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BEAVER VALLEY UNITS 1 AND 2 WESTINGHOUSE SERIES 51 STEAM GENERATOR SLEEVING REPORT – LASER WELDED SLEEVES

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October 2002

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ABSTRACT

This document is revised because the unit power is being uprated approximately 9.4 per cent and this causes changes in the fluid conditions in the SG, resulting in changes to the stress state of the steam generator (SG) repairs such as laser welded sleeves (LWSs). This document addresses those revised structural analyses. During the period from the date of the last issue of this document, several topics requiring illumination or involving new features have occurred in the LWS product/process. These include weld width clarification, addition of the elevated tubesheet sleeves, improved nondestructive inspection, etc. These topics were addressed and documented separately as they occurred; summaries of them have been added to this document for licensing convenience.

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 (Model) 51 steam generators, a tubesheet sleeve and a support plate sleeve. There are, in turn, two types of tubesheet sleeves. The first one extends the full length of the tube within the tubesheet, is joined to the tube in the vicinity of the tubesheet bottom and is referred to as the full length tubesheet sleeve (FLTS). The other type extends over approximately one-third of the tube length within the tubesheet, is joined to the tube approximately 15 inches above the tubesheet bottom and is referred to as the elevated tubesheet sleeve (ETS). The latter type of sleeve allows much greater radial coverage of the bundle, i.e., installation closer to the bundle periphery, than the FLTS.

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.

Mechanical tests were used to provide information related to performance of the lower joints of tubesheet sleeves. 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. Some joints were tested to determine the sleeve-to-tube mechanical interference fit contact pressure.

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 post weld heat treated joints were tested, in comparison with an Alloy 600 tube roll transition, a structure which is potentially susceptible to PWSCC. 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.

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.

This a General Revision.

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 portion between the attachment points.

This report presents the technical bases developed to support licensing of the laser welded sleeve installation process for use in the Westinghouse Series 51 (aka Model 51) steam generators of Beaver Valley Power Station Units 1 and 2 (Beaver Valley, BV, BV1 or BV2 as appropriate).

Sleeves for two different regions of the tubes are addressed, namely tubesheet sleeves and tube support plate sleeves. Each of these sleeve types has several installation options which can be applied. There are two types of tubesheet sleeves. The first one extends the full length of the tube within the tubesheet, is joined to the tube in the vicinity of the tubesheet bottom and is referred to as the full length tubesheet sleeve (FLTS). The other type extends over approximately one-third of the tube length within the tubesheet, is joined to the tube approximately 15 inches above the tubesheet bottom and is referred to as the elevated tubesheet sleeve (ETS). The latter type of sleeve allows much greater radial coverage of the bundle, i.e., installation closer to the bundle periphery, than the FLTS. The FLTS is appropriate for all plants which have degradation at the top of the tubesheet, and/or within the tubesheet above the lower joint because the lower joint is formed at the bottom of the tubesheet. Depending on the length of the FLTS and elevation of the lowest baffle/support plate in the bundle, this sleeve may also address degradation above the tubesheet. The ETS is appropriate for all plants with SG tubes which have degradation at the top of the tubesheet, and/or within a distance of several inches below the top of the tubesheet. Depending on the length of the ETS and elevation of the lowest baffle/support plate in the bundle, this sleeve may also address degradation above the tubesheet. The tube support plate sleeve (TSS) 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.

1.1 REPORT APPLICABILITY

This report is applicable to the Westinghouse Series 51 steam generators of Beaver Valley. 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 the two sleeve designs: tubesheet and tube support plate. Moreover, with each design, several utility-selectable application options are provided. The sleeve sizes and options are:

<u>Tubesheet sleeves</u>

Full Length:

- 27 to 36 inches long (30 and 36 inches are stock lengths)
- straight or bowed (enhanced for peripheral coverage)
- weld joint with post weld heat treatment

Elevated:

- 12 to 36 inches long
- weld joint with post weld heat treatment

<u>Tube support plate sleeve</u>

- 12 inches long
- welding with post weld heat treatment

The sleeves described herein have been designed, analyzed, and/or tested to meet the service requirements of the Series 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. Installation in the hot leg is the bounding case and therefore demonstrates applicability of the sleeve design for cold leg installations as well. All of the FLTS, TSS and ETS upper joints and the FLTS and ETS mechanical interference fit (MIF) lower joints have been qualified previously and are in use. The ETS MIF lower joint is a two-roll-expansion design; one of the two FLTS lower joints is a single-roll-expansion design, the other is a two-roll-expansion design.

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. Owing to the constant development of tooling, designs and processes, essentially 100 percent coverage of the tubesheet map, for tubesheet and tube support plate sleeves, is expected.

2.0 SLEEVE DESCRIPTION AND DESIGN

2.1 SLEEVE DESIGN DESCRIPTION

Tube sleeves can effectively restore a degraded tube to a condition consistent with the design requirements 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 B&PV 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. The sleeve material, thermally treated Alloy 690, was selected to provide additional resistance to stress corrosion cracking.

2.1.1 Tubesheet Sleeve

2.1.1.1 Full Length Tubesheet Sleeve

The reference design of the full length tubesheet sleeve (FLTS), 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) and it occurs in the free span, i.e., above the tubesheet.

The FLTS extends from the tubesheet primary face to the free span, i.e., above the top of the tubesheet (TTS). The tube degradation may be anywhere between the inboard extent of the "separation distances" of the respective upper and lower joints. (The separation distance is an axial length of tube which separates the main structural part of a sleeve joint, such as the "inboard-most" weld for the upper joint of an FLTS, from the extreme extent of the degradation which caused the tube to be repaired by sleeving.) For the FLTS and all other types of laser weld sleeves, assessment of the extreme extent of the degradation will be performed with the NDE process, essentially ECT, appropriate to the type of degradation expected and/or known to exist based on previous inspections. The ECT process will be consistent with meeting an appropriate uncertainty in elevation of the degradation extreme extent. If the uncertainty in elevation for a particular ECT process exceeds this value, appropriate changes will be made in the separation distances during the preparation phase of the outage. In order to optimize the sleeve length and allow for axial tolerance in locating degradation by eddy current inspection, the inboard-most weld, i.e., either the initial weld or the reweld at the specified lower elevation, must be separated from the extreme extent of the degradation by a [

]^{a,c,e}

The upper joint is designed to provide [

]^{a,c,e}

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

]^{a,c,e}

The separation distance for degradation in the vicinity of, and above, the roll expansion portion of the FLTS MIF lower joint is determined similarly to that of the upper joint. In this case, the uppermost extent of the effective axial length (EAL) of the roll expansion, based on a study of the sleeve and tube component and installation axial dimensions and roll expansion installation tolerances, must be a minimum of the uncertainty in elevation per ECT (ECTU) "outboard" of the degradation lowermost extent of the tube degradation. Within the tubesheet, as in the free span, the separation distance between degradation and the EAL of the roll expansion portion of the MIF joint is based on avoiding locating the roll expansion portion of the joint in a portion of degraded tube. No attenuation length is necessary within the tubesheet. [

]^{a,c,e}

2.1.1.2 Elevated Tubesheet Sleeve

The ETS is illustrated in Figure 2-2. It is applicable to steam generators in which the tubes were installed in the tubesheet by a full-depth expansion. The ETS upper joint is identical to other free span joints, i.e., to the upper joint of the FLTS and to both joints of the TSS. The ETS lower joint is fabricated by the same types of processes which are used to fabricate the FLTS lower joints, i.e., hydraulic expansion and roll expansion. The ETS lower joint is qualified for both the explosive expanded tube joints of Unit 1 and the roll expanded tube joints of Unit 2.

The ETS is similar to the FLTS in that it is designed to address tube degradation in the tube free span and in the vicinity of the tubesheet top. However, unlike the FLTS, it is limited to these applications and is not designed to address degradation in the remainder of the tube within the tubesheet. [

]a,c,e Although the use of the same type of MIF joint at the ETS lower end as used at the FLTS lower end enables the same types of qualification tests and analytical bases, the ETS joint requires a higher roll torque per unit of effective axial length than the FLTS joint.

As in the case of the FLTS free span joint the ETS inboard-most weld, i.e., either the weld at the initial elevation or the reweld at the specified lower elevation, must be separated from the extreme extent of the degradation by a [

]a,c,e A smaller separation distance may be used if it is documented.

The separation distance for degradation in the vicinity of, and above, the ETS MIF lower joint roll for both Units 1 and 2 is determined the same way as it is determined for the FLTS MIF lower joint. As discussed for the FLTS, the ECT process used to determine the extreme extent of degradation will be appropriate for the type of degradation expected and it will meet the required uncertainty in elevation of the degradation. [

]a,c,e

2.1.2 Tube Support Plate Sleeve

The tube support plate sleeve (TSS) is shown in Figure 2-3. 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 plate sleeves are qualified for the second-from-highest support plate elevation through the lowest elevation. (Qualification of the sleeve at the top support plate would require a structural evaluation and modifications to the tooling. The primary side hydraulic equivalency and flow reduction calculations have already been made for support plate sleeves at all elevations and are reported in Section 3.) [

] a,c,e

As in the case of the FLTS and ETS free span joint, the TSS inboard-most weld, i.e., either the weld at the initial elevation or the reweld at the specified different elevation, must be separated from the extreme extent of the degradation by a [

] a,c,e The upper and lower joints of the TSS are identical.

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 separation distance between the extreme extent of degradation and the bounding elevation of sleeve welds, [ ] a,c,e, 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, for example, the sleeve-to-tube lower joint of an FLTS.

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,e nominal OD sleeves into 0.875 inch nominal OD tubes of the BV steam generators 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

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

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

]^{a,c,e}

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

2.2.2 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-3000, Design
	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 MIF Joints	10CFR100	Predicted Steam Line Break Leak Rate
	Technical Specifications and administrative rules	Operating Primary-to-Secondary Leak Rate
Sleeve Weld Joints	Section IX	Weld Qualification
	Code Case N-395 Section IX Section XI	Laser Welding Essential Variables, Procedure Qualification Record, Sleeving Procedure Specification, Certified Design Report, etc.

a,c,e

Figure 2-1
Full Length Tubesheet Sleeve - Laser Welded - Installed Configuration

a,c,e

Figure 2-2

Elevated Tubesheet Sleeve (ETS) - Laser Welded Installed Configuration

a,c,e

Figure 2-3

Tube Support Plate Sleeve (TSS)
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 laser welded sleeves. The structural qualification is performed in two parts. The first part addresses the qualification of the tube and sleeve, and is performed using the results of the previously completed laser welded sleeving evaluation for Westinghouse steam generators with 7/8 inch tubes. The second part addresses the qualification of the [ ]^{a,c} inch minimum average weld width consistent with the guidelines of Section III of the ASME Code.

The loading conditions considered in this analysis umbrella the conditions specified in the generic design specification for laser welded sleeves, Reference 8.1, the steam generator design specifications for Beaver Valley Units 1 and 2 (DLW / DMW), References 8.2 – 8.4, and the uprating specific transients for DLW / DMW, documented in Reference 8.5. 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 and to estimate the change in sleeve/tube/tubesheet contact pressures at the lower joint of the elevated tubesheet sleeve.

3.1.1 Summary of Material Properties

The material of construction for the tubing in Westinghouse Series 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 (TT) Alloy 690. Summaries of the applicable mechanical, thermal, and strength properties for the tube and sleeve are provided in Tables 3-1 and 3-2, for Alloy 600 and 690, respectively. The fatigue analysis of the sleeve, tube, and laser weld is performed using the ASME Code fatigue design curve for and nickel-chromium-iron (Alloys 600 and 690) given in Figures I-9.2.1 and I-9.2.2 of Appendix I of Reference 8.6.

The sleeve evaluation also includes the influence of the tubesheet, channel head, and secondary shell, which are constructed of SA-508 Class 2, SA-216 Grade WCC, and SA-533 Grade A Class 1 steels, respectively. A summary of the applicable mechanical and thermal properties for these materials is provided in Tables 3-3 to 3-5. Thermal properties for air and water, used in performing the heat transfer analysis, are provided in Tables 3-6 and 3-7, respectively.

3.1.2 Applicable Criteria

The applicable criteria for evaluating the sleeves is set forth in the ASME Code, Section III, Subsection NB, 1986 Edition, Reference 8.6. A summary of the applicable stress and fatigue limits for the sleeve and tube are summarized in Tables 3-8 and 3-9. In establishing sleeve minimum wall requirements for repair limits, Regulatory Guide1.121, Reference 8.7, is used.

Since the laser weld interface between the sleeve and tube is essentially loaded in essentially pure shear by the primary to secondary pressure differential, the special stress limit given in Section NB-3227.2 of the ASME Code is used to define the allowable direct average shear stress (τ_a) in the weld. A summary of the applicable primary stress limits for the weld is summarized in Table 3-10. The primary plus secondary stress limits for the welds are same as those specified in Table 3-9 for the sleeve.

3.1.3 Loading Conditions Considered

The analysis considers a full duty cycle of events that includes, design, normal, upset, faulted, and test conditions. Transient conditions based on the generic transient definitions, as well as conditions specific to the DLW / DMW uprating are evaluated. For the uprating conditions, transients have been defined for two sets of full power conditions, identified as Low T_{avg} and High T_{avg}. In addition, plugging levels of 0% and 22% are considered. Thus, four separate sets of conditions are defined for the uprating. The normal and upset transients are generally given in terms of transient changes relative to an initial steady state condition, usually at full power operation. A comparison of the full power conditions for the generic analysis to those corresponding to the DLW / DMW uprating is provided in Table 3-11. The corresponding transient parameters for the generic set of conditions are shown in Table 3-12. For the uprating conditions, the 22% plugging case results in higher primary to secondary pressure loads which are limiting for the LWS. Summaries of the transient parameters for the 22% plugging case for the High T_{avg} and Low T_{avg} conditions are provided in Tables 3-13 and 3-14, respectively.

3.1.4 Analysis Methodology

The analysis of the laser welded sleeve configurations utilizes both conventional and finite element analysis techniques. Several finite element models are used for the analysis. For the tubesheet sleeve analysis, separate models are developed for the lower and upper joints. Interaction between the two models is accomplished by coupling appropriate tube and sleeve nodes. The tubesheet sleeve upper joint model is also used to evaluate the tube support plate sleeve. Typically, the tubesheet sleeve model incorporates a "unit cell" of the tubesheet, based on an effective radial area surrounding the tube in the tubesheet.

For Series 51 steam generators, the type and extent of tube expansion inside the tubesheet varies from a full depth expansion to a partial depth expansion at the bottom of the tubesheet. The sleeving analysis is intended to umbrella all Series 51 steam generators. As such, the limiting geometry, judged to be the [ ]^{a,c}, is evaluated. The tolerances used in developing the sleeve models are such that the maximum sleeve outside diameter is evaluated in combination with the minimum sleeve wall thickness. This allows maximum stress levels to be developed in the sleeve and tube.

The results for the upper joint for the full length tubesheet sleeve (FLTS) are concluded to apply conservatively to the elevated tubesheet sleeve (ETS) and the tube support plate sleeve (TSS). This is based on the temperature and pressure loads for the full length tubesheet sleeve for all transient conditions being greater than or equal to those for the elevated tubesheet and tube support plate sleeves and the tube/sleeve attenuation lengths. The upper joints of all three laser welded sleeves are essentially the same. The attenuation lengths (given by the well known parameter $4.9(rt)^{1/2}$, where r = mean radius and t = nominal wall thickness, Reference 8.8) for the sleeve and tube are relatively small, on the order of [ ]^{a,c} inch, respectively. Structural effects from the laser weld are fully attenuated over these distances, isolating the welded joints in all three sleeve designs. Therefore, only the FLTS, which is typical and limiting of all of the sleeves, is modeled and evaluated. Figure 3-1 shows a schematic of the FLTS sleeve configuration that was simulated in the finite element model of the sleeve, tube, and tubesheet ligament. Note that the FLTS finite element model was developed and executed for an earlier [ ]^{a,c} long hydraulically expanded upper joint region, compared to the [ ]^{a,c} long hydraulically expanded region in the current sleeves. Again, based on the relatively small attenuation lengths, there would be essentially no difference in the structural response, since the upper welds are isolated. Therefore, the structural evaluation of the FLTS, based on stress models with [ ]^{a,c} long hydraulically expanded regions, also applies to the three current sleeves with [ ]^{a,c} long hydraulically expanded regions.

The lower joint for the tubesheet sleeve is a [

]^{a,c}.

The analysis considers both an [

]^{a,c}.

In addition to the sleeve models, a separate model of the tubesheet, channel head, 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. A plot of the tubesheet, channel head, and shell model is shown in Figure 3-2.

Results from this and previous sleeve analyses have identified regions in the tube/sleeve assembly that are most critical and have also quantified the effects of various potential considerations (such as tubesheet rotation, tube separation etc.) that could influence the stresses in various regions. It has been determined that the [

]^{a,c} As discussed elsewhere in this document, the mechanical interference fit (MIF) lower joints have been qualified and have been in service for many years. The qualifications of the MIF joints of the FLTS and ETS are based on test, analysis including the contact pressure analysis discussed in Sections 3.1.14 and 4.0, and previous experience with MIF joints.

3.1.5 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, eight enveloping transients were selected for evaluation. They include the following events:

Small Step Load Increase
Small Step Load Decrease
Large Step Load Decrease
Hot Standby Operations
Loss of Load
Loss of Power
Loss of Flow
Reactor Trip Full Power

The plant heatup/cooldown, plant loading/unloading and steady state fluctuation events are slow acting transients and are evaluated as pseudo-steady state conditions.

In performing the heat transfer analysis, an air gap is included between the tube and the sleeve, and, conservatively between the tube and tubesheet. Although these gaps may be filled with secondary fluid, assuming the physical properties of air is conservative for the thermal analysis. Primary fluid physical properties are used for the gap between the tube and sleeve above the laser welded joint (LWJ). A sketch of the model boundary conditions for the heat transfer analysis is shown in Figure 3-3.

In order to determine the appropriate boundary conditions for the heat transfer analysis, a thermal hydraulic analysis has been performed to define the primary and secondary side fluid temperatures and film coefficients as a function of time. Both boiling and convective heat transfer correlations have been considered.

3.1.6 Tubesheet/Channel Head/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 two pressure loadings and three temperature loads.

The pressure load cases consist of primary side and secondary side pressure 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 three temperature loadings consist of applying a uniform thermal expansion to each of the three component members, one at a time, while the other two remain at ambient conditions. A typical set of boundary conditions, and the resulting deformed geometry, for the case of channel head expansion is shown in Figures 3-6 and 3-7.

Once the stress solutions for the reference load cases are obtained, polynomial expressions are developed for radial stress as a function of distance from the tubesheet primary face for each of the load cases. Using the polynomial expressions, radial stresses are then calculated at the element centroid elevations for the tubesheet ligament elements in the sleeve model. Next, using these interface stresses (pressures), reference load cases are run for the sleeve model, which are then scaled to actual conditions, and summed to give the overall response.

The results from the tubesheet/channel head/shell model of Figure 3-2 show that the [

]^{a,c} compared to either the primary or secondary stresses resulting from the pressure and temperature loads acting on the sleeve, tube, and weld.

3.1.7 Stress Analysis

In performing the stress evaluation for the sleeve models, thermally induced and pressure induced stresses are calculated separately and then combined to determine the total stress distribution. As discussed previously, a number of tube/sleeve/tubesheet interface conditions are evaluated. Separate reference pressure cases are run for both an intact and severed tube, and for the [

]^{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.

As discussed above, the structural analysis considers both undented and dented tubes, i.e., unlocked and locked, respectively, at the first TSP. The following effects on stress components of the dented tubes are analyzed:

- effect of thermal conditions in the tube and wrapper/shell regions
- effect of pressure drop across the tubesheet
- effect of pressure drop across the tube support plates
- effect of interaction among the tubesheet, tube support plates,
- shell/wrapper, stayrods, and spacer pipes

The effect of pressure drop across the tubesheet and the tube support plates, as well as the tubesheet/tube support plate assembly interactions, are taken into account for central dented tubes, while they are neglected for the outermost tubes where interaction effects are not significant. The end cap pressures due to the axial pressure stress induced in the tube away from discontinuities are taken into consideration for undented tubes. For assumed dented conditions, the end cap load is not required. Finally, thermal stresses are calculated for each steady state solution, as well as for the thermal transient solutions at those times during the transients that are judged to be limiting from a stress standpoint. The total stress distribution in the sleeve-to-tube assembly is determined by combining the calculated stresses as follows:

$$\begin{aligned}\sigma_{total} = {} & \frac{P_{PR}}{1000}\left(\sigma_{unit\ primary\ pressure}\right) + \frac{P_{SEC}}{1000}\left(\sigma_{unit\ secondary\ pressure}\right) + \left(\sigma_{thermal\ transient\ stress}\right) \\ & + \frac{P_{PR}}{1000}\left(\sigma_{unit\ primary\ pressure\ for\ tubesheet\ motion\ effect}\right) + \frac{P_{SEC}}{1000}\left(\sigma_{unit\ secondary\ pressure\ for\ tubesheet\ motion\ effect}\right) \\ & + \frac{\Delta T_{TB}}{500}\left(\sigma_{unit\ load\ for\ tubesheet\ thermal\ expansion\ effect}\right) + \frac{\Delta T_{SHL}}{500}\left(\sigma_{unit\ load\ for\ shell\ thermal\ expansion\ effect}\right) \\ & + \frac{\Delta T_{CH}}{500}\left(\sigma_{unit\ load\ for\ channel\ head\ thermal\ expansion\ effect}\right)\end{aligned}$$

3.1.8 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 tube and sleeve are shown in Figure 3-16.

The umbrella loads for the primary stress intensity evaluation are summarized in Table 3-15. The largest magnitudes of the ratio "Calculated Stress Intensity / Allowable Stress Intensity" are [ ]a,c for design conditions, [ ]a,c for faulted conditions, and [ ]a,c for test conditions. The analysis results show the primary stress intensities for the tube and sleeve to satisfy the allowable ASME Code limits. A summary of the limiting stress conditions is provided in Table 3-16.

The results for maximum range of stress intensity and fatigue are summarized in Table 3-17 for the tube being dented at the first tube support plate, and severed between the upper and lower joints, the limiting set of boundary conditions. Based on the sleeve design criteria, the fatigue analysis considers a design objective of 40 years for the sleeved tube assemblies. The analysis results show the ASME Code limits to be satisfied.

In evaluating seismic stresses, [

]a,c

3.1.9 Weld Evaluation

3.1.9.1 Primary Stress Analysis

The evaluation of the laser weld to show compliance with ASME Code requirements for primary pressure stress is performed using closed form solution techniques. The limiting condition for the laser weld in terms of primary membrane pressure stress occurs when the host tube is assumed to be fully severed inboard (below) the weld. Assuming the host tube is not locked to the tube support plates, the shear force in the weld must be in force equilibrium with the end cap load on the host tube, as shown in Figure 3-17. Since the weld is also the pressure seal, the maximum tube inside radius defines both the pressure drop end cap load and the shear area of the weld. Applying force equilibrium to the free body of the tube portion above the assumed fully severed section gives:

End Cap Load Due to ΔP = Shear Load on the Laser Weld

$$\pi R^2 \Delta P = 2\pi R w \tau ,$$

where: R = inner radius of host tube (inch),
ΔP = primary to secondary pressure differential (psi),
w = weld axial engagement length ([ ]a,c inch minimum),
τ = direct average shear stress on weld (psi).

Solving for the average shear stress on the weld gives:

$$\tau = \frac{R\,\Delta P}{2w}$$

The maximum average shear stress is:

$$\tau_{\max} = \frac{R_{\max}\,\Delta P_{\max}}{2\,w_{\min}}.$$

Using a refined finite element model analysis of the tube/sleeve weld interface, it has been shown that the stress intensity across the weld throat is very nearly twice the average shear stress, which is essentially a pure shear condition. The allowable maximum average shear stress (τ_a) is the ASME Code limiting value for pure shear given in NB-3227.2 of Reference 8.6. A summary of the resulting primary stresses in the weld is provided in Table 3-18.

3.1.9.2 Fatigue Analysis

The evaluation presented in this section demonstrates that the current minimum required laser weld axial engagement (fused) length of [ ]^{a,c} inch satisfies the fatigue requirement of the ASME Code with respect to the specified cyclic loads. The fatigue evaluation considers all possible combinations of host tube status, either fully severed or fully intact, and all possible structural boundary conditions at the tube support plates, either fully locked (dented) or fully free. Note that for the primary and secondary hydro test load events, the pressure drops are limited to the design pressure (see footnote to Table 3-15).

Thermal Analysis

The purpose of the thermal analysis is to estimate the tube and sleeve temperatures, as functions of the primary side hot leg temperature (T_{hot}) and the secondary side steam temperature (T_{stm}), to calculate the thermal-structural loading on the laser welds for the fatigue evaluation. The hot leg is limiting structurally since the largest difference between the tube and sleeve temperature occurs in the hot leg. The heat transfer coefficients (inside the sleeve and tube and also outside the tube) are very high compared to the heat capacity and the conduction of the thin-walled metals. Since the thermal transients are relatively slow, it is reasonable to expect the rather thin tube and sleeve wall temperatures to follow the transients without significant thermal lag. In addition, the axial or longitudinal temperature gradients are small compared to the radial gradients which transfer heat from the primary water inside the tube at about 600°F to the steam outside the tube at about 500°F. Therefore, axisymmetric "slab" finite element thermal models are used to calculate the radial gradients in the sleeve and tube above the tubesheet. Three sections, or slabs, are simulated to estimate the radial temperature gradients through the walls of the sleeve and tube above the tubesheet: (1) a section through the unexpanded sleeve, gap and tube; (2) a section through the expanded sleeve and tube; and (3) a section through only the tube at the far field above the sleeve.

For the first thermal model through the wall of the tube and sleeve, the gap between the unexpanded sleeve and tube was filled with thermally conducting static air. Nonlinear thermal radiation link elements were also used to thermally connect the sleeve and tube finite element nodes across the gap. The resulting calculated tube and sleeve wall temperatures lead to the following conclusions:

(1) [ ]a,c
(2) [ ]a,c
(3) [ ]a,c

[ ]a,c
Thus, the average temperature distribution of both the tube and sleeve may be determined for any of the transient cyclic loads using the listed values of T_{hot} and T_{stm} and the above conclusions.

Structural Analysis Models Used in Fatigue Evaluation

Based on the thermal analysis, [

]a,c

As stated earlier, a state of essentially pure shear exists at the weld, and the average stress intensity across the weld is essentially given by 2τ. Therefore, the radial, hoop, and axial stress components at the sleeve-tube laser welded interface are not required to calculate the average stress intensity on the weld for the fatigue evaluation. The shear force, *F*, acting on the laser weld is calculated by finite element simulation of the various sleeve types, host tubes, adjacent tube bundle, tubesheet, and the welds. Since only [

]a,c,e

[

]^{a,c}

The effect of the relatively "rigid" tubesheet on the tube thermal expansion is simulated using a very stiff spar element that has the material properties of the tubesheet and spans the distance from the top of the hard roll to the top of the tubesheet. The tubesheet, host tube, and adjacent tube bundle nodes (located at the top of the tubesheet) are coupled in the vertical direction to force the tubesheet longitudinal expansion onto the tubes. This approximates a full length hard rolled tube/tubesheet condition and is conservative compared to a partial hard roll, since free tubes (inside the tubesheet) would expand more due to the higher expansion coefficient of the tube compared to the tubesheet, resulting in less of a thermal expansion mismatch with the sleeve.

In the case of the weld, it has been shown that under dented conditions, it is conservative to assume that the tubes surrounding the sleeved tube are also dented. In all of the structural spar models, the host (sleeved) tube is assumed to be at the center of a [

]^{a,c}

In all of the [

]^{a,c}

The end cap loading due to pressure is applied to the uppermost nodes at the 2nd TSP in each model. If the pressure load on the [

]^{a,c,e}

[

]a,c,e

Shear Forces on Weld Due to Unit Loads

The LWS structural finite element models shown in Figure 3-18 are used to calculate the shear forces acting in the various longitudinal spring elements simulating each laser weld. The following model combinations were simulated:

Three Sleeve Types:	FLTS, ETS, TSS,
Two Tube States:	Severed, Intact,
Two TSP Conditions:	Locked, Free.

The following four unit load cases were run for each of the model combinations:

Case 1:	$P_p = 1000$ psig	$P_{stm} = 0$	$T_h = 70°F$	$T_{stm} = 70°F$
Case 2:	$P_p = 0$	$P_{stm} = 1000$ psig	$T_h = 70°F$	$T_{stm} = 70°F$
Case 3:	$P_p = 0$	$P_{stm} = 0$	$T_h = 570°F$	$T_{stm} = 70°F$
Case 4:	$P_p = 0$	$P_{stm} = 0$	$T_h = 70°F$	$T_{stm} = 570°F$

All thermal expansion cases are relative to a reference temperature of 70°F. Table 3-19 lists the resulting finite element calculated shear forces due to the above unit loads for each of the possible boundary condition combinations.

The limiting set of boundary conditions corresponds to the case when the tube support plate sleeve (TSS) host tube is intact and the tubes are free at the TSPs. A summary of the resulting weld forces and stresses for each of the five sets of transient conditions is provided in Table 3-20. The weld stresses for the Low T_{avg} case are observed to be generally higher than the forces for the other cases.

Stress Range Calculations

For any of the combinations of sleeve type, host tube state, and TSP condition listed in Table 3-19, the shear force F_i on the weld may be found for any of the load events (say the i[th] load event) as follows:

$$F_i = \frac{(P_p)_i}{1000}\left(F_{P_p = 1000}\right)_k + \frac{(P_{stm})_i}{1000}\left(F_{P_{stm} = 1000}\right)_k + \frac{(T_{hot})_i - 70}{570-70}\left(F_{T_{hot} = 570}\right)_k + \frac{(T_{stm})_i - 70}{570-70}\left(F_{T_{stm} = 570}\right)_k$$

where $(P_p, P_{stm}, T_{hot}, T_{stm})_i$ for the particular i[th] load event, and $(F_{Pp=1000}, F_{Pstm=1000}, F_{Thot=570}, F_{Tstm=570})_k$ are the finite element calculated shear forces due to the unit loads in Table 3-19 for the k[th] combination. The shear force F_i (in lbf) is divided by the weld's assumed minimum shear area [

]a,c The average shear stress range for the i[th] and j[th] load events is:

$$\Delta\tau_{ij} = \left|\tau_i - \tau_j\right| = \frac{\left|F_i - F_j\right|}{A_w},$$

where F_j is the shear force for the loads $(P_p, P_{stm}, T_{hot}, T_{stm})_j$ as given by an expression similar to the above expression for F_i.

For pure shear conditions at the weld, the average stress intensity range is:

$$(\bar{S}_r)_{ij} = 2\Delta\tau_{ij} = 2\left|\tau_i - \tau_j\right|$$

The calculated stress amplitude $(Sa)_{ij}$ for entering the ASME Code S-N curve for the stress range given by load (i) - load (j) is:

$$(S_a)_{ij} = K_f \frac{(\bar{S}_r)_{ij}}{2} \frac{E_{curve}}{E_{model}} = K_f \Delta\tau_{ij} \frac{E_{curve}}{E_{model}},$$

where: K_f = fatigue strength reduction factor (discussion to follow),
E_{curve} = elastic modulus for ASME Code S-N curves = 28.3×10^6 psi,
E_{model} = average elastic modulus used in FE model = 28.325×10^6 psi

Note that all primary plus secondary stress ranges satisfy the $3S_m$ limit for a [ ]a,c inch minimum average weld size. Therefore, an additional K_e factor is not required when calculating the stress range. The number of applied cycles n_{ij} for the i-j stress range is:

$$n_{ij} = \left[noc_i, noc_j\right]_{\text{USE\_MIN\_VALUE}},$$

where: noc_i = current number of unused cycles for i[th] load event,
noc_j = current number of unused cycles for j[th] load event.

The fatigue usage factor u_{ij} for the i-j stress range is:

$$u_{ij} = \frac{n_{ij}}{N_{ij}},$$

where N_{ij} = allowable cycles from ASME Code S-N curve for $(S_a)_{ij}$.

The number of applied cycles remaining for the next usage calculation, involving either the i[th] or j[th] load events, is reduced by n_{ij}, as shown below:

$$(noc_i)_{\text{FOR\_NEXT\_USAGE\_CALC}} = \lfloor noc_i - n_{ij}, 0 \rfloor_{\text{USE\_MAX\_VALUE}},$$
$$(noc_j)_{\text{FOR\_NEXT\_USAGE\_CALC}} = \lfloor noc_j - n_{ij}, 0 \rfloor_{\text{USE\_MAX\_VALUE}}.$$

In forming the average shear stress range on the weld $\Delta\tau_{ij}$, τ_i and τ_j are selected such that the absolute value of the range $\Delta\tau_{ij}$ is always the maximum of all currently active τ_i and τ_j, subject to the order in which the various transients can logically combine, as discussed below. When a load event's current number of cycles (noc) reaches zero, that load event has been used up, and it is removed from the process, which is repeated until all cycles for all load events are used up.

Fatigue Strength Reduction Factor

Calculation of the stress amplitude $(S_a)_{ij}$ requires definition of the fatigue strength reduction factor K_f, which gives the combined effect of the local stress field at the surface of a notch-like section, and the material's microstructure relative to the average stress over the section. [

]a,c,e

[

]^{a,c} This then, is the fatigue strength reduction factor, K_f, used in the fatigue calculations.

Calculated Cumulative Usage Factors

Cumulative fatigue usage factors are calculated for each of the 12 possible combinations of LWS type, host tube state, and condition at the TSPs listed in Table 3-19 to assure that the maximum cumulative usage factor has been determined. All calculated cumulative usage factors are substantially less than the ASME Code limit of one. The overall largest calculated fatigue usage factor of [ ]^{a,c} occurs when the tube support plate sleeve (TSS) host tube is intact and the tubes are free at the TSPs. A summary of the resulting fatigue cycles, stress ranges, stress amplitudes, allowable cycles and fatigue usage is contained in Table 3-21. The transient conditions corresponding to the transient condition combinations listed in the first column of Table 3-21 are summarized in Table 3-22.

3.1.9.3 Maximum Range of Stress Intensity

Referring to Table 3-21, the maximum range of shear stress ($\Delta\tau_{ij}$) is [ ]^{a,c} ksi. The corresponding stress intensity is [ ]^{a,c} ksi. Referring to Table 3-9, the allowable stress is 79.8 ksi for the sleeve, which is also applicable to the weld as has been discussed earlier. Thus, the weld is shown to satisfy ASME Code limits for maximum range of primary plus secondary stress intensity.

3.1.10 Minimum Required Sleeve Wall Thickness

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

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

$$t_{min} = \frac{\Delta P_i R_i}{P_m - 0.5 \Delta P_i}$$

where: ΔP_i = Primary-to-secondary pressure differential
R_i = Sleeve inside radius
P_m = Allowable stress.

<u>Normal/Upset Operation Loads</u>

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

$$\text{Normal: } P_m < S_u / 3$$

$$\text{Upset: } P_m < S_y$$

Accident Condition Loadings

LOCA + SSE

The dominant loading for LOCA and SSE loads occurs at the top tube support in the form of bending stresses in the tubes. At tube support intersections below the top support, LOCA loads drop off dramatically. Because the sleeve is located at the second-from-top support or below, the LOCA + SSE bending stresses in the sleeve are quite small. The governing event for the sleeve, therefore, is a postulated secondary side blowdown, either FLB or SLB.

FLB/SLB + SSE:

The maximum primary-to-secondary pressure differential occurs during a postulated feedline break (FLB) accident. Again, because of the sleeve location, 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}

[

]^{a,c} The applicable criteria for faulted loads is:

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

A summary of the resulting minimum acceptable wall thickness for the generic, High T_{avg} and the Low T_{avg} conditions is provided in Table 3-23. Table 3-23 also indicates the corresponding structural limit for each case considered, where the structural limit is defined to be

$$\text{Structural Limit} = \frac{(t_{nom} - t_{min})}{t_{nom}} \times 100\%$$

3.1.11 Determination of Repair Limits

The minimum acceptable wall thickness and other recommended practices in Regulatory Guide 1.121 are used to determine a repair limit for the sleeve. The Regulatory Guide was written to provide guidance for the determination of a repair limit for steam generator tubes undergoing localized tube wall loss and can be conservatively applied to sleeves. Tubes with sleeves that are determined to have indications of degradation of the sleeve in excess of the repair 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 also 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. Thus, the final sleeve repair limits are established by subtracting from the structural limits an allowance for eddy current uncertainty and continued growth.

3.1.12 Application of Repair Limits

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

1) [

2)

3)

4)

5)

6)

]a,c,e

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 structural limits for the sleeves are summarized in Table 3-23.

3.1.14 Effect of Tubesheet Rotations on ETS Contact Pressures

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

Loads are imposed on the sleeve as a result of tubesheet rotations under pressure and temperature conditions. A 2-D axisymmetric finite element analysis of a Series 51 tubesheet, channel head, and lower shell has been performed. The model is shown in Figure 3-21. This provided displacements throughout the tubesheet for two pressure and three thermal unit loads. The three temperature loadings consist of applying a uniform thermal expansion to each of the three component members, one at a time, while the other two remain at ambient conditions.

Previous calculations performed with a 3-D finite element model of this region of a Westinghouse Model D-4 steam generator showed that the displacements at the center of the tubesheet when the divider plate is included are 0.76 of the displacements without the effect of the divider plate (Reference 8.12). Although the reduction in the displacement components throughout the tubesheet is a more complex function of the reduction in the vertical displacements at the center due to the divider plate, applying the same 0.76 factor to all of the displacement components is a reasonable approximation since all displacement components will decrease when the maximum displacement decreases. This is also supported by an independent 3-D analysis of the Westinghouse Model E tubesheet, channel head, stub barrel complex. The radial displacements produced by the thermal unit loads are unaffected by the divider plate.

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

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

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

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

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

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

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

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

where SF is a scale factor between zero and one. For the eccentricities typically encountered during tubesheet rotations, SF is usually between 0.50 and 0.60.

This hole expansion includes the effects of tubesheet rotations and deformations caused by the system pressures and temperatures. It does not include local effects produced by interactions between the sleeve, tube, and tubesheet hole. Thick shell equations, from References 8.8 or 8.11 in combination with the hole expansions from above, are used to calculate the contact pressures between the sleeve and tube, and between the tube and tubesheet.

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

<u>Normal Operation</u>

From Reference 8.5, the limiting temperatures and pressures for normal operating conditions are:

Primary Pressure	=	2235 psig
Secondary Pressure	=	679 psig

Primary Fluid Temperature (T_{hot})	=	622.5 °F
Secondary Fluid Temperature	=	502.3 °F

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

Faulted Condition

From Reference 8.5, the temperatures and pressures for the limiting faulted condition are:

Primary Pressure	=	2485 psig
Secondary Pressure	=	0 psig
Primary Fluid Temperature (T_{hot})	=	212 °F
Secondary Fluid Temperature	=	212 °F

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

Summary of Results

The contact pressures between the sleeve and tube, and between the tube and tubesheet are plotted versus radius in Figures 3-22 through 3-25. Results from these figures are summarized in the table below: (Note: For the normal operation {N.Op.} condition, the SG leg which has the lowest contact pressure is listed. For example, for the N.Op., Intact tube case, the minimum contact pressure at the 18.03 inch elevation occurs on the hot leg. For the faulted condition, the contact pressures are the same on the HL and CL for both the intact tube and separated tube cases.)

a,c,e

These contact pressures are for the elevation three inches below the top of the tubesheet, which corresponds to the intended top of the hard roll of the ETS. They are conservative for any lower elevation in the tubesheet. Note that these contact pressures are in addition to the substantial interference fit pressures between the sleeve and tube and tube and tubesheet produced during installation of the sleeves. Note also that, in all but one case, the net effect of the tubesheet rotations, thermal expansions, and pressures is an increase in the contact pressure between the sleeve and tube, thereby enhancing the joint leakage resistance and structural integrity. (Joint strength, based on the resultant sleeve-to-tube interference fit contact pressures, is calculated in Section 4 of this report.)

Table 3-1
Summary of Material Properties
Tube Material
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-4	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)							
S_m	23.30	23.30	23.30	23.30	23.30	23.30	23.30
S_y	35.00	32.70	31.00	29.80	28.80	27.90	27.00
S_u	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-4	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

Strength Properties (ksi)							
S_m	26.60	26.60	26.60	26.60	26.60	26.60	26.60
S_y	40.00	36.80	34.60	33.00	31.80	31.10	30.60
S_u	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-sec^2/in^4 x 1.0E-4	7.32	7.3	7.29	7.27	7.26	7.24	7.22
Thermal Conductivity Btu/sec-in-°F x 1.0E-04	5.49	5.56	5.53	5.46	5.35	5.19	5.02
Specific Heat Btu-in/lb-sec^2-°F	41.9	44.5	46.8	48.8	50.8	52.8	55.1

Strength Properties (ksi)							
S_m	26.70	26.70	26.70	26.70	26.70	26.70	26.70
S_y	50.00	47.50	46.10	45.10	44.50	43.80	43.10
S_u	80.00	80.00	80.00	80.00	80.00	80.00	80.00

Table 3-4

Summary of Material Properties

Channel Head Material
SA-216 Grade WCC

Property	Temperature (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E06	29.50	28.80	28.30	27.70	27.30	26.70	25.50
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	5.53	5.89	6.26	6.61	6.91	7.17	7.41
Density lb-sec^2/in^4 x 1.0E-4	7.32	7.30	7.29	7.27	7.26	7.24	7.22

Table 3-5

Summary of Material Properties

Secondary Shell Material
SA-533 Grade A Class 1

Property	Temperature (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E06	29.20	28.50	28.00	27.40	27.00	26.40	25.30
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	7.06	7.25	7.43	7.58	7.70	7.83	7.94
Density lb-sec^2/in^4 x 1.0E-4	7.32	7.30	7.29	7.27	7.26	7.24	7.22

Table 3-6

Summary of Material Properties
Air

Property	Temperature (°F)						
	70	200	300	400	500	600	700
Density lb-sec^2/in^4 x 1.0E-8	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+1	9.27	9.31	9.38	9.46	9.55	9.66	9.78

Table 3-7

Summary of Material Properties
Water

Property	Temperature (°F)						
	70	200	300	400	500	600	700
Density $lb\text{-}sec^2/in^4 \times 1.0E\text{-}5$	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 $Btu\text{-}in/lb\text{-}sec^2\text{-}°F \times 1.0E+2$	3.82	3.88	3.96	4.12	4.37	5.26	8.51

Table 3-8

Criteria for Primary Stress Intensity Evaluation

Alloy 690 Sleeve and Alloy 600 Tube

Condition	Criteria	Limit (ksi)	
		Sleeve	Tube
Design	$P_m \leq S_m$	26.60	23.30
	$P_l + P_b \leq 1.5\ S_m$	39.90	34.95
Faulted	$P_m \leq 0.7\ S_u$	56.00	56.00
	$P_l + P_b \leq 1.05\ S_u$	84.00	84.00
Test	$P_m \leq 0.9\ S_y$	36.00	31.50
	$P_l + P_b \leq 1.35\ S_y$	54.00	47.25
Emergency	$P_m \leq S_y$	40.00	35.00
	$P_l + P_b \leq 1.5\ S_y$	60.00	52.50
All Conditions	$P_1 + P_2 + P_3 \leq 4.0\ S_m$	106.4	93.20

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

Table 3-9

Criteria for Primary Plus Secondary Stress Intensity Evaluation
Alloy 690 Sleeve and Alloy 600 Tube

Condition	Criteria	Limit (ksi)	
		Sleeve	Tube
Normal, Upset, and Test	$P_l + P_b + Q \leq 3\ S_m$*	79.80	69.90
Normal, Upset, and Test	Cumulative Fatigue Usage	1.0	1.0

* - Range of Primary + Secondary Stress

Table 3-10

Criteria for Primary Stress Intensity Evaluation

Alloy 690 Weld

Condition	Criteria	Limit (ksi)
Design	$P_m \leq 0.6\ S_m$	15.96
Upset	$P_m \leq 1.1\ (0.6\ S_m)$	17.56
Faulted	$P_m \leq 0.6\ (0.7\ S_u)$	33.60
Test	$P_m \leq 0.6\ (0.9\ S_y)$	16.79

Table 3-11

Comparison of Full Power Operating Parameters
Generic Series 51 Versus Beaver Valley Plant Specific

a,c

Table 3-12

Summary of Transient Parameters
Generic LWS Analysis

a,c

Table 3-13

Summary of Transient Parameters
DLW / DMW Uprating Conditions
High T_{avg} – 22% Plugging

a,c

Table 3-14

Summary of Transient Parameters
DLW / DMW Uprating Conditions
Low T_{avg} – 22% Plugging

a,c

Table 3-15

Umbrella Pressure Loads for
Design, Faulted, and Test Conditions

a,c,e

Table 3-16

Summary of Maximum Primary Stress Intensity
Full Length Tubesheet Laser Welded Sleeve
Tube Intact

a,c

Table 3-17

Maximum Range of Stress Intensity and Fatigue
Full Length Tubesheet Laser Welded Sleeve
Tube Severed and Dented

a,c

Table 3-18

Summary of Calculated Stress Margins
[ ]a,c inch Average Laser Weld Size

a,c

Table 3-19

**Calculated Shear Forces (lbf)
on 7/8 LWS Welds Due to
Indicated Unit Load Cases**

a,c

Table 3-20

Summary of Weld Forces and Stresses

a, c

- Continued –

Table 3-20 (Continued)

Summary of Weld Forces and Stresses

a, c

Table 3-21

Summary of Fatigue Calculations
Tube Support Plate Sleeve

Tube Intact: Tube Free at Tube Support Plate

a,c

Table 3-22

Summary of Fatigue Loading Conditions

a,c

Table 3-23

Summary of Minimum Acceptable Wall Thickness

a,c

a,c

Figure 3-1

Schematic of Full Length Tubesheet Sleeve Configuration

a,c

[ ]

Figure 3-2
Channel Head / Shell / Tubesheet Model

a,c

Figure 3-3
Thermal Hydraulic Boundary Conditions
Tubesheet Sleeve Analysis

a,c

Figure 3-4
Channel Head / Shell / Tubesheet Model
Primary Pressure Boundary Conditions

a,c

Figure 3-5

Channel Head / Shell / Tubesheet Model

Distorted Geometry Primary Pressure Loading

a,c

Figure 3-6

Channel Head / Shell / Tubesheet Model

Channel Head Thermal Boundary Conditions

a,c

Figure 3-7

Channel Head / Shell / Tubesheet Model

Distorted Geometry Channel Head Thermal Loading

a,c

Figure 3-8

Boundary Conditions for Unit Primary Pressure

Intact Tube: $P_{PRI} > P_{SEC}$

a,c

Figure 3-9

Boundary Conditions for Unit Primary Pressure

Intact Tube: $P_{PRI} < P_{SEC}$

a,c

[ ]

Figure 3-10
Boundary Conditions for Unit Primary Pressure
Severed Tube: $P_{PRI} > P_{SEC}$

a,c

Figure 3-11
Boundary Conditions for Unit Primary Pressure
Severed Tube: $P_{PRI} < P_{SEC}$

a,c

Figure 3-12
Boundary Conditions for Unit Secondary Pressure
Intact Tube: $P_{PRI} > P_{SEC}$

a,c

Figure 3-13
Boundary Conditions for Unit Secondary Pressure
Intact Tube: $P_{PRI} < P_{SEC}$

a,c

Figure 3-14

Boundary Conditions for Unit Secondary Pressure

Severed Tube: $P_{PRI} > P_{SEC}$

a,c

Figure 3-15
Boundary Conditions for Unit Secondary Pressure
Severed Tube: $P_{PRI} < P_{SEC}$

a,c

[ ]

Figure 3-16
ASN Location - Laser Weld Joint

a,c

Figure 3-17
Schematic of Sleeve, Tube and Weld and Free Body Diagram of Severed Tube Showing Shear Force on Laser Weld

a,c

[ ]

Figure 3-18
Schematic of Structural Models
FLTS, ETS, and TSS Laser Welded Sleeve Types

a,c,e

Figure 3-19
K_t / K_f as a Function of Notch Radius

a,c,e

Figure 3-20
q * K_t as a Function of Notch Radius

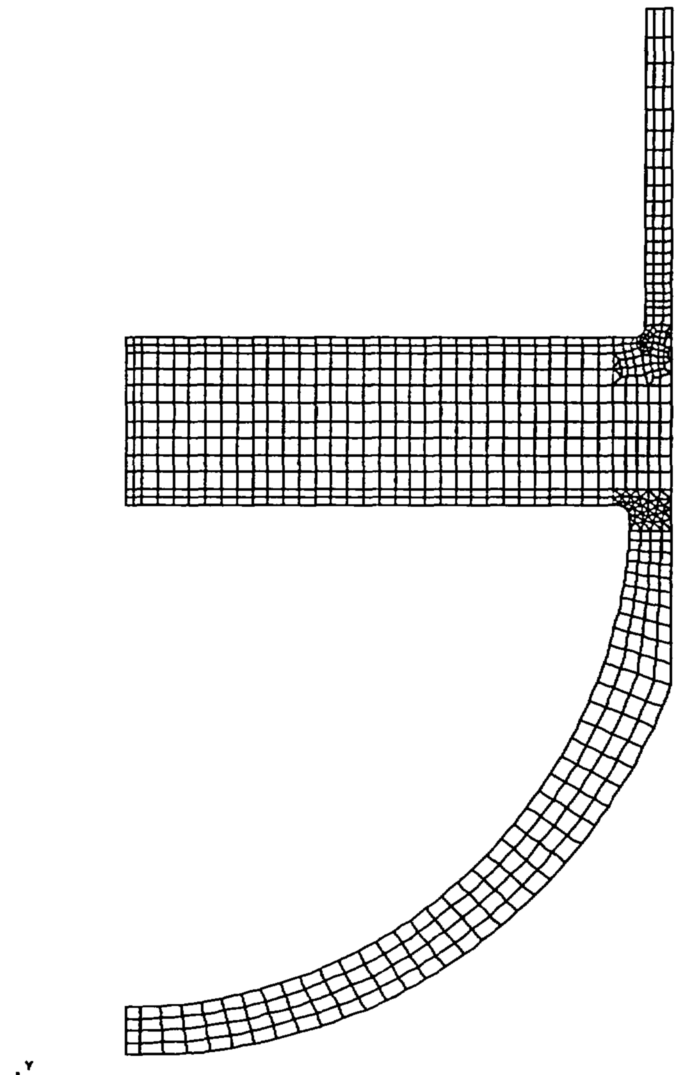

Figure 3-21
Finite Element Model of Channel Head/Tubesheet/Stub Barrel of Series 51 S/G

a,c,e

Figure 3-22
Contact Pressures for Normal Conditions with an Intact Tube

a,c,e

[ ]

Figure 3-23

Contact Pressures for Normal Conditions with a Separated Tube

a,c,e

Figure 3-24

Contact Pressures for Faulted Conditions with an Intact Tube

a,c,e

Figure 3-25

Contact Pressures for Faulted Conditions with a Separated Tube

3.2 THERMAL HYDRAULIC ANALYSIS

3.2.1 Safety Analyses and Design Transients

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

Each NSSS is analyzed to demonstrate acceptable operation to a level of plugging denoted as the plugging limit. When the steam generators include both plugs and sleeves, the total effect must be shown to be within the plugging limit. To do this, an equivalency relationship between plugged and sleeved tubes needs to be established. The following section derives a hydraulic equivalency number. This number represents the number of sleeved tubes which are hydraulically equivalent to a single plugged tube. It is a function of various parameters including 1) the number and location of sleeves in a tube, 2) the steam generator model, and 3) the operating conditions. Conservative bounding values have been determined so that a single number applies to a given steam generator model and tube sleeve configuration. The results presented in this section are applicable to Model 51 steam generators and therefore to the steam generators in Beaver Valley Units 1 & 2.

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

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 in a single tube (tubesheet and/or tube support plate sleeves) will lead to a larger flow reduction in the 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" (N_{hyd}) 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 flow resistance of sleeved and unsleeved tubes operating in parallel. This difference in resistance is then used to compute the difference in flow between sleeved (W_{slv}) and unsleeved (W_{unslv}) tubes. The hydraulic equivalency number is then simply:

a,c,e

$$N_{hyd} = \left[\qquad\qquad\qquad \right]$$

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 hydraulic equivalency number calculations generated conservative results which envelope the results for all plants which have Series 51 steam generators. As such, these results provide conservative values for all sleeving configurations which may be applied at Beaver Valley.

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 insure 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, the upper joint and 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 sleeving program.

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 structural evaluation and modifications to the tooling.) Nonetheless, the hydraulic equivalency and flow reduction calculations were made for support plate sleeves at all elevations.

Table 3-24 presents a summary of the hydraulic equivalency numbers for the limiting combinations of tubesheet and support plate sleeves in 51 Series steam generators. For example in Table 3-24, the hydraulic equivalency number for a configuration with no tubesheet sleeve and four support plate sleeves is 8.7 (Set #4) and occurs when the sleeves are positioned at the top four support plates in the cold leg (#4, #5, #6, and #7). This means that about nine 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 5.2 for a configuration with four support plate sleeves (Set #21 for support plate locations #6 and #7 in both legs).

The tubesheet sleeves specified in Table 3-24 refer to full length tubesheet sleeves (FLTSs). However, the N_{hyd} and percent flow reduction results conservatively apply to 36 inch-long elevated tubesheet sleeves (ETSs). Similarly, the Nhyd and percent flow reduction results for 12 inch tube support plate sleeves (TSSs) conservatively apply to 12 inch ETSs. Elevated tubesheet sleeves of lengths between 12 and 36 inches may be conservatively considered as 36 inch FLTSs. Similar to the discussion elsewhere in this section for total plugging equivalency near the SG plugging limit, in the event that plant-specific equivalencies for ETSs are required, less conservative calculations may be made to justify increased sleeving.

The information presented in Table 3-24 has also been used to construct Figure 3-26. This figure graphically illustrates the enveloping hydraulic equivalency numbers for 51 Series steam generators based on normal operating conditions.

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 plugs by the following formula:

$$P_e = P_a + \sum_i S_i / N_{hyd,i} + P_c$$

where:

P_e	=	Equivalent number of plugged tubes
P_a	=	Number of tubes actually plugged
S_i	=	Number of active tubes with a sleeve combination
$N_{hyd,i}$	=	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 a 51 Series steam generator are plugged.

Using the conservatively high primary flow rate (110,000 gpm), for a 0% plugging condition, the velocity through an unplugged tube is approximately 28 ft/sec. With 20% of the tubes plugged, the fluid velocity through an unplugged and unsleeved tube is about 34 ft/sec, and for a tube with a single tube support plate sleeve, the local velocity in the sleeve region is computed to be 45 ft/sec. 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 (for example, Wp = 90,000 gpm, Th = 610 °F, and Tc = 545 °F) the estimated velocities are significantly lower (21, 26, and 35 ft/sec, respectively). 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.

Table 3-24

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

a,c,e

Figure 3-26
Hydraulic Equivalency Number for
Series 51 Steam Generators

a,b,e

4.0 MECHANICAL TESTS

Mechanical tests are used to provide additional information related to performance of the lower joints of tubesheet sleeves. Unit test cells are used for mechanical testing. A unit test cell or specimen is one which is a single sleeve joint and involves sufficient tubesheet simulant, tube and sleeve length to bound transition effects. 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 tubesheet.

Mechanical testing was initially applied to sleeves with mechanical interference fit joints because it was not possible to describe analytically the interaction between the sleeve and tube.

4.1 MECHANICAL TEST CONDITIONS - FLTS & ETS SLEEVE-TO-TUBE MECHANICAL JOINTS

Mechanical testing has been applied to the mechanical interference fit, i.e., lower, joints of the FLTS and ETS confirm analyses that evaluated the interaction between the sleeve and tube. Mechanical testing is primarily concerned with leak resistance and joint strength, including fatigue resistance.

4.1.1 FLTS Lower Joint

A consistent characteristic observed in the testing of the FLTS MIF joints is that leakage, when observed, is generally higher at room temperature (RT) and normal operation, steamline break (SLB) and greater-than-SLB pressure differential conditions than at elevated temperature and other applied-load conditions. This is due to the thermal growth mismatch (TGM) between the Alloy 600 tube and Alloy 690 sleeve materials and the carbon steel material of the tubesheet simulant. Thermal growth mismatch increases the interfacial mechanical interference fit between the sleeve and tube, reducing leakage. The TGM effect is the same in the laboratory as it is in the plant, providing a direct projection of the laboratory results to the plant. It is also due to the greater pressure tightening effect of the higher primary-to-secondary side differential pressure of the SLB and greater-than-SLB pressure differential conditions. This result obviates essentially all of the combined or separate elevated temperature leak resistance and applied-load types of tests and permits qualification of additional MIF joints such as the ETS lower joint on the basis of RT leak resistance tests and the previous testing. (For redundancy, sleeve pullout resistance testing and testing to determine the sleeve-to-tube contact pressure are performed for ETS MIF joints.) During testing, specimens are subjected to cyclic thermal and mechanical loads, simulating plant transients. [

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

4.1.2 ETS Lower Joint

Elevated tubesheet sleeve MIF lower joints have been developed for all applicable tube sizes for Westinghouse steam generators, including the 7/8 inch tube SGs of BV and for several models of a competitor SG.

The ETS is illustrated in Figure 2-2. It is applicable to steam generators in which the tubes were installed in the tubesheet by a full-depth expansion. The ETS upper joint is identical to other free span joints, i.e., the upper joint of the FLTS and to both joints of the TSS. The ETS lower joint is fabricated by the same types of processes which are used to fabricate the FLTS lower joints, i.e., hydraulic expansion and roll expansion. The ETS lower joint is qualified for both the explosive expanded tube joints of Unit 1 and the roll expanded tube joints of Unit 2.

The ETS is similar to the FLTS in that it is designed to address tube degradation in the tube free span and in the vicinity of the tubesheet top. However, unlike the FLTS, it is limited to these applications and is not designed to address degradation in the remainder of the tube within the tubesheet.

The ETS is designed such that the elevation of the upper end of the shortest ETS, 12.00 inches in length, is approximately 2.50 inches below the elevation of the upper end of the 30 inch long FLTS. The difference between the two designs is that the sleeve-to-tube lower joint of the ETS is elevated relative to the lower joint of the FLTS and the bottom of the ETS is approximately 15 inches above the tube end. Although the use of the same type of MIF joint at the ETS lower end as used at the FLTS lower end enables the same types of qualification tests and analytical bases, the ETS joint requires a higher roll torque per unit of effective axial length than the FLTS joint.

As in the case of the FLTS free span joint the ETS inboard-most weld, i.e., either the weld at the initial elevation or the reweld at the specified lower elevation, must be separated from the extreme extent of the degradation by a minimum of [

]^{a,c,e} (A smaller separation distance may be used if it is documented.)

The separation distance for degradation in the vicinity of, and <u>above</u>, the ETS MIF lower joint roll for both Units 1 and 2 is determined the same way as it is determined for the FLTS MIF lower joint. As discussed for the FLTS, the ECT process used to determine the extreme extent of degradation will be appropriate for the type of degradation expected and it will meet the required uncertainty in elevation of the degradation. The extent of uncertainty in elevation of the ECT, whether reckoned down from the tubesheet top, or up from the tubesheet bottom or tube end, will have sufficient margin in elevation to ensure that the tube portion at the roll expansion of the MIF joint will be adequately assessed prior to initiation of the sleeving process.

Separation distance does not apply below the elevation of the ETS MIF lower joint for Unit 1; that portion of the tube must have no detectable degradation. However, the separation distance for degradation below the ETS MIF lower joint for Unit 2 is determined similarly to that for degradation above the ETS MIF lower joints. The lowermost extent of the effective axial length (EAL) of the roll expansion portion of Unit 2 ETS MIF joint, based on the appropriate sleeve, tube and tubesheet component dimensions and sleeve and tube installation tolerances, must also be separated from the uppermost extent of degradation below the joint by the ECTU. The separation distance between degradation and the roll expansion portion of the MIF joint is based on avoiding locating the roll expansion portion of the joint in a portion of degraded tube; an attenuation length is unnecessary there. The inside diameter of both ends of the sleeve are tapered to reduce the end effects of the sleeve on eddy current inspection.

4.2 ACCEPTANCE CRITERIA

Generic analyses have been performed to determine the allowable leakage during normal operation for sleeve application. The primary-to-secondary side leak rate criteria that have been established are based on BV Technical Specifications. The criteria are based on the assumption that each tube containing a sleeve with a within-tubesheet mechanical joint is degraded throughwall in the tube portion spanned by the sleeve; this is a conservative assumption. In actuality, based on tens of thousands of similar within-tubesheet, Westinghouse, mechanical joints, leakage has been negligible or essentially zero. The laser weld joint is hermetic and exhibits no leakage.

Table 4-2 shows the permissible leak rate for normal operation and for postulated accident condition for BV steam generators. These criteria can be compared to the qualification leak test results to provide verification that the sleeve MIF joints exhibit essentially no leakage under what would be considered normal operating conditions and only slight leakage under the umbrella test conditions used. Leak rate measurement in laboratory tests is based on counting the number of drops leaking during a 10-20 minute period. Conversion to volumetric measurement is based on assuming 19.8 drops per milliliter. (There are approximately 75,000 drops in one gallon.)

For tensile and compressive testing of the MIF joints, loads exceeding [

]a,c,e

lbs.

4.3 FLTS LOWER JOINT DEVELOPMENT

The full length tubesheet sleeve MIF lower joint consists of a hydraulic expansion and a roll expansion. As discussed earlier, the test 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.

Two FLTS lower joint processes have been developed, the single-roll expansion-pass process and the two-roll expansion process. The latter process was developed to provide additional integrity, for instance, in cases where the sleeve is installed in a tube which had been deplugged by a TIG relaxation process.

4.3.1 Single-Roll Pass Process

4.3.1.1 Results of Testing

The test results for the single-roll pass, Series 51 MIF joint specimens, applicable to the FLTS lower joints for BV1&2, are presented in Table 4-3. The specimens [

]a,c,e

For the tests the following joint performance was noted:

Specimen MS-2: Initial leak rates at all pressures and at normal operating pressure following thermal cycling were [

]a,c,e

Specimen MS-3: [

]a,c,e

Specimen MS-7: [

]a,c,e

4.3.1.2 Description of Additional Test Programs - Lower Joint with Exceptional Conditions

Additional test programs were performed to verify acceptable performance of the sleeve lower 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 exceptional tube conditions and changes to the sleeving process parameters tested in the first program are shown in Tables 4-4 and 4-5.

4.3.1.3 Conclusion – Single-Roll Pass Process Tests

The test conditions were conservative to the plant conditions in the same way that the FLTS two-roll pass process joint conditions were conservative to the plant conditions, as shown in Section 4.3.2 below. This joint meets the per-sleeve leakage criterion listed in Table 4-2 and the stringent criterion of 0.5 dpm per sleeve in the qualification test procedure. The leakage for the sample joints was zero at the elevated temperature condition and negligible at the room temperature condition. Due to the leakage in laboratory testing being essentially negligible and projected to be negligible at plant conditions, the Accident Induced Leakage Limit (AILL), related to the alternate repair criterion for degradation at the support plates, is not affected. All of the AILL leakage limit can continue to be allocated to the support plate ARC. (Refer to Section 4.3.2 for additional explanation of the AILL conditions.) The pullout resistance of the joint far surpasses the (conservative) required $3\Delta P_{N.Op.}$ endcap load of 3048 lbs. This lower joint is insensitive to the sequence of "roll-first" or "weld-first." Thousands of these joints have been in installed and have provided satisfactory service and are expected to continue to provide satisfactory service at the BV uprated conditions.

4.3.2 Two-Roll Pass Lower Joint Development

This section summarizes the qualification of the two-roll pass lower joint for full length tubesheet sleeves for BV Units 1 and 2.

4.3.2.1 Joint Design and Development

Development of the two-roll pass lower joint for this FLTS was based on the "roll first" sleeve installation sequence. In this sequence, the sleeve-to-tube weld is performed after the lower joint roll expansion. However, it was determined that the process was equally effective in the "roll-last" sequence. In the two-roll-pass, a.k.a. two-pass, process selected for this design, the lower elevation pass is performed first, followed by the upper pass.

The qualification involved three types of tests for the lower joint:

1) primary-to-secondary side leak resistance testing
2) secondary-to-primary side "onset of significant leakage" (OSL) testing, and
3) sleeve pullout testing.

The purpose of the primary-to-secondary leak resistance testing is to determine, for potential perforations in the section of the tube (in any sleeved tube) spanned by the sleeve, the leakage for 'normal operation, for feedline break/steamline break (FLB/SLB) and for a higher pressure which approximates the SG initial primary side hydrostatic pressure test. [

]^{a,c,e} The pullout resistance as determined by OSL testing can be compared with the direct pullout testing. Sleeve pullout testing is a direct determination of the resistance to pullout of the sleeve joint. The resistance to pullout determined in the laboratory is conservative compared to the resistance expected to be realized in the plant.

For the sake of design standardization, it is desirable that the lower joints of the FLTSs for BV Units 1 and 2 be of the same axial length. On this premise, the effective axial length of the joints was determined by the roll expanded axial portion of tube available in the vicinity of the tubemouth of Unit 1; Unit 2 is full-depth roll expanded and has no such limit in the vicinity of the tubemouth.

4.3.2.2 Primary Side Testing of FLTS

Rolled Joint Geometry and Torque

In this task, the appropriate values of the two-pass sleeve-to-tube joint, MIF roll expansion parameters were qualified. This involved the roll expansion effective axial length, number of roll steps (two), the effective length(s) of the individual roll step(s), effective length of individual rolls ("pins") of the roll expander, number of pins in the tool, roll expander model number and rolling motor approximate RPM. The required resistance to pullout of the LWS two-pass lower joint is the "endcap" load exerted by three times the primary-to-secondary side pressure differential at normal operation times the expanded tube maximum "inside" area. This is referred to as the "three delta P" or 3ΔP force.

A roll expansion torque of [

]^{a,c,e}

Primary-to-Secondary Side Leakage Testing and Results

Ten primary-to-secondary side qualification, conforming-condition, leak tests were performed using a total of nine test samples. (Note: Because the primary side leakage testing tends to be non-destructive of the samples, one of the test samples was tested, then rerolled at a higher torque, and leak tested a second time.) All samples exhibited small amounts of leakage. As discussed above, five nonconforming condition samples were made and leak tested. The results were included in the averages of the conforming test results to show the relative insensitivity of the leakage resistance to values of the joint variables slightly outside of the selected range.

In the plant, the most stringent location in the tubesheet, i.e., at the bundle periphery, where the tubesheet upward bending causes [

]^{a,c,e} This bounding condition is reproduced in the laboratory leakage testing. For the plant, all of the joints in the non-peripheral locations benefit from tubesheet upward bending due to the tubesheet hole contraction, i.e., "tightening" effect. (The terms "benefit" and "beneficial" are used in the context of reducing leakage.) This is conservatively neglected in the laboratory.

In this room temperature (RT) testing, the thermal growth mismatch contribution to increasing contact pressure in going from the as-installed (RT) condition to normal operation (N.Op.) elevated temperature, was conservatively also absent. However, the differential pressure tightening, an effect beneficial to reducing leakage, was present in the laboratory testing. The BV FLTS Verification Test results are shown in Table 4-6.

Leak test results at the normal operation (N.Op.) condition should be compared with the leak rate criteria value of [

]^{a,c,e}

The average leakage under SLB/FLB conditions was determined to be [

]^{a,c,e}

[ ]^{a,c,e} can be allocated to the support plate ARC.

4.3.2.3 Direct Pullout Testing Criteria and Results

Pullout test results should be compared with the criteria of the larger of three times the maximum endcap load during normal operation, (3ΔP) or 1.43 times the endcap load during FLB/SLB. The larger of these two loads is usually the N.Op. case and for this summary, this load will be used for comparison with the test results. For BV, the maximum N.Op./Normal/Upset Transient, primary-to-secondary side pressure differential for the "uprate" condition is [

]^{a,c,e}

Two pullout test samples were fabricated at the selected process, i.e., torque values of [

]^{a,c,e}

4.3.2.4 Onset of Significant Leakage (Contact Pressure) Testing and Results

The OSL testing was performed on sleeve/tube/tubesheet unit cells (collars) at ambient pressure and room temperature. [

]^{a,c,e} Refer to Tables 4-6 and 4-.8.

Secondary side pressure, a.k.a. [

]^{a,c,e}

The pullout resistance as determined by the OSL testing can be compared with that of the direct pullout tests. The CPs measured in the OSL tests provide an average pullout resistance of approximately [

]^{a,c,e}

4.3.2.5 Conclusion – Two-Roll Pass Lower Joint

A torque of [

]^{a,c,e}

The test results show that this joint meets all design criteria. It is to be installed with the appropriate-length-cage roll expander of the same model number, pin length, lubrication conditions and approximate rpm, used in the qualification.

4.4 ETS LOWER JOINT DEVELOPMENT

The Unit 1 ETS lower joint was developed separately from the Unit 2 lower joint. There were two reasons for this: (1) The Unit 1 joint required [

]^{a,c,e} Additional development work was performed for the Unit 2 joint to permit degradation in the host tube below the elevation of the lower joint. For these reasons, the ETS lower joints for the two units are discussed separately.

4.4.1 Beaver Valley Unit 1 ETS Lower Joint Design and Development

This section summarizes the qualification of the lower joint for sleeves elevated in the tubesheet (ETSs) for BV1. The bottom of the ETS is nominally [

]^{a,c,e}

The qualification involved three types of tests for the lower joint:

1) Primary-to-secondary side leakage resistance testing of the sleeve-to-tube (S/T) interface
2) Secondary-to-primary side "onset of significant leakage" (OSL) testing of the S/T interface
3) Sleeve pullout testing

The purpose of the primary-to-secondary leak resistance testing is to determine, for potential perforations in the section of the tube (in all of the sleeved tubes) spanned by the sleeve, the leakage for normal operation, for feedline break/steamline break (FLB/SLB) and for a higher pressure which approximates the SG initial primary side hydrostatic pressure test. The secondary-to-primary OSL test is performed to determine the sleeve-to-tube interference fit radial contact pressure (CP) and is used to determine pullout resistance. The pullout resistance as determined by OSL testing can be compared with the direct pullout testing. Sleeve pullout testing is a direct determination of the resistance to pullout of the sleeve. The resistance to pullout determined in the laboratory direct pullout testing is conservative compared to the resistance calculated for the plant.

4.4.1.1 Primary Side Testing of ETS and Results

Rolled Joint Geometry and Torque

In this program, the appropriate values of the two-pass sleeve-to-tube joint, MIF roll expansion parameters were qualified. This involved the roll expansion effective axial length, number of roll steps (two), the effective length(s) of the individual roll step(s), effective length of individual rolls ("pins") of the roll expander, and number of pins in the tool.

The required resistance to pullout of the LWS two-pass lower joint is the "endcap" load exerted by [

]^{a,c,e}

Primary-to-Secondary Side Leakage Testing and Results

Twenty-three primary-to-secondary side qualification, conforming-condition, leak tests were performed using a total of 19 test samples. Refer to Table 4-9. (Because the primary side testing tends to be non-destructive of the samples, four of the test samples was leak tested, then rerolled at a higher torque, and leak tested a second time.) All samples exhibited small amounts of leakage. Leak test results at the normal operation (N.Op.) condition should be compared with the leak rate criteria value of [

]a,c,e

Because Beaver Valley Unit 1 has alternate repair criteria (ARC) for tube degradation at the support plates, the combination of ARC-permissible leakage and potential leakage from sleeve nonwelded joints in a given steam generator at the SLB/FLB condition are considered. The total allowable primary-to-secondary accident-induced leakage limit (AILL) is several gpm and was discussed earlier in this report. Based on the test results of this MIF joint, the average leakage under SLB/FLB conditions was determined to be [

]a,c,e

In the plant the largest reduction in contact pressure between the sleeve and tube in the ETS lower joint occurs at a radius of approximately [ ]a,c,e from the tubesheet vertical axis. This applies to both the N.Op. and FLB/SLB conditions. This bounding condition is essentially reproduced in the laboratory leakage testing. For the plant, all of the ETS lower joints in the non-peripheral locations of the bundle are negatively affected by tubesheet upward bending due to the tubesheet hole dilation above the "midplane", i.e., neutral bending surface of the tubesheet. This is referred to as a "loosening" effect; it is also referred to as a detrimental effect, in terms of leakage. (The terms "detrimental" and "beneficial" are used in the context of reducing leakage or pullout resistance.)

In this room temperature (RT) laboratory testing, the thermal growth mismatch contribution to increasing contact pressure in going from the as-installed (RT) condition to normal operation (N.Op.) elevated temperature, was conservatively also absent. However, the differential pressure tightening, an effect beneficial to reducing leakage, was present in the laboratory testing. Reference to Table 4-10 shows that the beneficial thermal growth mismatch effect offsets about 65 percent of the detrimental tubesheet bow loosening effect; testing may be performed without these effects. The leakage and CP results can be projected to the plant conditions, based on the laboratory results and conditions.

Reference to Table 4-10 shows that the test joint was approximately [

]a,c,e

4.4.1.2 Secondary Side Testing and Results

Secondary side, a.k.a. OSL, pressure testing, or contact pressure testing, does not prototype any operating condition, but is performed to determine, conservatively, the interfacial radial contact pressure between the rolled sleeve and the tube. These [

]a,c,e

The pullout resistance as determined by the OSL testing can be compared with that of the direct pullout tests. The CPs measured in the [

]a,c,e

4.4.1.3 Pullout Testing and Results

Direct pullout test results may be compared with the same criteria as listed for the FLTS joint. The testing was performed on sleeve/tube/tubesheet unit cells (collars) at ambient pressure and room temperature. [

]a,c,e

[

]a,c,e It was unnecessary to compare the direct pullout test results with the criteria at the SLB/FLB condition because in all previous ETS lower joint developments the N.Op./Normal/Upset Transient conditions were limiting and the same result was assumed in this case.

4.4.1.4 Conclusion – Beaver Valley Unit 1 ETS Lower Joint

The test results show that the "2/2.65 inch" joint identified above meets all design criteria. It is to be installed with the appropriate-length-cage roll expander (to attain the elevation of the sleeve bottom to be nominally [

]a,c,e (Note: If this process were used on BV Unit 2, it would develop a slightly greater resistance to leakage and pullout than developed for BV1.)

4.4.2 Beaver Valley Unit 2 ETS Lower Joint Design and Development

This section summarizes the qualification of the lower joint for ETSs installed in tubes which are undegraded in the joint (roll expansion) area in BV2. However, it addresses the case of the tube being [

]a,c,e Prototypical materials, sample designs and installation processes were used.

4.4.2.1 Joint Design and Development

Development of this joint was similar to the Unit 1 MIF joint; it is based on the "roll last" sleeve installation sequence. In the two-roll-pass process selected for this design, the lower elevation pass is performed first, followed by the upper pass. The joint is located at the same elevation as the Unit 1 joint, i.e., extending from approximately [ ]a,c,e below the upper surface of the tubesheet.

The qualification involved five types of tests:

1. Sleeve-to-tube primary-to-secondary side leakage testing
2. Tube-to-tubesheet primary-to-secondary side leakage testing
3. Sleeve-to-tube secondary-to-primary side "onset of significant leakage" (OSL) testing
4. Tube-to-tubesheet secondary-to-primary side "onset of significant leakage" (OSL) testing
5. Sleeve pullout testing

The objective of test types 1 and 2 was to establish the sleeve baseline rolling torque and the range of the torque needed to obtain a satisfactory MIF joint. The test criteria involved both primary-to-secondary and secondary-to-primary side leakage limits. This configuration was also used for sleeve pullout testing. The leakage resistance in the laboratory, at the sleeve-to-tube (S/T) and tube-to-tubesheet (T/TS) interfaces, is appropriately related to the plant. The S/T primary-to-secondary leakage test criteria were the same as determined for Unit 1. In the case of Unit 2, leakage could emanate [

]a,c,e

The objective of test types 3 and 4 was to determine the CP between sleeve and tube and between the tube and tubesheet within the roll expansion of the MIF joint for Unit 2. All of the types of test methods and related analytical evaluations used for the Unit 1 test were used in this test. Fluid pressure at the sleeve-to-tube interface (S/T) and separately at the tube-to-tubesheet (T/TS) interface was used to determine the CP at the onset of significant leakage (OSL) at the respective interface. The leakage resistance in the laboratory, at the S/T and T/TS interfaces was appropriately related to the plant.

Test type 5 involved sleeve pullout testing. The configuration used was the same as used in the first four types of tests and in the Unit 1 test.

4.4.2.2 Primary Side Testing of S/T and T/TS Interfaces of ETS

Rolled Joint Geometry and Torque

In this part of the program, the appropriate values of the MIF roll expansion parameters were identified in a process development test and then qualified in the Qualification Test. (The values of the hydraulic expansion parameters were the same as developed for the Unit 1 process; hydraulic expansion is essentially insensitive to the type of tube expansion process used in the factory and to MIF joint performance.) This involved the roll expansion effective axial length, number of roll steps (two), the effective length(s) of the individual roll steps(s), effective length of individual rolls ("pins") of the roll expander, number of pins in the tool, roll expander stalling torque and roller approximate RPM.

A roll expansion torque of [

]a,c,e

Primary-to-Secondary Side Leakage Testing, Contact Pressure Testing and Results

Test Type 1 – Results of Tests - Leakage

Six test samples were fabricated for Test Type 1. These included three torque values and two simulated tubesheet hole diameters. The primary side of the joint was pressurized and leakage was measured from the S/T interface.

At the N.Op., i.e., [

]^{a,c,e} inch-lbs. (Note: The effect of the uprate on the main parameter determining reduction in CP and therefore, leakage increase, was maximum primary-to-secondary side differential pressure at the N.Op. /Normal/Upset Transient condition. This increased differential pressure was small and the leakage projected for the uprate condition was unchanged due to roundoff effects.)

Test Types 1 and 2 - Results of Tests - Leakage

Four samples involving both the S/T and T/TS interfaces were tested. Refer to Table 4-13. The primary side of the joint was pressurized and leakage was measured simultaneously from the S/T and T/TS interfaces. At the [

]^{a,c,e}

Additionally, six samples were tested for the S/T interface. At the [

]^{a,c,e} (Table 4-14).

Laboratory leak rates (unadjusted for plant conditions) trended [

]^{a,c,e}

Test Types 3 and 4 - Contact Pressure Results

Contact pressure test results are shown in Table 4-17. As-installed, i.e., in both the plant and laboratory, sleeve-to-tube interface contact pressures ranged between [

]^{a,c,e}

Test Type 5 - Sleeve Direct Pullout Testing Results

Two pullout tests were performed. Refer to Table 4-18. In the first test, a sleeve pullout test sample was fabricated with [

]^{a,c,e}

In the second test, a sleeve pullout test sample was fabricated with undegraded sleeve-to-tube interfaces at a torque of [

]^{a,c,e}

4.4.2.3 Conclusion – Beaver Valley Unit 2 ETS Lower Joint

The test results show that the [

]^{a,c,e}

a, c, e

Figure 4-1

Full Length Tubesheet Sleeve Lower Joint Test Specimen

a,c,e

Figure 4-2

Elevated Tubesheet Sleeve Lower Joint Test Specimens

Table 4-1

Mechanical Test Program Summary

Full Length Tubesheet Sleeve - Mechanical Interference Fit Joint

(Single Roll Pass)

a,c,e

Table 4-2
Maximum Allowable Leak Rates for
Beaver Valley Steam Generators

a,c,e

*Based on installation of 667 tubesheet sleeves with non-welded lower joints in one steam generator (BV is a three loop plant - 2,000 sleeves in the plant assumed in example)

Table 4-3(a)

Verification Test Results for As-Rolled Lower Joints - 7/8 Inch Full Length Tubesheet Sleeves

Alloy 690 Sleeves – Single Roll Pass Process

a, c, e

Table 4-3(b)

Verification Test Results for As-Rolled Lower Joints - 7/8 Inch Full Length Tubesheet Sleeves

Alloy 690 – Single Roll Pass Process

a,c,e

Table 4-3(c)
Verification Test Results for As-Rolled Lower Joints - 7/8 Inch Full Length Tubesheet Sleeves
Alloy 690 – Single Roll Pass Process

a,c,e

Table 4-4

Verification Test Results for 7/8 Inch FLTS Lower Joints with Exceptional Conditions for Tube and Sleeve – Single Roll Pass Process

a, b, 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 Verification Test Results for 7/8 Inch FLTS Lower Joints with Exceptional Conditions for Tube and Sleeve– Single Roll Pass Process

a,c,e

TABLE 4-6 Page 1 of 2

Verification Test Results - Mechanical Interference Fit Lower Joint, FLTS
Alloy 690 Sleeve for 7/8 Inch Tube – Two-Roll Pass Process

a,c,e

TABLE 4-6 Page 2 of 2
Verification Test Results - Mechanical Interference Fit Lower Joint, Full Length Tubesheet Sleeve
Alloy 690 Sleeve for 7/8 Inch Tube - Two-Roll Pass Process

a,c,e

Table 4-7

COMPARISON OF LABORATORY LEAK TEST CONFIGURATION WITH PLANT CONFIGURATION FOR *NORMAL OPERATION

FLTS - Two-Roll Pass Process - Beaver Valley Units 1 And 2

a,c,e

Table 4-8

Comparison of S/T FLTS Laboratory OSL & Direct Pullout Test Configuration With Plant Configuration for *Normal Operation Two-Roll Pass Process

a,c,e

Table 4-9
Verification Test Results - Mechanical Interference Fit Lower Joint, Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 7/8 Inch Tube – Unit 1

a,c,e

Table 4-9
Verification Test Results - Mechanical Interference Fit Lower Joint, Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 7/8 Inch Tube – Unit 1

a,c,e

Table 4-9
Verification Test Results - Mechanical Interference Fit Lower Joint, Elevated Tubesheet Sleeve
Alloy 690 Sleeve for 7/8 Inch Tube – Unit 1

a,c,e

Table 4-10
Comparison of Laboratory S/T Leakage Resistance Test Configuration with Plant Configuration for *Normal Operation
Elevated Tubesheet Sleeve - Unit 1

a,c,e

Table 4-11
Comparison of Laboratory S/T Leakage Resistance Test Configuration with Plant Configuration for Accident (SLB/FLB) Condition
Elevated Tubesheet Sleeve - Unit 1

a,c,e

Table 4-12
Comparison of Laboratory S/T OSL & Direct Pullout Test Configuration with Plant Configuration for *Normal Operation
Elevated Tubesheet Sleeve - Unit 1

a,c,e

Table 4-13
Summary of Primary-to-Secondary Leak Tests at Normal Operation
Elevated Tubesheet Sleeve - Unit 2

a,c,e

Table 4-14

****Comparison of Series "A" Laboratory S/T Leakage Resistance Test Configuration with Plant Configuration for *Normal Operation - Elevated Tubesheet Sleeve - Unit 2**

a,c,e

Table 4-15

Comparison of Series "B" Laboratory S/T Leakage Resistance Test Configuration with Plant Configuration for *Normal Operation - Elevated Tubesheet Sleeve - Unit 2

a,c,e

Table 4-16
Comparison of Laboratory T/TS Leakage Resistance Test Configuration with Plant Configuration for *Normal Operation - Elevated Tubesheet Sleeve - Unit 2

a,c,e

Table 4-17
As-Installed ETS MIF Joint S/T & T/TS Contact Pressures
for Tube Undegraded in Joint Area for Unit 2

a,c,e

Table 4-18
Conclusion on Direct Pullout Qualification Test Results - Sleeve-to-Tube MIF Joint
Elevated Tubesheet Sleeve - Unit 2

a, c, e

5.0 STRESS CORROSION TESTING OF LASER WELDED SLEEVE JOINTS

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

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

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

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

Not all data in this section are for Series 44 or Series 51 SGs, i.e., 7/8 inch OD tubing. Where the intent is merely to illustrate the effect(s) of certain variables or parameters on far-field stress or corrosion resistance, data from test programs or mockup fabrications of other size tube-sleeve assemblies are also used.

5.1 LWS PROCESS AND SG DESIGN VARIABLES

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

As installed, i.e., prior to thermal stress relief or final hard rolling, the far-field stresses are generally low, on the order of a few ksi. The peak residual stresses at the laser weld, however, are quite high; they have been estimated as approaching 80 - 85% of the tensile yield strength of the sleeve-tube assembly. When corrosion tested in this condition, the failures occur in the parent Alloy 600 tube near the weld-tube interface at times [

]a,c,e

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

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

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

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

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

5.2 RESIDUAL STRESSES VS. STRESS RELIEF TEMPERATURE IN LWS SLEEVE REPAIRS

Table 5-2 summarizes the expected range of far-field stresses that result as a function of the stress relief process. These are conservative stress values from strain gage measurements above and below the laser weld location and are for temperatures measured at the weld and upper hydraulic expansions of sleeve mockups. The data shown were measured during preparation of pre-heat model SG sleeve mockups and are directly applicable to Model D or E SGs [

]a,c,e

These data show the substantial reduction of far-field stress that can be realized in LWS-repaired SG tubing by controlling the stress relief temperature to be in the lower portion of the allowable range. They also show the general trend that separate stress relief of the upper hydraulic expansion (UHE) region tends to increase the far-field stress, and final hard rolling for the roll-last sequence contributes to a small reduction in far-field stress.

5.3 CORROSION TEST DESCRIPTION

Since approximately 1988, Westinghouse has used the doped steam corrosion test to evaluate the resistance of test mockups or repair assemblies to primary water stress corrosion cracking (PWSCC). This test is conducted in dense steam in an autoclave operating at 750°F (400°C). [

]a,c,e

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

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

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

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

The second configuration is somewhat more complex. In this mockup test, the specimen is fabricated using a test stand as shown in Figure 5-2. The purpose of the test stand is to permit the sleeve installation, hydraulic expansion, welding, and post weld thermal stress relief under locked tube conditions. The nominal span length between supporting plates is varied to simulate the appropriate values for the SG model/design of interest. The stresses that result from the several stages of fabrication are measured by placing strain gages above the weld location. Temperatures are recorded throughout the stress relief process.

Following all specimen fabrication steps, the specimens are unloaded and prepared for corrosion testing. The configuration of the test assembly used for these tests is shown in Figure 5-3. By means of the threaded end fitting at the top of the assembly and the compression cylinder/Belleville washer assembly at the bottom, the axial load is established and maintained on the sleeve joint throughout the corrosion test.

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

5.4 CORROSION RESISTANCE OF FREE-SPAN LASER WELD-REPAIRED TUBES - AS-WELDED CONDITION

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

The corrosion tests on as-welded mockups have been performed on specimens of the configuration shown in Figure 5-1; i.e., without added axial load. The doped steam test results for these tests are summarized in Table 5-3. (Table 5-3 also includes some data for stress-relieved Nd:YAG welds.) While the data exhibit typical scatter in the results from different test sets, the results generally show that the as-welded joints [ ][a,c,e] while the specimens stress relieved at 1400°F exhibit much greater resistance to cracking.

A limited number of as-welded 3/4 inch tube-sleeve mockups have also been tested (ca. 1994) to support a field sleeving campaign. For these tests, failures [ ][a,c,e] encompassing the range observed previously.

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

5.5 CORROSION RESISTANCE OF FREE-SPAN LASER WELD-REPAIRED TUBES - WITH POST WELD STRESS RELIEF

In addition to the results presented in Table 5-3 referred to in the previous subsection, doped steam corrosion tests were performed on 3/4 inch tube-sleeve mockups to support the 1994 field sleeving campaign. These specimens were tested without the imposition of axial loading. One of the objectives of this test program was to evaluate the effectiveness of the post weld thermal stress relief over the temperature range [ ]^{a,c,e} The results of these doped steam tests are presented in Table 5-4.

These tests were, for the most part, terminated at [ ]^{a,c,e} a time period agreed upon with the utility as sufficient to demonstrate adequate resistance to in-service degradation through the remaining service performance of the steam generators. All specimens were post-test destructively examined by splitting and flattening. Only specimens that were intentionally stress relieved well above the field process maximum temperature [ ]^{a,c,e}

5.6 CORROSION RESISTANCE OF FREE-SPAN LASER WELD-REPAIRED TUBES - WITH POST WELD STRESS RELIEF AND CONDITIONS OF AXIAL LOAD DURING TEST

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

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

Nine 7/8 inch sleeved-tube mockups were prepared for doped steam corrosion testing using parameters appropriate to tubesheet sleeves in Series 51 SGs. These mockups were prepared in sets of three to represent the following variations in sleeve installation:

- Mockups APR-1 through -3
  The post-weld stress relief was performed only at the laser weld elevation. The distance from the LW to the UHE transition was [ ]^{a,c,e} This set of mockups represent the conditions used to install most laser welded tubesheet sleeves in operating Series 51 SGs.

- Mockups APR-4 through -6
  Post-weld stress relief was performed at the laser weld elevation, the tube was permitted to cool to near room temperature, and the UHE transition was subsequently stress relieved. The distance from the LW to the UHE transition was [ ]^{a,c,e}

  This set of mockups was prepared to examine the efficacy of performing stress relief of the UHE transitions in the future - i.e., after some period of operation of the initial LW sleeve installations.

- Mockups APR-7, -8, -11
  This set of mockups was fabricated using modified tooling which establishes the distance from the laser weld to the UHE transition at [ ]^{a,c,e} This modification was performed to permit a single post weld stress relief, performed just above the laser weld elevation, to effect at least partial stress relief of the UHE transition as well.

A summary of the stress relief temperatures realized during mockup fabrication, the stresses used for corrosion testing and the results of testing are provided in Table 5-5.

In order to test under the most conservative conditions, i.e., under conditions of maximum far-field stress, the test stress values reported in Table 5-5 include: the residual stress (from strain gages) measured during mockup fabrication, plus two standard deviations; an "end cap" stress term due to internal pressurization; and an additional 10% allowance for stress relaxation during testing at 750°F. These latter additional stress terms add significantly to the total stresses used during testing. For example, the following table summarizes the various stress components for each set of mockups.

Mockups	Avg. Stress During Fabrication, ksi	Additional Stresses Added, ksi			Total Test Stress, ksi
		2 std. dev'ns	End Cap Stress	Stress Relaxation	
APR-1 thru -3	8,703	2,220	982	1,191	13,096
APR-4 thru -6	10,483	2,660	982	1,413	15,538
APR-7, -8, -11	8,964	2,220	982	1,217	13,383

The above test data shows that mockups APR-4 through -6 have higher fabrication stresses due to two stress relief operations as compared to the other mockups which experienced only one stress relief.

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

]^{a,c,e} Both of these factors were recognized in the test matrix described in Table 5-5.

Use of the conservatively high applied stresses should ensure that the corrosion data are appropriate to the earliest field failures, i.e., those sleeved-tube assemblies with maximum residual-plus-applied stresses.

Note re. Current Field-Installed Laser Welded Sleeves

The performance of laser welded sleeve repairs in operating steam generators has been excellent. Tubesheet and TSP sleeves have been in service in a domestic nuclear power plant for over four years with no indications of degradation. These sleeves are in tubes known to have some degree of lock-up at the TSPs; far-field stresses are estimated [

]^{a,c,e}

In a non-domestic plant, approximately 5 years of operation had been attained with LWS-repaired tubes at the time the repaired SGs were replaced, again with no incidents of degradation. In another non-domestic plant, over 11,000 elevated tubesheet sleeves were in service for approximately 24 months at the time the SGs were replaced. After approximately 10 months of operation, NDE of all sleeved tubes and destructive examination of ten pulled tube-sleeve assemblies revealed no in-service corrosion degradation of the laser welds, the hydraulic expansion regions, or the tube bulges that resulted from stress relief under locked tube conditions.

In the following subsection an estimate is provided of the service performance that might reasonably be expected for sleeve installations in Series 51 SGs.

5.7 ESTIMATED SLEEVE PERFORMANCE AT PLANT A

An estimate of the sleeve performance at Plant A was performed using experience from previous programs and extrapolating the results to Plant A SG conditions.

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

In performing the following estimates, the operating temperature of Plant A SGs ($T_{hot} \approx 607°F$) is taken into consideration.

[ ]^{a,c,e} Stress relief of the upper hydraulic expansion transitions was not performed.

Tubes Free to Expand Axially

In this case, following thermal stress relief of the laser weld region, the primary stresses acting on the tube-sleeve assembly in the steam generator are the remaining residual weld stress and the operating pressure stress. Doped steam accelerated corrosion tests on mockups prepared under the condition of no axial fixity have run for periods [ ]^{a,c,e} (average of five mockups - no failures in test). Based on comparison with roll transition mockups, prepared of the same Alloy 600 material and tested at the same time, the sleeved tubes are projected to exhibit resistance to PWSCC for periods [ ]^{a,c,e}

For Plant A, the earliest in-service degradation due to PWSCC is estimated to have occurred after about [ ]^{a,c,e}

Tubes Fixed at the First Tube Support Plate

In the Plant A Series 51 steam generators, the first TSP is at an elevation approximately 50 inches above the top of the tubesheet. For fixed conditions at this elevation, the far-field stresses after thermal stress relief of the weld will be in the range of [ ]^{a,c,e}

Corrosion testing of mockups under this condition of stress, again from comparison with roll transition mockups exposed at the same time, indicates degradation-free sleeve performance in primary water for periods approximately twenty times those required to initiate PWSCC in roll transitions. For Plant A, operating at a relatively modest T_{hot}, this suggests [ ]^{a,c,e} of service for the laser welded sleeves.

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

a,c,e

5.8 Outer Diameter Surface Condition

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

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

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

Table 5-1

Summary of Impact of Laser Welded Sleeve Operations on Stresses

a,c,e

Table 5-2

Far-field Stress as a Function of Stress Relief Temperature

Data shown are for 3/4 inch OD Tube-Sleeve Mockups

a,c,e

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

a,c,e

Table 5-4

Doped Steam Corrosion Test Results for 3/4 inch Tube-Sleeve Mockups - Tested Without Axial Load

a,c,e

Table 5-5

Summary of Temperatures, Stresses and Corrosion Test Results for

7/8 inch Sleeve Mockups - Tested with Applied Axial Load

a,c,e

(a) Data not recorded

1 CE = Circumferential extent

2 WT = Wall thickness

Mean cracking time for five roll transitions = 74 hours. (One roll transition did not crack in 244 hours which was inconsistent with the failure time of other roll transitions. This sample was not considered while calculating mean cracking time of the roll transitions.)

a,c,e

[ ]

Figure 5-1
Corrosion Test Specimen for Doped Steam Testing of a LWS Joint

a,c

Figure 5-2
Test Stand used to Fabricate 7/8 inch OD Tube/LWS Mockups under Locked Tube Conditions

a.c

Figure 5-3
Schematic of Test Assembly used for Doped Steam Testing of Tube/LWS Mockups under Conditions of Applied Axial Loading

a,c,e

Figure 5-4
IGSCC in Alloy 600 Tube of YAG Laser Welded Sleeve Joint after 109 Hours in 750°F Steam Accelerated Corrosion Test

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 of the ASME Code (Reference 8.13), 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 full length tubesheet 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, post-weld stress relief and eddy current inspection. The elevated tubesheet sleeve (ETS) installation consists of the same steps as the full length tubesheet sleeve (FLTS) installation. However, in the case of the ETS, the welding and rolling steps are reversed in sequence. 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 8.14 through 8.16.

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

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 tungsten carbide brush with a flushing water orifice. 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. The water jet from the brush is above the hone; it directs the water downward on the tube surface, thus rinsing away residue from the surface. This water flush also lubricates and cools the hone during operation. The Tube Cleaning End Effector mounts to a tool delivery robot and consists of a guide tube sight glass and a flexible seal designed to surround the tube end and contain the spent flushing water. A flexible conduit is attached to the guide tube and connects to the tube cleaning unit on the steam generator platform. The conduit acts as a closed loop system which serves to guide the drive shaft/hone brush assembly through the guide tube to the candidate tube and also to carry the spent flushing water to an air driven diaphragm pump which routes the water to the radioactive waste drain.

6.2 SLEEVE INSERTION AND EXPANSION

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

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

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

Insertion of the sleeve/mandrel assembly into the candidate tube is accomplished by a combination of SALEE's translating gripper assembly and the motorized drive assembly which pushes the sleeve to the desired axial elevation. For 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)

6.3.1 Full Length Tubesheet Sleeves

At the primary face of the tubesheet, the sleeve is joined to the tube by a mechanical interference fit joint, a.k.a. hard roll, (following the hydraulic expansion). For the generic process, the hard roll is performed with a roll expander which extends up to approximately 2.00 inches into the tube. (For a site specific process, the particulars of the roll expansion will be provided in a site specific WCAP document.) The control of the mechanical expansion is maintained through a torque setting. The tool automatically shuts off when it reaches a preset torque value. The roll expander torque is calibrated on a torque calibrator prior to initial hard rolling operations and periodically verified during and at the completion of tool operation. This control and calibration process is a technique used throughout industry in the installation of tubes in heat exchangers.

6.3.2 Elevated Tubesheet Sleeves

As discussed in Section 2, this sleeve is elevated approximately 15 inches from the primary face of the tubesheet. However, the ETS MIF lower joint is fabricated by the same types of processes which are used to fabricate the FLTS lower joints, i.e., hydraulic expansion and roll expansion. In this case, the joint processes are performed at the proper elevation by extensions of the hydraulic and roll expanders from the tubesheet bottom face.

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 pre-aligned 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.

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, if the sleeve/tube has not been perforated by the initial weld, up to two rewelds, having the same nominal characteristics as the initial weld, will be made at the same nominal elevation of the initial weld (refer to Figure 6-1). If the three welds at the initial elevation are unacceptable, and if a perforation of the <u>sleeve</u> is suspected at the initial weld elevation, up to two rewelds, having the same nominal characteristics as the original weld, will be made in the expansion zone inboard of the initial weld.

6.6 POST-WELD HEAT TREATMENT

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

Since stress corrosion cracking is related to a large extent to residual stresses, a reduction in the residual welding stress level will enhance the corrosion resistance of the LWS. The Westinghouse development program determined that a stress relief in the 1250°F to 1650°F range for five minutes reduces the level of residual stress without significant microstructural changes. Accordingly, upon completion of all of the welds, the weld sites are stress relieved using a quartz lamp with sufficient power to maintain the tube temperature in the desired range for five minutes. The value of the heating power is established based on tube surface emissivity information derived from pulled tubes, operating history, visual observation, and prior heat treat programs. This post-weld heat treatment (PWHT) is effective over a tube length sufficient to cover the actual weld length as well as any heat affected zone.

6.7 LOWER JOINT (ELEVATED TUBESHEET SLEEVES)

In the tubesheet, the sleeve is joined to the tube by a hard roll, a.k.a. roll expansion (following the hydraulic expansion), performed with a roll expander which extends up to approximately 18 inches above the tube end. As discussed earlier, this joint is referred to as a mechanical interference fit (MIF) joint; it has also been referred to in the past as a hybrid expansion joint (HEJ). Control of the mechanical expansion is maintained through a torque setting. The tool automatically shuts off when it reaches a preset torque value. The roll expander torque is calibrated on a torque calibrator prior to initial hard rolling operations and periodically verified during and at the completion of tool operation. This control and calibration process is a technique used throughout industry in the installation of tubes in heat exchangers.

6.8 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.

TABLE 6-1
Sleeve Process Sequence Summary

Main Step	Step No.	Detailed Process
TUBE PREPARATION	1	Light Mechanical Roll Tube Ends (if necessary)
	2	Clean Tube Inside Surface
SLEEVE INSERTION	3	Insert Sleeve/Expansion Mandrel Assembly
	4	Hydraulically Expand Sleeve, Top and Bottom Joints
WELD OPERATION	5	Weld Tubesheet Sleeve Upper Joints
WELD OPERATION	6	Weld Upper and Lower Support Plate Sleeve Joints
INSPECTION	7	Ultrasonically Inspect Sleeve Welds (On a sampling plan)
STRESS RELIEF	8	Post Weld Stress Relief Sleeve Welds
TUBESHEET SLEEVE LOWER JOINT FORMATION	9	Roll Expand Tubesheet Sleeve Lower End
INSPECTION	10	Baseline Eddy Current Sleeves

a,c,e

Figure 6-1
Full Length Tubesheet Sleeve With Reweld

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

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 end effector

The fiber optic probe is used in conjunction with the pop-up end effector. The end effector places a probe within the proper zone to perform the stress relief operation. To verify the temperature achieved, a fiber optic filament is used to obtain the inside sleeve temperature by means of an optical pyrometer. After determining the proper power profile, the production probes are used to stress relieve the balance of the sleeve/tube interfaces. 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.

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

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, produce repeatability of the weld process. In addition, two non-destructive examination (NDE) capabilities have been developed to evaluate the success of the sleeving process. One method is used to confirm that the laser welds meet critical process dimensions related to structural requirements. The second method is then applied to provide the necessary baseline data to facilitate subsequent routine in-service inspection capability.

7.1 INSPECTION PLAN LOGIC FOR INSTALLATION

7.1.1 Tubesheet Sleeve Basic Inspection Plan

The basic tubesheet sleeve inspection plan shall consist of:

A. Ultrasonic Inspection (Section 7.2) [ ]^{a,c,e} or alternate methods (Section 7.3).

1. Verify minimum required weld width.

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

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

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

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

7.1.2 Tube Support Sleeve Basic Inspection Plan

The basic tube support sleeve inspection plan shall consist of:

A. Ultrasonic Inspection (Section 7.2) [ ]^{a,c,e} or alternate methods (Section 7.4).
   1. Verify minimum required weld width.

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

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

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

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

7.2 GENERAL PROCESS OVERVIEW OF ULTRASONIC EXAMINATION

The ultrasonic inspection process is based upon field proven techniques which have been used on laser welded sleeves installed by Westinghouse. The inspection process developed for application to the laser welds uses the transmission of ultrasound to the interface region (the sleeve OD/tube ID boundary) and analysis of the amount of reflected energy from that region. An acceptable weld joint should present no acoustic reflectors from this interface above a predetermined threshold.

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

7.2.1 Principle of Operation and Data Processing of Ultrasonic Examination.

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

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

[

]^{a,c,e}

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

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

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

7.2.2 Laser Weld Test Sample Results

Ultrasonic test process criteria are developed by [

]^{a,c,e}

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

- Set system sensitivity (gain).
- Provide time of flight reference for sleeve ID, OD and tube OD signals.
- Verify proper system function by scanning of the standard.

Figure 7-4 depicts a calibration standard for the sleeve weld UT exam.

7.2.3 Ultrasonic Inspection Equipment and Tooling

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

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

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

7.3 EDDY CURRENT INSPECTION

Upon conclusion of the sleeve installation process, a final eddy current inspection is performed on every installed sleeve to meet the process verification and baseline inspection requirements outlined in Sections 7.1.1 B and 7.1.2 B. Non-destructive examination techniques qualified to EPRI Appendix H requirements for detection of both circumferential and axial degradation will be utilized for performance of this baseline inspection.

7.4 ALTERNATE POST INSTALLATION ACCEPTANCE METHODS

Ultrasonic and eddy current inspection are the prime methods 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

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.

a,c,e

Figure 7-1

Ultrasonic Inspection of Welded Sleeve Joint

a,c,e

[ ]

Figure 7-2

Typical Digitized UT Waveform

a,c,e

[ ]

Figure 7-3

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

a,c,e

Figure 7-4

UT Calibration Standard

8.0 REFERENCES

8.1 Design Specification 412A04, "Duquesne Light Company Beaver Valley Power Station Unit No. 1, Steam Generator Heat Transfer Tube Sleeving, ASME Boiler & Pressure Vessel Code, Section III, Code Case 1, Safety Class 1", Revision 0, 7/20/92

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