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Laser Welded Sleeves For 3/4 Inch Diameter Tube Feedring-Type and Westinghouse Preheater Steam Generators Generic Sleeving Report

Westinghouse Energy Systems

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LASER WELDED SLEEVES
FOR
3/4 INCH DIAMETER TUBE FEEDRING-TYPE AND
WESTINGHOUSE PREHEATER STEAM GENERATORS

Generic Sleeving Report

July, 1998

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ABSTRACT

This report provides the technical basis for licensing the use of the Westinghouse Laser Welded Sleeve (LWS) technique to return a 3/4 inch diameter tube with indications of degradation to an operable condition. This report summarizes the generic design, structural, thermal-hydraulic, materials and inspection analyses and corrosion and mechanical tests, as well as installation processes of two distinct types of sleeves. It addresses a tubesheet sleeve and a tube support sleeve for Asea Brown Boveri-Combustion Engineering feedring-type steam generators and for Westinghouse Models D3, D4, D5, E1 and E2 preheater-type steam generators, all of which utilize 3/4 inch outside diameter tubes.

The Westinghouse LWS technique has been previously licensed for use within 7/8 inch, 3/4 inch and 11/16 inch diameter steam generator tubing, has been installed and is in operation. This revision addresses installation in 3/4 inch tubes which were installed in the tubesheet by roll, explosive and hydraulic expansion processes. This revision also includes updated information in the installation NDE and corrosion testing areas.

TABLE OF CONTENTS

Section	Title	Page
1.0	INTRODUCTION	1-1
1.1	Report Applicability	1-1
1.2	Sleeving Boundary	1-3
2.0	SLEEVE DESCRIPTION AND DESIGN	2-1
2.1	Sleeve Design Description	2-1
2.1.1	Tubesheet Sleeve	2-1
2.1.2	Tube Support Sleeve	2-3
2.1.3	Sleeving of Previously Plugged Tubes	2-4
2.2	Sleeve Design Documentation	2-4
2.2.1	Weld Qualification Program	2-4
2.2.2	Weld Qualification Acceptance Criteria	2-5
3.0	ANALYTICAL VERIFICATION	3-1
3.1	Structural Analysis	3-1
3.1.1	Summary of Material Properties	3-1
3.1.2	Applicable Criteria	3-1
3.1.3	Loading Conditions Considered	3-4
3.1.4	Analysis Methodology	3-4
3.1.5	Heat Transfer Analysis	3-9
3.1.6	Tubesheet/Channel Head/Shell Evaluation	3-10
3.1.7	Stress Analysis	3-10
3.1.8	ASME Code Evaluation	3-11
3.1.9	Weld Evaluation	3-12
3.1.10	Minimum Required Sleeve Wall Thickness	3-27
3.1.11	Determination of Plugging Limits	3-28
3.1.12	Application of Plugging Limits	3-29
3.1.13	Analysis Conclusions	3-30
3.2	Thermal Hydraulic Analysis	3-79
3.2.1	Safety Analysis and Design Transients	3-79
3.2.2	Equivalent Plugging Level	3-79
3.2.3	Fluid Velocity	3-83
3.3	Sleeved Tube Relative Flow Induced Vibration Assessments	3-89
3.3.1	Flow Induced Vibration Evaluation Methodologies	3-89
3.3.2	Effects of Damping on Relative Evaluations	3-91
3.3.3	Flow Induced Vibration Results and Conclusions	3-92
3.4	References	3-106

TABLE OF CONTENTS (cont)

Section	Title	Page
4.0	MECHANICAL TESTS	4-1
4.1	Tubesheet MIF Joint Tests - 3/4 Inch Tube Sleeves	4-1
4.1.1	Case No. 1 - Feedring Steam Generator (FSG)	4-1
4.1.2	Case No. 2 - Feedring Steam Generator	4-3
4.2	Tubesheet MIF Joint and Free Span LWS Tests - 7/8 Inch Tube FLTSs	4-4
4.2.1	Acceptance Criteria – 7/8 Inch Tubesheet MIF Joint Sleeves	4-5
4.2.2	Results of Testing - 7/8 Inch Sleeves	4-5
4.3	Reference	4-7
5.0	STRESS CORROSION TESTING OF LASER WELDED SLEEVE JOINTS	5-1
5.1	LWS Process and SG Design Variables	5-2
5.2	Residual Stresses vs. Stress Relief Temperature in LWS Sleeve Repairs	5-2
5.3	Corrosion Test Description	5-3
5.4	Corrosion Resistance of Free-Span Laser Weld-Repaired Tubes-As-Welded Condition	5-4
5.5	Corrosion Resistance of Free-Span Laser Weld-Repaired Tubes with Post Weld Stress Relief	5-5
5.6	Corrosion Resistance of Free-Span Laser Weld-Repaired Tubes with Post Weld Stress Relief and Conditions of Axial Load During Test	5-5
5.7	Estimated Sleeve Performance	5-8
5.8	Outer Diameter Surface Condition	5-9
6.0	INSTALLATION PROCESS DESCRIPTION	6-1
6.1	Tube Preparation	6-1
6.1.1	Tube End Rolling (Contingency)	6-1
6.1.2	Tube Cleaning	6-2
6.2	Sleeve Insertion and Expansion	6-2
6.3	Lower Joint Hardroll (Tubesheet Sleeves)	6-3
6.4	General Description of Laser Weld Operation	6-3
6.5	Rewelding	6-4
6.6	Post-Weld Heat Treatment	6-4
6.7	Inspection Plan	6-5
6.8	References	6-6

TABLE OF CONTENTS (cont)

Section	Title	Page
7.0	NDE INSPECTABILITY	7-1
7.1	Inspection Plan Logic for Installation	7-1
7.1.1	Tubesheet Sleeve Basic Inspection Plan	7-1
7.1.2	Tube Support Sleeve Basic Inspection Plan	7-1
7.2	General Process Overview of Ultrasonic Inspection	7-2
7.2.1	Principle of Operation and Data Processing of Ultrasonic Examination	7-2
7.2.2	Laser Weld Test Sample Results	7-3
7.2.3	Ultrasonic Inspection Equipment and Tooling	7-4
7.3	Eddy Current Inspection	7-4
7.4	Cecco-5/Bobbin Principles of Operation	7-4
7.5	Alternate Post Installation Acceptance Methods	7-5
7.5.1	Bounding Inspections	7-6
7.5.2	Workmanship Samples	7-6
7.5.3	Other Advanced Examination Techniques	7-6
7.6	Inservice Inspection Plan for Sleeved Tubes	7-6
7.7	Reference	7-7

LIST OF TABLES

Table	Title	Page
2-1	ASME Code Rules and Regulatory Requirements	2-6
3-1	Summary of Material Properties Alloy 600 Tube Material	3-31
3-2	Summary of Material Properties-Sleeve Material- Thermally Treated Alloy 690	3-32
3-3	Summary of Material Properties- Tubesheet Material SA-508 Class 2	3-33
3-4	Summary of Material Properties Air	3-34
3-5	Summary of Material Properties Water	3-35
3-6	Criteria for Primary Stress Intensity Evaluation Alloy 690 Sleeve and Alloy 600 Tube	3-36
3-7	Criteria for Primary Plus Secondary Stress Intensity Evaluation Alloy 690 Sleeve and Alloy 600 Tube	3-37
3-8	Summary of Transient Events	3-38
3-9	Umbrella Pressure Loads for Design, Faulted, and Test Conditions	3-40
3-10	Stress Modification Factors 7/8 Inch to 3/4 Inch Tube Sleeves	3-41
3-11	Tubesheet Comparisons for Westinghouse Steam Generators	3-42
3-12	Comparison of Tubesheet Stresses for FSG and Series 51 Steam Generators	3-43
3-13	Transient Stresses at Sleeve/Tube Weld-Series 51 SG	3-44
3-14	Ratio of Model D, E and FSG to Series 51 SG Transient Stresses	3-45
3-15	Summary of Maximum Primary Stress Intensity- Full Length Tubesheet Laser Welded Sleeve Sleeve/Tube Weld Width of [ ]a,c [ ]a,c	3-46

LIST OF TABLES (cont)

Table	Title	Page
3-16	Maximum Range of Stress Intensity and Fatigue- Full Length Tubesheet Laser Welded Sleeve Sleeve/Tube Weld Width of [ ]a,c [ ]a,c	3-47
3-17	Maximum ΔP Loads (psi) Used to Size Laser Welds	3-48
3-18	Ratios of Maximum Calculated Average Shear Stress to the ASME Code Allowable Shear Stress	3-49
3-19	Summary of Test Sample Matrix	3-50
3-20	Summary of Pressure Test Results 7/8 Inch OD Tube	3-51
3-21	Loads Used in Fatigue Evaluation of 3/4-W and ¾-CE LWS from Reference 2 (NOC Cycles are for 40 years)	3-52
3-22	Calculated Shear Forces (lbf) on Sleeve / Tube Laser Welds Due to Indicated Unit Load Cases	3-54
3-23	Calculation of Weld Forces / Stresses Generic 3/4 Inch OD Tube [ ]a,c	3-55
3-24	Max Overall Calculated Fatigue Usage Table [ ]a,c Min Weld THk of [ ]a,c inch & 40 Year Fatigue Design Life	3-57
3-25	Summary of Minimum Wall Thickness Calculations Laser Welded Sleeve	3-58
3-26	Summary of Recommended Plugging Margins Laser Welded Sleeves	3-59
3-27	Hydraulic Equivalency Sensitivity Study	3-85

LIST OF TABLES (cont)

Table	Title	Page
3-28	3/4 Inch Tube-Laser Welded Sleeve Evaluations Sleeve Position Definitions and Lengths	3-95
3-29	3/4 Inch Tube-Laser Welded Sleeve Evaluations Tube and Sleeve Cross Sectional Properties	3-96
3-30	Laser Welded Sleeve Superelement Geometry and Nodes for Models D3, D4 and D5 SGs	3-97
3-31	Model E2 LWS Superelement Geometry and Nodes	3-98
3-32	FSG (Specific Case) LWS Superelement Geometry and Nodes	3-99
3-33	Laser Welded Sleeve Relative Evaluations Tube Density Distribution Estimates	3-100
3-34	Relative Flow Induced Vibration Evaluation Results for Laser Welded Sleeve Configuration with Various Tube Support Plate Boundary Conditions	3-101
4-1	Case No. 1 – Feedring Steam Generator Mechanical Test Program Summary Tubesheet MIF Joint Tests – 3/4 Inch Tube Sleeves	4-8
4-2	Typical Bounding Maximum Allowable Leak Rates for Feedring-Type and Preheater Steam Generators	4-9
4-3	Verification Test Results-Lower Joint (MIF Joint) Alloy 690 Sleeve for 3/4 Inch Tube (FSG)	4-10
4-4	Case No. 2-FSG Mechanical Test Program Summary Tubesheet MIF Joint Tests-3/4 Inch Tube Sleeves	4-15
4-5	Verification Test Results-Lower Joint (MIF Joint) Alloy 690/625 Bimetallic Sleeve for 3/4 Inch Tube (FSG)	4-16

4-7 Verification Test Results for MIF Lower Joints- 7/8 Inch Sleeves 4-22

4-8 Verification Test Results for MIF Lower Joints with Exceptional Conditions for Tube and Sleeve - 7/8 Inch Sleeves 4-25

4-9 Additional Verification Tests Results for MIF Lower Joints with Exceptional Conditions for Tube and Sleeve - 7/8 Inch Sleeves 4-26

5-1 Summary of Impact of Laser Welded Sleeve Operations on Stresses 5-11

5-2 Far-field Stress as a Function of Stress Relief Temperature 5-12

5-3 Results of 750°F Doped Steam Tests for Nd:YAG Laser Weld-Repaired Mockups 5-13

5-4 Doped Steam Corrosion Test Results for 3/4 inch - Tube-Sleeve Mockups Tested Without Axial Load 5-14

5-5 Summary of Fabrication Parameters, Temperatures, Stresses, and Corrosion Test Results for 3/4 inch Sleeve Mockups Tsted with Applied Axial Load 5-15

5-6 Summary of Temperatures, Stresses and Corrosion Test Results for 7/8 inch Sleeve Mockups - Tested with Applied Axial Load 5-16

6-1 Sleeve Process Sequence Summary 6-7

LIST OF FIGURES

Figure	Title	Page
2-1	Tubesheet Full Length Laser Welded Sleeve Installed Configuration	2-7
2-2	Tubesheet Elevated Laser Welded Sleeve Installed Configuration	2-8
2-3	Tube Support Laser Welded Sleeve Installed Configuration	2-9
3-1	ASN Location-Lower Welded Joint	3-60
3-2	Finite Element Model of FSG Channel Head/Tubesheet/Shell	3-61
3-3	FSG Channel Head/Tubesheet/Shell Model Primary Pressure boundary Conditions and Deformed Geometry	3-62
3-4	FSG Channel Head/Tubesheet/Shell Model Tubesheet Expansion Boundary Conditions and Deformed Geometry	3-63
3-5	Thermal/Hydraulic Boundary Conditions Full Length Tubesheet Sleeve Analysis	3-64
3-6	Boundary Condition for Unit Primary Pressure [ ]a,c,e $P_{PRI} > P_{SEC}$	3-65
3-7	Boundary Condition for Unit Primary Pressure [ ]a,c,e $P_{PRI} < P_{SEC}$	3-66
3-8	Boundary Condition for Unit Primary Pressure [ ]a,c,e $P_{PRI} > P_{SEC}$	3-67
3-9	Boundary Condition for Unit Primary Pressure [ ]a,c,e $P_{PRI} < P_{SEC}$	3-68
3-10	Boundary Condition for Unit Secondary Pressure [ ]a,c,e $P_{PRI} > P_{SEC}$	3-69

LIST OF FIGURES (cont)

Figure	Title	Page
3-11	Boundary Condition for Unit Secondary Pressure [ ]a,c,e $P_{PRI} < P_{SEC}$	3-70
3-12	Boundary Condition for Unit Secondary Pressure [ ]a,c,e $P_{PRI} > P_{SEC}$	3-71
3-13	Boundary Condition for Unit Secondary Pressure [ ]a,c,e $P_{PRI} < P_{SEC}$	3-72
3-14	Schematic of Sleeve, Tube and Weld and Free Body Diagram of Severed Tube Showing Shear Force on Laser Weld	3-73
3-15	Schematic of Structural Models FLTS, ETS, and TSS Laser Welded Sleeve Types	3-74
3-16	K_t / K_f as a Function of Notch Radius	3-75
3-17	q * K_t as a Function of Notch Radius	3-76
3-18	Finite Element Model - Element Layout	3-77
3-19	Transient Operating Cycle Generic 3/4 Inch OD Tube (Transient Numbers Refer to Loads Listed in Tables 3-21 and 3-23)	3-78
3-20	Hydraulic Equivalency Number 3/4 In. OD Tube, Model D S/G	3-86
3-21	Hydraulic Equivalency Number 3/4 In. OD Tube, Model E S/G	3-87
3-22	Hydraulic Equivalency Number 3/4 In. OD Tube, FSG	3-88
3-23	LWS Effects on Stability Ratio [ ]a,c,e [ ]a,c,e	3-102

LIST OF FIGURES (cont)

Figure	Title	Page
3-24	LWS Effects on Stability Ratio [ ]a,c,e [ ]a,c,e	3-103
3-25	LWS Effects on Turbulence Response [ ]a,c,e [ ]a,c,e	3-104
3-26	LWS Effects on Turb. Response [ ]a,c,e [ ]a,c,e	3-105
4-1	Tubesheet Sleeve Lower Joint Test Specimen	4-27
5-1	Corrosion Test Specimen for Doped Steam Testing of a LWS Joint without Axial Load	5-17
5-2	Test Stand used for Fabrication of LWS Mockups under Locked Tube Conditions	5-18
5-3	Schematic of Test Assembly used for Doped Steam Testing of Tube/LWS Mockups under Conditions of Applied Axial Loading	5-19
5-4	IGSCC in Alloy 600 Tube of YAG Laser Welded Sleeve Joint After 109 Hours in 750°F Steam Accelerated Corrosion Test	5-20
6-1	Full Length Tubesheet Sleeve With Reweld	6-8
7-1	Ultrasonic Inspection of Welded Sleeve Joint	7-8
7-2	Typical Digitized UT Waveform	7-9
7-3	A,B,C, and Combined C-Scan Display for Weld in UT Calibration Standard	7-10
7-4	UT Calibration Standard	7-11

LIST OF FIGURES (cont)

Figure	Title	Page
7-5	Cecco-5 Sleeve Calibration Standard	7-12
7-6	Strip Chart Display for Cecco/Bobbin Data	7-13
7-7	Response of Cecco-5 Probe to 60% OD Axial Notch in Parent Tube Located at Expansion Transition	7-14
7-8	Response of Cecco-5 Probe to 60% OD Circumferential Notch in Parent Tube Located at Expansion Transition	7-15

1.0 INTRODUCTION

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

This report presents the technical bases developed to support licensing of the laser welded sleeve installation process for use in 3/4 inch outside diameter (OD) tubing. Two distinct types of sleeves are addressed, a tubesheet sleeve and a tube support sleeve. Each of these sleeve types has several installation options that 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 since 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 in the bundle, this sleeve may also address degradation above the tubesheet top. 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 in the bundle, this sleeve may also address degradation above the tubesheet top. The tube support sleeve (TSS) may be installed to bridge degradation located at tube support locations or in the free span section of the tube. The types of tube supports include flow distribution baffles, drilled plates and grids (a.k.a., "eggcrates").

This technical basis for laser welded sleeves is applicable to Asea Brown Boveri-Combustion Engineering (ABB-CE) feedring-type steam generators, (FSGs) and Westinghouse Model D3, D4, D5, E1 and E2 steam generators of the preheater-type design (PSGs), all of which utilize 3/4 inch OD tubing.

1.1 Report Applicability

Each FSG tube bundle contains both U-tubes and modified U-tubes. The modified U-tubes are designed such that the bends at the bundle top have horizontal extent. All of these FSG heat transfer tubes are Alloy 600 and have a nominal OD of 3/4 inch and a nominal wall thickness of 0.048 inch.

The PSGs are U-tube heat exchangers with Alloy 600 heat transfer tubes which have a 3/4 inch nominal OD and 0.043 inch nominal wall thickness. The Model D3/4, E1 and initial E2 steam generators have mill annealed tubes; the Model D5 and later E2 steam generators have thermally treated tubes.

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

Tube support sleeve

- 6 to 12 inches long (12 to 15 inches long for the grid supports of the FSGs)
- welding with post weld heat treatment

Tubesheet sleeve

- 27 to 36 inches long FLTS [ ]b (Variations apply for some models.)
- 12 to 30 inches long ETS
- weld joint with post weld heat treatment

The sleeves described herein have been designed and analyzed to meet the service requirements of the FSGs and the PSGs through the use of conservative and enveloping thermal boundary conditions and structural loadings. Field experience and previous testing of sleeve lower mechanical joints of sleeves for 3/4 inch OD and 7/8 inch OD tubes have been utilized. It has been determined that the results of the field experience and tests are applicable to the lower mechanical joints of sleeves for the 3/4 inch OD tubes in this report. In those few configurations where previous results are unavailable, confirmatory qualifications are performed during preparation for the sleeving outage.

Similarly, previous field experience for tens of thousands of laser welds in sleeves installed in 3/4 inch, 7/8 inch and 11/16 inch tubes exists. Additionally, previous extensive testing of laser welds for 7/8 inch tubes has been performed. The results of these efforts continue to be applicable to the corresponding joints of the sleeves for 3/4 inch OD tubes in this report. These data are provided, in addition to the analytical bases for the laser welds of this sleeve.

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

]c

1.2 Sleeving Boundary

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

The boundary is determined by the amount of clearance below a given tube, as well as tooling and robot delivery system constraints. At the time of application, the exact sleeving boundary will be developed. Owing to the constant development of tooling, designs and processes, essentially 100 per cent coverage of the tubesheet map, for tubesheet and tube support 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, i.e., the strength and pressure retaining capabilities of the tube. The design of the sleeve and sleeve weld is predicated on the design rules of Section III, Subsection NB, of the American Society of Mechanical Engineers Boiler & Pressure Vessel Code (ASME Code). Also, the sleeve design addresses dimensional constraints imposed by the tube inside diameter and installation tooling. These constraints include variations in tube wall thickness, tube ovality, tube inside diameter, tube to tubesheet joint variations and runout/concentricity variations.

2.1.1 Tubesheet Sleeve

2.1.1.1 Full Length Tubesheet Sleeve

The reference design of the full-length tubesheet sleeve, as installed, is illustrated in 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 full length tubesheet sleeve (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

2.1.1.2 Elevated Tubesheet Sleeve

The sleeve elevated in the tubesheet, or elevated tubesheet sleeve (ETS), is illustrated in Figure 2-2. It is applicable to the steam generators in which the tubes were installed in the tubesheet by the roll expansion and explosive expansion processes. These include the [ ]a,c,e. The ETS design is also applicable to steam generators in which the tubes were installed in the tubesheet by hydraulic expansion, based on confirmatory qualification of the ETS lower joint process for the respective tube joint design. The ETS upper joint is identical to other free span joints, i.e., the upper joint of the FLTS and the tube support sleeve. 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 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

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

The separation distance for degradation in the vicinity of, and above, the ETS MIF lower joint roll 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 [

]a,c,e

2.1.2 Tube Support Sleeve

The 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 weld in the tubesheet sleeves. The tube support sleeve for installation at drilled plate supports, for FSGs and PSGs, is 12 inches long. It may be up to 15 inches long for application at grid supports of the FSGs. Tube support sleeves are qualified for the second-from-highest support [

]a,c,e.

[

]a,c,e

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

2.1.3 Sleeving of Previously Plugged Tubes

Previously plugged tubes must meet the same requirements as sleeving candidates as never-plugged, active tubes. An example of this requirement is that the separation distance, as measured along the tube axis between the extreme extent of the degradation and the bounding elevation of the 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 the sleeve-to-tube lower joint.

2.2 Sleeve Design Documentation

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

2.2.1 Weld Qualification Program

All of the laser welding processes have been qualified, used in the field and have produced structures which are now operating, for [ ]a,c,e. All of these laser welding processes were qualified per the guidelines of the ASME Code. These requirements specify the generation of a procedure qualification record and welding procedure specification. The processes for the larger-diameter sleeve/tube joints required requalification for the smaller-diameter sleeve/tube joints. This is due to a change in two of the essential variables, in excess of limits as defined in ASME Code Section XI, IWB-4313.1. Therefore, the welding processes for PSGs were qualified separately from the welding processes for FSGs.

Specific welding processes are generated for:

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

Representative field processes are used to assemble the specimens to provide similitude between the

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

Item	Applicable Criteria	Requirement
Sleeve design	Section III	NB-3000 Design
	Operating Requirements	Analysis Conditions
	Reg. Guide 1.83	SG Tubing Inspectability
	Reg. Guide 1.121	Plugging Limit
Sleeve Material	Section II	Material Composition
	Section III	NB-2000, Identification, Tests and Examinations
	Code Case N-20-3	Mechanical Properties
Sleeve 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 Sections IX & XI	Laser Welding Essential Variables, Procedure Qualification Record, Sleeving Procedure Specification, Certified Design Report, etc.

a,c,e

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

a,c,e

Figure 2-2
Tubesheet Elevated Laser Welded Sleeve
Installed Configuration

a,c,e

Figure 2-3
Tube Support 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, Section 3.2 provides the thermal/hydraulic justification, and Section 3.3 addresses flow induced vibration concerns for laser welded sleeving.

3.1 Structural Analysis

Section 3.1 summarizes the structural analysis of laser welded sleeves for feedring and preheater steam generators with 3/4 inch tubes in ABB-CE and Westinghouse plants, respectively. 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 (Reference 1), accounting for any changes in geometry and loads. The second part addresses the qualification of the 0.015 inch minimum weld width, and is performed using a combination of test and analysis, consistent with the guidelines of Section III of the ASME Code.

The loading conditions considered in the analysis represent an umbrella set of conditions based on the applicable design specifications, and are defined in Reference 2. The analysis includes development of the finite element models, a heat transfer and thermal stress evaluation, a primary stress intensity evaluation, a primary plus secondary stress range evaluation, and a fatigue evaluation for mechanical and thermal conditions. Calculations are also performed to establish minimum wall requirements for the sleeve. Finally, the analysis addresses a number of special considerations as they affect the adequacy of the sleeve designs.

3.1.1 Summary of Material Properties

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

3.1.2 Applicable Criteria

The steam generator tube sleeve repair is performed per the requirements in Section XI (IWA 4120) of the ASME Boiler and Pressure Vessel Code, Reference 3, which refer back to

Section III (code of construction) as the preferred method of repair. Section III, paragraph NB 3649, of the ASME Code provides two alternative approaches to qualify a component: analysis or experiment.

3.1.2.1 Primary Stress Requirement

For the tube and sleeve, which are qualified solely by analysis, a summary of the applicable stress limits for the sleeve and tube is provided in Table 3-6. The evaluation of the laser weld to show compliance with ASME Code requirements for primary stresses is based on Paragraph NB-3649. This paragraph requires that, in the case of burst testing, that the burst pressure "be equal to or greater than that of the weakest pipe to be attached to the piping product, where the burst pressure of the weakest pipe is calculated by the equation" below.

$$P = \frac{2St}{D_o}$$

where,

S = specified minimum tensile strength of pipe material

t = minimum specified wall thickness of pipe

D_O = outside diameter of pipe

The minimum specified wall thickness of the bounding 7/8 OD tube is [ ]a,c inch. However, there is significant margin in the tube wall thickness. The minimum required wall thickness for the tube can be established using equation NB-3641.1 for piping, or NB-3324.1 for vessels. The equations used to calculate a minimum required wall thickness for the tube are shown below:

NB-3641.1

$$t_{\min} = \frac{P D_o}{2(S_m + P y)} + A$$

where,

t_{min} = minimum required wall thickness
P = internal design pressure
D_O = outside diameter of pipe
S_m = allowable stress intensity
y = 0.4
A = 0.

NB-3324.1

$$t_{\min} = \frac{P R}{S_m - 0.5P} \text{ or } \frac{P R_o}{S_m + 0.5P}$$

where,

t_{min} = minimum required wall thickness
P = design pressure
R = inside radius of pipe
R_O = outside radius of pipe
S_m = allowable stress intensity

The governing minimum wall requirement for the bounding 7/8 OD tube is 0.026 inch. Substituting this value for the minimum wall thickness in the formulation for required test pressure above gives a required burst pressure for the test of 4754 psi.

In a more conservative manner, compliance with elastic ASME Code limits for design conditions requires a factor of safety of three, consistent with the allowable membrane stress for design conditions of $S_u / 3$, for the maximum test pressure to the maximum design pressure. For a design pressure of 1600 psi, this corresponds to a minimum test pressure of 4800 psi. This limit is independent of temperature, as it is based on the ASME Code specified material ultimate strength, which is constant over the temperature range of interest.

Both sets of criteria result in a minimum test pressure close to three times the design pressure. Since the 4800 psi is more conservative, it is used in assessing the structural integrity of the welds.

3.1.2.2 Fatigue Requirement

The ASME Code, Reference 3, requires that the elastically calculated cumulative usage factor for the 0.015 inch minimum weld be less than unity when summed over all applied cyclic load conditions, namely:

$$\sum_i u_i \leq 1,$$

where u_i = the usage factor for the ith cyclic stress range = n_i / N_i, n_i = number of occurrences for the ith cyclic load combination range, and N_i is the allowable number of occurrences at the stress amplitude for the ith cyclic load combination range, as obtained from the ASME Code fatigue design (S-N) curves.

3.1.2.3 Maximum Range Of Stress ($3S_m$) Requirement

The range of maximum range of stress is limited to $3S_m$. A summary of the corresponding stress limits for the sleeve and tube are summarized in Table 3-7. The purpose of the $3S_m$ limit in the ASME Code is to prevent incremental distortion in structures under successive thermal cycles in the presence of a sustained mechanical (pressure) loading. Thermal stresses develop in the weld due to differential thermal expansion between the tube and sleeve. There are two scenarios that

lead to thermal stresses in the weld. The first is the case where the tubes are assumed to be dented at the first tube support plate, with the parent tube below the laser welded joint assumed to be fully severed. In this case the sleeve / tube combination tries to grow axially relative to the wrapper, which supports the tube support plate, and compressive loads develop that pass through the welded joint. The second scenario is for the case where the parent tube below the weld is assumed to maintain its axial load carrying capability. In this case, the tube and sleeve are at different temperatures, and a shear load is developed across the welded joint due to differential thermal expansion of the tube and sleeve.

It will be shown that for both of the above scenarios, that the combined primary plus secondary stresses in the tube and sleeve meet the $3S_m$ limit. The 0.015 inch minimum laser weld engagement length represents a highly localized region that is subjected to essentially pure shear stresses due to both pressure (end cap) and thermal loads. The weld is surrounded by elastic members (tube and sleeve) which are within the $3S_m$ Code limit. Even if plastic strains occur in the weld, large deformations cannot occur due to the geometry of the welded joint and the constraint of the surrounding elastic members.

Based on the above, the combined pressure and thermal stresses in the weld due to normal, upset and test loadings need only be considered from a fatigue standpoint in order to show compliance with the ASME Code for cyclic operation.

3.1.3 Loading Conditions Considered

The loadings considered in the analysis represent an umbrella set of conditions and are defined in Reference 2. The analysis considers a full duty cycle of events for both FSGs and PSGs with 3/4 inch tubes that includes design, normal, upset, faulted, emergency and test conditions. A summary of the applicable transient conditions is provided in Table 3-8. The applicable temperatures and pressures are based on the transient definitions in Reference 2. Umbrella pressure loads for Design, Faulted, Emergency and Test conditions are summarized in Table3-9.

3.1.4 Analysis Methodology

A detailed evaluation of 7/8 inch tube sleeves has been performed and documented in Reference 1. This evaluation was performed to demonstrate the acceptability of installing laser welded sleeves in Westinghouse Series 44 and 51 steam generators and identifies the critical locations in the sleeve and tube. Detailed finite element models of the sleeve/tube/tubesheet were assembled to determine the response of the components with a sleeve installed in the tube at the tubesheet elevation. Another model was developed to determine the response of the components with a sleeve installed in a tube at a tube support (TSP) location. The evaluation considered the potential for the tube to be either separated or intact.

The results of the [

]a,c,e

The analysis has also investigated the potential effects of the various [

]a,c,e

Since the size of the tubes and sleeves [

]a,c,e

The analysis of the laser welded sleeve designs utilizes both conventional and finite element analysis techniques. Several finite element models are used for the analysis (Reference 1). For the tubesheet sleeve analysis, [

]a,c

Typically, the tubesheet sleeve model incorporates a [

]a,c in the tubesheet. The analysis considers both [

]a,c

All PSGs and FSGs are full-depth expanded in the tubesheet. However in spite of the actual configuration, the limiting geometry, judged to be a [

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

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

Qualification tests for the weld process have shown that the laser weld joining the tube and sleeve may be as small as [ ]a,c Thus, in performing this analysis, a weld width of [ ]a,c is considered. The acceptability of the [ ]a,c inch weld is evaluated using pressure tests to establish the pressure retaining capability of the welds (primary stress) and a separate finite element analysis to evaluate fatigue usage in the welds. The stress and fatigue results reported later in the report are for the limiting weld geometry, or the [ ]a,c width.

3.1.4.1 Sleeve/Tube Size Considerations

As indicated earlier, results from the previously completed evaluation of sleeving for 7/8 inch tubes (Reference 1) are used to form a basis to demonstrate acceptability of sleeving for 3/4 inch steam generator tubes. [

]a,c

Since the designs of the 7/8 inch tube sleeves and the 3/4 inch tube sleeves are similar except for basic dimensions, the 7/8 inch tube sleeve results were used with corrections to account for these geometry differences. Correction factors have been developed [

]a,c,e

The correction factors were developed by [

]a,c

3.1.4.2 Tubesheet Rotation Effects

Loads are imposed on the sleeve as a result of tubesheet rotations under pressure and temperature conditions. Reference 1 established the tubesheet rotations for five reference loading conditions for the 7/8 inch tube sleeve. The five reference loading conditions consisted of [

]a,c. The [

]a,c loadings. The [

]a,c. This section establishes the applicability of the tubesheet rotation loadings determined in Reference 1 to the laser welded sleeves for the PSGs as well as for theFSGs.

Differences among the geometries of the Westinghouse steam generators are given in the top part of Table 3-11. Plate bending equations are used to calculate the stresses in the perforated part of the tubesheet for the different geometries. As is shown in the bottom part of Table 3-11, the bending stresses produced by pressure are [

]a,c,e

The geometry of the FSGs is markedly different from the Westinghouse steam generators, since the diameters of FSG tubesheets are larger with a central stay between the channel head and tubesheet. Accordingly, a finite element analysis was performed for the FSG to determine the tubesheet rotations produced by the five reference pressure and temperature conditions. Figure 3-2 shows the finite element model of the channel head, stay, tubesheet, and lower shell. The boundary conditions and deformed geometry for the [

]a,c,e. Thus the results obtained for the Series 51 steam generator sleeves in Reference 1 are conservative when applied to the FSGs.

As is described in Reference 1, [

]a,c

3.1.4.3 Thermal Transient Comparisons

Since the size of the tubes and sleeves are not identical for the Series 51 SG (7/8 inch) and the preheat steam generators (PSGs) and FSGs (3/4 inch), a potential exists that the [

]a,c,e

The [ ]a,c transients used in the Reference 1 evaluation were applied to the Series 51 SG, and stresses were calculated for the times selected in the Reference 1 analysis. Axial stresses and stress intensities were tabulated at the inside and outside surfaces adjacent to the weld. These stresses are given in Table 3-13 for each of the transients. The WECEVAL LC# in the last column of Table 3-13 refers to the load condition number of the thermal transient stresses used in the Reference 1 fatigue analysis.

Thermal boundary conditions [

]a,c These transients were applied to the appropriate finite element model (PSG or FSG sleeve/tube geometry), and stresses calculated at selected times comparable to those selected in the Reference 1 evaluation.

As for the Series 51 model, [

]a,c,e

3.1.5 Heat Transfer Analysis

A detailed heat transfer analysis [

]a,c,e

The first step in calculating the stresses induced in the sleeves as a result of the thermal transients is to perform a heat transfer analysis to establish the temperature distribution for the sleeve, tube, and tubesheet. Based on a review of the transient descriptions, [ ]a,c enveloping transients were selected for evaluation in the previous 7/8 inch tube sleeve analysis (Reference 1). They include the following events:

a,c

[ ]

The [

]a,c

In performing the heat transfer analysis for the enveloping transients, [

]a,c A sketch of the model boundary conditions for the heat transfer analysis are shown in Figure 3-5.

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

]a,c

3.1.6 Tubesheet/Channel Head/Shell Evaluation

A detailed tubesheet/channelhead/shell evaluation for 7/8 inch tube sleeves was performed in Reference 1. This previously completed analysis has determined that [

]a,c

3.1.7 Stress Analysis

In performing the stress evaluation for the sleeve models, [

]a,c Sketches of the model boundary conditions for the primary side pressure cases are shown in Figures 3-6 through 3-9. Sketches of the model boundary conditions for the secondary side pressure cases are shown in Figures 3-10 through 3-13. It should be noted for both sets of loads that the end cap load on the tube is not included, but is considered in a separate load case.

The analysis considers [

]a,c

The effects of [

]a,c

Finally, [

]a,c

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

$$\sigma_{total} = P_{PR}\,(\sigma)\text{ unit primary pressure / 1000 } + P_{SEC}\,(\sigma)\text{ unit secondary pressure / 1000 } + (\sigma)\text{ thermal transient stress } + P_{Axial}\,(\sigma)\text{ unit axial load / 1000}$$

Note that the 7/8 inch tube sleeve evaluation has determined that [

]a,c

3.1.8 ASME Code Evaluation

The ASME Code evaluation was performed using a Westinghouse proprietary computer code. The evaluation was performed for specific analysis sections (ASN's) through the finite element model. The ASN's evaluated to determine the acceptability of the sleeve design are shown in Figure 3-1. Note that this location has been determined to be limiting in the evaluation performed for 7/8 inch tubes.

The umbrella loads for the primary stress intensity evaluation have been given previously in Table 3-9. The largest magnitudes of the [

]a,c

The results for maximum range of stress intensity and fatigue are summarized in Table 3-16 for the tube being [

]a,c The analysis results show the ASME Code limits to be satisfied.

Note that in evaluating seismic stresses, [

]a,c,e

3.1.9 Weld Evaluation

3.1.9.1 Limiting LWS Host Tube Size For Pressure Testing

The evaluation of the laser weld to show compliance with ASME Code requirements for primary pressure stress is based on an experimental stress analysis as discussed in Section 3.1.4. This section determines the limiting or bounding host tube size for burst pressure testing of the LWS installation.

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 3-14. 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:

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

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 3. The ratio of calculated maximum shear stress to allowable shear stress ϕ is:

$$\phi = \frac{\tau_{max}}{\tau_a} = \frac{R_{max} \Delta P_{max}}{2 w_{min} \tau_a}$$

The ratio ϕ determines the limiting host tube size and loading condition for testing.

Per NB-3227.2, the allowable shear stress in the weld (τ_a) is:

Design Allowable:

$$\tau_a = 0.6\ S_m = 0.6\ (26.6) = 15.96 \text{ ksi}$$

Test Allowable:

$$\tau_a = 0.6\ (0.9\ S_y) = 0.6\ (0.9)\ (35.3) = 19.06 \text{ ksi}$$

Emergency Allowable (largest of the following):

$$\tau_a = 0.6\ (1.2\ S_m) = 0.6\ (1.2)\ (26.6) = 19.15 \text{ ksi}$$

$$\tau_a = 0.6\ S_y = 0.6\ (35.3) = 21.18 \text{ ksi. (use as allowable)}$$

Faulted Allowable:

$$\tau_a = 0.42\ S_u = 0.42\ (80) = 33.6 \text{ ksi}$$

A summary of the maximum primary to secondary pressure differentials (ΔP_{max}) is provided in Table 3-17. Loads are based on the defined transient duty cycles in Reference 2 for various steam generator models, identified by the corresponding nominal outside diameter of the host tubes[1]. Table 3-18 lists the calculated values for the ratio ϕ for each nominal host tube size and load condition. It is observed that the maximum value of ϕ [ ]a,c occurs for the 7/8 inch OD host tube under Design Condition loads. Therefore, experimental justification of the [ ]a,c inch minimum weld width is performed for the 7/8 inch OD tube under design loads as a bounding set of parameters for the 3/4-W, 3/4-CE, and 11/16 OD host tube sizes.

3.1.9.2 Primary Stress Analysis

The evaluation of the laser weld to show compliance with ASME Code requirements for primary stress is based on an experimental stress analysis following the guidelines of Paragraph NB-3649 of the Code. Based on the results in Table 3-18, the limiting geometry is the 7/8 inch OD tube under design pressure conditions. Test samples were prepared for a 7/8 inch OD tube, pressure tested, and then using the test results, a failure pressure is calculated that corresponds to a [ ]a,c inch minimum weld width, maximum tube / sleeve interface radius, and with ASME Code minimum strength properties. The resulting failure pressure is then compared to the design

[1] For CE steam generators, a primary-to-secondary ΔP of 1600 psi is used for Design Conditions. The original design qualification for the laser welds conservatively used 2250 psi for CE Design Conditions. This, however, is judged to be unrealistic. For any CE plant where a primary-to-secondary ΔP higher than 1600 psi is specified for Design Conditions, additional calculations are required to qualify the 0.015 inch minimum weld.

pressure load of 1600 psi to determine if a factor of safety of three or greater exists, satisfying the ASME Code requirements for primary stress.

Two sets of test samples were prepared. In both cases, the test samples were prepared consistent with field installation procedures, with one exception. In an attempt to achieve an average width of [ ]a,c inch, the power setting was deliberately set outside the bounds of the field process (below the low end) for the first set of samples, sample numbers 1 to 15. For the second set of samples, sample numbers 16 to 27, the power setting was within the allowable power range, but at the low end.

In the course of the sample preparation, the welds were UT inspected using the same technique as in the field to determine acceptability. As a result of these UT inspections, several of the welds, samples (1, 2, 6, 7, 11 - 15), were rejected and are not included as part of this evaluation. There is also a requirement for the field process that the tube / sleeve weld be more than 0.50 inch away from the end of the expansion zone in the sleeve. Three samples (25, 26, and 27) did not meet this requirement and are also not included as part of the evaluation. A complete summary of the test sample matrix is provided in Table 3-19, indicating which samples have been included in the evaluation of the weld. It should be noted that although samples 9 and 20 did not pass the UT inspection, the results are conservatively included in the evaluation. Finally, sample 19 was not included because accurate measurements of the weld thickness could not be made due to scarring of the sleeve OD surface.

A summary of the average weld widths for each of the samples that were pressure tested is provided in Table 3-20. Also provided is a summary of the resulting failure pressure for each test. In a number of cases, particularly for the second set of samples (15 - 27), the welds did not fail. Rather the tubes experienced a fish-mouthed burst failure. In order to measure the weld size for the samples where a burst failure of the tube occurred, it was necessary to expose the weld by failing the samples in tension. A summary of the pull forces necessary to cause tensile failure for these specimens is also listed in Table 3-20. For those samples where the weld failed during the pressure test, "N/A" is listed for the pull force.

As discussed earlier, compliance with elastic ASME Code limits for design conditions requires a factor of safety of three, consistent with the allowable membrane stress for design conditions of $S_u/3$, between the maximum test pressure and the maximum design pressure. For a design pressure of 1600 psi, this corresponds to a minimum test pressure of 4800 psi.

In the course of evaluating the test results, the failure pressures [

]a,c

[

]a,c

Substituting in the above equation,

[

]a,c

The test samples satisfy the 4800 psi pressure requirement as long as the calculated Safety Factor (SF_i) is ≥ 3.0.

Using the above formulation, safety factors are calculated for each of the test samples where the sample failure occurred in the weld joint (samples 3, 8, and 10). In calculating the safety factors for the test specimens, the average of the weld width readings is used as a conservative upper bound of the minimum weld width to account for variability and uncertainty in the optical readings. In the formulation above for the safety factor, use of a larger weld size is conservative, in that it results in a smaller safety factor. The resulting safety factors are shown in Table 3-20. Note that for samples, 5 and 9, assuming the welds to have failed at the reported maximum test pressure is conservative, and the above algorithm is conservatively applied to the test results, with the safety factor representing a minimum value for these tests.

---

[2] Since the field acceptance criteria for the welds is based on a go/no go relative to the minimum weld width anywhere around the circumference, the measured minimum weld width is used to have a consistent set of criteria.

For the samples where the tube burst, an estimate of the weld strength is made by comparing the weld geometry and failure pressure for the ith sample to the same parameters for the samples where the weld failed. The pressure that would have failed the weld in these samples is higher than the maximum test pressure that was achieved for the test.

For those samples where the tube burst, an estimated failure pressure is calculated using the results of the pull force tests. Comparison of the pull force to the measured weld width shows that the samples have consistently greater strength with increasing weld size. Thus, it would be expected that these samples would also have a failure pressure for the welds that increases with increasing weld size. In order to estimate the failure pressure for the welds, a relationship is needed between the pull force and weld failure pressure. Since a pull force does not exist for samples where the weld failed under pressure, a direct one-to-one relationship cannot be established between pull force and failure pressure. For the available test data, sample 5 is judged to give the best approximation of the ratio between pull force and burst pressure, simply because it is one of the samples with a relatively small weld, and the expected failure pressure for the weld is expected to be close to the pressure at which the tube failed (based on the weld failure pressure for samples 3, 8, and 10). Thus, for each of the samples where tube burst occurred, an estimated failure pressure is calculated by scaling the failure pressure for sample 5 by the ratio of the pull force for the ith test to the pull force for sample 5. The resulting estimated failure pressures are summarized in Table 3-20. The estimated failure pressures are then substituted in the algorithm above to calculate SF for the samples where tube burst occurred.

An overall summary of the resulting safety factors is provided in Table 3-20. For the samples where the weld failed (3, 8, 10), the minimum safety factor is 4.0. For the remaining samples, where a fish-mouthed failure of the tube occurred, the minimum calculated safety factor is 3.5. Overall, these results show that significant margin exists relative to the strength of the [ ]a,c inch minimum weld width.

The following conclusions, regarding the pressure retaining capability of the [ ]a,c inch minimum laser weld width for the 7/8, 3/4-W, 3/4-CE, and 11/16 inch OD host tube sizes, are based on the results of the experimental stress analysis:

1. Scaling the results for each of the test samples to minimum strength and weld width requirements shows that the ASME Code factor of safety of 3.0 for design conditions is met for each test sample, with a minimum safety factor of 4.0 for the samples where the weld failed under pressure.

2. Welds performed using a power setting at the low end of the field weld process specification have weld widths well above the minimum specified weld width of [ ]a,c inch.

3. Given that strength properties for representative tube and sleeve material is well above the ASME Code minimum specified values, significant additional margin exists for field welds.

4. The safety factors calculated in this analysis are judged to represent a lower bound for welds in the field. The probability of having a weld with the minimum acceptable weld width of [ ]a,c inch, a sleeve with minimum ASME Code strength properties, a tube with minimum section properties (maximum inside radius), and a tube that is completely severed below the welded joint is judged to be extremely low. Even if all of these highly unlikely events would occur simultaneously, the results of the experimental analysis show that the ASME Code minimum margin of 3.0 for design loads is satisfied.

5. The pressure tests show that for welds made within the weld process specifications, using a tube and sleeve with prototypic strength characteristics, that the welded joint is stronger than the tube itself, in that the tube burst in twelve out of twelve cases.

Overall, it is concluded that a minimum weld width of [ ]a,c inch for the tube / sleeve weld is structurally acceptable for all specified pressure loads acting on the FLTS, ETS, and TSS laser welded sleeves for each of the host tube sizes summarized above.

3.1.9.3 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, Reference 3, with respect to the specified generic cyclic loads given in Reference 2. The evaluation considers the following sleeve types for installation in Westinghouse steam generators with 3/4 inch OD x [ ]a,c inch wall host tubes and ABB-CE steam generators with 3/4 inch OD x [ ]a,c inch wall host tubes:

Full Length Tubesheet Sleeve (FLTS),

Elevated Tubesheet Sleeve (ETS),

Tube Support Plate Sleeve (TSS).

For each of the above sleeve types, the fatigue evaluation considers all possible combinations of [

]a,c

<u>Geometry and Materials</u>

The weld is located at approximately the center of the 2.5 inch hydraulically expanded length of sleeve. The residual stresses due to the hydraulic expansion and the laser welding process are removed by heat treatment prior to returning the sleeved tube to service. Therefore, it is reasonable to assume that the strength properties (including the S-N fatigue curves) of Alloy 690 in the ASME Code also apply to the weld.

The fatigue evaluation of the laser weld considers the following sleeve types:

Full Length Tubesheet Sleeve (FLTS), 36 inch length,

Elevated Tubesheet Sleeve (ETS), 12 inch length,

Tube Support Plate Sleeve (TSS), 12 inch length for 3/4 Westinghouse Host Tubes.

Tube Support Plate Sleeve (TSS), 15 inch length for 3/4 ABB-CE Host Tubes .

All hydraulic expansion lengths are assumed to be 2.5 inches with 0.25 inch long transitions at each end. Most geometric parameters are assumed to be at their nominal values, except that the minimum weld engagement length of [ ]a,c inch is assumed for all laser welds. The nominal outer diameter and wall thickness of the sleeve and tube are:

Westinghouse 3/4 Host Tube: [ ]a,c inch wall,

Sleeve: [ ]a,c inch wall.

ABB-CE 3/4 Host Tube: [ ]g inch wall,

Sleeve: [ ]a,c inch wall.

Material Data

The following material properties, taken from the ASME Code, Reference 3, are used in the fatigue evaluation:

Alloy 600 Tubes at 550 °F

E = elastic modulus = 28.85×10^6 psi

μ = Poisson's ratio = 0.3

α = mean coefficient of thermal expansion from 70°F = 7.77×10^{-6} (°F)$^{-1}$

K = thermal conductivity = 2.57×10^{-4} BTU / (sec-in-°F)

Alloy 690 Sleeve at 600 °F

E = elastic modulus = 27.8×10^6 psi

μ = Poisson's ratio = 0.3

α = mean coefficient of thermal expansion from 70°F = 8.16×10^{-6} (°F)$^{-1}$

K = thermal conductivity = 2.31×10^{-4} BTU / (sec-in-°F)

SA-508 Class 2 or 2a Tubesheet at 600 °F

E = elastic modulus = 26.4×10^6 psi

μ = Poisson's ratio = 0.3

α = mean coefficient of thermal expansion from 70°F = 7.42×10^{-6} (°F)$^{-1}$

Air at 600°F (assumed in the gap between the unexpanded sleeve and host tube)

K = thermal conductivity = 5.78×10^{-7} BTU / (sec-in-°F)

Cyclic Load Conditions

The cyclic loads used in the analysis are defined in the generic laser welded sleeve (LWS) design specification for the 3/4 inch OD host tubes, Reference 2. The normal, upset, and test transients are generally given in terms of transient changes relative to an initial steady state condition, usually at full power operation. The full power conditions, which are assumed in the generic LWS fatigue evaluation, are listed below:

100% Full Power Steady State Conditions
Assumed in the Generic 3/4 LWS Fatigue Evaluation
(Conditions Apply to Both Westinghouse and ABB-CE 3/4 LWS)

a,c

[ ]

All of the pressure and thermal loads are defined in terms of the transient values of the four parameters, P_p, P_{stm}, T_h, and T_{stm}, whose full power steady state values are defined above. The variations in these load parameters, and the specified number of occurrences (cycles) for each transient, are obtained from the design specification, Reference 2. Table 3-21 lists values of P_p, P_{stm}, T_h, and T_{stm} and the number of occurrences (NOC) for each of the specified transients for a 40 year fatigue design life. The transient load values in Table 3-21 are relative to the above assumed generic full power conditions, for which the primary to secondary pressure differential is [ ]a,c psi, and the hot leg (primary) to steam (secondary) temperature differential is [ ]a,c°F. These generic full power load differentials and the number of occurrences (NOC in Table 3-21) conservatively bound the various plants with Westinghouse and ABB-CE 3/4 inch OD host tubes.

For the primary and secondary hydro test load events in Table 3-21, the pressure drops are limited to the design pressure.

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_h) 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 of the 7/8 LWS were employed to calculate the radial gradients in the sleeve and tube above the tubesheet. (The 3/4 LWS sleeve and tube will exhibit similar thermal responses. Therefore, the results of the 7/8 LWS thermal analysis also apply to the 3/4 LWS.) Three sections, or slabs, were 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; (3) a section through only the tube at the far field above the sleeve.

In section (1) of the thermal model, the gap between the unexpanded sleeve and tube was filled with thermally conducting static air, plus 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 specified in Table 3-21 using the listed values of T_h 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

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 (SA-508 Class 2) 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 all of the [

]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

Thermal loads are simulated [

]a,c

Shear Forces on Weld Due to Unit Loads

The LWS structural finite element models shown in Figure 3-15 were used to calculate the shear forces acting in the various longitudinal spring elements simulating each laser weld. The following 24 possible model combinations were simulated:

[

]a,c

The following four unit load cases were run for each of the 24 above model combinations:

[a,c]

All thermal expansion cases are relative to a reference temperature of 70°F. Table 3-22 lists the resulting finite element calculated shear forces due to the above unit loads for each of the 24 possible combinations of [

]a,c

Stress Range Calculations

For any of the 24 combinations of sleeve type, host tube state, and TSP condition listed in Table 3-22 (say the kth combination), the shear force F_i on the weld may be found for any of the 71 load events (say the ith load event) listed in Table 3-21 as follows:

[a,c]

where $(P_p, P_{stm}, T_h, T_{stm})_i$ for the particular i^{th} load event are defined in Table 3-21, and $(F_{Pp=1000}, F_{Pstm=1000}, F_{Th=570}, F_{Tstm=570})_k$ are the finite element calculated shear forces due to the unit loads in Table 3-22 for the kth combination. The shear force F_i (in lbf) is divided by the weld's assumed minimum shear area [

]a,c The typical average shear stress range for the ith 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 $(P_p, P_{stm}, T_h, T_{stm})_j$ 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 [

]a,c

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 the ith or j^{th} load events, is reduced by n_{ij}, as shown below:

$$(noc_i)_{\text{FOR_NEXT_USAGE_CALC}} = \left[noc_i - n_{ij} \, , \, 0\right]_{\text{USE_MIN_VALUE}} ,$$

$$(noc_j)_{\text{FOR_NEXT_USAGE_CALC}} = \left[noc_j - n_{ij} \, , \, 0\right]_{\text{USE_MIN_VALUE}} .$$

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. 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 [

]a,c listed in Table 3-22 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 for the [

]a,c

The overall maximum cumulative fatigue usage factor of [ ]a,c was calculated using the process discussed above to obtain the stress ranges, subject to a logical ordering of the transients. Using the FE calculated weld shear forces for the pressure and temperature unit load cases from Table 3-22 for the maximum cumulative fatigue usage condition, the shear force transferred across the weld is calculated for each of the 71 transient load conditions specified in Table 3-21. A summary of the resulting calculated weld shear forces and average shear stresses is provided in Table 3-23. Using the transient conditions summarized in Table 3-23, a load histogram is developed to logically order the transients, as shown in Figure 3-19. This histogram is then used to establish fatigue cycles for the various transient conditions. A summary of the resulting fatigue cycles, stress ranges, stress amplitudes, allowable cycles and fatigue usage is contained in Table 3-24, for which the calculated cumulative usage factor is [ ]a,c.

Note that load range combination 9 (load 5 in Table 3-21 minus load 19 in Table 3-21), which accounts for the majority of the usage [ ]a,c, involves a conservatively large number of load/unload transients. The number of load/unload transients ([ ]a,c in Table 3-5) from the generic specification, Reference 2, assumes a load ramp from full power to hot standby approximately once a day, everyday, throughout the design lifetime. This represents a very conservative generic bounding value. In actuality, most plants base load (i.e., remain at 100% power), and the actual number of load/unload transients over 40 years is a fraction of the [ ]a,c cycles. Assuming a more realistic, yet conservative, number of load/unload transients of [ ]a,c rather than the [ ]a,c for u_9, results

in a cumulative usage factor of [ ]a,c compared to [ ]a,c for the reference number of transients.

Fatigue Analysis Conclusions

A conservative analytical fatigue evaluation of the 0.015 inch minimum weld engagement length for laser welded sleeves has been completed. The fatigue evaluation considered [

]a,c All calculated cumulative fatigue usage factors are less than the ASME Code allowable of one. The fatigue evaluation is conservative for the following reasons:

1. In the fatigue evaluation all welds are assumed to be at the minimum thickness of 0.015 inch around a full 360° of circumference. In practice, due to the QA inspection procedure, the weld thickness (averaged over the circumference) is significantly larger than 0.015 inches (see Table 3-19).

2. The number of load/unload transients in the generic specification, Reference 2, is very conservatively based on operating the plant using load follow. Using the maximum number of load cycles from the generic specifications, without modification, gives an overall maximum cumulative usage factor of [ ]a,c. Actually, all Westinghouse plants base load (i.e., remain at 100%), and the actual number of load/unload transients are a fraction of the number given in the generic specifications. Assuming a much more realistic number of [ ]a,c load/unloading cycles over a 40 year fatigue design life, results in an overall maximum cumulative factor of [ ]a,c.

Overall, it is concluded that the [ ]a,c inch minimum thickness weld satisfies the ASME Code fatigue cumulative usage factor limit of one or less for a 40 year fatigue design life, for all 3/4 inch OD host tubes, Westinghouse and ABB-CE, for all sleeve types [

]a,c and all combinations of specified normal, upset, and test service conditions and loads.

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,

$$t_{min} = \frac{\Delta P_i \, R_i}{P_m - 0.5 \, (P_i + P_o)} 1$$

Separate calculations are performed for the Model D, Model E, and Feedring steam generators.

Normal/Upset Operation Loads

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

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

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

Accident Condition Loadings

LOCA + SSE

The dominant loading for LOCA and SSE loads occurs [

]a,c

FLB/SLB + SSE:

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

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

A summary of the resulting minimum required wall thicknesses are given in Table 3-25. Also provided in Table 3-25 is a summary of the limiting minimum wall requirements for each model steam generator considering all of the loading conditions.

3.1.11 Determination of Plugging Limits

The minimum acceptable wall thickness and other recommended practices in Regulatory Guide 1.121 are used to determine a plugging limit for the sleeve. The Regulatory Guide was

written to provide guidance for the determination of a plugging limit for steam generator tubes undergoing localized tube wall loss and can be conservatively applied to sleeves. Tubes with sleeves which are determined to have indications of degradation of the sleeve in excess of the plugging limit, would have to be repaired or removed from service.

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

Paragraph C.3.f of the Regulatory Guide specifies that the bases used in setting the operational degradation analysis include the method and data used in predicting the continuing degradation. To develop a value for continuing degradation, sleeve experience must be reviewed. To date, no degradation has been detected on Westinghouse designed mechanical joint sleeves and no sleeved tube has been removed from service due to degradation of any portion of the sleeve. This result can be attributed to the changes in the sleeve material relative to the tube and the lower heat flux due to the double wall in the sleeved region. Sleeves installed with the laser weld joint are expected to experience the same performance. As a conservative measure, the conventional practice of applying a value of [ ]a,c of the sleeve wall, applied as an allowance for continued degradation, is used in this evaluation. In summary, the operational sleeve thickness acceptable for continued service includes the minimum acceptable sleeve wall thickness, and the combined allowance for NDE uncertainty and operational degradation [ ]a,c. A summary of the resulting plugging limits as determined by Regulatory Guide 1.121 recommendations are given in Table 3-26.

3.1.12 Application of Plugging Limits

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

1) Indications of degradation in the length of the sleeve, between the inboard-most weld joints of TSSs or between the inboard-most weld and the separation distances (SD) of the roll top of the lower (MIF) joint of the tubesheet sleeves, must be evaluated against the sleeve plugging limit.

2) For TSSs, indications of tube degradation of any type, including a complete break in the tube between the SDs of the inboard-most of the upper and lower weld joints does not require that the tube be removed from service.

3) For tubesheet sleeves, indications of tube degradation of any type, including a complete break in the tube between the sleeve inboard-most weld and the upper extent of the SD of the top of the effective axial length of the roll expansion of the lower joint, does not require that the tube be removed from service.

4) At all weld joints, degradation must be evaluated in both the sleeve and tube.

5) In a joint with more than one weld, the final re-welded joint is the joint to be inspected.

6) The tube plugging limit continues to apply to the portion of the tube outside of the sleeved regions.

3.1.13 Analysis Conclusions

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

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

Property	Temperature (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E06	31.00	30.20	29.90	29.50	29.00	28.70	28.20
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	6.90	7.20	7.40	7.57	7.70	7.82	7.94
Density lb-sec^2/in^4 x 1.0E-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 (Section III Appendices)	40.00	36.80	34.60	33.00	31.80	31.10	30.60
S_y (Code Case N20-3)	40.00	38.20	37.30	36.30	35.70	35.30	35.00
S_u	80.00	80.00	80.00	80.00	80.00	80.00	80.00

Note: A discrepancy exists between the properties specified for S_y for Alloy 690 in the ASME Code Section III Appendices and Code Case N20-3. In transferring the Code Case numbers for N20-3 to Section III, properties for Alloy 690 and Alloy 800 (also listed in the Code Case) were transposed. The sleeve material is purchased to the requirements of Code Case N20-3, and the N20-3 properties are applicable to the sleeves. In the structural evaluation of the LWS, the Section III properties have been used for Alloy 690 for the sleeve, and N20-3 properties for the evaluation of the weld, which has been shown to have the same chemical composition as the sleeve.

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
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 3-5
Summary of Material Properties
Water

Property	Temperature (°F)						
	70	200	300	400	500	600	700
Density lb-sec^2/in^4 x 1.0E-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-in/lb-sec^2-°F x 1.0E+2	3.82	3.88	3.96	4.12	4.37	5.26	8.51

Table 3-6
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
	$P_1 + P_b \leq 1.5\ S_m$	39.90	34.95
Faulted	$P_m \leq .7\ S_u$	56.00	56.00
	$P_1 + P_b \leq 1.05\ S_u$	84.00	83.88
Test	$P_m \leq 0.9\ S_y$	36.00	31.50
	$P_1 + P_b \leq 1.35\ S_y$	54.00	47.25
Emergency	$P_m \leq S_y$	40.00	35.00
	$P_1 + P_b \leq 1.5\ S_y$	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 3-7
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	$P_1 + P_b + Q \leq 3\ S_m$*	79.80	69.90
Normal, Upset, and Test	Cumulative Fatigue Usage	1.0	1.0

* - Range of Primary + Secondary Stress

Table 3-8
Summary of Transient Events

a,c,e

- Continued -

Table 3-8 (continued)
Summary of Transient Events

a,c,e

Table 3-9
Umbrella Pressure Loads for
Design, Faulted, and Test Conditions

a,c,e

[ ]

1) For tubes repaired by sleeving
2) [ ]b,c
3) [ ]b,c
4) [ ]b,c
5) [ ]b,c
6) [ ]b,c
7) [ ]b,c

Table 3-10
Stress Modification Factors
7/8 Inch to 3/4 Inch Tube Sleeves

a,c,e

Table 3-11
Tubesheet Comparisons for
Westinghouse Steam Generators

a,c

Table 3-12
Comparisons of Tubesheet Stresses for
FSGs and Series 51 Steam Generators

a,c,e

Table 3-13
Transient Stresses at Sleeve/Tube Interface - Series 51 SG

a,c,e

Table 3-14
Ratio of Models D, E, and FSGs to Series 51 SG Transient Stresses

a,c,e

Table 3-15
Summary of Maximum Primary Stress Intensity
Full Length Tubesheet Laser Welded Sleeve

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

a,c,e

[ ]

Table 3-16
Maximum Range of Stress Intensity and Fatigue
Full Length Tubesheet Laser Welded Sleeve

Sleeve/Tube Weld Width of [ ]a,c

[ ]a,e

a,c,

(1) Including K_e factors for simplified elastic-plastic analysis.

Table 3-17

Maximum ΔP Loads (psi) Used to Size Laser Welds

a,c

* Section XI (IWA 4700, IWA 5000, and IWB 5000) specifies that hydrostatic test loads will be run on these repair welds that will be below the design ΔP load at a maximum test temperature of 600°F.

Table 3-18
Ratios of Maximum Calculated Average Shear Stress to the ASME Code Allowable Shear Stress

a,c

[ ]

Table 3-19
Summary of Test Sample Matrix

Sample	UT Results[1]	Pressure Tested	Pull Tested	Data Used
1	IWW	No	---	---
2	IWW	No	---	---
3	ACC	Yes	Yes	Yes
4	Not Evaluated	No	---	---
5	ACC	Yes	N/A	Yes
6	IWW	Yes	N/A	No[2]
7	IWW	No	---	---
8	ACC	Yes	N/A	Yes
9	IWW	Yes	Yes	Yes[3]
10	ACC	Yes	N/A	Yes
11	IWW	No	---	---
12	IWW	Yes	N/A	No[2]
13	IWW	No	---	---
14	IWW	No	---	---
15	IWW	No	---	---
16	ACC	Yes	Yes	Yes
17	ACC	Yes	Yes	Yes
18	ACC	Yes	Yes	Yes
19	ACC	Yes	Yes	No[4]
20	SHI	Yes	Yes	Yes[3]
21	ACC	Yes	Yes	Yes
22	ACC	Yes	Yes	Yes
23	ACC	Yes	Yes	Yes
24	ACC	Yes	Yes	Yes
25	ACC	Yes	Yes	No[5]
26	ACC	Yes	Yes	No[5]
27	ACC	Yes	Yes	No[5]

(1) IWW-Insufficient Weld Width / ACC-Accept / SHI-Surface Indication
(2) Weld did not pass UT requirement
(3) Although weld did not pass UT requirements, results conservatively included in weld evaluation
(4) Scarred OD sleeve surface prevented accurate weld measurements
(5) Tube was cut too close to weld (outside field tolerance for weld location)

Table 3-20
Summary of Pressure Test Results
7/8 Inch OD Tube

a,b,c

Notes: (a) Estimated based on results of pull test.

(b) In an attempt to achieve an average width of 0.015 inch, the power setting was deliberately set outside the bounds of the field process (below the low end) for the first set of samples, sample numbers 1 to 15. For the second set of samples, sample numbers 16 to 27, the power setting was within the allowable power range, but at the low end.

Table 3-21 (part 1 of 2)
Loads Used in Fatigue Evaluation of
3/4-W and 3/4- CE LWS from Reference 2
(NOC Cycles are for 40 years)

a,c

Table 3-21 (part 2 of 2)
Loads Used in Fatigue Evaluation of
3/4-W and 3/4- CE LWS from Reference)
(NOC Cycles are for 40 years)

a,c

Table 3-22
Calculated Shear Forces (lbf)
on Sleeve/Tube Laser Welds
Due to Indicated Unit Load Cases

a,c

Table 3-23 (part 1 of 2)
Calculation of Weld Forces / Stresses
Generic 3/4 Inch OD Tube

[ ]a,c

a,c

Table 3-23 (part 2 of 2)
Calculation of Weld Forces / Stresses
Generic 3/4 Inch OD Tube

[ ]a,c

a,c

Table 3-24

Max Overall Calculated Cumulative Fatigue Usage Table

[ ]a,c

Min Weld Thk of [ ]a,c inch & 40 Year Fatigue Design Life

a,c

[ ]

Table 3-25
Summary of Minimum Wall Thickness Calculations
Laser Welded Sleeve

a,c,e

Table 3-26
Summary of Recommended Plugging Limits
Laser Welded Sleeve

a,c,e

[ ]

a,c

Figure 3-1
ASN Location - Laser Weld Joint

a,c,e

Figure 3-2
Finite Element Model of
FSG Channel Head / Tubesheet / Shell

a,c,e

Figure 3-3
FSG Channel Head / Tubesheet / Shell Model
Primary Pressure Boundary Conditions and Deformed Geometry

a,c,e

Figure 3-4
FSG Channel Head / Tubesheet / Shell Model
Tubesheet Expansion Boundary Conditions and Deformed Geometry

a,c

Figure 3-5
Thermal / Hydraulic Boundary Conditions
Full Length Tubesheet Sleeve Analysis

a,c

Figure 3-6
Boundary Conditions for Unit Primary Pressure
[ ]^{a,c,e} $P_{PRI} > P_{SEC}$

a,c

Figure 3-7
Boundary Conditions for Unit Primary Pressure
[ ]^{a,c,e} $P_{PRI} < P_{SEC}$

a,c

[ ]

Figure 3-8
Boundary Conditions for Unit Primary Pressure
[ ]^{a,c,e} $P_{PRI} > P_{SEC}$

a,c

Figure 3-9
Boundary Conditions for Unit Primary Pressure
[ ]^{a,c,e} $P_{PRI} < P_{SEC}$

a,c

[ ]

Figure 3-10
Boundary Conditions for Unit Secondary Pressure
[ ]^{a,c,e} $P_{PRI} > P_{SEC}$

a,c

Figure 3-11
Boundary Conditions for Unit Secondary Pressure
[ ]^{a,c,e} $P_{PRI} < P_{SEC}$

a,c

Figure 3-12
Boundary Conditions for Unit Secondary Pressure
[ ]^{a,c,e} $P_{PRI} > P_{SEC}$

a,c

Figure 3-13
Boundary Conditions for Unit Secondary Pressure
[ ]^{a,c,e} $P_{PRI} < P_{SEC}$

a,c

Figure 3-14
Schematic of Sleeve, Tube and Weld and Free Body Diagram of Severed Tube Showing Shear Force on Laser Weld

a,c

Figure 3-15
Schematic of Structural Models
FLTS, ETS, and TSS Laser Welded Sleeve Types

a,c

[ ]

Figure 3-16
K_t / K_f as a Function of Notch Radius

a,c

Figure 3-17
q * K_t as a Function of Notch Radius

a,c

Figure 3-18
Finite Element Model - Element Layout

Figure 3-19
Transient Operating Cycle
Generic 3/4 Inch OD Tube
(Transient Numbers Refer to Loads Listed in Tables 3-21 and 3-23)

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 are determined so that a single number applies to a given steam generator model and tube sleeve configuration.

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

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

The calculation of the flow reduction and equivalency number for a sleeved tube is dependent upon: 1) the tube geometry, 2) the sleeve geometry, and 3) the steam generator primary flow rate and temperature. These parameters are used to compute the relative

difference in flow resistance of sleeved and unsleeved tubes operating in parallel. This difference in resistance is then used to compute the relative difference in flow between sleeved (W_{slv}) and unsleeved (W_{unslv}) tubes. The hydraulic equivalency number is then simply:

a.c.e

[ ]

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

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

The specific LOCA conditions used to evaluate the effect of sleeving on the 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.

Hydraulic Equivalency Calculation

The goal of the calculations described below is to develop conservative values of hydraulic equivalency to bound all possible sleeve configurations that might be considered for steam generators with 3/4 inch tubes. The steam generators included FSG configurations with heat transfer areas of 88,500 ft^2 and 103,600 ft^2. Hydraulic equivalency numbers are generated for a tube with each of the following tubesheet sleeve configurations and up to 12 tube support sleeves.

1) No tubesheet sleeve

2) One tubesheet sleeve (hot or cold leg)

3) Two tubesheet sleeves (hot and cold leg)

Based on previous evaluations (Reference 1), the most conservative sleeve configurations and operating conditions were selected for determining hydraulic equivalency. A sensitivity study was then performed with the least conservative limit of the same configurations and operating conditions to verify that the parameters selected were conservative.

Previous evaluations have shown that for any given sleeve, location of the sleeve in the cold leg at the highest tube support elevation gave the lowest (most conservative) value of equivalency number. Therefore, for each sleeve configuration examined, the maximum possible number of sleeves were located in the cold leg at the higher tube support elevations. Additional dynamic structural evaluations would be required to verify sleeves in the cold legs of PSGs because of the additional effects of the preheater crossflow). Also, the longest tubesheet sleeve (36 inches) was used for all calculations. This sleeve gives a lower equivalency value than shorter sleeves. Only one tube support sleeve length (12 inches) is under consideration for the Westinghouse Models. The longest TSS (15 inches for the "grid" (eggcrate)) was used for the FSGs.

Operating conditions affect equivalency to a smaller degree, with high values of primary flow or T_{hot} and low values of T_{cold} giving the most conservative values of equivalency. The following values of these parameters were selected for each of the steam generator models. These operating conditions are at the conservative end of the typical range for the particular model. For the FSG models, the 88,500 ft^2 generator was chosen because it gave the lowest hydraulic equivalency numbers.

Operating Conditions Used for Hydraulic Equivalency Calculations

	Conservative Parameter Value		
Parameter	FSG	Model D	Model E
Primary Flow - GPM	190,000	100,000	100,000
Primary T_{hot} - °F	615	620	626
Primary T_{cold} - °F	540	543	555

Calculated values of hydraulic equivalency are presented for these three steam generator models as a function of sleeve configuration in Figures 3-20 through 3-22. The table at the bottom of each figure displays the values of hydraulic equivalency plotted along with the configuration of tube support plate sleeves for each case. Notice that the tube support plate sleeves fill up the cold leg, top tube support plate locations first and then spill over to the hot leg. This procedure conservatively minimizes the hydraulic equivalency for each tube support plate sleeve configuration.

Hydraulic Equivalency Sensitivity Study

In order to confirm previous evaluations with respect to the most conservative values for sleeve configuration and operating conditions, a sensitivity study was performed with the Model D. Sleeve configurations with one tubesheet sleeve and up to 12 tube support sleeves, presented in Figure 3-20, were used as the reference configurations. The following four cases made up the sensitivity study.

Reference case, tube support plates in the cold leg, conservative operating conditions (high primary flow and T_{hot}, low T_{cold})

Sleeves shifted to the hot leg

Least conservative operating conditions (low primary flow and T_{hot}, high T_{cold})

LOCA operating conditions

The operating conditions for the various cases are as follows:

	Model D Operating Condition		
Parameter	Reference	Least Conservative	LOCA*
Primary Flow	100000 gpm	89000 gpm	20000 lbm/hr
Primary T_{hot} - °F	620	612	522
Primary T_{cold} - °F	534	558	522
Primary Pressure-psia	2250	2250	37

*LOCA conditions are superheated vapor during the reflood phase

Table 3-27 presents the hydraulic equivalency values for the sensitivity study cases. For each variant from the reference case, the ratio to the reference case hydraulic equivalence value is also tabulated. The table shows that in every case, the reference equivalency ratio is equal to or smaller than the variants. The equivalency numbers of Figures 3-20 through

3-22, therefore, can be used as bounding values for each model, all sleeve configurations and at all 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.. These calculations may be provided before or during the outage preparation.

The method and values of hydraulic equivalency and flow loss per sleeved tube outlined above can be used to represent the equivalent number of sleeves by the following formula:

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

where,

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

3.2.3 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 per cent of the tubes in a steam generator are plugged.

Using the conservatively high primary flow rates defined previously for the various models with 20 per cent of the tubes plugged, the fluid velocities through an unplugged and unsleeved tube are in the range [ ]^{a,c,e}. For a tube with a single tube support plate sleeve, the local velocity in the sleeve region is computed to be [ ]^{a,c,e}. These velocities are smaller than the inception velocities for fluid impacting, cavitation, or

erosion-corrosion for Alloy 600 and 690 tubing. As a result, the potential for tube degradation due to these mechanisms is low.

Table 3-27
Hydraulic Equivalency Sensitivity Study

a,c,e

[ ]

a,c,e

Figure 3-20
Hydraulic Equivalency Number 3/4 In. OD Tube, Model D SG

a,c,e

Figure 3-21
Hydraulic Equivalency Number 3/4 In. OD Tube, Model E SG

a,c,e

Figure 3-22
Hydraulic Equivalency Number 3/4 In. OD Tube, FSG

3.3 Sleeved Tube Relative Flow Induced Vibration Assessments

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

Results from these assessments are intended to show that the limiting cases of a tube modification caused by laser welded sleeves do not cause significant potential field issues with respect to FIV responses. These results, along with the experience that FIV problems have not occurred in field SG straight-legs, either of FSG or PSG design, are intended to provide adequate assurance that laser welded sleeves are acceptable in each of the designs considered.

3.3.1 Flow Induced Vibration Evaluation Methodologies

Westinghouse capabilities and methodologies for the evaluations of flow induced vibrations are under continuous development (see References 7 through 15). To perform the subject evaluations a relative analysis method was developed and used. This relative method is described below.

The first case considered for each laser welded sleeve configuration was that a laser welded sleeve has been installed in a tube and, at the same time, the tube is conservatively assumed to be severed through 360 degrees of arc at some location within bounds of the length of the sleeve. The second, and reference case, is that of the unmodified (nominal) tube. Ratios of the vibration responses for these cases provide the desired relative results, which are then put into perspective relative to actual field and test operating experiences to provide the required demonstration of acceptability. These evaluations address three specific laser welded sleeve (off-nominal) configurations. They are characterized as: [ ],[a,c] [ ][a,c] and [ ][a,c] These configurations are defined in Table 3-28 and in Figures 2-1, 2-2, and 2-3, respectively.

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

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

Another Westinghouse computer program, WECAN, provides for the generation of a finite element model of the tube and tube support system in the form of a linear superelement. The finite element model provides the vehicle to define the mass and stiffness matrices for the tube system as well as the geometry of the tube and tube support plate. This information is used to determine the modes (eigenvalues) and mode shapes (eigenvectors) for the linearly supported tube being considered. Table 3-29 provides the tube and sleeve cross sectional properties used in the creation of the 20 developed superelements. Schematics of the superelements showing the tube, tube support, and salient structures geometry and node designations are provided in Tables 3-30 through 3-32. Table 3-30 gives this information for the Models D, Table 3-31 is for the Model E1/2, and Table 3-32 addresses the FSGs.

Inputs to the FASTVIB code are, typically, the mass and stiffness matrices, the secondary fluid flow velocity and density distributions, a set of pre-determined permissible boundary conditions for each tube (or tube span) in the bundle to be evaluated, the fluidelastic constant, beta, and damping appropriate to the flow, boundary conditions, and the lower limit value to the reduced velocity parameter. Because the present evaluations are relative, however, several of these inputs are not required. Notable among these are the velocity distributions and the beta values.

The secondary side fluid density distributions used for the present evaluations were developed from three-dimensional flow studies for each of the SG models being considered. For the Models D and E, ATHOS computer code results were used. The FSG distributions were based on the THIRST code as reported in Reference 16. Density as a function of elevation was extracted from these code results in a region of the cold leg near the

periphery of the bundle. These density distributions were intentionally chosen to provide conservative evaluation results as they have nearly the highest values in the bundle at the selected full power operating conditions. They are given in Table 3-33 for each of the relevant SGs along with the associated equivalent tube density profiles. It is these latter profiles which are input to the WECAN superelement models to form the tube mass matrices.

These evaluations are intentionally and conservatively limited to hot leg geometries for each SG model. (Additional dynamic structural evaluations would be required to verify in the cold legs of PSGs because of the additional effects of the preheater crossflow.) Specific boundary conditions considered for each tube location are typically obtained on the basis of results from the application of Monte Carlo methods. However, in this present evaluation, the boundary conditions considered are conservatively chosen as up to two missing tube supports at the four lowest (true) tube supports a.k.a., TSPs on the hot leg side. Included in these conditions are: 1) all supports active, 2) any one support inactive, 3) any two supports inactive, including the conservative case of two consecutive supports inactive. In all cases the fifth and higher supports are assumed to provide pinned tube support.

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

3.3.2 Effects of Damping on Relative Evaluations

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

In order to establish the magnitude of the effects of damping on the FIV evaluation results and the difference in these damping effects given different damping relations associated with different SG straight-leg conditions, a parametric evaluation was completed. This evaluation was accomplished before the final relative evaluations and was intentionally made independent of the mode shape integral effects. Results from these parametric evaluations are provided in Figures 3-23 through 3-26. These four figures illustrate the basis for our developed damping position for these laser welded sleeve FIV evaluations. They demonstrate that; 1) it is beneficial to consider damping for these relative evaluations of FIV responses at all frequencies and frequency changes due to the introduction of a laser welded sleeve and an assumed severed tube, and, 2) the results are insensitive to the choice of absolute damping relation of which SG model is used. Given this latter result, damping originally developed for a specific SG straight-leg evaluation was chosen for use in all the present laser welded sleeve and nominal tube configuration evaluations. Based on physical considerations associated with the various tube / sleeve configurations, it is expected that this chosen damping relation is relevant and conservative for laser welded sleeve configurations and relevant for the nominal configurations.

3.3.3 Flow Induced Vibration Results and Conclusions

The subject laser welded sleeve FIV evaluation results are provided on Table 3-34. As can be seen from this table, each of the five SG configurations forms a sub-table. On each of these sub-tables both fluidelastic and turbulence results are presented for all the boundary conditions considered and for each of the three sleeve configurations considered. The boundary conditions are varied between pinned and open at the four lowest true tube support plates. Again, each individual result is the ratio of the FASTVIB predicted response for the vibration mechanism and sleeve configuration indicated at the top of the columns to the FASTVIB predicted response for the nominal sleeve configuration subjected to the same mechanism and conditions.

Fluidelastic Stability

The Model D3 results show that there are only three configurations with a ratio exceeding 1.10, which implies a 10 percent increase for the sleeved configuration over nominal. The first of these is for the ELEV sleeve, a.k.a., ETS, configuration and shows about 21 percent increase for the case of open boundary conditions at the lowest two (consecutive) plates. The last two are for the FLTS configuration and show about 29 percent increase for the lowest TSP open condition, and about 53 percent for open boundary conditions at the lowest two (consecutive) plates.

The Model D4 results show that there are five configurations with a ratio exceeding 1.10. The first two of these are for the ELEV sleeve configuration and show about 12 percent increase for the lowest TSP open condition, and about 19 percent for open boundary conditions at the lowest two plates. The last three are for the FLTS configuration and show about 45 percent increase for the lowest TSP open condition, about 48 percent for open boundary conditions at the lowest two (consecutive) plates, and about 28 percent for open boundary conditions at the first (lowest) and third plates.

The Model D5 results are very nearly identical to those for the Model D4.

The Model E results are also very nearly identical to those for the Model D4 with only minor variations in the percentages for each of the (same) configurations (see the table).

The FSG results also show that the same five configurations have a ratio exceeding 1.10. In this case the results for the ELEV sleeve configuration show about 14 percent increase for the lowest TSP open condition, and about 21 percent for open boundary conditions at the lowest two plates. The last three are again for the FLTS configuration and show about 38 percent increase for the lowest TSP open condition, about 53 percent for open boundary conditions at the lowest two (consecutive) plates, and about 16 percent for open boundary conditions at the first and third plates.

Because there are no known unacceptable cases of straight-leg fluidelastic vibration and wear conditions in SGs where design conditions are prevalent at any of the field units where the subject SG models are employed, the fluidelastic stability ratio increases implied by the results discussed above and presented in Table 3-34, are expected to be acceptable.

Turbulence Response

The turbulence response results show that there are more cases where the turbulence ratios exceed 1.10 than there are fluidelastic cases for the same S/G model. However, it is well known on the bases of both tests and field results that the absolute turbulence response for the nominal condition case for the hot leg in any of the S/G models considered is quite small, on the order of tenths of mils. Thus, it is fully expected that there would be no real vibration and wear issues introduced into any of these S/G models if the turbulence amplitudes were increased by the largest ratio in the table, which is about 3.5. It is also expected that, at these higher amplitudes, the turbulence response would remain below the

endurance limit and, therefore, would not change the tube / sleeve system fatigue evaluation outcome relative to the nominal case.

Table 3-28
3/4 Inch Tube Laser Welded Sleeve Evaluations
Sleeve Position Definitions and Lengths

a,c,e

Table 3-29
3/4 Inch Tube Laser Welded Sleeve Evaluations
Tube and Sleeve Cross Sectional Properties

a,c,e

Table 3-30
Laser Welded Sleeve Superelement Geometry and Nodes for Models D3, D4 and D5 SGs

a,c,e

Table 3-31
Model E2 LWS Superelement Geometry and Nodes

a,c,e

Table 3-32
FSG (Specific Case) LWS Superelement Geometry and Nodes

a,c,e

Table 3-33
Laser Welded Sleeve Relative Evaluations
Tube Density Distribution Estimates

a,c,e

Table 3-34
Relative Flow Induced Vibration Evaluation
Results for Laser Welded Sleeve Configuration
with Various Tube Support Plate Boundary Conditions

a,c,e

a,c,e

[ ]

Figure 3-23
LWS Effects on Stability Ratio

[ ]a,c,e

[ ]a,c,e

a,c,e

[ ]

Figure 3-24
LWS Effects on Stability Ratio

[ ]a,c,e

[ ]a,c,e

a,c,e

[ ]

Figure 3-25
LWS Effects on Turbulence Response

[ ]a,c,e

[ ]a,c,e

a,c,e

[ ]

Figure 3-26
LWS Effects on Turbulence Response

[ ]a,c,e

[ ]a,c,e

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4.0 MECHANICAL TESTS

Mechanical tests are used to provide [

]a,c,e

Mechanical testing for the tubesheet sleeve lower joint is primarily concerned with leak resistance and joint strength, including fatigue resistance. Note that leak testing is not performed for the laser welded joint, because as a welded structure, the laser welded joint is taken as leak tight. A consistent characteristic observed in the testing of MIF lower joints for sleeves 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 temperatures and other applied-load conditions. This result obviates all of the combined, or separate elevated temperature, leak tightness and applied-load types of tests, and permits qualification of the 3/4 inch sleeve-to-tube MIF lower joints on the basis of the RT leak tightness test and the previous testing. During testing, some of the specimens were subjected to cyclic thermal and mechanical loads, simulating plant transients. [

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

Section 4.1 summarizes previous mechanical tests and results for 3/4 inch tube sleeve MIF joint, within-tubesheet, lower joints which are applicable to the installation of the MIF lower joint of this tubesheet sleeve in 3/4 inch tubing, based on confirmatory room temperature leak tightness pressure tests. Section 4.2 summarizes previous mechanical tests and results for the within-tubesheet, MIF joint, lower joint of the 7/8 inch sleeve. The 7/8 inch sleeve results show the adequacy of obtaining the required strength of the roll expanded portion of the MIF joint, based on optimal roll thinning of the sleeve. This same method is used to achieve the required strength of the roll expanded portion of the MIF joint for the 3/4 inch sleeves.

4.1 Tubesheet MIF Joint Tests – 3/4 Inch Tube Sleeves

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

The mechanical tests of the tubesheet lower joint provided for a feedring 3/4 inch OD (nominal) tube steam generator are applicable to the 3/4 inch OD (nominal) tubes of the PSGs and generically applicable to the other FSGs. The test conditions are listed in Table 4-1 and the generic, allowable,

primary-to-secondary leak rates are listed in Table 4-2. The test results are provided in Table 4-3. As discussed earlier, the MIF joints are formed in tube-to-tubesheet joint unit cells. End caps are installed on the collar and sleeve top, per Figure 4-1, to permit the samples to be pressurized. The end caps are threaded to permit tensile and compressive loading.

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

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

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

The test results for the within-tubesheet MIF joint specimens are presented in Table 4-3. (Note that in the test portions of this report, the units of primary-to-secondary side differential pressures are listed simply as "psi," rather than "psid." The secondary side pressures were zero psig.) For normal operating conditions, i.e., 1485 to 1600 psi at RT and 600°F, [

]a,c,e

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

[

]a,c,e

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

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

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

]a,c,e As stated earlier in this report, if the FSGs or PSGs of individual plants require minor modifications to the qualified MIF joint processes, due to environmental or other conditions, these needs will be addressed in the specific preparations for the repair project. Any additional qualifications will be documented separately, typically in the site specific report (WCAP) during the sleeving outage preparation. (Note: Leak rate measurement is based on counting the number of drops leaking during a 10-20 minute period. Conversion to volumetric measure is based on assuming 19.8 drops per milliliter. There are approximately 75,000 drops in one gallon.)

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

d. Fatigue tests of the MIF joint had no discernible adverse effect on joint leak resistance or structural integrity. [ ]a,c,e

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

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

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

4.1.2 Case No. 2 - Feedring Steam Generator

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

]a,c,e The test conditions are listed in Table 4-4.

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

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

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

From the test results obtained (Table 4-5), the following conclusions were reached:

a. [

]a,c,e

b. [

]a,c,e

c. [

]a,c,e

d. [

]a,c,e

4.2 Tubesheet MIF Joint and Free Span LWS Tests – 7/8 Inch Tube FLTSs

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

The mechanical interference fit joints at the lower ends of the tubesheet sleeves, for the two cases are very comparable. The similarity lies in the [

]a,c,e

Because of the [

] a,c,e

[

]a,c,e As pointed out earlier in this report, if the sleeving of FSGs or PSGs requires minor modifications to the qualified MIF joint processes due to environmental or other unique conditions and this entails testing, these needs and potential tests at RT conditions will be addressed and documented separately.

The test conditions summarized in Table 4-6 (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.

4.2.1 Acceptance Criteria - 7/8 Inch Tubesheet MIF Joint Sleeves

The leak rate criteria that have been established are based on typical Technical Specifications and Regulatory requirements. Table 4-2 shows the generic leak rate criteria for the Series 44 and 51 steam generators. [ ]a,c,e indicate acceptable joint performance.

4.2.2 Results of Testing - 7/8 Inch Sleeves

4.2.2.1 MIF Lower Joint

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

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

]a,c,e

For the tests summarized in Table 4-7, the following joint performance was noted:

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

]a,b,c,e

b. Specimen MS-3: [

]a,b,c,e

c. Specimen MS-7: [

]a,b,c,e

4.2.2.2 Description of Additional Test Programs - MIF Lower Joint With Exceptional Conditions

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

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

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

The specific exceptional tube conditions and changes to the sleeving process parameters tested in the first program, are shown in Table 4-8. Each process operation and sequence of operations employed in fabricating each test sample was consistent with those specified for sleeves to be installed by field procedures. In addition, the exceptional tube conditions and changes to the sleeving process parameters described in Table 4-9 were included in the assembly of tube and collar subassemblies.

4.3 Reference

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

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

a,c,e

Table 4-2
Typical Bounding Maximum Allowable Leak Rates for Feedring - Type and Preheater Steam Generators

d,e

* Based on an example of installation of 2000 tubesheet sleeves with MIF lower joints - for plant. (Note: these allowable leak rates are applied to the MIF joints only; the laser weld joints are hermetically sealed.)

Table 4-3 (Page 1 of 5)
Verification Test Results - Lower Joint (MIF Joint)
Alloy 690 Sleeve for 3/4 Inch Tube (FSG)

a,c,e

Table 4-3 (Page 2 of 5)
Verification Test Results - Lower Joint (MIF Joint)
Alloy 690 Sleeve for 3/4 Inch Tube (FSG)

a,c,e

Table 4-3 (Page 3 of 5)
Verification Test Results - Lower Joint (MIF Joint)
Alloy 690 Sleeve for 3/4 Inch Tube (FSG)

a,c,e

Table 4-3 (Page 4 of 5)
Verification Test Results - Lower Joint (MIF Joint)
Alloy 690 Sleeve for 3/4 Inch Tube (FSG)

a,c,e

[ ]

Table 4-3 (Page 5 of 5)
Verification Test Results - Lowe[illegible] [illegible]oint (MIF Joint)
Alloy 690 Sleeve for 3/4 In[illegible] [illegible]be (FSG)
Notes to Table 4-3

a,c,e

[ ]

Table 4-4
Case No. 2 - FSG
Mechanical Test Program Summary
Tubesheet MIF Joint Tests - 3/4 Inch Tube Sleeves

a,c,e

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

b,c,e

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

b,c,e

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

b,c,e

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

b,c,e

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

a,b,c,e

[ ]

Table 4-6
Mechanical Test Program Summary
Tubesheet MIF Joint Tests - 7/8 Inch Tube Sleeves

a,c,e

Table 4-7 (Part 1 of 3)
Verification Test Results for MIF Lower Joints - 7/8 Inch Sleeves

a,c,e

[ ]

Table 4-7 (Part 2 of 3)
Verification Test Results for MIF Lower Joints - 7/8 Inch Sleeves

a,c,e

[ ]

Table 4-7 (Part 3of 3)
Verification Test Results for MIF Lower Joints - 7/8 Inch Sleeves

a,c,e

[ ]

Table 4-8

Verification Test Results for MIF Lower Joints with Exceptional Conditions for Tube and Sleeve - 7/8 Inch Sleeves

a,c,e

Table 4-9
Additional Verification Test Results for MIF Lower Joints with Exceptional Conditions for Tube and Sleeve - 7/8 Inch Sleeves

a,c,e

a,c,e

Figure 4-1
Tubesheet Sleeve Lower Joint test Specimen

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 advantages 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 un-relaxed 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 steam generators with 3/4 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 - [ ]a,c,e; 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 simulates 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 non-representative 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 [ ]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.

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

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

stress relief of the weld provides a measure of stress relief to the UHE as well. [

]a,c,e

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 thru -3 - The post-weld stress relief was performed only at the laser weld elevation. [ ]a,c,e.

Mockups APR-4 thru -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.

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	Avgerage 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. Stress relief was limited to the weld region and was performed at [ ]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 steam generators with ¾ inch tubing.

5.7 Estimated Sleeve Performance

An estimate of the sleeve performance was performed using experience from previous programs and extrapolating the results where necessary.

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). Two cases were considered for the fixity, one of them being with 47 inch tube span length and the other being with the minimum tube span length that would result in maximum far field stresses. In all cases, the stress relief was performed for the weld and not for the hydraulic expansion.

Tubes Free to Expand Axially

In this case, following thermal stress relief at [ ]a,c,e 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.

Tubes Fixed at the First Tube Support Plate

The average failure time of the mockups with applied axial stress of 15.8 ksi (span length = 47 inches), included in Table 5-5, during corrosion testing was [ ]a,c,e. The average failure time for the roll transitions was [ ]a,c,e. Based on comparison of the failure times of the mockups and the roll transitions, the laser welded tubes will exhibit resistance to PWSCC for periods greater than 20 times the operating time required to crack roll transitions in primary water. The stress relief operation in this case was carried out at a temperature of 1450 to 1500°F. The present practice is to perform the stress relief operation at a temperature of 1350 to 1400°F as indicated in Table 5-6. The lower stress relief temperature will reduce the far field stresses and correspondingly increase the failure time of the laser welded sleeved tubes.

In addition, the life of the laser welded sleeves was estimated for the worst case of far field stresses. Considering the various 0.75 inch tubed SGs, the minimum distance between the top of the tubesheet and TSP1 is 29 inches for Series D3. If the tubes are locked at TSP 1 for this SG, it will result in maximum far field stresses. From the extrapolation of the existing far field stresses data, the stresses for this span length were determined as [ ]a,c,e. Considering that the time to crack the roll transitions is [ ]a,c,e as indicated in the previous example, the laser welded joints are projected to exhibit a corrosion life more than 7 times that required to crack the roll transitions in primary water

A summary of the estimates for the service performance of laser welded sleeve-repaired tubes discussed above, for the different conditions assumed for tube fixity, is provided below. In order to make a conservative estimate of the service performance, the time to crack the roll transition was considered as 1.5 efpy. Roll transitions have not cracked earlier than this time in any of the plants with 0.75 inch tubing.

a,c,e

Notes: (a) Ratios from doped steam results expressed as "equivalent" ratios in primary water

(b) Based on earliest roll transition cracking of tubes with 0.75 inch OD > 1.5 efpy

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, micro-analytical 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 mm (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

(a) Magnitude also depends on temperature and length of tube stress relieved.

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

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

*- Stress relief was well above 1600°F max. of the field process.

Table 5-5
Summary of Fabrication Parameters, Temperatures, Stresses, and Corrosion Test Results for ¾ Inch Sleeve Mockups Tested With Applied Axial Load

a,c,e

Mean cracking time for roll transitions tested with mockup MHEs was 78 hours

Table 5-6
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 and 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

Figure 5-1
Corrosion Test Specimen for Doped Steam Testing of an LWS Joint Without Axial Load

a,c

Figure 5-2
Test Stand Used for Fabrication of 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

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

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

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. Elevated tubesheet sleeve installation consists of the same steps as the FLTS except for the ETS the weld and rolling steps are typically 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 2, 3, and 4.

6.1 Tube Preparation

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

6.1.1 Tube End Rolling (Contingency)

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

Testing of the rolling of all three of the types of tube welds, i.e., tube OD weld (for the protruding tube joint), recessed and flush, has been performed and has been confirmed to be

acceptable based on mechanical considerations. Westinghouse has performed tube end rolling of all of these types of tube welds in the field.

6.1.2 Tube Cleaning

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

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

6.2 Sleeve Insertion and Expansion

When all the candidate tubes have been cleaned, the tube cleaning end effector is removed from the tool delivery robot and the select and locate end effector (SALEE) is installed. The SALEE consists of two pneumatic cam locks, 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. Cam locks 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 SALEEs, translating gripper assembly and the motorized drive assembly which pushes the sleeve to the desired axial elevation. For tube support sleeves, the support is located 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 tube support. 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 LEU 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)

In the tubesheet, the sleeve is joined to the tube by a mechanical interference fit joint, a.k.a., a hard roll (following the hydraulic expansion) performed with a roll expander [

]a,c,e

6.4 General Description of Laser Weld Operation

Welding of the upper tubesheet sleeve joint and the upper and lower tube support sleeve joints is performed 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. (Hardstop positioning may also be used for tubesheet sleeves.) 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 a weld being rejected. In these cases, if the sleeve/tube has not been perforated by the initial weld, an additional weld, having the same nominal characteristics as the initial weld, will be made at the same nominal elevation of the initial weld. If the sleeve/tube has not been perforated by the interrupted weld, or if a perforation of the sleeve 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. If the sleeve/tube were perforated during interruption of the initial weld, the tube would be removed from service.

6.6 Post-Weld Heat Treatment

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, are discussed in Section 5. The data presented in Section 5 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 [ ]^{a,c,e} 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 [ ]^{a,c}. 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. The 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 Inspection Plan

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

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

6.8 References

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

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

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

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

Table 6-1
Sleeve Process Sequence Summary

Step	Step Number	Function
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 Joints
Tubesheet Sleeve Lower Joint Formation	6	Roll Expand Tubesheet Sleeve Lower End
Weld Operation	7	Weld Upper and Lower Support Sleeve Joints
Inspection	8	Ultrasonically Inspect Sleeve Welds (On a sample plan)
Stress Relief	9	Post Weld Stress Relief Sleeve Welds
Inspection	10	Baseline Eddy Current Sleeves

a,c,e

Figure 6-1
Laser Welded Sleeve with Reweld

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 7.4).

   1. Verify minimum required weld width.

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

   1. Demonstrate presence of upper and lower hydraulic expansions.
   2. Demonstrate lower roll joint presence.
   3. Verify weld is located within the hydraulic expansion.
   4. Verify presence of a post weld heat treatment.
   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. The combined Cecco-5/bobbin probe is utilized towards this end to provide an enhanced baseline inspection without sacrificing data acquisition speed. The bobbin probe provides the inspection to verify the presence and location of the expansions, as well as weld location. The Cecco-5 probe provides baseline examination of the sleeve and tube.

7.4 Cecco-5/Bobbin Principles of Operation

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

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

directly underneath the coils of a transmit receive probe. For this reason, the second bracelet is offset relative to the first to achieve full coverage.

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

The calibration standard used for Cecco-5 sleeve inspection includes various axial and circumferential notches as depicted on Figure 7-5. Notches are located in the expansion transitions as well as in the tube and sleeve free span. Figure 7-6 depicts a 20 channel strip chart plot of the calibration standard. The analysis software allows the data from the two bracelets and the bobbin coil to be displayed in an aligned fashion. The channels may be selected so that data from each sensing point is viewed, enabling viewing of an entire tube circumference on a single screen.

Figures 7-7 and 7-8 show the response of the Cecco 5 probe to [
] a,c,e notches in the parent tube at the sleeve expansion transition.

Cecco-5 Probes have been qualified to EPRI Appendix H requirements for detection in 3/4 inch and 7/8 inch sleeved tubing.

7.5 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.

7.5.1 Bounding Inspections

[

]a,c,e

7.5.2 Workmanship Samples

[

]a,c,e

7.5.3 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.

7.6 Inservice Inspection Plan for Sleeved Tubes

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

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

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

The inspection of sleeves will necessitate the use of an eddy current probe that can pass through the sleeve ID. For the tube span between sleeves, this will result in a reduced fill factor. The possibility for tube degradation in free span lengths is extremely small, as plant data have shown that this area is less susceptible than other locations. Any tube indication in this region will require further inspection by alternate techniques (i.e., surface riding probes) prior to acceptance of that indication. Otherwise the tube shall be removed from service by plugging. Any change in the eddy current signature of the sleeve and sleeve/tube joint region will require further inspection by alternate techniques prior to acceptance. Otherwise the tube containing the sleeve in question shall be removed from service by plugging.

7.7 Reference

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

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

a,c,e

Figure 7-5
Cecco-5 Sleeve Calibration Standard

a,c,e

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

a,c,e

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

a,c,e

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