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SPECIFIC APPLICATION OF LASER WELDED SLEEVES FOR THE CALVERT CLIFFS POWER PLANT STEAM GENERATORS

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Abstract

Under Plant Technical Specification requirements, steam generator tubes are periodically inspected for degradation using non-destructive examination techniques. If established inspection criteria are exceeded, the tube must be removed from service by plugging, or the tube must be brought back into compliance with the Technical Specification Criteria. Tube sleeving is one technique used to return the tube to an operable condition. The purpose of this evaluation is to establish the applicability of a generic laser welding sleeving analysis for 3/4 inch diameter tube feedring-type and Westinghouse preheater steam generators (WCAP-13698, Rev. 2) to the Calvert Cliffs steam generators.

All of the sleeve design, mechanical testing, stress corrosion resistance testing, installation processes and nondestructive examination discussed in the generic report apply directly to Calvert Cliffs.

Based on the combined results of this evaluation and the generic evaluation (WCAP-13698, Rev. 2), the laser welded sleeves are concluded to meet applicable ASME Boiler and Pressure Vessel Code and regulatory requirements for Calvert Cliffs. The allowable plugging margin for sleeve degradation is 40%.

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1.0 Introduction

This report documents the results of an analysis to evaluate the applicability of the generic laser welded sleeving analysis for 3/4 inch diameter tube feedring-type and Westinghouse preheater steam generators (WCAP-13698, Rev. 2) to the Calvert Cliffs Units 1 and 2 steam generators. In performing the generic analysis, transient loads are used that umbrella the steam generators in question. Included in the generic analysis are calculations to determine minimum wall thickness requirements for the sleeves. These calculations are a function of plant operating parameters, which vary from plant to plant, and which can change with the implementation of operating or system modifications. The purpose of this evaluation then, is to compare the current set of transient and operating parameters for Calvert Cliffs to those used in the generic analysis, with the intent of confirming that the generic analysis provides a bounding analysis for Calvert Cliffs, and to also remove any conservatism in the generic analysis for minimum wall thickness, if possible. The results of this analysis are based on transient data supplied by Baltimore Gas and Electric Company in Reference 5.

In establishing the structural adequacy of the laser welded sleeves in the generic analysis, criteria were evaluated for primary stress limits, maximum range of stress intensity and fatigue, and minimum wall thickness requirements. The load conditions applicable to each of these areas are reviewed in this analysis to establish the applicability of the generic analysis. In general, the discussions to follow provide only a brief overview of each area. More in-depth discussions are contained in Reference 1 for the generic analysis.

2.0 Sleeve Design and Description

The sleeve design, as shown in Reference 1, including the design documentation, is directly applicable to Calvert Cliffs, without exception. A weld qualification, specific to Calvert Cliffs, will be performed, if necessary, as part of the preparation for the site work.

3.0 Analytical Verification

3.1 Applicable Loading Conditions

The umbrella loading conditions for the generic analysis are defined in Reference 2, and are based on a review of the applicable design specifications for CE feedring steam generators and for Westinghouse Model D3, D4, D5 and E1/E2 steam generators. The applicable loading conditions for Calvert Cliffs steam generators are those supplied by Baltimore Gas and Electric for use in this evaluation (Reference 5).

Normal Operation Parameter Ranges

Parameter	Operating Range
NSSS Power	2570 MWt
RCS Vessel T_{avg}	577 °F
Vessel T_{cold}/T_{hot}	550/604 °F
Steam Pressure	850 psia
Steam Temperature	525.2 °F

3.2 Steam Generator Geometry Effects

The CE steam generators at Calvert Cliffs are slightly different from the one that was modeled in Reference 1. The major difference is that the tubesheet is thicker in the Calvert Cliffs steam generators. Table 1 was constructed to determine the effect of this difference on the deflections and bending stresses in the perforated part of the tubesheet. Plate bending equations from Reference 3 (Table 24, Case 2b) were used to compare the stresses in the perforated part of the tubesheet for the two geometries.

As can be seen in Table 1, deflections and stresses calculated for the Calvert Cliffs steam generators are less than those obtained in Reference 1 for the CE steam generators with thinner tubesheets. Thus the results obtained for the CE steam generator in Reference 1 are conservative when applied to the CE steam generators at Calvert Cliffs.

3.3 Sleeve/Tube Contact Pressures

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

Loads are imposed on the sleeve as a result of tubesheet rotations under pressure and temperature conditions. A 2-D axisymmetric finite element analysis of a CE tubesheet, channel head, and lower shell was performed in Reference 1. The previous section established that the results from that analysis are conservative when applied to the Calvert Cliffs steam generators. The model is shown in Figure 1. This yielded displacements throughout the tubesheet for two pressure and three thermal unit loads. The three temperature loadings consist of applying a uniform thermal expansion to each of the three component members, one at a time, while the other two remain at ambient conditions.

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

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

This expression is used to determine the radial deflections along a line of nodes at a constant axial elevation (e.g. neutral axis) within the perforated area of the tubesheet. A fifth order polynomial is fit to the U_R versus R data so that U_R may be expressed as a continuous function of the tubesheet radius.

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

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

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

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

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

This hole expansion includes the effects of tubesheet rotations and deformations caused by the system pressures and temperatures. It does not include local effects produced by interactions between the sleeve, tube, and tubesheet hole. Thick shell equations from Reference 4 in combination with the hole expansions calculated from the finite element model displacements are used to calculate the contact pressures between the sleeve and tube, and between the tube and tubesheet.

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

3.3.1 Normal Operation

The temperatures and pressures for normal operating conditions at Calvert Cliffs are:

Primary Pressure	=	2235 psig
Secondary Pressure	=	835 psig
Primary Fluid Temperature (T_{hot})	=	604 ^{o}F
Secondary Fluid Temperature	=	525.2 ^{o}F

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

3.3.2 Faulted Condition

The temperatures and pressures for the limiting faulted condition are:

Primary Pressure	=	2235 psig
Secondary Pressure	=	0 psig
Primary Fluid Temperature (T_{hot})	=	348 ^{o}F
Secondary Fluid Temperature	=	304.2 ^{o}F

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

3.3.3 Summary of Results

The contact pressures between the sleeve and tube, and between the tube and tubesheet are plotted versus radius in Figures 2 through 4. Results from these figures are summarized in Table 2.

These pressures are for the elevation 4.04 inches below the top of the tubesheet, which corresponds to the top of the hard roll of the ETS. They are conservative for any lower elevation in the tubesheet.

Note that, in all cases, the net effect of the tubesheet rotations, thermal expansions, and pressures is an increase in the contact pressure between the sleeve and tube. This contact pressure is in addition to the interference pressures between the sleeve and tube and tube and tubesheet produced during installation of the sleeves.

3.4 Primary Stress Limits

The limiting pressure loads used in the Calvert Cliffs analysis for evaluating the sleeve primary stresses are summarized in Table 3. In comparing the plant specific loads to the generic loads found in References 1 and 2, with respect to primary stress limits, it has been determined that all of the Calvert Cliffs loads are enveloped by the generic loads.

The limiting stresses for primary stress evaluations are summarized in Table 4. Note that for primary stresses, the limiting condition for the sleeve is with the [

]a,c

3.5 Maximum Range of Stress and Fatigue

In evaluating the maximum range of stress and fatigue, the number of transients, as well as the temperature and pressure fluctuations are significant. A comparison of the transient cycles considered in the generic analysis to the applicable transients for Calvert Cliffs is provided in Table 5. This comparison shows that the generic analysis considers a larger number of transients, and in general, more transient cycles, than are applicable to Calvert Cliffs.

Relative to the temperature and pressure fluctuations, the transient definitions for both the generic and Calvert Cliffs design specifications are defined in terms of changes in applicable parameters from an initial starting point, typically normal operation. Comparing the generic and plant specific transient definitions shows the Calvert Cliffs transients differ slightly from those defined in the generic design specification in terms of the some of the magnitudes. In general, the overall magnitude of the changes are typically bounded by the generic transients. However there are some notable exceptions. [

]a,c. The second and third exceptions deal with the [

]a,c

A summary of the limiting stress ranges is shown in Table 6, along with the accumulated fatigue usage for the limiting cross section.

3.6 Minimum Wall Thickness Requirements

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

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

Where:

P_i = Primary side pressure
P_o = Secondary side pressure
ΔP_i = Primary-to-secondary pressure differential
R_i = Sleeve inside radius
P_m = Allowable stress

A comparison of the calculations to determine the minimum required thickness for the generic effort and for Calvert Cliffs is provided in Table 7. These results show the plugging margin for to be 40% of the nominal sleeve thickness for Calvert Cliffs, versus 38% for the generic analysis.

3.7 Use of Preheat S/G Sleeve in Feedring S/G

An assessment has been made relative to using a sleeve designed for preheat steam generators, which has a [ ]a,c inch outer diameter, in tubes of a feedring-type steam generator, which has a [ ]a,c inch outer sleeve diameter. Relative to structural issues, using the larger sleeve in the feedring-type steam generator, is bounded by the analysis of the [ ]a,c inch outer diameter sleeve in the preheat steam generators.

The critical region of the sleeve is the unexpanded zone, and this is unaffected by placing the larger sleeve in the preheat steam generator. The sleeve geometry in the expanded region will be essentially the same as when using the [ ]a,c inch diameter sleeve, so the tube/sleeve interface conditions will not be significantly affected. Finally, the transition region between the expanded and unexpanded regions of the sleeve will see less of a discontinuity due to the smaller amount of expansion, and is therefore, less limiting than the reference cases.

Thus, it is concluded that use of a [ ]a,c inch sleeve in a feedring-type steam generator is bounded relative to structural issues by the analysis for the reference geometries.

3.8 Conclusions

Based on the combined results of this analysis and the generic evaluation, the following conclusions are made regarding the structural requirements for laser welded sleeves for the Calvert Cliffs steam generators.

1. The laser welded sleeves are concluded to meet applicable code and regulatory requirements.

2. The allowable plugging margin for sleeve degradation is 40% for the Calvert Cliffs steam generators.

4.0 Mechanical Tests

The mechanical tests documented in Section 4.0 of Reference 1 apply directly to Calvert Cliffs. A portion of the mechanical tests in Section 4.0 of Reference 1 determined the resistance to primary-to-secondary leakage for non-welded lower joints and the applicable leakage criteria for full-length tubesheet sleeves for Calvert Cliffs. Confirmatory strength and leak resistance testing has also been performed for sleeves elevated in the tubesheet for the Calvert Cliffs type of tube joint configuration.

5.0 Stress Corrosion Testing of Laser Welded Sleeve Joints

The conclusions reached in Reference 1 for performance of free-span laser welded joints apply directly to Calvert Cliffs. In addition, the following service experience and design considerations are applicable to Calvert Cliffs.

Approximately 12,000 Westinghouse laser welded sleeves have been installed in foreign and domestic plants since 1988. This includes sleeves installed in both 7/8 inch and 3/4 inch tubes. Operating experience has been good with no indication of corrosion, either at the laser weld or the hydraulic expansion of the upper joint, or at the hydraulically expanded and rolled joint in the tubesheet, after five cycles of operation. The performance of tubes that were sleeved by laser welding and stress relieved under conditions that included some degree of lockup between the tube and the support plates has also been good. In one plant there have been no reports of corrosion problems noted after two 18 month operating cycles. The axial tensile stress levels in these tubes from sleeve installation under locked tube conditions have been estimated from laboratory tests to have been less than [ ]a,c. A second plant, with approximately 11,000 tubes sleeved under conditions of lockup, has operated for approximately 9 months with no evidence of corrosion. (Laboratory tests have shown that the axial tensile stresses in these tubes could have been up to approximately [ ]a,c.) NDE of all the sleeved tubes in this plant, and examination of ten pulled tubes revealed no corrosion of the laser welds, the hydraulic expansion transition regions, or the tube bulges that resulted from stress relief under locked tube conditions.

The axial stresses for LWS sleeved tubes in Calvert Cliffs, conservatively assuming that the tubes have complete lockup and have been stress relief heat treated at 1500°F, are estimated to be less than [ ]a,c. This estimate is based on a model developed from laboratory far field stress tests of LWS fabrication under conditions of full lockup. The model includes the effects of span length and stress relief temperature. The difference between the Calvert Cliffs design and the tested design was in the length of the span from the tubesheet to the first tube support structure, i.e., 38 inches versus 47 inches. This difference will have impact on both the resulting bulge and the residual stress on the tube. Considering the difference in span length and the residual stress level obtained in the laboratory tests with a 48 inch span, the residual stress levels for Calvert Cliffs tubesheet sleeves installed under the conditions of maximum lockup are estimated to be less than [ ]a,c. This includes the reduction of residual stress in the tube that occurs by hard rolling the sleeve into the tube/tubesheet after the stress relief operation.

The temperature at which the stress relief operation is conducted has a significant effect on the residual stress level of the sleeved tube. For example, if the stress relief were conducted at 1400°F the resultant residual tensile stress level would be about [ ]a,c, or about 40 percent of that when stress relieved at 1500°F.

Accelerated laboratory corrosion testing of similar tubesheet sleeve configurations under stress levels of [ ]a,c, with results adjusted for the Calvert Cliffs service temperature, indicates resistance to PWSCC-related failures (of the parent tube) for the [ ]a,c residual stress levels estimated for Calvert Cliffs.

6.0 Installation Process Description

The outline of the installation processes in Reference 1 apply directly to Calvert Cliffs. The discussion in Reference 1 was intended to provide an overview; the detailed installation process verification steps are all specified in the individual applicable field service procedures that will be provided by Westinghouse as part of the job. The sequence of the installation steps will be optimized to minimize tube far-field stresses. The following is also applicable and is included for clarification:

The length of the tube heated to temperatures above the minimum stress relief temperature is approximately [ ]a,c inches. Consideration of positioning tolerances of the weld and the heater, and the extent of the zone to be stress relieved, has been included in heater design.

7.0 Nondestructive Examination (NDE) Inspectability

The NDE Section of Reference 1 was intended to specify the installation NDE plan logic and to define the principles of the NDE processes to be used. It applies directly to Calvert Cliffs.

8.0 References

1. WCAP-13698, Rev. 2, "Laser Welded Sleeves for 3/4 inch Diameter Tube Feedring-Type and Westinghouse Preheater Steam Generators Generic Sleeving Report", Westinghouse NSD, Pittsburgh, PA, April, 1995.

2. Design Specification 412A24, "Laser Welded Sleeves for 3/4 inch O.D. Tubes of Combustion Engineering Feedring Steam Generators and for Westinghouse Model D3, D4, D5, and E1/2 Steam Generators", Dated 4/30/93.

3. Roark, R. J. and Young, W. C., *Formulas for Stress and Strain*, Fifth Edition, McGraw-Hill Book Company, New York, NY, 1975.

4. Timoshenko, S., *Strength of Materials, Part II*, Third Edition, Van Nostrand Company, Princeton, NJ, 1956.

5. Fax from C. Smith (BG&E) to A. L. Thurman, "Excerpts from Calvert Cliffs Steam Generator Engineering Specification", Baltimore Gas and Electric Co., September 22, 1995.

Table 1

Tubesheet Comparisons for CE Steam Generators

a,c

Table 2

Minimum Sleeve/Tube Contact Pressures

a,c

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

b,c

(1) These conditions are not defined for Calvert Cliffs

Table 4

Summary of Maximum Primary Stress Intensity

Full Length Tubesheet Laser Welded Sleeve

[ ]a,c

a,c

Table 5
Comparison of Transient Cycles
Generic Series 3/4 Inch OD Tube Steam
Generators versus Calvert Cliffs

a,c

Table 6

Maximum Range of Stress Intensity and Fatigue

a,c

1) With thermal bending stress removed per NB-3228.5(a).
2) Including K_e factors for simplified Elastic-plastic analysis.

Table 7

Comparison of Minimum Wall Thickness Calculations for Sleeves
3/4 inch Diameter Tube Feedring-Type and Westinghouse
Preheater Steam Generators

a,c

(1) Normal Operation

(2) Loss of Load

(3) Feedline Break for Generic, Steamline Break for Calvert Cliffs

a,c

Figure 1. Finite Element Model of CE Channel Head/Tubesheet/Shell

a,c

Figure 2. Contact Pressures for Normal Conditions with an Intact Tube

a,c

Figure 3. Contact Pressures for Normal Conditions with a Separated Tube

a,c

Figure 4.
Contact Pressures for Faulted Conditions with Intact or SeparatedTube

ATTACHMENT (C-3)

NON-PROPRIETARY ABB COMBUSTION ENGINEERING

REPORT CEN-626-NP, REVISION 00

"BALTIMORE GAS AND ELECTRIC CALVERT CLIFFS STATION

UNITS 1 AND 2 STEAM GENERATOR TUBE REPAIR

USING LEAK TIGHT SLEEVES,"

SEPTEMBER 1995

Baltimore Gas & Electric Company
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