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WCAP-14680

Qualification of Additional Roll Expansion for the Kewaunee Nuclear Power Plant Steam Generators

Westinghouse Energy Systems

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QUALIFICATION OF ADDITIONAL ROLL EXPANSION FOR THE KEWAUNEE NUCLEAR POWER PLANT STEAM GENERATORS

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ABSTRACT

A process has been qualified to modify the configuration of tube-to-tubesheet joints in tubes which become degraded within the tubesheet region of the Kewaunee steam generators (SGs). In SGs with partial-depth, roll expanded joints, the original expansion extends upward for a short distance from the primary face of the tubesheet. The qualified process described herein addresses degradation in the upper section of the factory tube roll expansion, in the transition between the expanded and unexpanded portions of the tube, and in the tube above the neutral bending plane of the tubesheet. The qualification consists of analyses and tests which quantify the structural effectiveness and leakage resistance of an added roll expansion of a specified length applied either immediately above the original tube expansion or to the portion of the tube approximately 15.5 to 17.0 inches above the bottom of the tubesheet. The original expansion contains the F* ("F-Star") distance, a term heretofore applied both to the sound roll[1] expansion beneath the bottom of the original roll transition and to an additional roll expansion (ARX) performed adjacent to the factory roll. The term F* is also applied within the sound region of the additional roll expansion (ARX) adjacent to the original roll transition. The distance of sound additional roll expansion in the elevated additional roll expansion (EARX) is referred to as elevated F* (EF*). The EF* distance performs all of the functions of the original welded and rolled tube/tubesheet joint and of the F* joint. Either the F* criterion or the EF* criterion apply to a tube degraded in the roll expansion or in the remainder of the tube within the tubesheet.

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[1] The F* distance is sound if it has no detectable degradation (NDD) as determined by non-destructive examination.

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1.0 INTRODUCTION

A program to perform additional roll expansions (ARX) and elevated additional roll expansions (EARX) has been proposed as a means of maintaining tubes in an operational condition within the tubesheet of the Kewaunee SGs. Application of ARX/EARX provides radial interference between the tube and tubesheet, above the original factory "roll", thus ameliorating the effects of potential tube degradation and reducing or eliminating any primary-to-secondary side leakage. The purpose of this report is to document the qualification program which demonstrates the integrity of the ARX/EARX joints proposed for Kewaunee and to confirm the capability of those joints to withstand the limiting conditions of plant operation. A critical element of this effort is the simulation of in-situ sludge characteristics of the tube-to-tubesheet (T/TS) crevice. The qualification test program includes successful demonstration of field installation under adverse tube "lock-up" conditions, capability of the ARX/EARX joints to withstand tensile loads exceeding postulated limiting accident conditions, leak resistance under worst case pressure drop loads, and fatigue cycling representative of the design specification transients. Development of non-destructive examination (NDE) uncertainties on crack elevations is not included in this report.

2.0 DESIGN

2.1 Accommodation of Existing Tube Joint Features

Additional roll expansions, ARX and EARX, are applied to tubes which are degraded in the upper section of the factory rolled joint, in the transition between the expanded and unexpanded portions of the tube, or in the tube below the EF* length. The ARX and EARX enable tubes with degradation in these regions to remain in service, with the ARX or EARX performing the same function as the original tube joint. The ARX/EARX design addresses dimensional constraints imposed by the tube and tubesheet, as well as the modification tooling. These constraints include normal tolerances in tube wall thickness, inside diameter, outside diameter, tube ovality and tubesheet hole diameter.

2.1.1 ARX Design and Basis in the F* Alternate Repair Criterion

The reference design of the ARX/EARX is illustrated in Figure 2-1 and Figure 2-2. The existing roll expansion (RE) performed in the factory is shown beginning at the primary side of the tubesheet and extending upward a short distance. The roll expansion terminates in the roll transition (RT), where the tube reverts to the unexpanded diameter. The top of the RT is referred to as the TRT; the bottom of the RT is the BRT. The ARX is formed immediately above the existing RE while the EARX is formed at an elevation of about 4 to 6 inches below the top of the tubesheet. In the design of the original tube joint, all of the structural and leakage prevention requirements were met by the tube-to-tubesheet weld, however, it has also been demonstrated that all of the functions of the weld are also adequately performed by the factory tube/tubesheet rolled joint.

Due to actual or potential degradation of the tube in the factory RE, an alternate repair criterion known as F* has been developed. Development of F* was Part 1 of a two-part program to address axial or near-axial tube degradation in the RE. The use of the F* criterion obviates plugging or sleeving tubes with NDE indications exceeding the specified maximum allowable depth. F* is the length of sound RE or hardroll between the top of the degradation and the BRT required to resist tube pullout forces during normal operation, faulted, upset and test conditions. The F* length of sound, original roll expansion was also shown to restrict primary-to-secondary leakage to negligible levels during all operating conditions. Below F*, the tube joint can undergo all degradation, including 360° throughwall degradation, and remain in service. The F* configuration is shown in Figure 2-3 (from Reference 2-1). The F* distance for the tubes in the Kewaunee SGs was determined to be 1.12 inches, excluding uncertainty in the determination of the degradation elevation.

Above the F* distance, an EARX of sufficient length, EF*, to provide structural stability and restrict primary-to-secondary leakage may be performed. The EARXs will be located about 4 to 6 inches below the top of the tubesheet as shown in Figure 2-4.

Similarly, the ARX of a certain axial length is designed to provide axial fixity of the tube and resistance to leakage if the original tube joint is degraded or potentially degraded to a "pluggable" extent within the F* region, the roll transition and immediately above the roll transition. These three regions of potential degradation are grouped together and referred to simply as RT degradation. Although this degradation, requiring plugging or sleeving, may be only a single axial crack, the bounding assumption is made that the remainder of the structure below the crack top provides no axial fixity or leakage resistance and that the ARX alone provides that function. Therefore, the ARX, like the EARX, must provide resistance to pullout for primary-to-secondary pressure differentials such as during normal operation and resistance to collapse for the reverse pressure differentials such as during LOCA conditions. Finally, the ARX and EARX are designed to provide resistance to leakage under the respective types of pressure differentials. (Note: ARX cannot be performed over outside diameter (OD) or inside diameter (ID) tube cracks, therefore the site of the ARX must be clear of NDE indications.)

In Part 2 of the program to address RT degradation, axial fixity and leakage resistance are shown to be achieved by the ARX, the axial length of which, excluding ECT uncertainty, may be determined as for F*. The required length of EF* anywhere above the neutral axis of the tubesheet down to the BRT is determined in the same manner as F* is in the original case. However, the EARX must account for the reduction in radial tube-to-tubesheet contact pressure which occurs due to upward tubesheet bending; hence, EF* is longer than F*. The EF* length for Kewaunee is 1.44 inches, not including NDE uncertainty. The length of the EARX is measured downward from the bottom of the upper roll transition to the top of the degradation or to the top of the lower roll transition, whichever is smaller. The degradation which is being addressed is contained within the original RT or above it. The uppermost elevation of the degradation is usually, but not always, the TRT; the downward extent usually is expected to be the BRT. However, the downward extent is unimportant because the entire joint below the TRT of the original RE or the top of the degradation, whichever is higher, is neglected for structural purposes.

The ARX and EARX are shown on Figure 2-1 and Figure 2-2, respectively. The ARX consists of the tube roll expanded by the two roll passes. In Figure 2-1, the ARX begins a short distance below the bottom of the RT. The intentional overlap in tube expansion addresses the expected small variation, caused by normal tolerances during manufacture in the shop, in the location of the bottom of the RT. The ARX includes the RT and extends a distance above the RT. The tested ARX is 1.11 inches in length which conservatively address all lengths of ARX to be installed. Eddy current test indications of the uppermost extent of degradation extending above the TRT may, in rare cases, require an extension of the ARX upward, so that the required length of ARX determined by calculation is installed above the degradation. Extension of degradation a short distance above the TRT can be accommodated within the existing two-pass configuration, consistent with uncertainty of the NDE in determining the degradation top elevation. Accommodation of the maximum extension of degradation beyond the TRT is limited by the tooling "reach" into the tube. A maximum of three full passes is permissible; the top of the top pass is approximately 5.69 inches above the tube end.

In the field, due to NDE uncertainty in the determination of the elevation of the top of the degradation in the factory RE, an additional ARX length may be added to insure that the minimum calculated length of ARX is formed above the degradation. The type of NDE used for determination of elevation of the degradation is almost always eddy current test (ECT). Determination of the elevation ECT uncertainty for ARX is the objective of a separate program and is not reported in this document. However, a potential uncertainty value was selected to define a minimum ARX length. This value was ± 0.200 inch. By adding the positive value of this tolerance, 0.200 inch, to the calculated EF* value, the minimum ARX length may be determined to be 1.30 inch. A 1.11 inch value was used to make most of the ARX test samples. The planned two-pass ARX length of 2.1 inches significantly exceeds the 1.30 inch minimum length. Table 2-1 describes the ARX design.

2.2 ASME B&PV Code and Regulatory Issues

Since the axial length of EARX or EF* meets the same axial fixity and leakage resistance requirements as F* for the original roll, no new regulatory and Code issues are introduced. Table 2-2 addresses these features.

2.3 References

2-1. WCAP-14677, "F* and Elevated F* Tube Alternate Repair Criteria for Tubes with Degradation Within The Tubesheet Region of the Kewaunee Steam Generators, estinghouse Electric Corporation, June 1996 (Proprietary).

TABLE 2-1a: ARX Design (for Factory RE Area)

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Tube joint, ARX Tooling feature, or NDE requirement	Action to meet requirement
Achieve 1.11 inch of ARX above TRT top of crack to be left in service by ARX. Margin should be provided for cracks extending above TRT.	
Expander roll design, to address potential variation in radial extent of expanded tube	
Normal elevation uncertainty of original BRT	
Avoidance of potential water entrapment zone at RT if PWSCC is or were to become throughwall	
Qualification of ARX roll expander	
Achieve adequate overlap between ARX passes	
Add length to ARX to account for ECT determination of indication uppermost elevation.	

TABLE 2-1a: ARX Design (for Factory RE Area)

Tube joint, ARX Tooling feature, or NDE requirement	Action to meet requirement
Provision for additional pass if pluggable degradation is indicated a certain maximum distance (approx. 1.3 inches) above TRT	
ARX tooling adjustments for off-nominal BRT positions	
NDE requirements prior to ARX application	
NDE uncertainties	
NDE requirements after ARX application	

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TABLE 2-1b: EARX DESIGN
(~4–6" BELOW TOP OF TUBESHEET)

Tube joint, ARX Tooling feature, or NDE requirement	Action to meet requirement
Achieve 1.44 inch of EARX starting about 4" below the top of the tubesheet. Margin should be provided for cracks extending above lower roll transition of the EARX.	
Expander roll design, to address potential variation in radial extent of expanded tube	
Avoid water entrapment zone in TS if degradation is or were to become throughwall	
Qualification of EARX roll expander	
Achieve adequate overlap between EARX passes	
Add length to EARX to account for ECT determination of indication uppermost elevation.	
Provision for additional pass if pluggable degradation is indicated a certain minimum distance from the top of the tubesheet	
NDE requirements prior to EARX application	
NDE uncertainties	

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TABLE 2-1b: EARX DESIGN (~4–6" BELOW TOP OF TUBESHEET)

Tube joint, ARX Tooling feature, or NDE requirement	Action to meet requirement
NDE requirements after EARX application	[ ]

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TABLE 2-2: ASME Code and Regulatory Requirements

Item	Applicable Criteria	Requirement	Change From Original Design or Existing Tech Specs?
Tube Design in ARX	Section III	NB-3200 NB-3300, wall thickness	No
	Operating Requirements	Analysis Conditions	No
	Reg. Guide 1.83	SG Tubing Inspectability	No
	Reg. Guide 1.121	Plugging Margin	No
	Tube Properties	Yield Strength, etc.	Unchanged from original condition, per code evaluation method
Tube Joint	10CFR100	Predicted SLB Leak Rate	No
	Technical Specifications	Operating Primary-to-Secondary Leak Rate	No

Figure 2-1: Kewaunee tube-to-tubesheet joint additional roll expansion (adjacent to factory expansion).

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ARX_ROLWPG

Figure 2-2: Kewaunee tube-to-tubesheet joint elevated additonal roll expansion above the midplane of the tubesheet.

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EARX_ROL.WPG

Figure 2-3: Kewaunee tube-to-tubesheet joint additional roll expansion (configuration of tubesheet region F*).

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Figure 2-4: Kewaunee tube-to-tubesheet joint elevated additional roll expansion (configuration of tubesheet region EF*).

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3.0 STRUCTURAL ANALYSIS

3.1 Cyclic Test Load Parameters

As part of the additional roll expansion program, cyclic load tests were performed on prototypic ARX tube-to-tubesheet joint samples to verify that the new joint maintains structural integrity and demonstrates resistance to leakage following the application of alternating loads. The test samples were made with the ARX separate from any other joint between the tube and the simulated TS; therefore, the results are applicable to both the ARX and the EARX. In essence, the specimens were more representative of an EARX joint, and the acronym ARX should be interpreted to mean both the ARX and the EARX within this section. As a result of the denting corrosion or incipient denting corrosion at the top of the tubesheet, the bounding assumption is made that the tubes are clamped at this location. Thus, as the tube undergoes thermal cycling, it experiences alternating axial compressive loads. The purpose of the structural analysis is to define the loads and corresponding number of cycles for the cyclic load test of the ARX tube.

3.1.1 Transient Parameters

A number of potential operating modes have previously been analyzed. Of the several sets of operating parameters, this analysis considers the limiting set of limiting conditions. The parameters of interest are T_{hot} and the primary-to-secondary pressure drop. The limiting value for T_{hot} considered is 615.2 °F, and the limiting value for primary-to-secondary pressure drop is 1524 psi. For Kewaunee, the primary-to-secondary pressure drop is 1567 psi, which is within 3% of the value used for analysis and would be expected to have no significant effect on the results. Temperature and pressure parameters for the normal and upset transient conditions are defined using References 3-1, 3-2 and 3-3 with the above temperature and pressures corresponding to normal operation, i.e., 100% power. A summary of the resulting transient parameters is presented in Table 3-1. Pressure loads are only evaluated at 100% power. Thus, the only transient parameter of interest is T_{hot} and the value used in the analysis conservatively bounds the Kewaunee operating conditions.

3.1.2 Material Properties

The material properties for this analysis, coefficient of thermal expansion and Young's Modulus, are taken from the 1989 edition of the ASME Code, Reference 3-4. The Code of construction for the WPS SGs is the 1965 edition. In that edition of the Code, however, material groupings are very broad, and the corresponding properties are not as well defined as in the later editions of the Code.

Comparing the material composition for the tubesheet (SA-508 Cl. 2a) and the tubes (SB-163) in the 1965 and 1989 editions of the Code shows essentially no change in these materials form 1965 to 1989. Thus, the 1989 properties are applicable to the materials in question. Young's Modulus is not strongly dependent on temperature, and the value used for the analysis is 28.70 x 10^6 psi for SB-163, taken at a temperature of 600°F. (Young's Modulus for the tubesheet is not required for this analysis.)

The coefficient of thermal expansion is more dependent on temperature, particularly the differential thermal expansion between the tubesheet and tube materials. Summaries of the coefficients of thermal expansion between the tube and tubesheet are provided in Table 3-2. In calculating the resulting tube loads, consideration is given to the temperature of the applied load. The differences in values for the coefficients of thermal expansion in the 1965 Code are greater than in the 1989 Code, therefore, it is conservative to use the 1989 Code values.

3.1.3 Calculation of Cyclic Loads

The alternating loads imposed on the tube are due to thermal cycling of the tube and tubesheet. However, there is an additional load resulting from pressure loading of the tube. Since the mechanism that results in the tube being locked in place at the top of the tubesheet will be operative while the plant is at 100% Power (as opposed to cold shutdown), there will be a tensile load due to pressure locked into the tube. During normal operation the differential pressure axial load on the tube is [$]^c$ pounds. Because a locked tube is restrained by the tubesheet during cool down of the plant, the tensile load increases to about [$]^c$ pounds at cold shutdown.

The test samples for the cyclic load test were manufactured in as prototypic a manner as possible. This included the application of the [$]^c$ pound tensile load prior to performing the additional roll expansion. As part of the test piece preparation, strain gages were mounted on the tube prior to the tensioning and rolling process. At the completion of the rolling process (two passes), it was observed that the tensile load had relaxed to essentially zero. The axial load following an optional third pass was compressive and was low. The load relaxation is explainable due to the rolling process resulting in plastic deformation of the tube. Thus, calculations to determine the loads for the cyclic test were based on a zero load condition at cold shutdown.

Calculations to determine the cyclic loads due to differential thermal expansion are summarized in Table 3-3. The transients listed in Table 3-3 are of two types. First, some of the transients begin at an initial temperature and then ramp either up or down to their final temperature. For the second type of transient, T_{hot} ramps up or down from the initial temperature followed by a swing in temperature in the other direction. Referring to Table 3-3, three values of T_{hot} are defined for each transient. The first value corresponds to the temperature at the start of the transient, while conditions "(1)" and "(2)" correspond to values of T_{hot} later in the transient. For transients where the temperature ramps either up or down (does not cycle), T_{hot} at point (1) is the same as at the start of the transient.

Using the T_{hot} values at the three time points, changes in T_{hot} relative to the start of the transient are calculated for conditions (1) and (2). Values for the variations in the coefficients of thermal expansion, α, used in the calculations are taken from Table 3-2, and correspond to the maximum temperature observed during each of the transients. Axial forces, P, in the tube are calculated at the start of the transient, and for time points, "(1)" and "(2)". A range of force (delta) is calculated as a measure of change observed for each transient, and is equal to force for point (2) minus point (1). Since the magnitude of change is of interest, the "delta" is expressed as a positive value.

The axial forces are calculated using the following algorithm.

$$
\begin{aligned}
\Delta L &= L\,\Delta\alpha\,\Delta T \\
\varepsilon &= \frac{\Delta L}{L} = \Delta\alpha\,\Delta T \\
\sigma &= E\varepsilon = E\,\Delta\alpha\,\Delta T \\
P &= \sigma A = E A\,\Delta\alpha\,\Delta T
\end{aligned}
$$

where E = Young's Modulus
A = Tube cross-sectional area = $0.1296\ \text{in}^2$
$\Delta\alpha$ = Variation in α's
ΔT = Temperature change

Using the forces in Table 3-3 as a basis, axial forces to be used in the cyclic test are calculated using the guidelines found in Appendix II of the ASME Code, Reference 3-3. Although the tests to be performed are not fatigue tests in the sense that a member is to be cyclically loaded until a fatigue crack develops and propagates to failure, the Appendix II criteria are judged to be a good guide in establishing the test parameters. Appendix II of the Code requires that an experimental analysis use loads and/or cycles that exceed the in-service loading conditions. For this analysis, the number of cycles will be kept the same for all conditions except Plant Load (Hot Shutdown/Standby to 100% Power) and Feedwater Cycling, and the applied loading increased.

Paragraph II-1520 (g) of the Code provides five criteria (factors) to be evaluated in determining the applicable load factor for the cyclic test. The first two criteria, K_{sl} and K_{sf}, deal with test specimen size and surface finish, which for these tests are prototypic, thus these factors have a value of unity. Factor K_{st} accounts for variations between test and actual temperatures. Since these tests will be performed at prototypic temperatures, this factor also has a value of unity. Factor K_{sc} accounts for differences in fatigue curves at various temperatures, which is not applicable to this analysis. Finally, factor K_{ss} accounts for statistical variation in test results, and must be included in this analysis due to the limited number of test samples, 3 in this case. Factor K_{ss} is calculated as follows,

$$\begin{aligned} K_{ss} &= 1.477 - (0.044 \; x \; \textit{number of replicate tests}) \\ &= 1.477 - (0.044 \; x \; 3) \\ &= 1.35 \end{aligned}$$

The resulting factor, K_{TS}, is the product of the five individual factors. However, since all the factors, except K_{ss}, are equal to unity, $K_{TS} = K_{ss}$.

As discussed above, due to the large number of cycles for Plant Load and Feedwater Cycling, it is desirable to reduce the number of cycles of these events. Appendix II of the Code specifies the minimum number of allowable cycles to be,

$$N_{T\min} = 10^2 \sqrt{N_D} \; .$$

Using this algorithm, the resulting number of cycles for Plant Load and Feedwater Cycling are 13,500 and 13,600, respectively.

When the number of cycles is reduced, an additional factor must be introduced to the applied loading. The additional factors for these two cases are calculated at the bottom of Table 4-4. The first step is to calculate the alternating stress (S_a) at the number of actual load cycles for the applied loading. The second step is to calculate the alternating stress, S_a', corresponding to the reduced number of cycles. S_a' is then multiplied by K_{TS} to get S_a''. The final factor to be applied to the cyclic load is the ratio of S_a'' to S_a'. The values for S_a used in these calculations are taken from the fatigue curve in the ASME Code corresponding to the tube material.

Summarized in the top part of Table 3-4 are the calculations to determine the forces to be used in the cyclic test. Note that some "umbrellaing" of events has been performed. For Umbrella Condition I, the force values are taken so as to bound all of the possible variations in load of the conditions being umbrellaed. The number of cycles is simply the sum of the cycles for the individual events. The conditions comprising the umbrella events are shown beneath each of the conditions.

Based on the results in Table 3-4, it is possible to further reduce the number of necessary cases to be considered in the cyclic test. First, the Small Step Load Increase and Decrease events are judged to have negligible cyclic load, and are not considered further. Second, two additional umbrella conditions are defined. The first is for Cold Shutdown to 100% Power and Primary Side Leak Test, and the second is for Hot Shutdown to 100% Power and Feedwater Injection. The applicable loads and number of cycles are summarized in Table 3-5. Note that the temperature specified for these two conditions corresponds to the lower temperature for the conditions being umbrellaed. This is concluded to be conservative, since radial interference between the tube and tubesheet due to tube expansion will reduce any subsequent leakage, and the lower temperature will result in a smaller radial interference between the tube and tubesheet. Table 3-5 also summarizes the loads and temperatures for the other conditions to be tested.

3.2 References

3-1. Design Specification G-677164, Revision 1, "Reactor Coolant System Series 51 Steam Generators", 12/18/69.

3-2. Design Specification 677031, Revision 4, "Wisconsin Public Service Corporation, Kewaunee Project - Reactor Coolant System "51" Series Steam Generators", R. L. Sylvester, 3/21/75.

3-3 Current Plant Operating Parameters, Fax from K. L. Hull (Kewaunee Nuclear Power Plant) to F. Sadofsky dated 5/7/96

3-4. ASME Code Section III, Appendices, 1989 Edition.

TABLE 3-1: SUMMARY OF TRANSIENT PARAMETERS
(*Based on Conditions for Maximum T_{hot} at 100% Power*)

Transient/Condition	Time	$P_{Primary}$	T_{Steam}	P_{Steam}	T_{Hot}
Cold Shutdown					
Hot Shutdown/Standby	---				
100% Power	---				
Small Step Load Decrease	40				
	150				
Small Step Load Increase	50				
	180				
Large Step Load Decrease	30				
	180				
	540				
	1200				
Feedwater Injection	540				
	3600				
Loss of Load	11				
	26				
	100				
Loss of Power	10				
	1900				
Loss of Flow	140				
Reactor Trip	100				
Primary Side Hydro	---				
Secondary Side Hydro	---				
Tube Leak Test	---				
Primary Side Leak Test	---				
Secondary Side Leak Test	---				

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Table 3-2: Comparison of Thermal Expansion Coefficients for Series 51 SGs Tubesheet versus Tube

1989 Asme Code Properties

Temperature, °F	Tubesheet (SA-508 Cl. 2a)	Tube (SB-163)	Difference, Δα
100	6.50	6.90	0.40
150	6.57	7.07	0.50
200	6.67	7.20	0.53
250	6.77	7.31	0.54
300	6.87	7.40	0.53
350	6.98	7.50	0.52
400	7.07	7.57	0.50
450	7.15	7.64	0.49
500	7.25	7.70	0.45
550	7.34	7.77	0.43
600	7.42	7.82	0.40
650	7.52	7.88	0.36

TABLE 3-3: CALCULATION OF AXIAL TUBE FORCES
Based on Conditions for Maximum T_{hot} at 100% Power

Transient / Condition	Cycles	T_{Hot} (°F)			ΔT_{Hot} (°F)		$\Delta\alpha$	Cyclic Force - lbs			
		Start	(1)	(2)	(1) Start	(2) Start	in/in/°F	Start	(1)	(2)	Delta
Cold Shutdown - 100% Power	200										
Hot Shutdown - 100% Power	18100										
Small Step Load	2000										
Small Step Load	2000										
Large Step Load	200										
Feedwater	18300										
Loss of Load	80										
Loss of Power	40										
Loss of Flow	80										
Reactor Trip	400										
Tube Leak Test	800										
Primary Side	200										
Secondary Side Leak Test	80										

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Tube Area =	0.1296 in^2
Young's Modulus =	2.87E+07 psi
Axial force after rolling	0 lb.
T(reference) =	70°F

(1), (2) = +/- Temperature Extremes

TABLE 3-4: CALCULATION OF AXIAL FORCES FOR CYCLIC TEST

Based on Conditions for Maximum T_{hot} at 100% Power

Transient / Condition	Cycles	Cyclic Force (Analysis) - lbs				K_{TS}	Cyclic Force (Test) - lbs			
		Start	(1)	(2)	Delta		Start	(1)	(2)	Delta
Cold Shutdown - 100% Power	200									
Hot Shutdown - 100% Power	13500									
Small Step Load Decrease	2000									
Small Step Load Increase	2000									
Feedwater Injection	13600									
Umbrella Condition I	800									
Large Step Load Decrease	200									
Loss of Load	80									
Loss of Power	40									
Loss of Flow	80									
Reactor Trip	400									
Primary Side Leak Test	200									
Umbrella Condition II	880									
Tube Leak Test	800									
Secondary Side Loak Test	80									

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Condition	Cycles	S(a)	N_{min}	S(a)'	K(TS)	S_a'' *	S_a'' / S_a
Hot Shutdown - 100% Power	18100	56.65	13500	60.17	1.35	81.23	1.43
Feedwater Injection	18300	56.52	13600	60.08	1.35	81.11	1.44

$* \; S_a'' = S_a' \cdot K_{TS}$

TABLE 3-5: SUMMARY OF TUBE AXIAL FORCES FOR CYCLIC TEST

Based on Conditions for Maximum T_{hot} at 100% Power

Transient / Condition	Cycles	T_{Hot}	Cyclic Force (Test) - lbs			
			Start	(1)	(2)	Delta
Umbrella Condition III	400					
Cold Shutdown - 100% Power	200					
Primary Side Leak Test	200					
Umbrella Condition IV	27,100					
Hot Shutdown - 100% Power	13,500					
Feedwater Injection	13,600					
Small Step Load Decrease	**Loading Judged to not be Significant**					
Small Step Load Increase	**Loading Judged to not be Significant**					
Umbrella Condition I	800					
Large Step Load Decrease	200					
Loss of Load	80					
Loss of Power	40					
Loss of Flow	80					
Reactor Trip	400					
Umbrella Condition II	880					
Tube Leak Test	800					
Secondary Side Leak Test	80					

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4.0 TEST PROGRAM

The parameters of the ARX and EARX processes were established primarily by test. The tests were designed to demonstrate:

(1) the applicability of ARX/EARX of tubes as a corrective action for eliminating leakage or for limiting it to a negligible level, from SG tubes potentially or actually throughwall degraded in a specified portion of the tube joint region, and

(2) the ability of the ARX/EARX joints to perform the same structural function as the original welded joint.

The only mechanism affecting meeting these two requirements for the ARX/EARX joints is the presence of foreign material, primarily sludge, in the T/TS crevice region, at the time of the retrofit expansion. If there were no sludge or other foreign material in the crevice, e.g., water, an extension of the same roll expansion process used during the fabrication of the SGs could be used without additional process development.

4.1 Pre-ARX/EARX Conditions

Because the test joints for these specimens were made as free-standing, the results are applicable to the ARX and the EARX; hence, further references to ARX in this section should be taken as equally applicable to EARX. For the purpose of the process development, four specific cases of crevice conditions relative to sludge in the crevice were considered.

1) No sludge, or a clean condition as a base case. There was no need to test this case; all leakage resistance and strength issues were addressed in Reference 2-1.

2) Soft sludge partially, radially filling the T/TS annulus before ARX and extending over the entire axial length of ARX. The layer of sludge had a nominal radial thickness of ~4 mils, and was applied uniformly to the outside surface of the tube before the tube was inserted in the tubesheet unit cell simulant (collar) for additional expansion.

3) Hard sludge partially, radially, filling the crevice before ARX and extending over the entire axial length of the ARX. The layer of sludge had a nominal radial thickness of ~4 mils, and was applied uniformly to the outside surface of tube. The sludge was also exposed to an inert atmosphere in an oven at

normal plant operation temperatures for an appropriate length of time to achieve the necessary consolidation.

4) Hard sludge, completely filling the crevice. The sludge was as described for condition 3), except that the crevice was completely filled in the radial direction.

4.1.1 Sludge-Free Case

After ARX, any primary side leakage that would pass through the tube to the secondary side must attempt to flow along the interface formed by the tube and the tubesheet in the newly rolled region. If this interface were free of sludge, the resistance would be expected to be sufficient to prevent flow. The tube-to-tubesheet interference fit contact pressure would exceed the fluid pressure and essentially prevent flow at all conditions, even feedline break.

4.1.2 Sludge-Present Cases

The resistance to leakage flow could potentially be lower if the crevice initially contained sludge and this potential reduction in resistance was postulated to affect the leakage flow rate. In the sludge cases, the interference fit contact pressure was also expected to approximate that which was achieved during manufacture in the shop, also preventing flow or limiting it to very low levels. It was expected that the relatively high residual contact pressure, also exceeding the primary side fluid pressure, compressed the sludge, reducing or closing voids in it, thereby preventing or severely limiting flow and resisting erosion due to operation or subsequent cleaning processes which are designed to clean flow paths in the bundle, at and above the first tube support plate.

It was also conservatively postulated that the sludge-to-tube and sludge-to-tubesheet interfaces could exhibit lower friction coefficients than the original (sludge-free) tube-to-tubesheet interface, for both the soft and hard sludge cases. If this were realized, and with the same interference fit contact pressure as in the sludge-free case, the axial fixity would be reduced, in proportion to the friction coefficient reduction. It was assumed that the strength of the sludge-present ARX joint could be determined by structural tests such as pullout resistance, cyclic axial loading and thermal cycling tests.

4.1.3 Potential Beneficial Effect of ARX on Roll Transition Degradation

If there is throughwall degradation in the original roll transition, and if the ARX process is applied in that location, the final state of the degradation after the rolling will be reduced in width with respect to crack opening in the circumferential direction. In addition, there will be a significant residual contact pressure between the OD of the tube and the ID of the TS hole, thus any leakage through such cracks would undergo a large portion of the primary-to-secondary pressure drop at the crack. In essence, there could be a significant resistance to flow in series with the ARX joint. This potential beneficial effect of the rolling was not tested since it might not be present in all cases. In addition, the application of an EARX might result in a residual compressive load on the original roll transition. This would tend to close circumferential cracks, but would also tend to open axial cracks, so excluding any additional resistance to flow in the testing program was appropriate.

4.1.4 Applicability of Westinghouse Simulated Plant Sludge to Tests for Kewaunee

Based on Westinghouse studies of sludges, for instance in one case of sludges from numerous plants, it was concluded that the permeability (resistance to fluid flow) of these plant sludges and of the Westinghouse simulated plant sludge (SPS) are relatively predictable and are within an order of magnitude from the lowest permeability to the highest permeability, in the as-collected condition. It was assumed that the permeability of SPS and potential sludge from Kewaunee, after compression due to ARX, would also be relatively comparable. In the absence of the appropriate physical properties of Kewaunee sludge from neither the planned vicinity of the ARX, nor the top of the tubesheet, it was assumed that the strength and leakage testing may be performed with Westinghouse soft and hard SPS.

Based on studies of removed SGs, only soft sludge is expected in the tube/TS crevice, i.e., in the regions for application of the ARX and EARX processes. Hard sludge is only expected at and above the top of the tubesheet. However, based on small amounts of evidence during installation of sleeve lower joints in this same portion of the tube joint at one other plant, and in the absence of adequate information to the contrary, the conservative assumption was made that hard sludge also existed in the ARX region and testing was performed with it.

It was also expected that the crush strength of the Kewaunee sludge and of the soft and hard SPS will be unimportant after the application of the ARX roll expander. It is expected that the line contact, producing relatively high contact pressures which the roller imparts to the tube ID during rolling, and which is transmitted through the tube wall to the sludge (backed up by the tubesheet hole surface) will reduce the diameters of essentially all sludge particles. This action may reduce the particles of the plant sludge and SPS to a common, typical particle diameter range, thereby tending to cause similar flow resistance and anchoring strength in these sludges and eliminating the need for extensive characterization of plant sludge.

The soft SPS was formed by [

]^{a,c}. The hard SPS deposits were formed by [

]^{a,c}. Westinghouse has considerable laboratory experience in the use of this mixture.

4.2 Test Samples

Test samples were designed, fabricated, and subjected to design tests to verify the results of application of an ARX/EARX program. The specific tests performed were:

Installation
Pull Test
Leak Test
Fatigue Test
Thermal Cycle
EDM Slitted Tubes

Each test specimen was assembled to represent a unit cell of the tube to tubesheet configuration. A unit test cell or specimen is one which has sufficient tube length to bound the ARX and transition effects. For tubesheet specimens, a collar is used to simulate the effect of the tubesheet. Each test specimen was fabricated from prototypical materials and utilized prototypical assembly processes. A unit cell consisted of a 2.25 inch diameter collar fabricated from AISI 1018 carbon steel into which a length of ASME SB 163 Alloy 600 tubing has been rolled to simulate designated field conditions or to provide special test conditions. The primary side of the SG tubesheet only is simulated.

Mechanical testing was applied to specimens with ARX joints made with a range of sludge crevice conditions, excluding no sludge present. To span the range of the hypothetical types of sludge which may be present in the tube to tubesheet region, two distinct types of sludge were individually applied to tube ODs. The sludge was applied in the region were ARX is to be performed in order to simulate in-situ crevice conditions. The simulated sludge consisted of [

]^{a,c}. Sludge composition was derived from characterizations of full depth tubesheet crevice deposits obtained from retired SGs.

Specific tube configurations were selected on the basis of their test purpose, as shown on Figures 4-1 through 4-9. To isolate the portion of the tube containing the ARX from the portion replicating factory installation, the tube segments were fabricated with [ ]^{a,c}, see Figure 4-1. The ARX was applied on the side of the holes opposite to where the factory simulated roll was preformed.

Mechanical testing is concerned primarily with leak resistance and joint strength. During testing, the specimens were subjected to cyclic thermal and mechanical loads and simulated plant operating conditions, including transients. The magnitudes of the forces are determined from plant normal operating conditions and postulated accident conditions. The force loadings considered locking of the tube to the top of the tubesheet and accounted for the attendant differential thermal expansion between the tube and the tubesheet as well as the pressure induced expansion of the tube. In all cases the tests demonstrated that the ARX joint strength exceeds the loading that the ARX joint would receive during normal plant operation or accident conditions. The loading conditions are summarized in Table 4-3.

4.3 Installation Tests

Installation tests were performed to determine the axial load in a *locked* tube following application of the ARX/EARX process. In the absence of denting corrosion at the tubesheet top and/or at the tube support plates, SG tubes are free to move axially during mechanical processes such as the original tube rolling process, or any subsequent rolling process. In the conservatively postulated event that a tube has become locked or fixed at the top of the tubesheet by denting corrosion products, the fixed boundary condition would have originated during normal operation. The difference in thermal expansion coefficients between the carbon steel forging material of the tubesheet and the Alloy 600 of the tubing produces a tensile load on the tube during shutdown. Section 3 of this report lists this load as being approximately [ ]^c at cold shutdown.

The test involved applying a *factory roll* to anchor a 22 inch length of Alloy 600 tubing in a test collar. A suitable end cap was installed on the opposite end. Strain gages were installed to measure axial strains and the tube was mounted in a preloading fixture, Figure 4-2. The test assembly was maintained at room temperature; the tube was preloaded to a tensile force of approximately [ ]^c, and a series of three ARX/EARX passes were applied, Figure 4-3, while strain gage data were collected. The data (Table 4-1) indicated that the ARX/EARX process had reduced axial loads to essentially zero by the end of the second ARX/EARX rolling sequence. Assuming the denting at the top of the tubesheet maintains a clamped tube condition, heatup to operating temperature following ARX/EARX would result in a compressive load at the ARX/EARX transition region. The compressive load would be expected to somewhat reduce the potential for circumferential cracking at the ARX transition region compared to the original roll. It is noted that the presumption of denting at the top of the tubesheet is conservative relative to denting at the first support plate because the tube stiffness associated with the former condition would be significantly greater than the stiffness associated with the latter condition.

4.4 Static Tensile Tests

Static tensile tests were performed to qualify the field parameters (F* length and roll expansion torque) necessary to obtain sufficient T/TS interference to withstand the axial load applied to the tube during the limiting normal or abnormal plant operating condition. There are three components to the T/TS radial interference which anchors the tube during operation:

(1) the ARX, supplemented by,

(2) the difference in thermal coefficient of expansion between the Alloy 600 tube and the AISI 1018 tubesheet, and,

(3) the primary to secondary side pressure difference.

These tests were performed with only the first of these three components, i.e., ARX, at atmospheric temperature and pressure. Accordingly, this approach results in a conservative measurement of the load carrying capability of the joint, because the assistance of temperature and pressure are not included. The maximum load applicable for a tube is [ ]^c, as reported in Reference 2-1.

A typical test specimen, shown on Figure 4-4, consisted of an 18 inch long tube mounted in a 3.5 inch long collar, almost flush with the "lower" end (primary side) and extending 14.5 inch above the "top" (secondary) side. Sludge was contained in the crevice between the tube and the collar. The 3.5 inch collar represents the ARX height above the factory-rolled joint. However, other configurations were also used, e.g., thermal and fatigue cycling specimens.

To perform the tensile test, the test specimen was mounted against a reaction plate on a universal testing machine and was attached to the loading mechanism of the machine. A gradually increasing axial tensile force was applied to the test specimen and the load-deflection curve was plotted. For qualification, the test specimen had to withstand a load of [ ]^c without ARX joint failure. The test results, summarized in Table 4-5, were that all but one of the test specimens readily withstood the required [ ]^c force and, accordingly, are considered qualified for their intended function.

4.5 Leakage Resistance Test

Leak tests are performed to qualify the leakage integrity of the ARX F* joint configuration. Leakage is measured in drops per minute. Each step is maintained for 10 minutes after the first drop occurs, or for 1 hour. A typical test specimen, shown on Figure 4-1, consists of a 10 inch long tube, mounted in a 2.5 inch diameter, 6 inch long collar and extending 2 inches beyond each end of the collar. Sludge is inserted into the tube/collar crevice before the ARX roll is performed to simulate field conditions. The test specimens are generally fabricated with one ARX roll joint, which represents the most conservative geometry.

There are three components to the tube-to-tubesheet radial interference which anchors the tube during operation: (1) the ARX/EARX, supplemented by (2) the difference in thermal coefficient of expansion between Alloy 600 tube and carbon steel tubesheet, and by (3) the primary-to-secondary side pressure difference. This test will simulate these conditions. It is noted that all test specimens are subjected to leak tests, both before and after any other test. Test results indicate that the ARX joint is essentially leak proof and, accordingly, is considered qualified for its intended function. Test data are summarized in Table 4-5.

4.6 Thermal Cycling

The thermal cycling test of the F* joint consists of three parts – leakage testing, followed by thermal cycling at prototype temperature and pressure load, followed by another leak test to assess any leakage change due to the operational duty simulation, for three sludge types.

There are three components to the T/TS radial interference which anchors the tube during operation with primary-to-secondary side pressure differentials - (1) the ARX, supplemented by (2) the difference in thermal coefficient of expansion between the Alloy 600 tube and the tubesheet, and by (3) the primary to secondary side pressure difference. This test was performed with all three of these attributes present, refer to Figure 4-5. The objective of this test is to demonstrate the leakage integrity of the ARX joint under simulated operational duty cycling.

During the leakage test the test specimen is generally connected to a pressure source and subjected to a hydrostatic pressure of 1900 or 2650 psig at ambient and elevated temperatures. After leakage testing, the specimen is subjected to a thermal cycle test at ambient pressure. The thermal cycling consists of subjecting the specimen to a temperature ramp from ambient temperature to 615°F at a rate of less than 200°F per hour. At 615°F the specimen is held for a minimum of 15 minutes and subjected to a down ramp to ambient temperature also at a rate of less than 200°F per hour. The cycle is repeated at least 25 times. Acceptance criteria is low leakage of an average of several drops per minute and no axial movement of the tube in the collar. The test specimens met the acceptance criteria.

4.7 Axial Cyclic Loading Test

This test has been designed to verify that the ARX/EARX process bonds the newly rolled length of the tube to the tubesheet, in the presence of either *hard* or *soft* sludge, well enough that in the postulated event that the tube has become bonded to the top of the tubesheet by sludge and/or corrosion products, the cyclic axial loads due to differential thermal expansion of the tube relative to the tubesheet during the thermal history of the SG will not degrade either the structural bond, or the primary fluid seal between the tube and the tubesheet which is formed by the ARX joint.

The test program utilized tubing samples which had been equipped with fittings to facilitate tube pressurization, leak testing and mechanical loading of the ARX joint. A simulated ARX tube to tubesheet joint was formed which was mechanically isolated from the simulated original tube to tubesheet joint. The ARX joints were rolled in the presence of three types of sludge, into a tube/tubesheet interface at the outer bounds of the tubesheet hole tolerances. A schematic of a typical test sample is shown in Figure 4-6. Rolling parameters are given in Table 4-2.

Test criteria were determined based on the design transients identified for the plant specific (Kewaunee) SG operating conditions. These are listed in Section 3.2

of this report. The resulting enveloping cyclic loading transients are repeated in Table 4-3. The test samples withstood the Axial Fatigue test and the leak test sequence. The results of the tests are provided in Table 4-5.

4.8 Damaged Roll Transition

This program has been designed to verify that Eddy Current Testing (ECT) can identify the type of tube wall flaws that may be associated with the ARX diagnostic process, and secondly, the type of flaws which might potentially be caused by the ARX process. Test samples were fabricated which simulate two types of tube wall cracks which might be encountered. The first type are cracks in SG tubes which might have been detected, thus initiating an *ARX roll*; and subsequently rolled over by the ARX process. The second type are cracks that might form in tube walls or the *new* roll transition region as a result of strain applied during the ARX process.

Tubing Geometry Type 1, Flaw Geometry Group 1 (Refer to Table 4-4): This sample is designed to verify crack identification and to simulate ARX rolling of ID surface cracks which might be detected in the existing roll transition of a SG tube. A group of four simulated cracks 0.005 in. wide, of varying length and depth, are put in the tube sample with crack initiation at the start of the roll transition. (Figure 4-7) The tubing sample is then ARX rolled to produce the ECT specimen shown in Figure 4-8).

The sample was mounted in epoxy and sectioned for metallographic examination. One sample was cut and polished to show cross sections of the four notches. A second sample was polished from the OD surface to provide a longitudinal view of the 0.70 inch through wall notch. Examination of the lateral sections showed that the remaining ligaments associated with notch depths in the range of 70 to 85% tended to fracture. The ligaments associated with notch depths in the range of 40 to 55% did not fracture, but did show reduction area due to the *drawing* process associated with the rolling operation. Examination of the longitudinal section showed that the ARX rolling operation did not significantly extend the *pre-existing* crack in the ARX effected region. (An additional crack approximately 0.001 inches in length was identified in the *drawn* region at the upper end of the 0.70 inch through wall notch.)

Tubing Geometry Type 2, Flaw Geometry Groups 2 and 3 (Refer to Table 4-4): These samples are designed to verify crack identification of ID surface cracks which might be formed either in the ARX/EARX rolled portion of the tube, or in the ARX/EARX rolled transition of the SG tube. A group of four simulated cracks, 0.005 inches wide and of varying length and depth, are put in the tube sample.

Two of the simulated cracks are in the *rolled* portion of the tube, and are arrayed at angles which are oblique to the tube axis, while two of the simulated cracks have crack initiation at the start of the roll transition and are arrayed *on axis*. A representation of this specimen is shown in Figure 4-9.

4.9 Conclusions from Tests

4.9.1 Leakage Resistance:

A summary of the leakage, thermal cycle, cyclic structural and pullout test results is shown in Table 4-5.

Performance for Leakage Test-Only — Sample Numbers 1-8 and 17-19 (as listed in the Table) were used only for leakage test purposes. The results for differential pressures of 1900 and 2650 psig, at room temperature were *overtests* because differential pressures of these magnitudes at room temperature are rare, especially after ASME Code pressure testing. The same differential pressures at elevated temperature, i.e., 600 to 615°F, match or exceed the normal operation and FLB differential pressures, respectively. In the case of normal operation, the typical limit of 1600 psig was exceeded in the test to ensure that the water pressurizing the tube-to-tubesheet interface in the ARX was subcooled. Of the Numbers 1-8 (counting Nos. ARXC15-89 and ARXC19-89 twice) because the ARX was extended from 1.11 inch to 1.65 inch, four of them leaked and four were leak tight. Leakage flows were greater at elevated temperature. The average leak rate for the leaking samples, averaged over all of the data points for those samples was [ ]^{b,c} drops per minute (dpm).[2] Averaging that leakage over all of the tests for those samples reduces the rate to [ ]^{b,c} dpm. It should be noted that the 1.11 inch is the minimum ARX length above the top of degradation confined to the TRT, the 1.65 inch length of ARX above the crack top is more typical. The effect of the added length of ARX was beneficial; the tests involving the minimum length leaked slightly; in the tests involving the greater length, no leakage was observed.

Samples with a greater amount of sludge in the crevice (diametrally) leaked significantly more than samples with a minimal amount of sludge. Samples ARXC6-90 and ARXC7-90 (Table Nos. 7 and 8, respectively, simulated the SG case involving the largest crevice, i.e., the case of the largest diameter tubesheet hole, coinciding with the smallest (unexpanded) tube OD. The other samples simulated the smaller crevice, or a nominal crevice filled only approximately 50% with sludge, i.e., a sludge diametral extent of 0.008 inch before ARX. Samples of the

---

[2] One gallon contains ~75,000 drops, thus one dpm is about 0.02 gpd.

thin sludge type, whether of the *soft* or *hard* type, leaked very little. Samples 17-19 were fabricated to simulate what is expected to be the more typical ARX case, length was 1.65 inches. The average leak rate for these samples was low, [ ]^{b,c} dpm for all data. The "ΔD" for these samples was relatively large. (ΔD is defined in the footnotes of Table 4.9-1 as the difference between the ID achieved in the factory roll and ID achieved in the ARX. Ideally, this difference would be zero, indicating little or no sludge. A large number indicates considerable sludge.) It was intended that Samples 7 and 8 have filled crevices. However, this probably was not realized because the ΔD was relatively small; it wasn't large as it was for other samples such as 11 and 12.

Sample Nos. 17-19, all with the smaller of two pre-ARX crevices (diametrally), were rolled to 1.65 inch ARX lengths. The average leakage was [ ]^{b,c} dpm.

<u>Performance for Pre-Mechanical and Post-Mechanical Test Samples</u> — The leakage resistance for these samples approximated that of the leak test-only samples discussed above. The leakage values for the cyclic, i.e., fatigue, test samples, Nos. 9-12 were [ ]^{b,c} dpm before loading. The *thin* sludge samples were leak tight; the *thick* sludge samples leaked small amounts. The average leakage increased to [ ]^{b,c} dpm after loading.

The average leakage for the thermal cycle samples was [ ]^{b,c} dpm before cycling; the thin-sludge samples having no measurable leakage and the thick-sludge samples exhibiting leakage for slightly over one-half of the tests. The average after cycling leakage was [ ]^{b,c} dpm; the same pattern of measurable leakage for the thick-sludge cases; none for the thin-sludge cases was observed. (Two of these samples, Nos. 15 and 16, were later pull-tested. No leak testing was performed after pulling because it was generally a destructive test.)

The leakage resistance for pull test samples, Table Sample Nos. 23 and 24, was not measured; the values would almost certainly have been low because the crevices were only partially filled, diametrally, before ARX.

4.9.2 Results of Mechanical Tests

<u>Thermal Cycling</u>

The thermal cycle test results were shown in the post-test leak tests discussed above and partially in the pull tests of Sample Nos. 13-16. For these samples, the leakage remained approximately the same or it decreased after cycling. The cycling apparently had no measurable effect on pull-out resistance; the pull-out values were acceptable for Samples 15 and 16.

Cyclic Loading (Fatigue) Test

These samples, Nos. 9-12, remained elastic throughout the test; no inelastic deflections were measured. This showed no slippage; in short, this was successful. The success, as determined by leakage resistance, was discussed above. However, one sample, No. 11, provided a low pull-out resistance result, [ ]^{b,c} lbs. This was less than the required [ ]^{c} lb. requirement. Because this pull-out test failure involved the largest crevice, completely sludge-filled, condition, in the program, a ΔD limit may have to be applied. However, no ΔD limit will be applied if ΔD's are found to be small in the field qualification at Kewaunee. The other thick-sludge sample in this batch, No. 12 exhibited very good pull-out resistance, exceeding the required level by almost a factor of two.

Pull-Out Tests

Of the eight pull-out tests, seven were successful, the one discussed immediately above was the only failure. Thermal cycling and fatigue loading preconditioning appeared to have no significant effect on pull-out resistance.

Conclusions

On the basis of the numerous leakage resistance tests, leakage is predicted to be low, on the order of several dpm per ARX tube, i.e., small compared to the 150 gpd (11.3 x 10E6 dpd) per SG Technical Specification limit.

Structural integrity of the ARX joint was shown to be adequate, with the provision for instituting a ΔD limit if the field qualification indicates a need for it. If used, the limit would eliminate the case of small diametral expansions for the ARX, i.e., large differences between the factory and ARX IDs, indicating an excessive amount of foreign material in a crevice.

TABLE 4-1: ARX INSTALLATION - TEST RESULTS

MEASUREMENTS OF POST-ROLLED ARX JOINTS

	ARX1			Axial Load, lb	
Test Sample	**Indist (in)**	**Torque (in/lb)**	**ID (in)**	**Start**	**Finish**
ARXC-14-89	--	[			]b,c
	--				

MEASUREMENTS OF POST-ROLLED ARX JOINTS

	ARX2			Axial Load, lb	
Test Sample	**Indist (in)**	**Torque (in/lb)**	**ID (in)**	**Start**	**Finish**
ARXC-3-90	--	[			]b,c
	--				

MEASUREMENTS OF POST-ROLLED ARX JOINTS

	ARX3			Axial Load, lb	
Test Sample	**Indist (in)**	**Torque (in/lb)**	**ID (in)**	**Start**	**Finish**
ARXC-5-90		[			]b,c

* Test fixture could apply only tensile loads to tube.

TABLE 4-2: TUBE ROLLING PARAMETERS

	Length	**Reduction in Area**	**Torque (in/lbs)**
ARX Roll	[		]b,c

Device:Airetool No. 1243 roll expander (4-roll), W-16-S Rolls
Rolling Motor:Airetool Model No. 850-600 (600 RPM)

TABLE 4-3: AXIAL FORCES FOR CYCLIC LOAD TESTING

				Force (#)		
Condition	**Cycles***	**Temp.***	**Starting***	**(1)+**	**(2)***	**Δ***
Umbrella II	880	250°F				
Umbrella III	400	400°F				
Umbrella IV	27,100	550°F				
Umbrella I	800	615.2°F				

b,c

Notes: * Tolerance envelope may exceed, but may not be less than this value.
+ Tolerance envelope may be less than, but may not exceed this value.

Leak Test Pressure Values

Normal Operation	1600 psid †
Steam Line Break (plus margin)	3100 psid

† If less than saturation pressure for given temperature, increase pressure to exceed saturation pressure by 100 psi.

TABLE 4-4: EDM PROCESS CRITERIA

Example	Description
Crack Geometry Group 1	
Crack Geometry Group 2	
Crack Geometry Group 3	

b,c

TABLE 4-5

STEAM GENERATOR ADDITIONAL ROLL EXPANSION PROGRAM SUMMARY OF QUALIFICATION TESTS

				Initial Leak Rate (DPM)				Number[1] Thermal Cycles	Number[1] Fatigue Cycles	Final Leak Rate (DPM)				Tensile Force
				Room Temperature		600/615 °F				Room Temperature		600/615°F		
Specimen No.	Sludge Type	(2)ΔD, inch	ARX Length inch	1900 psig	2650[2] psig	1900 psig	2650[2] psig			1900 psig	2650[2] psig	1900 psig	2650[2] psig	lb.
1.ARXC 8-90	HP													
2.ARXC13-90	SP													
3.ARXC15-89	SP													
4.ARXC15-89	SP													
5.ARXC19-89	HP													
6.ARXC19-89	HP													
7.ARXC 6-90	HC													
8.ARXC 7-90	HC													
9.ARXC 8-89	SP													
10.ARXC12-90	HP													
11.ARXC15-90	HC													
12.ARXC16-90	HC													
13.ARXC12-89	HP													
14.ARXC18-89	SP													
15.ARXC 4-90	HC													
16.ARXC10-90	HC													
17.ARXC 1-90	HP													
18.ARXC11-90	SP													
19.ARXC14-90	SP													
20.ARXC14-89	None													
21.ARXC 3-90	None													
22.ARXC 5-90	None													
23.ARXC 2-89	SP													
24.ARXX 2-90	HP													

b,c

S,P = Soft, partially, radially filled crevice H,P = Hard, partially, radially filled crevice H,C = Hard, completely, radially filled crevice Wet = 0 DPM but wet crevice ^ Intermediate leak check

[1] See Section 4 for cycle profile details. *615°F **Preloaded to 1465 lb tensile before ARX, relaxed to zero during second ARX (Installation Test).

***Effective length of expander roll taken as 1.00 inch initially, later measured to be 1.11.

[2] Leakage for ΔP of 2650 psi or for 3150 psi corrected to 2650 psi. (1) Test terminated. (2) $\Delta D = (ID_{FACTORY} - ID_{ARX})$ inch.

FIGURE 4-1
LEAK TEST SAMPLE

b,c

FIGURE 4-2
ARX INSTALLATION STRESS - PRELOAD FIXTURE

b,c

FIGURE 4-3
ARX INSTALLATION - TUBE ROLLING PATTERNS

b,c

*Selected configuration differs slightly from this configuration.

FIGURE 4-4
PULL TEST SAMPLE

b,c

FIGURE 4-5
ARX ROLLED EXPANSION "UPPER" SEAL CONFIGURATION MODIFIED FOR "THERMAL CYCLING" TEST

b,c

FIGURE 4-6
ARX TUBE FATIGUE SAMPLE

b,c

FIGURE 4-7
ARX TEST - TUBE/COLLAR - E/C TUBING GEOMETRY TYPE 1 CRACK GEOMETRY GROUP 1 (BEFORE ARX ROLL)

b,c

FIGURE 4-8

ARX TEST - TUBE COLLAR - E/C TUBING GEOMETRY TYPE 1 CRACK GEOMETRY GROUP 1 (FOLLOWING ARX ROLL)

b,c

FIGURE 4-9
ARX TEST - TUBE COLLAR - E/C TUBING GEOMETRY TYPE 2
CRACK GEOMETRY GROUP 2 & 3

b,c

5.0 INSTALLATION INSPECTION

Field implementation inspections will be performed to assure process control by providing ECT profilometry of the tube ID in the ARX vicinity. The inspections will be performed before ARX. The inspections will be performed after ARX only in the field qualification.