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NDE Inspection Length for San Onofre 2 & 3 Steam Generator Tubesheet Region Cold Leg Explosive Expansions

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NDE Inspection Length for San Onofre 2 & 3 Steam Generator Tubesheet Region Cold Leg Explosive Expansions

P.R. Nelson

Chemistry, Diagnostics, & Materials Engineering

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Reviewer: *Official Record Electronically Approved in EDMS*
T.P. Magee, Principal Engineer
Chemistry Diagnostics and Materials Engineering

Approved: *Official Record Electronically Approved in EDMS*
E.P. Morgan, Manager
Chemistry Diagnostics and Materials Engineering

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

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EXECUTIVE SUMMARY

NDE inspection by a qualified non-destructive evaluation technique to a defined inspection length below the top of the tubesheet ensures that steam generator tube burst and leakage requirements are met in the tubesheet region. A hot leg side NDE inspection length was provided in the C* generic topical report for Combustion Engineering designed steam generators (WCAP 16208, Revision 1, Reference 1). This supplement provides the cold leg side inspection length to supplement the hot leg side in the event that a cold leg side examination is performed. The cold leg inspection lengths provided in this supplement have been developed using the methods and test data used in the C* generic topical report.

The cold leg result is slightly greater than the hot leg result reported in the C* generic topical report. The C* generic hot leg result applicable to SONGS 2 and 3 was fixed at 10.4 inches for plant purposes so the slightly longer cold leg result is provided to supplement the hot leg result.

The inspection lengths in the table provide assurance that the NEI 97-06 requirements for leakage are met and that the conservatively derived maximum combined leakage from all tubesheet joints is less than 0.2 gpm for the WCAP 16208, Rev. 1 and the SONGS 2 and 3 cases.

MSLB Case	Leak Rate Criterion (gpm)	Cold Leg Inspection Length Corrected for Dilation and NDE (in.)	Hot Leg Inspection Length Corrected for Dilation and NDE (in.)
Generic Bounding	0.2	10.7	10.4

1.0 INTRODUCTION

1.1 PURPOSE

The Westinghouse Owners Group (WOG) completed a generic Combustion Engineering (CE) designed plant project, including the SONGS 2 and 3 units, entitled C*, that provides an inspection length in the hot leg side of the tubesheet region. The purpose of the testing and analysis program was to develop an inspection length for a portion of the tube within CE-designed tube-to-tubesheet explansion joints that provides statistically reasonable assurance of structural and leakage integrity. The temperature and tubesheet deflection effects considered the hot leg side of the tubesheet only. The cold leg side was not explicitly addressed because the cold leg temperature makes PWSCC for the life of a steam generator a negligible probability of occurrence unless an anomalous tube to tubesheet joint stress condition exists. The highest stress condition would normally be at the tube explansion transition and would therefore be the most susceptible location for PWSCC in the tubesheet region.

This supplement provides the cold leg side inspection length below the tube to tubesheet joint expansion transition for qualified eddy current techniques. Detection and removal of indications within the inspection length developed in this supplement provides a method to ensure that a postulated crack population within and below the inspection length is within the established criteria for burst and leakage. The inspection lengths developed in this supplement are based on a limiting leakage criteria so that a pre-determined assumed flaw population is conservatively postulated to be leaking at the rate determined from the C* test measurements.

The leak based inspection length is dependent on NDE uncertainty and temperature, pressure, and tubesheet flexure at main steam line break conditions. Tubesheet flexure is plant design dependent and the inspection lengths provided in this supplement have been determined using the tubesheet radial location corresponding to the greatest flexure on the basis of the bounding generic case utilized in WCAP 16208 (Reference 1).

Section 2 of this supplement provides the technical approach for determining the cold leg joint inspection distance. The approach is the same as the C* approach for the hot leg inspection distance determination but addresses the effects of differences in hot leg to cold leg temperature and pressure.

Section 3 provides the inspection length determination including adjustments for tubesheet deflection and tube to tubesheet joint contact force adjustments from RCS pressure inside the tube pushing the tube against the tubesheet wall and the differential thermal expansion force accounting for the different thermal expansion coefficients between the tubesheet and the tube materials. The NDE correction factor for the +Point probe is added to the inspection length result so that the joint length can be inspected directly. One further consideration that is not addressed in this supplement is any difference between the top of the joint and the top of the tubesheet. The results provided in this supplement represent the joint length.

Section 4 summarizes the inspection length determination and Section 5 lists the references.

1.2 BACKGROUND

This supplement provides a conservative inspection length of the tube to tubesheet joint on the cold leg side for the SONGS 2 and 3 units. It is a supplement to the C* topical report, WCAP 16208-P, which addressed the hot leg tube to tubesheet joint inspection length determination.

Both SONGS Units 2 and 3 have CE explosively expanded tube to tubesheet joints on the hot leg and cold leg side. Stress corrosion cracking has been detected in the tubesheet region below the tube expansion transition on the hot leg side. Examination to the inspection length ensures that the NEI 97-06 structural and leakage criteria and more restrictive plant-specific leakage criteria are met.

1.3 NDE INSPECTION TECHNIQUE

It is assumed that an NDE probe qualified for detection of axial and circumferential PWSCC in the tubesheet region is to be employed. The current practice for most plants is the use of the +Point probe. However, the results provided in this supplement are applicable to any qualified probe if the inspection length NDE uncertainty is confirmed as applicable and equivalent or conservative.

1.4 SONGS UNIT 2 AND 3 INFORMATION

SONGS 2 and 3 Pertinent Plant Design information:

Units 2 and 3 are a Combustion Engineering design 3410 Megawatt thermal NSSS with recirculating type steam generators. The SONGS units are the gun-drilled process tubesheet drilled hole finishes called "rough bore" in the C* report. The tube to tubesheet joint is a rough bore tubesheet type with CE design explosively expanded tubes. The WCAP 16208 assumption of number of tubes per steam generator is 9,300 or 18,600 hot leg and cold leg tube to tubesheet joints. The number of tubes assumed in this analysis exceeds the number of in-service tubes.

1.5 QUALITY ASSURANCE

This work was completed under the requirements of the Westinghouse Quality Assurance Program (Reference 2).

2.0 COLD LEG JOINT INSPECTION DISTANCE TECHNICAL APPROACH

The technical approach is the method used in the generic C* topical report (Reference 1).

2.1 ACCEPTANCE CRITERION

Acceptable joint length as reported for the hot leg joints in the C* topical report was determined by testing for two categories of concern: pullout load and leak rate. Pullout load and leak rate testing data were compared to industry accepted criteria (Reference 3). As reported in the C* topical report the length needed to ensure both criteria are met was dominated in all cases by the threshold length defined by the leakage criterion. Therefore, the leakage criterion defines the required cold leg tube-to-tubesheet joint length and bounds the inspection length for the cold leg side burst criterion.

The C* generically applied bounding limiting conditions for the leak rate criterion were based on a conservative assessment of conditions during a MSLB event. Leak rate data in the C* analysis was evaluated at a pressure of 2560 psid and 600°F for the development of the hot leg inspection length. The pressure value of 2560 psid corresponds to the pressurizer safety valve setpoint plus 3 percent for valve accumulation less atmospheric pressure in the faulted steam generator. This pressure differential represents the pressure that would be obtained during a main steam line break due to total depressurization of the faulted steam generator with reactor coolant pressure rising to the setpoint of the reactor coolant system safety valves assuming no operator action to modulate or terminate safety injection. This pressure differential represents the limiting pressure that would create the most limiting leak rate.

As in the C* development, the leak rate criterion is based on the generic allowable leakage technical specification limiting condition for operation of 0.5 gpm per steam generator. Operational assessment calculations include assumptions for undetected flaw populations and determine acceptable plant run-time based in part on acceptable end of cycle (EOC) leakage. In the C* generic topical work, the criterion was conservatively limited to one-fifth of the total allowable leakage, or 0.1 gpm, for this single type of flaw (tubesheet region cracking) representing all hot leg joints. The joint length leak rate (determined by testing) multiplied by the number of tubes assumed to be defective that results in a leak rate less than or equal to the leak rate criteria of 0.1 gpm is the plant-specific threshold length for leaks. The C* work determined an inspection length for the hot leg joints based on the assumption that all 9,300 hot leg joints were leaking at the leak rate derived from the C* testing that would cumulatively equal 0.1 gpm. The allowable leak rate on this basis is 1.08E-05 gpm per hot leg joint.

The leak rate criterion for the sum of the cold leg joints and the hot leg joints if all are assumed to be leaking based on the method and reference transient used in Reference 1 is 0.2 gpm or two times the 0.1 gpm used in Reference 1.

Two constraints guided the analysis for the development of the cold leg inspection length:

1. THE ACCEPTANCE CRITERION IS THE NDE INSPECTION LENGTH IN THE COLD LEG TUBE TO TUBESHEET JOINT THAT MEETS 0.2 GPM FOR THE GENERIC (REFERENCE 1) MSLB CASE.

   The 0.2 gpm is two times the WCAP 16208 leak rate criteria of 0.1 gpm based on doubling the number of leaking joints by adding the cold leg joints to the hot leg joint count in the affected steam generator.

   The inspection length must include consideration of the effect on leakage from:

   1. RCS pressure and temperature adjustments to the leak rate test data;
   2. the tubesheet hole dilation caused by tubesheet deflection under primary to secondary pressure differential, and
   3. tube to tubesheet joint contact force adjustment for the tubesheet hole dilation resulting from the internal pressure and the RCS temperature.

2. SCE REQUESTED THAT THE MINIMUM COLD LEG INSPECTION LENGTH BE DETERMINED WITH THE HOT LEG INSPECTION LENGTH NOT GREATER THAN THE CURRENT WCAP 16208 RESULT OF 10.4".

2.2 METHOD DISCUSSION

The method for the determination of the results for the tubesheet region cold leg side NDE inspection is taken from the C* generic topical report, Reference 1.

Limiting conditions for the parameters affecting leak rate have been considered. The combined effects of temperature and pressure as they affect the leak rate are factored into the determination of the NDE inspection length as explained in this section and the next. There are three steps to the determination of the minimum NDE inspection length:

- Determine the undilated joint length necessary to support the leak rate acceptance criterion assuming all joints are leaking. This requires adjusting the test data to the temperature and pressure of the event case;

- Adjust for the equivalent length in the dilated tubesheet hole at the limiting tubesheet radial position under main steam line break conditions using the sum of the forces technique considering the temperature and pressure of the event case;

- Add NDE uncertainty to the adjusted inspection length.

These three steps are addressed in Section 3. The approach for addressing these steps is addressed in this section.

2.2.1. MSLB CASE

The generic CE design MSLB input for temperature and pressure (Thot = 600°F., 2560 psid) is taken from WCAP 16208. Tcold for this case is taken as [ ][(a,b,c)] the temperature corresponding to the peak leak rate as function of temperature determined in the C* generic testing and analysis (Reference 1, Section 4.6).

2.2.2. UNDILATED LEAK LENGTH

The leak rate testing reported in WCAP 16208 was conducted for single tube mockups. The leak rate results from the single tube mockups are plotted in WCAP 16208, Figure 4-2. This supplement adds the cold leg joint leakage to the hot leg leakage for a total leakage from all tube to tubesheet joints. The number of cold leg joints conservatively assumed to be leaking is 9,300. The leak rate criterion of 0.1 gpm was used in WCAP 16208 as a basis value for the determination of the hot leg inspection length for 9,300 leaking joints. Each tube has two joints – hot leg and cold leg side. The combined number of joints per steam generator for both hot leg and cold leg joints is conservatively taken as 18,600. The combined hot leg and cold leg joints for a joint length would leak at a rate of 0.2 gpm. The leak rate per tube to tubesheet joint at a total leak rate of 0.2 gpm for 18,600 joints is 1.08E-05 gpm/joint. This is the same value as the WCAP 16208 basis. That is, the per joint leak rate is the same if the number of joints and the acceptable leak rate are doubled.

The WCAP 16208 hot leg joint length of [ ] inches, the undilated joint length, was determined for the generic MSLB event at a pressure of 2560 psid and 600°F. Analysis of C* test data (Reference 1) determined that the temperature dependent leak rate is maximized at [ ][(a,b,c)]. Therefore, the cold leg specific undilated leak length is determined at a Tcold value of [ ][(a,b,c)]. The WCAP 16208 data is adjusted for temperature and plotted. A 95% upper bound regression line is extrapolated to determine the undilated leak length.

2.2.3. SUM OF FORCES

As in WCAP 16208, a sum of the forces method is used as part of the determination of the equivalent length in the leak vs. length results. The sum of the forces at any elevation z, F_z, is the sum of the contact force; the force due to dilation; the force due to pressure; and the force due to temperature at the joint interface. The dilation force is negative in value.

$$\Sigma F_z = F_c + F_d + F_p + F_t$$

Where:

F_c = joint contact force.

F_d = force accounting for tubesheet hole dilation.

F_p = force from RCS pressure at MSLB differential pressure.
F_t = force from the differential thermal expansion of materials.

Force is distributed over an increment of the joint interface surface. For computational convenience in the deflection finite element methodology, an axial increment of [ ]$^{(a,c)}$ was used in WCAP 16208. The force due to RCS pressure acts on an incremental area on the inside diameter of the tube. The force is transmitted to the outside diameter of the tube and acts on the inside diameter of the tubesheet hole. The tubesheet and tube forces must be equal in equilibrium or steady state condition.

For clarity of the column headings in Tables 3-2 and 3-3, each factor in the sum of the forces method is further defined below.

2.2.3.1 Depth in Tubesheet

This is the length of the joint or the axial position z in the tubesheet in the dilated tubesheet hole in [ ]$^{(a,c)}$ increments. It is the dilated tubesheet hole joint length equivalent to the undilated ("Cumulative No-Dilate Length") tubesheet joint length that meets the leak rate criterion. It is the recommended inspection length without NDE correction at the leak rate criteria assuming all tubes are severed.

2.2.3.2 TS Joint Axial Force (F_c)

F_c is the contact axial force due to the explansion at each incremental elevation or joint length for the SONGS 2 and 3 joint design. Note that for the 95% bound line the extreme values for a small fraction (5%) of tubes are conservatively assumed to have no contact pressure to a joint length up to approximately one inch.

For the bounding generic MSLB case used in WCAP 16208, the solution applicable to the SONGS 2 and 3 units is the slope of the 95% bound line in WCAP 16208, Figure 5-1.

2.2.3.3 Primary to Secondary Differential Pressure and Differential Thermal Axial Force ($F_p + F_t$)

This is the force due to primary to secondary differential pressure plus the force due to the differential thermal expansion between the tube and tubesheet.

2.2.3.4 Initial Axial Force ($F_c + F_p + F_t$)

This is the sum of the TS Joint Axial Force, Primary to Secondary Differential Pressure, and Differential Thermal Axial Force.

2.2.3.5 Dilation Axial Force (F_d)

F_d is the axial force due to dilation which is the reduction of force due to tubesheet flexure from the differential pressure across the primary face to the secondary face of the

tubesheet at MSLB conditions. The results of the tubesheet deflection analysis provided in WCAP 16208 were developed for the hot leg side of the tubesheet. The system pressures are considered if there is a substantial variation between the hot leg and cold leg. The original design reports assume symmetry in the tubesheet for both the cold leg and hot leg sides. The hot leg and cold leg differential pressure deflection forces are essentially the same. The tubesheet deflection analysis is based on a steam line break event assuming a differential pressure of 2560 psid.

2.2.3.6 Net Axial Force ($F_c + F_p + F_t + F_d$)

The net axial force is the sum of $F_c + F_p + F_t + F_d$.

2.2.3.7 Net/Initial Ratio ($F_c + F_p + F_t + F_d$) / ($F_c + F_p + F_t$)

The ratio of the sum of all forces to the sum of the forces without dilation is the fraction of the contact force at MSLB compared to the "unbent" tubesheet condition.

2.2.3.8 Equivalent No-Dilate Length (Net/Initial Ratio x [ ]$^{(a,c)}$)

This is the incremental joint length in the "unbent" tubesheet corresponding to the equivalent "depth in tubesheet" [ ]$^{(a,c)}$ increment joint length in the first column of for the tubesheet at MSLB (or flexed) conditions.

2.2.3.9 Cumulative No-Dilate Length

The joint length at the leak rate criterion of 0.1 gpm for all cold leg joints is indexed in the "Cum. No-Dilate Length" column to the equivalent joint length for MSLB conditions in the "Depth in Tubesheet" column. The undilated joint length determined by the first step in the calculation is selected or interpolated from the values in this column and indexed to the value in the first column. The inspection length, excluding NDE probe positional error, is determined by linear interpolation of the table entries.

2.3. ANALYSIS INPUT

The bounding generic CE design MSLB input is taken from WCAP 16208. The differential pressure used for tubesheet hole dilation and contact force is 2560 psid. The cold leg temperature used in this analysis is [ ]$^{(a,b,c)}$.

2.3.1. Effect of Temperature and Pressure on Leak Rate

Leak rate in the joint varies with temperature and pressure changes. Increased primary to secondary pressure increases flow through a 100% TW flaw from the increase in the forcing function and, for flaws above the tubesheet mid-plane, through reduced resistance to leakage because of the tubesheet hole dilation. A competing effect also occurs in that the increased pressure increases the contact force in the joint above the flaw and increases the resistance to flow.

WCAP 16208 results indicate that a maximum leak rate is achieved at about [ ]^(a,b,c) In all cases there was evidence of hysteresis, showing that changing the temperature affects the leak rate. The values for adjustments to temperature and pressure effect on leakage in this analysis were taken from Reference 1.

2.3.2. Evaluation of Leak Rate Data

In the WCAP 16208 report, the largest leak rate was obtained at MSLB pressure. The cold leg temperature is taken as [ ]^(a,b,c) for this analysis to determine the bounding the cold leg leak rate. The joint length, unadjusted for tubesheet hole dilation and NDE error, that met leakage criteria was calculated using a statistical interpolation method assuming a leak rate criterion of 0.2 gpm for all tubes per steam generator assumed to be leaking.

3. COLD LEG JOINT INSPECTION LENGTH DETERMINATION

The hot leg inspection length was developed in the C* generic topical report. The inspection length with NDE correction is 10.4 inches. The cold leg inspection length is based on the same unadjusted leak rate but is longer than the hot leg inspection length after accounting for the difference in the sum of the forces resulting from pressure and temperature in the cold leg plenum as compared to the hot leg. A cold leg temperature of [ ]$^{(a,b,c)}$ is used for this case as a bounding value based on peak leakage as a function of temperature as determined in the C* generic topical report.

3.1. UNDILATED INSPECTION DISTANCE

The joint length leak rate (determined by testing) multiplied by the number of tubes assumed to be defective that results in a leak rate less than or equal to the leak rate criteria is the threshold length for leaks. In WCAP 16208, the results very conservatively assume that 100% of all tubes in the hot leg joints are severed circumferentially at the defined joint length and thus have an unrestrictive throughwall leak. The measured leak rate then represents only the flow resistance due to the joint without tubesheet deflection. The threshold leak rate based on the 0.1 gpm leak rate criterion utilized from the C* test data for SONGS Units 2 and 3 was determined to be 1.08E-05 gpm per joint based on 9,300 leaking joints from WCAP 16208. The same leak rate per joint applies for a criterion of 0.2 gpm for 18,600 joints. The upper level 95% confidence basis hot leg joint length that meets the leak criteria of 1.08E-5 gpm/tube joint for the SONGS Units 2 and 3 is [ ] inches unadjusted for temperature, pressure, and tubesheet deflection effects. The WCAP 16208 joint length of [ ] inches was determined for the generic MSLB event at a pressure of 2560 psid and 600°F. The Tcold value for the WCAP 16208 case in this analysis is based on the SONGS 2 and 3 specific value of [ ]$^{(a,b,c)}$ which is the temperature value at which maximum leakage would be expected for this joint design based on analysis completed in WCAP 16208. Figure 3.1 is a plot of the Tcold unadjusted leakage length for the WCAP 16208 case. The unadjusted leakage length is [ ]$^{(a,b,c)}$.

3.2 ADJUSTMENTS TO THE INSPECTION DISTANCE - SUM OF THE FORCES ADJUSTMENT

The sum of the forces at any elevation z, F_z, is the sum of the contact force; the force due to dilation; the force due to pressure; and the force due to temperature. The dilation force is negative in value.

3.2.1 TS Joint Axial Force (F_c)

F_c is the contact axial force due to the explansion at each incremental elevation or joint length. A 95% upper bound is derived and plotted in the WCAP 16208.

3.2.2 Primary to Secondary Differential Pressure and Differential Thermal Axial Force ($F_p + F_t$)

The force due to RCS pressure at 2560 psid inside the tube plus the force due to the differential thermal expansion between the tube and tubesheet at [ ]$^{(a,b,c)}$ is equal to [ ]$^{(a,c)}$ pounds-force as illustrated in Table 3-1. This is less than the hot leg value provided in WCAP 16208 for the hot leg because of the decreased temperature on the cold leg side.

3.2.3 Dilation Axial Force (F_d)

The results of the tubesheet deflection analysis provided in WCAP 16208 were developed for the hot leg side of the tubesheet. The original design reports assume symmetry in the tubesheet for both the cold leg and hot leg sides. The generic tubesheet deflection analysis in WCAP 16208 was based on a steam line break event assuming a differential pressure of 2560 psid.

3.2.4 Cumulative No-Dilate Length

The cumulative non-dilated joint length can be indexed to the results from the leak rate tests. The joint length is indexed in this column to the equivalent joint length for MSLB conditions in the "Depth in Tubesheet" column. The inspection length excluding NDE probe positional error is determined by linear interpolation of the results bracketing the [ ]$^{(a,b,c)}$ "Cum. No-Dilate Length" in Table 3-2.

3.2.5 Depth in Tubesheet Length

The interpolated length determined from the sum of the forces is 10.40 inches without NDE correction.

3.3 NDE AXIAL POSITION UNCERTAINTY

Table 3-4 summarizes the corrected cold leg result with and without the addition of the [ ]$^{(a,c,c)}$. As in the C* topical report the W* NDE measurement uncertainties are applied. The EPRI database for NDE techniques provides a qualified technique for the +Point probe detection of flaws in expansion transitions which has been qualified for both Model 51 and CE design steam generator tubes. By extension, based on the fact that the +Point capability is better away from the transition because of reduced probability of probe shoe lift-off, the NDE uncertainties developed for the W* region below the top of the tubesheet are taken here as equivalent for CE-designed units.

Figure 3.1: Tube to Tubesheet Joint Leak Rate Data Scaled to [ ](a,b,c) for ΔP = 2560 psid

(a,b,c)

[ ]

Table 3-1: Primary to Secondary Differential Pressure and Differential Thermal Axial Force (F_p + F_t)

(a,b,c)

[ ]

Table 3-2: Sum of the Forces

(a,b,c)

Table 3-3: Interpolated Depth in Tubesheet Length and Inspection Length

(a,b,c)

[ ]

Table 3-4: Recommended Cold Leg Inspection Lengths

MSLB Case	Cold Leg Inspection Length Corrected for Dilation (in.)	Cold Leg Inspection Length Corrected for Dilation and NDE (in.)
WCAP 16208	10.4	10.7

4. SUMMARY AND CONCLUSIONS

The recommended inspection lengths provided in this supplement are based on methods and results from the WOG C* work for the hot leg tube to tubesheet joints but adjusted for differences in temperature and pressure on the cold leg side for the WCAP 16208 generic bounding MSLB case. The inspection lengths developed meet the leakage criterion of a total of 0.2 gpm for all hot leg and cold leg joints and bound the inspection length for structural integrity. [

]$^{(a,c,e)}$.

Table 4-1: Recommended Hot Leg and Cold Leg Inspection Lengths for SONGS 2 and 3

MSLB Case	Leak Rate Criterion (gpm)	Number of Joints Assumed to be Leaking	Cold Leg Inspection Length Corrected for Dilation and NDE (in.)	Hot Leg Inspection Length Corrected for Dilation and NDE (in.)
Generic C*	0.2	18,600	10.7	10.4

5. REFERENCES

1. Westinghouse Report, WCAP 16208, Revision 1, "NDE Inspection Length for CE Steam Generator Tubesheet Region Explosive Expansions," May 2005.
2. "Nuclear Services Policies & Procedures," Westinghouse Quality Management System Level 2 Policies and Procedures, Westinghouse Electric Company LLC, Pittsburgh, PA, Effective 03/31/04.
3. NEI 97-06, Revision 1, "Steam Generator Program Guidelines," Nuclear Energy Institute, Washington, DC, January 2001.