleeve is 12 inches long, and is [

]^{a,c}

3.1.2 Summary of Material Properties

The material of construction for the tubing in Westinghouse designed Series 44 and 51 steam generators is a nickel base alloy, Alloy 600 in the mill annealed (MA) condition. The sleeve material is also a nickel base alloy, thermally treated Alloy 690. Summaries of the applicable mechanical, thermal, and strength properties for the tube and sleeve materials are provided in Tables 3-1, and 3-2, respectively. The sleeve evaluation also includes the response of the tubesheet, which is constructed of SA-508, Class 2 Carbon steel. A summary of the applicable properties for the tubesheet material is provided in Table 3-3. Thermal properties for air and water, used in performing the heat transfer analysis, are provided in Tables 3-4 and 3-5. The fatigue curve used in the analysis of the laser welds corresponds to the code curve for austenitics and nickel-chromium-iron (Inconel).

3.1.3 Applicable Criteria

The applicable criteria for evaluating the sleeves is defined in the ASME Code, Section III, Subsection NB, 1986 Edition, Reference (2). Although the lower joint in the tubesheet sleeve is classified as a seal weld, it is also evaluated to the ASME Code criteria. In establishing minimum wall requirements for plugging limits, Regulatory Guide 1.121, Reference (3), is used. A summary of the applicable stress and fatigue limits for the sleeve and tube are summarized in Tables 3-6 through 3-9.

3.1.4 Loading Conditions Considered

The loadings considered in the analysis represent an umbrella set of conditions and are defined in Reference (1). The analysis considers a full duty cycle of events that includes, design, normal, upset, faulted, and test conditions. A summary of the applicable transient conditions is provided in Table 3-10. Two test conditions, primary and secondary hydrostatic tests have been considered that are not defined in Reference (1), but are judged to be representative of current operating practices. The applicable temperatures and pressures are based on recent design specifications for modified steam generators. Umbrella pressure loads for Design, Faulted and Test conditions are summarized in Table 3-11.

3.1.5 Analysis Methodology

The analysis of the laser welded sleeve designs utilizes both conventional and finite element analysis techniques. Several finite element models are used for the analysis. For the tubesheet sleeve analysis, [

]^{a,c} Typically, the tubesheet sleeve model incorporates a [ ]^{a,c} in the tubesheet.

For Series 44 and 51 steam generators, the type and extent [

For Series 44 and 51 steam generators, the type and extent [

]a,c is considered in this analysis. The tolerances used in developing the sleeve models are such that [

]a,c The results for the upper joint for the tubesheet sleeve are concluded to conservatively apply to the tube support plate sleeve. This is based on the temperature and pressure loads for the tubeshet sleeve for all transient conditions being greater than or equal to those for the tube support plate sleeve.

The lower laser welded joint (LWJ) for the tubesheet sleeve is [

]a,c

The analysis also considers both [

]a,c

The nominal width (interfacial axial extent) of the laser weld joining the tube and sleeve for all joints is [ ]a,c However, qualification tests for the weld process have shown that the welds may be as small as [ ]a,c Thus, in performing this analysis, weld widths of both [ ]a,c and [ ]a,c were considered. The stress and fatigue results reported later in the report are for the limiting weld geometry, or the [ ]a,c width.

In addition to the sleeve models, a separate model of the tubesheet, channelhead, and lower shell was developed and used to calculate tubesheet rotations under combined pressure and temperature loadings. Resulting loads imposed on the sleeve as a result of the tubesheet rotations are applied to the sleeve model in the form of radial pressures on the model outer boundary.

For both the sleeve model and the tubesheet, channelhead, and shell model, separate models were developed for the Series 44 and 51 geometries. Separate calculations were then run for the two sets of models. A plot of the tubesheet, channelhead, and shell model for the Series 51 steam generators is shown in Figure 3-2.

3.1.6 Heat Transfer Analysis

The first step in calculating the stresses induced in the sleeves as a result of the thermal transients, is to perform a heat transfer analysis to establish the temperature distribution for the sleeve, tube, and tubesheet.

Based on a review of the transient descriptions, [ ]^{a,c} transients were selected for evaluation. They include the following events:

[ ]^{a,c}

The [

]^{a,c}

In performing the heat transfer analysis, [

]^{a,c} A sketch of the model boundary conditions for the heat transfer analysis are shown in Figure 3-3.

In order to determine the appropriate boundary conditions for the heat transfer analysis, [

]^{a,c}

3.1.7 Tubesheet/Channelhead/Shell Evaluation

As discussed above, loads are imposed on the sleeve as a result of tubesheet rotations under pressure and temperature conditions. For this evaluation, tubesheet rotations are established for five reference loading conditions, and subsequently scaled to actual transient conditions. The five reference loading conditions consist of [ ]^{a,c}

The [ ]^{a,c} loadings. The boundary conditions and subsequent deformed geometry for the primary side pressure load for Series 51 steam generators are shown in Figures 3-4 and 3-5, respectively.

The [

]^{a,c} A typical set of boundary conditions, and the resulting deformed geometry, for the case of [ ]^{a,c} for the Series 51 steam generators is shown in Figures 3-6 and 3-7.

Once the stress solutions for the reference load cases are obtained, [

]^{a,c}

3.1.8 Stress Analysis

In performing the stress evaluation for the sleeve models, [

]^{a,c} Sketches of the model boundary conditions for the primary side pressure cases are shown in Figures 3-8 through 3-11. Sketches of the model boundary conditions for the secondary side pressure cases are shown in Figures 3-12 through 3-15. It should be noted for both sets of loads that the end cap load on the tube is not included, but is considered in a separate load case.

The analysis considers [

]^{a,c}

[

]^{c}

The effects of [

]^{a,c}

Finally, [

]^{a,c}

The total stress distribution in the sleeve-to-tube assembly is determined by combining the calculated stresses as follows:

[ ]b,c

3.1.9 ASME Code Evaluation

The ASME Code evaluation is performed using a Westinghouse proprietary computer code. The evaluation is performed for specific "analysis sections" (ASN's) through the finite element model. The ASN's evaluated to determine the acceptability of the sleeve design are shown in Figure 3-16 for the upper LWJ and in Figure 3-17 for the lower LWJ.

The umbrella loads for the primary stress intensity evaluation have been given previously in Table 3-11. The largest magnitudes of the ratio "Calculated Stress Intensity / Allowable Stress Intensity" for both the Series 44 and 51 steam generators are [ ]a,c for design conditions, [ ]a,c for faulted (feedline break) conditions, and [ ]a,c for test (primary side hydrostatic) conditions. The analysis results show the primary stress intensities for the laser welded sleeved tube assembly to satisfy the allowable ASME Code limits. A summary of the limiting stress conditions are provided in Table 3-12 with the [ ]a,c

The results for maximum range of stress intensity and fatigue are summarized in Table 3-14 for the tube being [

]a,c

The analysis results show the ASME Code limits to be satisfied.

3.1.10 Minimum Required Sleeve Thickness

The heat transfer area of steam generators in a PWR nuclear steam supply system (NSSS) comprises over 50 percent of the total primary system pressure boundary. The steam generator tubing and sleeving, therefore, represents a primary barrier against the release of radioactivity to the environment. For this reason, conservative design criteria have been established for the maintenance of tube and sleeve structural integrity under the postulated design-basis accident condition loadings in accordance with Section III of the ASME Code.

Over a period of time under the influence of the operating loads and environment in the steam generator, some sleeves may become degraded in local areas. To determine the condition of the sleeving, in-service inspection using eddy-current techniques is performed in accordance with the guidelines of US NRC Regulatory Guide 1.83, Reference (4). Partially-degraded sleeves with net wall thicknesses greater than the minimum acceptable sleeve wall thickness are satisfactory for continued service, provided that leak before break is established, and that the minimum required sleeve wall thickness is adjusted to take into account possible uncertainties in the eddy current inspection, and an operational allowance for continued sleeve degradation until the next scheduled inspection.

The US NRC Regulatory Guide 1.121, Reference (3), describes an acceptable method for establishing the limiting safe conditions of degradation in the sleeves beyond which sleeved tubes found defective by the established in-service inspection shall be removed from service. The amount of degradation recorded by eddy current testing is customarily expressed as a percentage of the design nominal wall thickness, and the acceptable degradation is referred to as the "plugging margin".

Briefly, the regulatory guideline consists of verifying that, (1) in the case of tube thinning or wall loss, or for partial through-wall cracks, the remaining sleeve wall can still meet applicable stress limits during normal and accident loading conditions, and (2) in the case of sleeve cracking, the leak-before-break criteria is satisfied. Confirmation of leak-before-break assures that the maximum permissible crack length to protect against burst under accident loadings is greater than the crack length that would result in leakage at the Technical Specification limit during normal operation. The allowable tube plugging margin, in accordance with Regulatory Guide 1.121, is obtained by incorporating into the minimum required

thickness, a growth allowance for continued operation until the next scheduled inspection and also an allowance for eddy current measurement uncertainty.

Since Regulatory Guide 1.121 constitutes an operating criterion, it is permissible to derive the allowable stress limits based on expected lower bound material properties, as opposed to the Code minimum values. Expected strength properties are obtained from statistical analyses of tensile test data of actual production tubing. Lower bound statistical tolerance limits, LTL, for yield and ultimate strength values are computed in accordance with the accepted industry practice such that there is a [ ]^{a,c} than LTL values. The applicable values for the sleeve analysis are a yield strength of [ ]^{a,c} and an ultimate strength of [ ]^{a,c}, as taken from Reference (5).

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 (loads necessary for equilibrium) need be considered.

Considerations of the secondary and peak stresses from operating transients are relevant from the viewpoint of fatigue and related implications of the occurrence of through-wall cracking, if any. The implications and consequences of cracking, however, are accounted for in the leak-before-break requirement. In the unlikely event of unacceptably reduced design margin due to the increased secondary and peak stresses in the localized degraded tube regions, tube integrity would be safeguarded against any adverse consequences through leak-before-break.

The minimum required sleeve wall thickness, t_{min}, to sustain normal and accident condition loads is calculated [ ]^{a,c} For computing t_{min}, the pressure stress equation NB-3324.1 of the Code is used. That is,

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

3.1.10.1 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. During normal operation, the primary side pressure, P_i, is [

]^{a,c}

The limits on primary stress, P_m, for a primary-to-secondary pressure differential ΔP_i, are as follows:

$$\text{Normal: } P_m < S_u/3 = 30.33 \text{ ksi}$$
$$\text{Upset: } P_m < S_y = 37.00 \text{ ksi}$$

Using the pressure stress equation, the resulting values for t_{min} are [

]^{a,c}

3.1.10.2 Accident Condition Loadings

LOCA + SSE

The dominant loading for LOCA and SSE loads [

]^{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 criteria for faulted loads is:

$$P_m < \text{lesser of } 0.7\ S_u \text{ or } 2.4\ S_m$$
$$S_u = [\quad]^{a,c}$$
$$P_m < 0.7\ S_u = [\quad]^{a,c}$$

Using the pressure stress equation, the resulting value for t_{min} is [ ]^{a,c}

In summary, considering all of the applied loadings, the minimum required sleeve wall thickness is calculated to be [ ]^{a,c} remaining wall for nominal operating conditions.

3.1.10.3 Leak-Before-Break Verification

In addition to the limits on allowable stresses discussed previously, verification of leak-before-break must also to be satisfied. The rationale behind this requirement is to limit the maximum allowable (primary-to-secondary) leak rate during normal operation such that the associated crack length (through which the leakage occurs) is less than the critical crack length corresponding to the maximum postulated accident condition pressure loading. Thus, on the basis of leakage monitoring during normal operation, unstable crack growth is not expected to occur in the unlikely event of the limiting accident.

Burst pressure versus axial crack length data from multiple sources are shown in Figure 3-18 as taken from EPRI Report NP-6864-L. [

]^{a,c} The Belgian burst curve for the sleeves is shown in Figure 3-19. A tabular summary of the burst data is provided in Table 3-15. It is observed that a through-wall crack length of [ ]^{a,c} is required under FLB conditions.

The largest permissible crack length is determined using results from a computer program (CRACKFLO) that has been developed for predicting leak rates through axially oriented cracks in a steam generator tube (sleeve). The CRACKFLO leakage model has been developed for single axial cracks and compared with leak rate test results from pulled tube and laboratory specimens. Fatigue crack and stress corrosion cracking (SCC) leakage data have been used to compare predicted and measured leak rates as shown in Figure 3-20. Generally good agreement is obtained between calculation and measurement with the spread of the data being somewhat greater for SCC cracks than for fatigue cracks.

Leak rates for the sleeves are a function of sleeve geometry, material strength properties, and several operating parameters. The operating properties of significance are the primary and secondary side pressures and the primary side temperature. Based on design parameters for the plants under consideration, the primary side pressure is relatively uniform under normal operation at [ ]^{a,c} However, t_{hot} is found to vary from [ ]^{a,c}, and secondary side pressure is found to vary

from [ ]^{a,c} Calculations have been performed to determine the sensitivity of leak rate to t_{hot} and primary to secondary side ΔP, and are summarized in Table 3-16 relative to the sleeve geometry and material strength characteristics. The results show a [ ]^{a,c} for the range of values considered.

Relative to the leak-before-break requirement, the conditions resulting in the largest permissible crack under normal operation is limiting. Based on the results in Table 3-16, the limiting set of conditions is the highest secondary side pressure combined with the [ ].^{a,c} Thus, leakage calculations were performed for a t_{hot} of [ ]^{a,c} and a secondary side pressure of [ ]^{a,c}. A summary of the corresponding leak rates under normal operation as a function of crack length are summarized in Table 3-17, and are shown graphically in Figure 3-21. Leak rates are shown both for the mean data and for the lower 95% probability level.

Comparing the critical crack length for burst under SLB/FLB conditions, [ ]^{a,c}, to the critical crack lengths for leakage under normal operation, the maximum permissible leak rate under normal operation is [ ]^{a,c}. Beyond this leakage level, leak-before break behavior cannot be assumed. Thus, if and when laser welded sleeves are installed, plants should maintain a leak rate limit under normal operation at or below [ ]^{a,c}.

3.1.11 Determination of Plugging Limits

The minimum acceptable wall thickness and other recommended practices in Regulatory Guide 1.121 are used to determine a plugging limit for the sleeve. This 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 tube 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 eddy current measurement errors and other significant eddy current testing parameters. An eddy current measurement uncertainty value of [ ]^{a,c} of the tube wall thickness is applied for use in the determination of the operational tube thickness acceptable for continued service and thus determination of the plugging limit.

Paragraph C.3.f of the Regulatory Guide specified that the basis 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 is applied as an allowance for continued degradation is used in this evaluation.

In summary, the operational sleeve thickness acceptable for continued service includes the minimum acceptable sleeve wall thickness [ ]^{a,c} and the combined allowance for eddy current uncertainty and operational degradation [ ]^{a,c}. These terms total to [ ]^{a,c} resulting in a plugging limit as determined by Regulatory Guide 1.121 recommendations of [ ]^{a,c} of the sleeve wall thickness.

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:

[ ]^{a,c}

[ ]^{a,c}

3.1.13 Analysis Conclusions

Based on the results of this analysis, the design of the laser welded tubesheet sleeve and the tube support plate sleeve are concluded to meet the requirements of the ASME Code. The applicable plugging limit for the sleeve is [ ]^{a,c} of the initial wall thickness. Comparing the critical crack length for burst under FLB conditions to the critical crack length for leakage, the maximum permissible leak rate under normal operation is [ ]^{a,c}. Thus, based on leak-before-break criteria, plants where sleeves are to be installed should maintain a leak rate limit under normal operation at or below [ ]^{a,c}.

3.1.14 References

1. Design Specification 412A19, "Plants with Series 44 and 51 Steam Generators, Steam Generator Heat Transfer Tube Sleeving, ASME Boiler and Pressure Vessel Code, Section III, Code Case 1 Safety Class 1," Rev. 0, 12/17/92. (Westinghouse Proprietary Class 2)

2. "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, 1986.

3. USNRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes (For Comment)," August 1976.

4. USNRC Regulatory Guide 1.83, Rev. 1, "In-Service Inspection of Pressurized Water Reactor Steam Generator Tubes," July 1975.

5. WCAP-12522, "Inconel Alloy 600 Tubing - Material Burst and Strength Properties," J. A. Begley, J. L. Houtman, January 1990.

TABLE 3-1

SUMMARY OF MATERIAL PROPERTIES
TUBE MATERIAL
MILL ANNEALED ALLOY 600

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-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-in/lb-sec^2-°F	41.7	43.2	44.8	45.9	47.1	47.9	49.0

STRENGTH PROPERTIES (ksi)							
Sm	26.60	26.60	26.50	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 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	6.50	6.67	6.87	7.07	7.25	7.42	7.59
Density $lb\text{-}sec^2/in^4$ 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 $Btu\text{-}in/lb\text{-}sec^2\text{-}°F$	41.9	44.5	46.8	48.8	50.8	52.8	55.1
STRENGTH PROPERTIES (ksi)							
Sm	26.70	26.70	26.70	26.70	26.70	26.70	26.70
Sy	50.00	47.50	46.10	45.10	44.50	43.80	43.10
Su	80.00	80.00	80.00	80.00	80.00	80.00	80.00

TABLE 3-4

SUMMARY OF MATERIAL PROPERTIES
AIR

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Density lb-sec^2/in^4 x 1.0E-08	10.63	8.99	7.79	6.89	6.17	5.59	5.11
Thermal Conductivity Btu/sec-in-°F x 1.0E-07	3.56	4.03	4.47	4.91	5.35	5.78	6.20
Specific Heat Btu-in/lb-sec^2-°F x 1.0E+01	9.27	9.31	9.38	9.46	9.55	9.66	9.78

TABLE 3-5

SUMMARY OF MATERIAL PROPERTIES
WATER

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Density lb-sec^2/in^4 x 1.0E-05	9.28	9.01	8.58	8.04	7.34	6.35	4.65
Thermal Conductivity Btu/sec-in-°F x 1.0E-06	8.46	9.07	9.14	8.89	8.24	6.9	4.42
Specific Heat Btu-in/lb-sec^2-°F x 1.0E+02	3.82	3.88	3.96	4.12	4.37	5.26	8.51

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	$P_m \leq 0.9\ S_y$ $P_1 + P_b \leq 1.35\ S_y$	$P_m \leq 36.00$ $P_1 + P_b \leq 54.00$
ALL CONDITIONS	$P_1 + P_2 + P_3 \leq 4.0\ S_m$	$P_1 + P_2 + P_3 \leq 106.4$

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

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	$P_m \leq 0.9\ S_y$ $P_1 + P_b \leq 1.35\ S_y$	$P_m \leq 31.50$ $P_1 + P_b \leq 47.25$
ALL CONDITIONS	$P_1 + P_2 + P_3 \leq 4.0\ S_m$	$P_1 + P_2 + P_3 \leq 93.20$

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

TABLE 3-8

CRITERIA FOR PRIMARY PLUS SECONDARY STRESS INTENSITY EVALUATION
SLEEVE - ALLOY 690

CONDITION	CRITERIA	LIMIT (KSI)
NORMAL, UPSET, and TEST	$P_1 + P_b + Q \leq 3\ S_m$*	$P_1 + P_b + Q \leq 79.8$
NORMAL, UPSET, and TEST	Cumulative Fatigue Usage	1.0

* - Range of Primary + 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	$P_1 + P_b + Q \leq 3\ S_m$*	$P_1 + P_b + Q \leq 69.9$
NORMAL, UPSET, and TEST	Cumulative Fatigue Usage	1.0

* - Range of Primary + Secondary Stress Intensity

TABLE 3-10

SUMMARY OF TRANSIENT EVENTS

CLASSIFICATION	CONDITION	CYCLES
Normal	[	] a,c,e
Upset		
Faulted		
Test		

TABLE 3-11

UMBRELLA PRESSURE LOADS FOR DESIGN, FAULTED, AND TEST CONDITIONS

b,c

CONDITIONS	PRESSURE LOAD, PSIG PRIMARY	SECONDARY
Design		
Design Primary		
Design Secondary		
Faulted		
Reactor Coolant Pipe Break		
Feedline Break		
Steam line Break		
Loss of Secondary Pressure		
Test		
Primary Side Hydrostatic Test		
Secondary Side Hydrostatic Test		
Tube Leak Test		
Primary Side Leak Test		
Secondary Side Leak Test		

TABLE 3-12

SUMMARY OF MAXIMUM PRIMARY STRESS INTENSITY FULL LENGTH TUBESHEET LASER WELDED SLEEVE

Sleeve/Tube Weld Width of [ ]^{a,c}
[ ]^{a,c}

a,c

WP0321-3.CL3:1b/011493

TABLE 3-13

SUMMARY OF MAXIMUM PRIMARY STRESS INTENSITY
FULL LENGTH TUBESHEET LASER WELDED SLEEVE

Sleeve/Tube Weld Width of [ ]a,c
[ ]a,c

a,c

TABLE 3-14

MAXIMUM RANGE OF STRESS INTENSITY AND FATIGUE
FULL LENGTH TUBESHEET LASER WELDED SLEEVE

Sleeve/Tube Weld Width of [ ]a,c

Tube Severed and Dented

Component		Calculated S.I. (KSI)	Allowable S.I. (KSI)	Calculated / Allowable
Straight Sections	Sleeve	[ ]a,c	79.80	[ ]a,c
Upper LWJ:	Sleeve		79.80	
	Tube		69.90	
	Weld		69.90	
Lower LWJ:	Sleeve		79.80	
	Tube		69.90	
	Weld		69.90	

Cumulative Fatigue Usage Factor
[ ]a,c $\leq$ 1.0

TABLE 3-15

BURST PRESSURE VERSUS CRACK LENGTH
SERIES 44 AND 51 LASER WELDED SLEEVE

a,c

TABLE 3-16

SUMMARY OF LEAK RATE CALCULATIONS
FOR SERIES 44 AND 51 STEAM GENERATORS
FOR VARIOUS CRACK LENGTHS
AS A FUNCTION OF
PRIMARY-TO-SECONDARY PRESSURE DROP AND T_{HOT}

a,c

TABLE 3-17

SUMMARY OF LEAK RATE CALCULATIONS
FOR SERIES 44 AND 51 STEAM GENERATORS
AS A FUNCTION OF CRACK LENGTHS

a,c

a,c

Figure 3-1

Schematic of Tubesheet Sleeve Configuration

a,c

Figure 3-2

Channelhead/Tubesheet/Shell Model

a,c

Figure 3-3

Thermal/Hydraulic Boundary Conditions
Tubesheet Sleeve Analysis

a,c,e

Figure 3-4

Channelhead/Tubesheet/Shell Model
Primary Pressure Boundary Conditions

a,c,e

Figure 3-5

Channelhead/Tubesheet/Shell Model
Distorted Geometry Primary Pressure Loading

a,c,e

[ ]

Figure 3-6

Channelhead/Tubesheet/Shell Model
Channelhead Thermal Boundary Conditions

a,c,e

Figure 3-7

Channelhead/Tubesheet/Shell Model
Distorted Geometry Channelhead Thermal Loading

a,c,e

Figure 3-8

Boundary Condition for Unit Primary Pressure
Intact Tube: $P_{PRI} > P_{SEC}$

a,c,e

Figure 3-9

Boundary Condition for Unit Primary Pressure
Intact Tube: $P_{PRI} < P_{SEC}$

a,c,e

Figure 3-10

Boundary Condition for Unit Primary Pressure
Severed Tube: $P_{PRI} > P_{SEC}$

a,c,e

Figure 3-11

Boundary Condition for Unit Primary Pressure
Severed Tube: $P_{PRI} < P_{SEC}$

a,c,e

Figure 3-12

Boundary Condition for Unit Secondary Pressure
Intact Tube: $P_{PRI} > P_{SEC}$

a,c,e

Figure 3-13

Boundary Condition for Unit Secondary Pressure
Intact Tube: $P_{PRI} < P_{SEC}$

a,c,e

Figure 3-14

Boundary Condition for Unit Secondary Pressure
Severed Tube: $P_{PRI} > P_{SEC}$

a,c,e

Figure 3-15

Boundary Condition for Unit Secondary Pressure
Severed Tube: $P_{PRI} < P_{SEC}$

a,c,e

Figure 3-16

ASN Location - Upper LWJ

a,c,e

Figure 3-17

ASN Location - Lower LWJ

a,c,e

Figure 3-18

Burst Pressure Versus Crack Length
Comparison of Test Results

a,c,e

Figure 3-19

Burst Pressure Versus Crack Length
Series 44 and 51 Sleeves

a,c

Figure 3-20

Comparison Between Predicted and Measured Leak Rates

a,c

Figure 3-21

Leak Rate Versus Crack Length
Series 44 and 51 Sleeves

3.2 Thermal Hydraulic Analysis

3.2.1 Safety Analyses and Design Transients

The emergency core cooling system (ECCS) performance analysis being performed for Series 44 and 51 steam generator plants supports operation at up to 20 per cent equivalent steam generator tube plugging (SGTP) in each steam generator. (Refer to Ref. 1.) For the evaluation of acceptable number of sleeves, a uniform plugging level of 20% is considered. This analysis and the corresponding non-LOCA evaluation are considered applicable for the steam generator sleeving program with a combination of plugging and sleeving flow restriction equal to or less than the restriction due to the acceptable plugging level. In addition, in support of the steam generator sleeving program, Westinghouse has done an evaluation of selected LOCA and non-LOCA transients to verify that use of sleeves resulting in a plugging equivalency of up to 20 percent in the most plugged steam generator will not have an adverse affect on the thermal-hydraulic performance of the plant. For the accidents as evaluated, the effect of a combination of plugging and sleeving up to the limits of the existing analysis would not result in any design or regulatory limit being exceeded.

The items listed below were evaluated for a sleeving and plugging combination equivalent to the existing tube plugging limits and the results indicated no adverse effects.

Large Break LOCA
Small Break LOCA
LOCA Hydraulic Forcing Functions
Post-LOCA boron requirements
Time to switch over the ECCS to hot leg recirculation

The steam generator tube rupture (SGTR) accident is analyzed to ensure that the offsite doses remain below 10CFR100 limits. The primary parameters affecting the conclusion are the extent of fuel failure assumed for the accident, the amount of primary to secondary break flow through the ruptured tube, and the mass released to the atmosphere from the ruptured steam generator. The amount of fuel failure assumed for the FSAR SGTR analysis is 1% which is assumed to be independent of the transient conditions. The primary to secondary break flow and the mass released to the atmosphere are primarily dependent upon the RCS and secondary thermal hydraulic parameters.

An evaluation was performed which demonstrated that the effect of up to 20% steam generator tube plugging on the SGTR analysis would be acceptable. The SGTR evaluation was based on a uniform plugging level of 20%. The evaluation bounds the effect of non-uniform plugging with the most plugged steam generator at or less than 20% plugging. Thus with the combined sleeving and plugging, up to the limit based on the LOCA evaluation, the operating RCS temperature and steam pressure will not be reduced below the values for the evaluated tube plugging level. On this basis, the evaluation performed for the previously evaluated tube plugging level limit is applicable for the combined tube plugging and

sleeving, and it is concluded that the sleeving will not change the previous conclusion that the SGTR analysis will remain acceptable.

The effect of sleeving on the non-LOCA transient analyses has been reviewed. Since the effect of the reduced RCS flow rate at the tube plugging limit has been evaluated for the non-LOCA safety analyses, these analyses bound the equivalent effect of steam generator tube sleeving. Therefore, the steam generator sleeve installation up to the equivalent of plugging limit would not invalidate any non-LOCA safety analyses.

Evaluations of the level of sleeving and plugging discussed in this report have shown that the Reactor Coolant System flow rate will not be less than that for the analyzed plugging level. The effect of the reduction in RCS flow rate for the analyzed plugging level on the design transients has been evaluated and has no impact. Any combination of plugs and sleeves which does not result in an RCS flow rate less than that for the analyzed plugging level would not have an adverse effect on the previous evaluation of the design transients.

3.2.2 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 the sleeved tube. Furthermore, the insertion of multiple sleeves (tubesheet and/or tube support plate sleeves) 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 several parameters: 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 hydraulic 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:

$$Nhyd = \frac{1}{1 - (W_{slv} / W_{unslv})}$$

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 ECCS 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.

The goal of the hydraulic equivalency number calculations described below is to generate conservative results which envelop the results for all plants which have either Series 44 or 51 steam generators. As such, it was necessary to consider the effect of a wide variation in primary flow conditions for normal operation. Flow rates for these parametric calculations ranged from [

]^{a,c,e}.

It was determined that the most limiting results (largest flow reduction and smallest hydraulic equivalency number for a sleeved tube) occur with [

]^{a,c,e}.

In addition to the effect of variations in the primary coolant conditions, the effect of differences in nominal tube geometries was evaluated. For the 51 Series steam generators there are some differences in the tube geometry in the tubesheet region, specifically, in the length of the expanded or rolled region. For some plants, this zone is short (2-3 inches), while for others with a full-depth roll it extends throughout the full thickness of the tubesheet (21-22 inches). Parametric calculations were completed to determine the specific tube configuration which produces the most conservative result; this geometry was then used in developing the final reported results. No differences exist in the nominal length of the expanded region for the plants with Series 44 steam generators. Therefore, it was necessary to consider only one tube configuration for the Series 44 plants.

Many combinations of tubesheet (both hot and cold legs) and tube support plate sleeves have been considered in calculating the flow reduction and hydraulic equivalency. However, to ensure that the results are enveloping, only the longest sleeves were used in the calculations. These included a 36 inch long tubesheet sleeve and a 12 inch long tube support plate sleeve. The 36 inch long tubesheet sleeve is expected to be long enough to span the degraded areas in the tubesheet and places the upper joint above the sludge pile in either the hot or cold legs. The flow effects of this sleeve length bound a range of

possible tubesheet sleeve lengths which could be specified for any future sleeving program (27 to 36 inches).

The parametric calculations considered four configurations with regard to the location of sleeves:

1) No tubesheet sleeves with various combinations of support plate sleeves in both hot and cold legs,

2) No tube support plate sleeves - only hot and/or cold leg tubesheet sleeves,

3) One tubesheet sleeve (cold leg) with various combinations of cold leg support plate sleeves, and

4) Both hot and cold leg tubesheet sleeves with various combinations of support plate sleeves.

Note that the third configuration includes only cold leg tube support plate sleeves and no hot leg sleeves. The reason for this selection is that, because of the effect of the variation in primary fluid temperature in the two legs of the tube bundle, support plate and tubesheet sleeves located in the cold leg produce slightly more conservative results (greater flow reduction) compared to an identical number and placement of hot leg sleeves. Similarly, slightly more conservative results are obtained when support plate sleeves are located at the higher plate locations. For these reasons, the results presented herein are generally limited to only those particular sleeve locations which yield the more conservative results. Support plate sleeves are qualified for the second-from-highest support plate elevation through the lowest elevation for both series of steam generators. (Qualification of the sleeve at the top support plate would require a small structural evaluation and minor modifications to the tooling.) Nontheless, the hydraulic equivalency and flow reduction calculations were made for support plate sleeves at all elevations for both series of steam generators.

Table 3-18 presents a summary of the hydraulic equivalency numbers for the limiting combinations of tubesheet and support plate sleeves in 44 Series steam generators. Similar results for 51 Series steam generators are provided in Table 3-19. From Table 3-18, the hydraulic equivalency number for a configuration with no tubesheet sleeve and four support plate sleeves is [ ]^{b,c} and occurs when the sleeves are positioned at the top four support plates in the cold leg (#3, #4, #5, and #6). This means that about [ ]^{b,c} sleeved tubes of the type specified would have the same net flow reduction as a single plugged tube. Similarly, if sleeves were also installed in both hot and cold leg tubesheets, the equivalency number would decrease to [ ]^{b,c} for a configuration with four support plate sleeves (Set #21 for support plate locations #5 and #6 in both legs).

The information presented in Tables 3-18 and 3-19 has also been used to construct Figures 3-22 and 3-23. These figures graphically illustrate the enveloping hydraulic equivalency numbers for 44 and 51 Series steam generators based on normal operating conditions.

Table 3-18

Generic Tube Sleeving Calculations
Flow Reduction and Hydraulic Equivalency for Series 44 SGs

	Distribution of Tubesheet and Support Plate Sleeves						Normal Operating Condition		LOCA Condition		
	Set #	36" Hot Leg Tubesheet Sleeve	12" Hot Leg TSP Sleeve	12" Cold Leg TSP Sleeve	36" Cold Leg T-besheet Sleeve	Total # TSP Sleeves	% Flow Reduction	Nhyd	% Flow Reduction	Nhyd	b,c
No Tubesheet Sleeves	1	No		6	No	1					
	2	No		6 5	No	2					
	3	No		6 5 4	No	3					
	4	No		6 5 4 3	No	4					
	5	No		6 5 4 3 2	No	5					
	6	No		6 5 4 3 2 1	No	6					
	7-NA										
	8	No	3 4 5 6	6 5 4 3	No	8					
	9	No	1 2 3 4 5 6	6 5 4 3 2 1	No	12					
No Support Plate Sleeve	10	Yes			No	0					
	11	No			Yes	0					
	12	Yes			Yes	0					
1 Tubesheet Sleeve	13	No		6 5 4 3 2 1	Yes	6					
	14	No		6	Yes	1					
	15	No		6 5	Yes	2					
	16	No		6 5 4	Yes	3					
	17	No		6 5 4 3	Yes	4					
	18	No		6 5 4 3 2	Yes	5					
	19-NA										
2 Tubesheet Sleeves	20	Yes	6	6	Yes	2					
	21	Yes	5 6	6 5	Yes	4					
	22	Yes	4 5 6	6 5 4	Yes	6					
	23	Yes	3 4 5 6	6 5 4 3	Yes	8					
	24	Yes	2 3 4 5 6	6 5 4 3 2	Yes	10					
	25	Yes	1 2 3 4 5 6	6 5 4 3 2 1	Yes	12					
	26-NA										

Table 3-19

Generic Tube Sleeving Calculations
Flow Reduction and Hydraulic Equivalency for Series 51 SGs

	Set #	36" Hot Leg Tubesheet Sleeve	12" Hot Leg TSP Sleeve	12" Cold Leg TSP Sleeve	36" Cold Leg Tubesheet Sleeve	Total # TSP Sleeves	Normal Operating Condition	LOCA Condition
No Tubesheet Sleeves	1	No		7	No	1		
	2	No		7 6	No	2		
	3	No		7 6 5	No	3		
	4	No		7 6 5 4	No	4		
	5	No		7 6 5 4 3	No	5		
	6	No		7 6 5 4 3 2	No	6		
	7	No		7 6 5 4 3 2 1	No	7		
	8	No	4 5 6 7	7 6 5 4	No	8		
	9	No	1 2 3 4 5 6 7	7 6 5 4 3 2 1	No	14		
No Support Plate Sleeve	10	Yes			No	0		
	11	No			Yes	0		
	12	Yes			Yes	0		
1 Tubesheet Sleeve	13	No		7 6 5 4 3 2 1	Yes	7		
	14	No		7	Yes	1		
	15	No		7 6	Yes	2		
	16	No		7 6 5	Yes	3		
	17	No		7 6 5 4	Yes	4		
	18	No		7 6 5 4 3	Yes	5		
	19	No		7 6 5 4 3 2	Yes	6		
2 Tubesheet Sleeves	20	Yes	7	7	Yes	2		
	21	Yes	6 7	7 6	Yes	4		
	22	Yes	5 6 7	7 6 5	Yes	6		
	23	Yes	4 5 6 7	7 6 5 4	Yes	8		
	24	Yes	3 4 5 6 7	7 6 5 4 3	Yes	10		
	25	Yes	2 3 4 5 6 7	7 6 5 4 3 2	Yes	12		
	26	Yes	1 2 3 4 5 6 7	7 6 5 4 3 2 1	Yes	14		

Column group heading: Distribution of Tubesheet and Support Plate Sleeves

b,c

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a,b,c

Figure 3-22

Hydraulic Equivalency Number for
Series 44 Steam Generator

a,b,c

Figure 3-23

Hydraulic Equivalency Number for Series 51 Steam Generators

The total equivalent number of plugged tubes is the sum of the number of plugs associated with sleeving (number of sleeves divided by the hydraulic equivalency number) and the actual number of plugged tubes. In the event that the total plugging equivalency derived from this information is near the tube plugging limit for a particular plant application, then less conservative, plant-specific equivalency calculations may be completed to justify increased sleeving. Rather than using the preceding conservative, enveloping conditions, these calculations could make use of: 1) actual plant primary side operating conditions, 2) actual tube and sleeve geometries, and 3) actual locations of the tubesheet and support plate sleeves.

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 = [ ]

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

$N_{hyd,i}$ = Hydraulic equivalency number for a sleeve configuration

P_c = Equivalent number of plugged tubes due to other sleeve designs

3.2.3 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% of the tubes in either a 44 or 51 Series steam generator are plugged.

Using the conservatively high primary flow rate defined previously [ ]^{a,c,e}, for a 0% plugging condition, the velocity through an unplugged tube is approximately [ ]^{a,c,e}. With 20% of the tubes plugged, the fluid velocity through an unplugged and unsleeved tube is about [ ]^{a,c,e}, and for a tube with a single tube support plate sleeve, the local velocity in the sleeve region is computed to be [ ]^{a,c,e}. However, these velocities are unduly conservative as a result of the assumed enveloping primary flow rate and temperatures.

If these calculations are repeated using more typical primary fluid conditions [ ]^{a,c,e}, the estimated velocities are significantly lower [ ]^{a,c,e}. These more typical velocities are smaller than the inception velocities for fluid impacting, cavitation, or erosion-corrosion for Inconel tubing. As a result, the potential for tube degradation due to these mechanisms is low.

3.2.4 Flow Effects Summary

The effects of sleeving on LOCA and non-LOCA transient analyses have been reviewed. No adverse result is indicated for sleeve and plug combinations up to an equivalent of the analyzed steam generator level of up to 20 per cent in each steam generator. The ECCS performance analysis and the corresponding non-LOCA evaluations are considered applicable for the steam generator sleeving program with a combination of plugging and sleeving flow restriction equal to or less than the analyzed tube plugging level. Steam generator sleeve installation up to the equivalent of the analyzed plugging level would not invalidate any non-LOCA safety analyses or the evaluation of design transients.

The results of evaluations show that any combination of sleeving and plugging may be utilized as long as the effective analyzed plugging level, using the hydraulic equivalency number for normal operation, is not exceeded.

Accordingly, using the assumptions stated in this Section, sleeve installation up to the limit of the equivalent plugging level using laser welded sleeves in the tubesheet and at the tube support plates will not have an adverse effect on the normal operation, design transients, and postulated accident conditions.

3.2.5 References

1. WCAP-12966 "Duquesne Light Co. Beaver Valley Power Station Units 1 and 2, 20 Percent Steam Generator Tube Plugging Analysis Program Enginering & Licensing Report," 11/91. (Westinghouse Proprietary Class 2)

4.0 MECHANICAL TESTS

Mechanical tests are used to provide additional information related to sleeve joint performance. Unit test cells are used for mechanical testing. A unit test cell or specimen is one which is a single sleeve joint and sufficient tube and sleeve length to bound transition effects. For tubesheet specimens, a collar is used to simulate the effect of the tubesheet. The wall thickness of the collar has been selected to simulate the radial stiffness of the steam generator's tubesheet.

Mechanical testing was initially applied to Hybrid Expansion Joint sleeving since it was not possible to analytically describe the interaction between the sleeve and tube. Because welded joints can be modelled, these tests have been applied to verify the analytical models used.

4.1 Mechanical Test Conditions

Mechanical testing is primarily concerned with leak resistance and joint strength. During testing, specimens are subjected to cyclic thermal and mechanical loads, simulating plant transients. [

]a,c,e

Other specimens are subjected to tensile and compressive loads to the point of mechanical failure. These tests demonstrate that the required joint strength exceeds the loading the sleeve joint would receive during normal plant operations or accident conditions.

These conditions are summarized in Table 4-1, though 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.

Table 4-1

Mechanical Test Program Summary

a,c,e

[ ]

4.2 Acceptance Criteria

Generic analyses have been performed to determine the allowable leakage during normal operation for sleeve application. The leak rate criteria that have been established are based on Technical Specifications and Regulatory requirements. Table 4-2 shows the generic leak rate criteria for the Series 44 and 51 steam generators. [

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

4.3 Lower Sleeve Joint

The lower tubesheet sleeve joint is offered with and without a seal weld. Otherwise the joint construction is identical with a hydraulic expansion and hard roll zone; the same fabrication parameters are used with both joints.

As discussed earlier, the joints are formed in unit cell collars. End caps are then installed on the collar and sleeve (Figure 4-1) to permit the samples to be pressurized. The end caps are threaded to permit tensile and compressive loading.

4.3.1 Results of Testing; No Seal Weld

The test results for the Series 44 and 51 lower joint specimens are presented in Table 4-3. The specimens [

]^{a,c,e}

a,c,e

Figure 4-1

Tubesheet Sleeve Lower Joint Test Specimen

Table 4-2
Bounding Maximum Allowable Leak Rates for
Series 44 and 51 Steam Generators

	Allowable Leak Rate		
Condition	Four SGs	Most Limiting SG	Allowable Leak Rate per Sleeve*

d,e

[ ]

Limiting Leak Rate	Leak Rate per Sleeve

d,e

[ ]

* Based on installation of 2000 tubesheet sleeves with non-welded lower joints - for four SGs.

a,c,e

Table 4-3
Test Results for As-Rolled Lower Joints

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

4.3.2 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 anticipated 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 excep ι ıal tube conditions and changes to the sleeving process parameters tested in the first program, are showı ›n Table 4-4.

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 4-5 were included in the assembly of tube and collar subassemblies.

Table 4-4
Test Results for Lower Joints with Exceptional Conditions for Tube and Sleeve

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 4-5
Additional Test Results for Lower Joints with Exceptional Conditions for Tube and Sleeve

a,c,e

4.3.3 Results of Lower Joint Testing with Seal Weld

Nine specimens were fabricated in collars with laser seal welds added to the sleeve end at the elevation of the tubesheet clad. They were then subjected to the fatigue, thermal cycling, compressive, and tensile test as defined in Table 4-1. The results of this testing are summarized in Table 4-6. [

]^{a,c,e}

4.4 Free Span Joint Mechanical Testing

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

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.

4.4.1 Thermal Treatment of Specimens

All 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 4-7. The temperature was ramped up [

]^{a,c,e} Following stress relief the thermocouple attachments were filed off.

Table 4-6
Lower Joint Test Results (with Seal Weld)

a,c,e

Specimen Number	
M1	
M2	
M3	
M4	
M5	
M6	
M7	
M8	
M9	

(Leak rate in drops per minute)

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

a,c,e

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Table 4-7
Free Span Joint Maximum Stress Relief Temperature

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

a,b,c

Figure 4-2

Free Span Laser Weld Joint Test Specimen

4.4.2 Free Span Joint Test Results

The welds were subjected to leak testing [ ]^{a,c,e} No leakage was exhibited (Table 4-8). Some specimens were subjected to tensile and compressive loading to failure; acceptable results were obtained.

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

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

4.4.3 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 impact tensile loads on the tube. [ ]^{a,c,e}

[ ]^{a,c,e}

4.4.4 Results of Fixed Tube Free Span Welding

[ ]^{a,c,e}

[ ]^{a,c,e}

Table 4-8
Free Span Joint Leak Rate and Loading Data

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.

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5.0 STRESS CORROSION TESTING OF LASER WELDED SLEEVE JOINTS

The resistance of the laser welded sleeve joint to in-service corrosion is related to the resistance of the Alloy 600 tubing to intergranular stress corrosion cracking (IGSCC). The sleeve material, Alloy 690 TT, has been demonstrated to be highly resistant to IGSCC under steam generator conditions (Reference 1). Stresses in the tubing, either service imposed or residual, are a major factor determining the response of the material in terms of IGSCC. Two sources of residual stresses in the laser welded sleeving process are a) minor stresses related to the hydraulic expansion during sleeve placement and b) residual stresses that occur as the molten weld pool solidifies.

This section summarizes results of a testing program to evaluate the Primary Water Stress Corrosion Cracking (PWSCC) resistance of laser welded upper sleeve joints used to install sleeves in degraded steam generator tubing. The testing was conducted under conditions which accelerate corrosion in steam generator materials that may be susceptible to stress corrosion cracking in long term steam generator service. Some of the laser welding processes included in these corrosion tests are representative of the weld parameters used but were produced using a CO_2 laser. The CO_2 laser process has been used previously in a field sleeving applications.

5.1 Corrosion Test Description

An accelerated corrosion test developed by Westinghouse is used as a means to evaluate the resistance of steam generator materials to degradation in steam generator primary water environments. The test produces the same type of degradation through intergranular stress corrosion cracking that has been observed in some mill annealed Alloy 600 steam generator tubing. The test has also been found to provide the same relative ranking of material resistance to IGSCC that has been observed in service.

The accelerated test is conducted in an autoclave operating at 750°F (400°C) with steam at 3000 psig. The steam contains [ ]^{a,c,e} The ID of the specimen is exposed to the 3000 psi doped steam while the OD sees undoped steam at 1500 psi.

The configuration of the laser welded specimen used in this corrosion program is a free-span upper joint as illustrated in Figure 5-1. The sleeve joints were fabricated using equipment and practices representative of in field sleeving operations. The [ ]^{a,c,e} test environment is introduced to the inside of the sleeve and has access to the ID of the sleeve and, on one side of the weld joint, to the OD of the sleeve, the ID of the tube and the weld. The other side of the weld joint and the outside of the tube are exposed to the 1500 psi steam environment. The 1500 psi differential across the tube wall simulates the active loading that is present in operating steam generators. In this way it is possible to test the weld under stress conditions representative of those in the generator.

a,c,e

Figure 5-1

Accelerated Corrosion Test Specimen for Welded Joint Configuration

The corrosion performance of the sleeve weld joints is compared with that of tube roll transitions exposed to the same test environment. The roll transition control samples illustrated in Figure 5-2 are representative of the transitions found at the top of the tubesheet in full depth, hard rolled steam generator tubes. The inclusion of the potentially PWSCC susceptible configuration (the roll transition) in the test provides verification of the aggressiveness of the corrosion test environment. Any variability in the aggressiveness from one autoclave run to another is accounted for by having roll transition controls in each run.

The time-to-crack of the test sample is measured in the accelerated test. For both weld samples and roll transitions, cracking time is defined by the appearance of through wall cracks which is reflected in the loss of the 1500 psi differential pressure (3000 psi ID, 1500 psi OD) across the weld and tube.

5.2 Corrosion Resistance of Free-Span Laser Welded Joints - As Welded Condition

Most of the welded joint corrosion samples and all the roll transition sections were fabricated from mill annealed Alloy 600 tubing from Heat NX-1019. This is a high carbon heat (0.04% C) which previous testing has shown to be sensitive to PWSCC and has been used in a variety of corrosion test programs over the past several years. A set of CO_2 laser welded samples was also fabricated from a lower carbon (0.02% C) mill annealed Alloy 600 tubing, Heat NX-9621, which has exhibited susceptibility to PWSCC. The lower carbon heat was included to determine if the carbon difference produced adverse metallurgical changes during welding. [

]a,c,e

[

]a,c,e

The response of laser welded joints to the accelerated corrosion conditions is shown in Figures 5-4 and 5-5 for CO_2 laser welds and in Table 5-1 and Figure 5-6 for Nd:YAG laser welds. These figures are log-normal distribution plots of the cumulative percentage of samples exhibiting cracking as a function of time. The as-welded joints generally exhibited times for through wall IGSCC in [

]a,c than that of the roll transitions. One tubing heat, Heat NX-2721, exhibited [ ]a,c in the as-welded joint as in the roll transition.
[

]a,c,e

a,c,e

Figure 5-2

Accelerated Corrosion Test Specimen for Roll Transition Configuration

a,b,c

[ ]

Figure 5-3

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

a,b,e

Figure 5-4

Cumulative Percent Cracking for CO_2 Laser Welded Sleeves in 750°F Accelerated Steam Corrosion Test

a,b,e

Figure 5-5

Cumulative Percent Cracking for CO_2 Laser Welded Sleeves in 750°F Accelerated Steam Corrosion Test

Table 5-1
Summary of Accelerated 750°F Steam Corrosion Test Results for YAG Laser Sleeve Welds

a,c,e

CLW - Conduction Limited Weld
CMP - Continuous Molten Pool
* time to SCC is the time of pressure drop in test, i.e., time for through wall crack to from.
** Test terminated at 1000 hours, no through wall SCC.

a,b,e

[ ]

Figure 5-6

Cumulative Percent Cracking for YAG Laser Welded Sleeves
in 750°F Accelerated Steam Corrosion Test

[

]^{a,c,e}

5.3 Corrosion Resistance of Free-Span Laser Welded Joints - With Post Weld Heat Treatment

Because stress corrosion cracking is related to a large extent to residual stresses, a reduction in the residual stress level will enhance the corrosion resistance of the welded joint. During the CO_2 laser weld program, extensive development of a post weld heat treatment was performed. A local stress relief treatment [ ]^{a,c,e} was developed. The development program determined that [ ]^{a,c,e} would reduce the level of residual stresses without significant microstructural changes.

The effectiveness of a stress relief is evident in Figure 5-4 where a [ ]^{a,c} in the time to cracking in heat treated welds over "as-fabricated" welds can be seen. The beneficial effect of stress relief is also evident in the Nd:YAG laser welds (Figure 5-6) in both the conduction limited weld (CL) and continuous molten pool (CMP) weld regimes. The test of the stress relieved CL joints [ ]^{a,c}. This represents more than [ ]^{a,c} in time to cracking over that of the as-welded joint. The corrosion test of the stress relieved continuous molten pool weld was also terminated after [ ]^{a,c} hours with no indication of cracking.

The effect of the stress relief can also be seen in the cross section of the heat treated CL shown in Figure 5-7. [ ]^{a,c} In addition there was no evidence of the minor corrosion at the weld surface noted previously in the as-welded, corrosion test sample.

5.4 Corrosion Resistance Evaluation of Lower Tubesheet Sleeve Laser Welded Joints

Accelerated steam testing was performed on specimens representative of the lower tubesheet sleeve joint. These specimens were the same as those used for mechanical testing as illustrated in Figure 4.1, except a seal weld was added at the elevation of the tube clad (Figure 2-1). For control purposes, tube roll transition specimens were used as reference standards.

These specimens were subjected to the steam test described in Section 5.1 for a time period of [ ]^{a,c} The results, tabulated in Table 5-2, demonstrate [

]^{a,c}

a,b,c

Figure 5-7
Minor IGSCC in Alloy 600 Tube of Stress Relieved YAG Laser Welded Sleeve Joint after 1000 Hours in 750°F Steam Accelerated Corrosion Test

5.5 Effects of Sleeving on Tube-to-Tubesheet Weld

5.5.1 Lower HEJ Joint

The effect of hard rolling the sleeve over the tube-to-tubesheet weld was examined in the sleeving of 0.750 inch OD tubes. Although the sleeve installation roll torque used in a 0.750 inch OD tube is less than a .875 inch OD tube, the radial forces transmitted to the weld are comparable. Evaluation of the 0.750 inch tubes showed no tearing or other degrading effects on the weld after hard rolling. Therefore, no significant effect on the tube-to-tubesheet weld is expected for the larger 0.875 inch OD tube configuration.

5.5.2 Lower Seal Weld

[

]a,c,e

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Table 5-2

Corrosion Resistance Evaluation of Lower Tubesheet Laser Welded Sleeve Joints

Mockup: Alloy 600 MA (Heat 7368, 0.875 in. OD) tube, mechanically expanded into steel collar

Sleeve: Alloy 690TT

a,c,e

[ ]

* A slow leak was present at the start of the last run in Autoclave 11. At a cumulative exposure time of about 205 hrs, the leak rate during the last run in Autoclave 11 increased, but was not detected until a pressure plot was made at the end of the run. Specimen CTLSR-01 was found to exhibit minor leakage at the end of the run. It is assumed that the initiation time of the leak in CTLSR-1 corresponds to the time at which the leak rate increased in Autoclave 11.

5.6 Outside Diameter Surface Condition

Because the sleeving operation is conducted from the primary side, no operations are conducted on the tubing OD surface. In operational steam generators, the outside surfaces of the tubes can collect boiler water deposits and scales. These are typically oxides or minerals in the thermodynamically stable form of the constituent elements, magnetite being the most prominent deposit. At the temperatures of the tubing OD during the sleeve weldings and thermal treatment, these compounds are typically stable and do not thermally decompose. All such compounds have molecular structures that are too large for diffusion into the lattice of the Alloy 600 tubing. Reactions between these stable oxides and minerals and the alloying elements of the Alloy 600 tubing are thermodynamically unfavorable. Consequently the presence of boiler sludge/scale species on the OD surfaces of tubes that receive the temperatures associated with LWS is not expected to produce deleterious tube-sludge/scale interactions.

Three tests performed as a part of the development of a sleeve brazing technique, also support the preceding discussions. The first test involved a laboratory evaluation in which a braze cycle was applied to tubing in contact with simulated plant sludge. The braze cycle involved [ ][a,c]. Bend tests of longitudinal sections removed from the brazed area showed no embrittlement as a result of the thermal cycle or exposure to the sludge stimulant. A second test involved microprobe analyses of polished metallographic cross sections. Results indicated the presence of Fe, Ni, Cr, Cu and Zn on the tube OD surface, but no evidence was found of diffusion into the tubing. A third test involved removal of a tube from an operating plant which was brazed in the region of sludge. The pulled tube was analyzed for the presence of contaminants on the OD surface and beneath the OD surface. The microprobe analysis detected Fe, P, Si, Cu, Ca and Na on the tube OD, but there was no indication of diffusion into the tube.

In addition to the above tests, archive tubes from two plants were welded and a microanalytical examination was made for contaminant ingress before and after welding. Before welding, [ ][a,c].

A final test involved metallographic observations of three areas on a U-bend of Alloy 600 tubing which was coated with sludge and heat treated in air [ ][a,b]

To summarize, several observations have been made for a variety of Alloy 600 samples heated to temperatures from [ ][a,c] in the presence of typical secondary side chemical species. No significant diffusion, corrosion, or embrittlement of the tubing has been found.

5.7 References

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 and are considered to be acceptable for application. Section XI, Article IWB-4330 (Reference 1), of the ASME Code is used as a guideline to determine which variables require requalification.

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.

The 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, hard rolling the lower tubesheet joint locations, welding the upper joint, 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 2, 3, and 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 tube hard roll or the tube-to-tubesheet weld. Tube end rolling will be performed only as a contingency.

Testing of similar lower joint configurations in Series 27 steam generator sleeving programs at a much higher torque showed no adverse effect on the tube-to-tubesheet weld. Because the radial forces

transmitted to the tube-to-tubesheet weld would be lower for a larger Series 44 and 51 tube than for the above test configuration, no effect on the weld as a result of the light roll is expected.

6.1.2 Tube Cleaning (Optional)

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 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 man-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.

Currently tube cleaning is required as part of the sleeve installation process. However, test programs are planned to evaluate the necessity of this process step. Should subsequent testing indicate acceptable weld results without it (as judged by weld performance meeting the mechanical, leakage inspection criteria defined in this document, honing may be dropped from the installation sequence. To implement welding without honing, the weld would be requalified and a "no-hone" weld process specification prepared.

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.

Table 6-1

Sleeve Process Sequence Summary

TUBE PREPARATION	1)	Light Mechanical Roll Tube Ends (if necessary)
	2)	Clean Tube Inside Surface (Optional)
SLEEVE INSERTION	3)	Insert Sleeve/Expansion Mandrel Assembly
	4)	Hydraulically Expand Sleeve Top and Bottom Joints
TUBESHEET LOWER JOINT FORMATION	5)	Roll Expand Tubesheet Lower Sleeve End
WELD OPERATION	6)	Weld Upper Tubesheet Sleeve Joints [ ]^{a,c}
	7)	Weld Upper and Lower Support Plate Sleeve Joints
INSPECTION	8)	Visually Inspect Lower Tubesheet Sleeve Weld (if performed)
	9)	Ultrasonically Inspect Sleeve Welds (Free span welds only on a sample plan)
STRESS RELIEF	10)	Post Weld Stress Relief Sleeve Welds [ ]^{a,c}
INSPECTION	11)	Baseline Eddy Current Sleeves

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 support plate sleeves, the support plate is found by using an eddy current coil which is an integral part of the expansion mandrel. The sleeve is positioned by using the grippers and translating cylinder to pull the sleeve into position to bridge the support plate. 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 Lower Joint Hard Roll (Tubesheet Sleeves)

At the primary face of the tubesheet, the sleeve is joined to the tube by a mechanical hard roll (following the hydraulic expansion) performed with a roll expander [

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

]^{a,c,e}

6.4 General Description of Laser Weld Operation

Welding of the upper tubesheet sleeve joint and the upper and lower tube support plate sleeve joints 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.

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.

6.5 Rewelding

Under some conditions, the initial attempt at making a laser weld may be interrupted before completion. Also, the ultrasonic test (UT) examination of a completed initial weld may result 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 either inboard or outboard of the initial weld. If the sleeve/tube has not been perforated by the interrupted weld, an additional weld, having the same nominal characteristics as the original weld, will be made in the expansion zone near the original weld either inboard or outboard of this initial wall. If a perforation of the sleeve is suspected in the initial weld area, the repair weld will be located inboard of the initial weld. Otherwise, the repair weld will be located outboard of the initial weld. If the sleeve/tube were perforated during interruption of the initial weld, the tube would be removed from service.

6.6 Post-Weld Heat Treatment [ ]^{a,c}

6.6.1 Post-Weld Heat Treatment Tooling

The tooling required to perform the stress relief process consists of four basic items:

a. A fiber optic probe
b. A heater (production) probe
c. A pop-up end effector
d. A production and 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,c This is done by using the ROSA robotic arm and the SALEE to sequentially place production probes at the proper welded sleeve/tube interfaces, followed by application of the stress relief process.

6.6.2 Post Weld Heat Treat Process

The laser welded joints (LWJ) exhibit [

]b,c

Westinghouse has extensive experience in stress relief processes from prior work on U-Bend and support plate heat treat programs. The objective of the laser weld post-weld heat treatment is to relieve residual stresses in the sleeve/tube that may be introduced by application of the welding process. The length of sleeve/tube heat treatment spans the weld and the adjacent heat affected zone.

To satisfactorily relieve the residual stresses, it was necessary to develop the optimal heat up, soak, and ramp down power cycles. Several physical factors affect the control of tube temperature within the required temperature band:

1. The tube is predominantly cooled by radiation, with minor effects of conduction and convection.

2. The physical configuration (power density) of the heat source affects heat distribution within the tube.

3. The heat source and the heated portion of the tube cannot be excessively long. Under certain boundary conditions of tube fixity, excessive compressive stresses can occur within the tube during heat treatment. This could result in bowing or barreling of the tube.

4. The process has to account for weld axial positional tolerances as well as heater axial positional tolerances.

To address these factors, the heat source was sized such that it heated the area of interest with sufficient margin to allow for axial position variations.

Given the heat source, laboratory tests were performed which addressed the following issues:

a. Nominal heat source power.

b. Initial heat source power profile to expedite the time required to achieve acceptable tube temperatures.

c. Acceptable soak powers and temperatures.

d. Effect of varying tube emissivities.

e. Effect of a misplaced heater.

f. Circumferential tube temperature profile.

g. Axial tube temperature profile.

h. Sleeve to tube temperature gradient.

The test mockup shown in Figure 6-2 was used for stress relief process testing. The initial sleeve/tube samples are shown in Figure 6-3. [

]a,c

The sleeve/tube samples used for final process development were prototypic of the field sleeve/tube joint configuration, shown in Figure 6-4. The weld centerline was positioned [ ]a below the top of the expansion zone the samples were equipped with thermocouples. [

]a,c

The results of the above laboratory testing led to a typical power profile as shown in Figure 6-5. This figure represents a typical profile, for a tube with a particular emissivity. [

]a,c

a,c,e

Figure 6-1

Laser Welded Sleeve with Reweld

a,c,e

Figure 6-2

Vertical Test Stand Mock-Up

a,c,e

Figure 6-3

Initial Stress Relief Test Samples Detailed

a,c,e

Figure 6-4

Field Prototypic Test Samples Detailed

a,c,e

Figure 6-5

Typical Stress Relief Power Profile

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

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

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.

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.

4. Wagner, T. R., "Laser Welded Sleeving in Stem 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 efficacy of the sleeving process. One method is used to confirm that the laser welds meet critical process dimensions and acceptable weld quality. The second method is then applied to establish 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. Eddy Current Examination (Section 7.3) [ ][d]

1. Demonstrate presence of upper and lower hydraulic expansions
2. Demonstrate lower roll joint presence
3. Determine location of upper weld
4. Record baseline of entire sleeved tube for future inspections

B. Ultrasonic Inspection (Section 7.2) [ ][d] or alternate methods (Section 7.4).

1. Demonstrate quality of upper weld
2. Determine width of the upper weld

C. Visual Inspection [ ][d]

1. Exhibit presence and full circumference continuity of lower weld, if seal weld option selected

D. Weld Process Control [ ][d]

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

The basic tube support plate sleeve inspection of the sleeved tubes shall consist of:

A. Eddy Current Examination (Section 7.3) [ ][a]

1. Demonstrate presence of upper an. lower hydraulic expansions
2. Determine location of upper weld and lower welds
3. Record baseline of entire sleeved tube for future inspections

B. Ultrasonic Inspection (Section 7.2) [ ]^{d} or alternate methods (Section 7.4)

1. Determine quality of the upper and lower welds
2. Determine if minimum width requirement of the upper and lower welds is met.

C. Weld Process Control [ ]^{d}

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 on further refinements of past well-known and field-proven techniques used on brazed and CO_2 laser welded sleeves installed by Westinghouse.

The inspection process developed for application to the laser welds incorporates the basic idea of transmission of ultrasound to the interface region (i.e., the sleeve OD/tube ID boundary) and analyzing the amount of reflected energy from that region. An acceptable weld joint should present no acoustic reflections above a calibrated limit at the weld interface, but produce reflection from the tube OD that is above a calibrated limit.

Appropriate transducer, instrumentation and delivery systems have been designed and techniques established to demonstrate detectability and resolution of relevant defects at the interface. [

]^{a,c,e}

7.2.1 Principle of Operation and Data Processing of Ultrasonic Examination

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

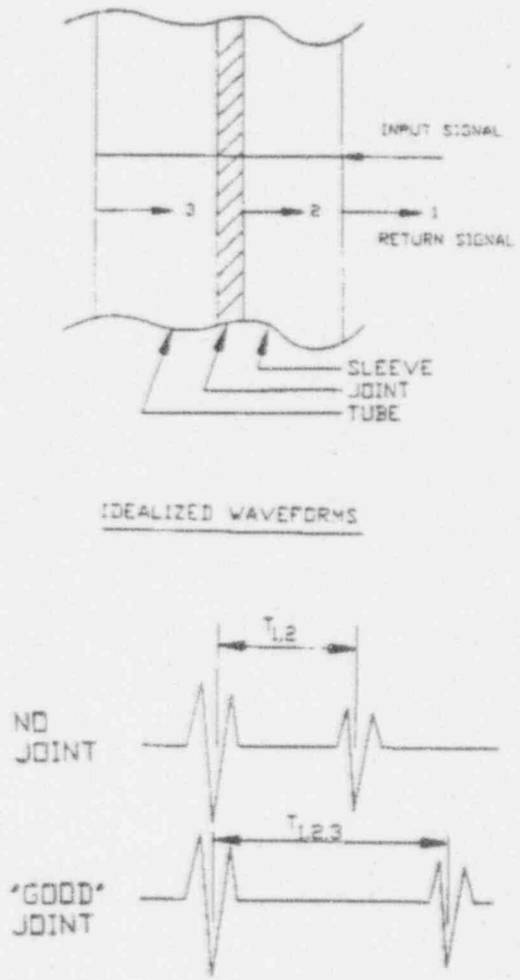

Figure 7-1

Ultrasonic Inspection of Welded Sleeve Joint

The transmitted wave propagates in the sleeve until it reaches the outside surface of the sleeve. If weld material is present, the wave continues to propagate through the weld joint into the tube. This wave then reaches the outer wall (back wall) of the tube and is reflected to the transducer. The resulting UT instrument display from a sound weld joint is a large signal from the sleeve-couplant interface, followed by a back wall "echo" spaced by the time of travel in the sleeve-weld-tube assembly ($T_{1,2,3}$). If no weld material is present, another pattern is observed with the large signal from the sleeve ID followed by a reflection from the sleeve OD ($T_{1,2}$). The spacing of these echoes depends upon the time of travel in the sleeve alone. If there are some void regions in the weld, a complex combination of these two signal patterns will result. Thus, by observing the patterns in the reflected pulse, a quality can be assigned to the weld joint.

The condition of the surface at the entry point of the sound energy, as well as subsequent grain structure of the weld fusion zone, determines the level of energy that reaches the back wall of a "fused" sleeve/tube section. To provide the required resolution and ability to maximize energy input to the interface appropriately focused transducers have been chosen. [

]^{a,c,e}

An automated system is used for digitizing and storing the UT wave forms [

]^{a,c,e}

7.2.2 Ultrasonic Inspection Equipment and Tooling

The probe system is delivered by the Westinghouse ROSA zero entry system. The various subsystems include the water couplant, UT, motor drives, electrical systems and data display/storage.

The probe motion is accomplished via rotary and axial drive modules which allow a range of speeds and axial advance per 360° scan of the transducer head. The axial advance allows for overlap providing a high degree of overlapping coverage without sacrificing resolution or sensitivity.

The controls and displays are designed for trailer mounting outside containment. The system also provides for easy periodic calibration of the UT subsystem on the steam generator platform.

a,c

Figure 7-2

Typical Digitized UT Waveform

The permanent record of the inspection is a color pilot C-scan derived from the digitized and stored A-Scan waveforms. Figure 7-3 is an example of an acceptable laser weld C-scan. The UT instrument is used with the gate modules synchronized to the front wall (sleeve I.D.) signal. [

]a,c,e

7.2.3 Laser Weld Test Sample Results

The calibration standards consist of:

(a) Equipment setup standard--solid Alloy 690 thick-walled tube (wall thickness 0.100").
(b) A sensitivity/resolution check "workmanship" standard, a typical laser welded sleeve/tube assembly.

The UT techniques were developed to assure that the flat bottom holes and notches of the setup standard (described in Figure 7-4) were detectable and measurable. A hard copy color plot, Figure 7-5 shows the C-scan of the setup standard. [

]a,c,e

The "workmanship" standard was prepared using the typical weld process. The sample was inspected before further processing was done. A set of two notches was introduced in the outside diameter across the weld. These notches extended across the width of the weld. The notches simulate a "breach" or leak path across the weld. [

]a,b,e

A "notched workmanship standard" C-scan plot is shown in Figure 7-6. The equipment is set up using the thick-walled tube standard to allow the operator ease in identifying and setting the UT instrument gates and gain. The setup standard presents uniform signals and is repeatable for every A-scan.

7.2.4 Ultrasonic Inspection Summary

The UT laser weld inspection system can confirm that there is a metallurgical bond between the sleeve and the tube. The system is used to determine any existence of leak path across the weld and a minimum acceptable weld width for 360 degrees around the circumference.

7.3 Eddy Current Inspection

Upon conclusion of the sleeve installation process, a final eddy current inspection is performed on every installed sleeve to provide interpretable baseline data on the sleeve and tube. This information is gathered by an eddy current process which utilizes a double cross wound coil. The double crosswound coil is designed to minimize the effects of geometry and weld zone changes that are 360° in nature, i.e.: upper and lower hydraulic expansion transition areas, roll expansion transition areas, top of sleeve, the band of good weld material, etc.

a,c

Figure 7-3

C-Scan from UT Examination of an Acceptable Laser Weld

a,c,e

Figure 7-4

UT Setup Standard

a,c

Figure 7-5

C-Scan from UT Examination of Equipment Setup Standard

a,c

Figure 7-6

C-Scan from UT Examination of Workmanship Sample of a Laser Welded Sleeve with Two EDM Notches

7.3.1 Eddy Current Inspection Principle of Operation

The eddy current inspection equipment, techniques, and results presented herein apply to the proposed Westinghouse sleeving process. Eddy current inspections are routinely carried out on the steam generators in accordance with the Plant's Technical Specifications. The purpose of these inspections is to detect at an early state tube degradation that may have occurred during plant operation so that corrective action can be taken to minimize further degradation and reduce the potential for significant primary-to-secondary leakage.

The standard inspection procedure involves the use of a bobbin eddy current probe, with two circumferentially wound coils which are displaced axially along the probe body. The coils are connected in the so-called differential mode; that is, the system responds only when there is a difference in the properties of the material surrounding the two coils. The coils are excited by using an eddy current instrument that displays changes in the material surrounding the coils by measuring the electrical impedance of the coils. Presently, this involves simultaneous excitations of the coils with several different test frequencies.

The outputs of the various frequencies are combined and recorded. The combined data yield an output in which signals resulting from conditions that do not affect the integrity of the tube are reduced. By reducing unwanted signals, improved inspectability of the tubing results (i.e., a higher signal-to-noise ratio). Regions in the steam generator such as the tube support plate, tubesheet laser weld area and sleeve transition zones are examples of areas where multifrequency processing has proven valuable in providing improved inspectability.

After sleeve installation all sleeved tubes are subjected to an eddy current inspection which includes a verification of correct sleeve installation for process control, degradation inspection and establishing a baseline for all subsequent inspection comparison.

There are a number of probe configurations that lend themselves to enhancing the inspection of the sleeve/tube assembly in the regions of laser weld as well as configuration transitions. The crosswound coil probe has been selected since it provides an advancement in the state-of-the-art over the conventional bobbin coil probe, yet retains the simplicity of the inspection procedure.

The inspection for degradation of the sleeve/tube assembly has typically been performed using crosswound coil probes operated with multifrequency excitation. For the weld free straight length regions of the sleeve/tube assembly, the inspection of the sleeve and tube is consistent with normal tubing inspections. In sleeve/tube assembly joint regions, data evaluation becomes more complex. The results discussed below suggest the limits on the volume of degradation that can be detected in the vicinity of the laser weld and geometry changes.

7.3.2 Transition Region Eddy Current Inspection

The detection and quantification of degradation at the transition regions of the sleeve/tube assembly depend upon the signal-to-noise ratio between the degradation response and the transition response. As a general rule, lower frequencies tend to suppress the transition signal relative to the degradation signal at the expense of the ability to quantify the degradation. Similarly, the inspection of the tube through the sleeve requires the use of low frequencies to achieve detection with an associated loss in quantification. Thus, the search for an optimum eddy current inspection represents a trade-off between detection and quantification. With the crosswound coil type inspection, this optimization leads to a primary inspection frequency for the sleeve on the order of [ ]^{a,c,e} and for the tube and transition regions on the order of [ ]^{a,c,e}.

Figure 7-7 shows a typical [ ]^{a,c,e} calibration curve for the sleeve from which OD sleeve indications can be assessed.

For the tube/sleeve combination, the use of the crosswound probe, coupled with a multifrequency mixing technique for further reduction of the remaining noise signals significantly reduces the interference from all discontinuities (e.g., a diameter transition) which have 360-degree symmetry, providing improved visibility for discrete discontinuities. As is shown in the accompanying figures, in the laboratory this technique can detect OD tube wall penetrations with acceptable signal-to-noise ratios at the transitions when the volume of metal removed is equivalent to the ASME calibration standard.

The response from the sleeve/tube assembly transitions with the crosswound coil is shown in Figures 7-8, 7-9 and 7-10 for the sleeve standards, tube standards and transitions, respectively. Detectability in transitions is enhanced by the combination of the various frequencies. For the crosswound probe, two frequency combinations are shown; the [ ]^{a,c,e} combination provides the overall detection capability while the [ ]^{a,c,e} combination provides improved sensitivity for the sleeve and some quantification capability for the tube. Figure 7-11 shows the phase/depth curve for the tube using this combination. As examples of the detection capability at the transitions, Figures 7-12 and 7-13 show the responses of a 20 percent OD penetration in the sleeve and 40 percent OD penetration in the tube, respectively.

For the inspection of the region at the top end of the sleeve, the transition response signal-to-noise ratio is about a factor of four less sensitive than that of the expansions. Some additional inspectability has been gained by tapering the wall thickness at the top end of the sleeve. This reduces the end-of-sleeve signal by a factor of approximately two. The crosswound coil, however, again significantly reduces the response of the sleeve end. Figure 7-14 shows the response of various ASME tube calibration standards placed at the end of the sleeve using the cross-wound coil and the [ ]^{a,c,e} frequency combination. Note that under these conditions, degradation at the top end of the sleeve/tube assembly can be detected.

a,c,e

Figure 7-7

[ ]^a,c,e Calibration Curve

a,c,e

Figure 7-8
Eddy Current Signals from the ASTM Standard, Machined on the Sleeve O.D. of the Sleeve/Tube Assembly Without Expansion (Cross Wound Coil Probe)

a,c,e

Figure 7-9
Eddy Current Signals from the ASTM Standard Machined on the Tube O.D. of the Sleeve/Tube Assembly Without Expansion (Cross Wound Coil Probe)

a,c,e

Figure 7-10

Eddy Current Signals from the Expansion Transition Region of the Sleeve/Tube Assembly (Cross Wound Coil Probe)

a,c,e

Figure 7-11

Eddy Current Calibration Curve for ASTM Tube Standard at [ ]a,c,e and a Mix Using the Cross Wound Coil Probe

WP0321-7.CL3:1b/011493

a,c,e

Figure 7-12

Eddy Current Signal from a 20% Deep Hole, Half the Volume of ASTM Standard, Machined on the Sleeve O.D. in the Expansion Transition Region of the Sleeve/Tube Assembly (Cross Wound Coil Probe)

a,c,e

[redacted]

Figure 7-13

Eddy Current Signal from a 40% ASTM Standard, Machined on the Tube O.D. in the Expansion Transition Region of the Sleeve/Tube Assembly (Cross Wound Coil Probe)

a,c,e

Figure 7-14

Eddy Current Response of the ASTM Tube Standard at the End of the Sleeve Using the Cross Wound Coil Probe and Multifrequency Combination

The cases considered above cover the inspection of laser-welded and mechanical sleeve/tube pressure boundaries in these areas:

(i) The entire length of the TSP sleeve between the upper and lower welds.

(ii) The entire length of the tubesheet sleeve extending from the upper weld down to the end of the sleeve.

(iii) The entire length of the tube from the hot leg tube entry to the top support of the cold leg, with the exception of the following areas:

iiia) The length of tubing between the upper and lower welds of each TSP sleeve.

iiib) The length of tubing between the upper weld of a tubesheet sleeve, down to the tube length behind the hardroll area of the tubesheet sleeve.

Note that indication of tube degradation of any type including a complete break between the upper weld joint and the lower weld joint does not require that the tube be removed from service.

Also, in a free span joint with more than one weld, the weld closest to the end of the sleeve represents the joint to be inspected and the limit of sleeve inspection.

7.3.3 Laser Weld Region Eddy Current Inspection

The only zone not addressed in Section 7.3.2 is the zone where the laser weld exists.

The basis for the ECT of this structure was developed by test, using a prototype laser weld. The test sample used for this study was a prototypical laser weld in an expanded sleeve zone of a sleeve/tube assembly. The weld was inspected before and after the introduction of a 40% thru-wall 3/16 inch diameter flat bottom hole placed on the outside surface of the tube at the centerline of the weld. This weld presents an axisymmetric condition similar to the transition geometry which is demonstrated by the low phase angle signal similar to transition signals. The weld also displays a material disturbance by its distinct lobes which can be successfully mixed out.

Figure 7-15 shows the [ ]^{a,c,e} response from the weld zone and Figure 7-16 shows the successful [ ]^{a,c,e} mix response using cross-wound coils.

The [ ]^{a,c,e} combination has proven to be optimum for detection in the weld zone, particularly at the tube I.D./sleeve O.D. interface. Figures 7-17 and Figure 7-18 show the response of the 40% FBH using [ ]^{a,c,e} and mix, respectively.

a,c,e

Figure 7-15

Crosswound [ ]^{a,c,e} Eddy Current
Baseline of Laser Weld

a,c,e

Figure 7-16

Crosswound Mix Eddy Current Response Baseline of Laser Weld

a,c

Figure 7-17

Crosswound [ ]a,c,e Eddy Current Response After 40% Flat Bottomed Hole was Placed in O.D. of Tube at Center of Weld

a,c

Figure 7-18

Crosswound Mix Eddy Current Response After 40% Flat Bottomed Hole was Placed in O.D. of Tube at Center of Weld

7.3.4 Eddy Current Inspection Summary

Conventional eddy current techniques have been modified to incorporate the most recent technology in the inspection of the sleeve/tube assembly. The resultant inspection of the sleeve/tube assembly involves the use of a cross-wound coil for the straight regions of the sleeve/tube assembly and for the transition regions. The advent of digital E/C instrumentation and its attendant increased dynamic range and the availability of eight channels for four frequencies has expanded the use of the crosswound coil for sleeve inspection. While there is a significant advancement in the inspection of portions of the assembly using the cross-wound coil over conventional bobbin coils, efforts continue to advance the state-of-the-art in eddy current inspection techniques. As enhanced techniques are developed, they will be utilized after they are verified. For the present, the cross-wound coil probe represents an inspection technique that provides additional sensitivity and support for eddy current techniques as a viable means of assessing the sleeve/tube assembly.

7.4 Alternate Post Installation Acceptance Methods

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 [ ]^{a,c,e}

[ ]^{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

[ ]^{a,c,e}

[ ]^{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, as plant data have shown that this area is less susceptible 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 change in the eddy current signature of the sleeve and sleeve/tube joint region will require further inspection by alternate techniques prior to acceptance. Otherwise the tube containing the sleeve in question shall be removed from service by plugging.

7.6 References

1. Stubbe, 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.