Westinghouse Non-Proprietary Class 3

WCAP-13699
Revision 2
Addendum 1

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

June, 1998

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ENERGY SYSTEM BUSINESS UNIT
NUCLEAR SERVICE DIVISION
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ABSTRACT

Under Plant Technical Specification requirements, steam generator tubes are periodically inspected for degradation using non-destructive examination techniques. If established inspection criteria are exceeded, the tube must be removed from service by plugging, or the tube must be brought 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 using a laser weld, forming a new pressure boundary.

Recent analysis to evaluate revised operating conditions for steam generators relative to the integrity of laser welded sleeves determined that the finite element model used to initially qualify the minimum acceptable weld width of 0.015 inch under-predicted the shear stress in the welds. This report documents analysis and test results used to verify the acceptability of the 0.015 inch minimum weld width for laser welded sleeves. The analysis addresses tubesheet, both full length and elevated, and tube support plate (i.e. plate and/or egg-crate for CE steam generators) sleeves. This analysis applies only to the qualification of the 0.015 inch laser weld. The qualification of the sleeve and tube documented in earlier revisions of the generic analysis, and in plant specific analyses, still applies. Overall, it is verified that the tube/sleeve minimum weld width of 0.015 inch is acceptable and meets the requirements of the ASME Code.

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INTRODUCTION

Under Plant Technical Specification requirements, steam generator tubes are periodically inspected for degradation using non-destructive examination techniques. If established inspection criteria are exceeded, the tube must be removed from service by plugging, or the tube must be brought 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 using a laser weld, forming a new pressure boundary. A schematic showing an installed full length tubesheet sleeve (FLTS) is provided in Figure 1-1.

Recent analysis to evaluate revised operating conditions for steam generators relative to the integrity of laser welded sleeves determined that the finite element model used to initially qualify the minimum acceptable weld width of 0.015 inch under-predicted the shear stress in the welds. Calculations using a refined finite element model in the weld region confirmed that the initial model had under-predicted the shear stress in the welds. It was subsequently determined that the shear stress for the 0.015 inch minimum weld width exceeded the ASME Code allowable.

The design of the laser welded sleeve is predicated on the design rules of Section III of the ASME Code. Section III of the ASME Code provides two alternative approaches to qualify a component: either analysis or experiment. Therefore, the acceptability of the 0.015 inch laser weld was evaluated using pressure tests to establish the pressure retaining capability of the welds (primary stress) and a revised finite element analysis to evaluate fatigue usage in the welds. This report documents the analysis and test results used to verify the acceptability of the 0.015 inch weld width for laser welded sleeves. The analysis addresses tubesheet, both full-depth and elevated, and tube support plate plate (i.e. plate and/or egg-crate for CE steam generators) sleeves.

This report applies only to the qualification of the 0.015 inch laser weld. The qualification of the sleeve and tube documented in earlier revisions of the generic analysis, and in plant specific analyses, still applies. Overall, this effort shows that a minimum width of 0.015 inch for the tube/sleeve weld is acceptable and meets the requirements of the ASME Code.

a,c

Figure 1-1

Schematic of Full Length Tubesheet Sleeve (FLTS)

SECTION 2

ASME CODE REQUIREMENTS

2.1 Introduction

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 (1), 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.

Based on the weld sizing calculations in Section 3.1, the design pressure is the limiting condition, and the 7/8 inch tube is the governing geometry. The ASME Code requires a margin of 3.0, or greater, on the ultimate tensile strength (S_u) of the material, as seen in the Code limit on primary membrane stress intensity (P_m), namely:

$$P_m \leq S_m \ where \ S_m = \frac{S_u}{3}.$$

Appendix II, Paragraph 1230, provides for tests to destruction to qualify piping, and the steam generator sleeve and tubing can be conside[illegible] to be piping. The requirements that must be met using this approach are described below.

2.2 Primary Stress Requirement

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.

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

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

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

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 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.

2.3 Fatigue Requirement

The ASME Code, Reference (1), 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 i^{th} cyclic stress range = n_i / N_i, n_i = number of occurrences for the i^{th} cyclic load combination range, and N_i is the allowable number of occurrences at the stress amplitude for the i^{th} cyclic load combination range, as read from the ASME Code fatigue design (S-N) curves, Figures I-9.2.1 and I-9.2.2 of Reference (1), for the autogenous weld material (Alloy 690).

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

The purpose of the $3S_m$ limit in the ASME Code is to prevent incremental distortion in structures under successive thermal cycles. 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 has been 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 (to about 0.040 inch maximum) 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.

SECTION 3

WELD ANALYTICAL VERIFICATION

3.1 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 3.2. 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 3-1. 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 (0.015 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_o) is the ASME Code limiting value for pure shear given in NB-3227.2 of Reference (1). 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:

$\tau_a = 0.6\ S_m = 0.6\ (26.6) =\ 15.96$ ksi

Test Allowable:

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

Emergency Allowable (largest of the following):

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

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

Faulted Allowable:

$\tau_a = 0.42\ S_u = 0.42\ (80) =\ 33.6$ ksi

A summary of the maximum primary to secondary pressure differentials (ΔP_{max}) is provided in Table 3-1. 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 3-2 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 0.015 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.

---

[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.

3.2 Primary Stress Analysis

3.2.1 Introduction

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 Section 3.1 and Table 3-2, 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 0.015 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 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.

3.2.2 Pressure Test Results

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 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.

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 3-3, 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 3-4. 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 3-4. For those samples where the weld failed during the pressure test, "N/A" is listed for the pull force.

3.2.3 ASME Code Evaluation

As discussed in Section 2.2, 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

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

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 3-4. 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.

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 i^{th} 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 i^{th} test to the pull force for sample 5. The resulting estimated failure pressures are summarized in Table 3-4. 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 3-4. 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 0.015 inch minimum weld width.

3.2.4 Primary Stress Analysis Conclusions

The following conclusions, regarding the pressure retaining capability of the 0.015 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 0.015 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 0.015 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 0.015 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.

3.3 Fatigue Analysis

In the laser welded sleeve (LWS) repair of steam generator tubes, the Alloy 690 sleeve is hydraulically expanded against the host Alloy 600 tube and a laser inside the sleeve is used to autogenously fuse the Alloy 690 sleeve and Alloy 600 tube over the full 360° circumference. The evaluation presented in this section demonstrates that the current minimum required laser weld axial engagement (fused) length of 0.015 inch satisfies the fatigue requirement of the ASME Code, Reference (1), with respect to the specified generic cyclic loads given in Reference (2). The ASME Code fatigue requirement is given in Section 2.3. 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

3.3.1 Geometry and Materials

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.

Geometry

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.

ube 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 0.015 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 (1), 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)

3.3.2 Cyclic Load Conditions

The cyclic loads used in this evaluation 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 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 3-5 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 3-5 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 3-5) 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 3-5, the pressure drops are limited to the design pressure (see footnotes on page 3-2 and to Table 3-1).

3.3.3 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 3-5 using the listed values of T_h and T_{stm} and the above conclusions.

3.3.4 Structural Analysis Models Used in Fatigue Evaluation

Based on the thermal analysis, [

]a,c

As stated in Section 3.1, a state of essentially pure shear exists (on the average) 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

3.3.5 Shear Forces on Weld Due to Unit Loads

The LWS structural finite element models discussed in Section 3.3.4 and shown in Figure 3-2 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 3-6 lists the resulting finite element calculated shear forces due to the above unit loads for each of the 24 possible combinations of [

]a,c

3.3.6 Stress Range Calculations

For any of the 24 combinations of sleeve type, host tube state, and TSP condition listed in Table 3-6 (say the k[th] combination), the shear force F_i on the weld may be found for any of the 71 load events (say the i[th] load event) listed in Table 3-5 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 3-5, 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 3-6 for the k[th] combination. The shear force F_i (in lbf) is divided by the weld's assumed minimum shear area [

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

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

where F_j is the shear force for the loads $(P_p, P_{stm}, T_h, T_{stm})_j$ 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 i[th] 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 in Section 3.3.8. 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.

3.3.7 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.

3.3.8 Calculated Cumulative Usage Factors

Cumulative fatigue usage factors are calculated for each of the [

]a,c listed in Table 3-6 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 in Section 3.3.6 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 3-6 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 3-5. A summary of the resulting calculated weld shear forces and average shear stresses is provided in Table 3-7. Using the transient conditions summarized in Table 3-7, a load histogram is developed to logically order the transients, as shown in Figure 3-6. 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 3-8, for which the calculated cumulative usage factor is [ ]a,c.

Note that load range combination 9 (load 5 in Table 3-5 minus load 19 in Table 3-5), 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.

3.3.9 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 3-4).

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.

Based on the analytical evaluations discussed in Section 3.3, it is concluded that the 0.015 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.

Table 3-1
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 3-2
Ratios of Maximum Calculated Average Shear Stress
to the ASME Code Allowable Shear Stress

a,c

Table 3-3
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 3-4
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 3-5 (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 3-5 (part 2 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 3-6
Calculated Shear Forces (lbf)
on Sleeve/Tube Laser Welds
Due to Indicated Unit Load Cases

a,c

Table 3-7 (part 1 of 2)
Calculation of Weld Forces / Stresses
Generic 3/4 Inch OD Tube

[ ]a,c

a,c

Table 3-7 (part 2 of 2)
Calculation of Weld Forces / Stresses
Generic 3/4 Inch OD Tube

[ ]a,c

a,c

Table 3-8
Max Overall Calculated Cumulative Fatigue Usage Table
[ ]a,c
Min Weld Thk of 0.015 inch & 40 Year Fatigue Design Life

a,c

a,c

Figure 3-1
Schematic of Sleeve, Tube and Weld and
Free Body Diagram of Severed Tube
Showing Shear Force on Laser Weld

a,c

Figure 3-2
Schematic of Structural Models
FLTS, ETS, and TSS Laser Welded Sleeve Types

a,c

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

a,c

Figure 3-4
$q * K_t$ as a Function of Notch Radius

a,c

Figure 3-5
Finite Element Model - Element Layout

a,c

Figure 3-6

Transient Operating Cycle

Generic 3/4 Inch OD Tube

(Transient Numbers Refer to Loads Listed in Tables 3-5 and 3-8)

SECTION 4

SUMMARY AND CONCLUSIONS

4.1 Primary Stress Analysis Summary and Conclusions

The following conclusions, regarding the pressure retaining capability of the 0.015 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 documented in Section 3.2:

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 0.015 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 0.015 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 0.015 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.

4.2 Fatigue Analysis Summary and Conclusions

Based on the results of the fatigue analysis in Section 3.3, the following conclusions are made regarding the cyclic loads on the welds.

1. The overall maximum calculated cumulative fatigue usage factor, fo. .ie two 3/4 host tubes (Westinghouse and ABB-CE) and the three types laser welded sleeves (FLTS, ETS, and TSS), is [ ]a,c for a 40 year fatigue design life and is less than the ASME Code allowable cumulative usage factor of one.
2. A maximum overall cumulative fatigue usage factor calculated using the number of load-unload cycles based on expected plant operation would result in a maximum fatigue usage factor of about [ ], much less than the above [ ]a,c value, which is based on the very conservative number of load-unload cycles specified in Reference (2).

4.3 Overall Structural Conclusions for 0.015 inch Minimum Laser Weld

Overall, it is concluded that the currently licensed minimum weld width of 0.015 inch for the sleeve-tube laser weld is structurally acceptable and meets the requirements of the ASME Code for the specified pressure and cyclic normal, upset and test transient loads.

SECTION 5

REFERENCES

1. ASME Boiler and Pressure Vessel Code, Section III, "Rules for the Construction of Nuclear Power Plant Components," and Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," American Society of Mechanical Engineers, New York, NY, 1989 Edition.
2. Design Specification 412A24, Rev. 0, "Laser Welded Sleeves for 3/4 inch O.D. Tubes of Combustion Engineering Feedring Steam Generators and for Westinghouse Model D3, D4, D5, E1/2 Steam Generators." April 30, 1993 (Westinghouse Proprietary)
3. R. E. Peterson, *Stress Concentration Design Factors*, John Wiley & Sons, Inc., New York, NY, 1953.
4. R. C. Juvinal, *Engineering Considerations of Stress, Strain, and Strength*, McGraw Hill Book Company, New York, NY 1967.
5. H. J. Gough, *Engineering Steels Under Combined Cyclic and Static Stresses*, The Institution of Mechanical Engineers - Proceedings, January - December 1949, Volume 160.